"Snapper™": an efficient and compact direct electric power take-off device for wave energy converters

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SYNOPSIS

Wave energy converters typically deliver their power output as a low speed high force motion. Most forms of electrical machine create reaction force by virtue of shear stress at the active surface due to the interaction of magnetic flux and electric current. Heat generated due to the I^2R loss in the winding limits the shear stress and reduces the efficiency. The only way to achieve acceptable efficiency is to operate with low current in the windings leading to low shear stress. The machine is thus very large and heavy. The design of such machines for low speed applications is therefore a difficult compromise between excessive weight and low efficiency; wave energy converters present an extreme example of this situation. A novel device is described which potentially offers significant advantages of conventional generator technology.

INTRODUCTION

Wave energy converters, WECs, typically receive their power input as a low-speed, high-force motion, whereas the electrical generators used to deliver the power output typically operate with high speed and low force. The wide range of alternative forms of WEC can be distinguished and classified according to the means by which this mismatch is overcome.

The force and velocity of the input naturally suggests the use of hydraulic systems for the first stage of power conversion. The Pelamis device is a good example of the successful application of hydraulic power transmission in a WEC. Pneumatic power conversion is an alternative as exemplified by oscillating water/air-column devices such as the shoreline Limpet device. Other devices use hydrodynamic effects to create a static head of water for use in a miniature hydro-electric plant; examples include the Wave Dragon and the Tapchan. The Archimedes Wave Swing, AWS, is the only device known to the authors in which the wave forces are directly reacted by the electrical generator working at the same speed as the wave motion itself [1].

Authors' Biography

Professor Ed Spooner is emeritus professor of engineering with the New and Renewable Energy Group of the School of Engineering, University of Durham, UK. He has worked in industry and academia on the conception, development and application of special electrical machines for more than 35 years. He is presently director of EM Renewables Ltd, Crook, County Durham, UK and also of Evolving Generation Ltd, a university spin-out. He has acted as consultant to many industrial companies worldwide concentrating on applications in the renewable energy sector.

Dr Jamie Grimwade is presently the Marine Renewables Technology Specialist at NaREC a position he has held since 2003. Prior to working for NaREC he was employed as a Marine Surveyor by the Maritime Coastguard Agency (MCA), gaining experience in UK maritime regulation, survey, inspection and documentation. Dr Grimwade gained a PhD from Newcastle University in 2003 concerned with the investigation of a novel floating vessel concept, optimised to minimise wave excited motions in offshore environments.

Most forms of electrical machine create reaction force by virtue of shear stress at the active surface as a consequence of the interaction of magnetic flux and electric current. Heat generated due to the I^2R loss in the winding limits the shear stress and reduces the efficiency. The only way to achieve acceptable efficiency is to operate with low current in the windings leading to low shear stress. The machine is thus very large and heavy. The design of such machines for low speed applications is therefore a difficult compromise between excessive weight and low efficiency; wave energy converters present an extreme example of this situation [2]. An uncommon class of electrical machine displays very high shear stress and zero loss. These machines are magnetic couplings. Two similar arrays of permanent magnets align, locking the two parts and shear stresses up to 10 times those in wound electrical machines can be developed before the coupling snaps. “Snapper” is a new form of electrical generator devised specifically for application in WEC’s and based on the concept of a snapping magnetic coupling, which promises to offer direct-drive, compact and lightweight generation opportunities.

PRINCIPLE OF OPERATION

The basic elements of the Snapper device are illustrated in Figure 1. The figure shows horizontal motion for convenience but in a WEC it would probably be installed vertically. The device uses a magnetic coupling designed to provide insufficient holding force to resist the input driving force. The magnetic coupling has two linear arrays of magnets; the array linked to the input is referred to as the translator and the array linked to the fixed base is the armature. The translator array is longer than the armature to allow for the range of relative movement due to the wave motion and changes in the water depth due to tides. The system would be arranged in a double-sided configuration to balance the magnetic attraction between the two sets of magnets and guides would be provided to maintain the separation. The armature is linked to the seabed or other fixed base through an elastic coupling that permits a limited range of movement and it would also run in guides. Alternatively the elastic coupling could be attached to the input drive rod.

