Emergency Breaking for Free Piston Energy Converters.

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Keywords

«Energy converter for HEV», «automotive application», «fault handling strategy», «permanent magnet motor», «linear drive»

Abstract

Free piston energy converters are a potential technology for future hybrid vehicles, as well as stationary power generation applications. A candidate 2-stroke system comprises of two opposing combustion chambers with a common piston rod, and integrated with a tubular permanent magnet electrical machine for the conversion of mechanical to electrical energy. A key issue for the ultimate adoption of such systems, however, is their robustness in the event of a fault to enable a safe shutdown, with minimal mechanical or electrical damage. The paper considers system braking issues and the importance of early fault detection. Results are presented to demonstrate the effectiveness of passive and active braking techniques for a range of dc-link supply voltage and operating output powers.

Introduction

In a free piston energy converter (FPEC), chemical energy is converted directly to electrical energy, offering itself primarily as a power source in serial hybrid configurations for automotive applications [1-3]. The FPEC is a 2-stroke system comprising of two opposing combustion chambers [4-5] having a common piston rod on which is mounted a linear permanent magnet translator, Fig. 1. Thus, motion is achieved by way of combustion in the two chambers occurring in anti-phase. This eliminates the crankshaft, such that the piston movement is free, being controlled by a linear permanent magnet machine via a power electronic converter, such that variable compression ratios may be achieved.

The proposed system utilises the latest technology in combustion research, *viz*. a Homogeneous Charge Compression Ignition (HCCI) combustion system, running on diesel fuel. Ignition of the air-fuel mixture in a HCCI combustion system occurs when the gas pressure and temperature have reached a certain value in or after the compression stroke. This is a highly unstable process, since, in order to achieve HCCI early fuel injection is required to ensure a homogenous distribution of fuel, with the risk that combustion could occur well before top dead centre (TDC), necessitating (state-of-the-art) control technologies.

The combination of HCCI combustion, the elimination of the crankshaft and the integration of a high power dense permanent magnet electrical machine, aims to provide a very clean and highly efficient new technology for vehicle propulsion. The target of such a system is to provide a power density in excess of 0.6kW/kg (excluding battery weight), and to have the potential of meeting Euro V emission limits when scaled up.

This paper describes the tubular electrical machine and outlines the FPEC system, focusing on the dynamic braking requirement, which is one of the many issues that need to be addressed throughout the development of such a system. The worst-case scenario, for which a high dynamic braking ability is required, occurs when the exhaust valve of the combustion chamber that opposes the chamber undergoing combustion, does not close. Hence, the translator is traveling at high velocity with no gas to compress, and hence no medium to absorb its high level of kinetic energy, and the energy of the pressure difference between the two chambers. The braking requirement is both a machine-design issue and a control issue, and more importantly, the ability to sense such a failure early enough to provide the largest range over which to apply the braking force.

