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Complementary power generation of double linear switched reluctance generators for wave power exploitation

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ABSTRACT

The wave power generation system based on the single linear generator scheme has low energy output and week robustness, especially in low speed conditions and parameter variations. To overcome the problem, a scheme of complementary power compensation generation for two asymmetric bilateral linear switched reluctance generators (ABLSRGs) is proposed in this paper. Mathematic model is first derived and machine characteristics are investigated by the finite element method. The compensation scheme is carefully investigated together with the independent control method. Under the conditions of parameter and velocity variations, experimentation demonstrates that both the voltage control accuracy and system robustness can be guaranteed with the proposed complementary power generation control scheme. Experiment results show that a voltage control precision of 11.75–12.23 V can be obtained, with the voltage reference of 12 V.

1. Introduction

The oceans possess enormous energy storage and an estimated wave power of more than 1 TW can be estimated [1]. The motions of waves can be ideally regarded as quasi-sinusoidal waveforms with the speed range normally falling into 0–2 m/s [2,3]. At present, wave power exploitation schemes are more and more focused on the direct-drive energy conversion methods [4–6]. By direct capture of translational wave energy in one dimensional, the linear generators can be employed to eliminate intermediate mechanical translators or converters from the traditional wave energy converters (WECs) that require linear-to-rotary power transformation mechanisms [7]. Therefore, the direct-drive WECs have the advantages of a simpler power take-off system with higher power efficiency [8]. Current research mainly concentrates on linear synchronous permanent magnetic generators (LSPMGs) [9], linear switched reluctance generators (LSRGs) and linear induction generators [10,11]. Though LSPMGs have relatively higher force-to-volume ratio and efficiency, the involvement of permanent magnets (PMs) often results in sophisticated assembly of PMs or winding schemes [12]. Therefore, the overall manufacture and assembly cost for such power generation systems based on LSPMGs are high. Moreover, the environment of wave power generation in the ocean experiences constant temperature variations and inevitably, this affects the normal operations of PMs [13] and the demagnetization of PMs will eventually cause performance deterioration or even malfunction of the entire power generation systems [14].

Like wind energy, the power density of wave is low for a designated ocean area. For any single direct-drive WECs, to keep power output at a reasonable level, the WECs should be designed with the dimensions comparable to five times of a standard human height [10]. However, for any single low-cost, low-power direct-drive WECs, the generator has low energy output and week robustness. Therefore, it is suggested that a certain number of linear WECs be deployed in a certain area and the deployed WECs extract the power coordinately in such area [15]. To keep the total generation cost at a reasonable price level, it is natural that the deployed linear WECs should have simple mechanical structures and they should be suitable for mass production as well [16]. LSRGs do not involve any PMs and the machines only consist of silicon-steel sheets, aluminum and copper wires. LSRGs have the characteristics of simple and robust mechanical structures and they are more suitable for the operation under the hostile environment. Though the efficiency is comparatively low, compared to their LSPMG counterparts, LSRGs are superior for the deployment of wave power generation in large numbers, since the manufacture and assembly cost is reasonable and the LSRGs are more suitable for mass production [17].

For single linear generator based power generation systems, current research mainly focuses on current commutation optimization and regulation, voltage and power control algorithms. In [18], a rectangular

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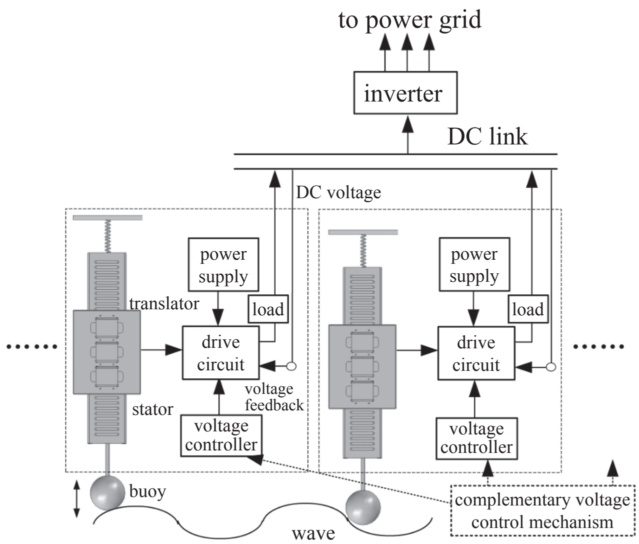

Fig. 1. Concept of complementary power generation.

current commutation scheme is proposed for the free-piston linear generator. A single switch chopping scheme for the output power control and the double switches chopping scheme for the phase current control are discussed for the LSRG, based on simulation [19]. Both open loop with turn-on and turn-off position optimization and closed loop current regulation scheme are investigated for the sensorless LSRG [8]. In [16], the closed loop current control scheme based on pulse width modulation is proposed. A DC link voltage control scheme is proposed to attenuate the low frequency ripple of a LSPMG [20]. In [10], the authors adopt a dual-loop control scheme to improve the voltage output precision with an optimized current distribution function. Power control is applied by directly collecting the power from individual coils for a linear, direct drive, air-cored, tubular, permanent magnet generator [21].

