Cogging force investigation of a free piston permanent magnet linear generator

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Abstract. Better performance and higher efficiency of the vehicles can be achieved by using free piston engine, in which the piston is connected directly to the linear generator and waiving of any mechanical means. The free piston engine has the ability to overcome or reduce many of the challenges, such as the carbon dioxide (CO_2) emission and fossil fuel consumption. The cogging force produces undesired vibration and acoustic noise in the generator. However, the cogging force must be minimized as much as possible, in order to have a high performance. This paper studies the effects of ferromagnetic materials on the cogging force of the permanent magnet linear generator (PMLG) to be used in a free piston engine using nonlinear finite-element analysis (FEA) under ANSYS Maxwell. The comparisons have been established for the cogging force of the PMLG under various translator velocities and three different ferromagnetic materials for the stator core, namely, Silicon Steel laminations, Mild Steel and Somaloy. It has been shown that the PMLG with a stator core made of Somaloy has a lower cogging force among them. Furthermore, the induced voltage of the PMLG at different accelerations has been studied. It is found that the PMLG with Mild Steel and Somaloy, respectively give larger induced voltage. Moreover, as the translator speed increase the induced voltage increased.

1. Introduction

As the fossil fuels and many of energy sources are contributing to CO_2 emission and other pollutants in both land and sea-based transport, many countries are promoting the development process of clean energy [1][2]. However, within the automotive industry, there are many kinds of research have been conducted to reduce the fossil fuel consumption which leads to high cost and environmental problems. The hybrid electric vehicle is one of the recently studied solutions [3, 4].

The configuration of the conventional internal combustion engines powering the hybrid electric vehicles generally used mechanical transmission means such as crank mechanism, which restricts the motion of the piston. Moreover, the major part of the total friction losses occurring in the conventional combustion engine because of the crank mechanism [5, 6]. Besides, it limits the range of the compression ratio of the engine. Hence, better performance and high efficiency of the conventional engine can be achieved by eliminating the crank mechanism. This can easily be realized by using free piston engine, in which the piston reciprocates linearly with PMLG without the need of any transmission means [7-9].

The free-piston engine converter composed of a permanent magnet linear generator coupled to a free-piston engine as illustrated in Figure 1, the major parts have been indicated. Recently, this technology is being a major of concern of many researchers worldwide. Basically, the flexibility and easy controllability as well as the high efficiency of electrical machines, make them an interesting concept [10, 11]. The growing interest of the automotive industry in the technology of electric hybrid vehicles is a driving force behind the interest in free-piston engine generators. The single piston and dual piston of free-piston engine generator designs have been reported [9, 12]. Moreover, the control can be well done by implementing appropriate power electronics control.

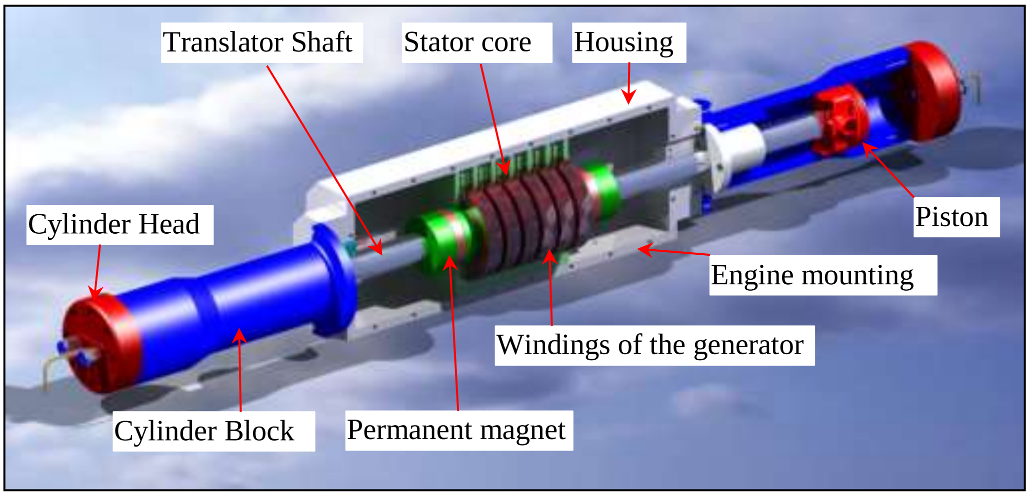

Figure 1. Free piston permanent magnet linear generator engine.

Mainly, there are four different approaches for producing a linear energy conversion. The first approach is to use the electrostatic properties. Thus, a maximum force density of around 16 N/m^2 can be obtained. The second approach is to produce a linear energy conversion by an electromagnetic way. The third and fourth approaches are based on the mechanical friction that uses the piezoelectric or magnetostrictive properties to interact with the translator [13, 14].

