Control of Linear Electrical Generators for Direct Drive Wave Energy Conversion

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Abstract—Linear generators have been proposed as a suitable power take-off system for direct drive wave energy conversion. Coupled directly to a reciprocating wave energy device, it is suggested that linear generators could be a viable alternative to hydraulic and pneumatic systems. This paper discusses the challenges involved in control of a direct drive wave energy converter, predominantly for maximum power extraction through electrical means. It highlights characteristics of linear generator control, particularly due to mechanical and electrical resonance, and the implications upon the power conversion stage. Results show that an overrated power converter is necessary due to the reactive power requirement for optimal control.

Index Terms—Control, direct drive, linear machines, wave energy conversion.

I. INTRODUCTION

The generation of electricity by harnessing the power of sea waves has been at the forefront of research into renewable energy for more than 25 years. Although extracting energy from the sea waves has been investigated for decades, it was the 1973 oil crisis that triggered a sudden growth in research into wave energy in several countries [1]. More recently, the 1997 Kyoto Treaty has prompted the continuation of this research.

Since the early seventies, many prototypes have been developed to extract energy from sea waves, and convert it into electricity. In comparison with wind energy, extracting power from sea waves is very much in its infancy. While there is a general consensus of the optimal design parameters for a wind turbine – three blades mounted on a horizontal axis; there is as yet no widely accepted design approach for wave energy converters (WECs).

Presently, the vast majority of WECs at a prototype or later stage use either pneumatic or hydraulic power take-off systems. Another form of power take-off system, which has often been overlooked, is the direct electrical power take-off system. It has been shown through a comparative study that a direct electrical power take-off system has potential and justifies further research and development [2]. In particular, the area of research that has attracted interest is the use of a linear electrical generator directly coupled to the wave energy device, as implemented in WECs such as the Archimedes Wave Swing [3], [4]. This eliminates the need for an interface between the wave energy device and an electrical generator, thereby reducing complexity and increasing the overall reliability. Fig. 1. shows a diagram of a generic direct drive WEC.

II. LINEAR MACHINE TOPOLOGIES

The introduction of high energy density permanent magnets in the 1980’s led to the development of novel permanent magnet machine topologies [5]. Neodymium-Iron-Boron or “rare earth” magnets enabled machines such as Variable Reluctance Permanent Magnet (VRPM) machines with high shear stresses to be developed. VRPM machines are particularly suited to low speed, high torque applications,
which prompted their use in wave energy conversion.

VRPM machines are described in papers by Harris, Iwabuchi and Weh [6]-[10]. They have a toothed structure that moves relative to a stationary part consisting of permanent magnets with a small pole pitch. A large force is developed in the airgap between the permanent magnets and the toothed translator, which is caused by an energy change over a very short distance. This is due to a rapid change in flux provided by the slotted surface, which varies the reluctance as the translator moves along the magnet pitches.

A study by Weh shows that a VRPM machine, namely, the Transverse Flux Permanent Magnet (TFPM) machine, can have a shear stress of up to 200kN/m²; 10 times greater than a conventional linear generator [10]. The study also suggests that the machine would be smaller, lighter and more efficient than a conventional linear generator with a similar power output. However, the inherent inductance in the TFPM machine meant that it would suffer from low power factor while operating at full load. The unconventional design also meant that construction may prove to be rather difficult [4].

Analysis has shown low power factor to be a trait of this machine type and is a compromise that needs to be made for the high specific output [11], [12]. Therefore, to achieve a high average power output, compensation by capacitor banks or active power factor correction is needed. It is most likely, however, that a combination of both would be required to allow for variations in electrical frequency.

Efforts made to overcome certain problems related to the VRPM topology include the Linear Vernier Hybrid Machine (LVHM), which was proposed as an alternative to the TFPM machine. Although the shear stresses are not as high as that of the TFPM machine, the more conventional machine structure simplifies construction considerably. Another topology proposed by Baker and Mueller is the air-cored tubular machine. Unlike the LVHM, this topology does not possess the favorable high shear stresses which are associated with the topologies mentioned above. But in turn, it does not suffer from low power factor, requires a simpler support structure due to the absence of large magnetic attraction forces, and facilitates the use of conventional seals due to its tubular design [13].