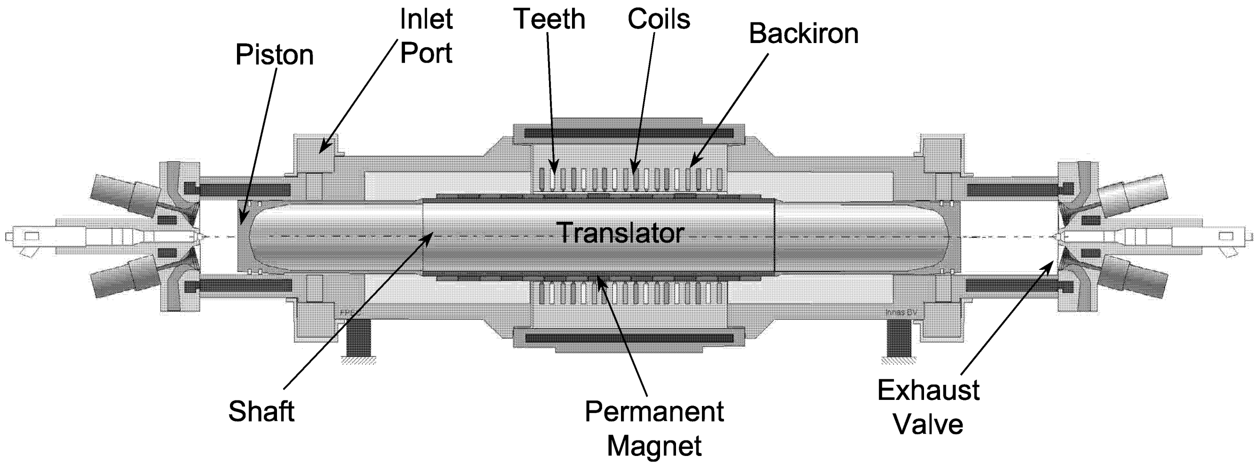

Fig. 1: Free piston energy converter (FPEC)

Braking Requirements

In the event of a failure that necessitates the translator to be stopped to prevent damage to the FPEC system, the electrical machine needs to provide sufficient braking ability. However, the machine has been optimised for a specified generating profile, which, to a certain extent compromises its braking ability. One common method of emergency braking employed with synchronous machines is resistive braking, [6-8], which also has the added benefit of being able to operate in the event that the failure includes the loss of the inverter/controller. The other means of braking, active braking, assumes that the machine controller is still operational during the fault condition, since it utilises appropriate control of the synchronous machine.

With an average velocity of 11m/s, the velocity and force profile of the FPEC system are as shown in Fig. 2, and given that the translator mass is 9kg, the kinetic energy of the translator may be approximated as 550J. In addition to the translator kinetic energy, there also exists the energy owing to the pressure difference between the two combustion chambers. Thus, a total energy in excess of 1kJ will need to be extracted under fault conditions to halt the translator.

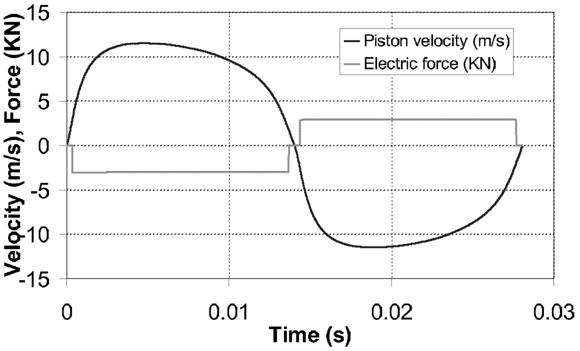

Fig. 2: Typical velocity profile of the free piston energy converter

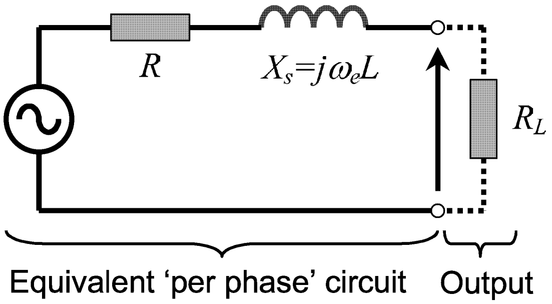

Fig. 3 Equivalent per phase circuit diagram under resistive braking

Resistive Braking

Fig. 3 shows the equivalent "per phase" circuit diagram of the linear permanent magnet machine under resistive braking. The electromagnetic force that can be produced by the machine under resistive braking conditions is dependent on the load resistance R_L, and is given by:

$$F = \frac{k^2 v(R+R_L)}{(R+R_L)^2 + (\omega_e L)^2} \tag{1}$$

where v is the linear velocity, k the rms-flux linkage, R the phase resistance, L the synchronous inductance and ω_e the electrical frequency which is related to the linear velocity v by:

$$\omega_e = \frac{\pi}{\tau_p} v \tag{2}$$

Fig. 4 shows the braking force as a function of linear velocity and load resistance. As is evident from Fig. 4, for a given velocity v, there exists an optimal value of R_L which yields maximum braking force. This optimal value can be found by differentiating F with respect to R_L and solving for:

$$\frac{\partial F}{\partial R_L} = 0 \tag{3}$$

which yields

$$R_L = \frac{\pi L v}{\tau_p} - R \tag{4}$$

The resultant maximum braking is given by:

$$F_{\max} = \frac{3k^2 \tau_p}{2\pi L} \tag{5}$$

As can be seen, if the load resistance R_L varies with the linear velocity v according to (4) during braking, the maximum possible braking force is constant and independent of v. Hence, as the speed is reduced, in order to maintain the maximum braking force, the load resistance needs to be reduced proportionally, as highlighted in Fig.5. It should be noted that when the linear velocity is below ~1.0 m/s, the optimal value of the load resistance becomes negative, but in practice can only be zero.