The developments based on the PMLG are very likable owing to efficient electromagnetic performance, despite, suffers from the cogging force. This force produces due to the attraction between ferromagnetic core and magnetic with zero current in the winding of the machine [15, 16]. The periodic waveform of the cogging force is depending on the relative position of the translator. When the excitation current assigned to the winding of the machine, the cogging force will be added to a thrust force. The cogging force makes a ripple in thrust force. The ripple resulted by the cogging force will deteriorate the position control and precise speed in many applications. The low-speed applications are more suffering from such ripple; moreover, it produces undesirable acoustic noises and vibrations. Thus, at the design stage must be minimized [15]. Numerous of techniques have been used to reduce the cogging force in permanent magnet machines, but most of these techniques contribute to the reducing of the main electromagnetic performance. Alternatively, air-cored PMLGs are preferred in terms of unavailability of cogging force, lightweight and simple. Nonetheless, they have limitations in electromagnetic performance and power generation [17-19].

An accurate and fast calculation of the magnetic field distributions are necessary for many of electromagnetic machines, they can provide more efficient design and execution of such machines, subsequently, higher performance of the machine can be obtained [20, 21]. However, numerous modeling methods exist for prediction and analysis the electromagnetic behavior of the electric machines. These methods vary from simple and accurate to complicated and time-consuming models [22]. The finite element analysis (FEA) is offering many features, thus, it is widely used for the modeling and simulation of the electrical machines. However, this technique empowers us to perform a complicated analysis of electrical machines in a minimum estimated time. This paper presents the

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cogging force investigation of a PMLG utilizing three different ferromagnetic materials for the stator core by using FEA under ANSOFT Maxwell software.

2. Research Method

The FEA has been used to compute the magnetic field along the cross-section of the proposed generator. By the fact that, with the rare-earth magnet materials and Halbach array configuration, the high magnetic field will be achieved. especially, with the. Moreover, the quasi-Halbach magnetization technique has been selected in this study because it has many advantages over the conventional PM array [23, 24].

The finite element two-dimensional (2-D) and three-dimensional (3-D) models adopted from ANSYS Maxwell simulation software for the proposed PMLG is shown in Figure 2. The PMLG with single phase and long translator. The stator contains 6 coils and 6 slots. The translator is made of the neodymium-iron-boron (NdFeB) permanent magnet with quasi-Halbach magnetized magnets. Quasi-Halbach magnetization provides higher air gap magnetic field distribution [25, 26]. The FEA is carried out for the PMLG with the three different ferromagnetic materials. The axisymmetrical coordinate system and vector orientation for magnets have been adopted in the software.

The FE mesh affects the FEA calculation, especially in terms of time and accuracy of the computation. The automatic mesh allowed for faster simulation and shorter execution time than a fine mesh. Nevertheless, the computation accuracy is low because the number of degrees of freedom is low [27]. However, the fine mesh has been utilized for this study.

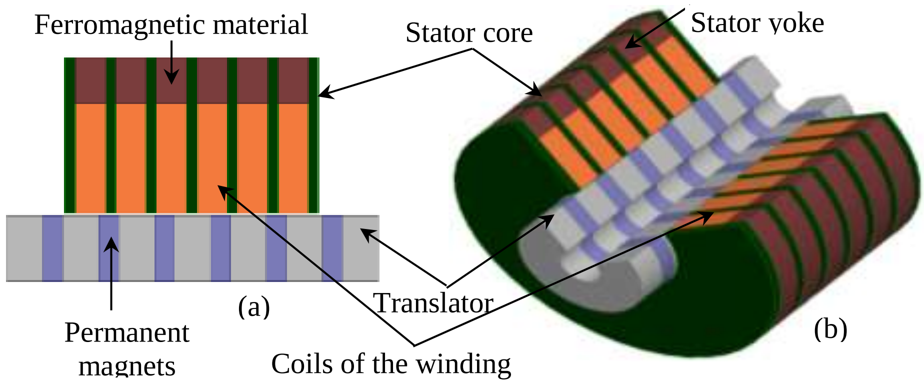

Figure 2. Configuration of the proposed PMLG. (a) two-dimensional (b) three-dimensional.

The magnetic field analysis is confined to two regions, namely the air region with a permeability of μ_0, and the magnetic region with a permeability of $\mu_0\mu_r$. μ_r is the relative recoil permeability and for rare-earth PMs is close to unity. Therefore, the magnetic flux density, B related to the magnetic field intensity, H in airspace region and magnetic region, respectively, can be expressed as [28-32]

$$B = \mu_0 H \tag{1}$$

$$B = \mu_0\mu_r H + \mu_0 M \tag{2}$$

The magnetization, M of the linear machine in the cylindrical coordinate system can be expressed as [30, 32-34]

$$M = M_r e_r + M_z e_z \tag{3}$$

The magnetization distribution was expandable into Fourier series, with M_r and M_z expressed as a function of z as in (4) and (5), respectively [16, 32].

$$M_r = \sum_{n=1,2,...}^{\infty} M_{rn} \cos m_n z \tag{4}$$

$$M_z = \sum_{n=1,2,...}^{\infty} M_{zn} \sin m_n z \tag{5}$$

where M_r and M_z denoted the components of *M* in the radially and axially directions, respectively, and $m_n = 2\pi n / T_{lp}$.