III. CONTROL

A. The need for control

The reciprocating motion of linear electrical generators suggests direct coupling to a “point absorber” or “heaving buoy” type of wave energy device. These are deep water wave devices with small physical dimensions compared to the incident wavelength. They are usually axisymmetric about the vertical axis and have a narrow bandwidth due to its small horizontal extension. Therefore, it is essential that the motion of a point absorber is controlled in order to extract as much energy as possible from the waves.

Due to the random nature of sea waves, an uncontrolled point absorber will operate mostly away from resonance and would therefore only extract a small percentage of the maximum power available, as shown in Fig. 2. In addition, control is required to limit the excursion of the point absorber so that maximum stroke length is not exceeded in the event of freak waves occurring. In a similar sense, although it is desired that as much energy as possible is extracted from the waves, the rating of the power take-off must not be surpassed. Therefore, it is desired for a WEC to operate away from resonance in some circumstances.

B. Physical implementation

Much of the research into implementing control for point absorber WECs has focused on mechanical methods; the majority of which have either been based on a form of mechanical braking system such as a friction coupling or a clutch mechanism, or a valve that regulates the fluid or air pressure. In a hydraulic system, the use of a variable valve would be the obvious choice for control as it would complement the power take-off without adding complexity to the overall system. Such mechanical methods could be implemented in a direct drive WEC although it would seem counter intuitive due to the lack of mechanical power take-off, thereby adding an extra degree of complexity to the WEC. A much simpler option would be to utilize the linear machine itself to control the motion of the point absorber; thereby having an electrical power take-off with electrical control. In addition, it is well known that linear machines benefit from being able to be controlled with a high degree of variability and precision that would not be possible with a mechanical system. This has been demonstrated in a number of applications ranging from nanopositioning mechanisms to high power inverter drives for high speed trains.

C. Control considerations

Similarly to oscillating water columns (OWCs), direct drive WECs are able to extract energy from both rising and falling waves. However, unlike the generator coupled to the Wells turbine in an OWC, the motion of a linear machine is bidirectional and therefore experiences both positive and negative forces. From the EMF profile of a linear generator, it is apparent that phase reversal occurs at the frequency of oscillation each time the translator reaches its maximum excursion, stops, and changes direction. Fig. 3. illustrates this point.
This is equivalent to a change in phase rotation for a conventional machine and is a concern if the generator is directly grid connected.

A point absorber WEC can be represented using the electrical analogue of a mass spring damper system.

\[ Z_1 = R_1 + j\alpha L - j\frac{1}{\alpha C_1} \]  
\[ Z_2 = R_2 + j\frac{1}{\alpha C_2} \]

Using the maximum power transfer theorem, the power transferred to \( Z_2 \) can be maximized if the impedances of \( Z_1 \) and \( Z_2 \) are complex conjugates of each other, as in (3). Therefore, the reactive components of \( Z_1 \) and \( Z_2 \) will be of opposite phase although their magnitudes will be equal.

\[ R_1 + j\alpha L - j\frac{1}{\alpha C_1} = R_2 + j\frac{1}{\alpha C_2} \]  

At resonance, the imaginary parts disappear, leaving the damping components \( R_1 \) and \( R_2 \). The energy in \( R_1 \) is radiated back into the sea; whereas the energy in \( R_2 \) is transferred to the power take off for electricity generation. Therefore, the theoretical limit for the wave energy absorbed by a point absorber WEC is 50 percent. \( V_{fe} \) and \( I_u \) are in phase with each other, which is analogous to wave excitation force being in phase with device velocity.

It should be noted that the selection of values for \( R_2 \) and \( C_2 \) determines the magnitude and phase of the voltage \( V_{fg} \), which represents the generator force. The physical model, however, controls the generator force to determine the hydrostatic spring stiffness, and hydrodynamic damping.

**IV. REACTION FORCE**

Similarly to a conventional electrical machine, the fundamental principle upon which a linear machine is based lies with the force on a current (\( I \)) carrying conductor within a magnetic field (\( B \)); a relationship that arises from the Lorentz force equation:

\[ F = qvB = IlB \]  

where \( q \) is the charge traveling along a conductor of length \( l \) at a velocity \( v \), assuming that the conductor is perpendicular to the magnetic field.

