Comparison of Linear Switched Reluctance Machines with Mutual Coupling and Permanent Magnet Machines with Halbach Array for Wave Energy Conversion

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Abstract — This paper is presented to compare two different generator systems for wave energy conversion, namely the linear switched reluctance generator with mutual coupling system (LSRM) and the linear permanent magnet generator with halbach array system (PMHA). The comparison is based on cost and annual energy yield for a given ocean climate. The LSRM is a cheaper solution and seems more reliable. Meanwhile, the PMHA has the higher energy yield.

I. INTRODUCTION

Most direct-drive generators being used at the moment in wave energy conversion system are linear permanent magnet machines. However, [1] and [2] are claiming benefits for linear switched reluctance machines with mutual coupling, which supply more reliable structure and lower cost as well as the competitive force density. This paper is proposed to quantify these differences through the mathematic modeling and the generator design, and the resulting performances are shortly described.

II. MODELING OF THE WAVE ENERGY CONVERSION SYSTEM

A. Modeling of the ocean wave

According to the data in [3], the wave characteristics can be simplified to be a sinusoidal waveform shown in Fig. 1, whose depth below mean seawater level is 19.5m, wave height is 0.6m, wave period is 2.7s, and wavelength is 37.3m.

As it can be seen in Fig. 1, four forces contribute to the dynamic modeling where the hydrodynamic forces are not taken into account due to the comparison of generator performance is given more considerations.

B. Modeling of the converter

A conventional voltage source rectifier shown in Fig. 1 is used to load the generator and it is important that the modeling can handle the case that the translator reverses direction, which can be modeled by the following system:

$$\begin{cases} \dfrac{d\lambda_a}{dt} = e_a - u_a - Ri_a = e_a - u_{dc}\dfrac{2s_a - s_b - s_c}{3} - Ri_a \\ \dfrac{d\lambda_b}{dt} = e_b - u_b - Ri_b = e_a - u_{dc}\dfrac{-s_a + 2s_b - s_c}{3} - Ri_b \\ \dfrac{d\lambda_c}{dt} = e_c - u_c - Ri_c = e_a - u_{dc}\dfrac{-s_a - s_b + 2s_c}{3} - Ri_c \\ C\dfrac{du_{dc}}{dt} = s_a i_a + s_b i_b + s_c i_c - i_{load} \end{cases} \quad (1)$$

where $\{s_a, s_b, s_c\}$ indicate the switch positions of each phase; s can be either *0* or *1*, which $s=1$ indicating that the output is connected to the positive terminal of the DC-link capacitor; back-EMF e is 0 in the LSRM system modeling; λ is the flux linkage of the phase winding; and subscripts stand for three phases.

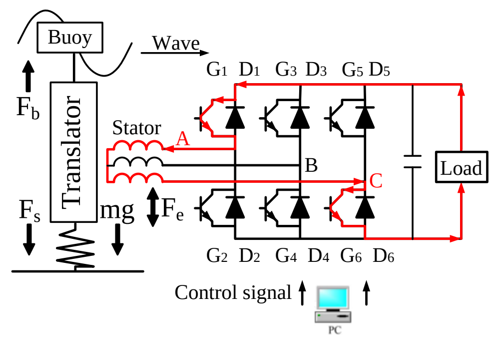
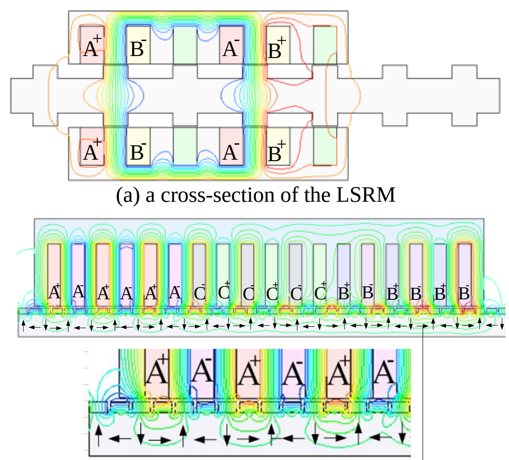


Fig. 1. System modeling scheme



(a) a cross-section of the LSRM

(b) a half cross-section of the PMHA

Fig. 2. Cross section views of generators

C. Modeling of the generator

The different generators are modeled using the magnetic equivalent circuit, which is solved for a two-dimensional section of the generator. And the end effect of the stator windings are modeled as impedances in the circuits as illustrated in [2] and [4].

III. GENERATOR DESIGN AND PERFORMANCE

To obtain comparative results, two generators studied in this paper have same power rating and similar overall dimensions shown in Table I.

A. Linear switched reluctance generator with mutual coupling

The cross-section of the LSRM is shown in Fig. 2(a) and the magnetic equivalent circuit is depicted in Fig. 3. And some results from the model as a function of the displacement: force and flux linkage are given in Fig. 4.

