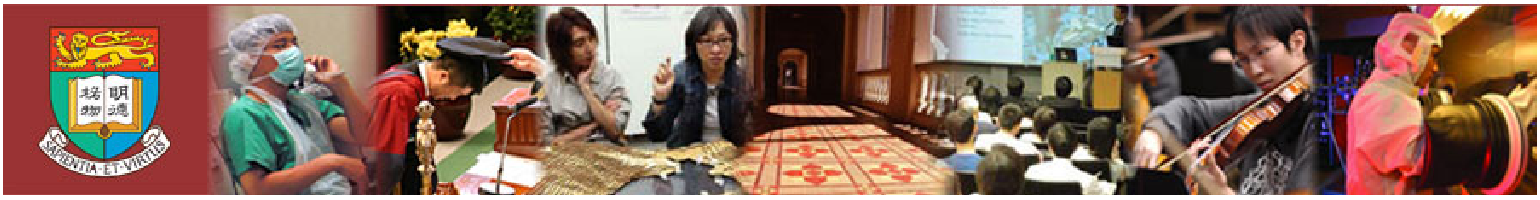

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A Linear Magnetic-geared Permanent Magnet Machine for Wave Energy Generation

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Abstract — This paper presents a new linear magnetic-geared permanent magnet (PM) machine for wave energy generation. In order to match the low speed of wave motion with the high-speed machine design, a linear PM machine is artfully integrated with a linear magnetic gear (MG). Namely, the low-speed mover of the gear is coupled to the buoy directly and reciprocates with the waves, while two sets of PMs, which function as the high-speed mover of the gear and the translator of the machine respectively, are integrated into a tubular iron core. By using the finite element method, the characteristics and performances of the proposed machine are analyzed and verified.

I. INTRODUCTION

With ever increasing demand of clean and renewable energy, the linear permanent magnet (PM) machine is increasingly attractive for direct drive wave energy conversion (WEC) since it can eliminate the bulky and costly rotary-to-linear mechanism. Compared with the conventional rotary WEC, the direct drive system possesses the potential to reduce the number of subsequent energy transformation steps and require fewer moving parts.

Some types of linear machines have been proposed and adopted in the direct drive system, such as the tubular PM synchronous machine and the linear transverse flux PM machine [1]. However, the speed of machine translator, which is equal to that of the reciprocating wave motion, is only of the order of 0.5-2 m/s. According to the machine design principle, the low translator speed results in the low power density [2]. So, the electric machine in the direct drive system needs to have a bulky size with a very large number of poles. It suffers from many disadvantages such as high cost, low efficiency, low power density, difficult to manufacture and costly installation. Sometimes, the mechanical gearbox is adopted to increase the speed of the translator in order to reduce the overall size and weigh of the system. However, the mechanical gearbox has other drawbacks, such as acoustic noise, bulky size, serious wear and tear, and lubrication requirement. Recently, the concept of radial flux magnetic gears (MG) using rare-earth permanent magnets (PMs) has been proposed in [3]-[4]. By adopting the coaxial topology with physical isolation between the input and output movers, the MG can offer some definite advantages such as high transmission capability, minimum acoustic noise, improved reliability, negligibly small friction, maintenance-free operation and inherent overload ability. In [5]-[9], the operation principle, torque speed characteristics and the torque transmission capability of the MG at different gear ratios have been analyzed and discussed. Consequently, the coaxial magnetic gears have been incorporated into in-wheel motors and wind generators for electric vehicles [10] and wind power generation [11], respectively, hence achieving low-speed operation and high-speed machine design simultaneously.

The purpose of this paper is to further extend the concept of magnetic gear to linear PM machine. Namely, a linear magnetic-geared PM (LMGPM) machine is proposed for wave energy generation, which can directly capture slow wave motion while adopting the high-speed machine design to achieve high power density. In Section II, the configuration of the proposed machine will be described, and its design will be discussed. In Section III, the characteristics of the proposed machine will be analyzed by using the finite element method (FEM). Finally, conclusion will be drawn in Section V.

II. MACHINE CONFIGURATION AND DESIGN

A. *Machine Configuration*

Fig. 1 shows the detailed configuration of the proposed machine for wave energy generation, in which a linear tubular PM machine and a linear tubular MG are integrated together artfully. The linear PM machine is composed of a tubular stator and a tubular translator. The stator consists of an iron core with salient poles wound with 3-phase concentrated windings. The translator is designed as a tubular iron core with two sets of PMs mounted on its outer and inner surfaces in such a way that the electric machine and the MG can share the same high-speed mover. The MG consists of a tubular high-speed mover (namely the machine translator), a tubular low-speed mover and a stationary ring. Different numbers of PM pole-pairs are employed on the high-speed and low-speed movers, and the two movers are separated by the stationary ring. The stationary ring is built with a number of ferromagnetic rings which are mounted by epoxy to enforce the structure for high force transmission. Totally, there are three airgaps which are located between the machine stator and the machine translator, between the high-speed mover and the stationary ring and between the stationary ring and the low-speed mover.