When the flux waveform of the open circuit is known, it can be used to calculate the induced voltage of the machine. Hence, with a time-varying magnetic flux, $\phi(t)$, the induced voltage can be calculated as [35, 36]:

$$e_c = -\frac{d\phi(t)}{dt} = -\frac{dB}{dt} A \tag{6}$$

where *B* is the magnetic flux density and *A* is the area that is occupying *B*. On the other hand, the thrust force for a given machine's current can be calculated from the electromagnetic power related to the translator speed, v_t. Therefore, F_T is quantified as in (7) [32]:

$$F_T = \frac{e_c i_a}{v_t} = K_E(z_d) i_a = K_T(z_d) i_a \tag{7}$$

Based on Alembert's equation, the dynamics of the system governing the armature movement of the proposed generator along the z-axis when the mass, m_m, is moving at speed; v_t with a damping coefficient, b, and spring elasticity, k, can be expressed as in (8) [37, 38]:

$$m_m \frac{dv_t}{dt} + bv_t + k\int v_t dt = K_T(z_d) i_a \tag{8}$$

By substituting the value of F_T from (7), equation (8) can be rewritten as in (9):

$$m_m \frac{dv_t}{dt} + bv_t + k\int v_t dt = F_T \tag{9}$$

When the linear velocity is related to the displacement and time, the velocity of the translator can be expressed as in (10) [39]:

$$v_t = \frac{dz_d}{dt} \tag{10}$$

By taking the integration of (9) and substituting the value of v_t, it results in:

$$m_m \frac{d^2 z_d}{dt^2} + b\frac{dz_d}{dt} + kz_d = F_T \tag{11}$$

where z_d, $d^2 z_d / dt^2$, K_T, i_a and dz_d / dt are the displacement of the translator, linear acceleration, thrust force constant, coil current and velocity of the translator, respectively.

3. Results and Analysis

In this study, the machine is running at no-load, hence the winding current is zero. The permeability into the magnets and the coils without demagnetization of the magnet is μ_0. The magnetic properties of silicon steel lamination, mild steel and Somaloy have been identified by their B-H curves and other quantities. The design specification and main dimensions of the proposed PMLG are tabulated in Table 1.

Table 1. Design specification and main dimensions of PMLG.

Parameter	Value	Unit
Magnet thickness	29.50	mm
Mechanical air gap	1.00	mm
Magnetic remanence	1.14	Tesla
Stroke	45.00	mm
The total length	221.00	mm

The quasi-Halbach provided the magnetization for the translator and created the flux lines in the round or the trapezoidal closed loop pattern. The conducted analysis and comparisons were based on various velocities and three different ferromagnetic materials, namely Silicon Steel laminations, Mild Steel and Somaloy. Further discussions on the outcomes are explained as below. The cogging force in the PMLG leads to oscillations of the generator speed and therefore output voltage and power fluctuations. The cogging force corresponds to the force due to the shape of the teeth and the permanent magnets when the current in the coil of the machine is zero. The cogging force evaluation is very sensitive to the mesh and its value is small as compared to the full load force. However, the preferred and accurate method to compute the cogging force is the use of the transient solver with motion; because the mesh will remain unchanged at all positions of the translator. Basically, the stator is fixed and the translator will move with steps. Thus, only the magnetic field from the magnets existed and then the effect of the slot will present. As the translator of the PMLG moved forward and backward, this effect was computed by using the FEA. Figure 3 shows the comparison of the cogging force resulted at the translator velocity of 1.0 m/s and using three different ferromagnetic materials for the stator core. The result is fluctuating between the positive and negative value as can be clearly observed. Furthermore, it can be observed that the average cogging forces have been obtained for the three ferromagnetic materials, namely Silicon steel, Mild Steel and Somaloy, respectively, are 121.5238 N, 55.0707 N and 5.2115 N. It can be concluded that in this range of speed Somaloy is preferred for the stator core of the proposed generator.

