# Investigation in Multiphase Tubular Permanent Magnet Linear Generator for Wave Energy Converters

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## Abstract

In this paper, an investigation into different magnetisation topologies for a Long Stator Tubular Permanent Magnet Linear Generator (LS-PMLG) is performed through a comparison based on the cogging force disturbance, the power output and the cost of the raw materials of the machines. The results obtained from the FEA simulation are compared with an existing linear generator described in [1]. To ensure accurate results, the generator developed in [1] is built with 3D CAD and simulated using Finite Element Method (FEM) and the obtained results are verified with the source.

**Keywords:** linear generator, wave energy, cogging forces

## 1. Introduction

Generally, direct drive technologies for Wave Energy Converters (WEC) reduce the complexity and higher the reliability of the WEC due to their design simplicity. The avoidance of mechanical or hydraulic systems in direct drive WEC can reduce the installation and maintenance costs. However, problems with the generator such as high magnetic forces have been reported. Searching for alternative ways for power generation has become an important topic in the last couple of decades owing to the global warming, the lack of fossil fuel resource and the increasing environmental pollution. Currently, the renewable energy provides sustainable solution with its zero carbon emission release during operation. The marine wave energy generation is relevantly underdeveloped unlike other renewable sources such as wind and photo voltaic, but it has vast potential [2]. The direct drive WEC's simplicity could lead to higher reliability; however, problems like large generator sizes and hence, high magnetic forces have been reported [3].

Number of concepts for direct drive WEC has been presented [4-15]. Caused by the relatively low vertical speeds of the marine waves and the desire for high output power, the generators share large sizes and hence, high magnetic forces such as cogging forces. In the linear permanent magnet iron-cored machines the cogging forces can cause vibrations, noise and unattended latching [9]. Therefore analysing the cogging forces is necessary when the bearings and the supporting structure of the WEC are designed.

Another challenge related with direct driven generators is the electrical output. As the voltage and the frequency are proportional to the translational speed, the electrical output varies over the length of each wave. Due to the electrical grid connection requirements, an integration system stabilizing the output voltage and the electrical frequency is required. Such integration systems are usually designed with back-to-back converter using energy storage connected to the DC link [16, 17].

In this paper, an investigation for different magnetisation topologies for Long Stator Permanent Magnet Linear Generator (LS-PMLG) is carried out. The investigation does a comparison based on the cogging forces, the power output and the cost of the raw materials of the machines. The results obtained from the simulations are compared with an existing technology for Short Stator Permanent Magnet Linear Generator (SS-PMLG) in [9]. To ensure accurate results, the generator developed in [9] is simulated using FEM and the results are verified with the source.

Additionally, slotting of the permanent magnets is an effective way of reducing the cogging forces. A reduction is achieved by displacing the peaks of the cogging forces where the total cogging force (all cogging forces added together) is much lower that the individual forces [18]. The study done in [18] presents a cogging forces reduction, where by applying the technique a reduction of around 30-40% can be achieved. However, the study does not show the additional magnetic reluctance added to the magnetic circuit due to the increased air gap lengths in the slots. Likewise, the effects on the output power or the induced voltage have not been mentioned.

A different approach for cogging force reduction shown, in [19], is manipulating the profile shape of the permanent magnets. The results are obtained by means of FEM and reveal that could bevelled bottom profile reduce the cogging forces compared with square profile.

Likewise, another very effective way to decrease the cogging forces is reducing the air regions among the teeth. The use of semi-opened coil slots rather than open slots can decrease the cogging by 34% [20].

In order to conduct complete investigation, the effects of the proposed techniques on the electrical power output have to be addressed.

## 2. Cogging force calculation

The normal operation of every electro-magnetic machine is dependent on the forces causing vibrations and has latching effect on the translator/rotor. Knowledge on the forces is very important for evaluation of mechanical vibrations and noise emissions. Furthermore, the forces are essential when the bearings and the foundations and supporting structures are designed. In the FEM used in the paper, the magnetic forces are calculated by means of the nodal force method [21-23]. The surface forces and the magnetic volume can be derived from Maxwell stress tensor as follows:

$$f_i^{\Omega} = \partial_k T_{ik} \tag{1}$$

$$f_i^{\Gamma} = (T_{ik}|_{2} - T_{ik}|_{2})n_k \tag{2}$$

where $\hat{n}$ is the outward unit normal vector in region one and Maxwell stress tensor $T_{ik}$ is given as:

$$T_{ik} = H_i B_k - \delta_{ik} w_m \tag{3}$$

Where $\delta_{ik} = \begin{cases} 1 & i = k \\ 0 & i \neq k \end{cases}$ is the Kronecker`s delta. Likewise, $w_m$ is the magnetic co-energy density of the element:

$$w_m = \int_0^H B.dH \tag{4}$$

For virtual displacement $\delta_l$ the virtual work done by magnetic volume and surface force is:

$$\delta W = \int f_i^{\Omega} \delta l_i \, dv + \int f_i^{\Gamma} \, \delta l_i \, d\Gamma$$

