Journal of Magnetics 30(4), 688-693 (2025)
ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
https://doi.org/10.4283/JMAG.2025.30.4.688

Analysis and Experimental Verification of Detent Force and Static Thrust of a 3 kW Single-phase Linear Permanent Magnet Generator for Free-piston Stirling Engines

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(Received 26 September 2025, Received in final form 20 November 2025, Accepted 20 November 2025)

Linear generators are used in free-piston Stirling engines (FPSE) because of their reciprocating mechanism. In the FPSE, the generator is driven using the motor mode to drive the engine. Once the engine begins to operate, the generator mode is used. For this reason, a single-phase linear permanent magnet generator (SPLPMG) suitable for the reciprocating motion of a mechanism-driven type and a simple initial driving operation is applied to a Stirling engine. However, compared with rotating machines, it is not as easy to evaluate the detent force and output power of a linear permanent magnet generator. It is particularly important to evaluate the former because the generator includes a permanent magnet. To analyze the characteristics of the linear generator, the detent force and static thrust were analyzed using finite element analyses. In addition, the composition and evaluation methods of the test rig for evaluating the detent force and static thrust are proposed. Finally, the evaluated static thrust was converted into an output and compared with the analytical results. Findings confirmed that the finite-element and experimental results of the proposed method were similar.

Keywords : linear generator, stirling engine, single-phase linear permanent magnet generator, detent force, static thrust

1. Introduction

A Stirling engine burns fuel in an externally installed combustion device to obtain thermal energy; it then uses this energy to change the state of the working fluid to generate mechanical energy. Mechanical energy is converted into electrical energy by a generator. Various Stirling engines have been developed for this purpose. When a linear permanent magnet generator is coupled with the engine, it is known as the free-piston Stirling engine (FPSE) [1-6].

When a linear drive system, such as an FPSE, is applied, the linear generator does not require a mechanical energy conversion device, such as a screw or crankshaft; thus, the mechanical loss is small, conferring a spatial advantage. The linear generator does not require lubrication and has a simple maintenance mechanism owing to its mechanical structure [7].

Despite these advantages, a linear generator suffers from a disadvantage in that its performance is very difficult to evaluate owing to its reciprocating linear motion [8]. Unlike rotating machines, evaluating the detent force and output power of a linear generator is complicated.

In a previous study, the output of a linear generator was evaluated using a servomotor and an engine as the driving source. The evaluation system included a crankshaft that converted rotary motion into linear motion [8].

However, owing to the vibration caused by the reciprocating movement of the crank section, which converts the self-oscillation and rotational motion of the engine and servomotor into linear motion, it is difficult to evaluate linear generators with short stroke lengths during operation at frequencies > 30 Hz.

In this study, a simple and efficient method is proposed to predict and evaluate the output of a single-phase linear permanent magnet generator (SPLPMG). First, the detent force of the SPLPMG was analyzed using the finite-element method (FEM), and a detent force test rig was fabricated to verify the validity of the FEM results. In addition, a direct current (DC) source was applied to the SPLPMG to evaluate the static thrust according to the

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mover position and to estimate the generator output based on this evaluation. For this purpose, a static thrust test rig system capable of measuring the static thrust with respect to the mover position was constructed, and the FEM analysis results were compared with the experimental results to verify the effectiveness of the proposed method.

2. Machine structure and the FEM

2.1. Structure of the SPLPMG

Fig. 1 shows the shape of an SPLPMG for a Stirling engine. The outer stator of the designed SPLPMG was composed of 12 divided structures, and a silicon steel sheet was laminated to reduce the iron loss. The inner core was composed of a silicon steel plate with a radial lamination structure. The main magnets, which affect the output, were divided into 24 segments to reduce eddy current loss, and the spring magnets, which influence the restoring force, were arranged with 12 pieces on each side of the main magnets.

Table 1 shows the design specifications of the SPLPMG used in the study. The permanent magnet mover of a linear generator generates a detent force owing to the tooth-slot structure of the stator and the end effect of the linear generator [9, 10]. SPLPMGs must be designed to minimize the detent force in the stroke section to ensure smooth operation. The spring magnet pushes the position of the mover within the stroke section, and uses the restoring force of the spring magnet when the mover of the SPLPMG leaves the stroke section. A spring magnet was used to utilize this restoring force. When the length of the spring magnet is appropriately used, the direction of the detent force at the displacement end of the power piston can be changed such that the detent force of the linear generator has the same stiffness as that of the mechanical spring.