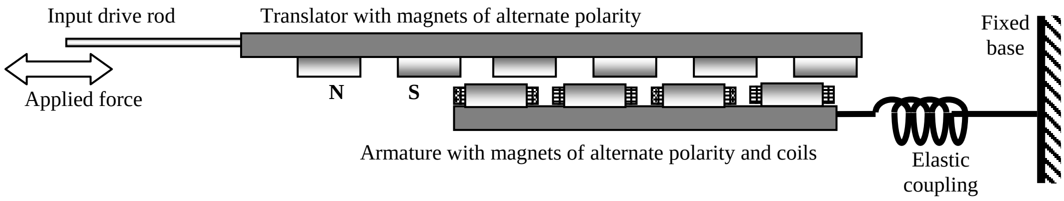

Fig. 1 Basic Arrangement of Snapper

Between snapping events the magnetic coupling extends, storing energy in the magnetic field and in the elastic mounting of the armature. When the extension of the magnetic coupling reaches a critical value, the coupling snaps and the armature moves rapidly to a new alignment position. The stored energy is released in a short violent pulse. Coils wrapped around the magnets of the armature experience rapidly changing magnetic flux, develop high emf and collect the stored energy for delivery to an external electric circuit. The high velocities reached by the stick-slip motion allow the electrical generation to proceed efficiently. The high shear stress typical of magnetic couplings leads to designs that are much more compact than is possible with conventional linear electrical machines. The high velocity reached by the armature leads to electrical power conversion with high efficiency.

The electrical circuit is shown for four coils in Figure 2. Each coil is connected to a bridge rectifier which feeds a dc system at fixed voltage.. The coil emfs are all in phase and so they may be connected in series or parallel combinations for convenience. The voltage at the dc load is the only means of controlling the machine. The dc busbar feeds power to the utility grid via a conventional three phase inverter.

AN OUTLINE EXAMPLE

We take for illustration a magnetic coupling comprising 80 magnets on each of the two armature arrays. The armature is 4m long and 250mm wide. Each magnet is 20mm thick. The armature magnets are 30mm wide in the direction of travel to provide space for the coils. Additional space may be provided by using shallow slots in the laminated core. The translator magnets are 40mm wide. All the permanent magnets are made of the modern rare-earth material Neodymium-Iron-Boron with a remanent flux density of 1.27T. Both translator and armature iron sections must be constructed from laminations typically 0.5mm thick to avoid unwanted eddy currents as the flux changes during operation. The permanent magnet material is electrically conductive and it is necessary to build the magnets from slices about 3mm thick.

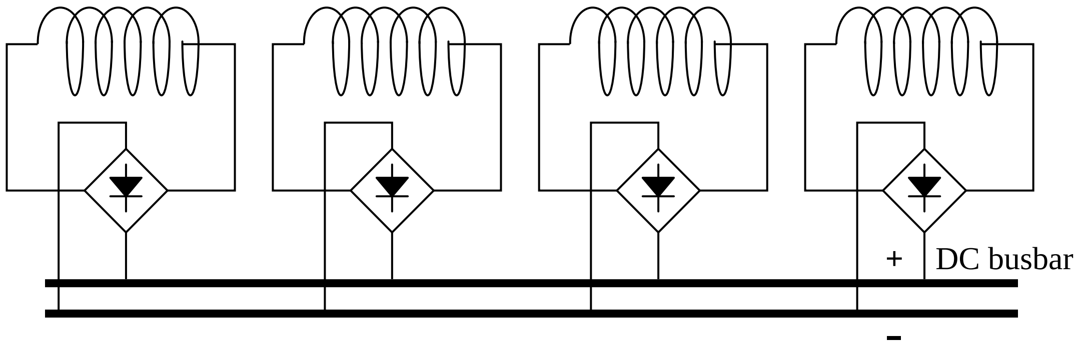

Fig. 2 Electric Circuit Arrangement

The mass of active iron copper and magnet is approximately 840kg, Additional steel and inactive magnets are required in the translator to accommodate the specified working stroke. The field pattern is illustrated in Figure 3 for a short section of the double-sided machine in the situation where the armature is displaced sufficiently to produce a shear force close to the maximum, tending to push the armature to the left. The central iron section of the translator is needed simply as a means of applying the drive force to the translator magnet arrays. The magnetic flux passes directly through and it has negligible effect on the magnetic fields.

