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Reduction Design of End Edge Effect in Stationary Discontinuous Armature PMLSM combined with Skewed Magnets and Stair Shape Auxiliary Teeth

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Abstract – In recent years, a permanent magnet linear synchronous motor (PMLSM) has been used in various kinds of transportation applications for its relative high power density and efficiency. The general transportation system arranges the armature on the full length of transportation lines. However, when this method is applied to long distance transportation system, it causes increase of material cost and manufacturing time. Thus, in order to resolve this problem, we suggested stationary discontinuous armature PMLSM. However, the stationary discontinuous armature PMLSM contains the edges which always exist as a result of the discontinuous arrangement of the armature. These edges become a problem because the cogging force that they exert bad influences the controllability of the motor. Therefore, in this paper we proposed the combination of skewed magnets and stair shape auxiliary teeth to reduce the force by edge effect. Moreover, we analyzed the influence of the design factors by using a 3-D finite element method (FEM) simulation tool.

Keywords: Linear motor, PMLSM, Stair shape auxiliary teeth, End edge cogging force, Finite element analysis

1. Introduction

Recently, current main driving source of Permanent Magnet Linear Synchronous Motors (PMLSMs) is the short-distance transportation system. However, the PMLSM has been more widely used in the factory automation (FA) field such as transportation system than the existing system which uses rotation machine, and has been also used in various kinds of transportation applications for its relative high power density and efficiency [1]. According to these situations, the importance of the long-distance heavy load transportation system in PMLSM is also steadily increasing, and lots of research results are shown [2-4].

The general transportation system arranges the armature on the full length of transportation lines. However, when this method is applied to long distance transportation system, it causes increase of material cost and manufacturing time. Thus, in order to resolve this problem, we suggested stationary discontinuous armature PMLSM (SDAPMLSM) which is able to decrease the number of windings and amount of iron required. Fig. 1 shows schematic representations of SDAPMLSM.

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However, as shown in Fig. 1, when the armature is arranged discontinuously the edge always exists due to the structure. For this reason, the end edge cogging force which is generated between the entrance end (entry interval) and the exit end (ejection interval) has become a problem. Due to the effect of the force that generates at the edge, it has become a problem that the velocity of the mover is different from that commanded velocity when the mover moves from freewheeling to re-acceleration or deceleration [5]. This hunting causes the vibrations and noise in the mover, and in the worst case, step out due to load disturbance. Thus, in the SDAPMLSM, the reduction of cogging force at each edge is highly desirable to ensure the smooth operation of the mover between freewheeling regions. In order to reduce the cogging force, many studies are in progress such as skew of permanent magnet and installation of auxiliary pole and teeth [6]. However, the studies that combine these methods to minimize the cogging force are insufficient. Therefore, in this paper, we installed stair shaped auxiliary teeth which is transformation of auxiliary teeth as the general reduction method of end edge cogging force. Moreover, we analyzed the characteristics of changes in cogging force through 3-D numerical analysis using finite element method and designed the auxiliary teeth of stair shape that minimizes the end edge cogging force.

2. The Basic Model of SDAPMLSM

2.1 The Specifications of SDAPMLSM

The full length of PMLSM's mover which is 264 mm with the 30 degree skewed 8-pole permanent magnets of Nd-Fe-B type was arranged on the magnetic plate. The permanent magnet itself had a length of 26 mm, width of 3 mm, and pole pitch of 30 mm, while the armature had a full length of 360 mm. Winding method utilized in this study was concentrated winding, and the number of turns per one phase was 75. There were 9 slots with slot pitch of 40 mm, and the air-gap between the armature and the mover was 5 mm. The specifications of SDAPMLSM are shown in Table 1.

