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The direct-drive sensorless generation system for wave energy utilization

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ABSTRACT

A direct-drive generator based on linear switched reluctance principle is investigated for wave energy utilization. Integrated with the sensorless technique, the direct-drive generator has the characteristics of low cost and robustness, and the power generation control system is especially suitable for the operation under hostile working environments since restrictions of physical sensors are eliminated. Simulation analysis based on the finite element methods (FEM) and joint simulation are carried out for performance analysis of the power generation control system, including position estimation, open loop turn-on and turn-off position optimization and closed loop current regulation. Experimental results validate the effectiveness of the position estimation scheme for the sensorless, linear switched reluctance generator based power generation control system.

Introduction

The earth is covered with 71% of ocean and it is estimated that an extractable power of more than 1 TW can be expected from wave energy globally [1]. Since wave energy originates from wind, wave motion exhibits low-speed translational characteristics, typically with the speed range of 0–2 m/s [2]. Nowadays, wave energy exploitation techniques mainly focus on indirect wave power conversion. By using mechanical linear-to-rotary translators such as the hydraulic or pneumatic converters, wave motion is transformed to high-speed rotary movement to propel high-speed generators for electricity [3–5]. Wave energy converters (WECs) that are considered to possess commercial values are the Pelamis from Ocean Power Delivery [3], the wave dragon from Wave Dragon APS [4], and the Archimedes Wave Swing from BV-AWS [5], respectively. However, the traditional methods of wave power extraction discussed above have the disadvantages of a complex and expensive power generation control system, and they are hard to maintain and have low overall transformation efficiency [6]. Therefore, the above WECs still have not been widely applied for mass production since electricity generated from such WECs is not cost effective.

Recently, the direct-drive methodology for wave energy exploitation has been proposed. By direct capture of translational wave energy in one dimension, the linear generators can be employed to eliminate intermediate mechanical translators or converters. Therefore, the direct-drive method brings a simpler power take-off system with higher power efficiency. Current research mainly focuses on the linear synchronous permanent magnet generators (LSPMG). Though the LSPMGs have relatively large force-to-volume ratio and high conversion rate and efficiency, the involvement of permanent magnets (PMs) can result in the complicated machine winding scheme [7,8] or sophisticated arrangement and assembly of PMs [9]. Therefore, the overall manufacture and assembly cost for the power generation control system is high. Furthermore, temperature variations and machine saturation due to PMs can lead to performance degradation or even malfunction of the generation system [10].

The linear WECs based on the direct-drive methodology usually rely on physical sensors that detect position/velocity information for correct phase excitation or proper output voltage and current control. The physical sensors such as the linear optical or magnetic encoders require certain working limitations, especially the temperature range. However, the WECs often work under the rough and unattended environment and there will be many uncertainties and disturbances exercised on the generation system. The variations of wave extraction conditions such as humidity, wave impact and particularly temperature variations, unavoidably affect the standard working operation of these sensors, and this ultimately influences the stability and output performance of the system. In addition, the position/velocity sensors are one of

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the indispensible factors for the cost of the power generation control system [11].

To solve the above problems, this paper investigates a direct-drive, sensorless, linear power generation control system based on switched reluctance principle. The linear generator has the characteristics of a simple and robust machine structure and it is suitable for the operation under hostile environment. The total manufacture cost is low and the machine is very suitable for mass production, since the switched reluctance machine itself is only composed of laminating steel sheets and copper wires. Material-wise, the proposed linear switched reluctance generator (LSRG) does not contain any expensive PMs or complex windings.

The position/velocity sensors is another factor for the total cost of the LSRG based power generation control system [12]. Therefore, the total system cost can be further reduced if such sensors can be eliminated by the integration of proper sensorless methods. By employing the pulse injection position detection technique, the sensorless approach is integrated on the LSRG based generation system. Therefore, the total cost of the power generation control system can be kept relatively low compared to the system from a LSPMG counterpart.

The paper is organized as follows. The principle of the LSRG and the sensorless technology are discussed in Section 2. Section 3 first investigates the characteristics of the LSRG based on finite element methods (FEM). Then simulation analysis for the power control system, position optimization in open loop and closed loop current regulation are performed for the LSRG-based generation system. Section IV focuses on the experimental validation of the sensorless power generation control system. Section V provides the conclusion and discussion remark.

Principle of the LSRG and sensorless technique

The LSRG and its symbols can be found in Fig. 1. It mainly consists of a moving platform, stator and a pair of linear guides to facilitate the linear motion along x axis. The LSRG has three-phase windings and it corresponds to a typical “6/4” rotary SR machine. The movers and the stator are made from laminated silicon-steel plates. Major machine parameters are listed in Table 1.