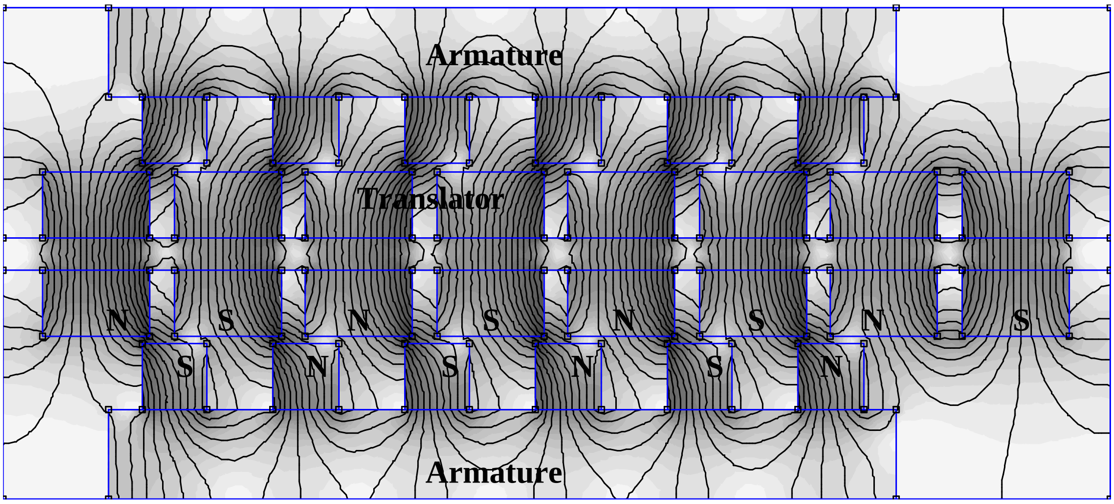

Fig. 3 Magnetic Flux Distribution for Alignment Near Position of Maximum Shear Force

Each coil has 960 turns of 0.63mm diameter wire and is placed around one of the armature magnets. The mass of active material in the armature, including both parts with their coils and the necessary magnetic iron supporting the magnets is 440kg; additional material is required for guides and mechanical supports. The main parameters of the device are given in Table 1.

Magnetic coupling maximum force	*kN*	565
Armature spring constant	*MN/m*	2.8
Total mass of armature	*kg*	531
Number of armature coils		160
Coil resistance	*Ω*	55
Coil inductance	*mH*	416
Coil emf (rms for relative velocity of 1m/s)	*V*	186

Table 1 Example Design Principal Parameters

If a slowly increasing force is applied to the translator then the spring will stretch up to 138mm before the tension exceeds the peak coupling force between armature and translator. The strain energy in the spring at this stage is 28.5kJ. If the energy is stored as strain energy within a steel spring operating at a stress of up to 500MPa, then approximately 500kg of steel is required. However, a practical design of spring would not stress all the material to the full extent and the mass required would be considerably greater. Alternative forms of mechanical energy storage are being considered including gas springs and magnetic couplings of similar form to the main coupling.

PERFORMANCE SIMULATION

The operation of the device is governed by the dynamic behaviour of the electrical and mechanical systems following the loss of coupling. A simulation reveals extremely complex behaviour. To simplify simulation we consider the device being driven by an input with defined position vs time characteristic, i.e. a very stiff drive. A sinusoidal variation is adopted, similar to the motion that would be typical of a WEC. The amplitude and period of the drive movement and the voltage of the dc load along with initial values of position and velocity determine the performance. Figures 4 to 11 display typical simulation results for a drive amplitude of 0.5m with period 6 sec and a dc load voltage of 400V.

