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# Permanent Magnet Linear Generator Design

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***Abstract:*** *The purpose of this design is to improve the efficiency of power extraction from sea waves. Sea waves are huge untapped energy resources. There are many methods to generate electricity from power of sea waves. But, all these conventional methods use mechanics, which have a lesser efficiency than electrical systems. A new design of permanent magnet linear generator is proposed which moves with the waves up and down. The structural design of generator is done using MAXWELL, a finite element analysis method. The generator magnetic field and no-load induced electromotive force are analyzed using the MAXWELL. The output of MAXWELL is analyzed in MATLAB with the help of single phase rectifier and inverter.*
***Keywords:*** *EMF, Linear generator, MATLAB, MAXWELL, Translator, Wave power.*

## I. Introduction

With fossil fuels being at the verge of exhaustion, the world is looking for the renewable energy sources. Also, the pollution problems or the green house effect due to these non renewable energy sources has increased the demand for a clean and sustainable energy. A vast research is going on to extract energy efficiently from various renewable energy sources. Ocean waves are huge untapped energy resources. Countries like India, which has a huge coastal line, can use this ocean wave energy to overcome the energy crisis.

This paper deals with various conversion mechanisms in wave energy and also presents a model linear generator to improve the efficiency of conversion. The linear generator is designed using MAXWELL. MAXWELL is a problem solver, which uses finite element analysis method. Linear generator output is analyzed in MATLAB for grid connectivity.

## II. Wave Energy Conversion Mechanisms

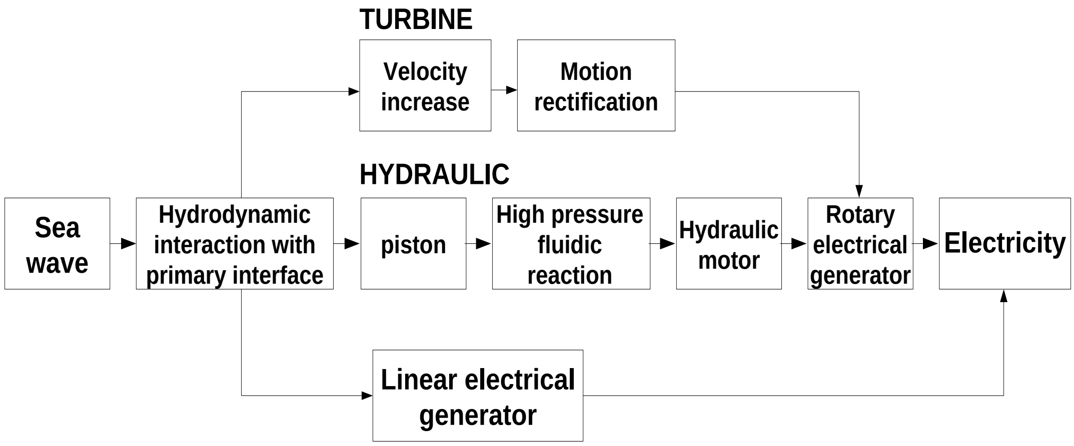


Fig.1: Conversion mechanisms

There are three main conversion mechanisms to convert sea wave potential to electrical energy as:[6]
A. Using turbine
B. Using hydraulics
C. Using linear generator.

**A. Using Turbine:**

Sea waves form an upward and downward motion called crests and troughs. The crests and troughs are used to create a wind movement i.e., the crests and troughs are allowed to a hollow cylindrical structure in which an air column movement occurs. This wind movement is projected on turbine blades with a nozzle making the turbine to rotate. This rotational motion is converted to electricity using rotational generator.

**B. Using Hydraulics***:*

The crests and troughs movement makes the cork floating on the surface to make a similar movement. This cork is connected to a piston, which moves the fluid present in the cylinder with a high pressure. This high pressure fluid rotates a hydraulic motor whose movement is used by the rotational electrical generator to generate electricity.

**C. Using linear generator:**

The sea wave motion of crests and troughs makes the floating cork take a similar motion. This cork motion acts as an input to the linear generator, which generates the electricity.

## III. Linear Generator Design Using Maxwell

In this paper, the linear generator is designed with a stationary part consisting of windings and a translator part consisting of magnets. Windings are used of copper material and NEODYIUM (NdFeB35) magnets are used. The translator part connected to a floating cork makes a linear vertical motion with reference to stationary part.