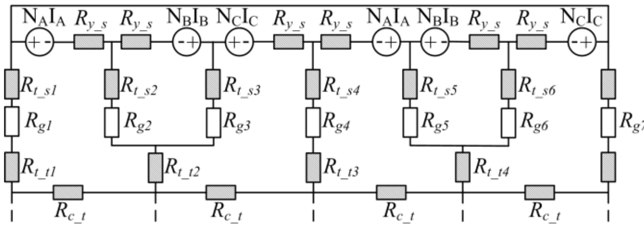


Fig. 3. The magnetic equivalent circuit of LSRMs

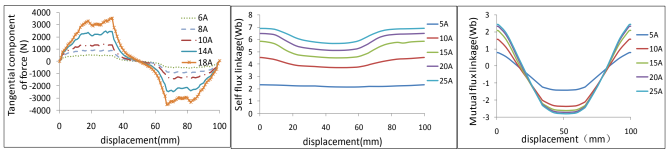


Fig. 4. Force and flux linkage of LSRMs

B. Linear permanent magnet generator with halbach array

The cross-section of the PMHA is shown in Fig. 2(b) and the magnetic equivalent circuit is depicted in Fig. 5. And some results from the model as a function of the time when velocity is 1.98m/s: force, no-load flux linkage and back EMF are given in Fig. 6.

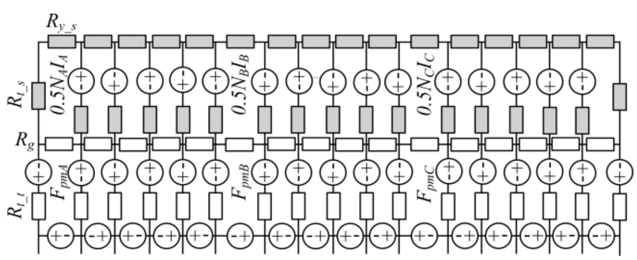


Fig. 5. The magnetic equivalent circuit of PMs

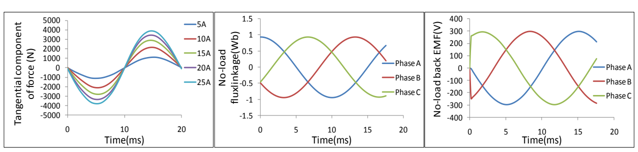
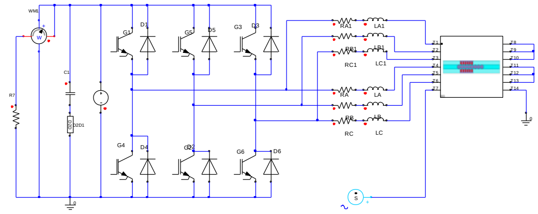


Fig. 6. Force, no- load flux linkage and back EMF of PMs

IV. FINITE ELEMENT ANALYSIS VERIFICATION

To verify the feasibility of modeling used in comparisons, this section compares the results calculated from magnetic equivalent circuit with the results predicted by the Maxwell12 and Simplore8 joint simulation method. The schematic diagram of the systematic simulation is developed and shown in Fig. 7.


(a) LSRMs model

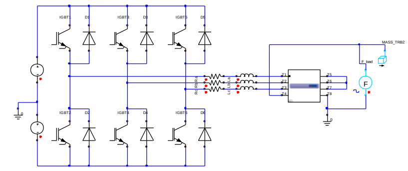

(b) PMHAs model

Fig. 7. Simulation models using FEA

V. COMPARISON AND DISCUSSION

From the comparison above, it can be obtained that the PMHA system seems a more interesting choice in term of energy yield. This is mainly due to the higher power density in halbach array permanent magnet. However, the LSRM system seems more attractive because of the simple structure, low cost, and comparative power density.

TABLE I
SPECIFICATIONS OF TWO GENERATORS

Item		Value	Unit
Axial length		190.5	mm
Air-gap length		1.5	mm
Stator tooth height		54	mm
Stator yoke height		21.5	mm
LSRMs	Stator tooth width	33	mm
	Stator slot width	33.5	mm
	Translator tooth width	35.5	mm
	Translator tooth height	19	mm
	Translator slot width	64.25	mm
	Translator yoke height	24.5	mm
PMs	Stator tooth width	9.9/11.65	mm
	Stator slot width	11	mm
	Permanent magnet	8.5*5	mm
	Translator yoke height	20	mm

VI. REFERENCES

[1] J. Du, “Modeling of a linear switched reluctance machine and drive for wave energy conversion using matrix and tensor approach,” *IEEE Trans. on Magn.*, vol.46, no.6, 2010.

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[3] J. G. Vining and A. Muetze, “Economic factors and incentives for ocean wave energy conversion,” *IEEE Trans. on Magn.*, vol.45, no.2, pp. 547-553, 2009.

[4] H. Polinder, “Modeling of a linear PM machine including magnetic saturation and end effects: maximum force-to-current ratio,” *IEEE Trans. on Magn.*, vol.39, no.6, pp. 1681-1687, 2003.