During the 1.5 second period simulated the average combined power output from the 200 coils was 43.2kW with I^2R loss of 2.2kW, giving an efficiency of 95.2%. However, the eddy current losses in the magnets described above have been neglected for the simulation as have iron losses and friction in the guides. An efficiency of approximately 90% is therefore a more realistic value.

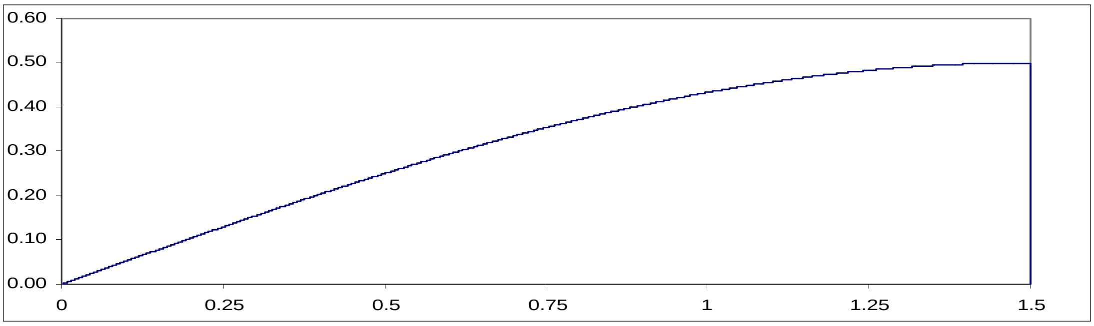

Fig. 4. Drive Input Position (m)

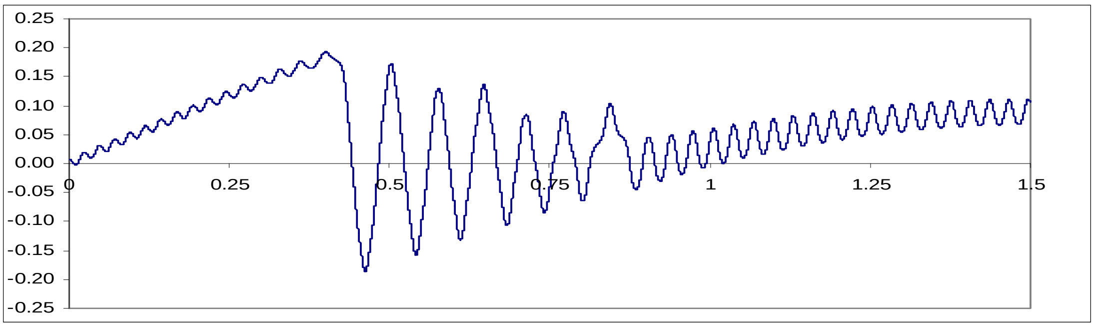

Fig. 5. Armature Position (m)

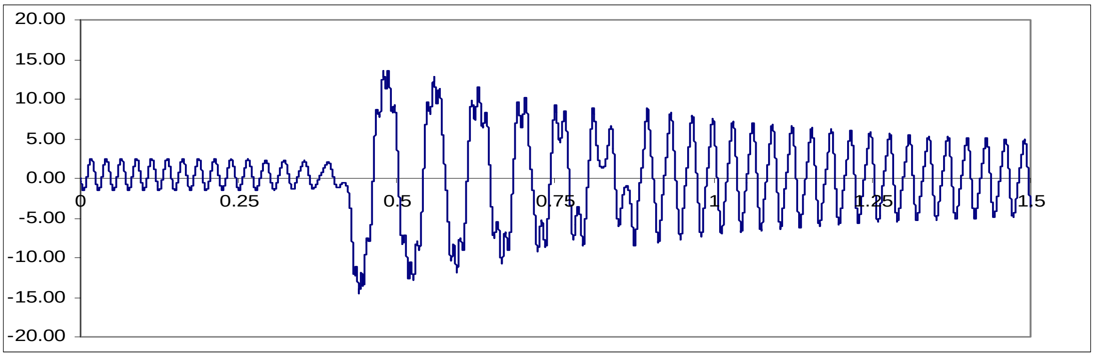

Fig. 6. Armature Velocity (m/s)

