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Design and Simulation of a Linear Switched Reluctance Generator for Wave Energy Conversion

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Abstract–This paper investigates the direct-drive linear switched reluctance generator for wave energy conversion. A double-sided linear switched reluctance generator is designed. Its nonlinear flux characteristics are simulated by finite element method. The excitation circuit of the linear switched reluctance generator is reviewed and the control algorithm for this generator is also discussed.

Keywords–Wave energy conversion, linear switched reluctance generator, finite element method, excitation circuit, cascaded control.

I. INTRODUCTION

Waves are generated by wind passing over the sea surface. Due to the difference of propagation speeds between the water and the air, there is always energy flowing from the wind to the waves. This energy could become a main source of electricity power if it can be properly harnessed. Therefore, wave energy conversion issues have attracted many scientists and engineers' attention.

Presently, there are two major challenges in wave energy conversion: the first one is to come up with a mechanical device which can convert wave power into mechanical motions efficiently under all operating conditions (wave energy capture). The second one is to convert the irregular mechanical motions into electricity with maximum efficiently (electricity generation). On top of this, the whole setup has to be robust enough to withstand the harsh environments of a stormy sea, and working unattended for many years [1].

Many projects have aimed at tackling the first problem since the late 1970s. As a result, many wave capturing mechanisms have been proposed and implemented [2-3]. However, there have been relatively few investigations into the core of the second problem.

The main difficulty to the second problem is the complexity of converting the slow moving linear motion into electricity with maximum efficiency, under harsh environment and very wide operating conditions. Due to the low speed piston motions of sea waves, traditional high speed rotary generators can not be applied directly for wave energy conversion. Furthermore, for wave energy conversion, some linear-to-rotary components and gear box are generally required in rotary generator system. However, the mechanical components would increase the complexity of the system and reduce its reliability [4].

These complex problems produced from rotary generator system for wave energy conversion can be solved by using direct-drive type generators. Permanent Magnet (PM) linear generators are used for wave energy conversion in [5-6]. Although PM generator is feasible, the material and manufacture of PM are expensive. On the other hand, Switched Reluctance Generator (SRG) has simple construction and high robustness. It does not contain any expensive and difficult to handle components (e.g. magnets, commutators, etc). This makes the SRG easy to mass produce and low in cost. Beside, SRG can work in a very large speed range and it is effective at low operating speeds [7-8].

However, unlike PM machines which are based on the assumption of constant air gap flux, SRG belongs to a class of machine which has a nonlinear control structure. SRG works on the principle of flux change, and its flux is inherently nonlinear in nature. Therefore, the design and control of SRG is difficult.

This paper proposes a scaled down linear direct-drive generator based on the switched reluctance principle. The simple, low cost, and robust structure of the linear SRG is very suitable for wave energy conversion. The design and structure of the linear SRG are described in section II. Section III simulates the nonlinear flux characteristics of the SRG by Finite Element Method (FEM). In section IV, the excitation circuit of the linear SRG is reviewed and the control algorithm of the linear SRG is discussed. Finally, conclusive remarks are given in section V.

II. THE DOUBLE-SIDED LINEAR SWITCHED RELUCTANCE GENERATOR

To design the linear switched reluctance generator, the typical wave capturing techniques for linear generators are reviewed firstly; then, a scaled down double-sided linear SRG is proposed for mechanical and electrical characteristics analysis.

2.1 Wave capturing techniques for linear generators

Presently two types of sea wave capturing techniques for linear generators are utilized. The first type is based on the floating buoy approach. The schematic illustration of this type of system is shown in fig. 1. Through the rope, the vertical movements of the floating buoy will translate mechanical energy to the power generator underneath, and the tension in the rope is maintained with a spring connected to the piston. The second type is the Archimedes Wave Swing (AWS) [3], as shown in fig. 2. The AWS is totally submerged in water, and the unit expands or contracts according to the water pressure change. This has the advantages of avoiding the rough sea condition, not obstructing the waterways of small vessels, and making the whole system visually invisible.

