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Separated magnet yoke for permanent magnet linear generator for marine wave energy converters

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ABSTRACT

In this paper the performance of a longitudinal flux permanent magnet linear generator (PMLG) for wave energy converters (WEC) is investigated. The influence of the number of slots per pole, phase *q* and the number of stator's winding sections are analysed. The power output and the cogging forces in the PMLG are calculated and reviewed with respect to the above design parameters. In addition, an optimised PMLG model is designed and simulated. Three-dimensional Finite Element Method (FEM) is used for solving the combined field and circuit equations of the generator.

1. Introduction

UE to the nature of marine waves, the take-off device for WECs usually operates between 0 and 2 m/s. Currently, some of the deployed WECs are designed to work with fast-speed rotational generators. In such systems, the relatively low-speed linear translation of the take-off device has to be converted to a high-speed rotational motion via an interface system. By integrating such system, the overall complexity of the WEC is increasing, whereas the efficiency and the robustness are reduced. A possible solution for overcoming such problems is a wave energy converter with a direct drive linear generator [1–4]. The linear generators are proposed for WECs to simplify the overall structure. The main problems with the linear generators are the high magnetic forces appearing between stator and translator during normal operation. These forces could reduce the lifetime of the bearings and therefore, increase the maintenance costs of the WEC. Hence, reduction of the magnetic forces in the linear generator may have significant effect on the maintenance cost.

Direct drive PMLGs have been proposed for WECs and several design solutions have been outlined in [4–12]. In [4] flat air-cored design has been suggested. The design has the advantage of eliminating the cogging force due to absence of stainless steel in the stator however, in order to generate sufficient magnetic field in the large air gap, an extra Permanent Magnets (PMs) are needed which on the other hand could increase the price of the machine.

A switched reluctance PMLG has been presented in [9]. The machine has iron-cored magnetic yokes and therefore, low magnetic reluctance path is provided however, high level of latching (cogging) forces can be expected due to the alignment of the stator and the translator. Another PMLG with excitation provided by a super conducting DC coil has been proposed in [13]. This kind of generator generally advantages from the possibility of control excitation applied on the excitation winding. On the other hand, heavy saturation in the magnetic core has been reported.

Furthermore, observations on the cogging forces [14,15] and the generated voltage harmonics [16] have also been performed on similar structure as structure presented in this paper. Additionally, constant speeds or speeds having sinusoidal shapes are common approximations for simulating PMLGs [14,16–19].

In this paper, a design for a flat longitudinal PMLG for marine wave energy is analysed. The influence of parameters, such as: the number of slots per pole, phase *q*, and the number of stator's winding sections are analysed with respect to the cogging forces and the output power of the PMLG. Based on the obtain results, an optimal model is proposed. The aims of the optimisation are reduction of the magnetic attraction forces between stator and translator and also increase of the electrical power output of the PMLG. By reducing the magnetic attraction force, the maintenance cost of the WEC can be reduced. Likewise, increasing the power output of the generator will reduce the pay-back time of the WEC.

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FEM is used as a simulation tool because of its high accuracy. Moreover, the simulations are performed using three-dimensional FEM with a time-varying electromagnetic field taking into consideration the non-linearity of the magnetic cores and the longitudinal ends of the machine. Furthermore, in the simulations full size generator models taking into account the magnetic flux distribution in the air gap and the regions at the longitudinal ends are simulated. Additionally, in order to simulate real sea conditions, an experimentally recorded vertical wave displacement is applied to the generator's translator for a period of 20 s.

The paper is organised as follows: after the introduction, a description of WEC is outlined. Then a theoretical explanation of the nodal force method used in the FEM is given. After that, a description of the investigated PMLG is given. In the next section, the results from the investigation are displayed and an optimal model is designed, before conclusions are presented.

2. Wave energy converter and forces calculations

Wave energy converter is a general title for devices that convert the kinetic energy of marine waves to electricity. The investigated PMLG in this paper is designed to be driven by a floater on the water surface, or installed in an Archimedes wave swing [20].

Generally, two types of construction employing either a non-flexible shaft [21] or a rope [22,23] have been proposed for WECs having direct drive electrical generators. The design using a non-flexible shaft is simpler, but it has only one degree of freedom and the energy absorption is limited up to 50% [24]. Furthermore, the forces normal to the motion axis are likely to be higher when using the non-flexible shaft design due to the restriction of the motion of the translator.

Conversely, an advantage of the design using a rope is that the flexibility of the rope provides additional degrees of freedom and hence, the energy absorption can be increased. Another difference in design is given by the springs, which have to be installed in order to pull the translator back to its lowest point.

Owing to the direct coupling of the take-off device and the generator, the generated voltage and the electrical frequency are in direct ratio with the translator's speed [25]. As a result, big fluctuations in the output voltage and the electrical frequency are observed during normal operation of the PMLG. In order to stabilise the fluctuation, a power-electronics converter and energy storage can be installed between the generator and the grid [26].

The calculation of the cogging forces is interesting from many perspectives. It is an important parameter for studying: the generator bearing system, the mechanical stress, and fatigue in the supporting structure. Additionally, the cogging forces are source of sound emission.

In this paper, the forces are calculated by FEA using 3D models with high mesh resolution. To increase the result accuracy the resolutions of the models have been set to around 1 million mesh nodes. The FEA software uses the nodal force method [27] as a tool for magnetic forces calculation. The nodal force method is derived from the Maxwell stress tensor and the method is proven to be as accurate as the virtual work method [27,28].The surface forces and the magnetic volume can be derived from the Maxwell stress tensor as follows:

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

$$f_i^{\Gamma} = (T_{ik}|_2 - T_{ik}|_1)n_k \tag{2}$$

- n_k is the outward unit normal vector in region one and Maxwell stress tensor
- T_{ik} is given as:

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

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

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

For virtual displacement δl_i the virtual work done by magnetic volume and surface force is:

$$\begin{aligned} \delta W &= \int f_i^{\Omega} \delta l_i \ dv + \int f_i^{\Gamma} \delta l_i \ d\Gamma \\ &= \int (\partial_i T_{ik}) \delta l_i \ dv + \int (T_{ik}|_2 - T_{ik}|_1) n_k \delta l_i \ d\Gamma \, . \\ &= -\int T_{ik} \partial_k \left(\delta l_i \right) \ dv \end{aligned} \tag{5}$$

The displacement is interpolated via the nodal shape function:

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

- N_n is the nodal shape function of the nth node. Using (5) and (6) the virtual work can be also expressed as:

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

So the force acting on the nth 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:

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

3. Description of the PMLG and the simulations

In this paper, it is assumed that the generator's translator is assembled from the permanent magnets and the separators. Likewise, the stator is assembled from two aligned magnetic cores on both sides of the translator with copper coils placed in slots (Fig. 1).

It is assumed that the PMLG's stator is assembled from the permanent magnets, the separators, and the upper magnetic core. The separators are made from non-magnetic and non-electrical conducting material and they are required in order to maintain the position of the permanent magnets against axial displacement. In addition, the PMLG's translator is assembled from the lower magnetic core and the windings.

The magnetic cores of the machine are formed by laminated silicon steel with a 95% stacking factor and they are treated as magnetically nonlinear material with single value magnetisation characteristics.