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Sung-Won Seo, Kyung-Hun Shin, Gang-Hyeon Jang, Tae-Kyoung Bang, and Jang-Young Choi

COLLECTIONS

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ABSTRACT
This study aims at improving the design of a linear magnetic gear (LMG) and verifying its reliability using a fabricated prototype. LMGs represent electromechanical energy-conversion machines employing permanent magnets (PMs). However, given the linear structure of power-transmission devices, LMGs are difficult to manufacture. The proposed study presents an LMG-design aimed at facilitating ease of its manufacturing. To this end, the PM-ratio performance was first analyzed for selection of an appropriate basic model, which can be subsequently optimized by changing the PM-shape and flux-modulation poles to realize optimum electromagnetic characteristics. Moreover, mechanical characteristics of the optimized model were analyzed to aid fabrication. Results of finite-element analyses and experiments performed in this study on a fabricated prototype demonstrate the reliability of the proposed model.

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I. INTRODUCTION
In recent years, several energy-conversion systems have been proposed and implemented in conceptual studies. Of these, magnetic gears (MGs) have gained large popularity. Contrary to mechanical gears that exhibit mechanical limitations due to physical contact, MGs transmit power along with an increase in both speed and torque by means of a contactless mechanism employing permanent magnets (PMs). Moreover, high-efficiency PMs are extremely useful owing to their characteristic of reducing the overall system volume and weight. MGs can be used in both linear and rotating systems. Several designs of linear magnetic gears (LMGs) characterized by a tubular structure have been proposed. However, despite the high power density and efficiency of LMGs, their utilization has been confined to concept-based researches owing to manufacturing complications.

This study aims at eliminating these manufacturing limitations and enhance LMG performance through use of a simple linear-motor-structure design. The proposed design strategy has been validated in the light of experimental results.

II. IMPROVED LMG DESIGN AND MECHANICAL CHARACTERIZATION

A. Basic model selection
LMGs are greatly influenced by flux-modulation poles (FMPs) that are sized in accordance with a gear ratio. Therefore, selection of a basic model assumes critical importance. Characteristic equations for an LMG include

\[ P_L = G_r \cdot P_H, \]
\[ N_p = \left( \frac{P_L}{2} \right) + \left( \frac{P_H}{2} \right). \]

where \( P_H \) and \( P_L \) denote the number of poles in the high-speed mover (HSM) and low-speed mover (LSM), respectively, \( G_r \) and \( N_p \) denote the gear ratio and number of FMPs, respectively. HSM and LSM speeds can be determined by the gear ratio as follows.

\[ \omega_L = -G_r/\omega_H \]

Here, \( \omega_H \) and \( \omega_L \) denote rated HSM and LSM speeds, respectively. Specifications of the basic LMG model were determined with...
TABLE I. Basic LMG model specifications considering PMLSG.

| Parameter                          | Value   | Parameter                          | Value   |
|------------------------------------|---------|------------------------------------|---------|
| Generator mover length            | 322 mm  | Generator output power             | 30 W    |
| Generator rate velocity           | 1 m/s   | Generator input power              | 36 W    |
| HSM length                         | 322 mm  | PM thickness                        | 10 mm   |
| Stack length                       | 30 mm   | Air-gap length                      | 2 mm    |
| Number of pole pairs of HSM       | 4       | Gear ratio                          | 5.75    |
| Number of FMP                      | 27      | FMP thickness                       | 9 mm    |

**Double-sided Linear Generator**

![Diagram of a double-sided linear generator](image)

**FIG. 1.** (a) Structure of a LMG, (b) performance characteristics according to gear ratio, and (c) force ripple according to thickness of air-gap and FMP.
FIG. 2. Force ripple results with respect to the shape of the LMG: (a) PM shape of the HSM, (b) filleted FMP shape, (c) characteristics of the selected PM shape (with the fixed optimized shape) and effect of FMP fillets.

FIG. 3. Air-gap flux density distributions of the basic model and model 1: (a) flux density waveforms and (b) flux density harmonic spectra.
due consideration of the permanent magnet linear synchronous generator (PMLSG), which has been previously studied, and the same are listed in Table I, which demonstrates that the PMLSG output and input powers equal 30 and 36 W, respectively. The generator mover, when coupled with the LMG–HSM, causes the generator input power to correspond to LMG output power. Therefore, the LMG output power must be comparable to the PMLSG input power. However, considering the mechanical losses that occur when PMLSG and LMG are used in combination, the LMG output power must exceed PMLSG input power (36 W). In this study, output power of the selected LMG model was found to exceed 40 W.

