Reduction of Cogging Force in Linear Permanent-Magnet Generators

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Although linear permanent-magnet generators (LPMGs) are widely used for converting wave energy into electrical energy, they suffer from large cogging force. The cogging force causes oscillatory output power, which shortens lifetime and increases the maintenance costs of the generators. To reduce this force in the generator, we have designed and simulated a three-phase LPMG for direct wave energy conversion and predicted its performance using the finite-element method. We studied the influence of different design parameters on the cogging force and minimized this force by varying the proposed parameters. The results obtained confirm a large reduction in the cogging force and an enhancement in the generator performance.

***Index Terms*—Cogging force, direct conversion of wave energy, finite-element method, linear permanent-magnet generator.**

I. Introduction

NOWADAYS, linear permanent-magnet generators (LPMG) are often considered for direct conversion of wave energy into electrical energy. The reason is unique features of the LPMGs such as high efficiency, simple structure, fixing and its capability to convert calm wave energy into electrical energy. Like other linear machines, there is oscillation in the linear movement of these generators. These oscillations are undesirable because they lead to the output power variation, shortening lifetime and increasing the maintenance cost of the generator system. The most important factor, causing the oscillation in LPMG, is cogging force. Cogging force tends to keep the path between the shaft and stator teeth at minimum and this disturbs the shaft movement. This force is generated by interaction of the stator teeth and PM fixed on the shaft, even in the open-circuit case. This force is important, because its peak value is high and thus it is one of the most important factors in the generator design [1]–[10]. In [11]–[19], many LPMGs have been designed, simulated and tested. In [20], a three-phase 100 kW LPMG has been simulated and the nature of the cogging force and its reduction method has been investigated. The peak value of the cogging force in the above-mentioned generator is 240 kN and the lowest value is 90 kN, a 62% difference. In [21], a new method for cogging force mitigation emphasizing the PMs dividing on the shaft has been introduced. In this design, the peak and lowest values of the cogging forces are 50 N and −50 N respectively, or 200% variations. In [22], a three-phase 16 kW LPMG for wave energy conversion has been designed and simulated taking into account minimization of the cogging force by PM shaping. In this case the peak and lowest cogging force is 30 N and −30 N respectively (200% variation) which are reduced to 5 and −5 respectively. Such variation in LPMG coupled to an internal combustion engine is 100% [23]. A similar 5 kW, LPMG with radial PMs has a peak force of 140 N and minimum value of −140 N [24]. It is noted that reduction of the peak force is essential in order to decrease its effect on the shaft movement. Of course, mitigation of the amplitude of the cogging force can reduce the voltage and power fluctuations. In [25], the cogging force for a 88 kW

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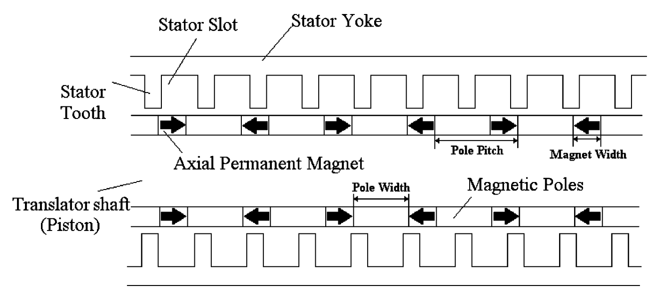

Fig. 1. Longitudinal section of a LPMG structure.

LPMG has been given with a very large peak value of 156.5 kN with a low variation. The reason for this low variation is using very narrow stator slots and small pole pitches. An LPMG has been simulated in the process of converting wave energy into electrical energy, but less attention has been paid to the alleviation of cogging force [14]–[19]; while decreasing this cogging force can considerably reduce the maintenance cost and lead to a longer lifetime of the generator; therefore, application of LPMG will be more economical.

In this paper, a three-phase 250 kW LPMG is designed and simulated to generate electrical energy from wave energy. A two-dimensional (2-D) finite-element method (FEM) is used for simulation. An attempt is made to study the effect of different parameters such as PM length and its magnetization orientation, and use of skewed PM and stator teeth shape on the design of the LPMG as such that the cogging force is reduced to its minimal value.

