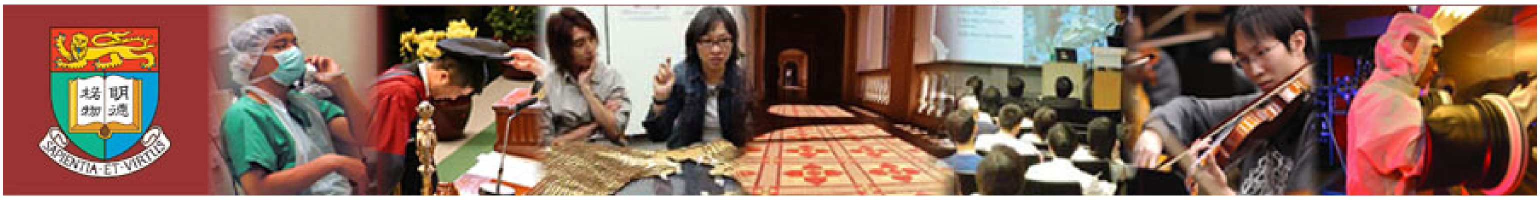

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A Linear Doubly-Salient HTS Machine for Wave Energy Conversion

Yi Du, K. T. Chau, Ming Cheng, Yubin Wang, and Jiangui Li

***Abstract*—This paper proposes a linear doubly-salient high-temperature superconductor (HTS) machine for wave energy conversion, which is composed of a tubular stator and a tubular translator. Since the translator is a simple iron core with salient poles, it is so robust that it can be directly coupled with the reciprocating buoy. The stator consists of an iron core with salient poles, DC HTS field windings and 3-phase HTS concentrated armature windings. By using the finite element analysis, the proposed machine is quantitatively compared with its permanent magnet and copper-winding counterparts. Hence, it validates that its performance, especially the power density, can be improved greatly.**

***Index Terms*—Doubly salient, high-temperature superconductor (HTS), HTS machine, linear machine, wave energy.**

I. Introduction

WITH ever increasing demand of clean and renewable energy, there is a fast growing interest in wave energy conversion. Due to the reciprocating nature of wave motion, the linear machine is preferred to the rotational machine to capture the wave energy as it can eliminate the bulky and inefficient linear-to-rotary conversion mechanism. Generally, the translator of the linear machine is directly coupled with the buoy and both reciprocate at the same speed. Because of the absence of linear-to-rotary mechanism, the power density and reliability of the whole system can be improved.

In recent years, the linear machines are becoming popular in direct-drive systems. Some types of linear generators have been proposed, such as the tubular permanent magnet (PM) synchronous machine [1] and the linear transverse flux PM machine [2]. However, since the PMs are located in the translator, these machines suffer from the possibility of irreversible demagnetization by armature reaction field, and the mechanical integrity problem. Recently, a new class of PM brushless machines, namely the doubly salient PM (DSPM) machine, has been developed [3], in which the corresponding PMs are located in the stator, while the rotor is a simple iron core with salient poles. Thus, it offers the merits of high power density, and good mechanical robustness. However, it still suffers from the drawbacks of high PM cost and uncontrollable airgap flux due to the PM excitation. Consequently, a stator doubly fed doubly salient (SDFDS) machine has been proposed in which the field windings are employed to replace the PMs, thus offering the flexibility of airgap flux control [4]. Nevertheless, the use of copper coils for field excitation can not provide the flux density as high as that by PM excitation under the same machine volume, which is due to the low current density of copper material, resulting in the degraded power density of the SDFDS machine.

Fortunately, the exceptionally high current density in the superconductor makes it possible to improve the power density of machines significantly. Especially, the discovery of high-temperature superconductor (HTS) materials, namely the yttrium barium copper (YBCO) and bismuth strontium calcium copper (BSCCO), results in the great advancement of superconductor coils which can be practically applied to machines based on the relatively less stringent refrigeration system [5]. Since the first 125-hp HTS motor was tested in 1996, various HTS machines have been proposed. Compared with conventional machines, the HTS machine has the distinct advantages of higher power density, higher torque density, higher efficiency and low life cycle cost [6].

The purpose of this paper is to propose a novel linear doubly-salient (LDS) machine with HTS windings (termed the LDS-HTS machine) for wave energy conversion. In Section II, the wave energy resource will be briefed. In Section III, the configuration and design of the proposed LDS-HTS machine will be discussed. In Section IV, its characteristics will be analysed by using the finite element method. Also, it will be quantitatively compared with the linear DSPM (LDS-PM) machine and its copper-winding counterpart (LDS-Cu).