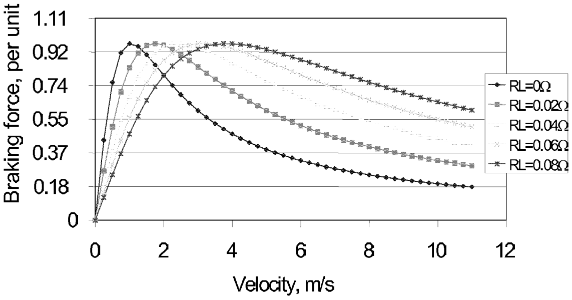

Fig. 4 Braking force – velocity characteristics

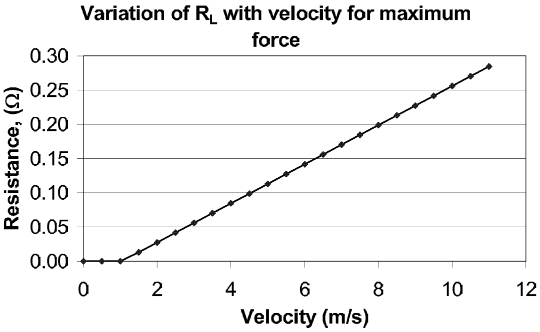

Fig. 5 Load resistance as a function of v for maximum braking force

Assuming the mean piston velocity and that a fault is detected at the point at which the exhaust valve should close, with 67% of the stroke remaining, then, if the resistance is switched appropriately such that the maximum braking force of 1.0 per unit is available at all speeds, the achievable braking as a function of linear velocity is shown in Fig. 6, and only ~250J of the total translator energy may be extracted prior to impact of the piston with the cylinder head at a velocity of 7.41 m/s, thus resulting in catastrophic system failure. Although switching a load resistance bank against the translator velocity according to (4) is possible, it is much easy to use a fixed-value load resistance. Fig. 7 shows the variation of impact energy with fixed value of load resistance over 0.1 m available braking distance. As will be seen, if a fixed load resistance is used, the optimal value is 0.227 Ω which yields the minimum impact energy of 232 J. Compared with the variable load resistance braking, utilising fixed R_L does not significantly compromise braking ability. In any case, however, it is apparent that some form of active braking is also required for this fault scenario.

