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Design and test of a linear switched reluctance generator for use in wave-energy applications

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Abstract

This paper describes the design of a double-sided linear switched reluctance generator for use in wave energy applications, and the build and test of a working bench-scale prototype. Beginning with a standard shape, the development of the design, from concept to detail, is presented. Numerical simulation results – magnetic, mechanical and electrical – inform the detailed design. Construction of the generator and test rig is described. Experimental results give good agreement with simulation predictions.

Keywords: Direct power take off, Linear switched reluctance generator, Wave Energy

1 Introduction

1.1 WEC and PTO development

The power take-off device (PTO) is a vital component in most wave energy converters (WECs). A number of floating, offshore WECs have been developed worldwide that can adaptively oscillate in response to the prevailing wave climate, to maximise energy absorption. The available energy in the oscillating system may be transformed, via the PTO, to useful electrical power; good PTO design can therefore improve energy conversion greatly.

Many developers have suggested that tuneable PTOs are needed to allow these WECs to work at their best. Such a tuneable PTO should be capable of adapting its performance in response to the prevailing wave climate and also to the irregularly-oscillating sea-state from one second to the next.

There is a considerable body of research in linear electric generators for wave energy devices, with most work based on permanent magnet machines. At least two wave energy converters fitted with linear permanent magnet generators have reached a sea-testing stage [1][2]. Nevertheless, permanent magnet technology has a number of reported drawbacks, including the high cost of permanent magnets, their weight and their risk of demagnetization over time.

1.2 Switched reluctance generation

Switched reluctance (SR) technology has a number of interesting features that makes it attractive for wave power applications [3]. SR generators do not usually include permanent magnets in their construction. They are scalable, robust and easy to manufacture, and enjoy reliable operation with low maintenance costs. Four-quadrant operation is possible by adjusting the switching sequence in the supply phases. They can absorb and convert mechanical power in an irregular way, unsynchronised to any AC supply; this suits them very well for wave power generation. They are *singly-fed*: a single cable can be used for both magnetic field excitation and power take-off. Each phase is electrically independent of the others, and a short-circuit fault in one phase therefore has practically no effect on the operation of the other phases. Rotating switched reluctance generators have found several industrial applications [4], and some attention has already been paid to linear switched reluctance generators (LSRGs) [5][6]; more work in this area is expected to prove fruitful.

This paper presents the design and test of a lab-scale LSRG. Section 2 outlines the principles of operation of an LSRG and power converter; Section 3 presents the electric and magnetic design of the LSRG and power converter circuit, and Section 4 presents the results of static and dynamic tests in the laboratory.

2 Principle of operation

2.1 Electromagnetic energy conversion

An LSRG consists of a translator part, made of salient electrical steel poles, moving relative to a stator made of electrical steel poles energised by current-carrying coils arranged in phases. The phases are energised in sequence, creating a magnetic field and a steady aligning force between opposing stator and translator poles. A prime mover pushes the translator against this force, and the mechanical energy thus input is converted into electrical energy, which can be delivered to an electrical load. Fig. 1 below shows three repeating sections, or *periods*, of an LSRG; the complete LSRG can be made of any number of repeating periods.

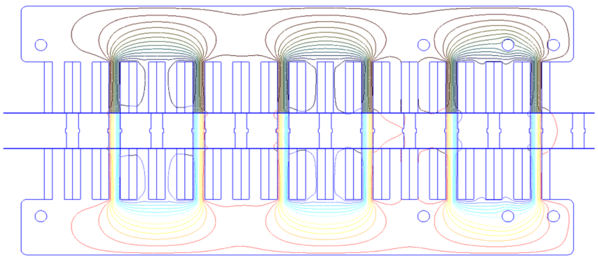

Figure 1: Outline of a 6/4 linear reluctance generator, showing magnetic field lines at alignment. The translator is moving in the +*x* direction, against the attractive force exerted by the magnetic field.

As the translator moves, translator poles come into and out of alignment with opposing stator poles. The geometry of the design is usually arranged so that when one group of translator poles is moving out of alignment, another group of stator poles is moving into alignment. This is often achieved by the use of unequal pole numbers on stator and translator, for example 6/4 – six poles in each period of the stator opposite four in the translator.