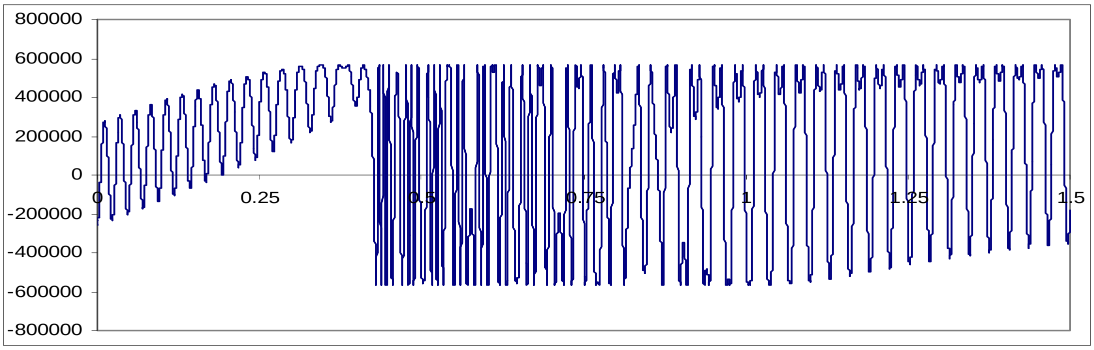

Fig. 7. Magnet Coupling Force (N)

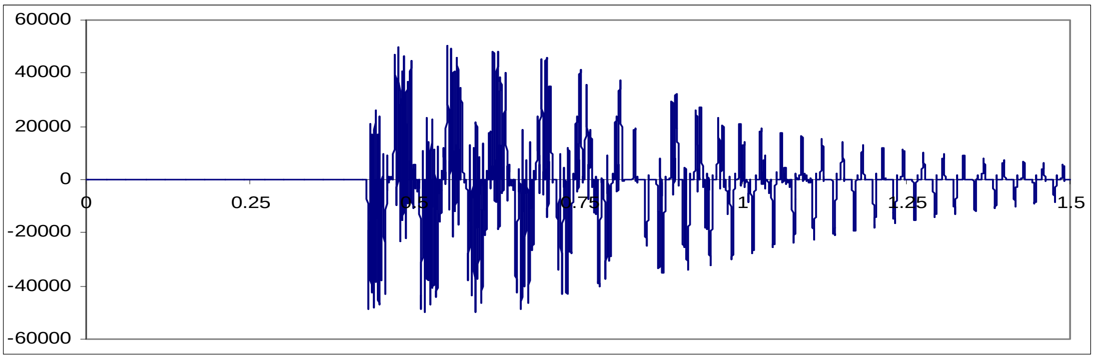

Fig. 8. Electrical Force (N)