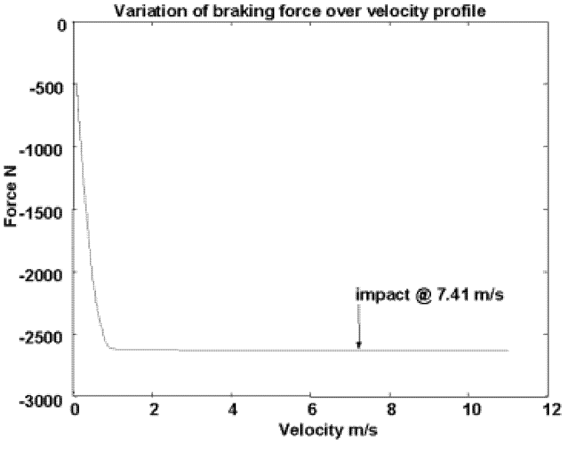

Fig. 6 Maximum achievable braking force as a function of linear velocity

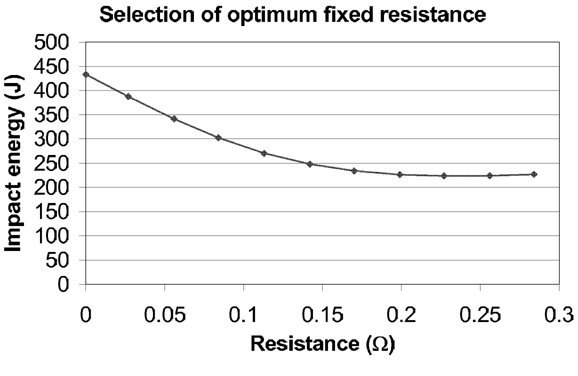

Fig. 7 Variation of Impact energy with fixed value of load resistance

Active Braking

A dynamic FPEC model is employed to demonstrate the active braking capability of the electrical machine, Fig. 8. It comprises of the FPEC combustion system, the tubular permanent magnet machine and the associated controllers, and is created in Simulink®. The PLEXIM® Simulink toolbox is used to model the electrical machine as a *dq0* non-linear model with a vector controller. In the event of an emergency braking, the velocity command is set to zero, and the velocity controller outputs a baking force (or q-axis current) demand to the electrical machine. This force demand is, however, limited to 2.7 times of the rate force, which is the maximum force that can be applied during braking [9]. The two combustion units compute the pressure and force due to combustion process for the given power demand. This force together with the frictional force calculated from a dedicated fiction model is fed into the mechanical model which governs the movement of the piston and the translator of electrical machine.

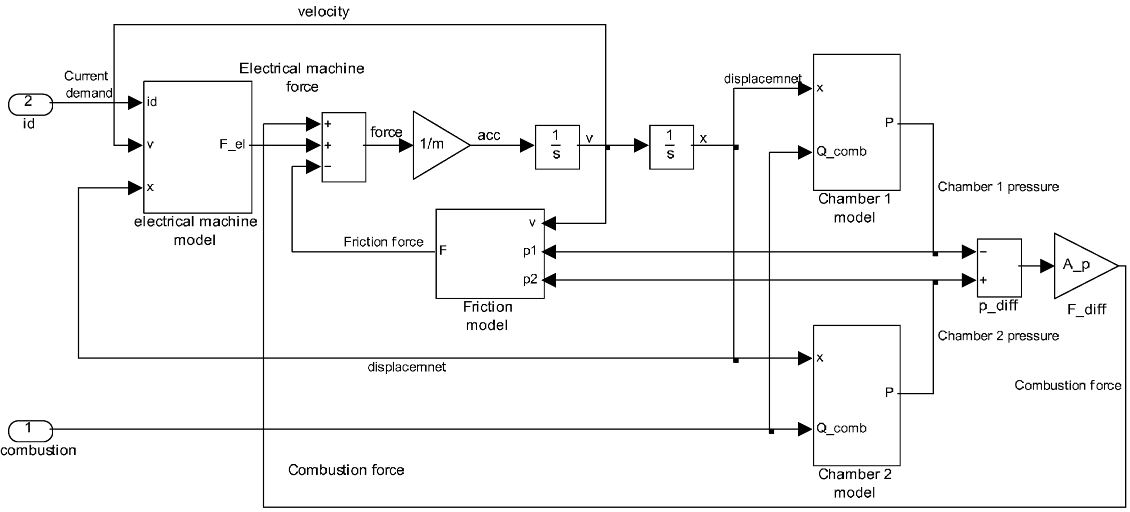

Fig. 8. Simulation block diagram of the FPEC, excluding controller.

To simulate the effects of a fault an exhaust valve failing to close, the simulation model assumes the fault is detected immediately, as the valve is ordered to close, and that no retarding force other than friction exists. In practice, the pressure in the 'opened' cylinder would actually present a relatively small but non-zero retarding force due to the choked flow of compressible gas through the opening of the exhaust, but this has been omitted in the following study, for simplicity.