II. Wave Energy Resource

Oceans cover almost 70% of the earth's surface and there is tremendous amount of energy which is stored in a variety of forms, such as ocean waves, ocean currents, ocean tides, oceanic temperature differences and so on. Thereinto, the global potential power represented by ocean waves has been estimated to be 1–10 TW [7], which is comparable with the world's present power consumption. Additionally, the average power flow intensity of wave energy is typically 2–3 $\mathrm{kW/m^2}$, which is about 15–20 times that of the wind energy or solar energy. So, it is a

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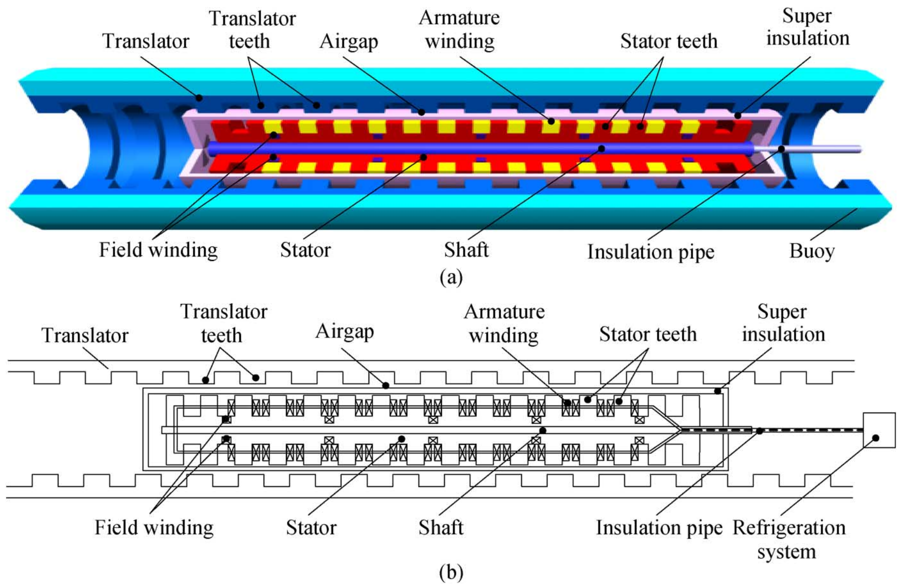

Fig. 1. Proposed LDS-HTS machine configuration. (a) 3-D model. (b) Schematic.

great impetus for researchers to develop effective and efficient wave energy converters.

In China, there is a total area of ocean of more than $4.7 \times$ 106 km^2, and a coastline of more than 1.8×10^4 km. The average ocean wave height is above 1 m and the period is about 5–9 s. The wave energy, which is the sum of the kinetic energy and potential energy of the wave, can be calculated by

$$P = K\,T\,H^2 \tag{1}$$

where P is the wave power per unit wave crest length in kW/m, T is the wave period in s, H is the wave height in m, and K is the wave energy absorption coefficient which is generally 1.0 $\mathrm{kW/m^3/s}$. So, in China, the corresponding wave power per unit wave crest length is about 2–7 kW/m, and the potential wave power along the coast is more than 12.8 GW.

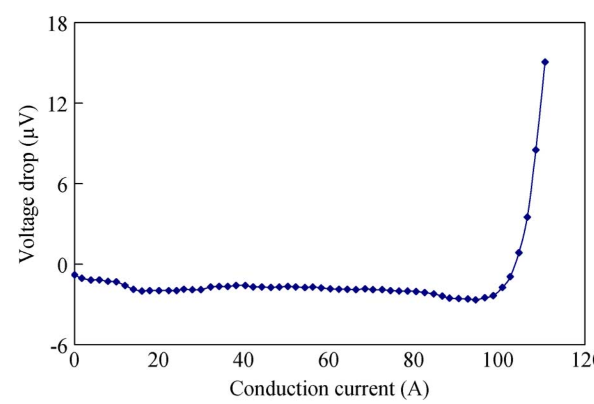

Fig. 2. Critical current of HTS tape.

III. Machine Configuration and Design

Fig. 1 shows the proposed LDS-HTS machine configuration, which is composed of a tubular stator and a tubular translator. It adopts an outer-translator arrangement, where the stator is vertically mounted on the seabed and the translator is vertically coupled with the reciprocating buoy. Since the translator is a simple iron core with salient poles, it is very robust. The stator, which is connected to the onshore grid via a submarine cable, consists of an iron core with salient poles wound with 3-phase HTS concentrated armature windings and DC HTS field windings. Since the DC field current is independently controlled, the airgap flux can be regulated in such a way that the no-load EMF is kept constant under varying wave speed.