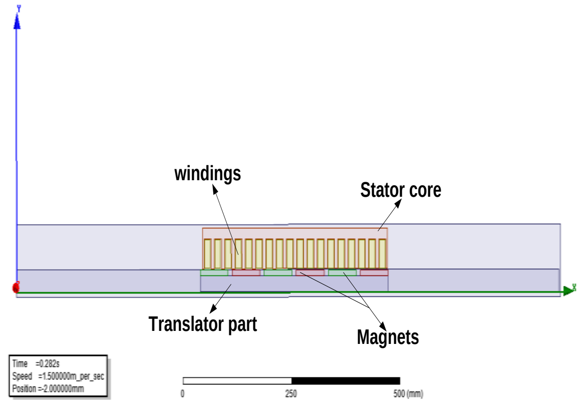


Fig.2: Designed linear generator one sided.

The magnetic flux lines cuts the copper windings in stationary part inducing EMF according to Faraday's laws of electromagnetic induction. Fig 2 shows the designed linear generator one sided.

In one sided linear generator, there is a large normal component of electromagnetic force. In order to offset the normal component, put four flat sided linear generators on side close together to form a unique permanent magnet linear generator. Fig 3 shows the 3D view of a four sided linear generator. In addition, permanent magnet N pole and S pole are arranged alternately and NdFeB magnets are used which give highest performance and cheap in current.

A generating station of linear generators consists of number of such units of four sided linear generators. Fig.4 shows a generating station with such four sided linear generators. The electrical outputs of all generators of the station are governed at power and control house of the station to give a voltage of grid frequency.

The specifications of the designed linear generator are given in table 1.

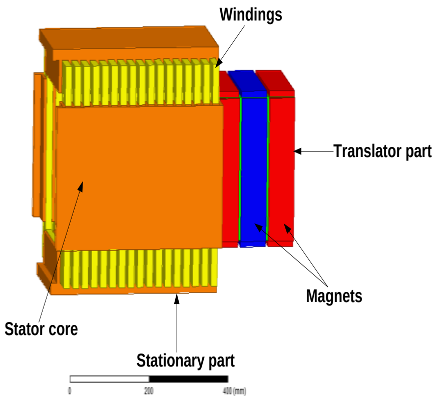


Fig.3: Four sided linear generator.

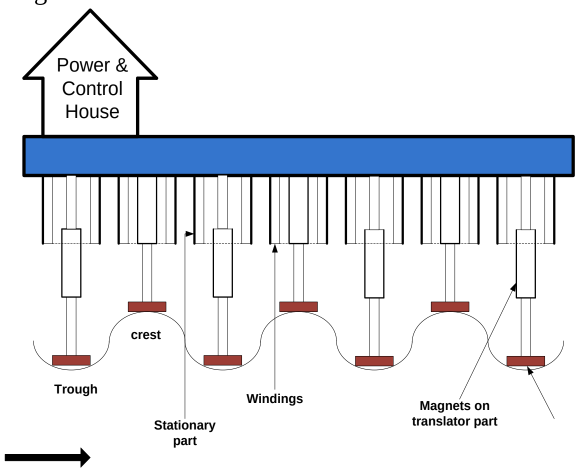


Fig.4: Generating station with four sided linear generators.

Table 1: Specifications of the linear generator

| **PART** | **PARAMETER** | **VALUE (mm)** |
|---|---|---|
| Stator core | Length | 432 |
| | Width | 200 |
| | Yoke | 16 |
| | Slot opening | 16 |
| | Tooth width | 8 |
| | Tooth height | 48 |
| | Pole pitch | 72 |
| Translator Core | Magnet length | 64.8 |
| | Yoke | 24 |
| | Magnet thickness | 9 |
| Air gap | | 2 |

## IV. Emf Solution

The waves up down motion are taken by the translator of the generator as a linear motion. Due to this linear motion, there is a difference in the teeth and slot reluctance, i.e., there is a different magnetic flux through teeth and slots in the magnetic circuit and the generator winding which is coupled to the change in magnetic flux will produce EMF. As the magnets are arranged alternately north and south poles, change in magnetic flux through coil change periodically. Fig 5 shows the magnetic flux lines distribution in stator and translator.

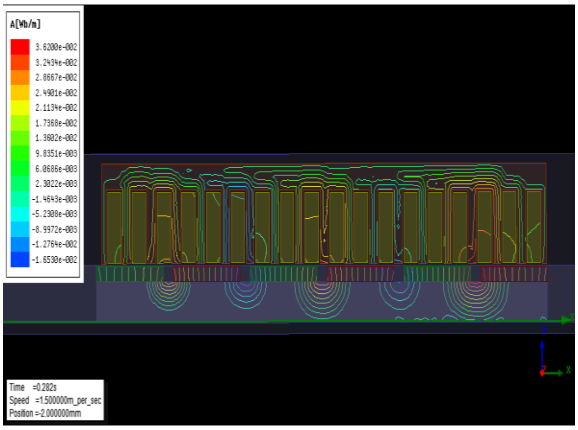

Fig.5: Flux lines distribution in stator and translator

According to Kirchhoff's second law of magnetic circuit (1), magnetic drop is equal to each magnetic circuit and in the process of generator working, reluctance in the circuit of two adjacent positions during the motion.[2]