Table 1. The specification of stationary discontinuous armature PMLSM

	Parameter	Value (Unit)
Armature	Number of slot	9 (slots)
	Slot width (x-axis)	24 (mm)
	Teeth width (x-axis)	16 (mm)
	Teeth height (y-axis)	14 (mm)
	Armature length	360 (mm)
	Slot pitch	40 (mm)
	Winding	Concentrated
	Turns per one phase	75 (turns)
Mover with PM	PM type	Nd-Fe-B
	Residual magnetic flux density	1.25 (T)
	Number of poles	8 (poles)
	Skew angle of PM	30(deg)
	Magnet length (x-axis)	26 (mm)
	Magnet thickness(y-axis)	3 (mm)
	Pole pitch	30 (mm)
	Back iron height	6 (mm)
	Back iron length	264 (mm)
Air gap		5 (mm)
Stack length		50 (mm)

2.2 Skewed Magnets

PMLSM should be set as (1) so that the skew angle of cogging force can cause a phase difference of 180 degree in order to reduce the cogging force efficiently [7].

$$\text{Skew Angle} = \frac{GCD}{2\tau_P} \times 180° \tag{1}$$

GCD is the greatest common denominator of pole pitch and slot pitch. When the pole pitch is 30 mm and the slot pitch is 40 mm, skew angle is 30 degree. Therefore skew angle of permanent magnet is 30 degree. Fig. 2 shows a model with skewed magnets.

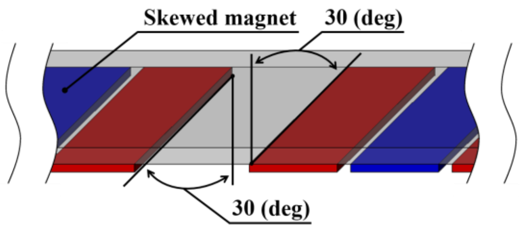


Fig. 2. Shape of skewed magnets

2.3 Analysis of Basic Model with Skewed Magnets

In order to analyze the effect of the cogging force generated from the end edge, we used the 3-D numerical analysis using finite element method. The number of nodes is 4831, and the number of elements is 11451. The amount of movement per step is an interval of 1 mm. The 3-D numerical analysis result of cogging force waveform of the basic model is shown in Fig. 3. As indicated by Fig. 3, the maximum end edge cogging force generated from the entry to ejection intervals when the mover enters the armature is ±14.61 N, and the maximum cogging force generated when the mover and the armature are in complete alignment interval is ±0.3 N.

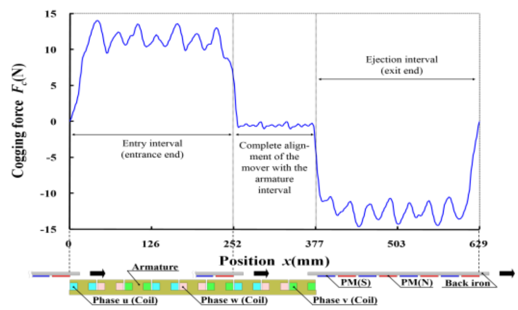


Fig. 3. Cogging force of basic model with skewed magnets

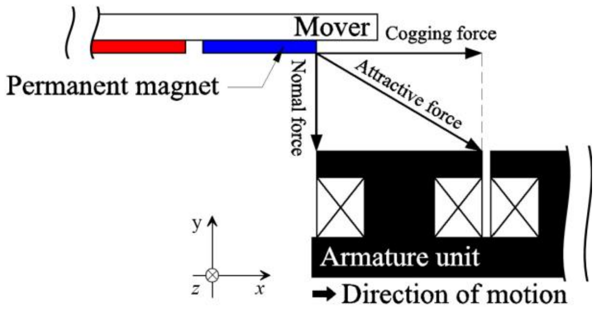
3. Design of the Stair Shape Auxiliary Teeth for Reduction of the End Edge Cogging Force

