ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 31(1), 91-95 (2026) https://doi.org/10.4283/JMAG.2026.31.1.91

Design of a Linear Yoke-less Permanent Magnet Synchronous Machine Employing GO Steel for Enhanced Efficiency and Cost Reduction

Jin Hwan Lee[1], Yong-Jae Kim[2], Dong-Kuk Lim[3], and Sang-Yong Jung[4]*

[1]*Department of Electrical Engineering, Chonnam National University, Gwangju 61186, Republic of Korea*
[2]*Department of Electrical Engineering, Chosun University, Gwangju 61467, Republic of Korea*
[3]*Department of Electrical, Electronic and Computer Engineering, University of Ulsan, Ulsan 44610, Republic of Korea*
[4]*Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon 16419, Republic of Korea*

(Received 6 December 2025, Received in final form 23 February 2026, Accepted 23 February 2026)

This study proposes a design approach that applies grain-oriented(GO) electrical steel sheet as a means to improve both the cost and efficiency of a yoke-less linear permanent magnet synchronous motor(LPMSM). Conventionally, LPMSM are designed and manufactured using non-grain-orient(NGO) electrical steel sheet, and thinner laminations are typically employed to enhance performance and efficiency. Although thin laminations offer favorable loss characteristics by reducing eddy-current losses, their high material cost increases the overall system price. In this study, we propose a design method that improves thrust and efficiency even when using thicker GO steel, which is generally less expensive than thin NGO steel. The potential cost advantages and performance benefits of the proposed are verified through electromagnetic design and finite element analysis(FEA).

Keywords : cost reduction, efficiency, grain-oriented electrical steel sheet, linear permanent magnet synchronous motor, yoke-less linear synchronous motor

1. Introduction

Recently, climate crises have driven continuous research efforts toward improving efficiency in the field of electric machines. In the mobility sector in particular, electrical power is supplied by batteries, making machine efficiency a key factor in determining driving range. Although the demand for efficiency improvement in industrial electric machines has historically been relatively low, the accelerating climate crisis has increased the need for enhanced efficiency in industrial applications as well [1-3].

Linear motors are widely used across various industrial sectors as actuators that provide thrust force. While efficiency improvement had not been a major priority in the past, growing emphasis on energy efficiency has recently sparked sustained research into design strategies for improving the efficiency of linear motors [4, 5].

In this study, we propose the use of grain-oriented(GO) steel sheet to enhance the efficiency of a linear permanent magnet synchronous motor (LPMSM). GO steel sheet exhibits superior magnetic and loss characteristics along the rolling direction, and can therefore serve as an effective solution for achieving both high performance and high efficiency when the magnetic flux path is aligned with the rolling direction. To realize the condition, a yoke-less stator structure is adopted so that the flux in the stator flows exclusively along the rolling direction. The validity of the proposed approach is verified through performance comparisons between designs employing GO steel sheet and non-grain-oriented (NGO) steel sheet [6-8].

2. Yoke-less LPMSM for using GO steel sheet

GO steel sheet exhibits excellent magnetic and loss characteristics along the rolling direction before mentioned, but its performance degrades significantly in other directions. Therefore, electric machines employing GO steel sheet must be designed such that the magnetic flux is constrained to follow the rolling direction. Conventional linear LPMSMs typically employ a single-mover

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*Corresponding author: Tel: +82-31-299-4926
Fax: +82-31-290-6947, e-mail: syjung@skku.edu

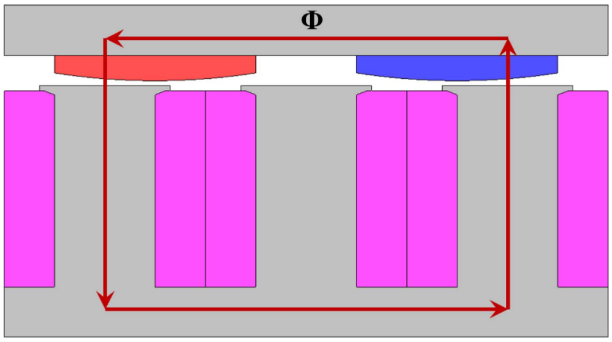


Fig. 1. (Color online) Topology and flux path of yoke type LPMSM.

structure with a yoke, and their topology and magnetic flux path are illustrated in Fig. 1. As shown in the magnetic flux path of Fig. 1, the magnetic flux generated by the permanent magnets flows vertically through the teeth but transitions to a horizontal path, transverse path, within the yoke. Due to this horizontal flux component, applying GO steel sheet to a conventional LPMSM results in substantial deterioration of the magnetic characteristics and efficiency in the yoke region.

