

A High Force Density Generator Using a Slipping Magnetic Coupling

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Abstract

A new form of permanent magnet generator is described in which coils surrounding the magnets of a permanent magnet coupling experience emf when pole slipping occurs. The device offers the possibility of developing high shear stress at the active surface along with reasonable efficiency at low speed. The operation of the device is highly complex and may exhibit chaotic behaviour. The static characteristics have been verified by finite element and experimental studies

1 Introduction

Renewable energy applications typically demand low-peed, high-force power trains and further demand the ability to work over a range of operating speeds, consequently it is usual for the electrical generator to be preceded by a gearbox to transform the torque and speed to more convenient values, despite the cost, weight and loss penalties incurred in the gearbox. Wave power is the most extreme field, most devices demanding not only very low-speed operation but also they naturally produce linear reciprocating action. The method of transforming the low speed reciprocating action of the waves to a high-speed continuous rotation is the defining feature of most wave power machines.

There is a large incentive to simplify the power train of a wave power device because every link in the chain represents a significant potential source of failure in the hostile environment in which the devices must work for long periods unattended. Direct-coupled permanent-magnet linear machines have been used [1] and new forms of linear machine [2,3] are under investigation.

In most types of electrical machine, heat generated due to the I^2R loss in the armature winding limits the shear stress that can be produced on a continuous basis. For low-speed applications, the only way to achieve acceptable efficiency is

to operate with low current density in the windings leading to low shear stress. The machine is thus very large, heavy and expensive.

The present paper describes a proposal at an early stage of development for an electromagnetic device that offers the possibility of providing a means of producing very high force in a reasonably compact form and capable of generating an electrical output with good efficiency.

2 Principle of operation

Unlike other types of electrical machine, magnetic couplings are not restricted in their shear stress by armature winding losses. The new device is developed from these couplings.

Similar arrays of permanent magnets on rotor and stator align locking the two parts and shear stresses up to 10 times those in wound electrical machines can be developed before the coupling snaps.

Whereas other electrical machine forms have two active members, the new device has three. In one form, illustrated in Figure 1, it is a linear generator, consisting of a long translator with many pairs of magnet poles, a short oscillating armature with fewer pole pairs and a spring. Many variations can be envisaged employing different types of spring: coil, leaf, gas, magnetic and having alternative geometric forms: linear, rotary, single- or double-sided or tubular; however, its operation is restricted to generation. In practice, the machine shown in Figure 1 would be constructed in double-sided form to balance the normal forces.

In the absence of an externally-applied force, the spring holds the armature in a position of zero displacement and the magnetic coupling holds the translator in one of many stable positions with the magnets aligned. Force applied to the translator is transmitted by the magnetic coupling to the armature, which in turn pulls against the spring causing it to stretch. Energy is thus stored in the spring and also in the magnetic coupling.

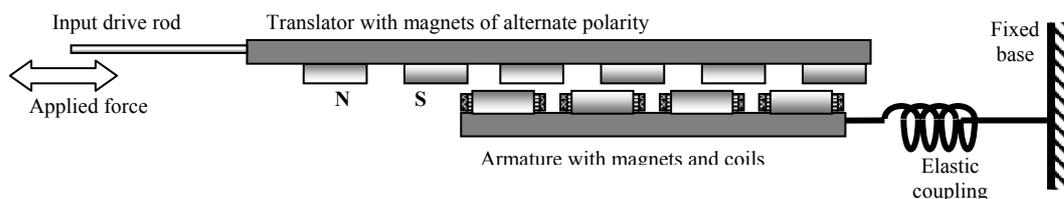


Figure 1: Arrangement of machine as a linear generator

When the force in the spring reaches a certain critical value, the magnetic coupling cannot transmit any further increase in force and the armature rapidly moves toward a new stable magnetic alignment. The rapid release of strain energy and magnetic energy is captured by coils surrounding the armature magnets and delivered to an external electrical circuit.