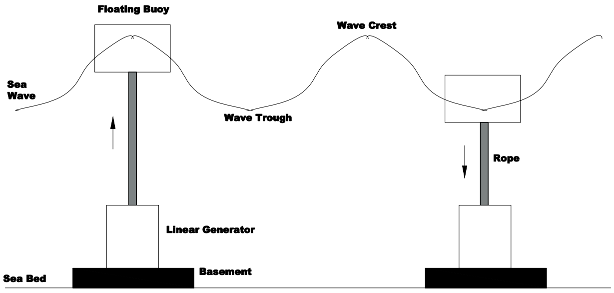

Fig. 1: Schematic drawing of floating buoy type

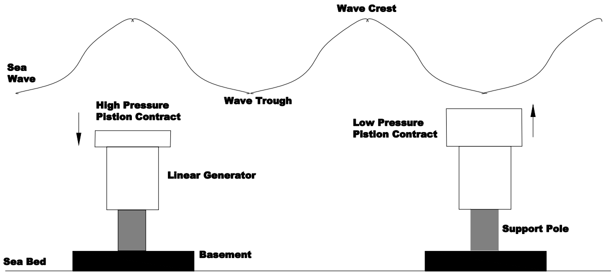

Fig. 2: Schematic drawing of AWS type

2.2 The double-sided linear SRG

Fig. 3 shows the design schematic of the proposed scaled down double-sided linear SRG. The experiences from switched reluctance motor design [9-10] are borrowed for this linear SRG construction. It is a three-phase structure in each side, and the active stators with coils placed in two sides are symmetric construction. The passive translator is mounted between the face-to-face stators and will slide with the fixed air-gap 0.5mm. This rugged mechanical structure of linear SRG can damp down the vibration during the motion operations. The double-sided structure can balance the normal force of each side; this balance would avoid the collision between stator and translator due to the normal force. Besides, in contrast with single-sided structure, the double-sided structure has high force density and lower inductance, as it has four air gaps in its flux path. Both the stators and translator are laminated with 0.5mm silicon-steel plates, by means of which the manufacture can be simplified and the total cost is reduced greatly. The specifications of the proposed linear SRG are listed in table 1.

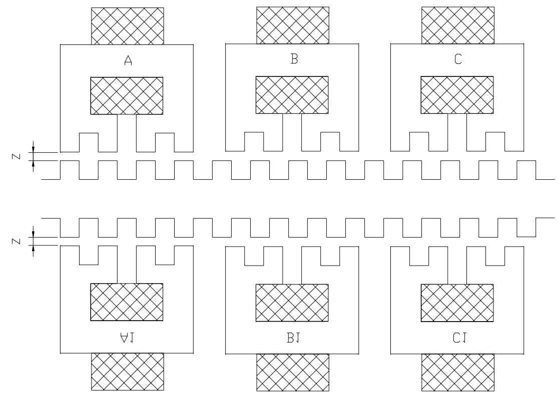

Fig. 3: Schematic of the double-sided linear SRG

Table 1: Specifications of the scaled down linear SRG

Definition	Value
Pole Width	6 mm
Pole Pitch	12 mm
Pole Height	6 mm
Stator York Width	10 mm
Translator York Width	12 mm
Winding Length	26 mm
Winding Width	10 mm
Phase Separation	10 mm
Air-gap	0.5 mm

2.3 The operation mode

For switched reluctance machines, both the motor and the generator share similar flux characteristics. In the design of the machine, whether it is mechanical or electrical, switched reluctance machines rely on the maximum change of inductance (or reluctance) to produce maximum power output. The dynamics of the whole drive system can be described by the mechanical equation (1) and the voltage equation (2). The voltage equation can be further expressed as (3) since the flux linkage is a function of current and position.

$$M\frac{dv}{dt} = \sum f_j + Bv + f_l \,. \tag{1}$$

$$V_j = r_j i_j + \frac{d\lambda_j}{dt}, j = a,b,c \,. \tag{2}$$

$$V_j = r_j i_j + \frac{\partial \lambda_j}{\partial i_j}\frac{di_j}{dt} + \frac{\partial \lambda_j}{\partial x} v, j = a,b,c \,. \tag{3}$$