The machine stator and the stationary ring are located at the seabed, while the gear low-speed mover is directly coupled with the reciprocating buoy and moves with the waves. When the translator of the machine (the gear high-speed mover) reciprocates along with the gear low-speed mover, an AC voltage is generated in the stator windings.

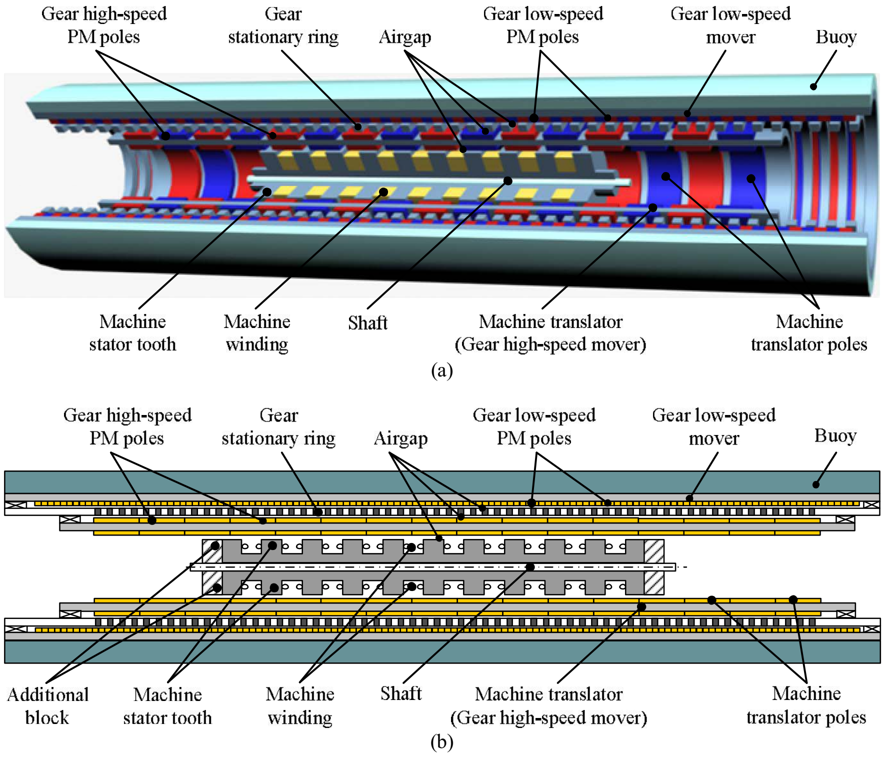


Fig. 1. Proposed linear magnetic-geared PM machine configuration. (a) 3-D model. (b) Schematic.

B. *Machine Design*

The operation fundamental of the MG relies on the stationary ring to modulate the magnetic fields produced by the PMs of the gear high-speed and low-speed movers. According to this principle, the general relationships among the active pole-pair numbers of the high-speed mover p_h and the low-speed mover p_l and the active number of ferromagnetic pole-pieces on the stationary ring n_s can be given by:

$$n_s = p_h + p_l \tag{1}$$

And the corresponding linear speed relationship between the two movers of the MG can be expressed as:

$$v_l = -G_r v_h \tag{2}$$

$$G_r = \frac{p_h}{p_l} \tag{3}$$

where v_l and v_h are the linear speeds of the gear low-speed mover and the gear high-speed mover respectively, and G_r is the gear ratio. The minus sign indicates the opposite movement directions of the two movers.

The output mechanical power of the gear low-speed mover should be equal to the input mechanical power of the gear high-speed mover theoretically. So, it yields:

$$F_l v_l = F_h v_h \tag{4}$$

where F_l and F_h are the thrust forces of the gear low-speed mover and the gear high-speed mover respectively.

Substituting (2) and (3) into (4), the relationship between the thrust forces of the two movers can be obtained as:

$$\frac{F_h}{F_l} = G_r = \frac{p_h}{p_l} \tag{5}$$

According to the wave speed and the desired machine speed, the proper pole-pair numbers of the proposed machine can be determined by using (1)-(5). By borrowing the design procedure for rotating PM machines, the sizing equation and hence the no-load EMF of the proposed linear PM machine can be deduced as:

$$D_s l_s = \frac{P_o}{\frac{\sqrt{2}\pi}{2}\eta k_w A_s B_{\max} v} \tag{6}$$

$$E_m = 2\pi n_{ph} k_w B_{\max} D_s v \tag{7}$$

where D_s is the stator outside diameter, l_s is the stator active length, P_o is the output power, η is the efficiency, k_w is the factor of phase windings, A_s is the stator electric loading, $B_{\max}$ is the magnitude of the airgap flux density, v is the machine translator speed, E_m is the magnitude of no-load EMF per phase and n_{ph} is the number of armature winding turns per phase.