$$= \int (\partial_i T_{ik}) \delta l_i \, dv + \int (T_{ik}|_{2} - T_{ik}|_{1}) n_k \, \delta l_i \, d\Gamma$$

$$= - \int T_{ik} \, \partial_k (\delta l_i) \, dv \tag{5}$$

The displacement $\delta_l$ is interpolated via the nodal shape function:

$$\delta l_i = \sum_n N_n \, \delta_{ni} \tag{6}$$

where $N_n$ is the nodal shape function of the $n^{th}$ node. Using (5) and (6) the visual work can be also expressed as:

$$\begin{aligned} \delta W &= -\int T_{ik} \partial_k \left(\textstyle\sum_n N_n \, \delta l_{ni}\right) dv \\ &= -\textstyle\sum_n \left(\int T_{ik} \, \partial_k N_n dv\right) \delta l_{ni} \end{aligned} \tag{7}$$

So the force acting on the $n^{th}$ node is given as:

$$f_{ni} = -\int_\Omega T_{ik} \partial_k N_n \, dv \tag{8}$$

Using summation for all the nodes in the part the total force can be written as:

$$[fn] = \begin{bmatrix} f_{nx} \\ f_{ny} \\ f_{nz} \end{bmatrix} = -\int_\Omega \begin{bmatrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{bmatrix} \begin{bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{bmatrix} N_n dv \tag{9}$$

## 3. Multiphase generator

Long stator generators share the same stator, where the stator consists of copper coils placed in a magnetic yoke. The coils are grouped in 15 phase windings and each winding consists of four series-connected coils. The coils are identical to the coils of the generator proposed in [1] (77 turns and 1.145-ohms resistance per coil).

The translator consists of NdFeB-35 magnets attached to a magnetic core. To decrease losses in the magnetic circuit, all magnetic cores are assembled by laminated silicon steel, where the laminations are radial to the Y-axis. Additionally, in order to increase the accuracy of the simulation results, three dimensional generator models are used in the simulations.

In this paper, long stator generators with axial and radial magnetisation are investigated. A slice on the X-axis showing the profile for the three generators is presented in Figure 1. The main advantage of the long stator generator design is the reduction of the volume of the permanent magnet material used in its assembly. Considering the recent price rise of the neodymium metals [24], the potential savings of using the long stator design can be significant.

The main idea of the design adopted in the long stator designs is “swapping the configuration” of more traditional SS-PMLGs (Figure 1), where the translator comprises coils that are exposed constantly to the PM’s flux. Reversing this structure allows a long stator to be assembled from copper coils and a short translator that consists of PMs (Figure 1).

An advantage of the topology for SS-PMLG is that it allows a standard three-phase rectifier to be connected directly to the winding terminals but a significant part of the PMs’ flux does not cross the coils and therefore, this flux does not contribute to the power generation. On the other hand, the long stator design utilises the PMs in a way that the entire flux crosses the coils at any time of operation. Therefore, the main advantage from such a design is the full usability of the excitation flux established by the permanent magnets. Conversely, the long stator design has a coil configuration that is more complex and requires a system excluding the unenergised coils (coils unexposed to the PM’s flux) from the electrical circuit. If the unenergised coils remain connected in series with the energised ones, they become an inductive load.