V_j is phase voltage, i_j is phase current, r_j is the winding resistance, λ_j is the phase flux linkage, x is the position and its derivate is velocity v. The generated electromagnetic force is the sum of each phase force f_j, f_l is the external prime mover, M is the mass and B is friction constant. In linear case, phase force produced can be expressed as (4). L_j denotes phase inductance.

$$f_j(x, i_j) = \frac{1}{2}\frac{dL_j}{dx} i_j^2, j = a,b,c \,. \tag{4}$$

If the phase is excited when the translator moves from the unalignment position, the machine operates as motor mode; in this mode, the electromagnetic force produced between stator and translator will drive the translator moving linearly, and the electrical energy will be transformed into mechanical energy. If the phase is excited when the translator moves from the alignment position, the machine operates as generator mode; in this mode, the external prime mover will push the translator moving linearly, and the mechanical energy will be transformed into electrical energy. The ideal inductance and current curves for the two modes are shown in Fig.4.

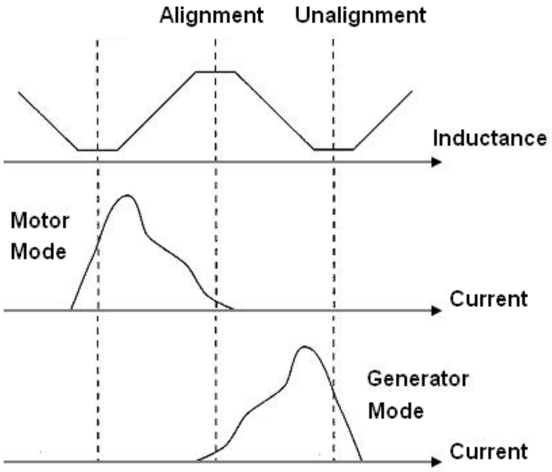

Fig. 4: Ideal inductance and currents for two working modes

III. THE MAGNETIC CHARACTERISTICS SIMULATION

Finite Element Method (FEM) is used to analyze the electromagnetic flux characteristics of the proposed linear SRG. The flux variations of one phase from the alignment position to the unalignment position are simulated. Fig. 5 shows the 3D mesh of the quarter FEM model. When the translator pass through the alignment position 2mm, the simulation results for magnetic flux density contours are shown in fig. 6 and fig. 7 as examples when currents are 5A and 15A separately. Fig. 8 shows the force vs. current curves along one complete pole pitch.

