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# Performance and design optimization of two model based wave energy permanent magnet linear generators

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A B S T R A C T

Linear generators are a quickly growing segment of renewable ocean wave energy converters. This paper presents the modeling, simulation and optimal design of two types of permanent magnet linear generators for generating 3-phase voltages based on finite element analysis and intelligent design optimization techniques. Each generator stator and rotor configurations are modeled by using Computer Aided Three Dimensional Interactive Application software and the magnetic field simulation studies are carried out by using finite element method software ANSYS. Two intelligent evolutionary methods, Scatter Search optimization and Particle Swarm Optimization techniques are employed on design analysis programs which are developed by using Visual C++ software to derive optimal design parameters of the linear generator models. Simulation results show the effective exploration of the design and analysis objectives.



## 1. Introduction

Linear generators are gaining acceptance as ocean wave energy converters, exploiting the wave energy which is derived from natural rise and fall of the waves. As compared to leading solar and wind renewable energy sources, harnessing wave energy is more favorable and much cheaper considering its high power density [1]. Besides, ocean wave energy is more predictable than solar and wind energy and can be derived throughout the day. In addition, the power generation by the ocean wave energy is environmentally attractive and in recent years, a number of researchers paid more attention on developing different wave energy conversion systems [2]. As the waves propagate with a velocity of about 1 m/sec on ocean surface, the energy transported is extracted and converted into an oscillatory motion through hydrodynamic forcing to create mechanical energy. The resultant mechanical energy is converted into electrical energy by employing a linear electrical generator.

Linear generators are being widely used in embedded power generation. Among various topologies of linear generators, tubular and rectangular type permanent magnet machines offer high efficiency and a high power force density [3,4]. As the number of moving parts and maintenance costs are reduced, a permanent magnet linear generator (PMLG) becomes more efficient, more compact and light weight as compared to a conventional generator. A PMLG for wave energy conversion is generally designed with a translator which moves back and forth in a tubular stator or over a linear stator. As the translator is provided with permanent magnets and the stator with winding coils, the axial-directional magnetic flux which links through stator windings generate an induced electromotive force (emf). The magnitude of the desired emf is based on linear speed of translator, number of stator winding turns and the total flux linking the stator winding. Recent developments on design considerations of PMLGs, which explain the need for optimal design based on intelligent techniques, are summarized as follows.

A permanent magnet linear synchronous generator based on Archimedes Wave Swing is designed and built [5] to analyze the correlation between the measured and calculated generator parameters. Based on the efficiency and the generator force, the authors described a method to calculate the annual energy yield from the wave distribution by comparing the effect of voltage source and current source inverters on the extracted energy. A review on linear

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generator systems for wave energy conversion is presented in Ref. [6], proposing cylindrical construction for stator with concentrated or distributed coils. A hybrid evolutionary algorithm based on Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) techniques [7] is applied for developing a high quasi-constant output voltage with smallest cogging force from a tubular permanent magnet linear generator (TPMLG) which is connected to a buoy. However, the generator parameters evaluated before and after applying optimization techniques are not reported. The simulation results of a novel TPMLG and the constructed prototype hardware results for a buoy system are compared in Ref. [8]. However, the generator parameters are derived iteratively in order to arrive at an optimal system design. The performance of a TPMLG as wave energy converter [9] is analyzed by using JMAG finite element method software. Analysis form prototype models developed by trial and error design methods could result in a good design but it is time consuming and also not cost effective. Therefore, as the construction technology on different wave energy converters by using PMLG is improving, an intensive study on optimal design parameters of PMLG is mandatory in view of the developments of intelligent design guidelines.

This paper aims to model, simulate and employ two intelligent optimal design techniques on a tubular type and a rectangular type PMLG which are examined in three stages. In the first stage, each generator stator and rotor is modeled with specified dimensions by using Computer Aided Three Dimensional Interactive Application (CATIA) software. On the generator models simulation studies are carried out to analyze flux distribution and the resultant induced emf, by using finite element method (FEM) software ANSYS, in the second stage. In the third stage, Scatter Search (SS) optimization technique on the tubular type generator and Particle Swarm Optimization (PSO) technique on the rectangular type generator are employed to optimize the design parameters and improve the performance of the generator models. The paper is organized as follows. After a brief introduction, the modeling of the generator stator and rotor parts of tubular PMLG and rectangular PMLG is described in Section 2. Magnetic field distribution studies based on FEM analysis by ANSYS and the resultant 3-phase generated voltage by stator winding are presented in Section 3. A design analysis of the linear generators carried out by using two intelligent evolutionary global optimization techniques is presented in Section 4. Subsequently, in Section 5 the results derived by effective use of SS and PSO techniques are discussed. The main motivation behind this study is explained as concluding remarks.