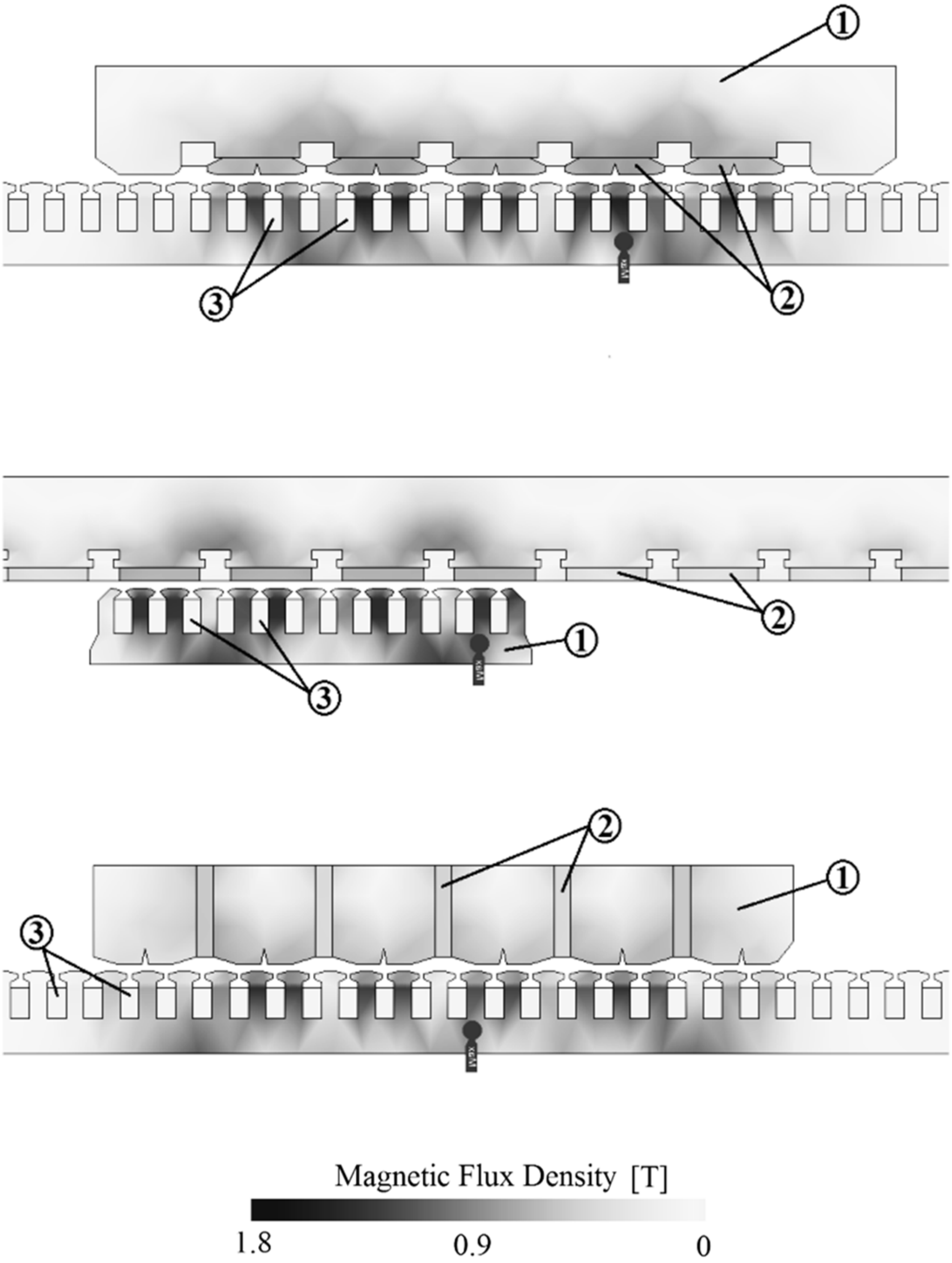


Figure 1 Two dimensional view of LS-PMLG with radial magnetized magnets (top), SS-PMLG shown in [1] (middle) and LS-PMLG with axial magnetized magnets (bottom), where 1 are the translators, 2 are the permanent magnets and 3 are the coils