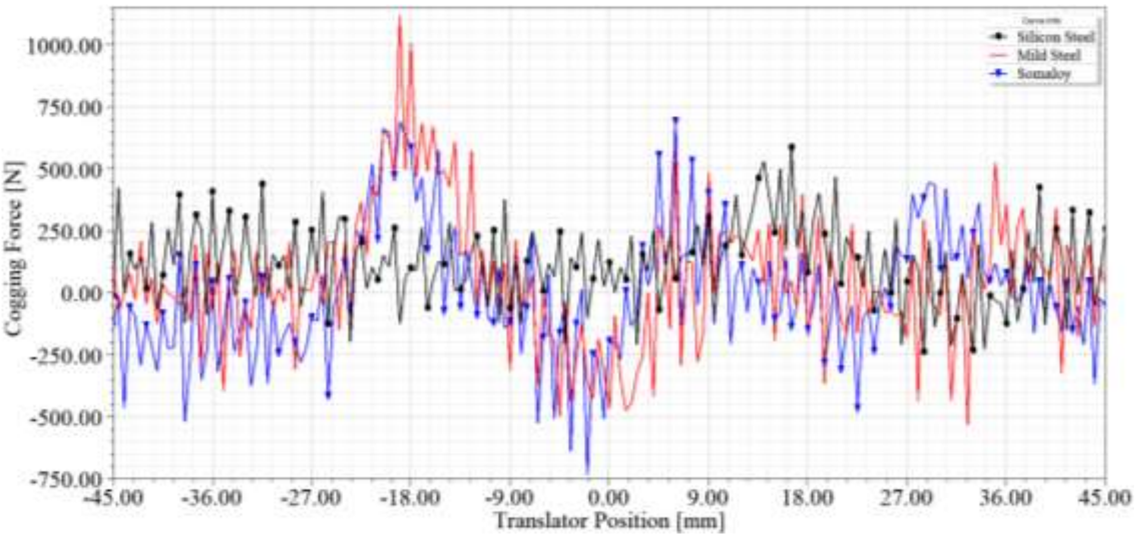

Figure 3. Comparison of the cogging force of the generator under three ferromagnetic materials when the excitation current is zero and 45.0 mm displacement of the translator each side and a linear velocity of 1.0 m/s.

Figure 4 shows the comparison of the cogging force of the generator under the three different materials at translator velocity of 3.0 m/s. It can be observed that the generator with a stator core made of Somaloy has a lower cogging force among the three materials. Furthermore, it can conclude that in this range of speed the Somaloy is preferred for the stator of the proposed generator.

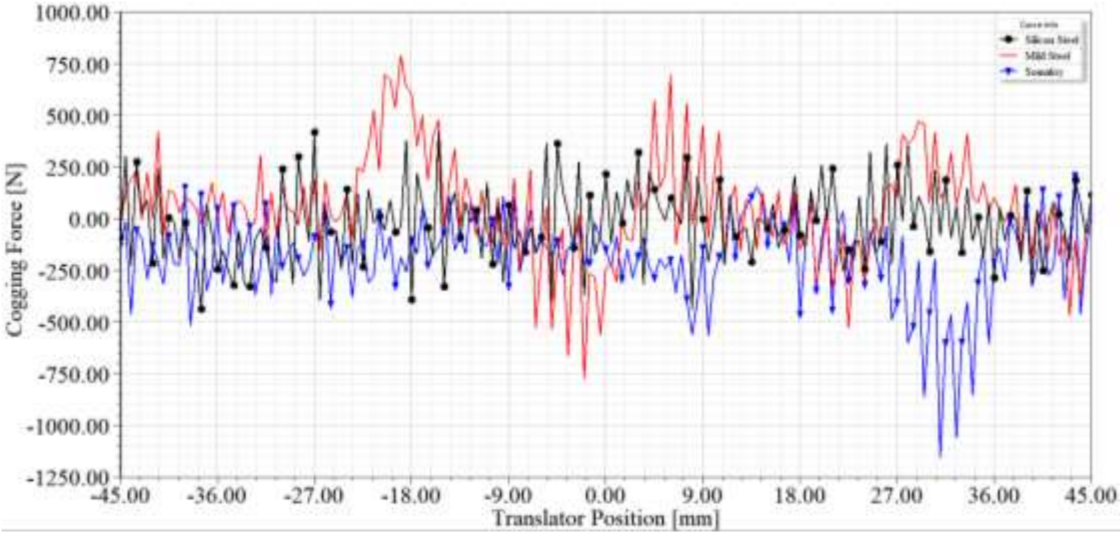

Figure 4. Comparison of the tangential electromagnetic force of the generator when the excitation current is zero and 45.0 mm displacement of the translator as well as a linear velocity of 3.0 m/s.

Figure 5 shows the comparison of the cogging force of the proposed generator that using three different materials for the stator core at translator velocity 5.0 m/s. It can be observed that the generator with a stator core made of silicon steel laminations has higher average cogging force, whereas the generator with Somaloy stator core has lower average cogging force.

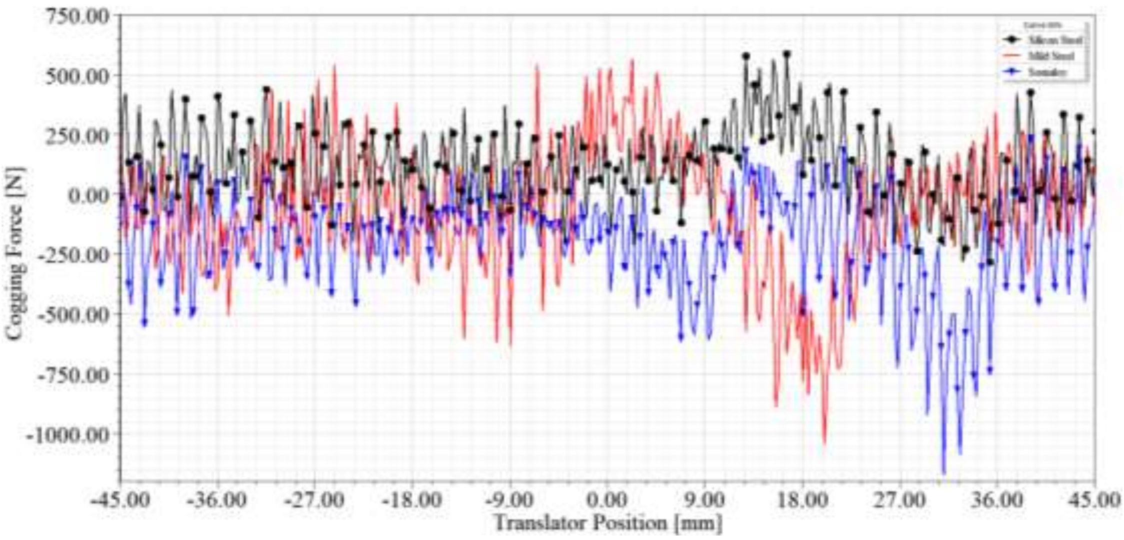

Figure 5. Comparison of the tangential electromagnetic force of the generator when the excitation current is zero and 45.0 mm displacement of the translator, under a linear velocity of 5.0 m/s.