For the wave energy generation, the cogging force of the machine indicates the retardation for initial movement of the translator. It is a very important parameter especially when the thrust force of the ocean wave is small. Generally, the cogging force of the linear PM machine is induced by both the slot-effect and the end-effect. The slot-effect component can be minimized by some techniques which are commonly adopted for the rotating PM machine design such as skewing, selecting the appropriate number of pole-pairs, dummy slots and so on. However, these techniques are ill-suited for the end-effect component. In [12], the cogging force of the slotless linear PM machine can be minimized by optimizing the stator length. In this paper, the pole numbers of the stator and translator of the proposed linear PM machine are selected as 9 and 8 respectively, and two additional blocks are set at the two ends of the stator. Thus, the length of the stator can be optimized by adjusting the length of the additional block l_b.

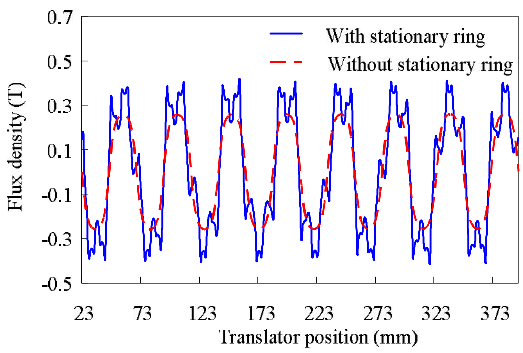
According to the design procedure above, a 3-phase 9/8-pole LMGPM machine is designed. And the MG contains 8 pole-pair high-speed mover and 31 pole-pair low-speed mover. The corresponding key parameters are listed in Table I.

TABLE I. Parameters of proposed machine

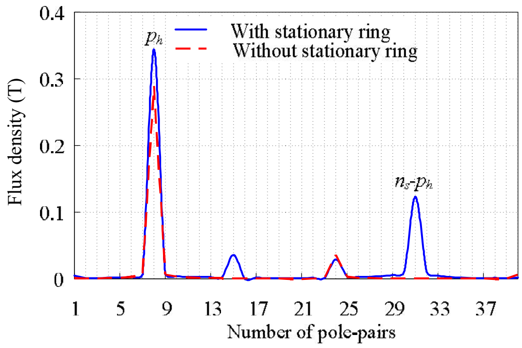
Rated total power (kW)	1
Rated voltage per phase (V)	120
Rated current per phase (A)	9
Rated low speed translator speed (m/s)	0.5
Active machine stator pole number	9
Active machine translator pole number	8
Gear high speed mover pole number	16
Active gear low speed mover pole number	62
Active ferromagnetic ring number	78
Pitch of machine stator (mm)	20.67
Pitch of high-speed mover (mm)	23.25
Pitch of low-speed mover (mm)	6
Stator outside diameter (mm)	100
Armature winding (Turn)	42
Airgap length (mm)	1
Additional block length (mm)	6.7

III. Finite Element Analysis

The characteristics and performances of the proposed machine are analyzed by using the FEM. With and without the stationary ring, the flux density waveforms due to the gear high-speed mover in the airgap adjacent to the low-speed mover are shown in Fig. 2 (a). The corresponding harmonic spectra are plotted in Fig. 2 (b). It can be found that there are a number of asynchronous space harmonics due to the modulation of the stationary ring, in which the component with the pole-pair number equal to $n_s–p_h$ is the highest harmonic. It should be noticed that $n_s–p_h$ is equal to the active pole-pair number of the low-speed mover p_l exactly. With and without the stationary ring, the flux density waveforms due to the gear low-speed mover in the airgap adjacent to the high-speed mover are shown in Fig. 3 (a). And Fig. 3 (b) depicts the corresponding harmonic spectra. It can be seen that the harmonic component with the pole-pair number equal to $n_s–p_l$ is the highest harmonic. It is worth noting that $n_s–p_l$ is equal to the active pole-pair number of the high-speed mover p_h. Therefore, the harmonic spectral analysis verifies the modulation function of the stationary ring.