II. Simulations

A. Structure and Simulation Equations

Fig. 1 shows a LPMG which consists of a stationary part (stator) and moving part (piston). The PM is the excitation magnetic field of the generator which is fixed on the piston and armature windings are inserted in the stator slots. Movement of the piston against the stationary stator produces variable flux and induces voltage in the armature windings.

The Maxwell 2D FE package is used for simulation. The vector magnetic potential (A) has been used instead of the magnetic flux density vector (B). A is defined as follows:

$$\nabla \cdot \nabla \times \bar{A} = 0. \quad (1)$$

In the simulation, the principle of magnetostatic field is used to calculate the flux and voltage. Using Gaussian law we have

$$\nabla \cdot \bar{\mathrm{B}} = 0 \tag{2}$$

$$\nabla \times \bar{\mathrm{H}} = \bar{\mathrm{J}} \tag{3}$$

$$\nabla \cdot \bar{J} = 0 \tag{4}$$

where $\bar{\mathrm{H}}$ is the magnetic field intensity vector and $\bar{J}$ is the total current density. Using (1), $\bar{\mathrm{B}}$ in (2) can be written versus A as follows:

$$\bar{B} = \nabla \times \bar{A} \tag{5}$$

where PM and ferromagnetic materials are used, there is the following relationship between the magnetic fields:

$$\bar{B} = [\mu]\,\bar{H} + \mu_0 M_0 \tag{6}$$

$$\mu_0 M_0 = B_r \tag{7}$$

where μ_0 is the air permeability, M_0 is the magnetization vector within the PM, and B_r is the PM residual flux density. The magnetic flux propagated in the environment is

$$\psi = \int \bar{B} \cdot \bar{n}\, \mathrm{ds} \tag{8}$$

where ds is the unit surface displacement and $\bar{n}$ is the vector normal to surface ds. In RZ system, vector $\bar{n}$ is defined as

$$\bar{n} = a_Z \tag{9}$$

and the scalar product of the magnetic flux density vector and vector $\bar{n}$ is as follows:

$$\bar{B} \cdot \bar{n} = B_Z. \tag{10}$$

Total flux passing the stator core cross section with thickness L_R is

$$\psi = 2\pi \int B_Z L_R d_R. \tag{11}$$

Thus, the induced voltage in the windings is

$$e = -N \frac{d\psi}{dt} \tag{12}$$

where N is the turn number of the winding and $d\psi/dt$ is the time variation of the flux. Finally, the cogging force is calculated as follows:

$$F_S = \int_{\mathrm{vol}} \bar{B}^T \frac{\partial \bar{H}}{\partial S} d(\mathrm{vol}) + \int_{\mathrm{vol}} \left(\int \bar{B}^T\, d\bar{H} \right) \frac{\partial}{\partial S} d(\mathrm{vol}) \tag{13}$$

where F_s is the force along element S and $\partial H/\partial S$ is the time derivative of the field intensity versus displacement.

Simulated LPMG is a 250 kW, three-phase and Δ-connected generator which has been designed to convert wave energy into electrical energy directly. Table I summarizes the LPMG specifications. Excitation field of the LPMG is provided by axially magnetized PM material NeFeB (Hs-55AH). Also, the stator core is silicon steel sheet, poles are M5 steel, and piston is aluminum. The speed of the LPMG is taken to be 1 m/s.

TABLE I
SPECIFICATIONS OF A THREE-PHASE LPMG

Pole pitch (mm)	60
Pole width (mm)	40
Magnet width (mm)	20
Magnet volume (cm^3)	2
Magnet cursive force (kA/m)	800
Magnet field density (T)	0.45
Air gap width (mm)	5
Air gap field (T)	0.40
Tooth width (mm)	65
Slot width (mm)	100
Piston length (m)	5
Stator length (m)	1
Load Resistance (Ω)	4

B. Reduction of Cogging Force

PM Length: When two poles stand opposite two teeth of the generator, both have the peak cogging force. In such a case, the cogging forces of the two poles opposite the two teeth are added up and generate a large cogging force. In order to reduce the cogging force, the lengths of PMs are adjusted as such that their summation becomes less by displacing the force curves; however, it is practically impossible to diminish the cogging force. Fig. 2 shows the cogging force for PM with length 5, 10, and 20 mm.

