

Detent Force Reduction of a Tubular Linear Generator Using an Axial Stepped Permanent Magnet Structure

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ABSTRACT

Various methods have been discussed to reduce detent force in a tubular permanent magnet type linear single phase AC generator. In particular, the proposed methods depend on variations of the permanent magnet construction. These methods include two approaches in the form of sloped magnets, and conical magnets in addition to the conventional method of optimizing the magnet length. The undesired detent force ripples were calculated by a two dimensional Finite Element Method (FEM). Moreover, the generated electromotive force in the stator coils was calculated for each configuration of the permanent magnet. The experimental results agreed well with those obtained from the FEM-based simulations. Sufficient reduction in the detent force was achieved over the range of 40% while the root mean square of the output voltage was maintained. It was found that sloping the permanent magnet decreased the detent force and at the same time increased the generated rms voltage of the AC generator. The performance of the designed linear AC generator was evaluated in terms of its efficiency, total weight, losses, and power to weight ratio.

Keywords: permanent magnet, detent force, induced voltage, linear generator, and finite element method

1. Introduction

The linear single-phase synchronous generator is an energy conversion device, which converts the kinetic energy of the reciprocating motion of the piston system to electrical energy, by means of a strong magnetic field generated by rare earth permanent magnets (PMs). The major advantages of linear generators are: the absence of a crankshaft and camshaft, lighter in weight than its rotary counterpart, higher efficiency, and safe operation [1]. Among various linear machine configurations, tubular

magnet type linear machines (motor/generator) with permanent magnet excitation have a number of distinctive features [2], such as a high force density and excellent servo characteristics, which make them an attractive candidate for industrial applications in which dynamic performance and reliability are crucial [3].

The main problem which occurs in all linear machines is detent force. This detent force is a result of magnetic attraction between permanent magnets (PM's) mounted on the translator and the stator teeth [4]. It is the attractive force component that attempts to maintain the alignment between the stator teeth and the PMs on the translator [5]. The ripples of the detent force produce both vibrations and noise, which are limiting factors for any machine. Thus, detent force should be minimized for single-phase linear generators. In this paper, a tubular type linear permanent

Manuscript received December 30, 2005; revised June. 19, 2006

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magnet (TL-PM) generator is designed for free piston engine applications. The detent force is reduced by three different methods. These methods include two different PM constructions in the form of sloped and conical PMs, as well as the effect of the PM length. The constraints for the machine design are the stator length and stator outer diameter. These constraints are apparent in the application of the TL-PM generator after its design. It can be integrated with an existing free piston linear combustion engine as the mechanical prime mover for the linear generator. A two dimensional Finite Element Method (FEM) is adopted to analyze the TL-PM generator. The simulation results of the induced back electromotive force and the ripples of the detent force are compared with the experimental data collected from the experimental test of the TL-PM single-phase AC generator.

2. TL-PM Linear Generator Features

2.1 The designed prototype

The structure of the TL-PM single-phase synchronous generator treated in this paper is shown in Fig. 1. The primary or stator-fixed part of the TL-PM generator consists of the stator core and coils. The core is assembled from 0.5 mm laminations of silicon steel material of grade 50H470 to reduce the eddy current loss and hence the total magnetic loss. These lamination discs are arranged in the r-direction. Thus, the flux goes through these laminations in a low reluctance path in stator teeth, while the flux returns to normal in the lamination discs in the stator back iron. There are only two copper coils in the stator to collect the generated AC voltage from the generator. The coil material is a rectangular copper conductor to maximize the winding fill factor and the load current value. These coils have a circular shaped cylinder which is placed in the stator iron core. The secondary (moving) part consists of a set of Nd-Fe-B material for the PMs which has a high-energy product, mild steel spacers between the PMs and a translator shaft of non-magnetic material. The PMs are embedded on the shaft and magnetized in the axial direction. The designed linear generator has a long translator (secondary) to continuously activate all the coils, and hence produces a higher induced voltage. Table 1 indicates the materials and dimensions of the TL-PM

single-phase synchronous generator.

