Thrust Force Analysis of Slotless Permanent Magnet Linear Generator for Wave Energy Converter

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Abstract. The WEC (Wave Energy Converter) that uses a permanent magnet linear generator continues to develop. The most important thing to know in designing WEC with a linear electric generator is the thrust required by the linear generator itself. Therefore, this paper discusses and analyses the thrust that occurs in linear electric generators used in WEC systems. Linear electric generators are simulated using FEMM (Finite Element Magnetic Method) software. FEMM simulation is used to analyse the magnitude of the induced magnetic field received by the conductor at a certain position of the stator. The conductor is given a constant current so that it produces thrust force between the stator and translator; the magnitude of thrust force depends on the magnitude of the magnetic field at the position. In the design and analysis, conductors were given 3A. The maximum thrust force in the linear electric generator design is 79N, and the average force is 75N, force ripple is 1.2%. The design of the permanent magnet linear generator was done, and the WEC system should produce thrust force at least equal to the force that the generator requires.

1. Introduction

The challenge to increase the availability of electrical energy has led to the use of renewable energy that is available in nature. The effort to reduce global warming caused by greenhouse gas emissions from fossil fuel burned in most power engine. The sea wave generator is one of the renewable energy sources found in nature. Ocean wave with potential wave height can be used to generate power, the repulsion force and falling waves are potential energy stayed in the waves so that the thrust force on these waves can be utilized.

In the last few decades, many developed countries have overcome the increasing amount of energy needs using wind or solar energy. Also, renewable energy such as geothermal, biomass, or marine energy is a solution for specific locations. Unlike solar or wind energy, which are present almost everywhere in the world, these forms of energy are somewhat rare, so they can be used in several regions (northern countries use geothermal energy for the production of...
electrical energy or home heating, agricultural areas use bio-mass for electricity production and areas with coastal shores use ocean energy[1].

Wave energy converter (WEC) combine with electric generator is the system that took the power of ocean wave energy. An electric generator is a machine that converts mechanical energy into electrical energy. Faraday's law shows that a wire or coil of a conductor in magnetic field that changes with time will produce induced voltage or electromotive force (emf). Faraday's Law is still used as a fundamental calculation for generator design in this modern era.

**Wave Energy Converters**

Thrust force in ocean waves with their characteristics which have a specific frequency and wave height cannot be directly used to drive a generator. In radial generators, the generator drive needs usually have to go through a rotating shaft. It requires a system that convert potential energy in ocean waves into energy that can be used to rotate the generator shaft. In linear generators, the process of converting potential energy from ocean waves can be used directly because of the characteristics of a linear generator that moves in a straight line with reciprocating movements.

Direct drive system is provided to eliminate mechanical transmission that reduced overall efficiency. The linear electric generator can be used in directly driven by ocean waves energy converter, for example, using float types of the WEC. The simplest using a float connected to the moving generator part (translator), while the stator mounted on the seafloor, as in figure 1 a). Another possible way is to place the stator above sea level using two floaters, positioned in such a way as to give a half-wave distance between the floaters and the translator, as in Fig. 1 b). Another solution is to let the stator float above sea level 1 c). or by placing the entire structure in a closed cylinder, such as Figure 1 d). Depending on the amount of water that is above the device, the air pressure in the cylinder will cause up and down movements of the translator to produce electric energy [2].

Wave Energy Converters (WEC) is used to change the direction of the force on ocean waves so that it matches the required generator drive. WEC can use to drive two types of electric generators, namely rotary generators or linear generators. Unlike a rotary generator, a linear generator can be directly driven by movement at the WEC because of the vertical movement of ocean waves while a rotary generator requires a transmission system to be driven [3]. Most Wave Energy Converters (WEC) devices use mechanical or hydraulic systems to transmit ocean wave power to linear generators, based on the device with a transmission system that uses many inefficient gearboxes, due to energy losses in the gearbox. In
general, the linear generator in the WEC operated by moving the translator up and down, adjusted to the wave motion at the WEC in contact with ocean waves, for example, buoy [4]

**Electric Linear Generator**

A linear generator is an electric machine that can produce electricity by converting it from linear motions. The advantage of linear generators is the use of movements that can directly use the kinetic motion of generators that move linearly without going through mechanical transmission [5].