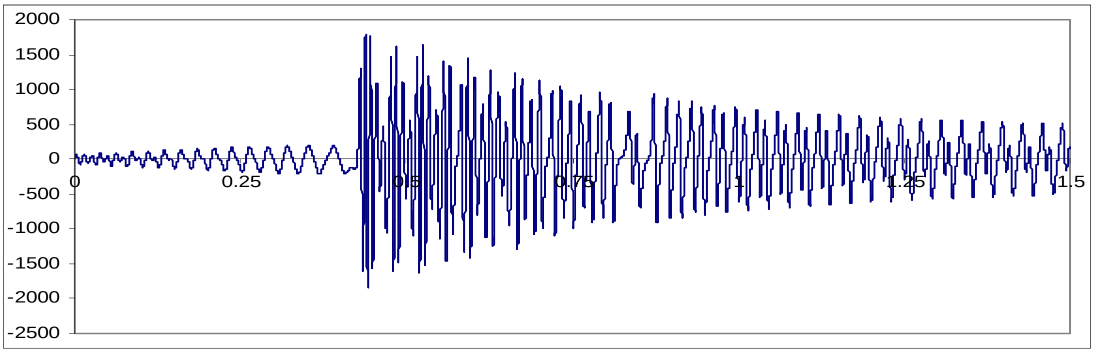

Fig. 9. Coil Emf (Volt)

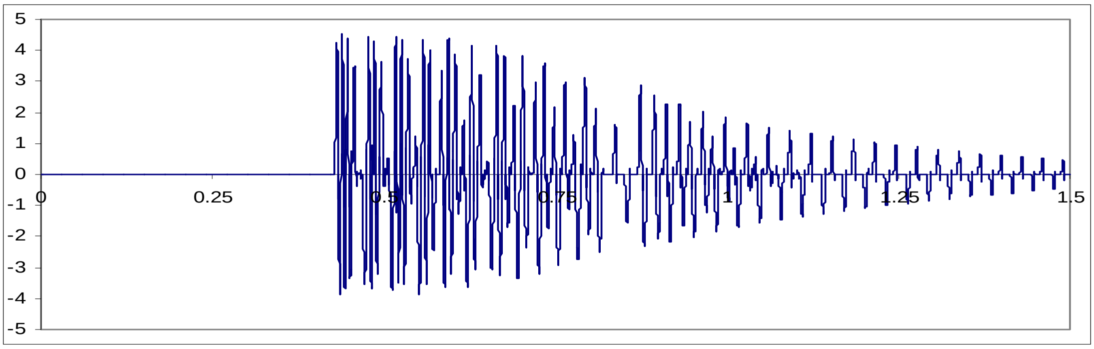

Fig. 10. Coil Current (Amp)

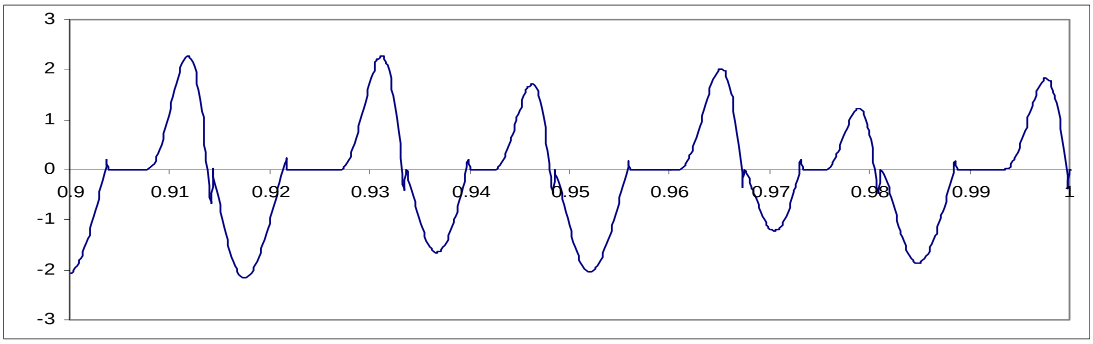

Fig. 11. Magnified View of Coil Current (Amp)

AVERAGE PERFORMANCE

The results given by the simulation vary dramatically with the initial position and velocity of the armature. Figures 12 illustrates the extent of the variation in both average power over a cycle and efficiency. One hundred simulations were carried out for input drive amplitudes of 0.5m and with 400V load voltage in each case. There is clearly a very large variation from cycle to cycle but the efficiency remains bounded.

