Minimizing Power Pulsations in a Free Piston Energy Converter

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Acknowledgements

The authors gratefully acknowledge funding from the Swedish Energy Agency.

Keywords

«Energy converters for HEV», «Linear drive», «Converter Machine Interactions», «Hybrid Electric Vehicle (HEV)», «Generation of Electrical Energy», «Distributed power», «Emerging technology»

Abstract

A Free Piston Energy Converter (FPEC) is a combination of a linear combustion engine and a linear electrical machine. This type of converter has many potential advantages like high efficiency, low fuel consumption and low emissions, which make it suitable for a series hybrid vehicle. However, the generated power pulsates due to the reciprocating motion of the translator.

This paper presents a comparative study on how different generator force profiles affect the electric power pulsations produced by the FPEC. In addition, the influence of these profiles on translator motion and the needed power converter current is investigated.

A dynamic free piston model is used for the investigation. Results show that the generator force profile has a major impact on the power pulsation amplitude and peak current demand. Thus the chosen force profile will affect dimensioning of power converter, electrical machine and energy storage. Furthermore, loading the translator heavily in the beginning or end of the stroke seems to affect the peak translator velocity more than evenly distributed load profiles.

Introduction

With the raising oil prices, the debate on fossil fuels and the harder environmental legislations alternative drivetrains and engines are gaining more interest. The Free Piston Energy Converter (FPEC) is an alternative with potential to be both environmental friendly and efficient. During recent years research around free piston engines has increased and several prototypes have been built [1–4].

Most work concerning FPECs has focused separately on the mechanical parts of the converter, the combustion process, [5, 6], linear generator design [7] or control [8]. There has been little research at system level of the FPEC. To optimize system performance and reduce size and cost such investigations are necessary.

One important system issue is the interaction between the generator force, the translator dynamics, and the drive system. The generator force affects the size of the supplying power converters, the size of the electrical machine, the amplitude of the generated power pulsations and thus the size of energy storage. This makes the force a critical parameter for system design and performance.

Earlier work in this area have been done by [9] who have investigated how different current and speed profiles in an FPEC will affect the system efficiency. Moreover, a parameter study of an FPEC has been performed by [10] who suggest that a complex force profile is needed to affect the motion of the piston.

This paper investigates what could be gained by varying the force over time. It also examines the influence of force profile on the supplying power converter dimensioning and amplitude of power pulsations. Furthermore, it studies how translator motion is affected by the force.

The Free Piston Energy Converter

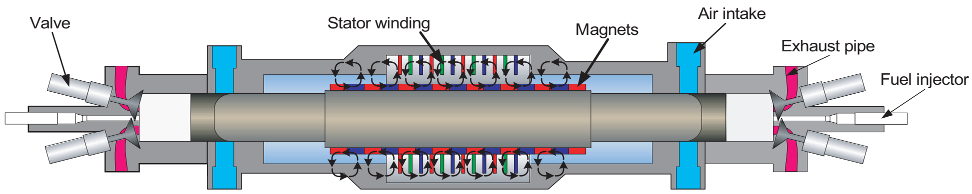

Figure 1: A Free Piston Energy Converter

A Free Piston Energy Converter is a combination of a linear combustion engine and a linear electrical machine converting chemical energy into electrical. A translator with pistons at each end is placed between two opposing combustion chambers as seen in Fig. 1. Combustion makes the translator reciprocate in an almost resonant way and a permanent magnetized linear electrical machine converts some of the translator's kinetic energy to electrical. The electrical machine is supplied by a switch mode power converter.

The features of the free piston energy converter are as follows:

- The electrical machine can be used as a motor to start and stop the translator, as a generator for energy conversion and as an actuator to control the combustion.
- There is no crankshaft constraining the translator motion, which enables variable compression. This makes HCCI possible, a promising combustion process where the air-fuel mixture is self ignited when the pressure and temperature are sufficient. This process has almost 50% chemical to mechanical conversion efficiency [6]. In addition, the emissions, especially of nitrous oxides (NOx) and particulate matter (PM), are very low.
- The variable compression ratio in combination with HCCI makes it possible to utilize different fuels with minor hardware changes [5].
- The energy converter can be started and stopped very fast, and change rapidly between different power levels, which will minimize the use of a battery if used in a drivesystem [11].
- The system is compact, modular and has high power density.