The operation temperature of the HTS windings, which are constructed by using the 2nd generation YBCO tape, is around 77 K. Because all HTS windings are located in the stator, hence stationary, the refrigeration process can be easily realized by feeding liquid nitrogen via the insulation pipe. 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.

The HTS field windings are wound as a circular ring. The corresponding critical current is about 100 A, which is approximately equal to that of the virgin tape [8] because the curvature of these windings is small.

Fig. 2 depicts the critical current curve of the HTS tape, which indicates that the resistance increases drastically when the conduction current is above 105 A. So, the rated field winding current is set to 70 A to take into account the safety margin. On the other hand, the HTS armature windings are wound as a racetrack ring. As a result of the bending radius of the HTS tape, the operating current is lowered by the strain sensitive nature of the conductor and the AC loss is also increased [8]. So, the critical current of these armature windings is about 55 A. Moreover, since the machine adopts the iron core in both the stator and translator, the magnetic saturation has to be taken into account when the rated currents of both the field windings and armature windings are designed.

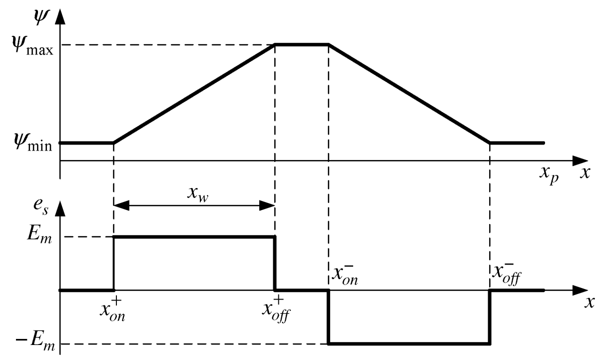

Fig. 3. Theoretical waveforms of flux linkage and no-load EMF.

The theoretical waveforms of airgap flux linkage Ψ and stator no-load EMF e_s with respect to the translator position x of the proposed machine are shown in Fig. 3, where $x_{on}^{+}, x_{off}^{+}, x_{on}^{-}, x_{off}^{-}$ are the four switching positions, x_w is the displacement of a stroke and x_p is the translator pole pitch. When the translator pole is approaching the stator pole, the flux linkage is increasing and a positive voltage will be induced in the armature windings. On the contrary, when the translator pole is leaving the stator pole from the aligned position, the flux linkage is decreasing, and a negative voltage will be induced. Hence, an AC voltage will be generated.

By following the derivation procedure of the rotational DSPM machine [3], the sizing equation of the proposed LDS-HTS machine can be deduced as

$$D_s l_s = \frac{P_o}{\frac{p_t}{p_s} 0.87\pi k_d k_i c_s A_s B_\delta v \eta} \tag{2}$$

where D_s is the stator outside diameter, l_s is the stator active length, P_o is the output power, p_t and p_s are the translator and stator active pole numbers, respectively, k_d is the flux leakage factor, $k_i = I_m/I_{rms}$ is the ratio of magnitude to rms value of the armature current, c_s is the stator pole arc factor, A_s is the stator electric loading, B_δ is the airgap flux density, v is the translator speed, and η is the efficiency. It should be noted that the factor 0.87π is due to the normalized variation of flux linkage for the DSPM machine [3]. Also, the induced no-load EMF can be deduced as

$$E_m = \frac{0.87\pi n_{ph} k_d c_s D_s l_s B_\delta v}{p_s d_s} \tag{3}$$

where E_m is the magnitude of no-load EMF, n_{ph} is the number of armature winding turns per phase, and d_s is the displacement of a stroke. According to the operation principle of the LDS-HTS machine, the general relationships among the active pole number of the stator p_s, the active pole number of the translator p_t and the number of phases m are given by

$$\begin{cases} p_s = 2mk \\ p_t = p_s \pm 2k \end{cases} \tag{4}$$

where k is a positive integer.

IV. Machine Analysis and Comparison

According to the aforementioned design procedure, a 3-phase 12/8-pole LDS-HTS machine is designed. For instance, the diameters of the stator and translator are initially determined by the sizing equation and then fine tuned by using finite element analysis. The corresponding key parameters are listed in Table I. In order to illustrate the merit of the HTS windings, the proposed machine is quantitatively compared with a conventional LDS-PM machine and its copper-winding counterpart (the LDS-Cu machine), all with the same configuration and under the same peripheral size as listed in Table I. Purposely, the slot height of the field windings of the LDS-Cu machine is longer than that of the LDS-HTS machine because the current density of copper windings is much lower than that of the HTS windings. Also the height of PMs of the LDS-PM machine is set equal to the height of the stator yoke. Even under these optimistic conditions for the LDS-PM and LDS-Cu machines, the proposed LDS-HTS machine can still offer a much larger output power and hence higher power density than that of the LDS-PM and LDS-Cu machines.

