ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 18(3), 352-356 (2013) http://dx.doi.org/10.4283/JMAG.2013.18.3.352

Design of Auxiliary Teeth on the Edge of Stationary Discontinuous Armature PM-LSM with Concentrated Winding

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(Received 31 May 2012, Received in final form 10 July 2012, Accepted 10 July 2012)

Recently, the stationary discontinuous armature, Permanent Magnet Linear Synchronous Motor (PM-LSM), was suggested as a driving source for long-distance transportation system. However, as these motors arrange armatures discontinuously, an edge occurs thereby leading to a cogging force. This works as a factor that hinders the acceleration and deceleration that takes place when movers enter into and eject from armatures. Therefore, in this study, the installation of auxiliary teeth on the edge of the armature of PM-LSM is suggested in order to reduce the cogging force caused by the edge when the armature is placed in a discontinuous arrangement. Auxiliary teeth are optimally designed by a 2-D numerical analysis using the finite element method was performed to generate the optimum design of the auxiliary teeth. The validity of the study was confirmed through the comparison of the cogging force induced at the edge in respect to the design parameter using the basic model.

Keywords : permanent magnet linear synchronous motor, discontinuous arrangement, transportation system, edge cogging force, auxiliary teeth, 2-D numerical analysis

1. Introduction

While the current main driving source of Permanent Magnet Linear Synchronous Motor (PM-LSM) is the short-distance transportation system, the importance of the long-distance heavy load transportation system in PM-LSM is steadily increasing [1, 2]. Due to the fact that long-distance PM-LSM requires the installation of armature that generates the propel magnetic field on the full length of the transportation path, a problem of higher initial cost rises as the transportation path become longer. In order to solve this problem of increases in initial cost, the armature of the discontinuous arrangement method is suggested. Fig. 1 shows the speed profiles of PM-LSM in horizontal transportation systems. As indicated in Fig. 1, the edge must exist when the armature is discontinuously arranged. This edge creates an intense cogging force in the case of entry or ejection between the mover and the armature. The cogging force is the cause of the thrust force ripple that not only makes noise and vibration, but also leads to poorer performance [3, 4]. Thus, there have been many studies so as to reduce the cogging force, such as width adjustment of permanent magnet, skew of permanent magnet, width adjustment of slot, width adjustment of teeth, application of semi-enclosed slot, etc [5-8].

In this study, the concept of installation of auxiliary teeth onto the edge of stationary discontinuous armature PM-LSM with concentrated winding is used to reduce the cogging force. In addition, this paper considers the characteristics of changes in cogging force through a 2-D

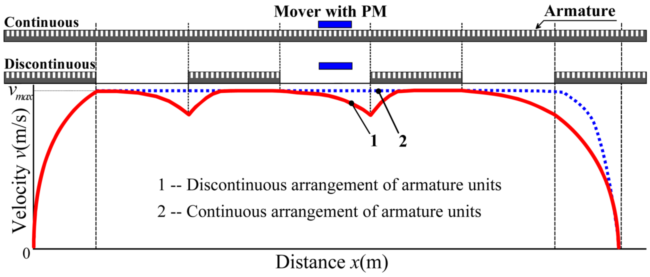

Fig. 1. (Color online) Speed profiles of PM-LSM horizontal transportation systems.

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This paper was presented at the ICM2012, Busan, Korea, July 8-13, 2012.

numerical analysis using the finite element method and designed auxiliary teeth, which use the minimum edge cogging force.

2. Force generated at the edge of the stationary discontinuous armature PM-LSM

In the discontinuous arrangement method of PM-LSM, when a mover passes through the boundary of an installation part and a non-installation part of the armature, the attractive force between the armature's core and the mover's permanent magnet changes significantly. Fig. 2 shows the effect of the force from the edge on the mover. The direction of the attractive force, which is produced at the entry interval, where the mover enters the armature, is identical to the operation direction. Specifically, this attractive force draws the mover into the armature area in order to accelerate the mover. On the other hand, the attractive force produced at the ejection interval, where the mover goes off the armature, works in the opposite direction of its operation. This attractive force turns the mover back into the armature area, decelerating the mover [9]. Therefore, the edge cogging force should be reduced.