To realize coordinated power generation for multiple LSRGs, this paper first attempts to investigate the complementary power generation of two asymmetric bilateral LSRGs (ABLSRGs). Since the characteristics of the phase current are direct current (DC) pulsed waveforms [14], it is important to keep the quality of the output DC voltage signal at a reasonable level for future inversion or even grid connection.

The wave power generation system based on multiple LSRGs can be found in Fig. 1. As the buoys travel with waves, the translators are propelled and move along with the buoys. According to the working principle of LSRGs, current from each phase of the LSRGs can be generated based on the proper phase excitation scheme according to position. The load regulates the phase current from each phase to DC voltage. By the regulation of voltage control schemes, DC voltage signals can be output from the drive circuits to the DC link. Then the DC voltage can be inverted to three-phase alternating current (AC) for grid connection. More linear generators can be included in the power generation system for the contribution to the DC link. If each generator outputs the voltage to the DC link individually, it is called the "independent power generation" scheme. Since each generator generates power alone and neglects the wave energy input from others, in this scheme, the quality of the voltage from the DC link cannot be guaranteed. Since voltage ripples influence the inverted AC signals, it is important to keep the ripples at a reasonable level to facilitate the future applications for grid connection.

Instead of independent power generation, the two linear generators can work complementarily to achieve the ultimate goal of output voltage precision and increase the power volume at the same time. With the introduction of the complementary voltage control mechanism in Fig. 1, the two linear generators can work cooperatively to improve the precision of the total voltage from the DC link.

The innovation of this paper can be summarized as follows. First, the investigation of two identical ABLSRGs for wave power generation is investigated. Second, an effective voltage complementary scheme is proposed, based on theoretical analysis. Third, experimental results for performance comparisons under the independent and complementary control of ABLSRGs are carried out. Experimental results prove that the proposed power complementary control scheme not only ensures output voltage precision, but owns certain robustness under the conditions of control parameters or speed variations. An absolute output voltage value of 11.75–12.23 V can be achieved with 12 V voltage reference under the environment of parameter change or speed variations.

2. The ABLSRG and characteristics

The magnetic structure and picture of the ABLSRGs can be found in Fig. 2(a) and (b). The linear generator mainly consists of a stator base with stator blocks. The generator utilizes an asymmetric machine structure. Instead of perfect mirroring along the axis of the moving platform, both the stator and the mover phases apply an asymmetric scheme to improve a higher force-to-volume ratio and efficiency [17]. The moving platform is supported by a pair of linear guides. Each phase of the ABLSRGs has the same dimensions and ratings and the phases are defined as AA′, BB′ and CC′, respectively. Major specifications can be found in Table 1.

3. Theoretical background and characteristics

The ABLSRG can be considered as a typical energy transformation system and the motion equation can be described as [22],

$$F_j = M\frac{d^2x_j}{dt^2} + Q\frac{dx_j}{dt} + f_j \quad (j = 1, 2) \tag{1}$$

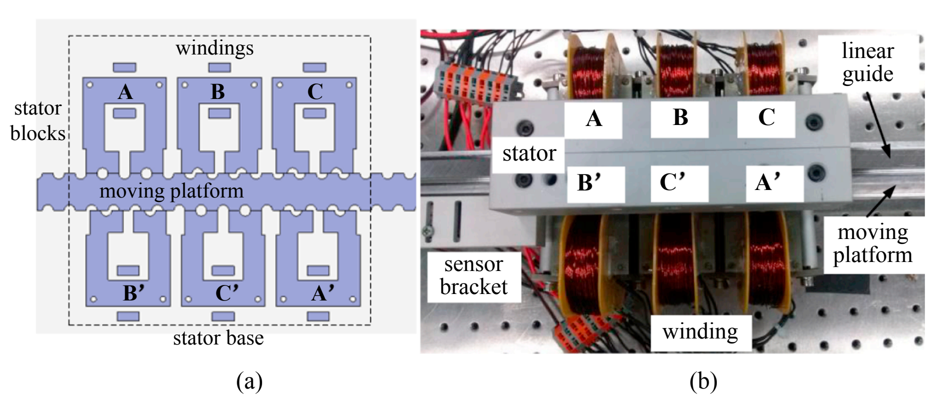

Fig. 2. The LSRM (a) and machine structure (b).

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