In the case of a VRPM machine, the magnetic field \( B \) is produced by the armature currents and therefore able to control the generator reaction force. Indeed, it is the only feasible approach for force control as all other factors such as geometry and permanent magnet properties are generally fixed parameters.

For any WEC, there are two parts to the resonance requirement in extracting maximum power.

**Mechanical resonance:** the natural frequency of the wave energy device must be in tune with the frequency of the driving wave. Hence, the velocity of a point absorber will be in phase with the wave excitation force. This is required to transfer as much energy as possible from the waves to the point absorber.

**Electrical resonance:** the armature current must be in phase with the induced EMF. This gives unity power factor, and hence unidirectional power flow, which is required to reduce \( I^2R \) losses.

For a directly driven WEC, an additional factor must be taken into account as both requirements need to be achieved through armature current control. As stated previously, the armature currents must be in phase with the induced EMF for electrical resonance, which was the basis of a control algorithm proposed in [14]. Since the induced EMF is directly proportional to the velocity of the point absorber, the same can be said of the armature currents if it is controlled to follow the EMF profile. Therefore, this will produce a reaction force in
the form of damping \((B)\), which is linearly dependent on velocity as shown in the differential equation for a forced mass spring damper:

\[
M \frac{d^2 x}{dt^2} + B \frac{dx}{dt} + Kx = f(t)
\]  

(5)

The spring stiffness \((K)\) is proportional to the displacement of the point absorber as shown in (5). Therefore the envelope of the armature currents required to produce this spring stiffness force will be 90 degrees out of phase with the envelope of the induced EMF, as shown in Fig. 5. This suggests that mechanical and electrical resonance can only be achieved simultaneously if no spring stiffness force is required from the generator.

Fig. 6. shows the instantaneous power produced by a linear generator for a point absorber WEC with a natural frequency of 1.4 rad/s excited by a sinusoidal wave force with a frequency of 1.3 rad/s. The spring stiffness force required for mechanical resonance means that energy is returned from the power take-off system to the sea for part of the cycle in order to extract more energy for the rest of the cycle. The result is higher overall net power flow.

V. POWER CONVERTER

The electrical output from a linear generator varies in both amplitude and frequency due to its reciprocating motion. Grid connection requires a constant voltage and frequency, which can be provided through the use of a power converter. A diode rectifier and inverter would be sufficient for this purpose since the converter merely rectifies the generator output and reconstructs the mains voltage and frequency. However, the need for armature current control means that active rectification would be required, prompting the use of two back-to-back inverters. The DC link voltage is particularly important for generator force control as it determines the rate of change of the armature currents according to (6).

\[
V = L \frac{dl}{dt}
\]

(6)

\(V\) is the voltage across the inherent inductance of the generator and \(l\) is the armature current. If the generator has a large inherent inductance such as is the case for electrical machines based on the VRPM topology, a much larger DC link voltage would be required in order to compensate for the large inductance, which imposes a greater restriction on the rate of current change. A poorly maintained DC link voltage would obviously result in poor current control.

For an uncontrolled point absorber, the current is controlled to be in phase with the induced EMF to maximize the real power generated. In this case, the power converter is rated for the maximum power, which is not more than twice the average power at steady state. For a controlled point absorber, where the current is controlled to produce a specific reaction force from the generator, the power converter needs to be overrated to cope with the reactive power demands. The average power may be orders of magnitude lower than the peak power, as shown in the comparison between a resonant (fig. 7(a)) and an off-resonant (fig. 7(b)) point absorber WEC. Fig. 8. emphasizes this point by showing the variation in peak power compared to the average power as the frequency of wave excitation changes. As expected, the peak power is lowest when the wave frequency coincides with the natural frequency of the point absorber, which has been set to 1.4 rad/s.
that is unrealizable in real seas. These however, along with an overrated power converter, are not drawbacks due to the fact that the linear generator performs the dual function of a power take-off and control mechanism, and there are in fact advantages to the gained. Further investigation is required to realize these advantages.

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