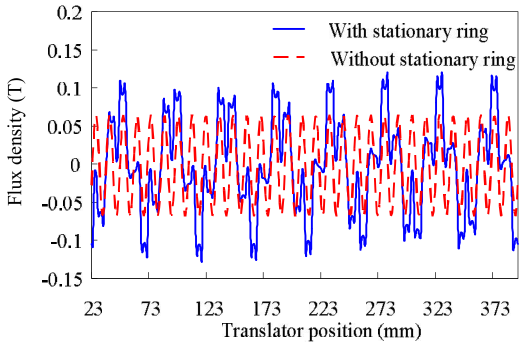


(a)

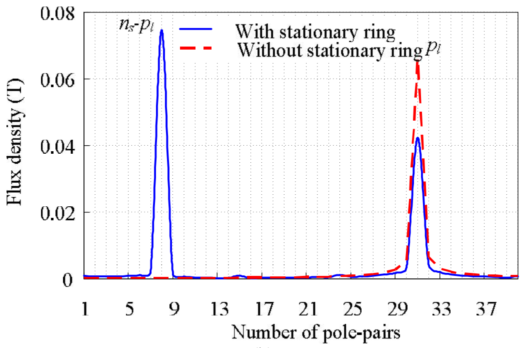


(b)

Fig. 2. Flux density due to high-speed mover in airgap adjacent to low-speed mover of linear MG. (a) Waveforms. (b) Spectra.



(a)



(b)

Fig. 3. Flux density due to low-speed mover in airgap adjacent to high-speed mover of linear MG. (a) Waveforms. (b) Spectra.

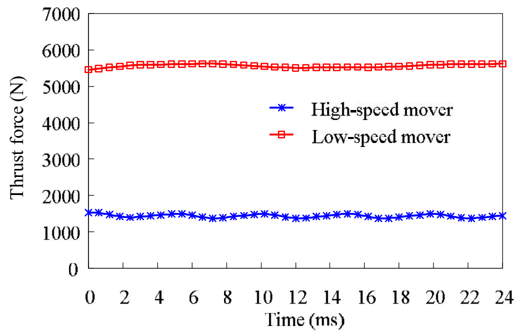


Fig. 4. Thrust force characteristics of linear MG.

Fig. 4 shows the maximum thrust force characteristics of the gear high-speed mover and the gear low-speed mover when they move in the opposite directions. It can be seen that the average thrust forces of the high-speed and low-speed movers are 1441.6 N and 5564.5 N, respectively. The thrust force ratio is about 3.86, which well agrees with the designed gear ratio of 31/8. According to the (4), the speed ratio between the high-speed and the low-speed movers is also about 3.86, namely the speed of the wave will be amplified by the MG by about 3.86 times. Hence, the design aim to improve the power density through the increase of machine speed can be realized by using the MG.

Fig. 5 shows the no-load EMF waveforms of the proposed LMGPM machine, which confirms that the machine can generate 120 V. The corresponding THD is only about 2.52, which is low enough for practical application.

Fig. 6 shows the cogging force waveforms of the proposed LMGPM machine versus different lengths of the additional blocks. The magnitude of cogging force is 258 N without using additional blocks. The magnitude decreases to 198 N and 123 N when the lengths of the additional blocks are 3.1 mm and 5.2 mm, respectively. Finally, when the length of the additional blocks is equal to 6.7 mm, the magnitude is only 39 N which is less than 5% of the rated thrust force of the LMGPM machine.

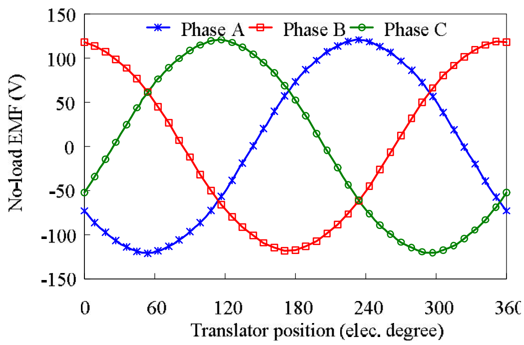


Fig. 5. EMF waveforms.

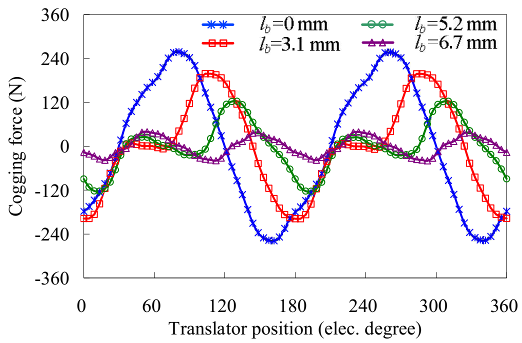


Fig. 6. Comparison of the cogging force waveforms versus different lengths of additional blocks.

IV. Conclusion

In this paper, a novel LMGPM machine has been proposed for wave energy generation. The machine configuration, operation principle, and design criteria have been discussed. By using the FEM, the proposed LMGPM machine has been analyzed. It confirms that the proposed machine can achieve the low-speed requirement for wave energy generation and the high-speed requirement for machine design simultaneously. Thus the machine can offer the advantages of high power density, large no-load EMF, low cogging force and inherent overload protection.

Acknowledgment

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