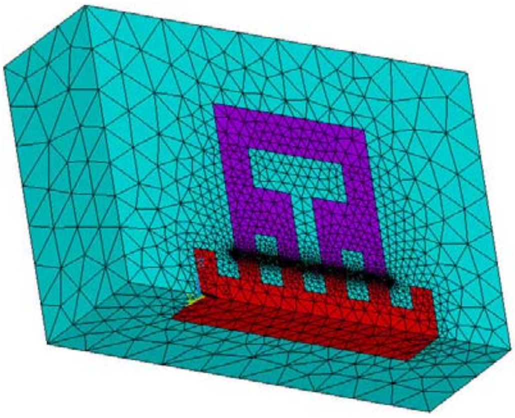

Fig. 5: 3D mesh of the quarter FEM model

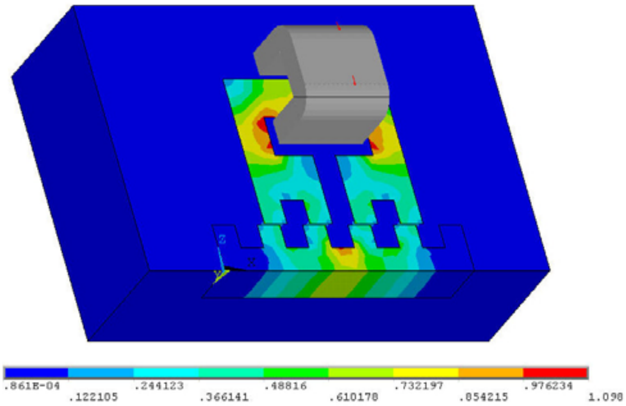

Fig. 6: Magnetic flux density when i=5A

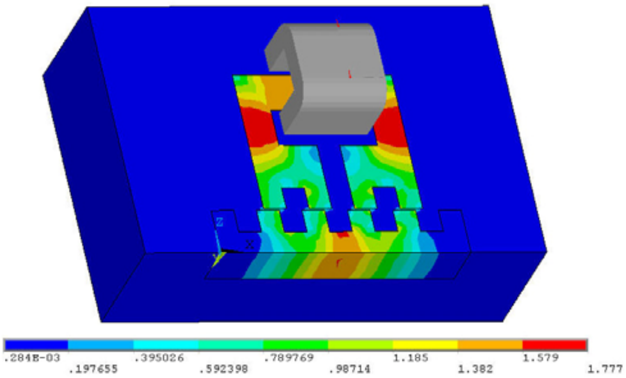

Fig. 7: Magnetic flux density when i=15A

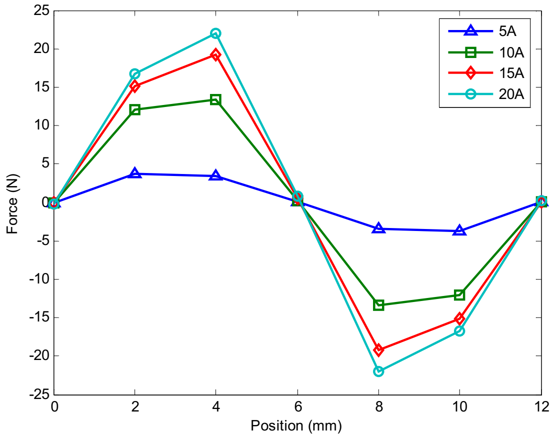

Fig. 8: Force vs. current along one pole pitch

As shown in fig. 6, when current is 5A, the maximum value of magnetic flux density is about 1.1Tesla, while the saturation value at B-H characteristics curve of the silicon steel is around 1.5Tesla, which means the instauration of flux in the magnetic loop. In contrast to fig. 6, when current is 15A, fig. 7 shows that the maximum piece value of magnetic flux density is almost between 1.58Tesla and 1.78Tesla, this piece value means there is flux saturation in the magnetic loop. Fig. 6 and fig. 7 give the flux characteristics of the linear SRG, and their comparison results also suggest the effective work region between position and current.

Fig. 8 can reveal the flux variation too; the force increase slows down when the current is over 10A, this variation means that flux saturation comes out. Additional, fig. 8 shows the high force ripples along the pole pitch for one phase. Those ripples would result in high phase currents, and may eventually produce the output voltage ripples. To obtain smooth output voltage, a force sharing strategy among the three phases, which is similar to the torque sharing approach for SRM [9], could be applied by using a winding excitation scheme. The Force Distribution Function (FDF) is used to calculate the desired phase force according to the position and the total desired force. The current calculate function is applied to compute the desired phase current and fire angles by using the desired phase force and the position.

IV. THE EXCITATION CIRCUIT AND CONTROL ALGORITHM

For the SRG, the driving circuit and its control methods would pursue high efficiency with a constant dc-link voltage at a desired value, over a wide speed range. Fig. 9 shows a conventional three-phase SRG Converter circuit. This circuit is also very popular for SRM, and it provides the maximum control flexibility and efficiency, with a minimum of passive components. An external power source is needed to initiate the generating operation, and the filter capacitor is chosen large enough to guarantee the constant dc-link voltage. Both the two transistors per phase turn on and turn off at the same time according to the appropriate translator position. The stator coil is excited and winding current increases when the transistors turn on. When the transistors turn off, the currents flow through the external resistive load and the electrical power generated is supplied to the resistive load. Since this circuit topology needs two power devices per phase, the converter cost is relatively higher than that with less power devices. In order to reduce the power devices, a Suppression Resistor Converter (SRC) converter is used [11]. Fig. 10 shows the schematic diagram of the SRC converter.

