Dynamic performance simulation of a four sided linear permanent magnet machine for power generation from sea waves

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The paper presents the design procedure and the modeling of performance for a special four sided linear permanent magnet generator, used in sea wave energy extraction applications. In order to efficiently exploit the wave energy through a floating buoy, it is important to tune its movement with the main frequency of the wave by using appropriate control. This leads to limited duration saturation of the generator and the system analysis requires particularly developed electromagnetic – mechanical – hydraulic models. The saturation effects under this operational condition were studied, while the dynamic variations of the respective operational parameters of the machine were estimated.

1. Introduction

A special linear 16 kW permanent magnet generator was designed [1], [2], [6], for power generation from sea waves. Also, appropriate coupled electromagnetic-mechanical-hydraulic models for the analysis of the linear permanent magnet generator and the hydraulic system have been developed [3].

The case of optimization of the generated power by tuning the loading through appropriate control was considered, in order to adapt the buoy movement to the wave dominant frequency. Under this case of operation and for relatively small time intervals, the linear generator is overloaded and the magnetic circuit is driven to important local saturation.

For the estimation of the inductance variations when the generator is overloaded, a coupled finite element model [2,3,4], has been adopted enabling to determine appropriate look up tables.

2. Construction of electromechanical system

The sea wave motion is transferred to the linear generator, via a cylindrical floating buoy that is fixed on the translator of the machine. The arrangement of the electromechanical system for the sea wave energy extraction with the use of a linear permanent magnet generator is shown in Fig. 1.
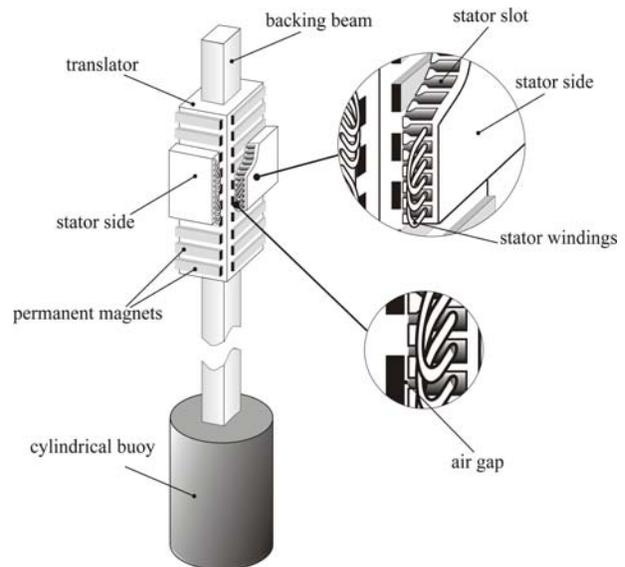

Fig. 1. Construction of the linear permanent magnet machine, for power generation from sea waves.

The total applied force ΣF on the floating buoy [2], [4], [5] is consisted of the hydraulic force F_h, the wave force F_w and the force from the generator F_G, which opposes to the movement of the buoy:

$$M\ddot{z} = F_h + F_w + F_G \quad (1)$$

where M is an equivalent mass which incorporates the total inertial characteristics of the system and z is the displacement of the buoy.

2.a. Hydraulic subsystem

The time variation of a sinusoidal sea wave of height H, period T and wavelength L is given by (1).

$$n(x,t) = \frac{H}{2}\sin(kx - \omega t) \qquad (1)$$

where $k = 2\pi / L \; [rad/m]$, $\omega = 2\pi / T \; [rad/s]$

For a sea depth h<L/20 from the wave surface to the bottom of the sea, the constants L, ω and c, are related as follows:

$$L = T\sqrt{gh}, \quad \omega = k\sqrt{gh}, \quad c = \sqrt{gh} \quad (2)$$

Then the applied force from the sinusoidal wave on a floating buoy F_w is given by (3):

$$F_w = \left[\rho g A_s - \omega^2 (\rho V + a) \frac{\sinh(kz + kh)}{\sinh(kh)} \right] H \sin(\omega t) \quad (3)$$

where A_S [m^2] is the active cross section of the buoy, ρ=1025 kgr/m^3 the sea water density and α is a constant equal to $0,167\rho D^3$ with D the diameter of the cylindrical buoy.
The total hydraulic force on the buoy F_h, for a displacement z, is then derived by (4):

$$F_h = -P + \rho g (l - z) A_s = -\rho g A_s z = -cz \quad (4)$$

where *P* is the weight of the buoy, *l* [m] the length its submersed part and c = ρgA$_s$ [N/m].