To improve this issue, a yoke-less LPMSM topology must be adopted to constrain the magnetic flux path to the rolling direction [9, 10]. The topology and magnetic flux path of a yoke-less LPMSM are presented in Fig. 2. As shown, the magnetic flux path is aligned in the rolling direction, ensuring compatibility with the directional properties of GO steel sheet. By utilizing this structural characteristic and applying GO steel sheets to the stator teeth, the overall performance of the machine can be effectively enhanced. Additionally, to help in structural understanding, an explode view for the implementation of the yoke-less LPMSM is in shown in Fig. 3. Typically,

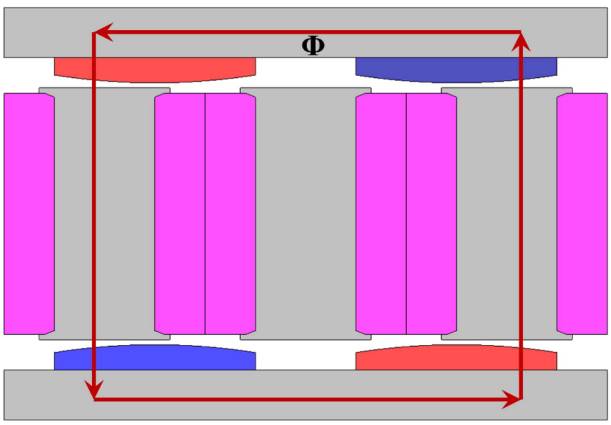


Fig. 2. (Color online) Topology and flux path of yoke-less type LPMSM.

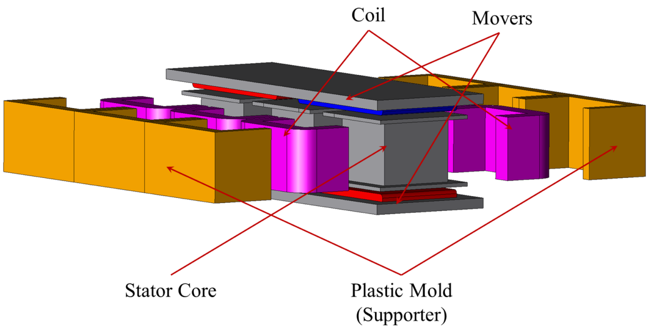


Fig. 3. (Color online) Explode view of yoke-less type LPMSM.

models employing a yoke-less structure require a complex design for stator support. In this study, the proposed yoke-less structure secures discrete stator segments using a plastic mold. This assembly is then fastened to the external frame via bolts, ensuring a stable stator support structure.

3. Magnetic properties Comparison between GO and NGO

As previously mentioned, the magnetic properties of GO steel sheet exhibit significantly different results in the rolling direction compared to the transverse direction. The GO steel sheet used in this study is a thin steel sheet with a thickness of 0.23 mm, typically used in thin-gauge applications. For property comparison, we utilized a NGO steel sheet with a relatively higher cost and thinner gauge of 0.2 mm. If the 0.23 mm GO steel sheet exhibits superior properties compared to the 0.2 mm NGO steel

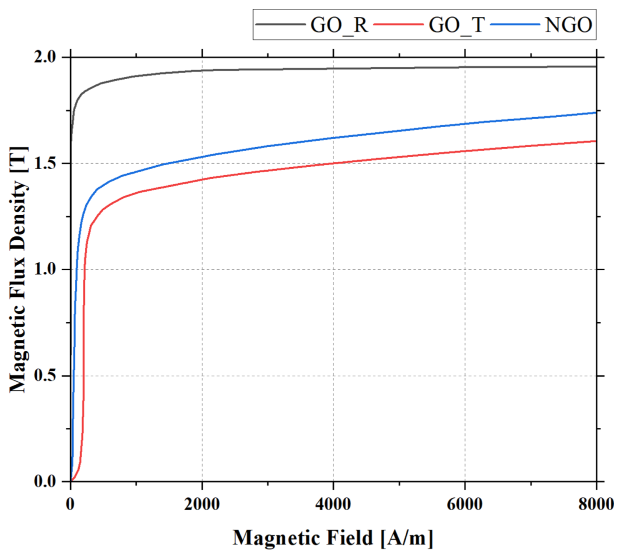


Fig. 4. (Color online) B-H curve comparison.