$$\Sigma F = \Sigma \Phi R_m \qquad (1)$$

According to change in magnetic flux, flux linkages $\Psi_i$ through a coil in this position a stator tooth flux is as $N\Psi_i$, where N is number of turns in winding. Consider, change in displacement of the translator as Δs. When Δs is small enough we can regard that:[2]

$$e(i) = -(\Delta\Psi_i/\Delta s)(\Delta s/\Delta t) = -(\Delta\Psi_i/\Delta t)\ V \qquad (2)$$

$$\text{where, } \Delta\Psi_i = \Psi_{i+1} - \Psi_i$$

## V. Maxwell Analysis

### *Establish motion model:*

Waves are natural motion of sea water caused mainly due to attraction force between sun, moon and earth. Waves are mainly affected by the climate and topographical conditions. They have an irregular periodic movement. For simplicity in simulation consider an ideal sine wave motion of the wave with a speed of 2.2rad/s, which is the average wave speed near the coasts.

## VI. Result Analysis:

With the above description of the linear wave generator with MAXWELL, we make a simulation operation and calculate that the parameters of the electromagnetic generator have reached the requirements. The color codes in the left of the figure represent the flux distribution level making Red to be saturation and Blue to be no interaction of flux.

Depending on the positions of the translator the induced voltage varies. During the starting and ending positions the translator magnets have a less alignment to the stationary windings. When the translator is in the midway there is maximum alignment to the winding giving the peak value. Due to alternate North and South Pole arrangement the waveform is sinusoidal in nature.

The windings are designed to be single phase and the voltage waveform in Fig. 7 illustrates the single phase induced emf in the single phase winding. The single phase winding is designed with 18 coils and 4 conductors in each coil. The windings are designed with 2 parallel paths. The voltage can be improved to KV by varying the above values or the physical dimensions of the linear generator.

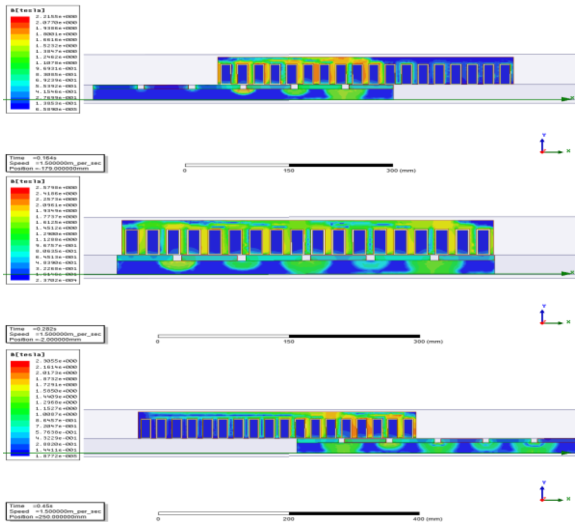

Fig.6: Flux distribution at various positions of the translator.

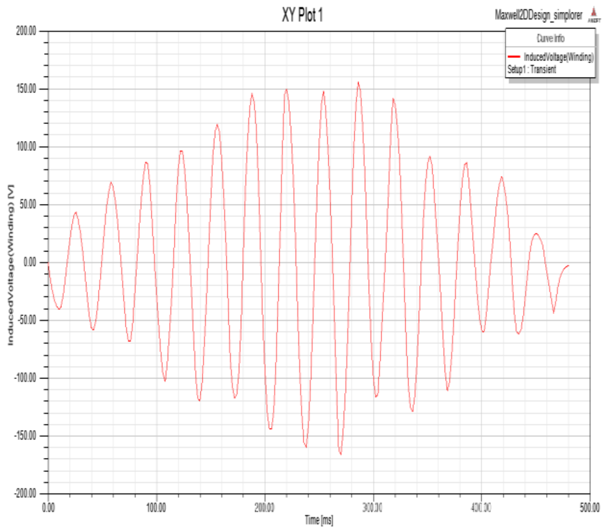


Fig.7: Induced voltage in single phase winding

## VII. Matlab Model Analysis

The output of the linear generator is analyzed using MATLAB. The output from MAXWELL as shown in fig.7 is given to a diode rectifier in MATLAB. The diode rectifier rectifies the intermittent source output to a dc value with the help of a dc link capacitor. This dc output of the rectifier is given to single phase inverter in order to convert it to a single phase 50Hz ac signal. The MATLAB circuit is shown in fig.8. The input to the rectifier bridge is given from the linear generator output and is shown in fig.9.The output voltage is shown in the fig.10.