2.b. Mechanical subsystem

The total applied force *ΣF* on the floating buoy is consisted of the hydraulic force F_h , the wave force F_w and the generating unit force F_G, which opposes to the movement of the buoy, as expressed by relation (5):

$$M\ddot{z} = F_h + F_w + F_G \quad (5)$$

where M is an equivalent mass which incorporates the total inertial characteristics of the mechanical system.
From the simulations of the considered cylindrical buoy movement, a maximum power is transferred for angular frequency of ω = 2.8 rad/s of a sinusoidal sea wave as shown in Fig. 2.
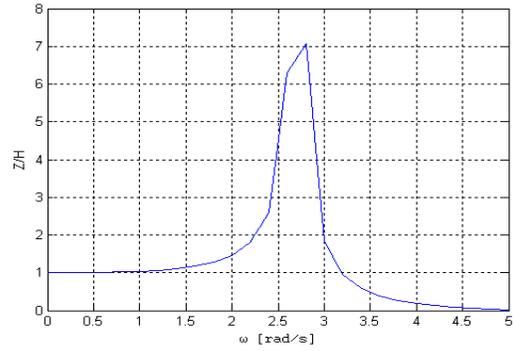

Fig. 2. Tuning characteristics of the cylindrical floating buoy considered.

The generator control is tuned in a way to obtain such a system operation. These characteristics of the sea wave, taking into consideration the adopted mechanism, correspond to a linear velocity of 0,9 m/s for the floating buoy. In Fig.3 the relevant the simulated motion of the floating buoy relatively to a sinusoidal sea wave variation is shown.
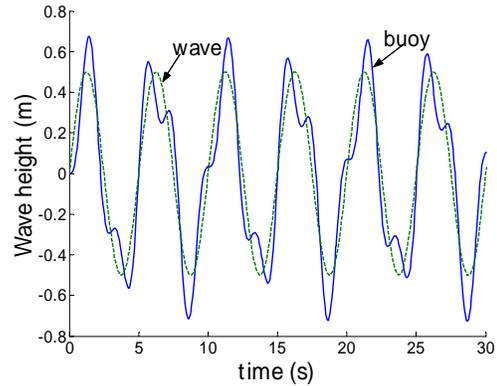

Fig. 3.Simulated motion of floating buoy for a sinusoidal incident sea wave

3. Design and simulation performance of linear permanent magnet generator

The translator of the machine is made of solid steel with rectangular cross-section. Neodymium alloy permanent magnets are used on the four sides of the translator. The stator magnetic circuits are fixed on the non moving parts and involve three phase windings [7].
By assuming the dominant frequency of the waveform of the sea wave, a maximum vertical linear velocity of 0.9m/s for the cylindrical floating buoy has been derived. The study has been carried out for a linear generator of 16 kW. The main parameters of the designed PM linear generator are tabulated in Table 1.

Table 1. Main parameters for the pm linear synchronous generator.

Parameter	Nominal Value
Power	16 kW
Voltage	U_N=326 V
Nominal armature current.	I_{AN}=28.3 A
Produced frequency	10 Hz
Number of poles per side	40
Number of sides	4

Appropriate coupled electromagnetic-mechanical-hydraulic models incorporating Finite Element Analysis (FEA) have been developed, enabling the dynamic simulation of performance of the whole system as well the permanent magnet linear generator in particular.

A variety of designs for the linear generator were studied, in order to the performance simulation to be optimized. The magnetic field distribution in the linear generator under no load condition is shown in Fig. 4.
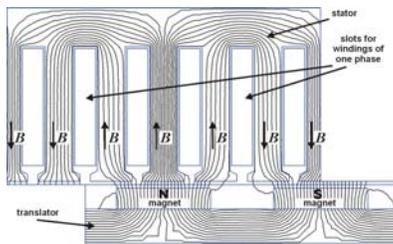

Fig. 4. Magnetic field distribution in the linear PM generator under no load.

The optimized magnet geometry involves a magnet width of approximately 2/3 of the pole pitch. This can be observed in Figs. 5 giving the flux density distribution in the air gap of the linear PM generator under nominal load, the optimum magnet width and a narrower one with the same cross section.
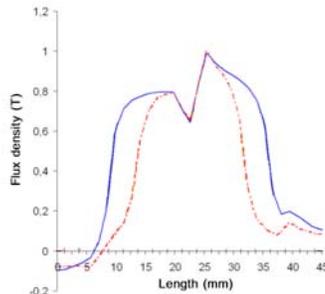

*Fig. 5. Flux density distribution in the air gap of the linear PM generator under nominal loading current.
——: optimum PM geometry and - - -: narrower PM geometry.*

The developed voltage V_a across the terminals of one phase of the generator is given by equation (6):

$$V_a = -r_a i_a + L_{self}\frac{di_a}{dt} + L_{mu}(\frac{di_b}{dt} + \frac{di_c}{dt}) + E_a \quad (6)$$

The inductances L_{self} and L_{mu} , are varying in the case of the overloaded operation of the generator. The induction variations depend on the value of the armature current and the position of the magnet with respect to the stator.