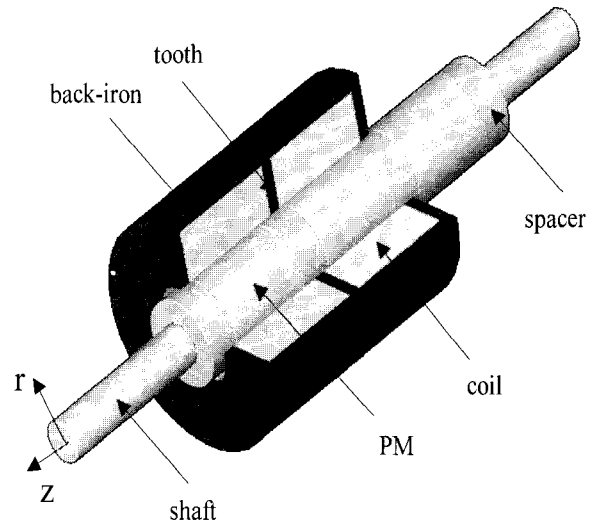


Fig. 1 The structure of TL-PM generator as 3D section

Table 1 Linear generator parameters and dimensions

Part	Item	Value	Unit
Stator	Pole pitch	76	mm
	Slot pitch	76	mm
	Slot depth	30	mm
	Tooth width	8	mm
Translator	Magnet thickness	15	mm
	Magnet length	56	mm
	PM material	Nd-Fe-B	
	PM remnant Br	1.06	T
Air gap	Air gap length	1	mm

2.2 Main FEM governing equations

A two-dimensional FEM is employed in the analysis and calculations of the magnetic field values. The governing equation of the TL-PM single-phase synchronous generator is described using the magnetic vector potential, A as ^[6]:

$$\nabla \times [\nu(\nabla \times A)] = J_o + J_m \tag{1}$$

Where, J_o is the current density of the primary source, and J_m is the equivalent magnetization current density of the PM. The equivalent magnetizing current is expressed as:

$$J_m = \nabla \times (\nu \mu_0 M) \tag{2}$$

Where, ν is the magnetic reductivity, μ_0 is the free space permeability, and M is the magnetization vector intensity of the PM. By solving the above equations in the finite region of the problem, the field values can be obtained. The detent force at any position of the translator is calculated using the Maxwell Stress Tensor Method [7]. The governing equation of the detent force is represented as:

$$F = \oint_s \frac{1}{2\mu_0} (B_n^2 - B_t^2) ds.t + \frac{1}{\mu_0} B_n B_t ds.n \tag{3}$$

where s is the surface enveloping the body under force, B is the flux density; n and t are unit vectors in the normal and tangential direction on the surfaces.

The generated electromotive force (emf) at stator coils terminals is calculated by Faraday's law of magnetic induction as:

$$emf = -N \frac{d\phi}{dz dt} \tag{4}$$

where N is the number of turns per coil, ϕ is the flux passing in each turn in real time t , dz/dt is the translator speed, z is the distance along z -direction.

3. Detent Force Reduction Methods

Three different methods are presented in this paper to reduce the detent force in TL-PM single-phase synchronous generators. These methods include the effect of the PM length and the other two methods depend on changing the construction of the PM shape, which are sloped and conical. In each method, the generated voltage in the stator coil terminals is calculated for different slope length. Another factor taken into consideration is the air gap length effect on both the detent force and the emf-induced voltage. These methods are further elaborated in the following sections:

3.1 Permanent magnet length effect

The field values are calculated by the FEM for different

values of the PM length. For each length of the PM, the detent force on the TL-PM single-phase synchronous generator is calculated as well as the induced emf voltage across the stator coils terminals. The variation of the detent force versus the PM length is illustrated in Fig. 2. The detent force is calculated for different air gap lengths, g . When the PM length is decreased, it will result in a decrease of the equivalent PM current density J_m , thus the detent force is decreased. Accordingly, the air gap length, g , is increased and the detent force is reduced due to less flux interaction between the stator teeth and the PMs. The root mean square (rms) AC voltage of the emf is calculated for each case of the PM length and is plotted in Fig. 3. When the PM length is reduced, the flux linking the stator coils will change rapidly during the motion of the PM across the coils. Thus the rms voltage increases in accordance with the decreasing PM length. It is worthy to mention that this increase in the induced voltage is not always preferable if the voltage waveform has sharp peaks, and a high amount of harmonic content, which is harmful for various electrical loads.