Decreasing the PM length reduces the equivalent current density of the PM that finally decreases the cogging force. As seen, decreasing the PM length to 5 mm along magnetizing orientation can reduce the cogging force up to 80%. Lower length of the PM has more effect. One of the most important effects is enhancing the generator output voltage. However, this is not always good, especially when harmonics and large peaks appear in the output voltage.

Skewed PMs: Structure of the generator with the skewed PMs has been shown in Fig. 3. The skewing angle versus longitudinal direction of the shaft has a very large effect on the cogging force. By skewing the PMs, the force curves can be displaced as such that the peak cogging force becomes lower. Fig. 4 shows the cogging force of the generator for angles: $\alpha = 30, \alpha = 45$, and $\alpha = 60$ degrees. As seen, decreasing α also reduces the cogging force. Henceforth, the PM length is assumed equal to 5 mm for simulation purpose. According to Fig. 4, using an skewed PM with $\alpha = 30$ degrees, the cogging force decreases from 6400 N to 720 N. Fig. 2(c) exhibits the cogging force of the LPMG for angle $\alpha = 90$ degrees which is larger than 8000 N.

As seen in Fig. 3, when the LPMG moves upward, the right-hand-side PMs have a 30-degree angle and left-hand-side PMs have a 150-degree angle. Similarly, when the LPMG moves downward, the left-hand-side PMs have a 30-degree angle and right-hand-side PMs have a 150-degree angle. Therefore, the cogging force reduces on bi-direction. The skewed PMs is normally designed as trapezoid when the radial PMs are used [26], [27]; however, application of radial PMs could decrease the flux-linkage and voltage and a large number of PMs or stronger PMs must be used to compensate the flux reduction.