3. Cogging force verification at the edge of the stationary discontinuous armature PM-LSM

3.1. Basic model

A 2-D finite element analysis program was used to analyze the effect of the cogging force generated at the edge. Fig. 3(a) shows the shape of the basic model and Fig. 3(b) shows the element divisions of the basic model for a 2-D numerical analysis. Specifications of PM-LSM are shown in Table 1. The full length of the mover in the basic model was 264 mm, and Nd-Fe-B type 8-pole permanent magnets were placed on the magnetic circuit steel sheet. The permanent magnet itself had a length of 26 mm, width of 3 mm, and pole pitch of 30 mm, whereas the armature had a full length of 360 mm. The winding method utilized in this study was concentrated winding,

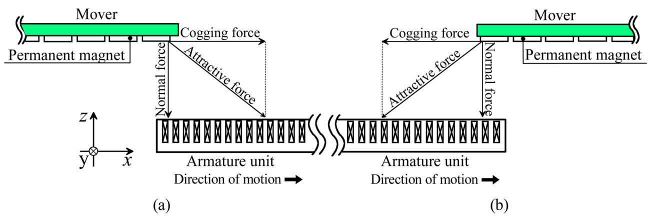

Fig. 2. (Color online) Effect of the force from the edge on the mover: (a) entry interval (entrance end) and (b) ejection interval (exit end).

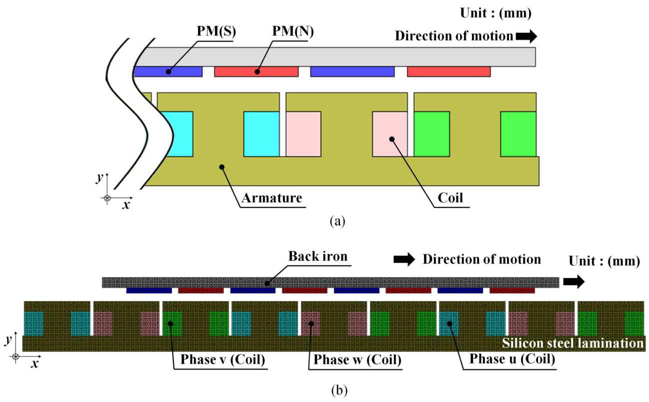

Fig. 3. (Color online) Basic model: (a) side view of the armature and mover and (b) element divisions of the basic model for a 2-D numerical analysis.

Table 1. Specifications of PM-LSM.

	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
Mover with PM	Number of poles	8 (poles)
	Magnet length (x-axis)	26 (mm)
	Magnet thickness (y-axis)	3 (mm)
	Type	Nd-Fe-B
	Pole pitch	30 (mm)
	Back iron height	6 (mm)
	Back iron length	264 (mm)
Air gap		5 (mm)
Stack length		50 (mm)

and the number of turns per one phase was 75. There were 9 slots with a slot pitch of 40 mm, and the air-gap between the armature and the mover was 5 mm. At this point, the node number was 13745 and the element was 28180. The system was configured so that it moved 1 mm per step. Fig. 4 shows the cogging force waveform of the basic model. As indicated by Fig. 4, the maximum edge cogging force generated by the mover at the entry and ejection interval of the armature was 27.73 N, and the maximum cogging force at the interval where the mover and the armature were perfectly aligned was ± 0.8 N.