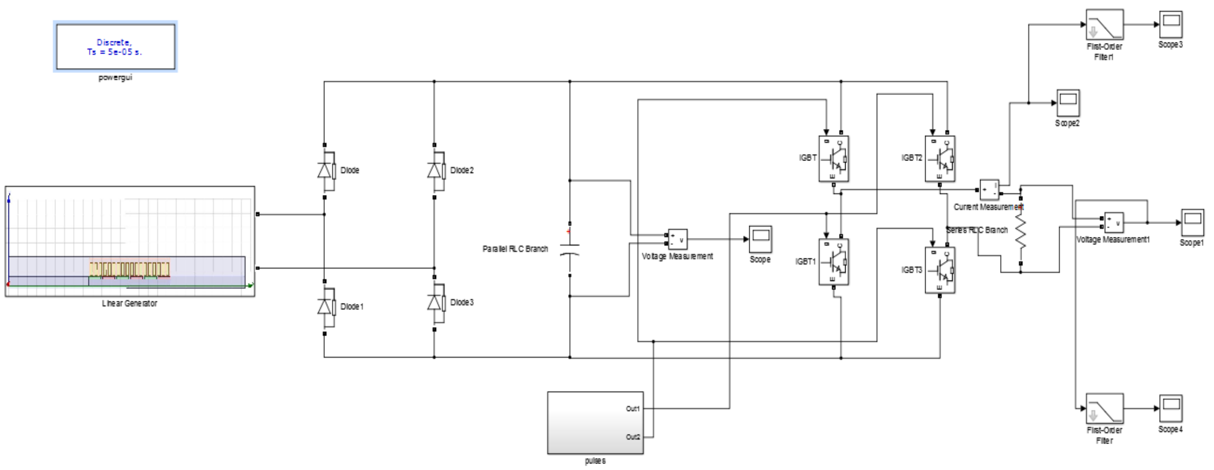


Fig.8 MATLAB model used for analysis

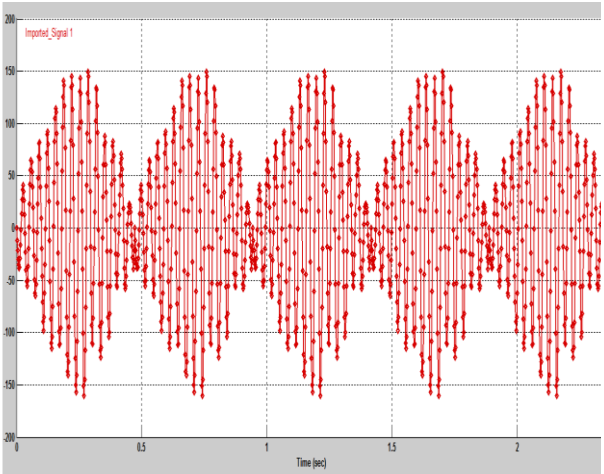

Fig.9 Input to the rectifier in the MATLAB model.

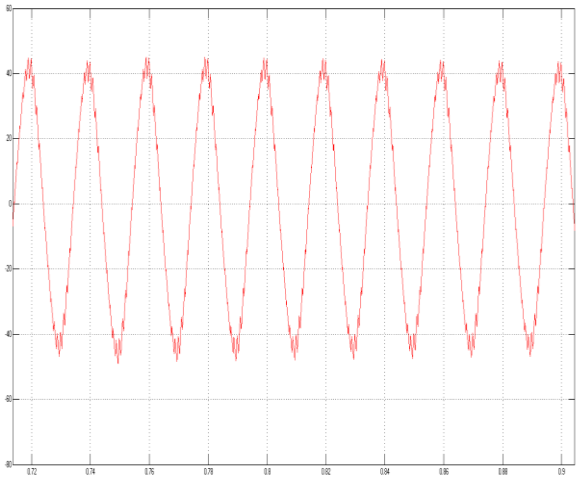

Fig.10 Single phase output voltage of the MATLAB model.

## VIII. Conclusion

This paper gives a brief description of various conversion mechanisms to convert wave power to electricity and also introduces a linear permanent magnet generator design using MAXWELL. With the help of linear generator the efficiency of energy extraction is improved as it involves very less mechanical systems. The EMF induced in winding and flux distributions are analyzed using MAXWELL. The post processing is done in MATLAB to convert the output to a 50Hz.

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