Figure 6 shows the comparison of the cogging force of the linear generator for the three different ferromagnetic materials for the stator core at translator velocity 7.0 m/s. It can be seen that the generator with a stator core made of mild steel laminations has higher average cogging force, 122.0425 N, whereas the generator with Somaloy stator core has a lower average cogging force, 183.5258 N.

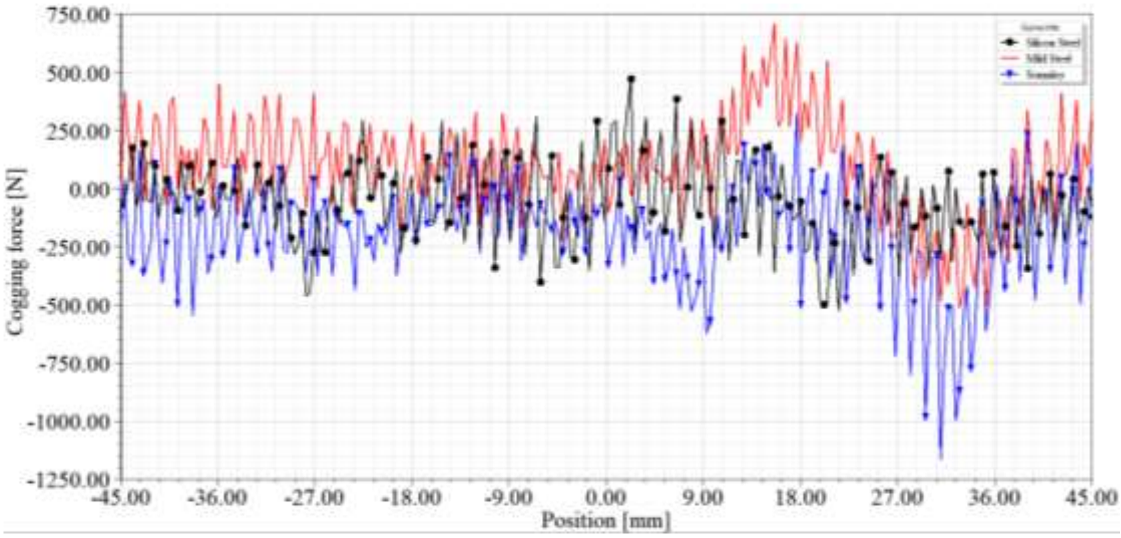

Figure 6. Comparison of the tangential electromagnetic force when the excitation current is zero and 45.0 mm displacement of the translator on both sides under a linear velocity of 7.0 m/s.

Because of inherent lower magnetic permeability, would Somaloy components be chosen to compete on magnetic performance at either adequate level or to be better than steel lamination assemblies. The improvement of the densities of Somaloy components correspondingly leads to increment of the magnetic induction and permeability as well. The cogging force, in general, has a positive value and is an undesirable force, but the negative cogging force will add to the current-generated force (main force), mainly from the perspective of engineering education [40].

Figure 7 shows the comparison of the average cogging force of the PMLG at various accelerations of the translator and three different ferromagnetic materials for the stator core. It can be observed that there is an optimal point for the operation of the PMLG at which the generator run with minimum cogging force, such as 6.0 m/s for the Somaloy, 5.0 m/s for mild steel and 7.0 m/s for laminated silicon steel.