3.2. Proposed model for reduction of the edge cogging force

Auxiliary teeth were installed at the edge of the armature

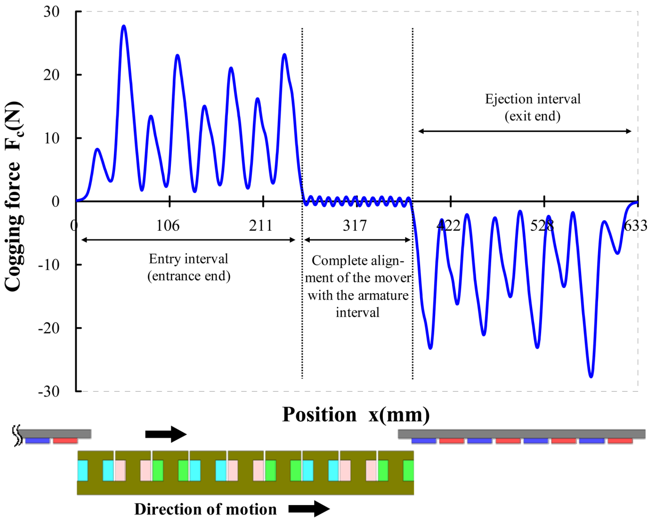

Fig. 4. (Color online) Cogging force waveform of the basic model.

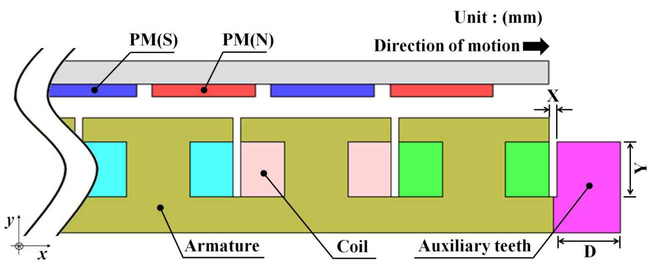

Fig. 5. (Color online) Side view of proposed model with auxiliary teeth.

in order to reduce the cogging force generated at the edge. As shown in Fig. 5, the design parameter for the optimum design of the auxiliary teeth is represented by the interval distance (X) between the armature and the auxiliary teeth, the width (D) of the auxiliary teeth, and the height (Y) of the auxiliary teeth. In addition, the laminated width was made equal to that of the armature.

Table 2 shows the maximum edge cogging force relative to the adjustments to the height of the auxiliary teeth (Y-length). In order to determine the height of the auxiliary teeth, the interval distance (X) between the armature and

Table 2. Maximum edge cogging force relative to the adjustments to the height of the auxiliary teeth.

		X (Unit)	Y (Unit)	D (Unit)	Maximum outlet edge cogging force (Unit)
Basic model			-		27.73 (N)
Case No.	1	2 (mm)	20 (mm)	16 (mm)	27.18 (N)
	2	2 (mm)	17 (mm)	16 (mm)	19.51 (N)
	3	2 (mm)	14 (mm)	16 (mm)	16.96 (N)
	4	2 (mm)	11 (mm)	16 (mm)	20.68(N)

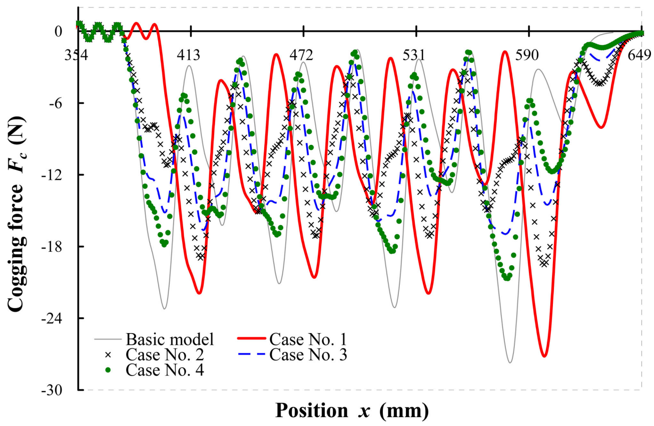

Fig. 6. (Color online) Waveform of edge cogging force according to the adjustments on the height of the auxiliary teeth.