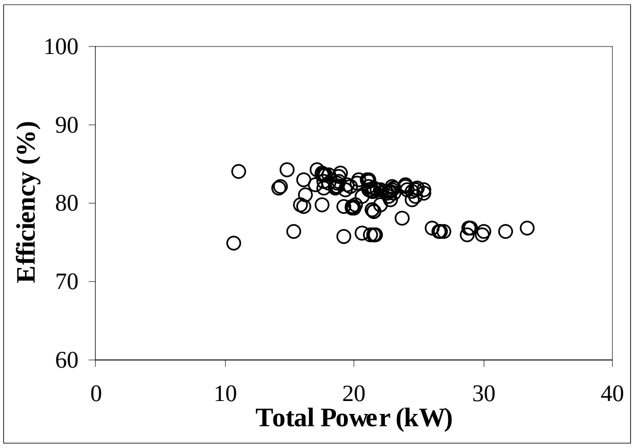

Fig. 12 Efficiency (%) vs Power (W) for 400V dc, 0.5m amplitude

Taking the average of 100 simulations each of 1.5 seconds duration and for a range of dc load voltages produces the characteristics in Figures 13 and 14 which are reasonably well defined. The characteristics display the potentially useful properties that the output power and efficiency are fairly insensitive to the amplitude of the driving motion and to the voltage at the dc load. This means that the electrical power conversion system can be a simple low cost variety and requires little or no control invention to match the system to changing conditions.

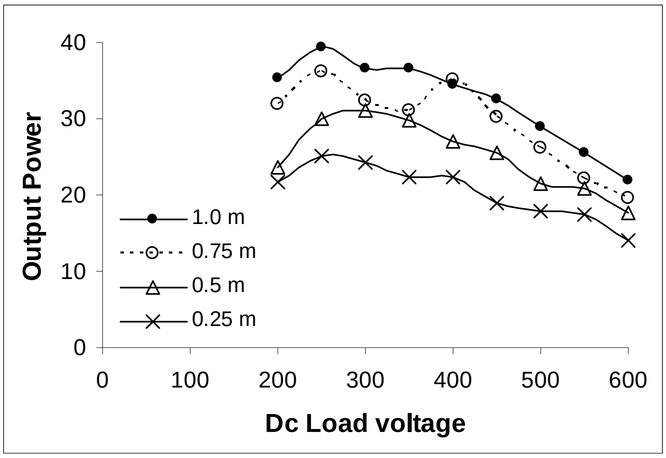

Fig. 13: Variation in Average Output Power (W) vs DC Voltage for various input amplitudes

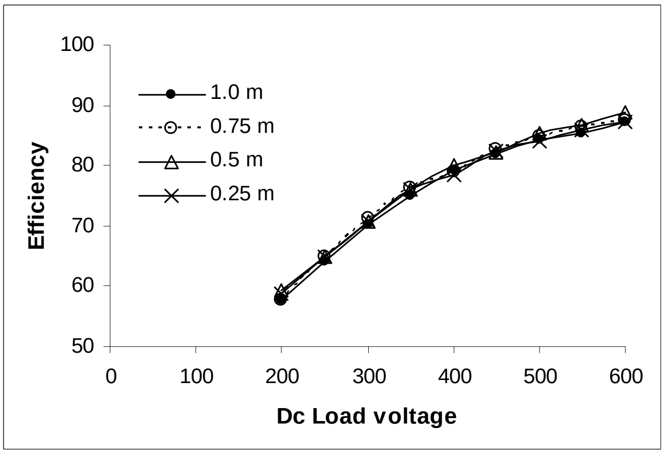

Fig. 14: Variation in Average Efficiency (%) vs DC Voltage

Operating the machine at a fixed dc voltage of 500V yields output of 20 to 30 kW for wave amplitudes over a 4:1 range and with efficiency of about 85%.