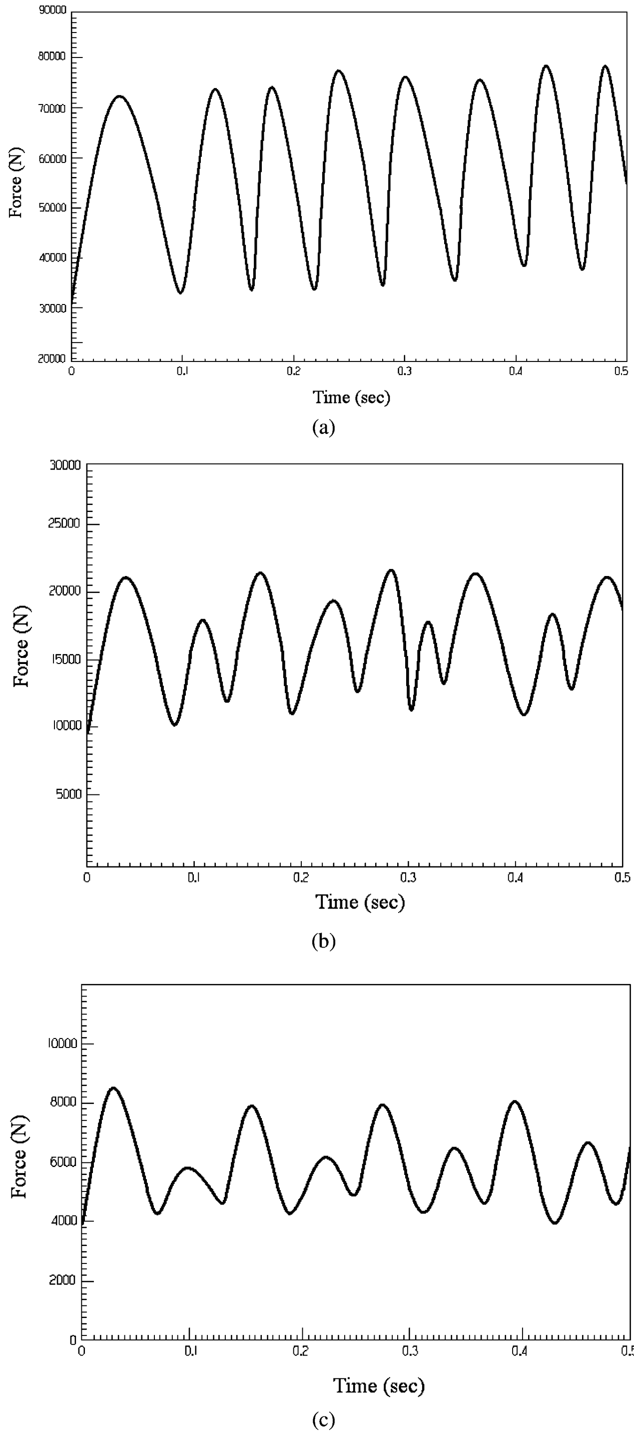

Fig. 2. Influence of PM length along magnetization orientation upon cogging force: (a) 20 mm, (b) 10 mm, and (c) 5 mm.

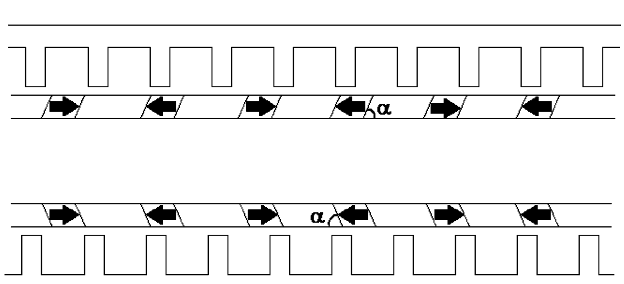

Fig. 3. Generator structure with skewed PMs.

