Tubular Permanent Magnet Linear Synchronous Generator for Wave-power Generation

Behrooz Rezaeealam, Assistant Professor
Lorestan University, Khorramabad, IRAN
rezaeealam@gmail.com

Abstract:
In this paper tubular type slotless Permanent Magnet Linear Synchronous Generator (PMLSG), which produces neither the detent force nor normal force is proposed for wave power generator. The characteristics of the stator configuration are estimated using the Finite Element (FE) analysis and the relation between the output and loss characteristics with pole pitch is examined. Moreover, the operating performance of the generator is analyzed under the no-load and loads with variable resistance. In the generator performance with variable resistance load, while the load increases, the characteristics of the induced voltage and load current are investigated and the efficiency is also defined from the comparison between electrical output (induced voltage and load current) and mechanical input (external force) in each load.

Keywords: PMLSG, Wave power, Finite element method

1. Introduction
Recently, the environmental problems such as global warming caused by excessive use of fossil fuels have been produced over the world. In order to overcome this problem, renewable energy has received spotlight and the wave power, especially, has infinitude of potentiality. According to one research, 1TW of energy, equivalent of twice the world’s electricity production, could be harvested from the world’s oceans [1]-[7]. However, the conventional method of the wave power generation using air turbine has many disadvantages such as its huge size, high cost and low efficiency. The wave power generation using a linear generator has received attention and has begun to be researched. The linear generator has an advantage which can convert the reciprocating motion of a wave directly into electrical energy without any intermediate mechanism. As such, linear generator system is expected to be made smaller and to have high efficiency [1]-[7].

Meanwhile, a linear generator is structurally equal to a linear motor but there are some points to be considered as generator. First of all, despite the small wave power, an obstacle to motion such as the detent force and normal force should be minimized in order to obtain easy reciprocating motion of the mover. When a linear generator is applied to the general application system, the aspect of structural stability should be considered for the useful wave power generation [1]-[7].

In this paper, hence, the tubular type slotless Permanent Magnet Linear Synchronous Generator (PMLSG), which produces neither the detent force nor normal force, is designed to overcome the these problems. First of all, the characteristics of the stator configuration are estimated using the Finite Element (FE) analysis and the relation between the output and loss characteristics with pole pitch is examined. Moreover, the operating performance of the generator is analyzed under the no-load and loads with variable resistance. In the generator performance with variable resistance load, while the load increases, the characteristics of the induced voltage and load current are investigated and the efficiency is also defined from the comparison between electrical output (induced voltage and load current) and mechanical input (external force) in each load.

1.1. Flat type PMLSG
The flat type PMLSG has been used in a wide range of general application system. However, there are some disadvantages in the structural aspect. The attractive force that makes bad influence to the bearings must be existed between the stator and the mover. In case of the double side type, both sides have a balanced attractive force and it does not have the normal force. But it is hard to keep the ideal air-gap caused by the bearing loads [1].

Furthermore, the normal force is also produced largely and acts as a friction force between the linear guide and mover. A general the friction force curve is shown in Figure 1. \( F_s \) signifies the static friction force and \( F_{sliding} \) refers the sliding friction force. The stopped mover must have a larger force than the maximum value of static friction in order to start...
moving. The maximum value of static friction force is described as below:

$$F_{\text{max}} = \mu_s \cdot N$$

(1)

where, $F_{\text{max}}$ is the maximum value of static friction force, $\mu_s$ is the coefficient of static friction force and $N$ is the normal force. The equation above shows that the $F_{\text{max}}$ is proportional to $N$. This means that the maximum value of the static friction force is increased based on certain increasing amounts of normal force. The efficiency of the machine should decrease due to the increasing mechanical input, if the normal force is larger. Therefore, it is necessary for the normal force to be reduced in order to the high efficiency and desired induced voltage.

![Friction force change curve](image)

**Fig. 1**: Friction force change curve

Figure 1 shows the configuration of the flat type PMLSG with the Halbach magnet array. This permanent magnet array makes bigger flux than others in air-gap. In this model, the normal force is $\mu_s A \cdot N$; it could be large enough to cause a mechanical problem. In this paper, the tubular type linear generator, which structurally does not cause normal force, is proposed.

**.2. Tubular type PMLSG**

Figure 2 indicates the cross section of the typical tubular type PMLSG. The tubular type PMLSG has higher efficiency than the flat type linear generator, because it does not have the end-turn of windings, which is not related to the effective magnetic flux.

In case of the cylindrical structure, the normal force is not produced, from the balanced attractive force and the friction loss can be reduced because the mechanical device such as a linear guide is not required.

In this paper, the three-phase concentrated windings are wound on the stator and the permanent magnet of the mover is magnetized in direction of the z-axis. Moreover, the Halbach array is applied for the concentration of magnetic flux and the high average flux density in air-gap.

The length of core, which located between permanent magnet, and thickness of back-iron are calculated by FE analysis for unsaturated core.

![Cross section of flat type PMLSG](image)

**Fig. 2**: Cross section of flat type PMLSG

**a) Compare configuration of stator**

There are two stators: the slotted-type stator, and the slotless-type stator in terms of stator structure. In the case of the slotted-type, the maximum value of flux density and the availability of the permanent magnet are higher than slotless-type, but the large detent force and vibration of the apparatus are generated by the harmonic component, which is generated from relation of teeth and the permanent magnet. On the other hand, in the case of the slotless-type, the maximum value of flux density and the availability of the permanent magnet are lower, but the detent force is not produced and the induced voltage waveform is sinusoidal in shape because the harmonic component caused by the slotted structure does not exist.

The induced voltage is analyzed by the two-dimension FE analysis using cylindrical coordinates under the assumption of the mover velocity of $1 \text{ m/s}$.

The induced voltage of slot and slotless-type are illustrates based on configuration of the stator. The RMS value of the fundamental harmonic component of the induced voltage was calculated. Compared to two values between the slotted and slotless-type, the induced voltage of slotted-type is approximately $10 \text{ V}$ greater than that of slotless-type. The higher flux density is produced by teeth.

By the way, the induced voltage waveform is distorted by the harmonic components and magnetic saturation in teeth.

The frequency analysis of two induced voltage waveforms is shown in Figure 5. In the case of the slotted-type, the undesired effects of $3$, $5$, and $7$th harmonic components are remarkably presented on the induced voltage waveform.