the auxiliary teeth was fixed at 2 mm, which is equal to the width of the slot opening; further, the width (D) of the auxiliary teeth was fixed at 16 mm, which is equal to that of the armature teeth. Analysis was performed as the length of Y was decreased from 20 mm (the height of the teeth including the cap of the armature) to 3 mm interval. Fig. 6 shows the waveform of the edge cogging force according to the adjustments on the height of the auxiliary teeth. The results show that as Y-length decreases, the edge cogging force decreases as well. However, it is notable that the edge cogging force increases when the height of the auxiliary teeth falls below 14 mm. Consequently, the height of the auxiliary teeth (Y-length) was determined to be 14 mm in Case No.3, a length that was decreased from the basic model by 10.77 N. The maximum edge cogging force was thereby at its minimum when the height of the auxiliary teeth was equal to that of the armature's teeth.

Then, in order to deduce the width (D) of the auxiliary teeth, the interval distance (X) between the armature and the auxiliary teeth was fixed at 2 mm. Table 3 shows the maximum edge cogging force according to the adjustments to the width of the auxiliary teeth. From Table 3, the width (D) of the auxiliary teeth was changed from 14 mm to 18 mm with 2 mm intervals. Fig. 7 shows the waveform

Table 3. Maximum edge cogging force according to the adjustments to the width of the auxiliary teeth.

		X (Unit)	Y (Unit)	D (Unit)	Maximum outlet edge cogging force (Unit)
Basic model			-		27.73 (N)
Case No.	5	2 (mm)	14 (mm)	14 (mm)	17.49 (N)
	3	2 (mm)	14 (mm)	16 (mm)	16.96 (N)
	6	2 (mm)	14 (mm)	18 (mm)	17.49 (N)

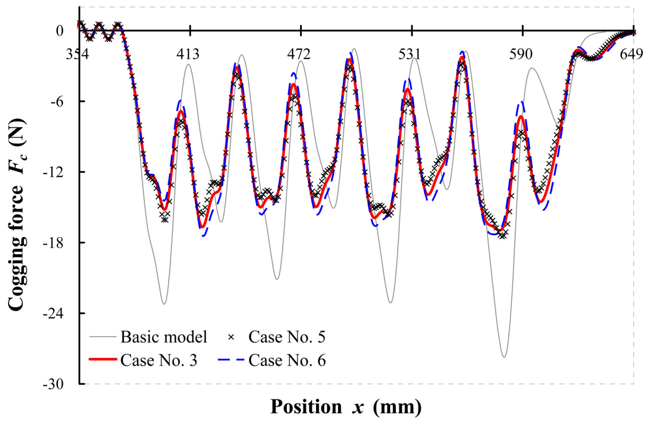

Fig. 7. (Color online) Waveform of edge cogging force relative to the adjustments to the width of the auxiliary teeth.

of the edge cogging force relative to the adjustments to the width of the auxiliary teeth. As a result, 17.49 N was generated in cases No.5 and No.6, and this showed that the maximum edge cogging force was greater than Case No.6 with a 16 mm width of armature's teeth. Therefore, it was shown that it is desirable to make the width of the auxiliary teeth equal to that of the armature's teeth.

Finally, the interval distance (X) between the armature and the auxiliary teeth was deduced using 14 mm and 16 mm as the height and width of the auxiliary teeth. Table 4 indicates the maximum edge cogging force relative to the adjustments on the interval distance. The interval distance (X) was adjusted from 1 mm to 4 mm. Fig. 8 shows the waveform of the edge cogging force corresponding to the interval distance adjustments. The interval distance (X) between the armature and the auxiliary teeth was at its lowest in cases No.3 and No.7, reaching 16.96 N. Therefore, it was concluded that it is reasonable to design the interval distance (X) as the same as the slot opening