TABLE I
Quantitative Comparison of LDS Machines

Parameters	LDS-HTS	LDS-PM	LDS-Cu
Rated total power (kW)	400	100	52
Rated voltage per phase (V)	1200	700	380
Rated current per phase (A)	200	64	64
Rated field winding current (A)	70	/	8
Rated translator speed (m/s)	1	1	1
Stator pole number	12	12	12
Translator pole number	8	8	8
Stator outside diameter (m)	1.65	1.65	1.65
Translator outside diameter (m)	1.99	1.99	1.99
Stator active length (m)	1.92	1.92	1.92
Translator active length (m)	1.92	1.92	1.92
Armature windings (Turn×path)	52×4	52×4	52×4
Field windings (Turn)	157	/	440
PM volume (m^3)	/	0.058	/
Magnet remanence (T)	/	1.2	/
Airgap between translator & stator (m)	0.012	0.01	0.01
Gap between field & armature windings (m)	0.001	0.001	0.001

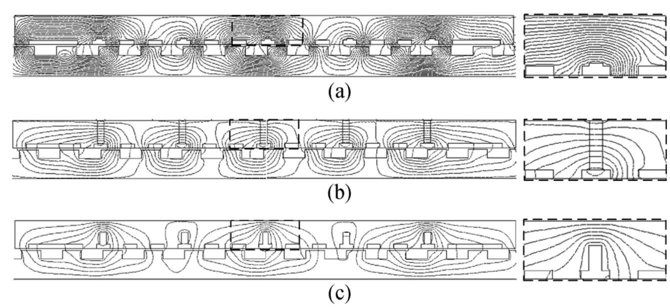

Fig. 4. Comparison of magnetic field distributions. (a) LDS-HTS. (b) LDS-PM. (c) LDS-Cu.

Fig. 4 shows the no-load magnetic field distribution of the LDS-HTS machine as compared with the LDS-PM and LDS-Cu machines, in which the important parts are separately enlarged. It can be found that the flux is concentrated on the overlapping areas between the stator and translator poles. To avoid saturation of the proposed machine, the field winding ampere-turns should be selected carefully. Fig. 5 shows the stator tooth flux density waveforms under various field currents. Magnetic saturation occurs at the overlapping areas with the field current over

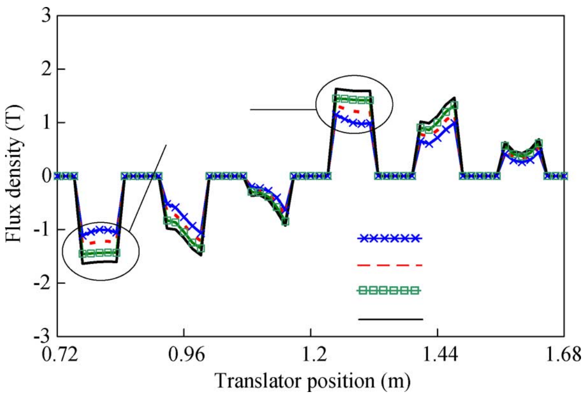

Fig. 5. Stator tooth flux density waveforms of LDS-HTS.

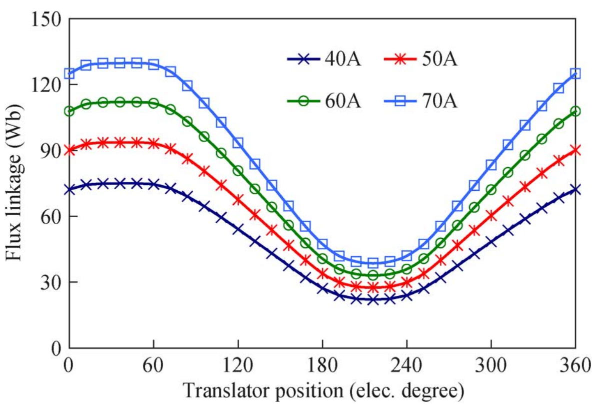

Fig. 6. Airgap flux linkage waveforms of LDS-HTS.