## 2. Permanent magnet linear generators

In this paper, two different types of PMLG consisting of a translator on which magnets are mounted with alternating polarity and a stator containing windings are considered for modeling, simulation and optimization. The first one is a tubular type with a long translator as compared to the stator and the second one is a vertical rectangular type with long stator as compared to the translator. A translator employing Neodymium-Iron-Boron (NdFeB) rare earth permanent magnets is considered for both types of machines. The rare earth permanent magnets are considerably more expensive than ferrite magnets but can produce high magneto-motive force for a relatively small magnet height [10].

The translator for tubular type PMLG consists of seven radial and six axial magnets, mounted alternately on an aluminum shaft to achieve the Quasi Halbach arrangement as shown in Fig. 1(a). The implementation of Quasi Halbach arrangement of permanent magnets makes stronger magnetic field on one side and cancels the magnetic field on the other side to near zero. Besides, the cogging force between the permanent magnets and stator teeth is reduced [4]. The magnets are wrapped around an aluminum shaft which will have a low relative permeability. A rectangular shaped translator made from M3 silicon steel with four magnets mounted on one side of the translator is selected for the rectangular type PMLG as shown in Fig. 1(b) [4]. The stator cores of both types of linear generator are considered with silicon steel laminations [11]. In the tubular type PMLG the stator with a 3-phase concentric winding and round copper conductors in six slots is considered. In the vertical rectangular type PMLG four poles and twenty four slots are selected for the stator and a 3-phase lap winding with flat copper wire to obtain a better coil fill factor is considered [3,4].

The 3-D models of stator and translator for both the types of generators are developed by using CATIA V 5, computer aided three dimensional interactive application software [12]. In order to arrive at the desired final model much faster and easier way, the generator model is divided into individual parts such as axial magnets, radial magnets, translator and the stator. By using basic shapes such as squares and circles, individual parts are manipulated and the configuration of each part is developed. After combining the individual parts the complex model is modified by using CATIA tools and the model produced is scaled down according to the real dimensions of the linear generator. Besides, relevant actions are performed such as positioning of base plane (X-Y plane), basis sketch, the elements distributed on layers, modeling parts in context etc. Fig. 1(a) and (b) show two prominent configurations of PMLG with a permanent magnet translator and a 3-phase stator [13]. The preliminary model of tubular type PMLG is based on the data as reported in Ref. [14] but the real dimensions are scaled down to the proposed PMLG model. Fig. 1(a) shows a Quasi Halbach arrangement of permanent magnets on the translator and a 3-phase concentric winding on the stator. The rectangular type PMLG model developed as in Fig. 1(b) by using four permanent magnets on the translator and a slotted stator with windings is based on the data as reported in Ref. [3].

## 3. Magnetic field analysis

The main aim of magnetic field analysis of the generator models is to study the flux distribution in the stator and translator and then to observe the induced emf from the generator coils. The magnetic field analysis is carried out by employing finite element method (FEM) analysis software ANSYS. A 2-D finite element model is selected for simulation studies as it needs less simulation time as compared to a 3-D model. To apply FEM analysis on the developed models, first it is essential to define the material properties [15] of each generator. The 2-D model is specified or assigned with the respective material for every part. In order to carry out an electromagnetic analysis by ANSYS a high density mesh by using PLANE-13 or PLANE-53 as the element applicable is essential. To perform the field analysis, for Tubular PMLG, element PLANE 13 which provides a 2-D magnetic, thermal, electrical, piezoelectric and structural field capability characteristics is selected. PLANE-13 is defined by four nodes with up to four degrees of freedom per node. Besides, PLANE-13 also has nonlinear magnetic capability for modeling B-H curves or permanent magnet demagnetization curves. For rectangular PMLG the element type PLANE-53 is selected that is an element for 2-D (planar and axis-symmetric) magnetic analysis [16]. This element is defined by eight nodes with up to four degrees of freedom per node and has nonlinear magnetic capability for modeling B-H curves or permanent magnet demagnetization curves.

Also to analyze the models under loading conditions, boundary and magnetic vector potential loads are applied. Incidentally, the boundary conditions do not allow the flux developed by the magnetic circuit to escape from the perimeter of the model. Fig. 2(a) and