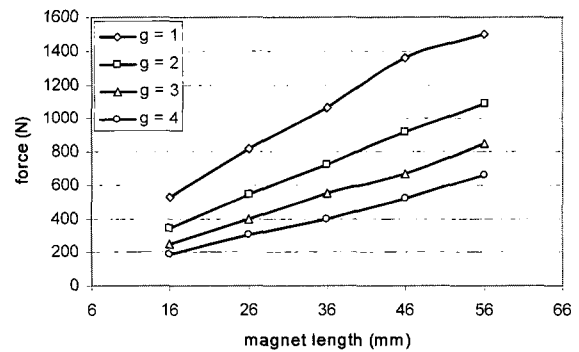


Fig. 2 PM length effect on detent force

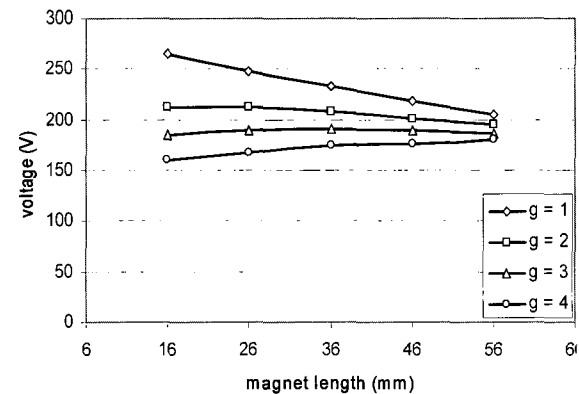


Fig. 3 PM length effect on induced voltage

In general, the induced voltage decreases when the air gap increases, as shown in Fig. 3, due to the increase of the leakage flux. For small air gap values, when the PM length is increased with less flux leakage, the flux may not change much. As a result, there is a decrease in the generated voltage. For large values of the air gap, the flux leakage is increased. Increasing the PM length at this time increases the flux change and hence the generated voltage, see Fig. 3.

3.2 Special Constructions of Permanent Magnet

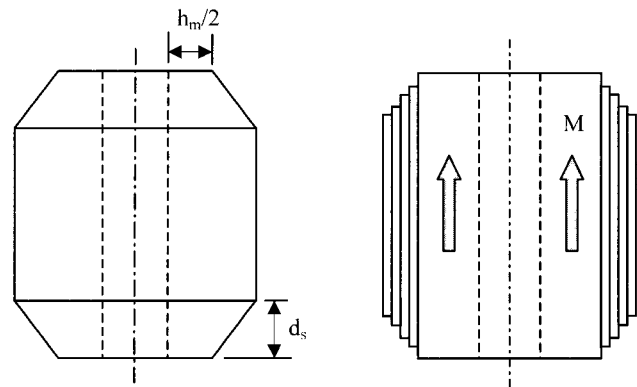
The special PM constructions analyzed in this paper are depicted in Fig. 4. These constructions are in the form of half sloped, complete sloped and inward conical PMs [8-10]. All these special PMs are magnetized in the axial direction and have the same thickness, h_m . The magnet thickness h_m equals 15 mm for all cases. The half sloped PM is shown in Fig. 4(a). To see its effect, the sloped height d_s is varied from 5 to 20 mm and in each case the detent force and the induced voltage are calculated as plotted in Fig. 5 and Fig. 6, respectively.

It is obvious that the detent force is reduced as slope length d_s increases. For small air gaps, the generated voltage increases with the slope length due the variations of the PM flux. However, for large air gaps the voltage drops as the slope length increases. The total length of the permanent magnet is kept at 56 mm for the three types of constructions in Fig. 4. The behavior of the full-sloped PM configuration, Fig. 4(b), is almost similar to the half sloped permanent magnet configuration.