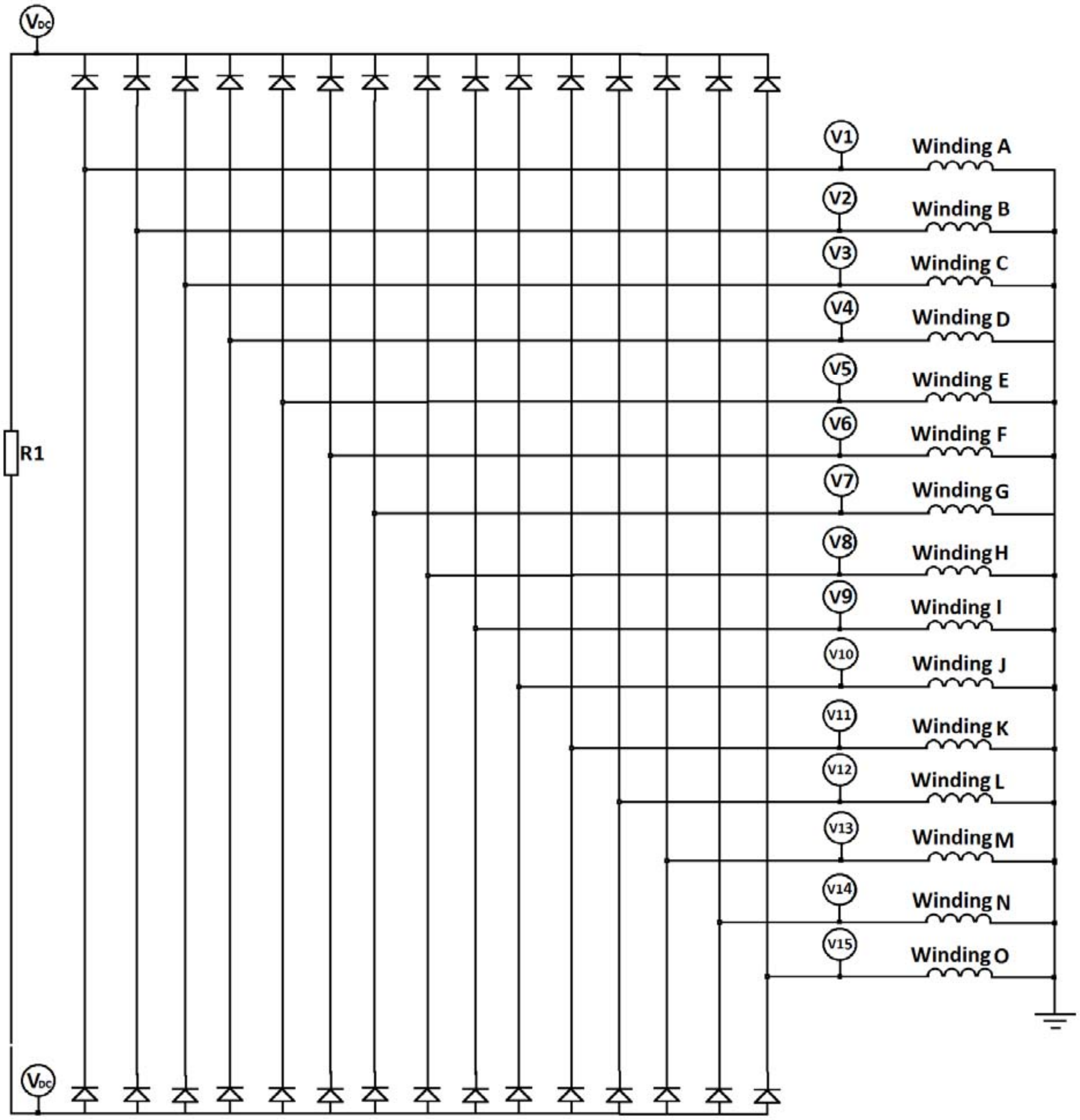


Figure 2 Passive rectification system for LS-PMLG

Table I Main dimensions

| | Axis | SS PMLG | LS PMLG radial magnetisation | LS PMLG axial magnetisation |
|---|---|---|---|---|
| Stator height [mm] | Y | 1152 | 1342 | 1342 |
| Translator height [mm] | Y | 284 | 484 | 422 |
| Permanent Magnet Length [mm] | Y | 52 | 70 | 10 |
| Magnet pole pitch [mm] | Y | 72 | 72 | 72 |
| Coil pitch [mm] | Y | 68 | 68 | 68 |
| Magnets height [mm] | X | 10.5 | 10.5 | 54.7 |
| Air gap length [mm] | X | 5 | 5 | 5 |
| | | | | |
| Turns per coil | | 77 | 77 | 77 |
| Coils resistance [ohm] | | 1.145 | 1.145 | 1.145 |
| Resistive load (on DC side) [ohm] | | 5 | 5 | 5 |
| Coil connection within a winding | | series | series | series |
| Windings connection | | star | star | star |

The electric circuit of the long stator generator is shown in Figure 2, where the output power is measured on the 5-ohm resistor (R1) after rectification. Each phase winding is assembled by four coils connected in series and the number of windings can be altered. The Voltmeters (V1 to V15) measure the voltage on every winding.

## 4. Simulation Results

In the simulations performed, the following parameters are kept the same for the three generators: winding slot dimensions, shoe dimensions, number of slots per pole and phase, number of turns per coil, coil resistance and all structural material properties used in the models. This is conducted to reveal only the differences caused by the generator design and to eliminate the influence of the material properties and of the coil configuration on the performance. In this section three major sets of simulations are performed:

- The first set compares the cogging force for the SS-PMLG shown in [1] with the cogging force for the LS-PMLGs having axial and radial magnetised magnets.
- The second set presents the electrical power output of the generators connected to 5-ohms resistive loads after rectification.
- The third set shows the volumes and the prices of the raw structural materials for the three machines.

### 4.1. Cogging forces

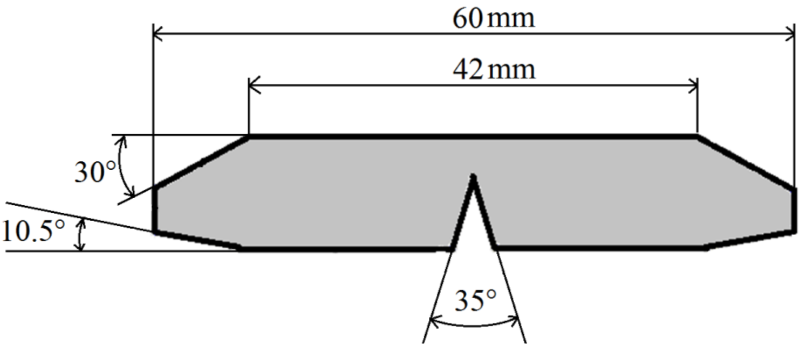
Cogging forces are caused by the interaction between the magnetic field of the PMs and the iron core of the PMLG. Such interaction has a latching effect on the translator. Moreover, the cogging forces are independent from the magnetic fields generated by the armature currents [25].

The cogging forces try to align the magnets with the steel core in a position that minimises the total reluctance of the magnetic circuit. When a minimum reluctance path is established at a certain position, the magnetic forces oppose any external force trying change this position (position on the Y-axis). The cogging forces generate both vibrations that have to be maintained by the bearings and the supporting structure and unwanted noise and latching of the generator's translator [1, 18, 26].