Because of its action of repeatedly snapping the magnetic coupling, the device is referred to as a “snapper”

3 Static characteristic

3.1 Analysis

Figure 2 illustrates a model used to analyse the magnet arrays to calculate the available coupling force.

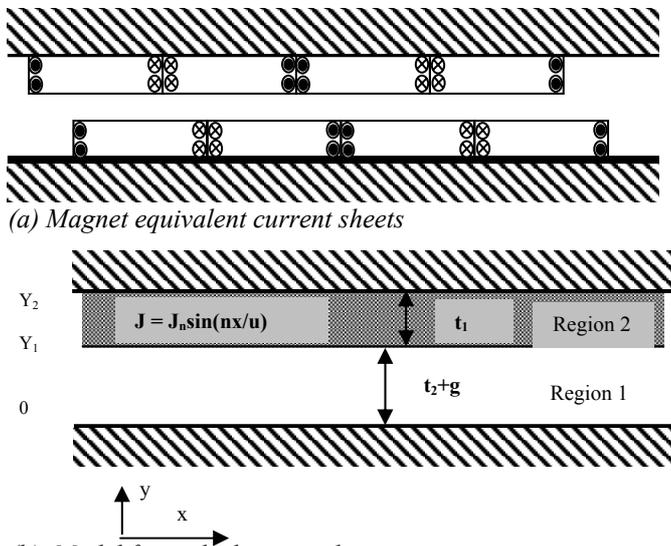


Figure 2: Analytical model

Each magnet is represented by a region of space surrounded by a current sheet of intensity equal to the coercivity of the material. The spatial distribution of current in each magnet layer is a sequence of impulse functions that may be decomposed into a space fundamental and harmonics. The fundamental component is the dominant source of force production.

To calculate the force we first find the y component of flux density in region 1 due to the currents in region 2. This result is then used to calculate the force directly on each current sheet in region 1.

Calculating the magnetic flux distribution in the lower layer produced by the current in the upper layer is a simple example of a 2D multilayer analysis problem and may follow the analysis as described by Grieg and Freeman [4], for example. The fundamental current density in region 2 has amplitude:

$$J_n = \frac{4H_c}{\pi u} \cos\left(\frac{n\phi}{2}\right) \quad (1)$$

where the wavelength, two magnet pitches is $2\pi u$ and the angle ϕ represents the width of the separation between magnets in angular measure.

The vector potential in region 1 is

$$A_1 = A_{1,1}e^{y/u} + A_{1,2}e^{-y/u} \quad (2)$$

where

$$A_{1,1} = \frac{u^2 \mu_0 \hat{J}_n \sinh\left(\frac{Y_2 - Y_1}{u}\right)}{2 \sinh\left(\frac{Y_2}{u}\right)} \quad (3)$$

and the flux density is:

$$B_y = \frac{\partial A}{\partial x} = \frac{A_{1,1}}{u} \left\{ e^{y/u} + e^{-y/u} \right\} \cos\left(\frac{x}{u}\right) \quad (4)$$

The force arising through the interaction of the magnet current sheets in the lower magnet layer with flux produced by the upper layer per metre of each magnet edge is

$$F = \int_0^{Y_M} \frac{A_{1,1}}{u} \left\{ e^{y/u} + e^{-y/u} \right\} \cos\left(\frac{x}{u}\right) H_c dy \quad (5)$$

where Y_M is the height of the magnet

The force varies cyclically with the displacement of the two magnet arrays and the maximum value in either direction is

$$F = 2 A_{1,1} H_c \sinh\left(\frac{Y_M}{u}\right) \text{ N/m} \quad (6)$$

3.2 FE Model

For the experimental system, equation [4] can be used to calculate the magnetic flux density at the surface of the armature due to the translator magnets for a 2mm clearance. This calculation is compared with a 2D finite element solution over two pole pitches in Figure 3. As expected the results are in full agreement.