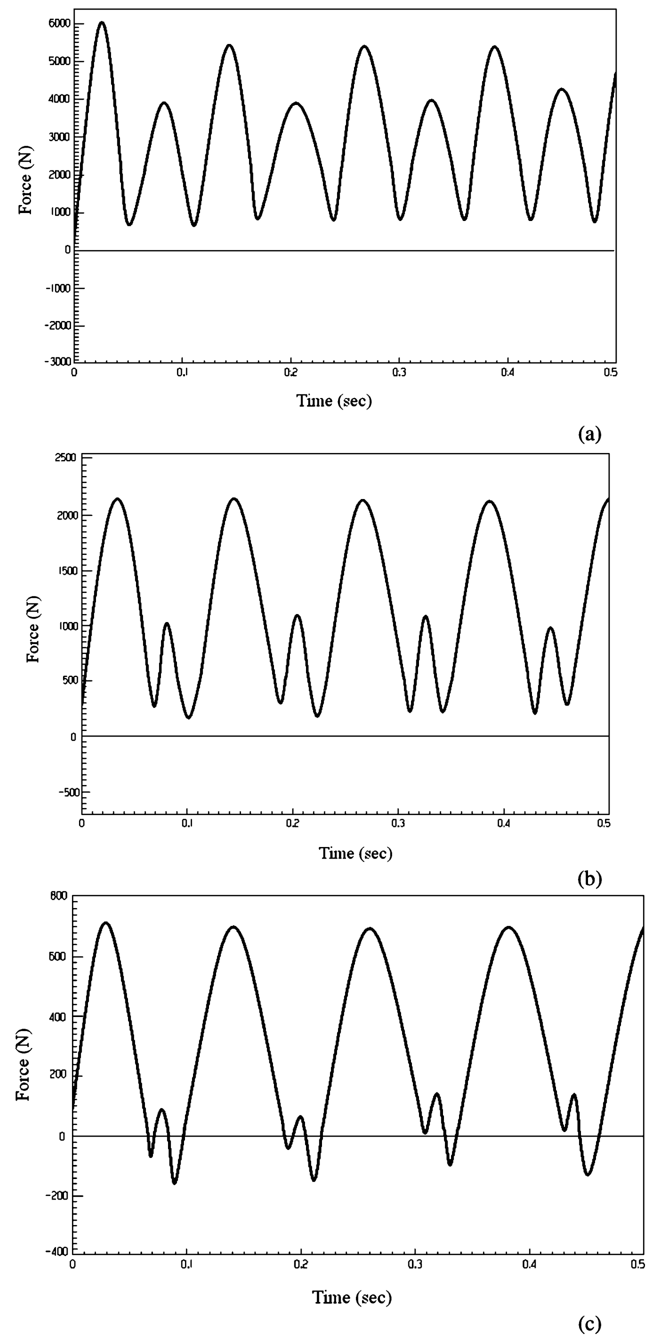

Fig. 4. Cogging force using skewed PMs: (a) $\alpha = 60, \alpha = 45$, and $\alpha = 30$ degrees.

Radial PMs: Fig. 5 shows the structure of the generator in which the PMs are radially fixed. In this structure, the ferromagnetic poles between PMs have been replaced by a ferromagnetic plate. Fig. 6 compares the cogging force where radial PMs and axial PMs are employed. It is clear that when the radial PMs are used, the cogging force reduces by 70%. The reason is that using radial flux decreases the accumulation of the flux density on the edges of PM; consequently, the cogging force deceases. To prevent the reduction of the flux-linkage and thus generator output voltage, in the radial PMs case, a stronger PM or a large number of PMs must be used which increases the cost of the generator.

Semi-Closed Stator Slots: Fig. 7 shows the cogging force when open- and semi-closed slots are used. As seen, the cog-

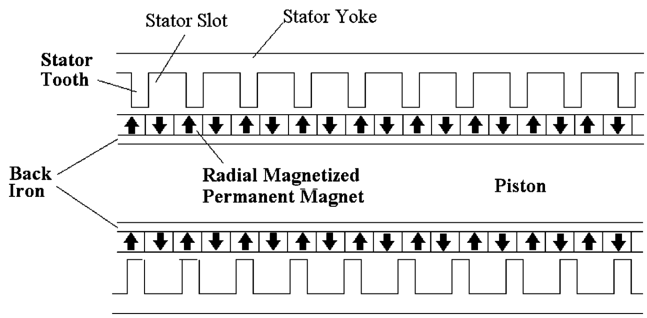

Fig. 5. Generator structure using radial PMs.

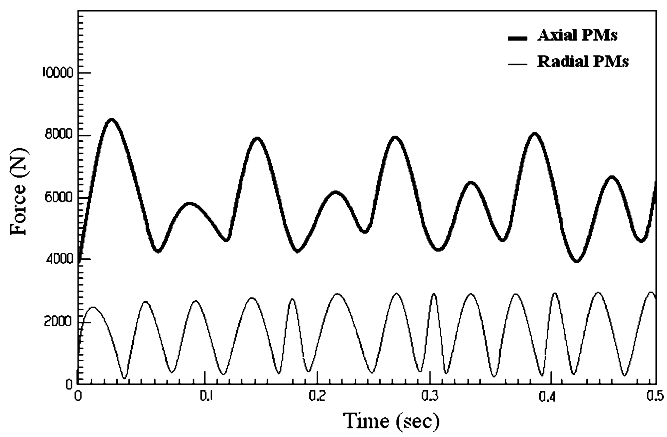

Fig. 6. Comparison of cogging force between axial PMs and radial PMs cases.