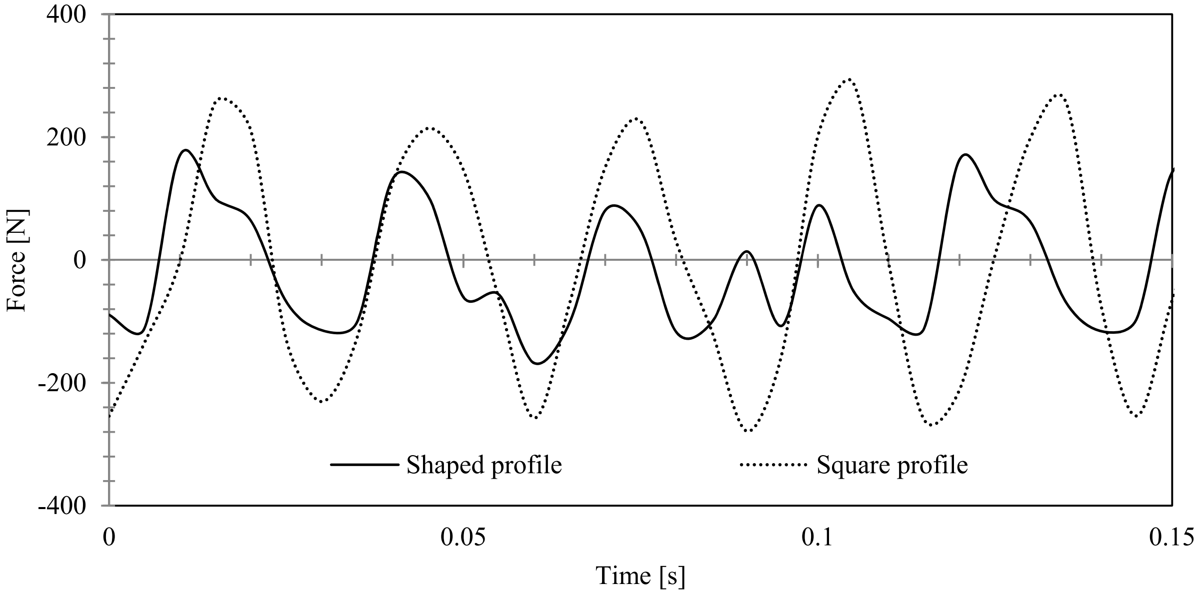
Several techniques, such as shaping and slotting have been applied for cogging force reduction in the LS-PMLG. The shaped profile of the magnets used in the radially magnetised LS-PMLG is shown in Figure 3a. The cogging forces comparison is shown in Figure 3b, where the shaped profile and the square profile are analysed. In order to compare the PM rings on an equal basis, the two magnet ring volumes are set to be the same. As a result (Figure 3b), a total reduction of 30% in the peak is achieved when pole slotting and shaping is applied on the PMs.

Initially, the long stator generators have been simulated with square profiles (Figure 3a). As one of main objectives is to reduce cogging, modifications have been applied to the magnet profile. Influenced by [19], the square profile has been modified to include to bevelled bottom profile with a 30° angle, which has been chosen based on the findings in [19].

Furthermore, in order to reduce the cogging force even further but to keep the power output approximately the same as for the SS-PMLG, modifications of shaping and slotting the magnets have been also done. The shaping and slotting modifications were influenced by [18]. Initially, an angle of 35° has been applied and the shaping (with an angle of 10.5°) has been adjusted to maintain the output power of the long stator machines close to that of the short stator PMLG.