COMPARISON

A conventional permanent magnet machine was designed with the same overall dimensions as the Snapper design, 4m long 250mm wide and similar materials and operating temperatures. It comprises two back to back linear stators with a permanent magnet translator sandwiched between. Operation at low speed is dominated by the effect of winding resistance and so very deep (120mm) slots are used. Nevertheless the low current density leads to a low shear stress at the working surface. The mass of the two stators and the enclosed section of the translator is 2200kg. If an efficiency of 85% is specified for motion with amplitude 0.5m and period 6 sec then it is found that the machine can deliver only about 8 to 9kW, giving a power to weight ratio of about 4kW per tonne compared with about 30kW per tonne for the Snapper. Furthermore, the machine develops an emf that varies in accordance with the input velocity and so the load must be controlled to accommodate the variation. Slightly better performance could be achieved with a more complex control strategy.

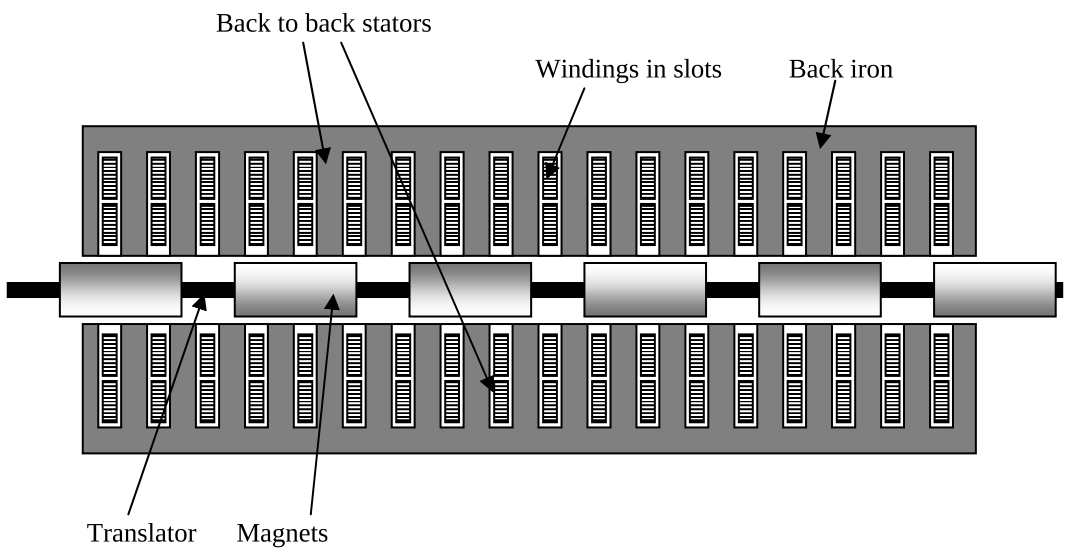

Fig. 15: Layout of PM Linear Generator

CONCLUSION AND FURTHER DEVELOPMENT

The Snapper device achieves a high power by virtue of the high velocity that occurs after the magnetic coupling has broken.

The dynamic behaviour is extremely complex with different movement in successive cycles. The operation appears chaotic but constrained within boundaries.

The study of the Snapper device is at a very early stage. Simple simulations have been carried out that indicate that the device offers a substantial improvement over conventional linear electrical generators in terms of power to weight ratio. No attempt has yet been made to optimise the design, although a number of example studies indicate trends.

The electrical performance is quite insensitive to the velocity of the input drive. The output voltage is determined almost entirely by the velocity that the armature acquires following the snapping of the magnetic coupling. Consequently the power conversion system can be a relatively simple low-cost type. Conventional linear generators would require a more complex converter controlled to adjust the generator loading continuously according to the velocity of the drive.

The mechanical spring is a potential source of difficulty. It is required to store a large amount of energy and could be a bulky and heavy component. Possible alternatives to the conventional coil, leaf or bellow spring include gas springs and magnetic couplings that have sufficient extension that they do not snap during the normal operation. Further work is required particularly to assess such alternatives.

REFERENCES

1. H.Polinder, F. Gardner, B. Vriesma, “LinearPM generator for wave energy conversion in the AWS”, Proc. ICEM 2000, Espoo, Finland

2. M.A. Mueller, “Electrical generators for direct drive wave energy”, IEE Proc., GTD., Vol 149, 4, pp446-456, July 2002.