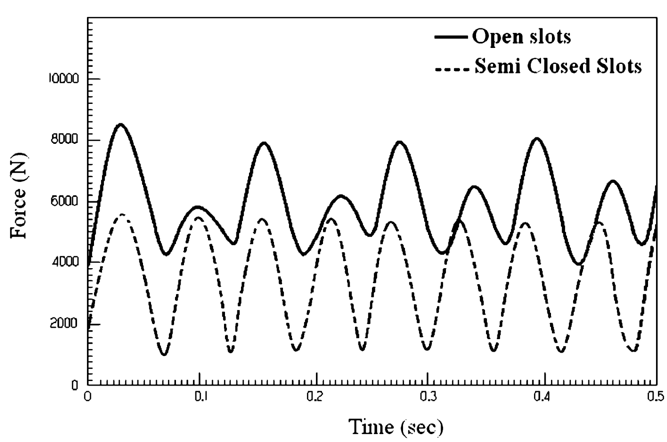

Fig. 7. Comparison of cogging force between open slots and semi-closed slots.

ging force decreases by 34% in case of the semi-closed stator slots. It means that using the semi-closed slots in the stator can largely decrease the cogging force, because the cogging force is the interaction between the PM edges and stator slots edges. In spite of decreasing the cogging force, using semi-closed slots leads to more leakage flux (as shown in Fig. 8) and this can reduce the efficiency of the generator. A further drawback of semi-closed slots is increased cost of manufacture due to difficulty of inserting the coils and often a reduction in slot fill factor. Table II shows the leakage flux, core losses, efficiency, and cogging force in the open and semi-closed stator cases. It is seen that the flux leakage may decrease the efficiency by 1% which is negligible.

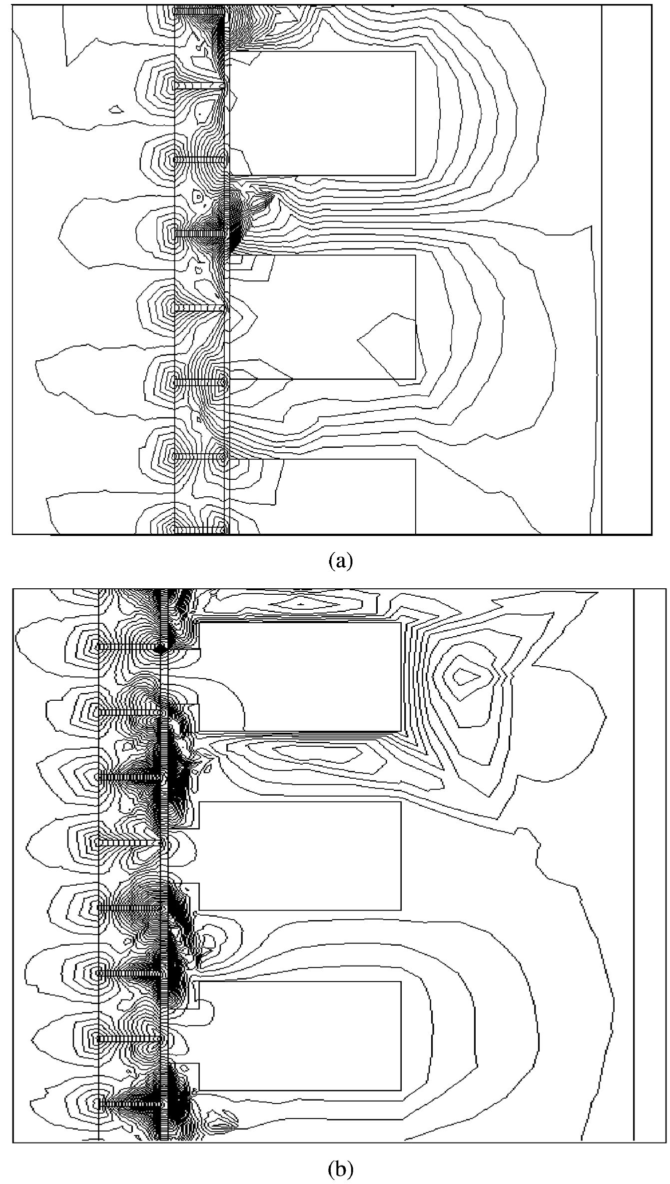

Fig. 8. Flux distribution within generator: (a) stator open slot, (b) stator semi-closed slot.