![Figure 2. The concept of a linear generator [5]](image)

Fig. 2 shows how a linear electric generator is formed from a rotary generator. When the rotary generator stator is cut and opened (Fig. 1 a and 1 b), a flat side topology is obtained for the stator for the linear generator. The same process applies to the rotor and as a result, a magnetic configuration will be reached (fig. 1 c and 1 d). The stator structure is flat, and the magnet is then converted to cylindrical shape (figures 1 e and 1 f). The coil is also rolled and inserted into the stator slot. And got a concept for a linear generator[6].

The working principle of a linear generator is not much different from other conventional generators, in general, the process of the magnetic induction of the coil is done to produce voltage, but to generate magnetic flux can be done by designing the windings or using permanent magnets on the rotor. In Linear Generators no current or excitation voltage is needed on the rotor because permanent magnets are used to generate magnetic flux, it can be explained simply, the voltage will be generated in the conductor (stator winding) if the conductor moves in a magnetic field. This certainly will increase efficiency because the flow of conversion of mechanical energy into electricity can be done directly without external generator excitation.

**Design Topology Modular Linear Generator**

In this paper, a linear generator is designed in an independent modular model, as shown in figure 3. It can be used in one separate generator module or can also be assembled in the form of a multi-module. Multi-module type, as shown in figure 4 assembly in series or parallel.
The linear electric generator design in this paper is designed with a coreless type, there is absence of laminating iron or iron core in the stator winding. The conductor winding is fixed by resin. Because of the absence of laminating iron or iron core in this design, this generator types are also called a slotless generator. Coreless type is better than the slotted type linear generator in terms of force ripple, because there is no interaction force between magnet and slotted iron. The linear electric generator parameters for one module are in the following table:

| Parameters                | Amount     | Unit |
|---------------------------|------------|------|
| Magnet dimension          | 150x40x8   | mm   |
| Type of Magnet            | -          | NdFeb 40 |
| Magnet per module         | 4          | module |
| Space between magnets     | 20         | mm   |
| Number of winding         | 100        | Turn |
| Diameter wire             | 1          | mm   |
| Air gap                   | 1          | mm   |

The linear design of a modular generator in one module is shown in Figure 3. The modular design for a multilevel connection is shown in Figure 4(a), and for an elongated connection in Figure 4(b).
Finite Element Method Magnetics Simulation

In this paper, the simulation is carried out using Software Finite Element Method Magnetics version 4.2 (FEMM 4.2). The topology and linear design of the generator are depicted in a 2-dimensional (2D) form, and parameters given to the component material used are as shown in table 1 above.

In figure 5 shows the linear generator topology in 2 dimensions, there are two sides of back iron with a thickness of 15 mm, on each side, there are four magnets, the type of magnet used is NdFeb 40, with air-gap of 1 mm. The thrust force on the translator of a linear generator is obtained by injecting the current in the windings.

2. Result and Discussion

The flux density is obtained by running a simulation. The magnetic field lines can be measured for strength, as in Figure 6 shows the distribution of the magnetic flux density in a linear generator module.

The flux density is shown in Figure 7 below, the flux density of each part of the linear generator in simulation has a certain color, where the color identifies the flux density.

Flux density results are obtained as shown in Figure 8, the maximum flux is 0.697 T. Flux density can be interpreted as the strength of the magnetic field used. In this paper, the type of magnet used is grade 40 Neodymium Feron Boron (NdFeB 40). The results shown in Figure 8 are the results of testing in one of the generator phases.
The purpose of this study is to measure the power needed to drive a linear generator. The required thrust force can be obtained by injecting a current into the windings. In this study the current injected during the simulation was 3.5 A, and Thrust Force was obtained in each phase, as shown in Figure 9 below.

Fig. 9 shows when each phase is injected with a current of 3.5 A, a maximum force of 35.7 N. and a maximum average thrust force of 79 N are obtained as shown in Figure 10 below.
3. Conclusion
Design and simulation of a linear generator with a 3-phase coreless configuration using permanent magnets have been done. The linear generator was in design modularwise for wave energy converter, where the number of turns per phase coil is 100 turns. Reaction force carried out on this generator is an average of 79 Newtons, at a fix current injected of 3.5 Amperes. The data is retrieved only for a set of 3 phase winding with star connections. The average thrust force is 75N, with 1.2% force ripple. In WEC the output of voltage depend on wave height and period which correspond to linear generator slider or translator speeds in direct driven system.

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