2005년도 대한전기학회 EMECS학회 추계학술대회 논문집 (2005.10.20-10.22)

Tubular Permanent Magnet Linear Synchronous Generator Design For Linear Engine Applications

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Abstract- Variety of methods were discussed to reduce the cogging force in tubular permanent magnet type linear single phase AC generator. In particular, the proposed methods depend on the 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 varying the magnet length. The undesired cogging 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 cogging force was achieved over the range of 40% while the root mean square of the output voltage was maintained. It was found that the sloping the permanent magnet decreased the cogging 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.

I. 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 strong magnetic field generated by rare earth permanent magnets (PMs). The major advantages of linear generator are: the absence of the 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 that appears in all linear machines is the cogging force. This cogging force is developed from the magnetic attraction between the 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 cogging force produce both vibrations and noise, which are limiting factors for any machine. Thus the cogging force should be minimized for the single-phase linear generator. In this paper a tubular type linear permanent magnet (TL-PM) generator is designed for the free piston engine applications. The cogging force is reduced by three different methods. These methods include two different PM constructions in the form of sloped and conical PM, as well as the effect of PM length. The constraints for the machine design are the stator length, stator outer diameter. These constraints come from 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 FEM is used to analyze the TL-PM generator. The simulation results of the induced back electromotive force and the ripples of the cogging force are compared with the experimental data collected from the experimental test of the TL-PM single-phase AC generator.

II. UNIQUE FEARTURES OF TL-PM LINEAR GENERATOR

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. These lamination discs are arranged in the r-direction. There are only two coils in the stator to collect the generated AC voltage from the generator. The secondary (moving) part consists of the Nd-Fe-B material for the PMs which has high-energy product, mild steel spacers between the PMs and the translator shaft of non-magnetic material. The PMs are embedded on the linear generator shaft and magnetized in the motion (axial) direction. Table 1 indicates the materials and dimensions of the TL-PM single-phase synchronous generator.

Two-dimensional FEM 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 primary source , 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, v is the magnetic reluctivity, μ_0 is the free space permeability, and M is the magnetization vector intensity of the PM. Solving the above equations in the finite region of the problem, the field values can be obtained. The cogging force at any position of the translator is calculated using Maxwell Stress Method [7]. The governing equation of the cogging force is represented as:

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

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 surface s.

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

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

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.

III. COGGING FORCE REDUCTION METHODS

Three different methods are presented in this paper to reduce the cogging 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 PM and the conical PM. In each method, the generated voltage in the stator coils terminals is calculated for different slope length. Another factor taken into considerations is the air gap length effect on both the cogging force and the emf-induced voltage generated. These methods are further elaborated in the following sections:

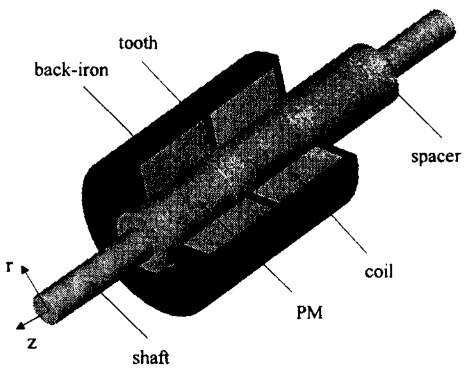


Fig. 1 The structure of TL-PM generator as 3D section

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

(A) 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 cogging 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 cogging force versus the PM length is illustrated in Fig. 2. The cogging force is calculated in for different air gap lengths, g. Decreasing the PM length decreases the equivalent PM current density J_m, thus the cogging force is decreased according to the increase of the air gap length, g. The root mean square (rms) AC voltage of the emf is calculated for each case of the PM length and 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 decreasing the PM length. It is worthy to mention that this increase in the induced voltage is not always preferable if the voltage waveform has a sharp peaks, thus has a high amount of harmonic content, which is harmful for various electrical loads. In general, the induced voltage decreases when the air gap increases as shown in Fig. 3 due to the increase in the leakage flux.

(B) 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 slope, complete slope and inward conical PMs.

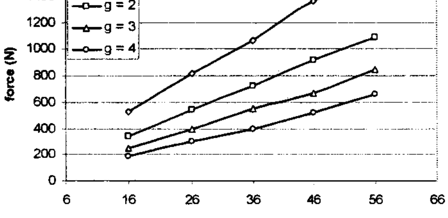


Fig. 2 PM length Effect on cogging force

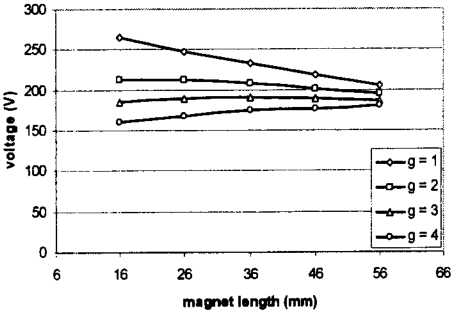
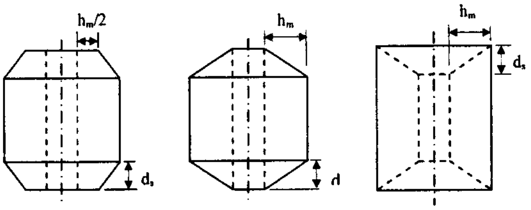