3.1 End Edge Cogging Force

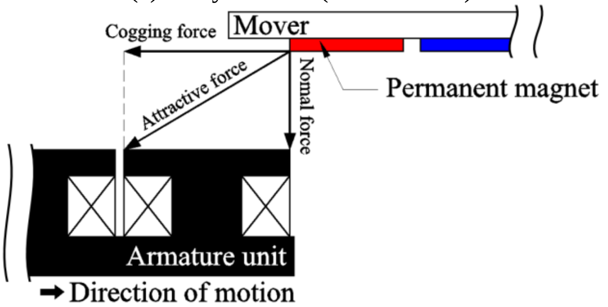
In discontinuous arrangement method of PMLSM, when a mover passes through the boundary between installation and non-installations parts of the armature, an attractive force generated between the armature's core and the mover's permanent magnet is greatly fluctuated.

Fig. 4 shows the effect that the force occurring at the end edge has on the mover. The attractive force generated when the mover enters the entry interval of the armature is an attractive force that directs toward the same direction as the operation direction of the mover.

Thus, this force accelerates the mover by attracting it toward the armature area. Furthermore, the attractive force that directs toward the opposite direction to the operation direction of the mover is generated when the mover exits the ejection interval of the armature. Thus it decelerates the mover as it functions as a returning force of the mover to the armature. Therefore, this end edge cogging force must be reduced.



(a) Entry interval (entrance end)



(b) Ejection interval (exit end)

Fig. 4. Forces exerted in the mover at the end edge

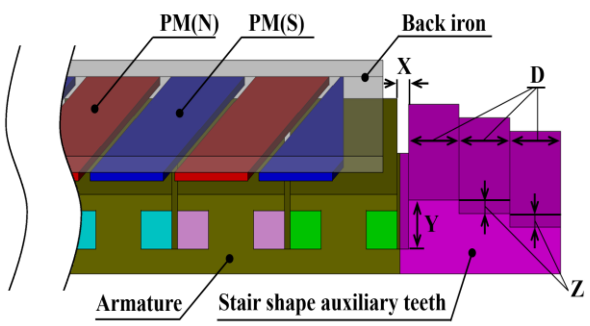


Fig. 5. Shape of model with skewed magnets and stair shape auxiliary teeth

3.2 Design Parameters of Stair Shape Auxiliary Teeth

The cogging force that generated when mover enters or exits from the armature is 48.7 times larger than cogging force that generated when complete alignment of the mover with the armature. Therefore, this large cogging force must be reduced. Stair shape auxiliary teeth were installed at the edge of the armature in order to reduce the cogging force generated at the edge. As shown in Fig. 5, design parameters for the optimum design of the auxiliary teeth are represented by the interval distance (X) between the armature and the auxiliary teeth, the width (D) of the auxiliary teeth, the height (Y) of the auxiliary teeth, interval (Z) between steps, and number of stair steps (S), that was fixed to 3 steps. Also, the laminated width was made equal to that of the armature.

3.3 Cogging Force according to each Stair Shape

In the table 2, model No. 1-4 shows the maximum end edge cogging force relative to the adjustments to the height of the auxiliary teeth (Y- height). In order to determine the height of the auxiliary teeth, the interval distance (X) between the armature and the auxiliary teeth was fixed at 1 mm, which is minimum interval of the slot opening. And the width (D) of the auxiliary teeth was fixed at 19 mm, which was most suitable width in the auxiliary teeth. Analysis that the height of Y, the height of the teeth including the cap of the armature, was decreased from 20 mm to 2 mm interval was performed. As a result, 13.75 N was generated in cases No. 2 with the 18 mm height of stair shape armature’s teeth. Fig. 6 Shows compared the maximum end edge cogging force of model No. 1-4 Cogging force increases and decrease based on the model No. 2. Also, they showed the change in the end edge cogging force of 0.8 N. Therefore, it was shown that it is desirable to make the height of the stair shape auxiliary teeth is smaller than that height of the armature’s teeth.