Fig. 9 shows the electromagnetic force profiles that are required of the electrical machine over a number of generating strokes for a constant power generation of 1.0 per unit, and the emergency braking force that may be actively obtained in the event of a detected fault. The profiles are given for various converter dc-link supply voltages. It can be seen that at high speed, due to the high back-EMF which is generated in the windings of the tubular machine, the developed electromagnetic force is limited when operated from low dc-link voltages. At maximum force, which can be obtained at almost all velocities for dc link voltage > 400V, the machine is operated at its current limit (the vector controller maintaining the phase currents at twice of the rated value)

Fig. 10 shows the emergency braking force of the electrical machine when operating at various output powers for a dc-link voltage of 350V. Whilst some limitation in the braking force at high speeds is evident, this is negligible compared to other factors, such as the retarding force due to 'pumping losses' and prospect for detecting the fault conditions slightly earlier.

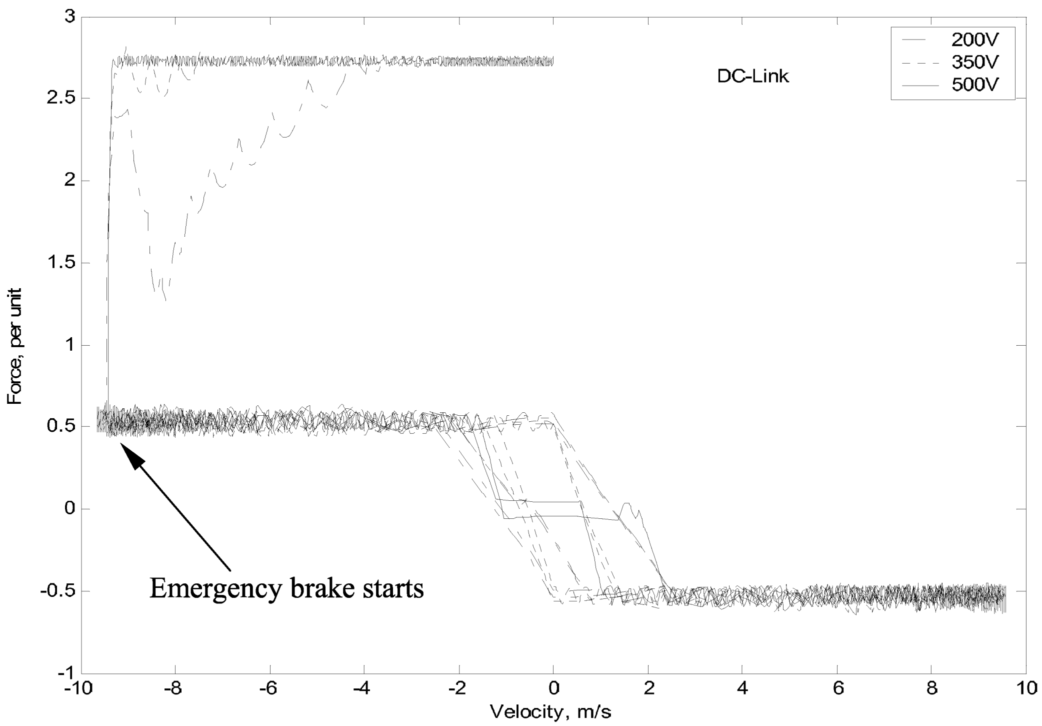

Fig. 9. Force-velocity profiles of free piston energy converter under normal operation and emergency braking for constant power generation of 1.0 per unit with three values of DC link voltage.