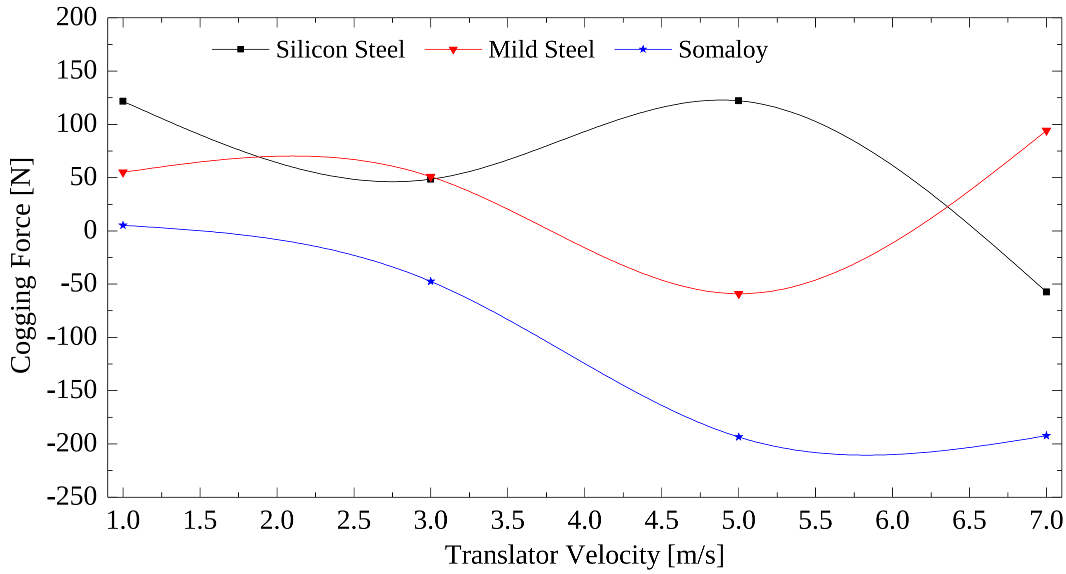

Figure 7. Comparison of average cogging force of PMLG under three different ferromagnetic materials and different translator velocities.

By moving the translator of the PMLG, the induced voltage is computed using the FEA. Figure 8 shows a comparison of the induced voltage waveforms of PMLG using three different ferromagnetic materials for the stator core at a constant translator velocity of 1.0 m/s. It can be seen that the PMLG with the mild steel and Somaloy gives an induced voltage of 13.0 V and 11.92 V, respectively, while the PMLG with silicon steel gives an induced voltage of 5.88 V. This means that the generator with mild steel and Somaloy can generate larger electrical power.

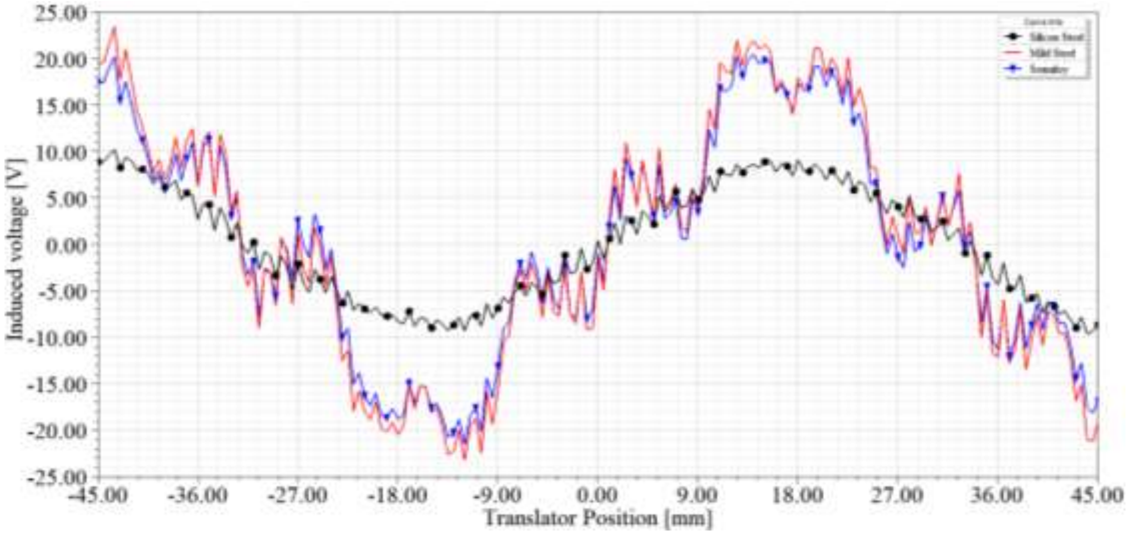

Figure 8. Comparison of the induced voltage among the three ferromagnetic materials for the stator core of the PMLG at the linear speed of 1.0 m/s.

Figure 9 shows a comparison of the induced voltage waveforms of PMLG using three different ferromagnetic materials for the stator core at a constant translator velocity of 3.0 m/s. It can be seen that the PMLG with the mild steel and Somaloy gives an induced voltage of 39.47 V and 36.27 V, respectively, while the PMLG with silicon steel gives an induced voltage of 18.03 V.