(a) Magnet profile for radial magnetized LS-PMLG with radial magnetisation



(b) Cogging forces for shaped and square magnets` profile

Figure 3 Effect on the cogging force caused by shaping the PMs

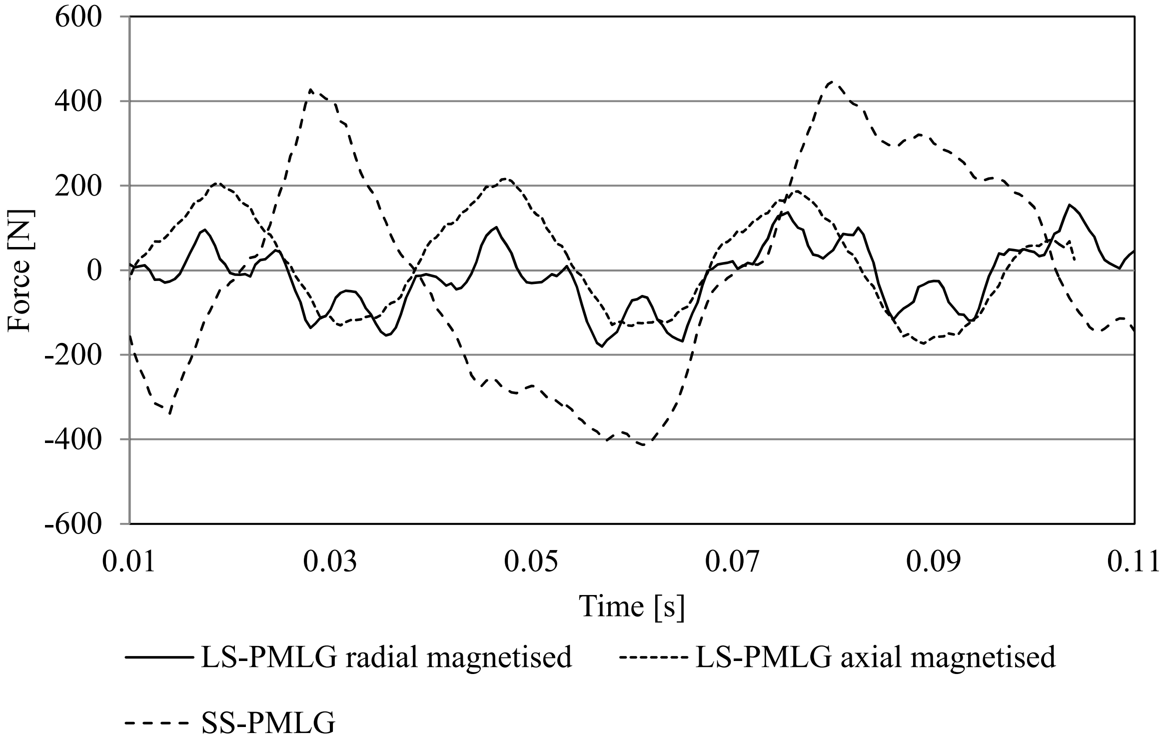


Figure 4 Cogging forces for the investigated topologies

The cogging force results for the three generators are shown in Figure 4, where it can be observed that the long stator designs have significantly lower cogging force amplitude.

Compared with the cogging forces for the PMLG shown in [1], the LS-PMLGs achieve a reduction of 60%.

### 4.2. Power output

The voltage output of the SS-PMLG [1] has been verified with the model of the simulated generator in this paper. The no-load voltage (line to neutral) obtained in [1] is 346 V and the no-load voltage obtained by FEA in this paper is 330 V at a constant velocity of 0.76 m/s. The difference of 4.6% is considered as acceptable in verifying the FEA model used in this paper.

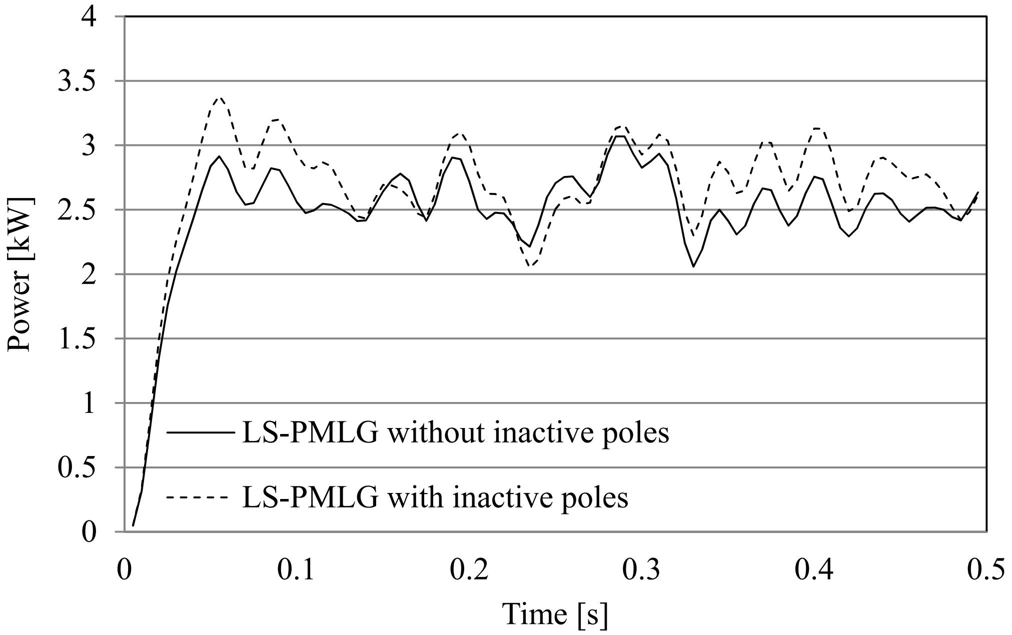


Figure 5 Power output from LS-PMLG with and without inactive poles

Another advantage of the LS-PMLG is the possibility of adding inactive poles at both ends of the translator. By installing the inactive poles, the additional flux distributed over the stator length generates a voltage in the additional coils at the ends of the translator and hence, electrical power. The RMS power outputs for the LS-PMLG both with and without the inactive poles are 2705 W and 2521 W respectively. The instantaneous output power can be seen in Figure 5. As a result, the output power is boosted by an extra 7% (RMS) without the use of extra permanent magnet material.

