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Analysis of Linear Generator for Marine Energy

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Abstract: Linear Machines offer tremendous advantages over conventional rotating generators. This paper aims to present design and analysis of linear generator for marine energy conversion. Direct-drive linear generator is preferred as compared to conventional rotating generator, as it circumvents the mechanical interface which is the main and critical issue in the existing rotational mechanism. An iron-cored configuration is selected as it provides highest magnetic flux density and better electromagnetic characteristics. The finite element method is used to compute the electromagnetic performance of proposed machine and the main results such as inducedEMF, FLUXlinkage are provided.

Keywords: marine energy, linear generator, finite element analysis, electromagnetic characteristic.

I. INTRODUCTION

Various efforts have been accomplished in the energy sector to improve the electrical energy conversion part. However ocean energy encompasses compelling advantages over other renewable energy sources. The marine energy occupies 2-3 kW/m^2 power density in comparison to wind and solar which occupies 0.4-0.6 kW/m^2 and 0.1-0.2 kW/m^2, respectively [1]. In the aspect of power generation this resource provides maximum 90% of power as compared to wind and solar resources [2]. Marine energy offers tremendous advantages and its estimated theoretical evaluated energy is 2TW per year as shown in Figure 1[1-2].

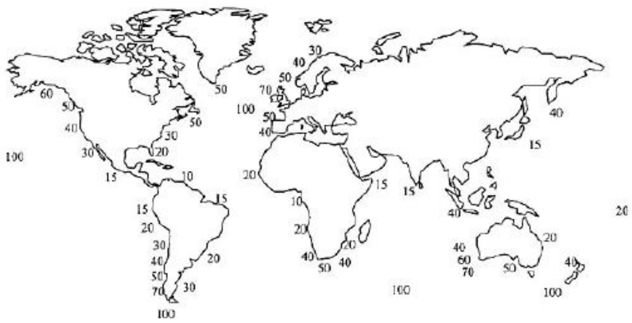

Figure 1. Marine energy overall map

The existing electrical generators are based on rotational mechanism [3] which encompasses mechanical section such as hydraulic pumps, gearbox and so on. On the other hand direct drive terminology eliminates all these shortcomings and eventually provides a simplified mechanism which can fulfils the required demands. The simplified structure of direct drive wave energy conversion system is shown in Figure 2 [4-5]. The existing mechanical energy in marine energy can be converted into electrical supply via several conversion stages as shown in Figure 3[6-7]; the first conversion stage is based on the conversion of available mechanical energy into the marine form into the aerodynamic form which in turn can run the ahead stage such as the conversion devices pelamis, wave dragon, oscillating water column, point absorber, mighty

whale, Archimedes wave swing, buoy and so many other devices can perform this task.

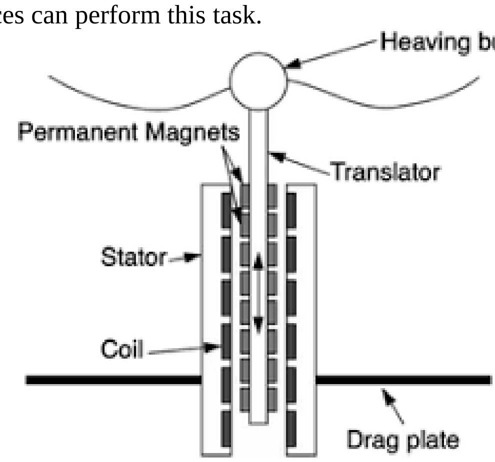

Figure 2. Direct-drive linear machine

The converted aerodynamic energy can be converted into the mechanical energy in order to run electrical machine and this is the task of second conversion stage. This task can be accomplished by turbine and there are so many turbines such as air turbine, well turbine, pitch turbine and so on. After this stage there is the stage of electrical energy which again can be accomplished by several forms. If the rotating machine which uses the rotating mechanism such as a stationary stator embodies a rotational rotor into the stator frame and it has several types such as synchronous generator, induction generator, reluctance generator, iron cored generator, air cored generator, DC generator, brushless generator, linear generator and so on.