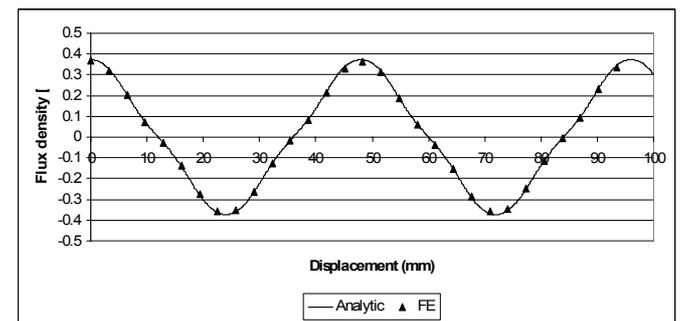


Figure 3: Flux density variation.

Flux plots are shown in Figure 4 for the magnets in the aligned, and fully un-aligned positions that produce zero force and the unaligned, maximum force, position when the armature has been displaced by $\frac{1}{2}$ a pole pitch

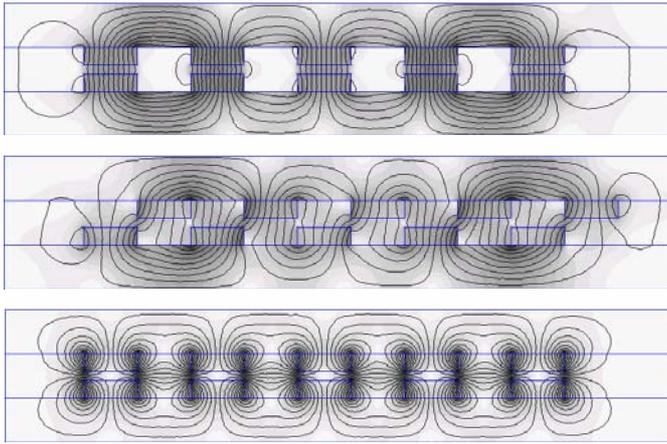


Figure 4: FE plots see text

3.3 Experimental study

To verify the analytic procedure described above a small laboratory test machine has been constructed using 50x12x4mm NdFeB magnets. This test machine is shown in Figures 5 and 6 and comprises of a central translator and two armatures without windings. Both the armatures and the translator are made from mild steel whilst the magnets are located on both the translator and the stator by aluminium location plates. The construction allows the running clearance and the number of magnets to be easily varied. In addition the pole pitch/magnet width ratio can be varied by making new magnet location plates.

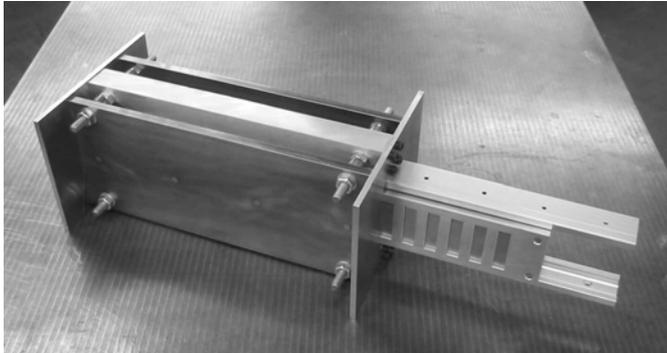


Figure 5: Experimental machine

Static force measurements were taken using a Lloyd testing machine with 5kN capacity in both tension and compression enabling the full force/displacement curve of the device to be recorded, Figure 6.

For preliminary testing of the system it was decided to limit peak forces to about 200N and force calculations showed that with 4 magnets on both the armatures and the translator this would be achieved with a running clearance of 12 mm, although in practice running clearance of 1 or 2mm would be appropriate it ably demonstrates the large shear stress that can be achieved with the snapper arrangement.

A comparison of the measured and computed force is shown in Figure 5. Good comparison is achieved even with this large running clearance with the measured force being slightly less than that calculated. This was expected and is due to the end

effects that are not fully accounted for in the 2D analytic model.