For generator action each group of stator poles is energised only when the translator poles are at (or near) alignment, and de-energised only when alignment ends. The retarding magnetic force that results stays approximately constant as the translator moves out of alignment, falling off abruptly as the overlap between poles ends. At this position the phase is de-energised; the next stator pole group are in alignment, their phase is energised, and the cycle repeats.

The electrical power produced can be controlled through regulation of the aligning electromagnetic force F_e acting on the translator. F_e is a non-linear function of both the translator's displacement and the phase currents. Since each phase is energized in turn the total electromagnetic force can be estimated by considering a typical phase of inductance L carrying current i, with the assumption that other phases behave identically:

$$F_e = \frac{i^2}{2}\frac{\partial L(x,i)}{\partial x} \qquad (1)$$

The phase inductance (Fig. 2(a)) is a maximum, L_a, when poles are in full alignment and a minimum, L_u, when poles are fully unaligned. In generating operation, therefore, a retarding electromagnetic force is produced when the phase current coincides with *falling* inductance. This provides a useful design principle for SR generators: the steeper the fall in inductance over a stroke, the higher the achievable peak F_e.

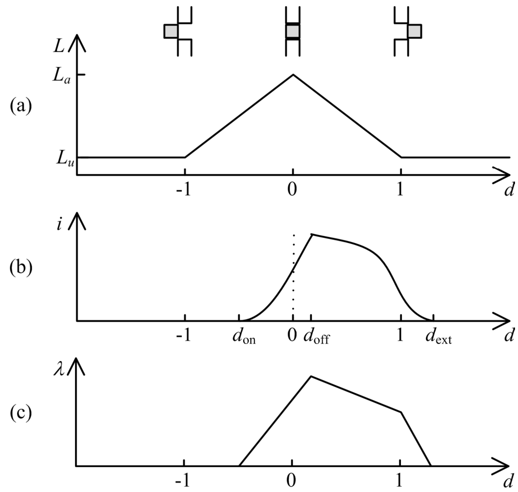

Figure 2: Performance characteristics with translator displacement *d* in one phase of an LSRG: (a) Inductance, (b) current and (c) flux linkage. *d* is normalized over a stroke, from alignment (*d*=0) to unalignment (*d*=1).

2.2 The power converter circuit

Each phase of a LSRG is usually energized by a separate power converter circuit [7], whose purpose is dual: to create and maintain a magnetic field in the air gap (fluxing), and then to deliver generated current to the load (regenerating). The most common and most flexible converter topology is the *asymmetric H-bridge converter* [3] (Fig. 3, below). An external DC voltage, usually supplied from a battery or a rectified AC supply, is needed to charge a filter capacitor; thereafter, energy drawn from the capacitor during the fluxing part of the stroke is replaced during regeneration.

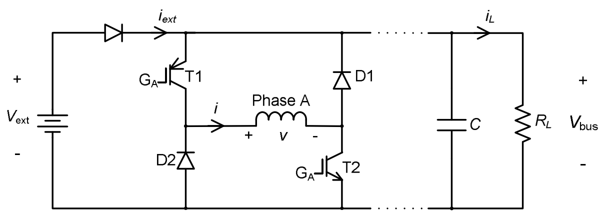

Figure 3: Asymmetric H-bridge power converter circuit, showing the power transistors and freewheel diodes for phase A. Other phases not shown.

The current in a phase leg can be regulated effectively through controlled switching of its power transistors. Turning on transistors T1 and T2 at alignment begins fluxing: a rising phase current flows and core flux develops (Fig. 2(b) and (c)). When the phase current reaches some target value, T1 and T2 are turned off. The energy stored in the magnetic field in air gap sustains the *regenerating current*, which flows through the freewheel diodes D1 and D2 to the load. In a phase of resistance R and inductance L the current i can rise or fall during regeneration, depending on the phase voltage v and translator speed $\dot{x}$, according to