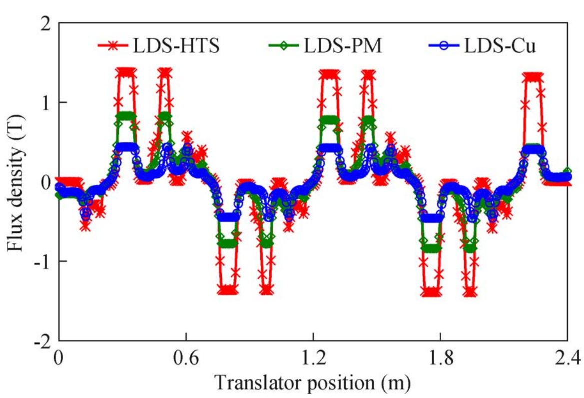

Fig. 7. Comparison of airgap flux density waveforms.

80 A. Then, the airgap flux linkage waveforms under various field currents are shown Fig. 6 which shows that the flux linkage can be flexibly controlled. Also, the no-load air-gap flux density of the proposed machine at the field current of 70 A is compared with that of the counterparts. As shown in Fig. 7, the maximum flux density of the LDS-HTS, LDS-PM and LDS-Cu machines can reach 1.4 T, 0.83 T and 0.43 T, respectively.

Fig. 8 compares the no-load EMF waveforms of all three machines at the rated speed of 1 m/s. It can be found the EMF magnitudes of the LDS-HTS, LDS-PM and LDS-Cu machines are 1200 V, 700 V and 380 V, respectively. It confirms that the no-load EMF of the LDS-HTS machine is 1.7 and 3.2 times that of the LDS-PM and LDS-HTS ones, respectively, which are consistent with the improvements in air-gap flux density.

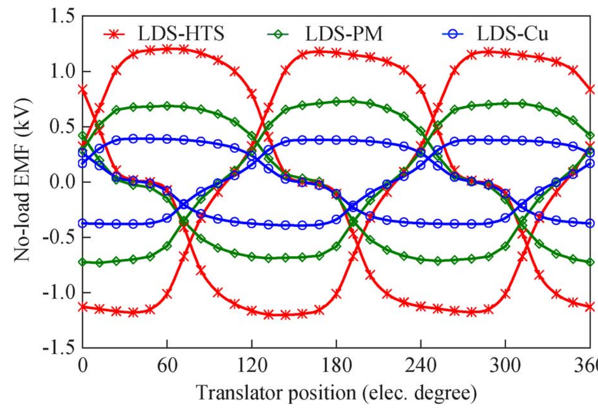

Fig. 8. Comparison of no-load EMF waveforms.

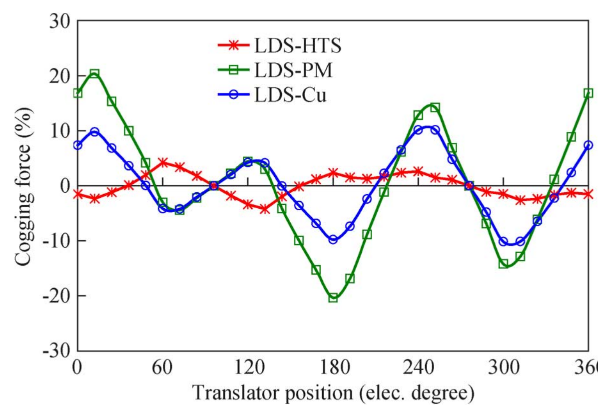

Fig. 9. Comparison of normalized cogging force waveforms.

For wave power generation, the open-circuit force (namely the cogging force) of the machine is an important parameter. It indicates the retardation for initial movement of the translator. To enable a fair comparison among the three machines, their cogging forces are optimized by adjusting the slot length at the two ends of the stator and then normalized by their respective rated thrust forces. So, the corresponding normalized cogging forces are compared as shown in Fig. 9. It can be found that the cogging force of the LDS-HTS machine is less than 5%.

Since the rated thrust force and airgap of the LDS-HTS machine are larger than that of its counterparts, the corresponding normalized cogging force is much lower than that of the LDS-PM and LDS-Cu machines.

V. Conclusion

In this paper, a novel LDS-HTS machine, adopting HTS field windings and HTS armature windings, has been proposed for wave energy conversion. The machine configuration, operation principle, and design criteria have been discussed. By using the finite element method, the proposed LDS-HTS machine has been analyzed and quantitatively compared with the LDS-PM and LDS-Cu machines. It confirms that the proposed machine can offer the advantages of higher power density, higher no-load EMF and lower cogging force than its counterparts. Although its refrigeration system inevitably consumes energy, the elimination of field and armature winding losses can outweigh such consumption and improve the overall efficiency of the whole system. Moreover, the HTS field windings provide the flexibility to online tune the airgap flux so as to regulate the output voltage and even optimize the system efficiency. There are no moving current leads in the machine since the translator is a simple iron core with salient poles. Finally, the quench protection and detection circuit of this machine is so important that will be investigated in future.

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