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A Linear Stator Permanent Magnet Vernier HTS Machine for Wave Energy Conversion

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Abstract—In this paper, a new linear stator permanent magnet (PM) vernier high-temperature superconductor (HTS) machine is proposed for wave energy conversion. The machine adopts a double-sided design and inner-translator arrangement where the stator consists of two plane iron cores with salient teeth wound with 3-phase armature windings and PMs mounted on the surface of the stator teeth. While the translator is designed as an iron core with salient teeth on the two sides, the HTS bulks are inset between every two adjacent salient teeth to shield the flux leakage, thus improving the power density of the machine. Based on using the finite element analysis, the characteristics and performances of the proposed machine are assessed. Also, the proposed machine is quantitatively compared with the existing linear stator PM vernier machine. Hence, it validates that its performance, especially the power density, can be improved significantly.

Index Terms—High-temperature superconductor (HTS), HTS machine, linear machine, stator PM machine, vernier machine, wave energy.

I. INTRODUCTION

In recent years, a variety of new wave energy conversion devices have been presented with increasing concerns on clean and renewable energy. Due to the low and reciprocating nature of wave motion, most of them adopt mechanical gears and linear-to-rotary mechanisms such as Wells turbine and hydraulics to couple with conventional high-speed rotary electrical generators. Compared with the conventional rotary drive system, the direct-drive system possesses the potential to reduce the number of energy transformation steps and requires fewer moving parts since the translator of the linear generator is coupled with the wave energy device directly. Consequently, the efficiency can be improved and the volume of the whole system is expected to be reduced. However, the electrical machine in the direct-drive system usually suffers from a bulky size and a very large number of poles because of the low speed of machine translator, which is equal to that of the reciprocating wave motion. So, some special machines which can offer low-speed operation have been proposed in recent years such as the magnetic-geared machine [1], transverse flux PM machine [2], vernier machine [3], vernier hybrid machine [4] to improve the power density.

A new class of linear stator PM vernier (LSPMV) machines has been presented in [5] as shown in Fig. 1. Based on the magnetic gear effect, this machine utilizes the translator teeth to modulate the stationary magnetic field produced by PMs to the high-speed traveling magnetic field in the airgap. Thus, the magnitude and frequency of the induced electromotive force (EMF) of the machine, which are proportional to the rate of change of the flux linkage, can achieve relatively large values even under a very low operation speed. Hence, the LSPMV machine can realize low-speed operation and high-speed machine design simultaneously, which is very suitable for the direct-drive system. However, because of the finite permeance of the translator teeth, the LSPMV machine inevitably suffers from severe flux leakage which deteriorates the performance significantly.

The purpose of this paper is to propose a new linear stator PM vernier high-temperature superconductor (LSPMV-HTS) machine which can offer high power density while directly and effectively capture the reciprocating wave energy. In Section II, the machine configuration will be described briefly. In Section III, the design principle of the proposed machine will be discussed. In Section IV, its characteristics will be analyzed by using the finite element method (FEM). Also, it will be quantitatively compared with the existing LSPMV machine, hence justifying the use of HTS bulks and verifying the merits.

Fig. 1. Configuration of existing LSPMV machine.
of high power density. At last, the conclusion will be drawn in Section V.

II. MACHINE CONFIGURATION

The configuration of the proposed LSPMV-HTS machine is shown in Fig. 2, which is composed of a stator and a translator. It adopts a double-sided design and inner-translator arrangement where the stator is vertically mounted on the seabed and the translator is vertically coupled with the reciprocating buoy floating on the surface of the sea. The stator consists of two plane iron cores with salient teeth wound with 3-phase armature copper windings and neodymium iron boron (NdFeB) PMs mounted on the surface of the stator teeth. The magnetization directions of these PMs alternate down the stator. Thus the magnetic flux in the airgap is almost sinusoidal. The translator which is sandwiched between the two stator sides is designed as an iron core with salient teeth on the two sides, while the HTS bulks are inset between every two adjacent salient teeth. According to the Meissner effect, the relative permeability of the HTS bulk is almost zero [6] when the operation temperature is below the critical temperature. So, the flux leakage in this area can be shielded and the power density of the machine can be improved consequently.

The refrigeration is realized by circulating liquid nitrogen that is led in through cooling pipes which are appressed along the HTS bulks in the translator iron core. So, the operation temperature can be regulated at around 77 K to insure that the HTS bulks work properly. Considering the reciprocating motion of the translator, the cooling pipes are connected with the refrigeration system through the soft tube which can be stretched and compressed with the reciprocating motion of the translator. The super insulation, which is composed of a vacuum chamber and a thermal shield, functions to minimize the penetration of convection heat and radiation heat. This insulation is considered to be good enough to avoid from possible condensation and ice formation in the airgap.