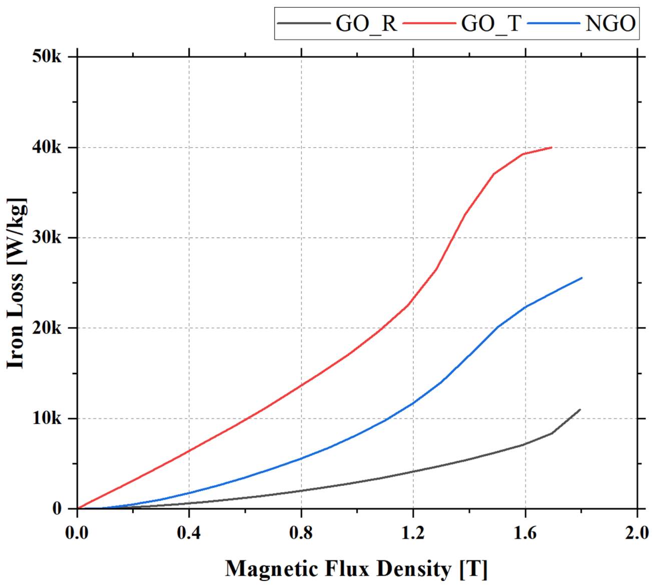


Fig. 5. (Color online) Iron loss curve comparison at 60 Hz.

sheet, it would offer an advantage in terms of unit cost.

The magnetic properties of the two steel sheets are compared in Fig. 4. Analysis of the B-H characteristics in Fig. 4 confirms that the B-H data for the GO steel sheet in the rolling direction are superior to those of the NGO steel sheet. Conversely, the B-H data for the GO steel in the transverse direction show less favorable properties compared to the NGO steel. Therefore, the rolling direction of the GO steel sheet demonstrates superior performance. Based on the B-H curves, it can be inferred that designing the magnetic flux path along the GO steel's rolling direction will result in relatively superior performance.

Fig. 5 shows the iron loss curves for the GO steel sheet in the rolling direction and the NGO steel sheet at 60 Hz.

The loss analysis of the steel sheet can be performed through electromagnetic field analysis using the Fast Fourier Transform (FFT), and the governing equations is as follows: [11, 12]

$$W_{iron} = W_h + W_e \tag{1}$$

$$W_h = \rho \int_v \Sigma_n k_h(n, B)\, f_n(B_{r,n}^2 + B_{\theta,n}^2)dv \tag{2}$$

$$W_e = \rho \int_v \Sigma_n k_e(n, B)\, f_n^2(B_{r,n}^2 + B_{\theta,n}^2)dv \tag{3}$$

Based on the iron loss graph and the equation above, when estimating the losses in the LPMSM, it can be anticipated that the motor utilizing the GO steel sheet will demonstrate superior efficiency compared to the motor based on the NGO steel sheet.

4. Design of yoke-less LPMSM

Based on the mentioned properties, a yoke-less LPMSM was designed for performance validation. The geometry of the designed model and its specifications are presented in Fig. 6 and Table 1, respectively.

Following the theory described previously, a yoke-less structure was adopted to constrain the magnetic flux path. The design was executed such that the magnetic flux path is vertical, by arranging the upper and lower movers as opposite poles relative to each other to facilitate the flux flow.

All material components, with the exception of the stator core steel sheet material, were kept identical. Nd-Fe-B magnets were used for the permanent magnets to ensure a high magnetic flux density.