Then, in order to deduce the width (D) of the stair shape auxiliary teeth, the interval distance (X) between the armature and the auxiliary teeth was fixed at 1 mm, which is minimum interval of the slot opening. In the table 2, model No. 5-8 shows the maximum end edge cogging force according to the adjustments to the width of the stair shape auxiliary teeth. From Table 2, the width (D) of the stair shape auxiliary teeth was changed from 17 mm to 21 mm with 1 mm intervals. As a result, 12.84 N was generated in cases No. 6 with the 18 mm width of stair shape armature’s teeth. Fig. 7 Shows compared the maximum end edge cogging force of model No. 5-8. Cogging force increases and decrease based on the model No. 2. And they showed the change in the end edge cogging force of 1.26 N. Therefore, adjustment to the width (D) of the stair shape auxiliary teeth is desirable for more reduce the cogging force than the height (Y).

Based on the results of model No. 1-8, Y was fixed to 18 mm and D was fixed to 18 mm in order to deciding Z and the remaining parameter was selected as same as the above. The model adjusted Z was model No. 9-12 and it was changed from 2 mm to 6 mm with 1 mm intervals. Among the 4 models adjusted Z, the end edge cogging force of model No. 11 was generated 12.79 N. Fig. 8 Shows compared the maximum end edge cogging force of model No. 9-12. In adjusted Z, the change in end edge cogging force was 0.16 N less than in adjusted Y, D. However, maximum end edge cogging force was more reduced than previous models. Thus, 5 mm was found to be the most appropriate height for Z.

Finally, the interval distance (X) between the armature and the stair shape auxiliary teeth was deduced using 18 mm, 18 mm and 5 mm as the height, width and interval between steps of the stair shape auxiliary teeth. The model adjusted interval distance (X) was model No. 13-16 and it was changed from 1 mm to 5 mm with 1 mm intervals. Fig. 9 Shows compared the maximum end edge cogging force of model No. 13-16. Cogging force increases and decrease based on the model No. 2. And they showed the change in the end edge cogging force of 1.05 N. But the force was increased at 2-5 mm. Therefore, the appropriate pitch of X is 1 mm.

Table 2. Maximum end edge cogging force of each model

		X mm	Y mm	D mm	Z mm	Maximum end edge cogging force
	1	1	20	19	3	14.54 (N)
	2	1	18	19	3	13.75 (N)
	3	1	16	19	3	13.83 (N)
	4	1	14	19	3	14.47 (N)
	5	1	18	17	3	13.17 (N)
	6	1	18	18	3	12.84 (N)
	7	1	18	20	3	13.30 (N)
Mode l No.	8	1	18	21	3	14.10 (N)
	9	1	18	18	2	12.95 (N)
	10	1	18	18	4	12.82 (N)
	11	1	18	18	5	12.79 (N)
	12	1	18	18	6	12.83 (N)
	13	2	18	18	5	13.39 (N)
	14	3	18	18	5	12.85 (N)
	15	4	18	18	5	13.90 (N)
	16	5	18	18	5	13.84 (N)

As a result, the model of optimized auxiliary teeth was model No. 11 and its appropriate pitch of X was 1 mm, height of Y 18 mm, the width of D per 1step of stair shaped auxiliary teeth was 18 mm, the interval between the steps of Z was 5 mm, and the numbers of stair-steps S was 3 steps. Fig. 10 shows the basic model and the waveform of end edge cogging force of the optimized stair shaped auxiliary teeth.