Linear variable reluctance machines (VRM) offer high force densities [8], but they have low power factor [4]. Iron cored and air cored machines have gained immense attention due to their compelling advantages [9]. Iron cored machines are preferred as they have strong electromagnetic performance [10-16] however, air cored machines offer low attraction forces which more or less affects its electromagnetic performance [8, 19-22].

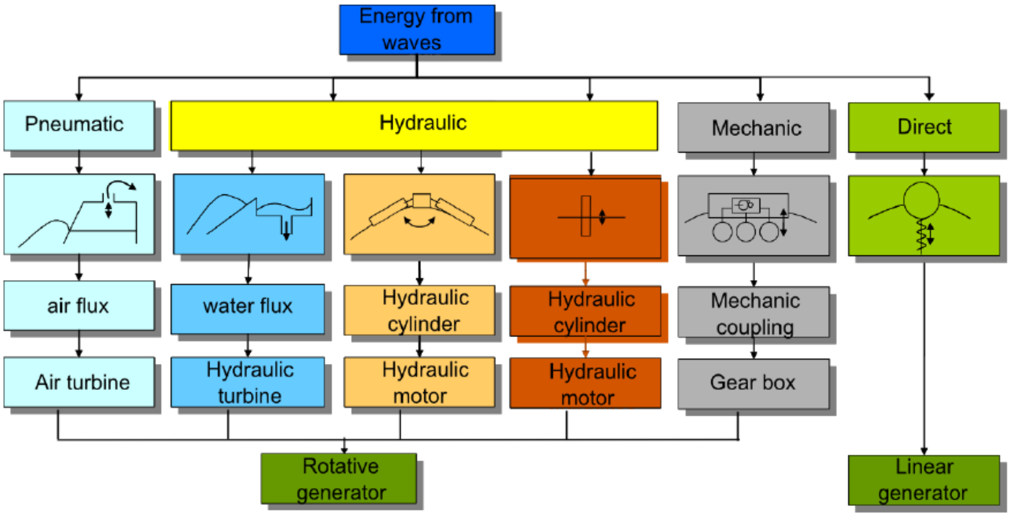

Figure 3. Wave to electrical conversion

Synchronous permanent magnet structure is employed as it eliminates the brush and separate excitation which is being given to the stator to excite it and besides the synchronous mode offers enormous advantage owing to it synchronization ability [23]. Moreover permanent magnets have interesting features as compared to other magnets as they retains their magnetization for ling time and allow the smooth and efficient operation of linear machines [24]. The available large scale developments [19, 8-9], complex structures [20], and massive weight [21] are the main issues in this field. This work aims to provide a linear generator based on synchronies working principle and embodies installed permanent magnets on the translator. Basically linear generator has two main parts, the first is stator which remains stationary and has installed windings in which electromagnetic voltage is generator, however the translator is like rotor in rotational machines and it reciprocates with respect to stator part [25]. The formation of conducting circuit such as magnetic circuit plays an important and vital part in the design assessment of linear machines [26-28]. Four diverse constitutions of conducting circuit are proposed rectangular, octagonal, tetrahedron and hexagonal. To analyse the electromagnetic performance i.e. open circuit flux distribution, flux density, induced-EMF, they are modelled and simulated in Finite Element Analysis (FEA).

II. PROPOSED DESIGN

The proposed configuration includes straight translating part and stator with coils [29, 8-9]. The air-gap is kept according to manufacturing tolerances. In order to analyse the electromagnetic characteristics Finite Element Analysis (FEA) simulations are carried out. The translator consists of series of conducting magnets. The stator uses coils connected to form winding. The schematic diagram is depicted in Fig. 4.

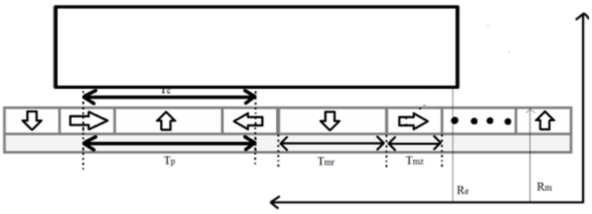

Figure 4. Schematic of linear generator

The permanent magnet configuration is kept in way that is maintained settled with the winding configuration because the coils are resides on the winding to form a complete section and in turn makes stator which is the stationary part as complete unit with the translating part of linear generator

III. RESULT ANALYSIS AND DISCUSSION

Finite Element Analysis (FEA) software is used to determine the performance of the proposed structures. The magnetic setting is employed in the software which uses an individual coordinate system based on the available structure. The main design parameters are given in Table I. Firstly, the open-circuit flux distribution is analysed for all the structures. Figure 5 shows the flux distribution. It can be seen that, there is complete and proper linkage of flux which is defined as that the flux which is available across the influence of magnet is starting from the one magnet and keeping into account of the rule of magnetic circuit the flux is ending at the other magnet.