$$v = iR + L\frac{di}{dt} + i\dot{x}\frac{dL}{dx} \qquad (2)$$

In fluxing mode, with T1 and T2 on, $v \approx +V_{\text{bus}}$, and in regenerating mode, with T1 and T2 off, $v \approx -V_{\text{bus}}$. The third term represents the generated voltage, and is approximately analogous to the E_a term in a DC generator. Power conversion performance is reported to be optimized when the regenerating current stays essentially flat until the end of overlap (d=1 in Fig. 2) [8]. This special i_{flat} can be expressed by observing that $di_{flat}/dt = 0$, and substituting into (2) above gives

$$i_{\text{flat}} = \frac{V_{\text{bus}}}{R + \dot{x}\frac{dL}{dx}} \qquad (3)$$

Maintaining $i = i_{\text{flat}}$ is not generally practicable at low speeds, however: the phase current is often maintained at an approximately constant level by chopping the power transistor switches.

2.3 Controlling the LSRG

As with many renewable generation technologies a special challenge is to convert the irregularly varying electrical power developed to a regular form that can be delivered to a power grid. Several regimes have been suggested to control the output voltage V_{bus} from an SR generator. Sawata [8] describes a number of methods, in which V_{bus} is controlled by choosing the phase current setpoint I_{HI} and the turn-on and turn-off displacements in various ways. He warns, however, that achieving a constant V_{bus} is difficult over a wide speed range; for this reason direct voltage control may not be feasible for the reciprocating LSRG rig over its full mechanical stroke.

Force and power control is also possible. The LSRG's ability to tune F_{e} over fractions of a second makes it a particularly attractive prospect for optimizing power transfer from ocean waves [9][10][11] – the voltage developed can then be stepped down to a nominally constant level.

3 Design

3.1 Magnetic and Electric design

The overall geometry of the LSRG was chosen to be double-sided, so that strong attractive forces on the translator cancel in the lateral direction [12]. Choice of the dimensions is informed by several primary requirements: top speed, electromagnetic force and output power, and also a number of secondary considerations: the level of magnetic saturation in the core and peak flux density, specific electric loading, stack depth etc.

The procedure for design of the LSRG is similar to that described by Krishnan and others [3]. A variation of the familiar torque equation for SR machines, derived for the LSRG, gives the approximate stator length based on these requirements, and provides a starting point for the design. Choice of the number of phases was informed by consideration of constraints such as force ripple and the cost of the power converter circuit. A 3-phase 6/4 arrangement was chosen, and from this the stator and translator pole pitches were derived.

Next the pole dimensions are chosen. The goal here is to maximize aligned inductance L_{a} and minimize inductance in the unaligned position L_{u}, while ensuring reasonably low copper losses in the coils and an acceptably flat F_e profile. Stator pole height was chosen to give enough room for the coils to achieve rated current at reasonably low current densities.

Sizing of the converter circuit and load is then carried out. A filter capacitor smoothes out the variation in phase currents, and an electrical load is chosen that develops rated voltage at rated current. The dimensions chosen for the LSRG are shown in **Table 1** below.

Number of periods	3
Number of phases	3
Pole ratio	6/4
Width of a period	144 mm
Stator pole pitch	10 mm
Stator pole enclosure	42 %
Translator pole pitch	10 mm
Translator pole height	32 mm
Turns per coil	350
Rated speed	1500 mm/s
Maximum magnetic stroke frequency	125 Hz

Table 1: Lab-scale LSRG dimensions

4 Test results

The linear test rig is designed to be capable of true four-quadrant operation, and of re-creating ocean wave conditions in a scaled way. It consists of a rotating 5 kW brushless PM motor driving a 1 m ball screw, capable of speeds of up to 2.6 m/s and controlled by a dSPACE DS1103 data acquisition and control unit connected to a host PC (Fig. 4).