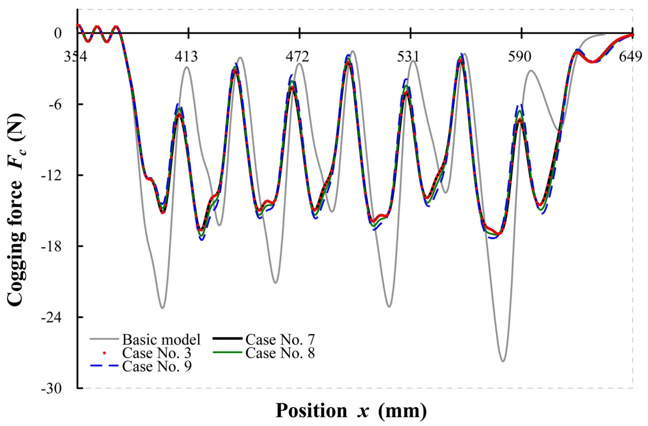

Fig. 8. (Color online) Waveform of edge cogging force corresponding to the interval distance adjustments.

Table 4. Maximum edge cogging force relative to the adjustments on the interval distance.

		X (Unit)	Y (Unit)	D (Unit)	Maximum outlet edge cogging force (Unit)
Basic model			-		27.73 (N)
Case No.	7	1 (mm)	14 (mm)	16 (mm)	16.96 (N)
	3	2 (mm)	14 (mm)	16 (mm)	16.96 (N)
	8	3 (mm)	14 (mm)	16 (mm)	17.12 (N)
	9	4 (mm)	14 (mm)	16 (mm)	17.52 (N)

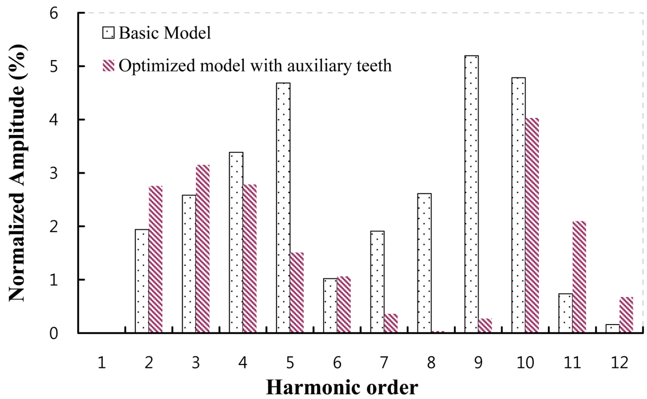

Fig. 9. (Color online) Harmonic analysis of the basic model and the model installed with auxiliary teeth.

width. Fig. 9 shows the harmonic analysis of the basic model and the model installed with the optimized auxiliary teeth. From Fig. 9, it is noteworthy that the components of the 5th and 9th harmonics greatly decreased when compared with the basic model.

4. Conclusion

In this paper, the installation of auxiliary teeth at the edge of the armature was proposed in order to reduce the cogging force caused by the edge effect, which acts as the thrust force ripple, ultimately increasing the driving characteristic of stationary discontinuous armature with concentrated winding. First, the edge cogging force of the basic model was analyzed by a numerical analysis using the finite element method. Then, the auxiliary teeth were designed to reduce the edge cogging force. Consequently, the height (Y) and the width (D) of the optimized auxiliary teeth were determined as 14 mm and 16 mm, respectively. Each figure was identical to the height and width of the armature teeth. Also, the interval distance (X) between the armature and the auxiliary teeth was figured as 2 mm, which is equal to the slot opening width. Furthermore, it was examined that the model with the auxiliary teeth installed represents 38.84% of the reduced edge cogging force compared to the one without the installation. This verifies that the auxiliary teeth greatly reduce the edge effect of stationary discontinuous armature with concentrated winding.

Acknowledgment

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2012-0003800).

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