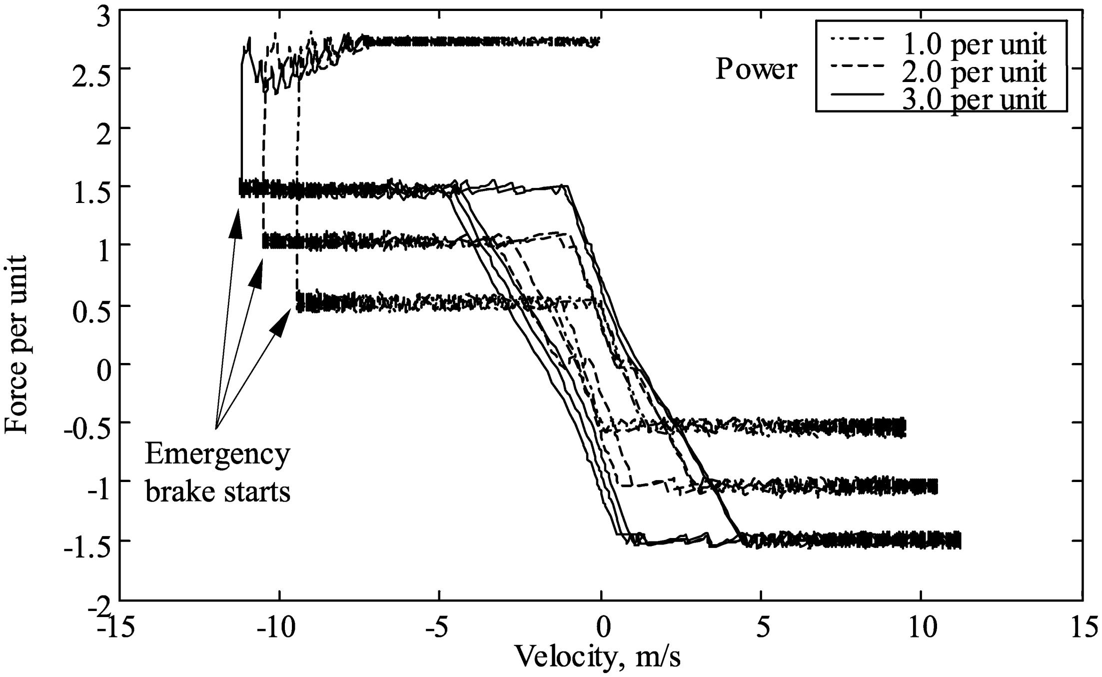

Fig. 10 Force-velocity profiles of free piston energy converter under normal operation and emergency braking for three levels of power generation with a DC link voltage of 350 V

The position of the translator, plotted against velocity, is shown in Fig. 11 for dc-link voltages of 200V, 350V and 500V, and a power of 1.0 per unit. It can be seen that in all three cases, if braking is applied immediately after the fault being detected, the translator will be stopped before reaching TDC. It is also evident that limited benefit is gained with regard to the braking of the translator for dc-link voltages > 350V; which again highlights the fact that early fault detection has a major influence on the braking capability.