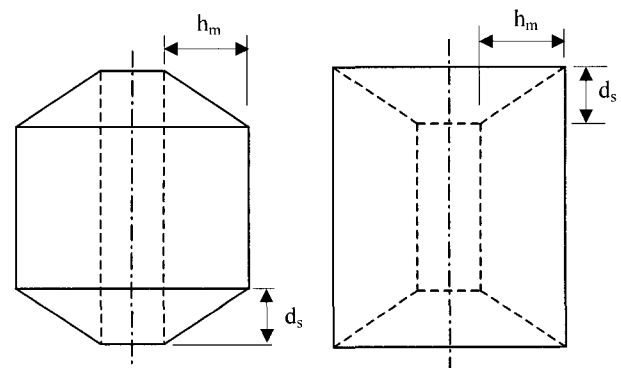
For comparison purposes, the detent force values for the full-sloped PM is slightly less than those of corresponding values for the half sloped PM for a constant air gap length, see Fig. 7. At the same time, the generated emf AC voltage for a full-sloped PM is higher than those of a half sloped PM at constant air gap length; see Fig. 8. Increasing the air gap length reduces the detent force as well as the induced voltage of the coils.

The last special construction of the PM analyzed here is the inward conical PM represented in Fig. 4(c). The detent force and the output voltage due to various changes in conical slope height d_s are shown in Fig. 9 and Fig. 10, respectively. In this case, the induced emf AC voltage decreases when slope height d_s increases, regardless of the

air gap length. Increasing the conical slope length results in decreasing the PM volume; thus decreasing the flux, which leads to a decrease in the induced voltage.



(a) Half slope approximate and actual



(b) Full sloped PM

(c) Conical PM

Fig. 4 Half, full sloped and conical PM constructions

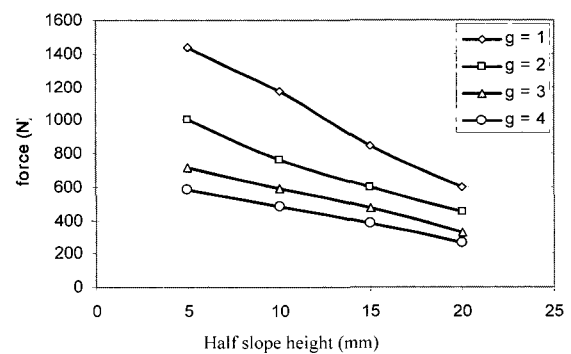


Fig. 5 half slope PM effects on detent force

It is noted that the detent force of the conical PM is less than those of half or full sloped PM cases. It is worth

mentioning that these special PM constructions are obtained by assembling PMs with different outer diameters as shown in Fig. 4(a). The more PMs used produces a smoother slope. Also, these PMs can be assembled in r- or z-directions to form the desired sloped PM.