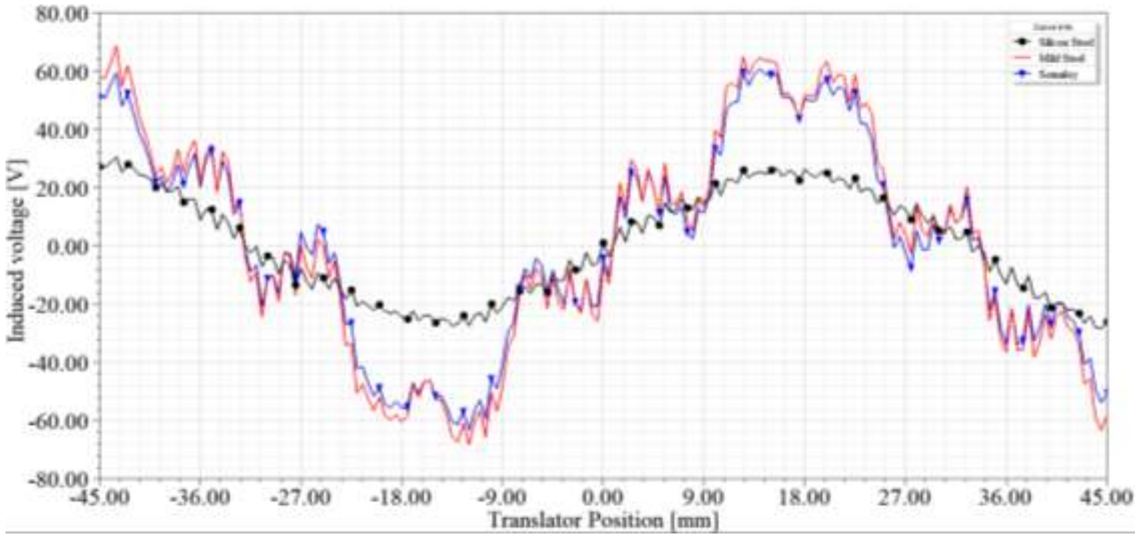

Figure 9. Comparison of the induced voltage among the three ferromagnetic materials for the stator core of the PMLG at the linear speed of 3.0 m/s.

Figure 10 and Figure 11 shows the comparison of the induced voltage waveforms of PMLG using three different ferromagnetic materials for the stator core at constant translator velocities of 5.0 m/s and 7.0 m/s, respectively. It can be seen that the PMLG with the mild steel and Somaloy at a speed of 5.0 m/s gives an induced voltage of 64.5 V and 59.15 V, respectively, while the PMLG with silicon steel gives an induced voltage of 29.35 V. Meanwhile, the PMLG with the mild steel and Somaloy at a speed of 7.0 m/s gives an induced voltage of 93.6 V and 85.76 V, respectively, while the PMLG with silicon steel gives an induced voltage of 42.71 V.

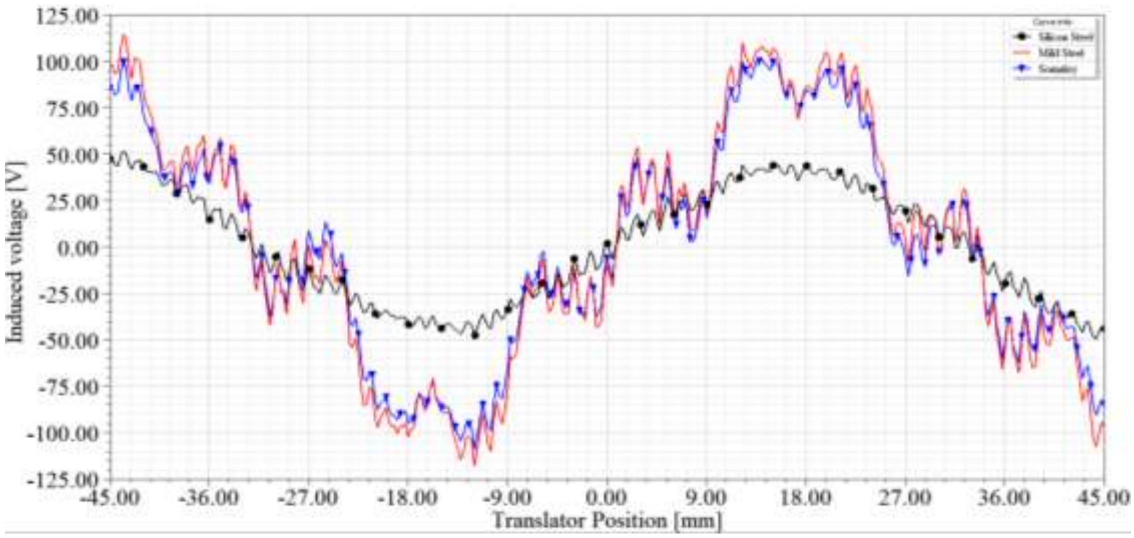

Figure 10. Comparison of the induced voltage among the three ferromagnetic materials for the stator core of the PMLG at the linear speed of 5.0 m/s.