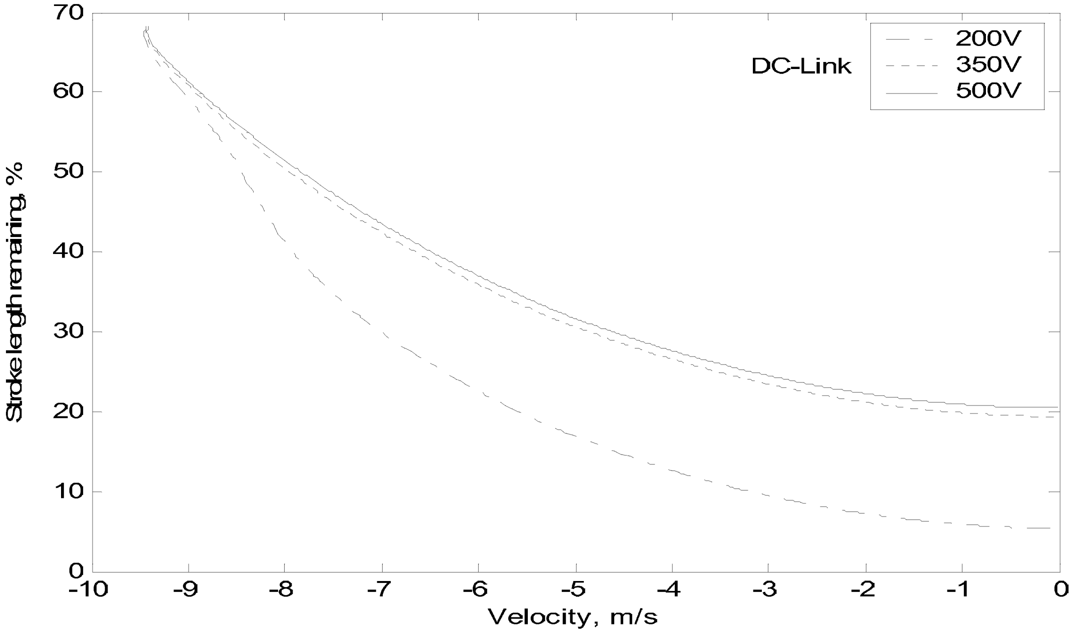

Fig. 11 Variation of translator position with velocity under braking

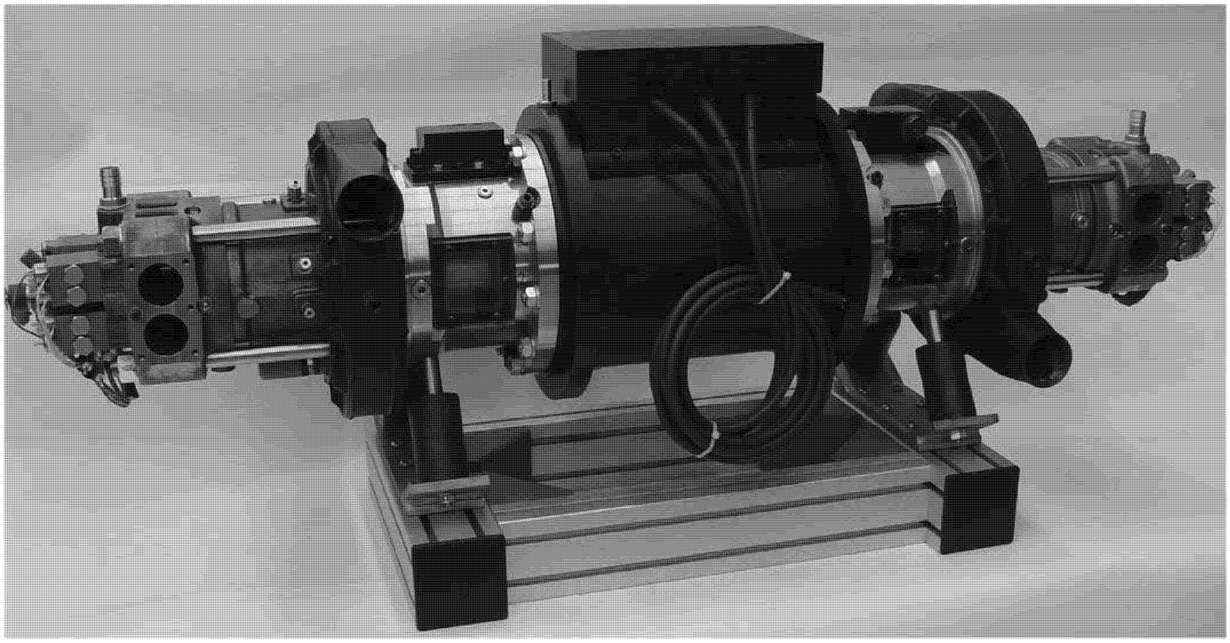

Fig. 12 Prototype of a free-piston energy converter

Prototype of FPEC

A prototype of FPEC, comprising a linear electrical machine and two combustion units as shown in Fig. 12, has been constructed. The system is currently under testing and its braking performance will be reported in the future.

Conclusion

The paper has identified a number of potentially catastrophic fault mechanisms that can arise during the operation of FPECs, and describes an investigation into passive and active electrical braking mechanisms to accommodate such fault conditions. A candidate FPEC with an integrated tubular PM synchronous generator has been used to demonstrate that either passive or active braking, or a combination of both may ultimately be necessary, and to highlight the fact that due to the very high combustion forces which are generated and the floating TDC characteristic of FPECs, early detection of a fault condition is essential if catastrophic damage is to be avoided. It has also been shown that the electrical machine impedance and the dc-link voltage have significant impact on the ability to brake the translator. Ultimately, this impacts on the size and rating of the electrical energy storage medium (capacitor, battery, flywheel etc) required for an FPEC system.

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