5. Simulation Results

FEA was conducted on the designed LPMSM model by

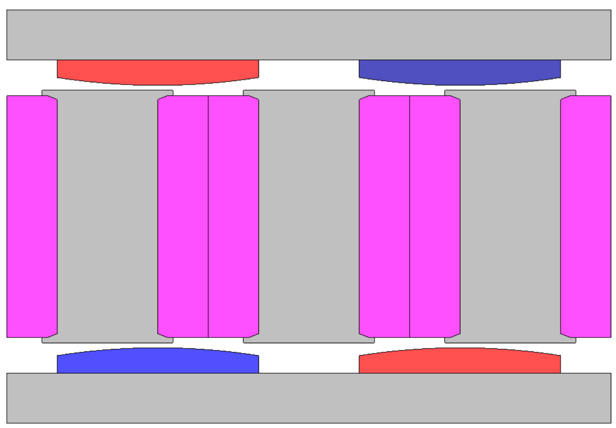
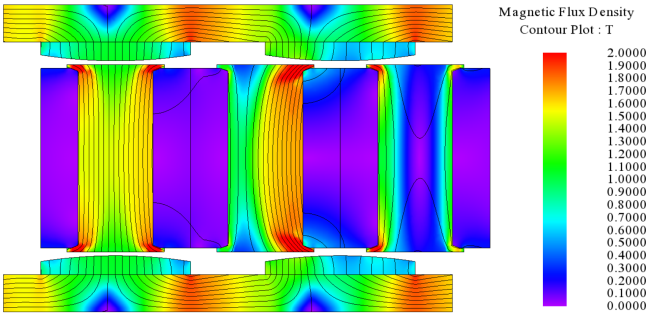


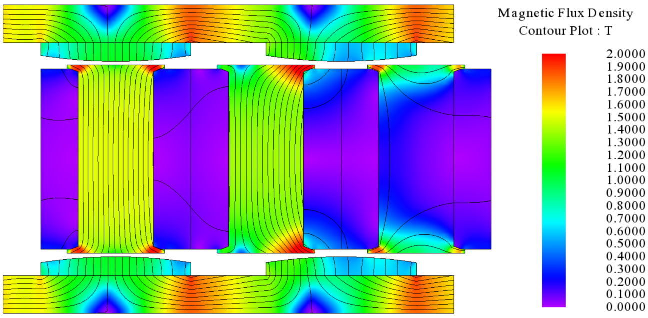
Fig. 6. (Color online) Partial model(1/3) topology of designed yoke-less LPMSM.

Table 1. Specifications of target motor.

Parameter	Unit	Value
Output Power	kW	9
Output Force	kN	1.25
Input Voltage	V_{dc}	24
Maximum Current Density	A_{rms}/mm^2	10
Width	mm	360
Height	mm	82
Depth	mm	50
Air-gap	mm	1
Magnet Flux Density	T	1.38



(a) GO Rolling Material



(b) NGO Material

Fig. 7. (Color online) Magnetic flux density distribution and flux line plot for both materials.

varying the stator core steel sheet material. The analysis was performed to achieve the target performance specifications while ensuring that the current density did not exceed the specified 10 A_{rms}/mm^2.

To compare the electromagnetic analysis results, the magnetic flux distribution and the magnetic flux line plot for both materials are shown in Fig. 7, and the thrust waveform is presented in Fig. 8.

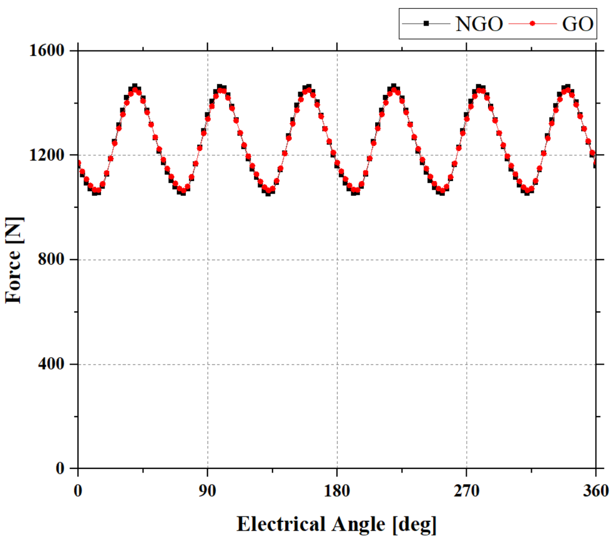
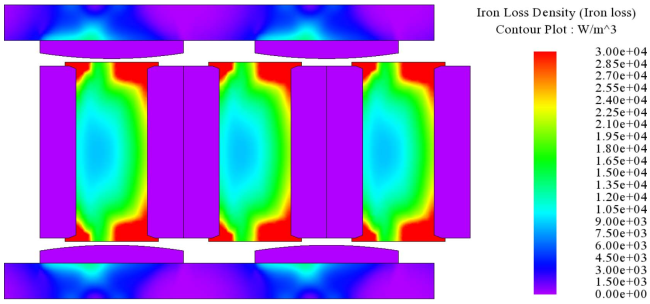
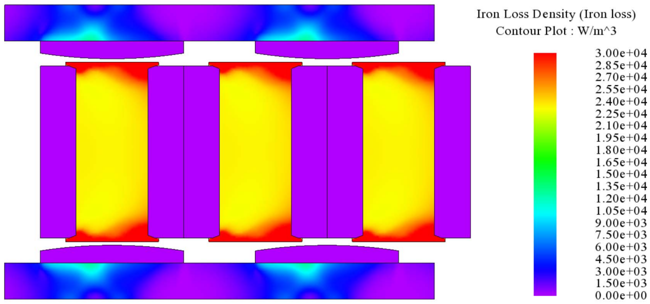