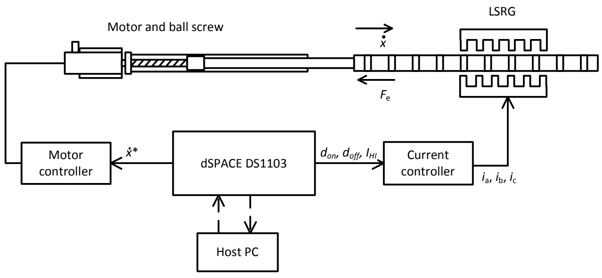

Figure 4: The test-rig

4.1 Static behaviour

As mentioned above a significant goal of the electromagnetic design of a switched reluctance machine is to maximize the phase inductance in the aligned position, while minimizing its unaligned value. The present design achieves an inductance ratio L_a/L_u of approximately 4 (Fig. 5 below). The resulting dL/dx maximizes at 27 H/m, or 250 mH per stroke.

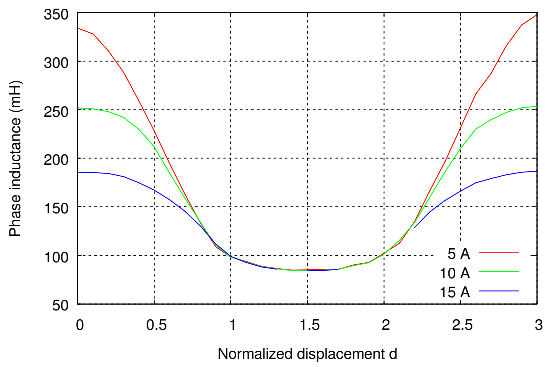

Figure 5: Variation in phase inductance with displacement and phase current

Measurement of the magnetic force developed F_e is important to validate the assumptions made during the design stage. Experimental F_e agrees well with that predicted using 2D finite-element simulation (Figs. 6 and 7, below). Fig. 7, in particular, suggests that F_e may be controlled through regulation of the phase current.

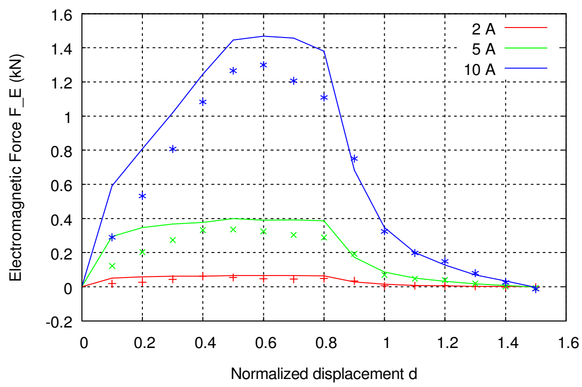

Figure 6: F_e vs normalized displacement d – predicted and experimental

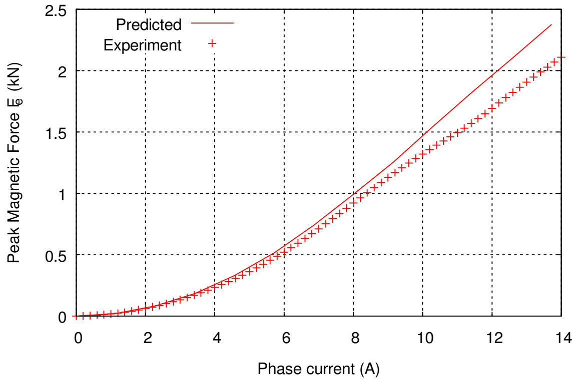

Figure 7: Peak F_e over a stroke vs. phase current. The relationship is appriximately quadratic at low excitations, and linear after the onset of saturation

4.2 High speed

Measurements of phase current, voltage and flux linkage etc. at high speed, made at a number of supply voltages, show that in single-pulse mode power output is highest when $i = i_{flat}$; this occurs when the supply voltage and generated voltage are approximately equal. In these tests turn-on displacement is fixed, and turn-off occurs at $i = I_{HI}$. Hard switching turns off both transistors T1 and T2 simultaneously at x_{off}, resulting in a generated phase voltage v equal to $-V_{bus}$, and an approximately triangular flux linkage characteristic (Fig. 8).

At $V_{ext} = 200$ V $I_{HI} \approx i_{flat}$ (**Table 2**) and average output power P_O over the stroke is maximized. At lower supply voltages maximum generated i is higher and endures for longer (Fig. 9), but at the expense of a slower build-up during the fluxing stage. At higher supply voltages i rises to its maximum more quickly during fluxing, but is quenched more quickly during regeneration.