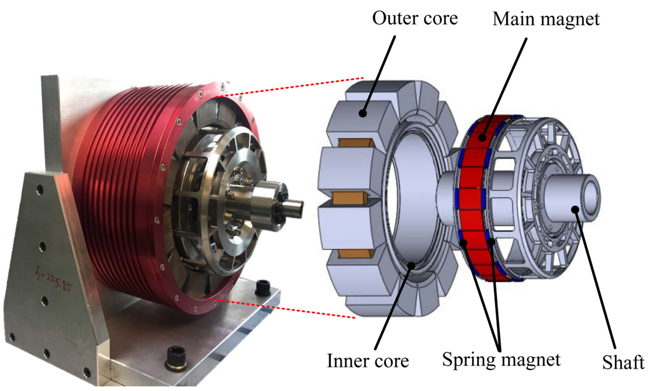

Fig. 1. (Color online) Topology of the single-phase linear permanent magnet generator (SPLPMG).

Table 1. Dimensions and design specifications of the single-phase linear permanent magnet generator.

Parameter	Value	Parameter	Value
Output power	3 kW	Airgap length	1 mm
Operation frequency	60 Hz	Mover stroke	±11 mm
Rated load resistance	15 Ω	Tuning capacitor	70 μF

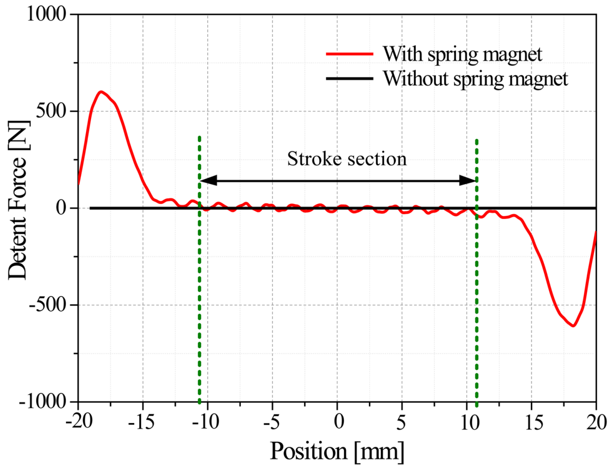

Fig. 2. (Color online) Plots of detent force as a function of position in the presence and absence of a spring magnet.

Fig. 2 shows that when a spring magnet is applied, the detent force plays almost no role in the stroke section and does not affect the operation of the generator mover. However, it can be confirmed that the restoring force created by the spring magnet, which deviates from the stroke section, acts similarly to the force generated by a mechanical spring. Thus, the mover did not deviate from the stroke range.

Based on these results, two-dimensional (2D) and three-dimensional (3D) FEMs were used to verify the detent and restoring forces of the spring magnet within the operating range of the mover. A detent-force test rig was constructed and experimentally verified to verify the FEM analysis results.

2.2. Analyzed results of the SPLPMG

The designed SPLPMG was analyzed using frequency-dependent output curves according to the load resistance using FEM. Fig. 3 shows the output curve for each frequency according to the SPLPMG load resistance.

The generator output exceeds 3 kW when the driving frequency is 60 Hz and load resistance is below 20 Ω. However, directly evaluating the load output of a linear generator under the 60 Hz driving frequency condition is relatively difficult, and in previous studies, output

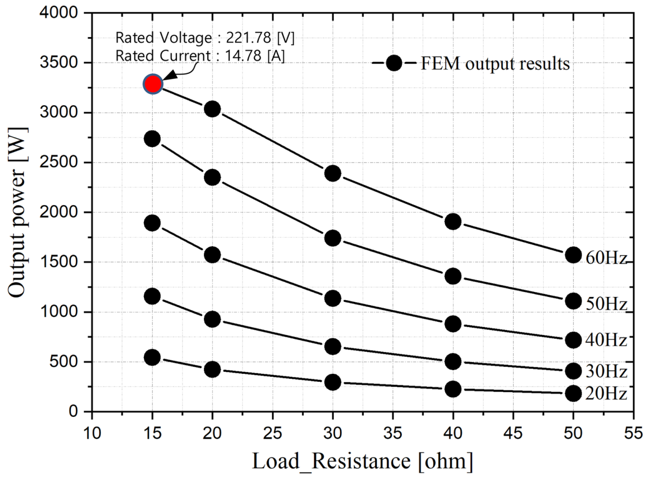

Fig. 3. (Color online) Finite-element method (FEM) output power curves as a function of load resistance at different frequencies.

evaluation was only possible up to a driving frequency of 30 Hz.

Therefore, in this study, to indirectly derive the load output of the SPLPMG, a load current was applied when the generator was in a static condition, and the static force was evaluated according to the mover position. Based on this evaluation, a method is proposed to indirectly estimate the generator output.