Fig. 8. (Color online) Thrust waveform comparison between GO Rolling direction and NGO.



(a) GO Rolling Material



(b) NGO Material

Fig. 9. (Color online) Iron loss distribution plot for both materials.

The current specifications that satisfy the target performance are 195.4 A_{pk} for the GO model and 200.2 A_{pk} for the NGO model. By applying the GO steel sheet, a higher thrust could be achieved at the same current due to its relatively superior magnetic properties compared to

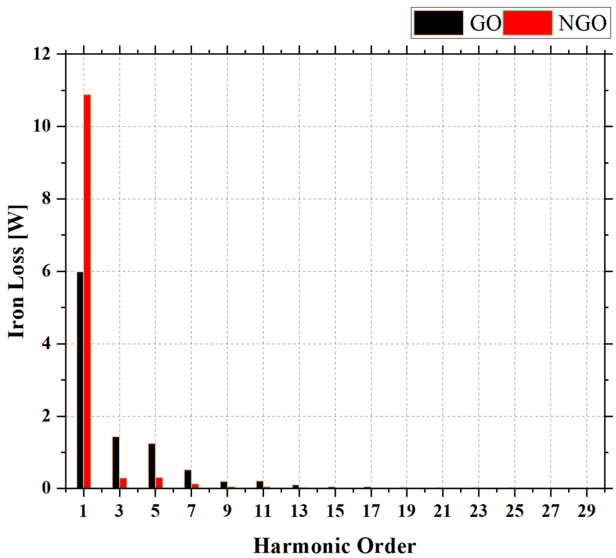


Fig. 10. (Color online) Iron loss FFT harmonic comparison.

Table 2. Loss comparison.

Parameter		GO Model	NGO Model
Copper Loss [W]		710.2	745.5
Iron Loss [W]	Stator	9.98	11.7
	Mover	1.12	1.2
Total Loss [W]		721.3	758.4

the NGO steel sheet. It was confirmed that if the design were conducted using the same current density, the depth could be reduced, consequently leading to a reduction in the total consumption of the steel sheet and magnets.

Next, to confirm the efficiency improvement effect of GO versus NGO, a iron loss analysis was performed for both models, and the resulting stator iron losses were compared.

The iron loss density distribution derived from the FFT-based iron loss analysis is shown in Fig. 9, and a comparison graph of the iron loss values by FFT order is presented in Fig. 10.

The comparison of the iron loss generated in the stator shows that the GO model exhibits a lower loss of 9.98 W, compared to 11.7 W for the NGO model, demonstrating loss suppression. The value for the total losses are compared in Table 2.

6. Conclusion

In this study, we proposed the potential for GO steel sheet application in an LPMSM to achieve advantages in both unit cost and efficiency. Furthermore, due to the superior properties of the GO steel sheet, it was confirmed that the motor's volume could be reduced by decreasing the depth, lamination length, when designed for the same current density.

A yoke-less type LPMSM was designed to constraint the magnetic flux path. The analysis results, comparing the application of GO and NGO steel sheets to the designed model, confirmed that the GO steel sheet yielded relatively superior thrust and lower losses. Notably, the GO steel sheet demonstrated better performance in terms of loss, despite being 0.03 mm thicker than the NGO steel sheet. This successfully validated the effectiveness of applying the GO steel sheet across the aspects of performance, efficiency, and unit cost.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2024-00333595).

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