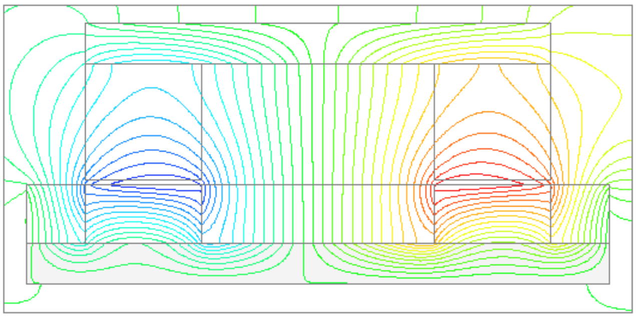

Figure 5. Open-circuit flux distribution

If in case flux is outward which is not in this case but if it happens it leads the design structure towards massive cogging force, high magnetic attraction force, detent force, high maintenance owing to support structure of overcoming these all aforementioned undesired forces.

TABLE I
Design specification of linear generator

Length of axially magnetized magnet	20 mm
Length of radially magnetized magnet	10 mm
Magnet height	55 mm
Outer radius of magnet	20 mm
Outer radius of stator core	42.8 mm
Radial thickness of supporting tube	3.5 mm
Coil axial length	1.20 mm
Stator steel height	3.5 mm
No. of turns per coil	250
Stroke length	2.50 mm
Velocity	1.83 m/s
Air-gap length	0.15 mm

The similar phenomenon is revealed by the magnetic flux analyzed in the air gap across the linear generator Fig. 6 shows the comparative analysis of the magnetic flux in linear generator. The maximum performance is achieved by rectangular conducting section.

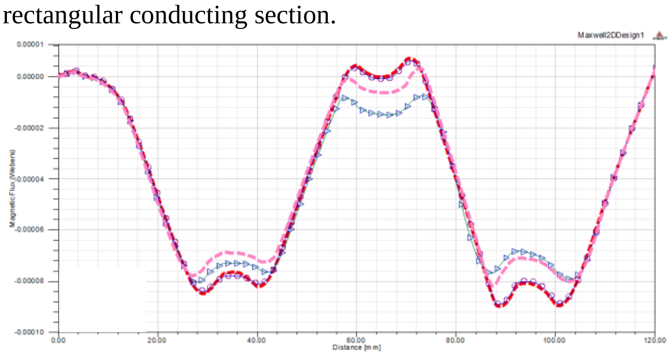

Figure 6. Comparison of magnetic flux in the air-gap for proposed designs

As the translator reciprocates with the stationary stator, the inducedEMF is produced in the coils of winding; this emf is proportional to the speed and FLUXlinkage of the machine and can be represented by as shown in Figure 7 [32];

$$E = \frac{d\lambda}{dz} * v \tag{1}$$

where E is the induced-EMF in the coil

λ is the flux linkage and can be represented as $\lambda = N\phi$

v is the reciprocating velocity of translator

N is the number of turns

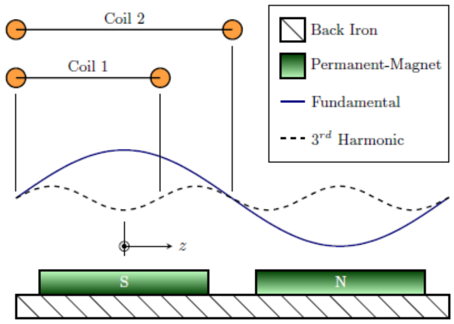

Figure.7 Magnet and coil voltage configuration

The comparative analysis of induced-EMF produced in linear generator is shown in Fig. 8. It can be seen that, the highest amplitude is obtained by rectangular conducting part.

