Study on Control Strategy of a Linear Switched Reluctance Machine with Mutual Coupling in Wave Energy Conversion

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Abstract — The robust structure, good thermal performance and flexibility of linear motion driving make linear switched reluctance machines become attracting candidates for energy conversion applications in ocean environment, which has both the energy density and capacity necessary to sustain energy needs in the foreseeable future. However, the dramatically changing frequency of the ocean wave and reciprocating motion of the machine make it very difficult to derive a comprehensive control algorithm to extract the energy from the waves efficiently. This paper presents an optimal control strategy which learns from the tuning control of a spring-mass-damper system, and verifies the control effectiveness in simulation and experiments.

I. INTRODUCTION

Linear switched reluctance machines (LSRMs) with mutual coupling are competitive candidates for wave energy conversion rather than the linear PM synchronous, induction, and other novel machines because of the higher reliability and lower cost [1]. However, the efficient control method needs more investigations due to highly variable wave climate and the strongly coupled system [2]. A reaction force control method for a vernier hybrid linear PM machine based on an electrical analogue is introduced in [3] and latching control algorithm of a heaving buoy is illustrated in [4], which supply a good foundation to further study of optimal control strategies in LSRMs wave energy conversion system. Therefore, an optimal control strategy of resonance point tracking is proposed in this paper.

II. MATHEMATIC MODELING OF THE LSRMS

The topology of the proposed wave energy conversion system includes a LSRM with mutual coupling, whose specifications are shown in Table I and a full-bridge rectifier, which is shown in Fig. 1.

A. Nonlinear inductance modeling

Different from the traditional SRMs, the LSRMs presented in this paper have the fully pitched winding configurations, which produce noticeable time varying mutual inductances and provide 20-30% more force [1].

B. Voltage and force equations

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} \quad (1)$$

$$\frac{dv}{dt} = \frac{1}{m}(F_e + F_{spring} + F_{buoy} + mg) \quad (2)$$

where V, R, i and λ are the voltage, resistance, current and flux linkage of the phase winding, and subscripts a, b and c stand for the three phase respectively; F_e, F_{spring} and F_{buoy} are the electromagnetic force, spring force and buoy force; v is the velocity of the translator; and m is the mass of moving parts.

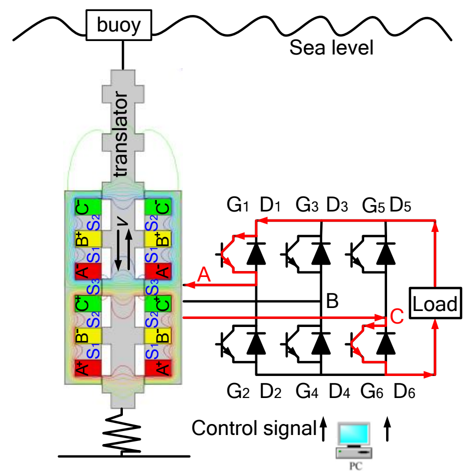

Fig. 1. System topology

III. CONTROL STRATEGY OF THE DIRECT DRIVE SYSTEM

To generalize and broaden the application of the power electronic device, conventional full-bridge converter is used to transfer the generated power to the load in the proposed system, and two-phase excitation with bipolar current is adopted in the proposed drive, whose control scheme is shown in Fig. 2.

A. Optimal control strategy of resonance point tracking

Due to the narrow resonance bandwidth of the point absorbers, the reactive power may be quite larger than the average useful power, which means the high conversion efficiency is needed. According to previous work which has been done in [2], the wave energy conversion system can be equivalent to a spring-mass-damper system. In other words, the optimum load force provided by the LSRMs is the product of this optimum load impedance and the velocity. Therefore, it is possible to find the system resonance frequency to increase the efficiency for a certain wave climate, which is the basic idea of the proposed optimal control strategy. Through the derivation, it is observed that the phase and amplitude of the device can be controlled by three phase currents.