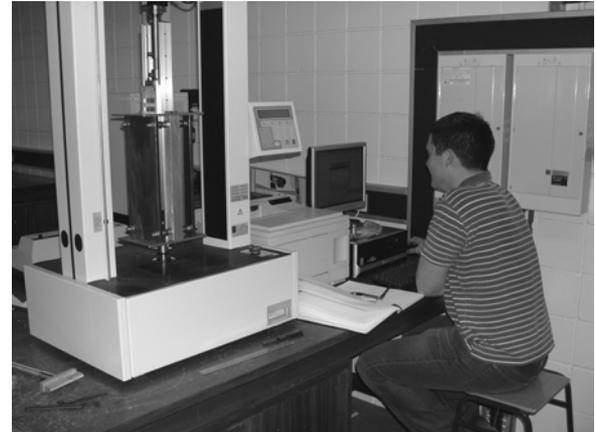


Figure 4: Force testing

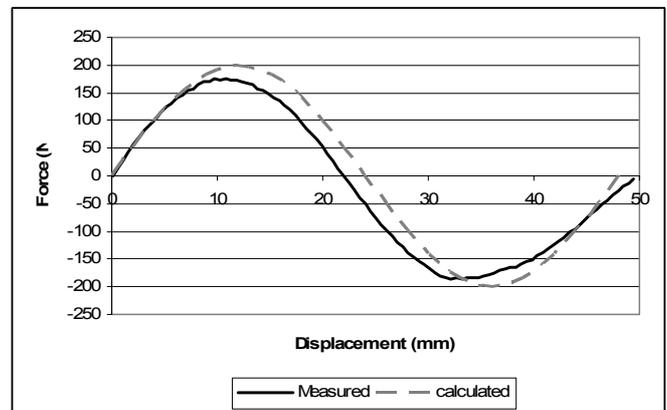


Figure 6: Measured and calculated force

4 Dynamic operation

4.1 Electrical Circuit

In order to deliver power the magnetic coupling must be broken. When this occurs the two magnet arrays are subject to large rapidly changing forces as they attempt to re align in the next stable position. Coils wound around the armature magnets experience changing flux linkage due to their movement in the field of the translator magnets. The coils may be connected in various ways to produce electrical output at the terminals; the simple arrangement with a separate single-phase bridge rectifier for each coil, Figure 3, has been assumed for the purpose evaluating the machine.

4.2 Simulation

A direct analysis of the machine behaviour has not been achieved. Instead the dynamic operation of particular design examples has been simulated. The simulation studies indicate a range of very complex behaviour patterns.

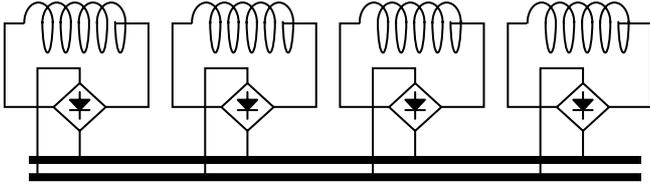


Figure 8: Electrical arrangement

The equations describing the behaviour of the machine during the transition between stable positions are listed below. The armature and translator positions, x_A , x_T are measured with reference to an initial preferred position for which there is zero force magnetic between the two:

Magnetic force

$$F_M = \hat{F}_M \sin\left(\frac{x_A - x_T}{u}\right) \quad (7)$$

Spring force

$$F_S = k_S x_A \quad (8)$$

Electrical force arising from the interaction of the armature coil currents with the magnetic field of the translator magnets

$$F_E = k_E I_{coil} \sin\left(\frac{x_A - x_T}{u}\right) \quad (9)$$

k_E is related to the peak flux linkage of the coil with the translator magnets field

Armature position

$$\frac{d^2 x_A}{dt^2} = -\frac{F_M + F_S + F_E}{M_{armature}} \quad (10)$$

Coil emf

$$E = \frac{\hat{\lambda}}{u} \left\{ \frac{dx_A}{dt} - \frac{dx_T}{dt} \right\} \sin\left(\frac{x_A - x_T}{u}\right) \quad (11)$$

Coil current

$$\frac{dI_{coil}}{dt} = \frac{E - I_{coil} R_{coil} - k_{rect} V_{load}}{L_{coil}} \quad (12)$$

The factor k_{rect} takes values of 1, -1 or 0 according to whether the bridge rectifiers are conducting in the forward or reverse direction or blocking. It should be noted that each coil experiences the same emf and carries the same current in both magnitude and phase.