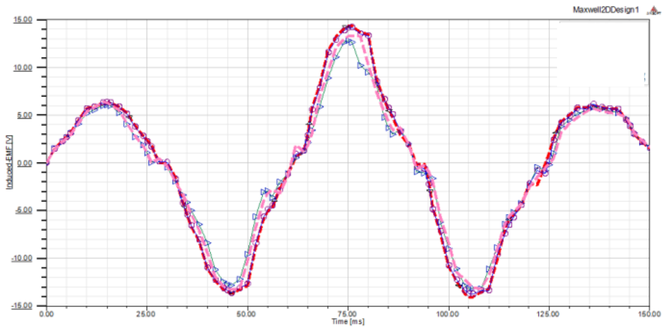

Figure 8. Comparison of Induced-EMF at speed of 1 m/s for for proposed designs

According to the law of Faradays inducedEMF magnitude raises as the flux linkage is time derivative portioned to the generated voltage, so same phenomenon is observed here, it can be seen that rectangular magnet obtains highest characteristics as compared to others.

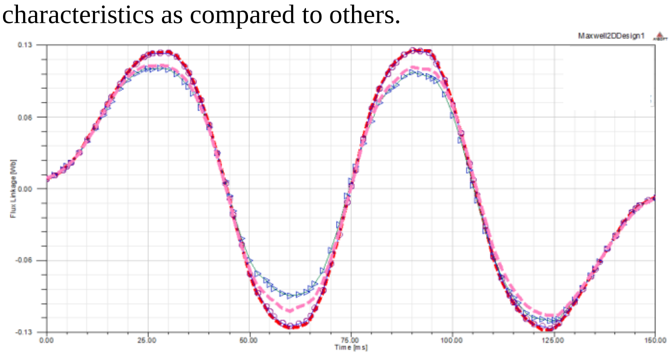

Figure 9. Comparison of flux linkage in the coil for proposed designs

The same relationship can be observed in the air-gap distribution for magnetic flux density across the translator and stator. Fig. 10 shows the magnetic flux density in the air-gap between translator and stator.

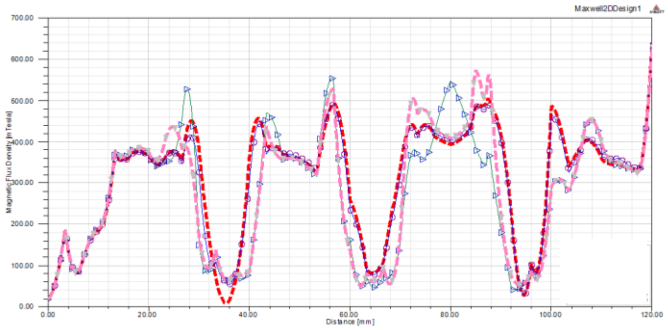

Figure 10. Comparison of magnetic flux density in the air-gap for proposed designs

The same trend is exhibited in Fig. 11 by magnetic field intensity in the air gap distribution between translator and stator.

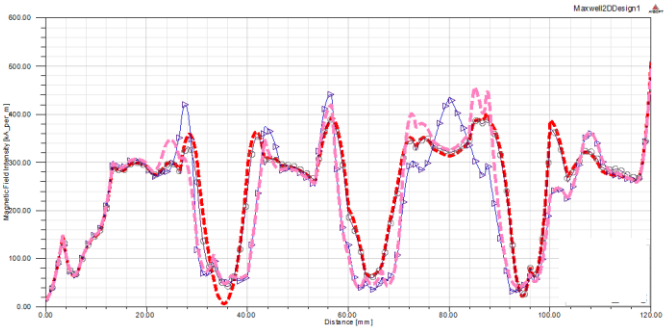

Figure 11. Comparison of magnetic field intensity in the air-gap for proposed designs

IV. CONCLUSION

The issues in conventional rotational generators have proved that the direct drive linear machines are simplified option to harness the marine energy. The eliminated mechanical interface which poses drastic problems in the conversion stage is minimized. A linear generator based on synchronous working principle is proposed. In order to enhance the electromagnetic performance several magnetic structures as conducting units are installed and their finite element analysis has been provided, the obtained results ascertain that rectangular conducting unit offers dominant characteristics as compared to others.

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