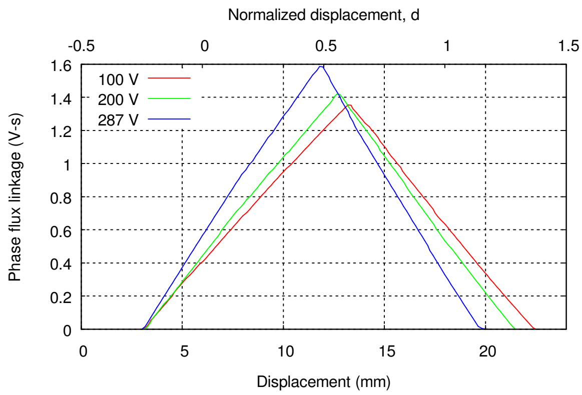

Figure 8: flux linkages in phase A, at a selection of supply voltages

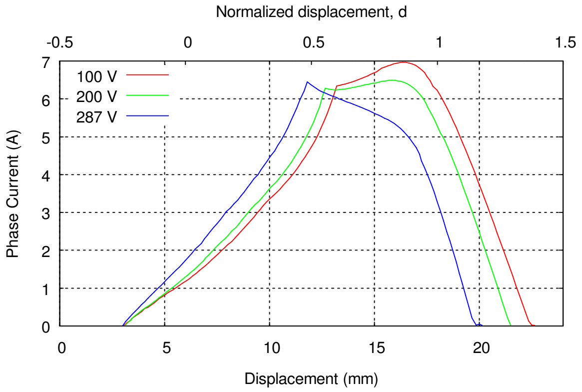

Figure 9: Phase currents at high speed, at a selection of supply voltages V_{ext}. Turn-on at d_{on}=-0.25; turn-off at max current (6.3 A)

In each magnetic stroke the operating point traverses a closed flux-current loop in the clockwise direction, and the energy converted is proportional to the area enclosed by the loop. Fig. 10 below shows the area is a maximum at V_{ext}=200 V.

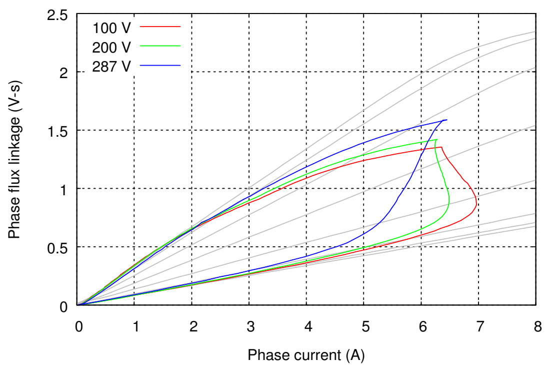

Figure 10: Dynamic flux-current loops at high speed at various supply voltages

It is important to characterise the energy flow in an SR generator. During the fluxing stage of each stroke the phase current i flowing through T1 and T2 must be supplied, either by the external power supply or the filter capacitor; it is desirable to minimize its average value over a stroke I_{IN} [8]. During regeneration i flows back via the freewheel diodes D1 and D2 into the RC combination, averaging I_{OUT} (Fig. 11).

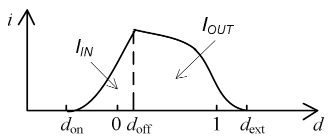

Figure 11: Average currents over a stroke

The charge lost from the filter capacitor C during fluxing is replaced during regeneration, so the *net* average generated current in the load is therefore given by

$$I_O = I_{OUT} - I_{IN}$$

The *excitation penalty* ε is defined as

$$\varepsilon = \frac{I_{IN}}{I_{OUT}}$$

This is an important measure of the energy flow in the generator, and is roughly analogous to power factor in an A.C. generator. In the present tests ε was found to be lowest at V_{ext} = 100 V; optimal power conversion at 200 V was therefore achieved at the expense of a slightly higher ε.

The test at V_{ext}=287 V shows the importance of maintaining $V_{bus} \geq V_{ext}$.. The predicted generated voltage is expected to be no more than 243 V by (2), with the result that current flows continually between the external supply and the load, compromising any generation that takes place.