Translator position

$$\frac{d^2 x_T}{dt^2} = \frac{F_M + F_S + F_E - F_{drive}}{M_{device}} \quad (13)$$

The relevant mass includes the translator itself, the mass of attached components such as a floating buoy in a wave power machine and any entrained fluid mass. The mass would normally be much greater than the armature mass and it may be appropriate to consider the translator as being driven at a known velocity which may be constant or may follow some determined profile.

4.3 Chaotic operation

If the translator is forced to move very slowly, then the armature follows it and the spring stretches. To maintain equilibrium the magnetic force must balance the spring force and there is a corresponding displacement between translator and armature. A point is reached where the magnetic force cannot balance the spring force and the armature is pulled back. As the armature moves, the magnetic force decreases and so the net force accelerating the armature increases and the motion may be quite violent. If the armature coils carry no current then the armature will oscillate about its new equilibrium position, damping will occur in practice due to eddy currents and friction. The high velocity reached can cause high voltage to be induced in the coils and the rectifiers begin to conduct the interaction of the coil current with the translator magnets produces a retarding force that damps the oscillation and one or more pulses of power are injected into the dc load.

As the translator continues to move the process is repeated after it has moved by two pole pitches.

If the translator speed is increased then the next event begins before the oscillations from the previous event have fully decayed. This leads to the snapping action occurring before or after the translator has moved by two pole pitches. The force, acceleration, velocity, emf, and current profiles therefore differ at each event and the behaviour becomes chaotic.

4.4 Simulation results

A very wide range of operating features is exhibited by results obtained, from which a sample is presented. The example machine is double sided with dimensions summarised in Table 1.

Magnet thickness	mm	15
Magnet width	mm	28
Active length	mm	100
Pole pitch	mm	40
Airgap each side	mm	2
Armature magnets per side		40
Magnetic peak force	kN	88
Coil wire diameter	mm	0.5
Coil turns		229
Coil resistance	Ohm	6.2
Coil inductance	mH	22
Armature mass	kg	96
Spring constant	MN/m	33

Table 1: Dimensions of simulated machine

The results below relate to a translator motion at constant speed of 1m/s. The dc voltage at the load is taken to be 100V. output power to the dc load is 19kW yielding an efficiency of 44%. If the dc load voltage is increased the stress, power and efficiency change as indicated in Figure 10. The efficiency being 82.5% for 500V dc. The traces in Figure 9 indicate the general nature of the behaviour, in this case the chaotic behaviour is not serious but it can dominate the performance in other examples.