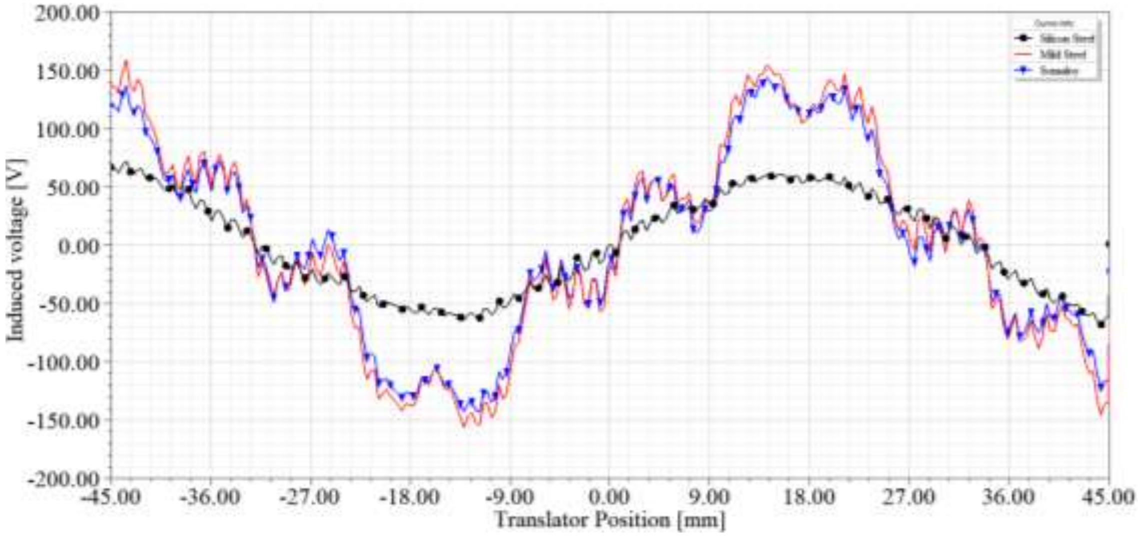

Figure 11. Comparison of the induced voltage among the three ferromagnetic materials for the stator core of the PMLG at the linear speed of 7.0 m/s.

Figure 12 shows the comparison of the RMS induced voltage of PMLG at different translator velocities and three different ferromagnetic materials for the stator core. It can be seen that the PMLG with mild steel has the highest induced voltage. The PMLG with Somaloy has second highest induced voltage, whilst the PMLG with silicon steel laminations has a lowest induced voltage. Furthermore, it can be observed that there is a direct proportion between the translator speed and the induced voltage.

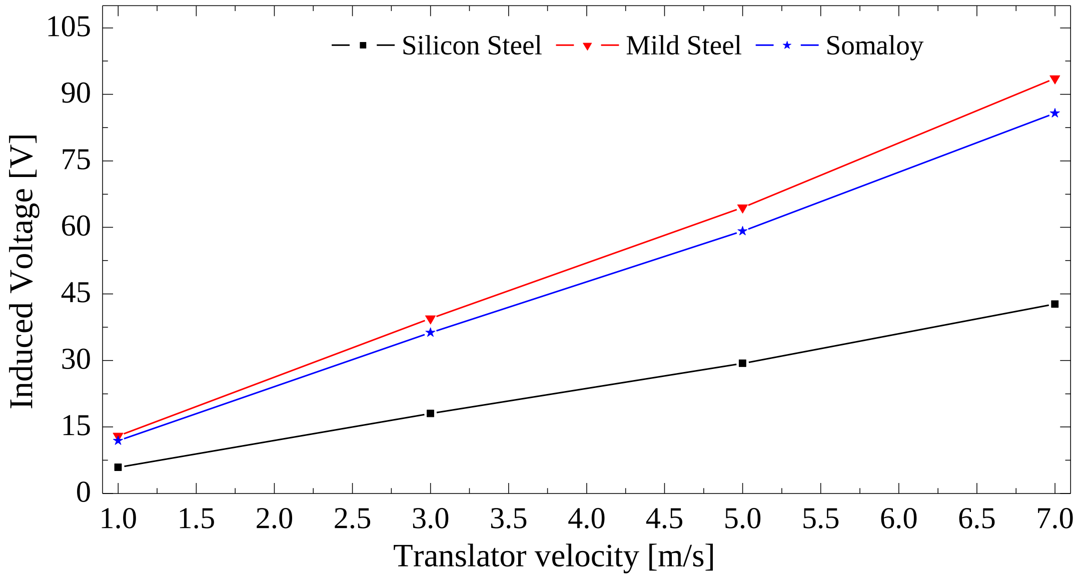

Figure 12. Comparison of the RMS induced voltage of PMLG at different translator velocities.

4. Conclusions

This paper investigated the influence of ferromagnetic materials of the stator core on the amount of induced cogging force in a free piston permanent magnet linear generator (FP-PMLG). The PMLG with laminated silicon steel, mild steel, and Somaloy is analyzed using FEA. The cogging force investigation is carried out for PMLG at various translator velocities along with main dimensions and specifications that have been given in Table 1. It is found that the properties of the material have a significant influence on the cogging force produced. Also, the velocity of the translator influences the cogging force dramatically. From the cogging force comparisons of the PMLG among the three different ferromagnetic materials, namely silicon steel laminations, mild steel and Somaloy, it has been found that Somaloy material for stator core is preferred for the less cogging force. However, when the translator velocity greater than 3.0 m/s and less than 7.0 m/s, the mild steel lamination for the stator core is preferred. Whereas, if the proposed PMLG with a velocity higher than 6.0 m/s, it is preferred to use silicon steel lamination in terms of minimum cogging force. Meanwhile, the comparison of the induced voltage showed that there is a direct proportion between the induced voltage and velocity of the translator. The highest, second highest and lower induced voltage has been obtained for the silicon steel laminations, mild steel, and Somaloy, respectively. Furthermore, with the check for the fabrication availability, it is found that is difficult to fabricate such generator with silicon steel laminations because it is difficult to assemble and de-assemble the stator core.

Acknowledgments

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