III. DESIGN PRINCIPLE

Fig. 3 shows the model of the LSPMV machine. In order to simplify the derivation of the analytical model, the following assumptions are made:

- The permeability of the iron core of the stator and the translator is infinite.
- The relative permeability of the HTS bulks is zero.
- Finite coercivities are ignored.
- The variation of magnetic field is in the $y$ direction only.

Based on the aforementioned assumptions, the equivalent magnetic circuit of the machine can be depicted as Fig. 3. So, the magnetic flux density excited by the PMs in the airgap can be expressed as:

$$B_{ag} = F_{PM}(x) \cdot A(x)$$  \hspace{1cm} (1)

where $B_{ag}$ is the magnetic flux density in the airgap, $F_{PM}$ is the MMF provided by the PMs and $A$ is the magnetic permeance per unit area in the $y$ direction.

The PMs are mounted on the surface of the stator teeth. Thus the MMF distribution of the PMs is stationary and can be expressed in a Fourier series. Taking the $y$ axis as the centerline of one of the PMs, it yields:

$$F_{PM} = \sum_{n \text{ odd}} \frac{4H_r h_{PM}}{n \mu_0 \mu_r \pi} \cos \left( np_{PM} \frac{2\pi}{L} x \right)$$  \hspace{1cm} (2)

where $\mu_0$ is the permeability of the free space, $B_r$ and $\mu_r$ are the remanence and the relative permeability of the PMs, respectively, $h_{PM}$ is the length of the PMs in the magnetization direction, $p_{PM}$ is the number of the PM pole-pairs and $L$ is the active length of the machine.

The translator teeth function to modulate the permeance in the airgap in this machine. The relative movement between the permeance and MMF distributions due to the movement of the translator leads to the desired flux variation. Thus the induced EMF can be generated in the stator windings. The magnetic permeance per unit area can be expressed as:

$$A(z) = \frac{1}{R_{PM} + R_{ag} + R_{tr}(x)}$$  \hspace{1cm} (3)

where $R_{PM} = h_{PM} / (\mu_0 \mu_r)$ and $R_{ag} = h_{ag} / \mu_0$ are the magnetic reluctances per unit area of the PMs and the airgap in the $y$ direction, respectively, $R_{tr}(x)$ is the magnetic reluctance per unit area of the translator teeth and slots in the $y$ direction which is a function of the position $x$ and $h_{ag}$ is the length of the airgap.

Based on the same assumptions, the waveform of the magnetic permeance of the LSPMV machine in the $y$ direction can
be depicted as Fig. 4. Hence, it can be expanded into a Fourier series:

\[ A(z) = A_0 + \sum_{m=1}^{\infty} A_m \cos \left[ \frac{mN_t}{L} (x-x_0) \right] \]  \hspace{1cm} (4)

\[ A_0 = \frac{N_t}{L} (A_1 \tau_t + A_s \tau_s) \]  \hspace{1cm} (5)

\[ A_m = \frac{2}{m\pi} \left[ (A_t - A_s) \sin \left( \frac{mN_t \tau_t \pi}{L} \right) \right] \]  \hspace{1cm} (6)

where \( A_0 \) is the DC component of the magnetic permeance per unit area, \( N_t \) is the active number of translator teeth, \( A_t = \mu_0/H \) and \( A_s = \mu_0/\left(\mu_h + H\right) \) are the magnetic permeance per unit area at the area of the translator tooth and slot, respectively, \( \tau_t \) and \( \tau_s \) are the length of the translator tooth and slot in the \( x \) direction, respectively, \( H \) equals \( \mu_0 h_0 + \mu_0 h_{PM} \), and \( h_t \) is the height of the translator tooth. Considering the DC component and the 1st-order harmonics only, the magnetic flux density can be obtained from (2) and (4)–(6) as:

\[ B_{ag} = F_{PM}(x) \cdot A(x) \]

\[ = \frac{4B_r h_{PM}}{\mu_0 \mu_r \pi} A_0 \cos \left( \frac{2\pi}{L} x \right) \]

\[ + \frac{2B_r h_{PM}}{\mu_0 \mu_r \pi} A_1 \cos \left[ \left( \frac{ppM}{L} + N_t \right) \frac{2\pi}{L} x - N_t \frac{2\pi}{L} x_0 \right] \]

\[ + \frac{2B_r h_{PM}}{\mu_0 \mu_r \pi} A_3 \cos \left[ \left( \frac{ppM}{L} - N_t \right) \frac{2\pi}{L} x + N_t \frac{2\pi}{L} x_0 \right] \]  \hspace{1cm} (7)

The 1st term of (7) describes the magnetic field component which is produced by PMs directly and stationary. The 2nd term describes the component with a very short wavelength of which the linear speed is very low. The first two terms are both not suitable for utilization. The 3rd term describes the component with a long wavelength. According to the principle of magnetic gears, the corresponding linear speed is amplified, so-called the working magnetic field component. Thus the armature winding should be wound according to its number of pole-pairs in order to obtain the maximum induced EMF.