Additionally, considering the PMLSG mover length, its rated velocity, and mover stroke, the LSM length must at least equal 500 mm, when calculated using above equation. Thus, considering HSM stroke variables, an LSM length of 595.5 mm was considered in this study, as depicted in Fig. 1(a). Figure 1(b) illustrates results

| Material   | Basic | Optimal 1 | Optimal 2 |
|------------|-------|-----------|-----------|
| Speed of LSM (m/s) | 0.1739 | 60.67     | 71.34     |
| Force of HSM (N)     | 87.78  | 361.19    | 360.66    |
| Force of LSM (N) | 377.03 | 445.73    | 441.53    |
| Pull-out Force of HSM (N\text{max}) | 82.04  | 88.95     |           |
| Pull-out Force of LSM (N\text{max}) | 457.36 | 441.53    |           |
| Force Ripple of HSM (%) | 20.1   | 4.5       | 6.3       |
| Force Ripple of LSM (%) | 4.86   | 3.66      | 3.7       |
| Output Power (W)     | 69.18  | 54.1      | 54.96     |
| Total Loss (PM) (W)  | 19.14  | 6.57      | 16.5      |
| Efficiency (%)       | 78.33  | 89.2      | 76.9      |

FIG. 4. Stress analysis of the FMP: (a) basic model, (b) model 1, and (c) model 2.
of performance analysis of the basic model under consideration of different gear ratio values. As observed, when using non-integral gear ratio values, force ripple values of the proposed LMG become small, and the output power decreases with increase in gear ratio. Consequently, with due consideration of the force ripple, output power, and efficiency, a gear ratio of 5.75 was selected in this study. Fig. 1(c) depicts analysis results based on the air-gap thickness and magnetic-flux modulation core thickness. The basic model was chosen based on performance results concerning the force ripple and output power.

B. Performance improving design

The process for selecting an optimal model consists of the following steps:

- analysis of the characteristics with respect to the PM ratio and shape of the HSM;
- analysis of the characteristics with respect to the shape of the FMPs;
- analysis of the characteristics considering all results.

PM and FMP shapes are, in general, characterized by chamfers, and therefore, filleted shapes were used in the proposed design owing to LMG characteristics that require presence of small air gaps and precise design.\textsuperscript{9,10} The results of all models for force ripple, which was used to improve the model, are shown in Fig. 2. Figure 3 depicts compares the proposed optimum and basic models in terms of results depicted in Fig. 2. Figures 3(a) and 3(b) depict results pertaining to the air-gap flux density between HSM and FMP. As can be seen, the said air-gap flux density of the optimal model is lower compared to that of the basic model because the amount of PM used is deducted from the HSM PM ratio. Moreover, the output power of the optimal model exceeds 40 W, and the force ripple can be observed to have greatly reduced. In the LSM case, because of the large number of poles needed for an MG, the change in the PM shape adversely affects many parts. Finally, the electromagnetic characteristics of the basic and optimized models are shown in Table II. Models 1 and 2 use different materials for the FMP. Laminated steel (50PN470) is electrical steel and is effective for reducing electromagnetic losses. However, because the FMP size of the analysis model is small, there is a risk of damage to the weld area.
Therefore, optimized model 2 was add selected considering mechanical properties.

III. ANALYSIS OF MECHANICAL CHARACTERISTICS AND EXPERIMENTAL VERIFICATION

Generally, the design of electrical machine equipment involves analysis of their electromagnetic characteristics. However, as mentioned above, manufacturing an LMG is challenging, and an alternative that reduces the breakage of small components is needed. The analysis in this study verifies the feasibility of actual LMG fabrication through an equivalent stress analysis of the FMP. Fig. 4 shows the equivalent stress analysis of the FMP for each model. A large force was applied in model 1, given the high force density of the mover; however, there is little deformation. Furthermore, given the excellent electromagnetic performance of the model 1 compared to other models, we can select model 1. The production model is depicted in Fig. 5(a), Figures 5(b) and 5(c) depict results obtained via experimentation and analysis, respectively. Errors observed in this case were attributed to mechanical losses due to presence of equivalent stresses. As observed, experimental results demonstrated good agreement with those obtained via analysis.

IV. CONCLUSION

Most MGs are characterized by electromagnetic designs, whereas MGs with linear structures are seldom investigated. Additionally, only very few studies have been performed to validate MG fabrication processes; however, verification of the manufacturability of MG FMPs is an essential task. To address these concerns, this study presents an LMG design approach along with its experimental validation. Results obtained in this study can be used as reference for optimizing designs of both linear PM machines and linear structured LMGs.

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REFERENCES

1 B. Drew, A. R. Plummer, and M. N. Sahinkaya, Proc. IMechE. Power Energy. 223, 887–902 (2009).
2 K. Atallah and D. Howe, IEEE Trans. Magn. 37, 2844–2846 (2001).
3 S. T. Boroujeni, J. Milimonfared, and M. Ashabani, IEEE Trans. Magn. 45, 5405–5413 (2009).
4 C. T. Liu, C. C. Hwang, and Y. W. Chiu, IEEE Trans. Ind. Appl. 53, 2401–2408 (2017).
5 E. Gouda, S. Mezani, L. Baghli, and A. Rezzoug, IEEE Trans. Magn. 47, 439–450 (2011).
6 N. W. Frank and H. A. Toliyat, IEEE Trans. Ind. Appl. 47, 1652–1660 (2011).
7 K. Atallah, J. Wang, and D. Howe, J. Appl. Phys. 97, 10N516 (2005).
8 S. Pakdelian, Y. Deshpande, and H. A. Toliyat, IEEE Trans. Energy Convers. 30, 1180–1191 (2015).
9 Y. Zhang, W. Cao, S. McLoone, and J. Morrow, IEEE Trans. Appl. Supercond. 26, 1–6 (2016).
10 X. Zhu, W. Hua, and Z. Wu, IET Elect. Power Applications. 12, 627–634 (2018).