Fig. 4 shows a flowchart of the detent force and static thrust evaluation method. Except for the application of the DC current to the generator in the evaluation flowchart, the detent force and static thrust evaluation methods are similar. The detent force and static thrust were evaluated using the proposed method.

3. Detent force analysis and evaluation

3.1. Detent Force Test Rig and FEM Results for the SPLPMG

To evaluate the detent and restoring forces of the fabricated SPLPMG, a test rig set was constructed, as shown in Fig. 5. The load cell was mounted on the shaft of the SPLPMG, and a position-control controller was used to adjust the position of the generator movers. The positioning controller was adjusted to evaluate the detent and restoring forces while changing the position of the mover. In addition, to minimize variations in the detent force caused by mechanical contact during the movement of the mover in the linear generator, the system was configured using a noncontact air bearing instead of a mechanical linear bearing.

Fig. 6 compares the results of the 2D and 3D FEM

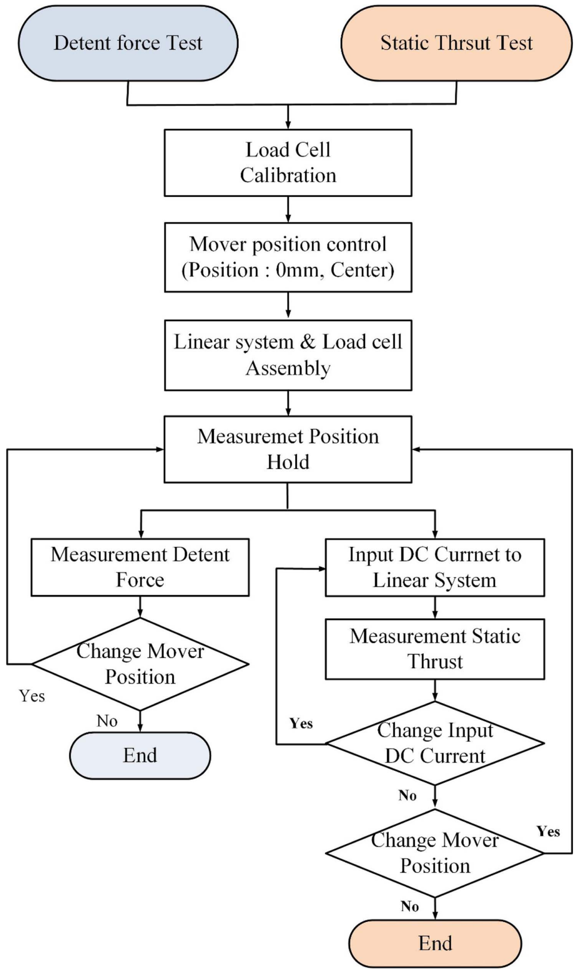

Fig. 4. (Color online) Flow chart summarizing the detent force and static thrust evaluation processes.

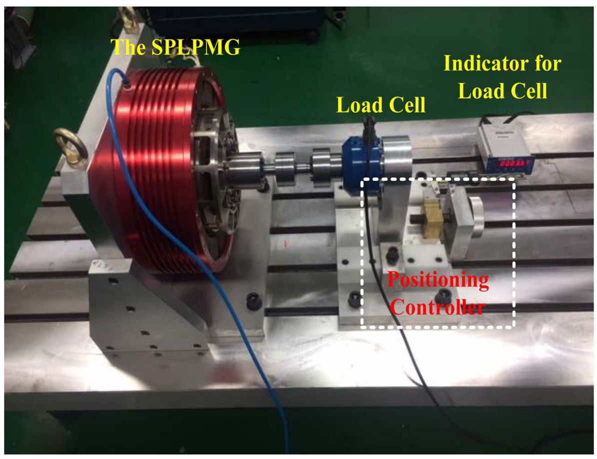

Fig. 5. (Color online) Test rig for evaluating the SPLPMG's detent and restoring forces.

analyses with those of the tested detent force. The detent force measured at the stroke interval while adjusting the

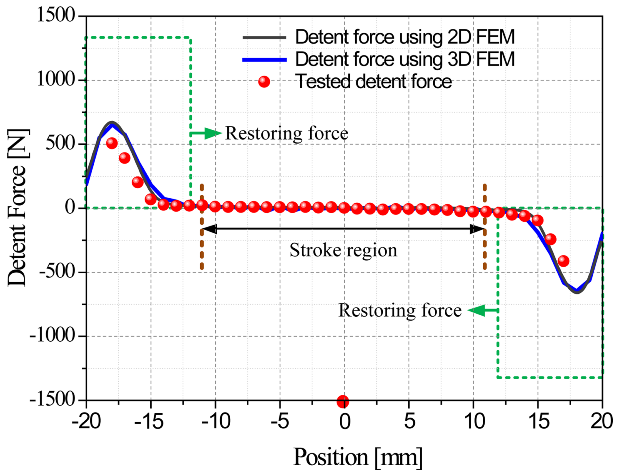

Fig. 6. (Color online) Two-dimensional (2D) FEM, three-dimensional (3D) FEM, and tested results of detent and restoring forces.