The simulated results for the power output are shown in Figure 6, where the three generator models are simulated with a monochromatic wave set for the translator’s displacement with a period of T = 2.1 seconds and height of 0.375 meters. This displacement is equal to the scaled statistical data for the sea state located north of Spain [27].

The following RMS output powers area achieved for the wave period of 2.1 seconds: SS-PMLG - 2.66 kW, LS-PMLG with axial magnetised magnets - 2.66 kW and LS-PMLG with radial magnetised magnets - 2.72 kW. From the result, it can be concluded that the electrical power output is very similar for the three machines.

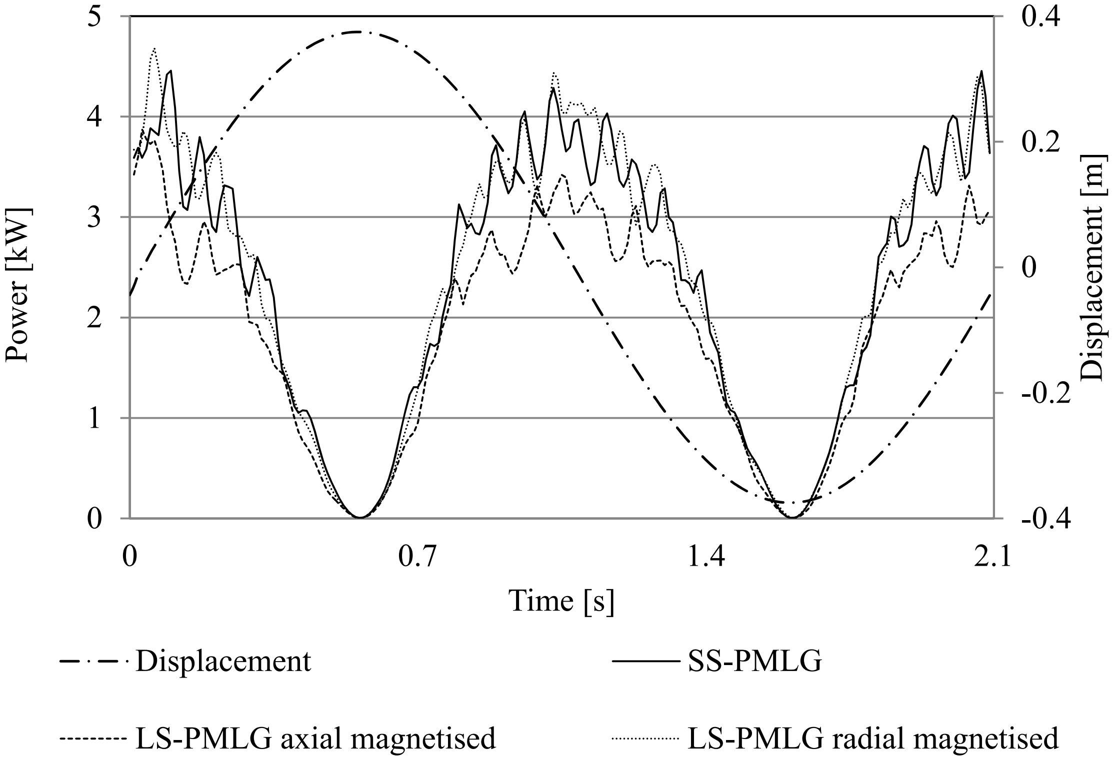


Figure 6 Power output of the SS-PMLG [1] and LS-PMLGs

Owing to the design consideration for the long stator generators, not all coils generate voltage at the same time. Only the coils covered by the translator magnetic field generate voltage during displacement of the translator (Figure 7). It can be seen that the coil voltages have the same frequency but different amplitude and phase. Such a complex output requires a modified rectification system. The voltages from the long stator generators in this paper are rectified by a passive rectification system.

Another benefit of the long stator design is the possibility of excluding a coil in case of failure, by using power electronics. Owing to the high number of coils, such an operation does not reduce the output of the generator significantly. Therefore, maintenance of the WEC can be postponed.