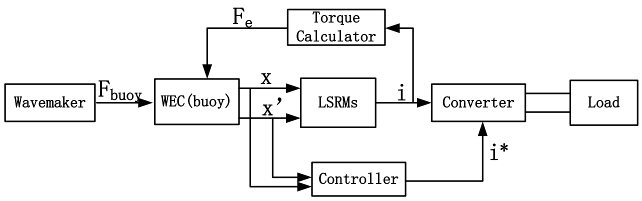

Fig. 2. Control scheme

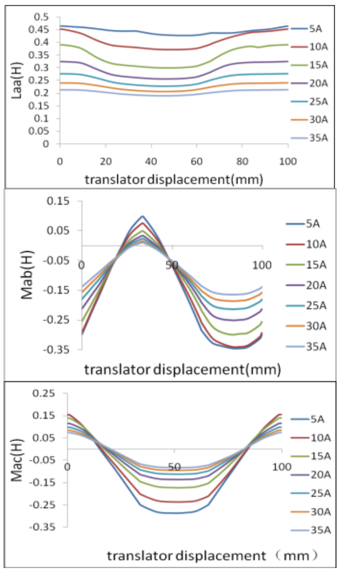

Fig. 3. Mutual and self inductance

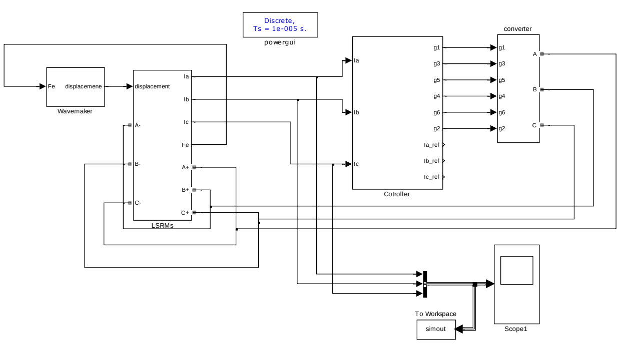

Fig. 4. Simulation model

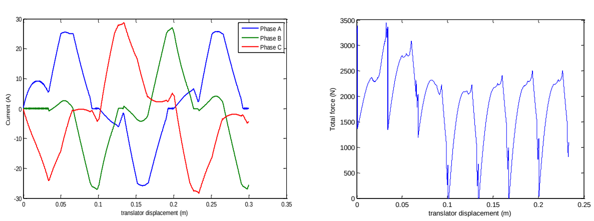

Fig. 5. Current and force waveforms

B. Simulation verifications

To verify the feasibility of the proposed optimal control strategy, FEA (Finite element analysis) and MATLAB/Simulink are used to build the simulation model.

It can be observed from Fig. 3 that the mutual and self inductances decrease according to the exciting current due to the magnetic saturation, and mutual inductance have a phase shift of 30° if the stroke length is considered as the period of 180° .

To simplify the calculations, the self inductance is assumed to be constant at a certain exciting current due to the slow-varying characteristic shown in Fig. 3 in the presented simulation model.

From the simulation model shown in Fig. 4, the current and force waveforms in Fig. 5 can be obtained, which are reasonable according to the previous studies [1-4].

C. Experiment verifications

The test bed is set up and the experiment is currently in progress. The experiment results will be presented in the following paper.

IV. CONCLUSION

In this paper, an optimal control strategy of resonance point tracking is proposed and applied to the LSRMs with mutual coupling winding configurations used in wave energy conversion system. Parameters of the LSRMs are obtained by FEA and will be verified by measurements. The comparisons between simulation and experiment results will identify the feasibility and effectiveness of the proposed control scheme.

TABLE I
MAJOR SPECIFICATIONS OF THE LSRM

Name	Value	Unit
Stack Length	190.5	mm
Air-gap Length	1.5	mm

V. REFERENCES

[1] J. Du, "Modeling of a linear switched reluctance machine and drive for wave energy conversion using matrix and tensor approach," *IEEE Trans. Magn.*, vol. 46, 2010.

[2] J. Falnes, "Optimum control of oscillation of wave-energy converters," *Annex Report B1: Device fundamentals/Hydrodynamics*, 1993.

[3] J.K.H Shek, "Reaction force control of a linear electrical generator for direct drive wave energy conversion," *IET Renew. Power. Gener.*, vol. 1, pp. 17-24, 2007.

[4] A. Babarit, "Optimal latching control of a wave energy device in regular and irregular waves," *Applied Ocean Research*, vol. 28, pp. 77-91, 2006.