mover position of the SPLPMG was almost equivalent to that obtained using the 2D and 3D FEM. The same was true for the evaluation results of the restoring force outside the stroke range.

In addition, the results indicate that the detent force was low in the stroke section, which constitutes the operating section of the mover. It is confirmed that the restoring force pushing the mover to the stroke section occurs when the mover moves out of the stroke section, that is, between ±13 and 20 mm.

4. Static thrust analysis and evaluation

Unlike a rotary generator, it is very difficult to evaluate the input/output of a linear permanent magnet generator owing to the structure of the reciprocating mover.

Specifically, it is difficult to implement an evaluation system for a linear generator that reciprocates at 60 Hz owing to the design of the mechanism for implementing high-speed reciprocating motion and vibration problems.

Therefore, in this study, instead of directly implementing reciprocating motion at 60 Hz, the static thrust of the linear generator was evaluated under various load current conditions. Based on this evaluation, the generator output was indirectly predicted to verify its performance. The generator output indirectly calculated using the static thrust evaluation was compared with the FEM analysis results.

4.1. Static Thrust Test Rig for the SPLPMG

Fig. 7 shows the evaluation system used to analyze the static thrust of the SPLPMG.

The position of the mover was controlled by a position

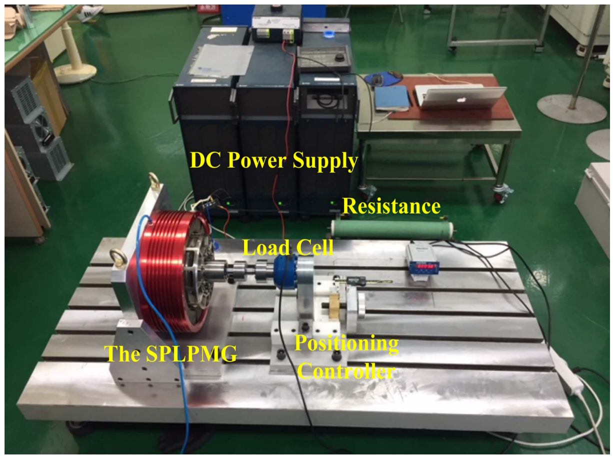

Fig. 7. (Color online) Static thrust test rig.

controller, and the load resistance and DC power supply were connected to a single-phase generator. The static thrust was evaluated under various conditions by varying the voltage of the DC power supply and a load current (in the range of 2–14 A) at each mover position. The mover position was adjusted at 2 mm intervals using a position controller, and the static thrust was evaluated at each position according to the load current.

According to the FEM results in Fig. 3, the load current of the SPLPMG under the rated output condition is approximately 14 A. Therefore, a static thrust evaluation was performed until the applied current reached 14 A. When currents in the range of 2–14 A were applied to the linear generator, the static thrust increased from 180.58 N to 1254.52 N within the mover's stroke operating range.

The output (power) created by the thrust and speed of the linear permanent magnet generator is expressed using (1).

$$P\ (power) = Fv \tag{1}$$

where F is the thrust (N) of the linear permanent magnet generator, and v is the velocity (m/s). If the mover of the SPLPMG reciprocates with a sine wave, v_{avg} can be expressed using (2).

$$v_{avg} = \frac{2}{T}\int_0^{T/2} v(t)dt = \frac{2}{T}\int_0^{T/2} v_m \sin(wt)dt = \frac{2}{\pi}v_m \tag{2}$$

When the stroke equals ±11 mm and the driving frequency is 60 Hz, v_{avg} is 2.65 m/s.

When a DC load current of 14 A was applied to the SPLPMG, the generator thrust was 1254.52 N. When the reciprocating motion frequency (60 Hz) and length (±11 mm) were converted to speed and then substituted into (1), the confirmed generator output was at least 3 kW.

4.2. Comparison of Tested Static Thrust and FEM Results of the SPLPMG

Fig. 8 compares the static thrust evaluation results (according to the mover position and load current of the SPLPMG) with the FEM results. It can be confirmed from comparison of the static thrust test and FEM results that when the same current was applied to the generator, a similar static thrust is generated within the mover's operating range (±11 mm).