TABLE II
SPECIFICATIONS OF LMPG IN TWO DIFFERENT STATOR SLOTS SHAPE

Slot Shape	Efficiency (%)	Maximum Leakage-Flux (mWb)	Core Losses (kW)	Peak Cogging Force (kN)
Open	86	2.9	0.8	8.6
Semi- Closed	85	3.36	2.88	5.6

III. FINAL MODIFICATIONS OF GENERATOR STRUCTURE FOR COGGING FORCE REDUCTION

Following investigation of effects of different parameters upon the cogging force, the generator structure is modified to reduce the cogging force. The following modifications are applied to the structure of the LPMG:

- the PM length magnetizing orientation is fixed to 5 mm;

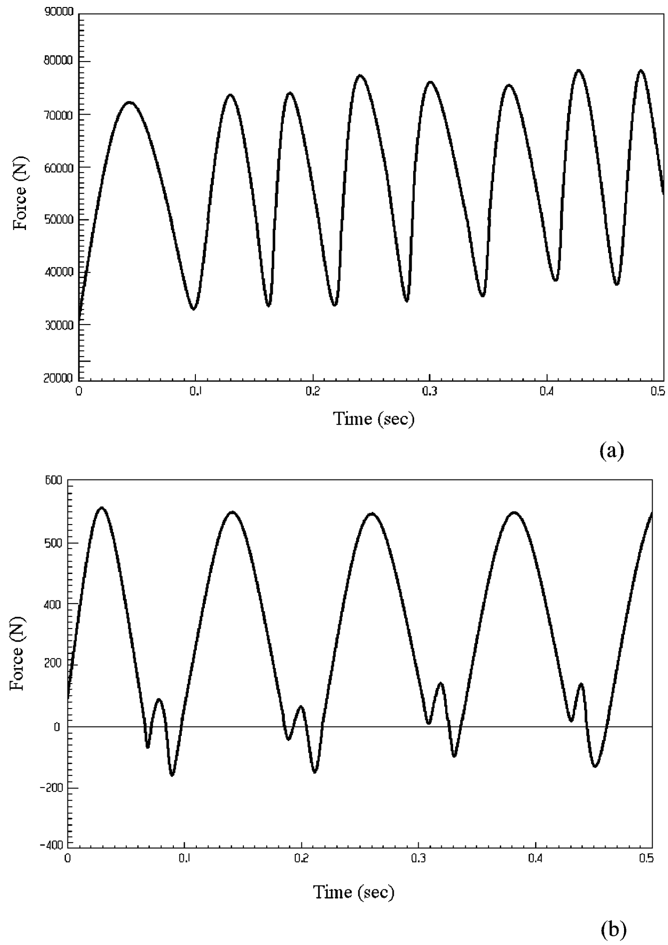

Fig. 9. Generator cogging force: (a) before modification, (b) after modification.

- the PMs are skewed with angle 30 degrees in respect to the generator shaft;
- semi-closed stator slots are utilized.

The PMs used in the generator have been magnetized axially. Although using the radial magnetized PMs reduces the cogging force, to prevent the reduction of the output voltage, more (or stronger) PMs must be used and this leads to a costly generator. Fig. 9 shows the cogging force before and after modifications of the generator structure. As seen, the peak cogging force was 78 kN before the modifications while it has been reduced to 550 N after modifications. The structure of the LPMG can be optimized by using arc-shape on the edge, inside and end of stator teeth and slots, which is normally helpful for reduction of the partial magnetic saturation and leakage flux of the LPMG. In this case, the generator will be more expensive. It is noted that the magnetic flux density within the core is low and normally there is no saturation in the generator.

Consequently, the modification of the generator structure can largely reduce the cogging force of the generator.