Using finite element method FEM, the values of inductances for various armature currents and different positions of translator, are calculated. In Fig 6 is given the flux linkage variation through one coil of the linear generator in respect to the current of the coil and the displacement of the translator, where the effect of the magnetic saturation is visible.
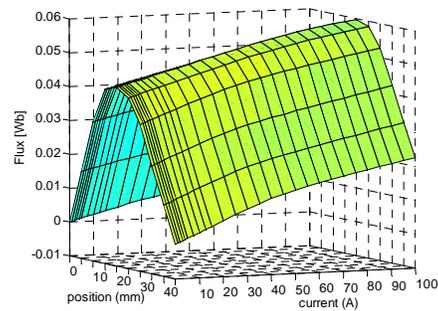

Fig. 6. Magnetic flux linkage variation in one stator coil for various loads and translator displacements

The variation of stator winding inductance with the current and the relative magnet position have been calculated by using the FEM model and are shown in Fig. 7.
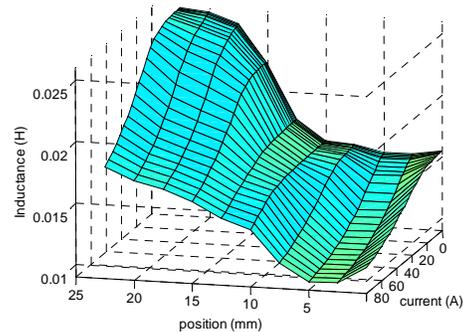

Fig. 7. Stator winding inductance variations as a function of the loading current and magnet position.

For the dynamic simulation of performance of the linear generator, the estimated via the FEM operational parameter variations, are considered by using look-up tables.

The performance of the LPM generator simulated for

the case that a sinusoidal sea wave of 1m height with frequency ω=2,8rad/s is moving the fixed on the translator floating buoy. The characteristics of such a sea wave correspond to a vertical sinusoidal linear velocity of mean value equal to 0,9m/s.

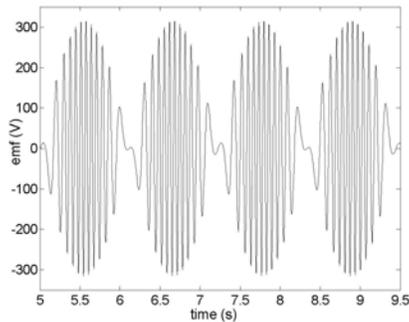A typical simulated emf waveform under no load condition for one phase is shown in Fig.8.

Fig. 8. Produced Emf under no load conditions for sinusoidal movement of the translator.

4. Results and discussion

The linear permanent magnet generator has been tested under various operating conditions by supplying a resistive load. The simulated no load emf of the linear generator, for the measured wave time variation of Fig.9.a, is presented in Fig.9.b.
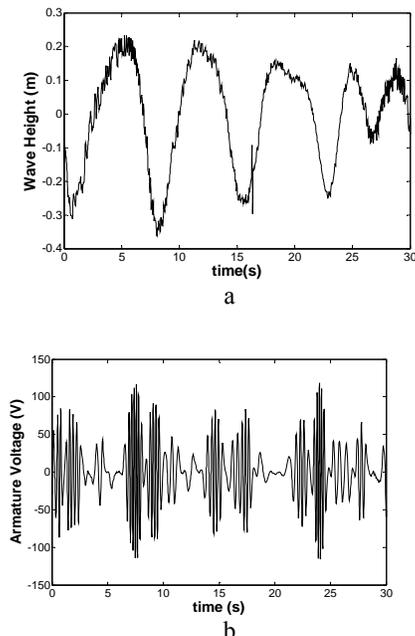

a

b

Fig. 9. a) Measured sea wave time variation with duration of 30 sec and b) respective simulated voltage under loaded condition for one of the phases of the linear generator.

In Fig. 10 is given the simulated and measured generated electric energy of the linear generator, for a real wave time variation of 300ms.
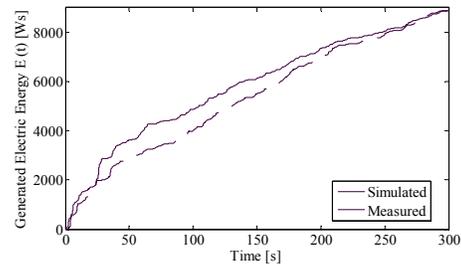

Fig. 10. Generated electric energy for a wave time variation of 300s.

From the reported in Fig.10 model results comparatively with the measured data about the generated energy, is concluded that the proposed coupled simulation model provides acceptable accuracy.

The above results illustrate the developed simulation model suitability for this class of applications.

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