Fig. 9 shows a comparison between the output of the SPLPMG obtained from the 3D FEM analysis and the output converted from the static thrust force using Equations (1) and (2). The 3D FEM results present the generator output characteristics with respect to load resistance when the SPLPMG is operated at a frequency of 60 Hz and a stroke of ±11 mm. In contrast, the output obtained by the indirect thrust-based calculation was derived by multiplying the measured static thrust force under each load current condition by the average mover velocity at the rated operating condition of the SPLPMG. As a result, it was confirmed that the generator output obtained from the FEM analysis and that calculated indirectly from the static thrust force exhibited a generally similar trend.

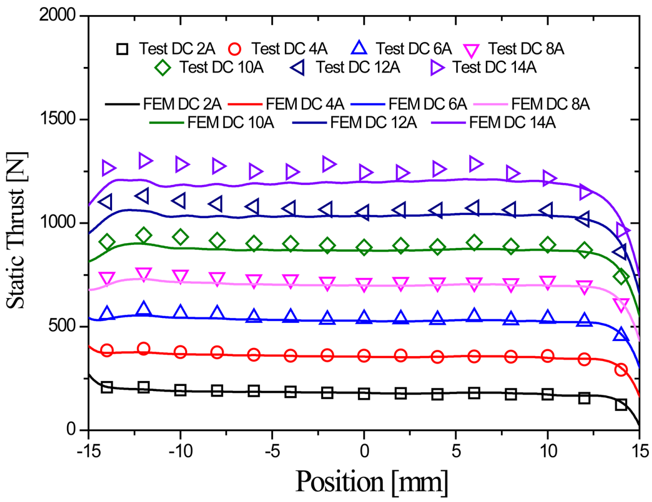

Fig. 8. (Color online) FEM and test results of static thrust.

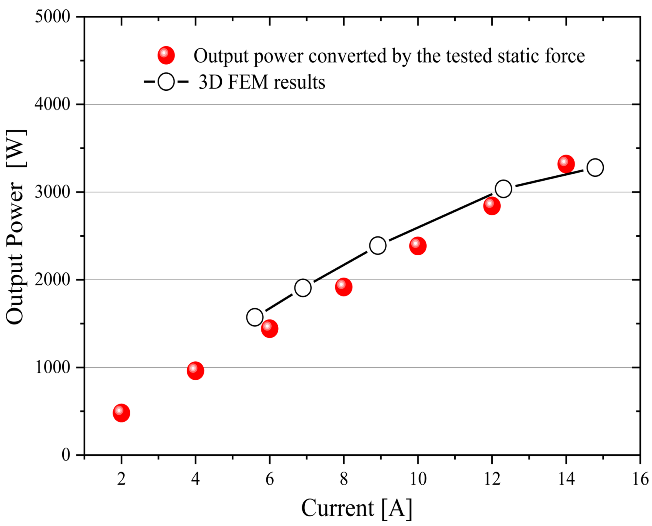

Fig. 9. (Color online) Comparison of FEM output results and the converted output using static thrust.

5. Conclusion

This paper presented a method for analyzing and evaluating the detent and restoring forces of SPLPMG. Because the position and number of applications of the main and spring magnets in the linear generator differ, a 3D FEM was applied to perform an accurate analysis. Subsequently, a test rig was constructed, and the detent and restoring forces were evaluated. The test results for the detent and restoring forces of the SPLPMG were similar to those of the 3D FEM.

In addition, it is very difficult to evaluate the performance of a generator by simply constructing an evaluation system for a linear generator with a short stroke and an operating frequency of 60 Hz. Therefore, the generator's output was estimated by evaluating the static thrust according to the position of the movers while the DC current applied to the generator was changed. A test rig was constructed to evaluate the static thrust. The average static thrust was measured to be 1254.52 N in the stroke section when a 14 A DC current was applied to the SPLPMG in the manufactured test rig. Considering the average mover velocity and the measured static thrust, it was confirmed that the output exceeded 3 kW.

When the same current was applied, the output of the FEM and the output converted to the evaluated static thrust were compared. This evaluation confirms that the outputs of the two methods are similar.

Therefore, in this study, the detent and restoring forces of a linear generator system with a reciprocating motion were analyzed and experimentally verified. In addition, the static thrust of the reciprocating generator was evaluated and compared with the FEM results to verify the validity of the proposed method.

Acknowledgment

This work was supported by the Ministry of Trade, Industry and Energy (MOTIE) and the Korea Evaluation Institute of Industrial Technology (KEIT) under grant number RS-2024-00456966.

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