IV. Effect of Cogging Force Reduction on Voltage and Power of LPMG

Cogging force in the LPMG leads to oscillations of the generator speed and therefore output voltage and power fluctuations. To visualize the influence of the cogging force on the electrical characteristics of the generator, an analytical model is used [11]. Figs. 10 and 11 show the open-circuit and output power of the generator before and after cogging force reduction. As seen, voltage and power fluctuations have been considerably reduced after cogging force reduction. Cogging force reduction may weaken the flux-linkage and consequently reduce the generator induced voltage. Fig. 10 shows that the peak open-circuit voltage is 1000 V before reduction of the cogging force and it rises to 1050 V after cogging force reduction. Therefore, not only did the open-circuit voltage not reduce, but it is slightly increased. The 50 V rise in the voltage is due to the shorter PM length and increase of the field intensity of the PM.

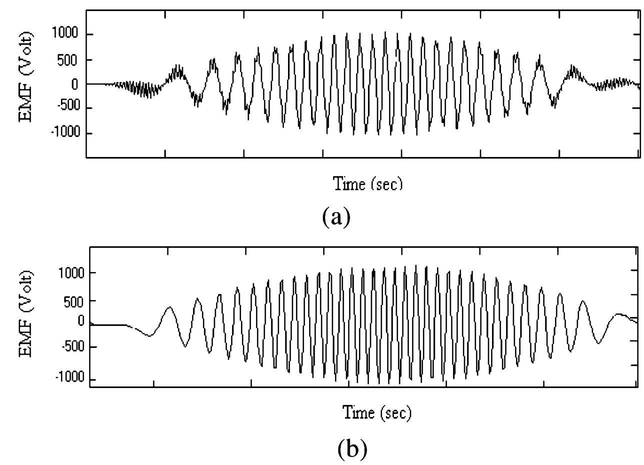

Fig. 10. Open-circuit voltage of generator before and after cogging force reduction.

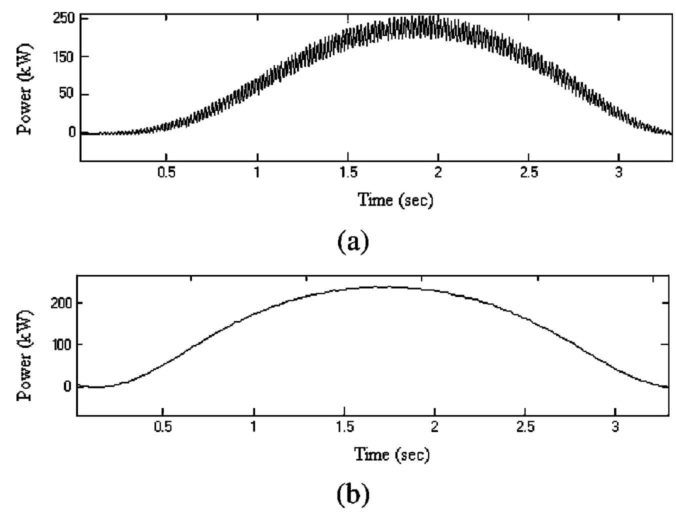

Fig. 11. Generator power: (a) before cogging force reduction and (b) after cogging force reduction.

V. Conclusion

The design and simulation of the LPMG for direct conversion of wave energy carried out in this paper enables the following conclusions to be made.

- The effects of several parameters including the PM length, skewed PMs, radial PMs application, and use of stator semi-closed slots upon the cogging force were investigated.

- Reduction of PM length in the magnetizing orientation to 5 mm decreased the cogging force by 80%.
- The 30 degree skewing PMs reduced cogging force from 8400 N to 720 N, around 90%.
- Stator semi-closed slots decreased the cogging force by 34%. As seen the effect of semi-closing is much smaller than the other two above-mentioned methods. Also, semi-closed slots increase the leakage flux resulting in efficiency reduction of the LPMG. So without semi-closing the slots, cogging force can still be reduced to 720 N with less cost and construction issues.
- Radial PMs decreased the cogging force by 70%. However this decreases the flux-linkage and consequently output voltage of generator. This can be improved by using a stronger PM or larger number of PMs. Of course, this increases the cost of the generator.

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