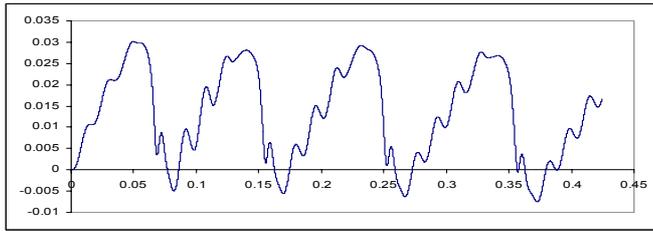


Figure 9a: Armature position

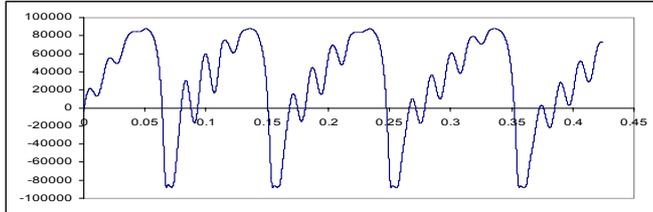


Figure 9b: Magnet force

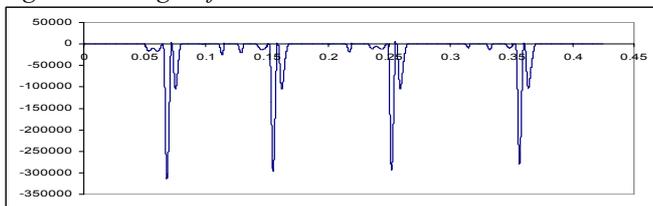


Figure 9c: Electrical force

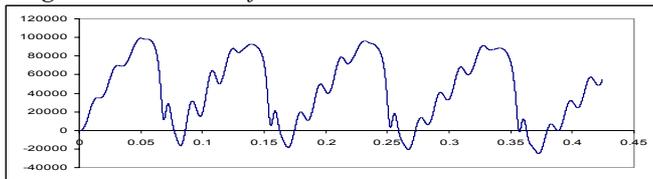


Figure 9d: Spring force

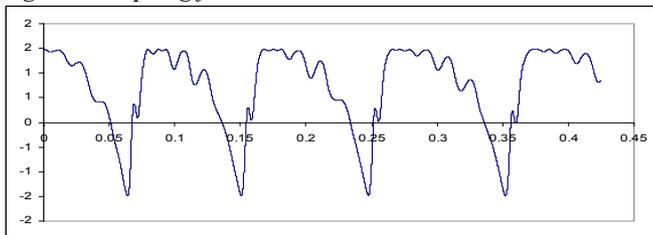


Figure 9e: Coil flux linkage

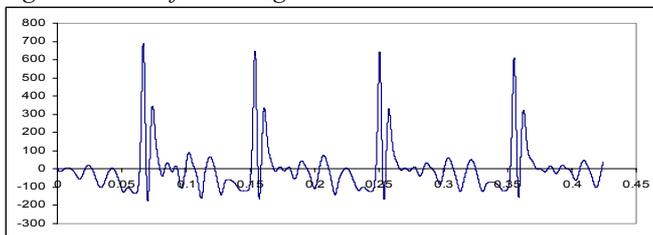


Figure 9f: Coil emf

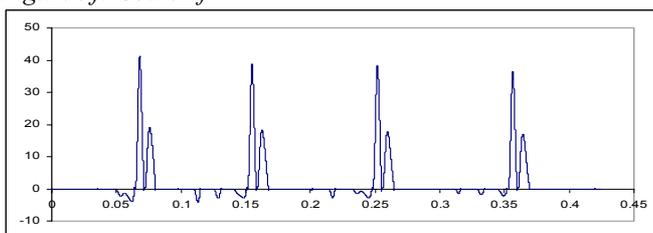


Figure 9g: Coil current

The mean value of the electrical force is 42.3kN which corresponds to a shear stress of 132kN/m^2 , which is several times greater than is commonly found in conventional machines. Peak values seen in Figure 9c correspond to much higher instantaneous stress. The average resistive loss in the coils is 23kW and the mean

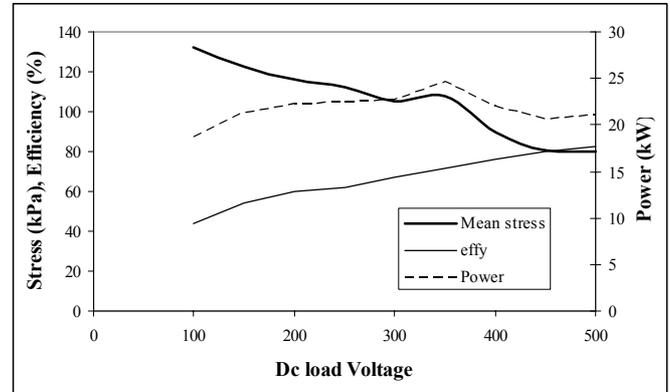


Figure 10: Effect of dc load voltage

5. Conclusion

The new machine offers the prospect of developing very high shear stress with reasonable efficiency as required for demanding direct drive generator applications in wave power devices.

The operating mode is complex

Experimental studies have confirmed the validity of the static analysis of the device, laboratory studies are needed to explore the complex dynamic operation and to inform design studies

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