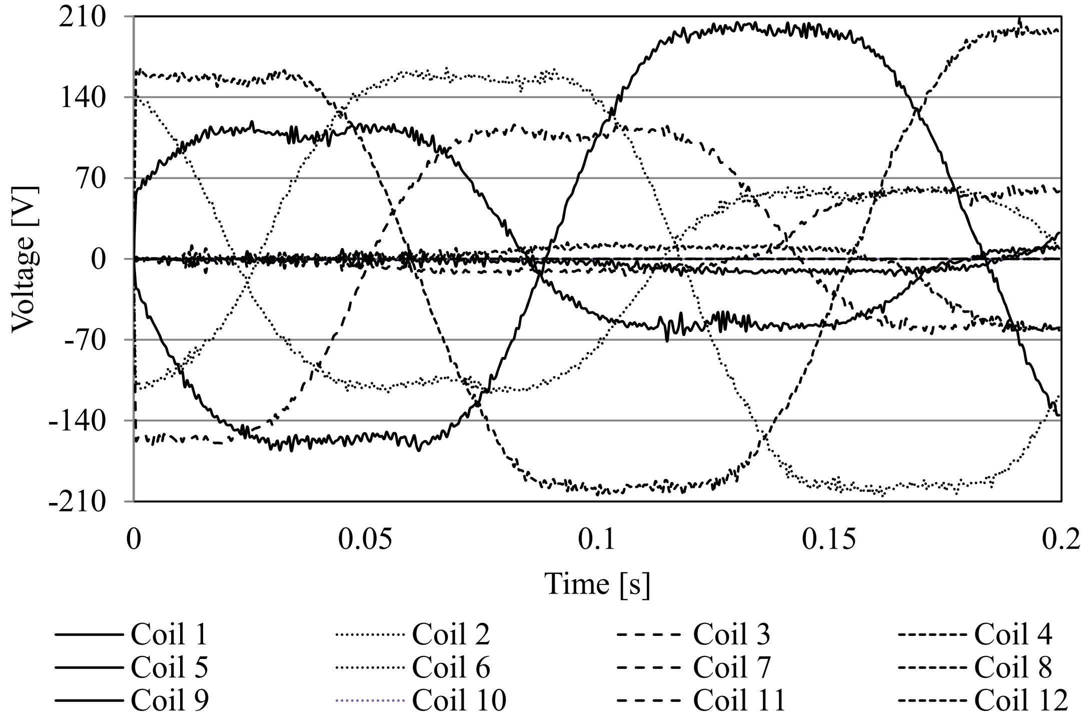


Figure 7 Voltage output for LS-PMLG

Moreover, a benefit of using the long stator design is the heat dissipation in the copper coils. In the long stator design, output electrical power is harvested from a high number of coils. Unlike the SS-PMLG in [1], the coils in the LS-PMLG are not energised at all times. Hence, for the same amount of total harvested energy from the generators, the power delivered by a single coil in the LS-PMLG will be much lower than in the SS-PMLG. Consequently, the coils in the long stator generator have much lower duty cycle and therefore they are allowed a longer cooling time. Consequently, overheating of the LS-PMLG`s coils is less likely to occur compared with those of the SS-PMLG.

## 4.3. Volumes and price of the structural materials

The volumes of the structural materials for both generators are shown in Table 1. As seen in the table, the total price of the long stator design is much lower than that of the SS-PMLG [1]; the main difference is in the price of the permanent magnets. The price of the materials is assumed as follows: non-magnetic and non-electrical conducting material - 1.43 £/kg, copper – 5.29 £/kg [28], laminated steel – 2 £/kg [28] and PMs, NdFeB, N35 – 216 £/kg [29].

Table 1 Volumes and Price of Structural Materials

| | SS PMLG | LS PMLG radial magnetisation | LS PMLG axial magnetisation |
|---|---|---|---|
| PM [m$^3$] | 0.034 | 0.011 | 0.011 |
| Laminated steel [m$^3$] | 0.303 | 0.264 | 0.270 |
| Copper [m$^3$] | 0.0111 | 0.0555 | 0.0555 |
| Non-magnetic and non-electrical conducting material [m$^3$] | 0.022 | 0.0052 | 0 |
| | SS PMLG | LS PMLG radial magnetisation | LS PMLG axial magnetisation |
| PM [k£] | 55.5 | 18 | 18 |
| Laminated steel [k£] | 4.64 | 4.04 | 4.13 |
| Copper [k£] | 0.52 | 2.6 | 2.62 |
| Non-magnetic and non-electrical conducting material [k£] | 0.08 | 0.018 | 0 |
| Total cost [k£] | 60.74 | 24.66 | 24.75 |

Considering the recent price rise of the neodymium metals reported in [24], the payback period of the long stator design is likely to be shorter than that for the existing generator. The assembly cost is not included in the calculations but it is expected to be similar among the three generators. Generally, fewer difficulties are expected for the assembly and handling of the PMs in the long stator generators, because of, the lower volumes of PMs used in their design.

## 5. Conclusions

The aim of this paper is to highlight the merits of the long stator design over the existing short stator three-phase design for SS-PMLG. The areas of focus are the price of the raw assembly materials, the cogging force and electrical power output. An increase in the electrical output and a reduction in the raw materials can lead to a lower initial investment and lower RoI of the WEC. Furthermore, the reduction of the cogging force reduces vibrations and hence, can increase the life of the bearings.

In this paper, an investigation of long stator generators has been performed by means of FEA. Long stator generators with axial and radial magnetisation have been analysed and optimised and the results reveal a cogging force reduction of up to 60% in comparison with an existing design having a short stator and similar size. Furthermore, the long stator generators simulated use three times less permanent magnet material in their assembly, which reduces the price of the raw assembly materials by 60% in comparison with existing SS-PMLG [1]. The results delivered in this paper suggest that use of LS-PMLGs can reduce the production and maintenance costs of the WEC in comparison with the SS-PMLG.

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