Fig. 3 PM length Effect on induced voltage



(a) Half slope (b) Full slope (c) Conical

Fig. 4 Special PM constructions

All these special PMs are magnetized in the axial direction and have the same thickness. The magnet thickness h_m equals 15 mm. the half slope PM is shown in Fig. 4(a). The slope height d_s is varied from 5 to 20 mm and in each case the cogging force and the induced voltage are calculated as plotted in Fig. 5 and Fig. 6, respectively. It is obvious that the cogging force is reduced as the slope length d_s increase. 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 height of the permanent magnet is kept at 56 mm for the three types of constructions in Fig. 4. The behavior of the full slope PM configuration, Fig. 4(b), is almost identical with the half slope permanent magnet configuration. For a comparison purposes, the cogging force values for the slope PM is slightly less than those of corresponding values for the half slope PM for constant air gap length. At the same time, the generated emf AC voltage for slope PM is higher than those of half slope PM at constant air gap length. The last special construction of the PM analyzed is the inward conical PM represented in Fig. 4 (c). The cogging force and the output voltage due to various changes in the conical slope height ds are shown in Fig. 7 and Fig. 8, respectively.

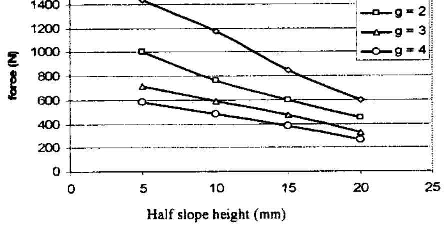


Fig. 5 half slope PM effects on cogging force

In this case, the induced emf AC voltage decreases when the slope height d_s increases regardless to the air gap length. Increasing the conical slope length results in decreasing the PM volume; thus decreasing the flux, which leads to a decrease of the induced voltage. It is noted that the cogging force of the conical PM is less than those of half and full slope PM.

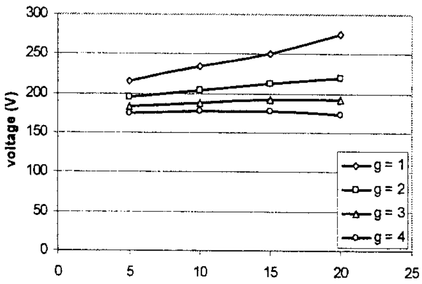


Fig. 6 half slope PM effects on induced voltage

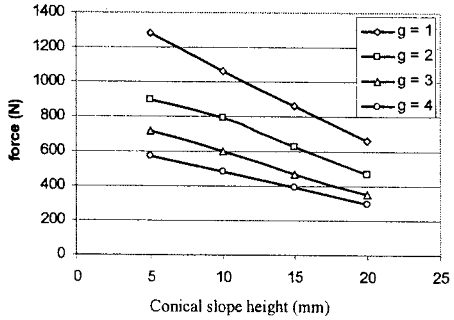


Fig. 7Conical PM effects on cogging force

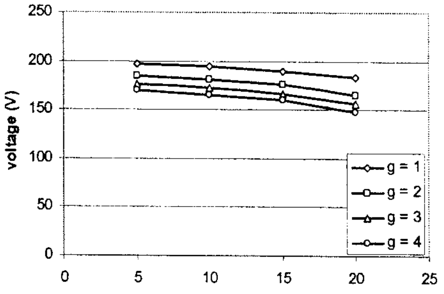


Fig. 8 Conical PM effects on induced voltage

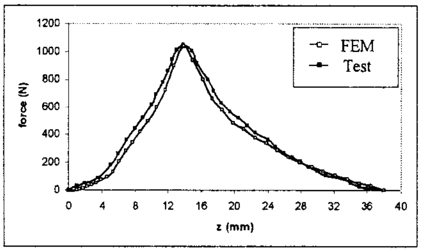


Fig. 9 Cogging force for half stroke for g = 1mm

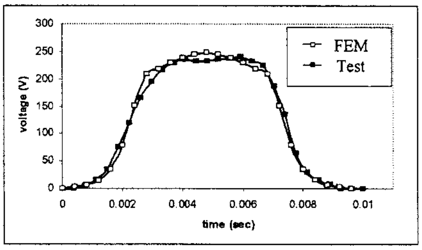


Fig. 10 The generated voltage for g = 1mm

IV. EXPERIMENTAL RESULTS AND EVALUATIONS

A prototype for a TL-PM single-phase AC generator is built, to verify validity of the simulation results. The dimensions of this prototype set up are listed in table 1. The cogging force and the generated emf AC voltage in the stator coils of the prototype assembly for half stroke are recorded and shown in Fig. 9 and Fig. 10, respectively. From the last figures, it can be observed that the simulated results agree with those obtained by the experiments. It is worth to mention that these experimental results were obtained in the first prototype before reducing the cogging force using the discussed above methods.

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 forms of half slope, full slope and conical PM were analyzed and their effects on the cogging force and the induced voltage are investigated. The PM length effect was studied as a method to reduce the cogging force of the linear AC generator. It was found that the sloping the permanent magnet decreases the cogging force and at the same time increases the generated rms voltage of the AC generator.

The performance of the designed linear AC generator is evaluated in terms of its efficiency, total weight, losses, and power to weight ratio. 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 for the automotive power feeding system architecture.

ACKNOWLEDGMENT

This work was financially supported by MOCIE through IERC program.

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