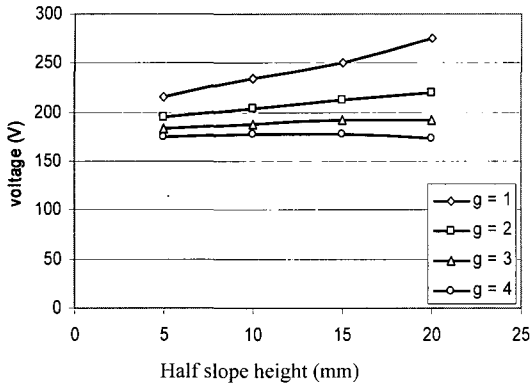


Fig. 6 half slope PM effects on induced voltage

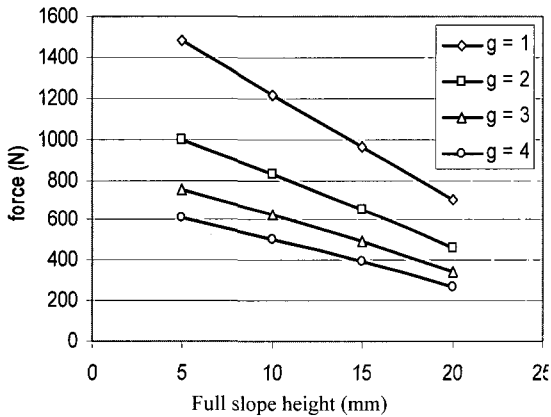


Fig. 7 Full slope PM effects on detent force

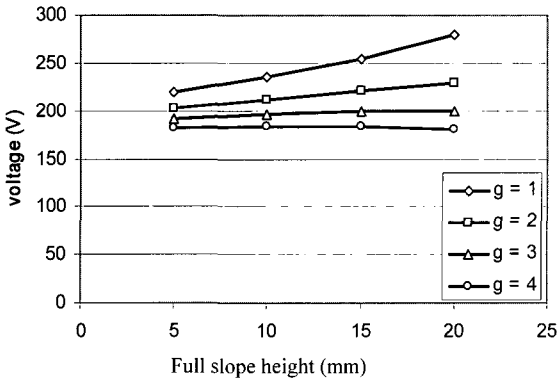


Fig. 8 Full slope PM effects on output voltage

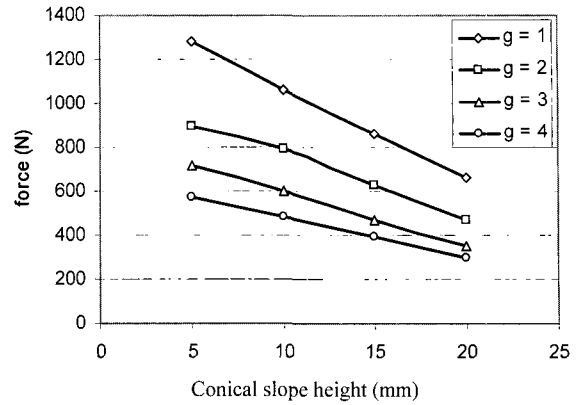


Fig. 9 Conical PM effects on detent force

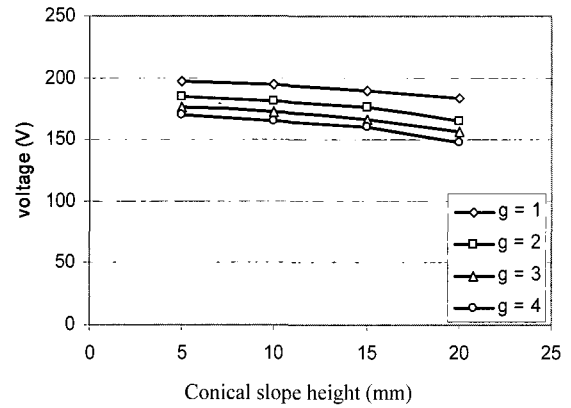


Fig. 10 Conical PM effects on induced voltage

4. Experimental Results and Evaluations

A prototype for a TL-PM single-phase AC generator is built, to verify the validity of the simulation results. The dimensions of this prototype are listed in Table 1. The detent force and the generated emf AC voltage in the stator coils of the prototype assembly at half stroke are recorded and shown in Fig. 11 and Fig. 12, respectively. From the last figures, it can be observed that the simulated results agree with those obtained by the experiments. The detent force depends mainly on the permanent magnet position with respect to the stator teeth. After using the techniques described above, the maximum detent force is reduced by around 40%; hence the maximum detent force was around only 600N. It is worth mentioning that these experimental results were obtained in the first prototype before reducing the detent force using the discussed above methods. The generated output voltage shown in Fig. 12

has a square-wave shape, and hence fewer harmonic contents with better performance if it is rectified before utilization as occurring in normal situations.

5. TL-PM Generator Performance and Efficiency

The performance of the generator is examined using the equivalent circuit analysis of the TL-PM generator as shown in Figure 13. The parameters of the generator equivalent circuit and its output performance were calculated and are listed in Table 2. The designed current density for copper wire is less than 4A/mm². The considered losses are the copper loss in the generator winding as well as the core loss in the iron parts. The friction loss is neglected in these calculations. As the core loss is a function of frequency, it is calculated for both low and high frequencies using FFT analysis.