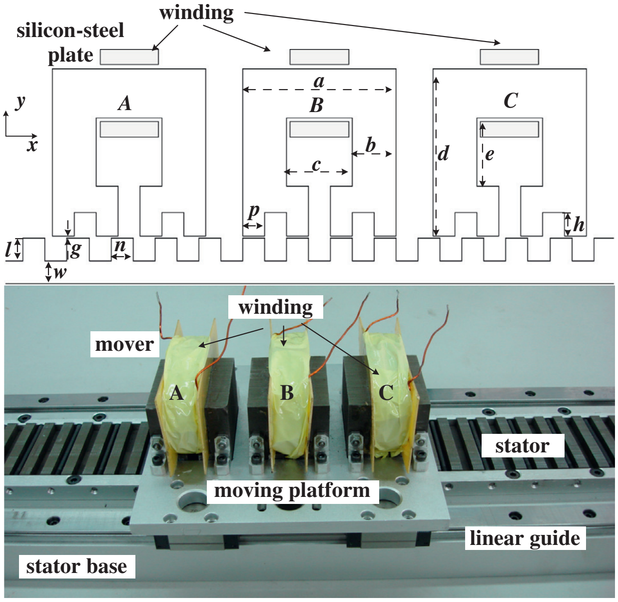

Fig. 1. The LSRG.

Table 1
Major machine parameters.

Parameter	Value	Parameter	Value
Mover pole width (a)	42 mm	Stator pole width (n)	6 mm
Mover yoke width (b)	12 mm	Stator pole height (l)	6 mm
Mover height (d)	44 mm	Stator yoke height (w)	6 mm
Height of winding slot (e)	18 mm	Air gap length (g)	0.5 mm
Width of winding slot (c)	18 mm	Stack length	50 mm
Mover pole height (h)	6 mm	Stroke length	450 mm
Mover pole width (p)	6 mm	Thickness of laminations	0.3 mm
Number of turns of each phase	160	Pole-pitch	12 mm

Theoretical background of the LSRG

The LSRG can be represented as a typical electromechanical system with one mechanical input and three electrical outputs. From the mechanical side,

$$F = M\frac{d^2s}{dt^2} + D\frac{ds}{dt} + f \tag{1}$$

where F stands for the mechanical force input, M is the mass of the moving platform, s is displacement, D is damping coefficient and f represents load force.

From the electrical terminal, the LSRG can be described in the form of voltage balance equation as [12],

$$u_j = R_j i_j + L_j\frac{d\lambda_j}{dt} \quad (j = A, B, C) \tag{2}$$

where u_j and λ_j represent voltage drop and flux-linkage of the j-th winding, respectively i and R are phase current and resistance. If the linear generator employs the typical three-phase asymmetrical

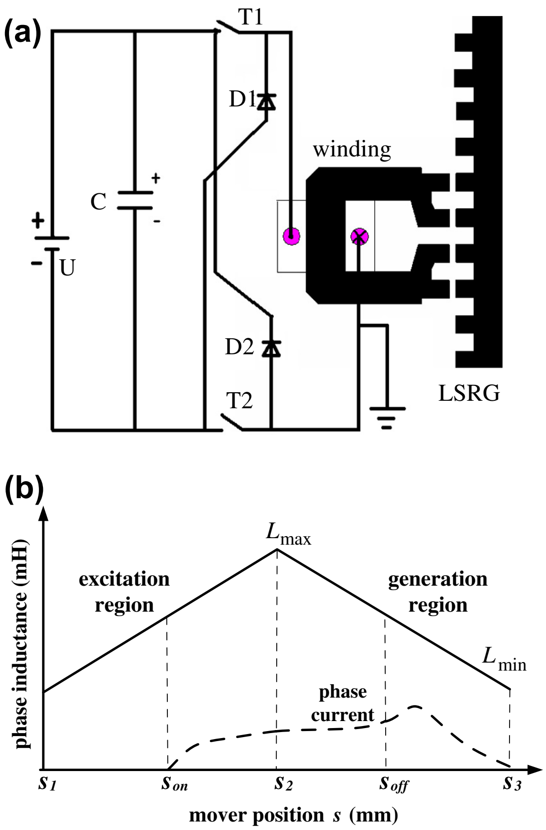

Fig. 2. (a) Drive topology of one phase and (b) turn-on and turn-off regulation.