V_{ext}	100 V	200 V	287 V
V_{bus}	207 V	230 V	286.97
i_{flat}	5.70 A	6.33 A	7.9 A
ε	0.535	0.554	0.664
I_O	2.14 A	2.02 A	1.40 A
P_O	443 W	464 W	403 W
$F_{e(max)}/F_{e(av)}$	2.06	2.04	2.20

Table 2: Average output current, power and excitation penalty at high speed (1500 mm/s), single-pulse. i_{flat} is computed using (4).

4.3 Low speed

While LSRG operation in single-pulse mode is desirable its wide speed range makes the requirement to grow and shrink the supply voltage as required especially challenging. For the present tests, then, the phase currents are controlled by fixing the turn-on and turn-off displacements d_{on} and d_{off}, and achieving a maximum current I_{HI} by means of a PWM current converter. Results for phase current and flux linkage are given in Figs. 12, 13 and 14 below.

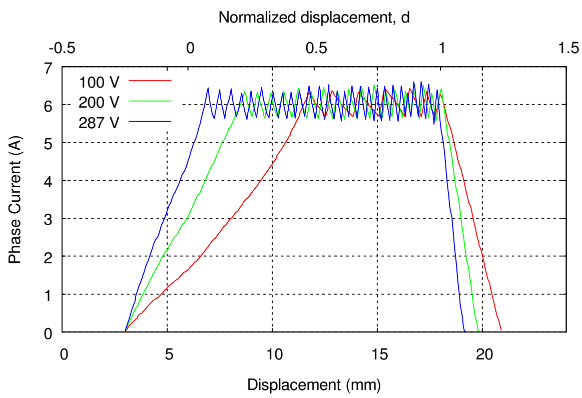

Figure 12: Phase currents at low speed, at a selection of supply voltages V_{ext}. Turn-on at d_{on}= –0.25; turn-off at d_{off}=1.

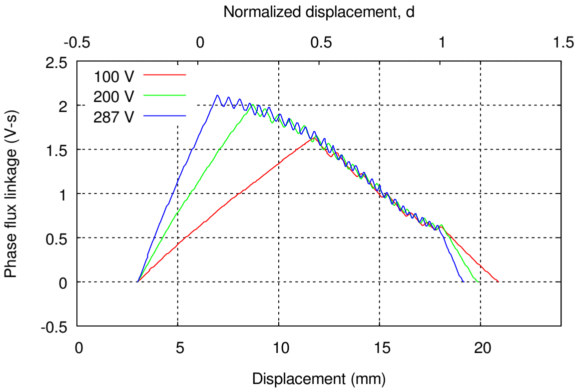

Figure 13: Phase flux linkage at low speed

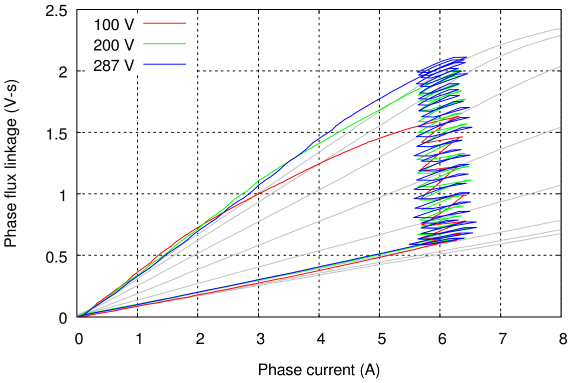

Figure 14: Phase flux linkage vs. current at low speed

5 Conclusion

Design and construction of the LSRG has shown that the use of SR technology in a direct-generation application involving reciprocating movement is a viable option for PTO designers. The electromagnetic force developed has been shown to be finely controllable over short timescales.

Construction of the linear test rig**,** capable of re-creating ocean wave conditions in a scaled laboratory environment, has proved to be an effective validating tool, and an invaluable test facility for the scaled linear PTO prototype.

Further work is under way to demonstrate the LSRG's performance using a number of control regimes in a scaled ocean wave environment.

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