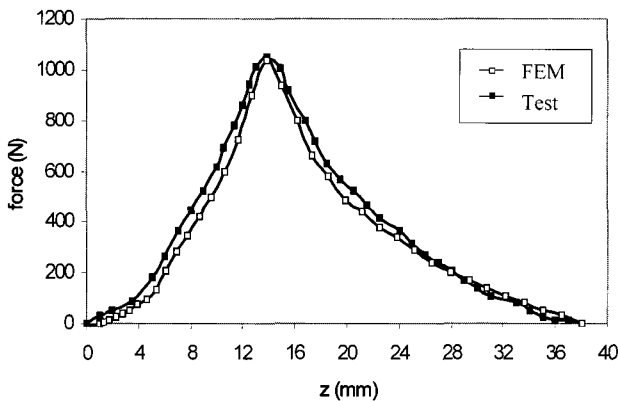


Fig. 11 Detent force for a stroke length

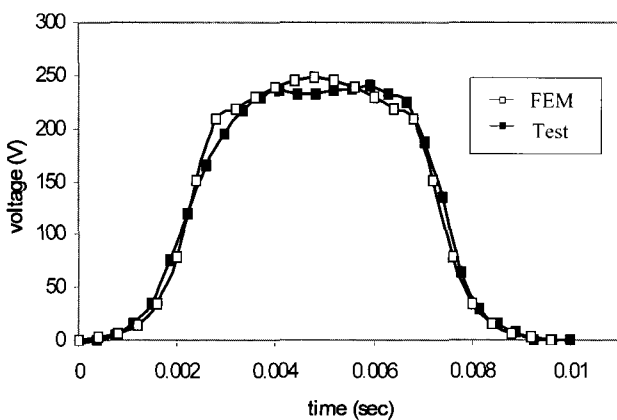


Fig. 12 The generated voltage for a stroke length time

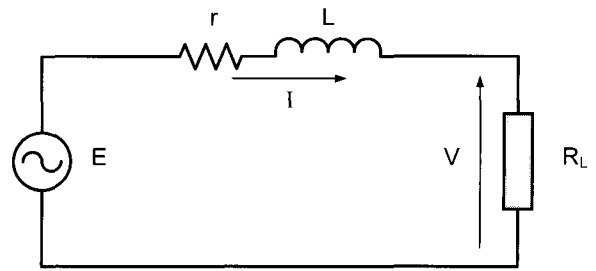


Fig. 13 TL-PM generator equivalent circuit

Table 2 TL-PM generator circuit parameters

Item	Value	Unit
Coil resistance (r)	0.3	Ω
Synchronous inductance (L)	7.6	mH
Output power	3.65	kW
Efficiency	0.90	pu
Generator weight	19.5	kg
Rated load current	25	A
Resistive loss	187	W
Core loss	25	W
Mechanical loss (5% assumed)	182	W
Power/Weight ratio	187	W/kg

The PM-LG is simulated under load conditions to calculate the generator performance while the armature reaction effect is taken into consideration. At first, the only source in the design is the PMs. After moving the translator a complete period, and collecting the flux linkage for each stator coil, the internal back-generated emf is calculated. From the simple equivalent circuit, the load current can be calculated. The AC output power and copper and core losses are then determined so the efficiency of the alternator can be calculated. In the next period, the flux is calculated again from the PMs and currents of the stator windings. This new flux is compared with the original flux derived from only the PMs. If the flux change exceeds a predetermined threshold, the entire process with voltage and parameter calculations is repeated [11]. Thus the armature (flux) reaction is taken into consideration in load cases and in the parameter calculations. The synchronous reactance can be cancelled by inserting an equivalent capacitor in series, to put the

load current in the same direction as the generated voltage waveform. Hence there are fewer harmonic contents and a better performance if it is rectified before utilization as occurring in normal situations.

6. Conclusions

In this paper, a two-dimensional finite element method has been introduced to analyze a tubular linear permanent magnet single-phase synchronous AC generator. Special permanent magnet constructions in the form of half sloped, full sloped and conical PMs were analyzed. Their effects on the detent force and the induced voltage were investigated. The PM length effect was studied as a method for reducing the detent force of the linear AC generator. It was found that sloping the permanent magnet decreases the detent force and at the same time increases the generated rms voltage of the AC generator.

The performance of the designed linear AC generator was evaluated in terms of its efficiency, total weight, losses, and power to weight ratio. A repetitive routine was adopted to take the armature reaction effect on the generated output voltage. The routine stopped calculations when the flux change became minimal. It was demonstrated that the simulated results obtained using the FEM basically agreed with those obtained from the experimental data for a real produced linear single-phase AC generator prototype.

Acknowledgment

Ministry of Commerce, Industry and Energy (MOCIE) financially supported this work through the Industry and Energy Research Center (IERC) program.

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