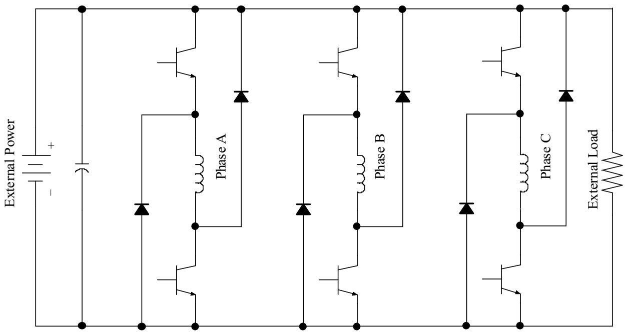

Fig. 9: Converter circuit with 2 transistors per phase

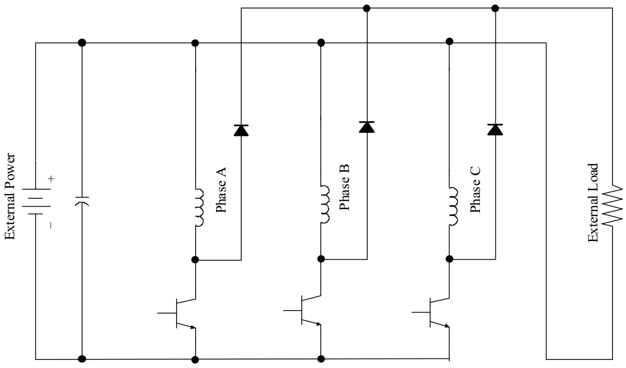

Fig. 10: SRC Converter circuit

Due to the complicated magnetic characteristics of the linear SRG, the design of a controller for the full-order system model is usually very difficult. A reasonable and feasible approach is to design the controller for the linear SRG system by using a cascaded structure. As shown in fig. 11, the whole driving system is decomposed into two subsystems. The inner loop is for the phase current control and outer loop is for the output voltage control. The obvious advantage by taking this measure is to simplify the complicated system model to two simply reduced models and design controllers for the two models respectively. Suppose that a linear motor is used as the prime mover and connected the scaled down linear SRG to emulate the wave energy conversion, and then the structure of the whole system is shown in fig. 12.

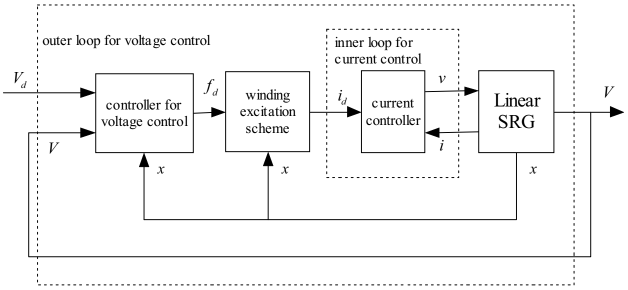

Fig. 11: Structure diagram of cascaded control

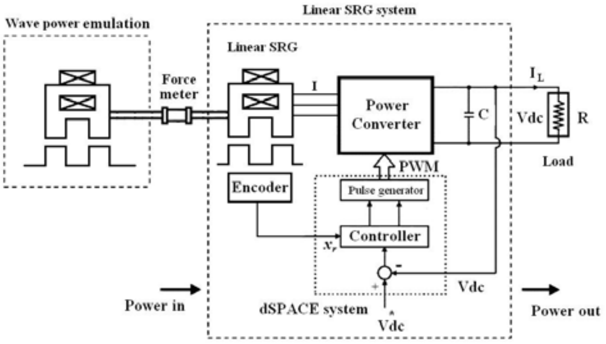

Fig. 12: Structure of the whole system to emulate the wave energy conversion

IV. CONCLUSION

This paper proposes a double-sided linear switched reluctance generator for wave energy conversion. The linear SRG is a potential candidate for wave energy conversion owing to direct-drive type, simple structure, low cost, high robustness, high power output and wide speed range. The proposed linear SRG is designed and its flux characteristics are simulated by FEM. The excitation circuits for SRG are reviewed and the control algorithm for the whole system is described. Those simulation and analysis provide useful information for the linear SRG design and implementation.

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BIOGRAPHY

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