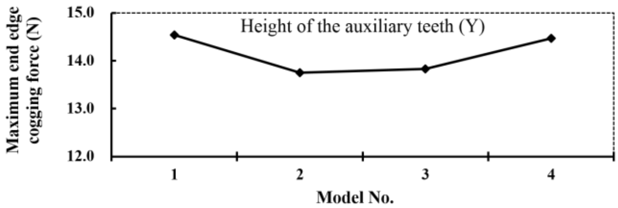


Fig. 6. Maximum end edge cogging force according to the adjustment to the Y- height

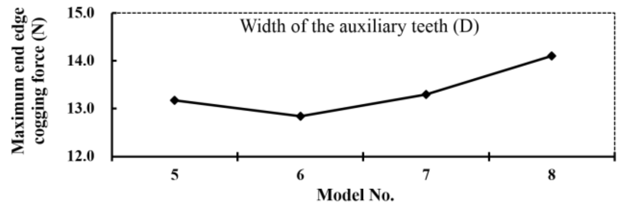


Fig. 7. Maximum end edge cogging force according to the adjustment to the D-length

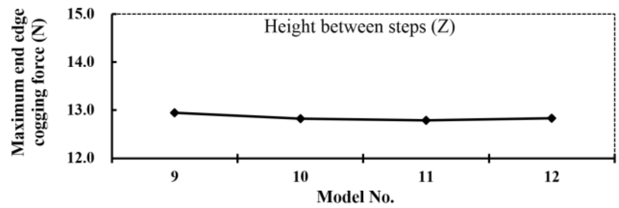


Fig. 8. Maximum end edge cogging force according to the adjustment to the Z- height

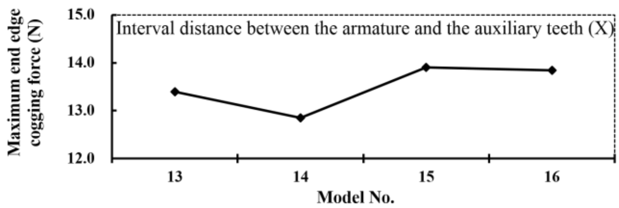


Fig. 9. Maximum end edge cogging force according to the adjustment to the X-length

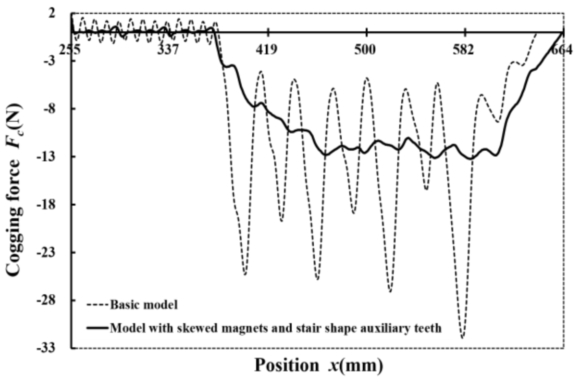


Fig. 10. End edge cogging force waveforms of each model

4. Conclusion

In this paper, we proposed the stair shaped auxiliary teeth installation method in order to reduce the end edge cogging force which functions as the thrust force ripple at the stationary discontinuous armature PMLSM. First, we analyzed the end edge cogging force of the basic model through the 3-D numerical analysis. Maximum end edge cogging force of basic model was 31.94 N. Next, we installed skewed magnets and we selected the designed parameter for the optimum design of the installed auxiliary teeth of stair shape then examined the end edge cogging force. As a result, the appropriate pitch of X from the armature in the case of the optimized stair shape auxiliary teeth was 1 mm, height of Y 18 mm, the width of D per 1step of stair shaped auxiliary teeth was 18mm, the interval between the steps of Z was 5 mm, and the numbers of stair-steps S was fixed to 3 steps. The maximum end edge cogging force of optimum designed model was 12.79 N. It was decreased 60.00 % in comparison to the basic model and 12.46 % of reduction compared to the basic model using skewed magnets. Thus, the effectiveness of the proposed model with auxiliary teeth of stair shape in regard the reduction of the end edge cogging force has been verified. Also, parameter which was the most affected to reduce the end edge cogging force is the width (D) of the auxiliary teeth that showed change in 1.26 N. It must be considered in the optimal design which cited our paper because it is the most sensitive part of the optimal shape design.

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