On the other hand, the magnetic flux density \( B_{ag} \) is proportional to \( A_1 \), namely the fundamental harmonic of the permeance per unit area of the equivalent circuit. From (6), it can be seen that there are two ways to maximize the value of \( A_1 \):

(i) Increasing the difference between \( A_t \) and \( A_s \):

It can be realized through adopting the material with larger permeance to enlarge \( A_t \) or increasing the height of translator teeth or adopting the material with smaller permeance than air inset in the slots of the translator to reduce \( A_s \). In the proposed LSPMV-HTS machine, the HTS bulks are placed in the translator slots to ejection the magnetic field which results in \( A_s \) equal to zero, hence maximizing the difference between \( A_t \) and \( A_s \). It should be noted that in this analytical model, the HTS bulks are considered as ideal superconductors in which the magnetic field is totally ejected. So the relative permeability of these HTS bulks is considered to be zero.

(ii) Optimizing \( \tau_t \) and \( \tau_s \):

The optimization can be achieved when \( \tau_t \) equals \( \tau_s \).

Fig. 5 shows the peak no-load EMF versus the height of translator teeth \( h_t \) of both the LSPMV and LSPMV-HTS machines. It can be seen that the no-load EMF increases with \( h_t \) for the LSPMV machine, whereas there is insignificant variation for the LSPMV-HTS machine. Thus, the height of translator teeth of the proposed machine can be designed with short in height for easy and convenient manufacturing. In this design, it is selected as 3 mm. Then, the peak no-load EMF and thrust force waveforms of the two machines versus the translator tooth ratio \( c_t \) (which is defined as the ratio of \( \tau_t \) to the translator tooth pitch) are compared in Figs. 6 and 7, respectively. It can be found that the no-load EMF and thrust force can achieve the maximum value when \( c_t \) equals 0.35 for both machines. It should be noted that this ratio differs from the theoretical value of 0.5 deduced from the analytical model, which is actually due to the nonlinearity and flux leakage of the magnetic circuit.

A 2-phase 6/2-pole LSPMV-HTS machine is designed. The corresponding key parameters are listed in Table I. Also, under the same airgap area, the same amount of PMs and the same
electrical loading, the key parameters of the LSPMV machine are also listed in Table I for comparison.

### IV. ANALYSIS AND COMPARISON

The static characteristics of the proposed machine are analyzed by using the FEM. In the finite element model, the permeability of the iron cores and PMs are based on the practical data of the material, while the permeability of the HTS bulks is set to zero.

Fig. 8 shows the no-load EMF waveforms of the LSPMV-HTS and the LSPMV machines at the rated speed of 1 m/s, indicating that the no-load EMF can achieve the values of 52 V and 43 V, respectively. It confirms that the no-load EMF of the proposed LSPMV-HTS machine, which is smaller in size, is 21% higher than that of the LSPMV one. This benefit is actually due to the leakage flux shielding of the HTS bulks. The corresponding total harmonic distortion is about 2.9% which is very acceptable.

The cogging force waveforms of the two machines are plotted in Fig. 9. As we can see, the peak to peak values of the cogging force of the LSPMV-HTS and LSPMV machines are 22 N and 32 N, respectively. The cogging force of the proposed machine is less than that of the existing one because of its larger airgap between the stator and the translator in which the additional super insulation is placed.

The value of the electromagnetic thrust force, which denotes the power density of the generator when the operation speed is governed by external impetus such as the buoyancy of the waves, should be as large as possible especially when the translator speed is very low. The thrust forces of the LSPMV-HTS and LSPMV machines are 2.0 kN and 1.6 kN, respectively, as shown in Fig. 10. Namely, the thrust force density of the proposed machine can achieve more than 54 kN/m² which is over 5 times that of the conventional PM machine. The corresponding force ripple is less than 1.3% only which is negligible.

### V. CONCLUSION

In this paper, a new LSPMV-HTS machine, adopting the HTS bulks for magnetic shielding, has been proposed for wave energy conversion. The machine configuration and design principle have been discussed. By using the FEM, the proposed LSPMV-HTS machine has been analyzed and quantitatively compared with the existing LSPMV machine. It confirms that the proposed machine can offer the advantages of higher power density, higher no-load EMF and lower cogging force than its counterpart. Also, it justifies that this machine is very suitable...
for low-speed and high-thrust force application, especially the wave energy generator.

It should be noted that the real use of this machine requires balancing the gain in increased EMF to the cost of HTS material and cryogenic environment. So a complete cost analysis is required before practical applications.

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