These features make it very suitable as a power unit in a series hybrid vehicle. In fact, using a free piston energy converter in a heavy duty application hybrid may reduce fuel consumption up to 25% [12]. Other possible applications could be auxiliary power units and distributed generation.

Power pulsations

The translator velocity and thus the delivered power reaches zero towards the end of the stroke. As a result the delivered power pulsates. These pulsations introduce issues that must be considered:

- The supplying power converter must be dimensioned to handle the pulsations.

- If the converter is used in a vehicle the pulsations can introduce torque ripple in the propelling electrical machine. To smoothen these pulsations an energy storage device could be used. Another solution is to overdimension the propelling electrical machine so it acts as an electrical flywheel. But to optimize size, cost and performance of the used components it is desirable not to have larger pulsations than necessary.

The amplitude of the power pulsations is determined by the translator velocity and the generator force. As the free piston system is almost resonant, the velocity will not change significantly with different force profiles. This could potentially be utilized to reduce the amplitude of the power by controlling the force the correct way.

Force profiles

To generate electric energy the force from the generator is doing work on the translator. The generator force is proportional to the current so the peak force decides the peak current the supplying power converter must be able to deliver. However, the same work, W, over the same distance can be done using different shapes of force, $F(x)$, in accordance with the integral

$$W = \int F(x)dx, \tag{1}$$

where x is translator position. This means that doing the same work using for example a triangular force shape, compared to a rectangular one, twice the peak force and thus twice the peak current is needed. The question is what could be gained by using different profiles. Possible load control goals could be:

- Loading the translator more at the beginning of the stroke which results in more time for fault handling and motion control.
- Loading the translator late in the stroke to utilize more of the kinetic energy for compression.
- Reducing power pulsations.
- High efficiency by using a force profile similar to the velocity profile [9].
- Minimizing the components.

These goals are in conflict with each other and will put different requirements on the converter and electrical machine performance. In this study the force profiles described below and seen in Fig. 2 are investigated to see if the goals can be fulfilled.

Profile 1: Rectangular

Loading the generator using a constant force is a simple way of controlling the system. As this results in a rectangle, the lowest current of all profiles investigated is needed.

Profile 2: Inverse velocity

The power delivered is proportional to the translator velocity times the force. Using a force that ideally should be the inverse of the speed results in a square power profile. This could reduce the power pulsations. To limit the peak force an approximation of the velocity inverse is used here.

Profile 3: Sinusoidal left

A sinusoidal profile starting with lower values.

Profile 4: Sinusoidal right

A sinusoidal profile starting with higher values.

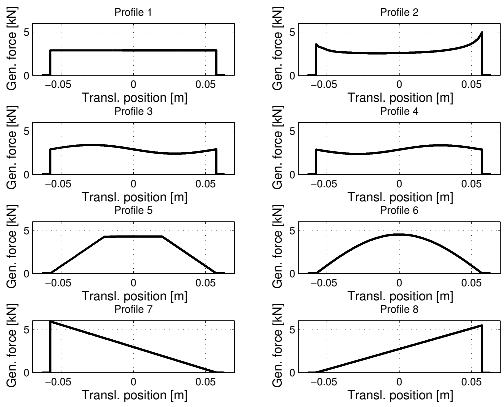

Figure 2: Generator force as a function of translator position when the translator is moving from left to right.

Profile 5: Trapezoid

The force can not reach maximal value instantaneously as assumed in the rectangular case; a trapezoid profile could be closer to reality. Furthermore, the translator velocity over time is similar to a trapezoid, which results in high efficiency when using trapezoidal current [9].

Profile 6: Half sinusoidal

Using this half-period sinusoidal profile may also result in high efficiency as it resembles the translator velocity [9].

Profile 7: Triangular left

A left triangular profile is used to investigate the effect of reducing much of the translator kinetic energy in the beginning of the stroke. Using this triangle, 75% of the total work is done within the first half of the stroke.

Profile 8: Triangular right

To investigate the influence of loading the generator more at the end of the stroke a right triangular profile is used. In contrast to the triangular left profile only 25% of the work is done within the first half stroke.

System modeling

To study the influence of force on the translator movement, a dynamic model of the free piston is needed. The motion of the piston is mainly determined by the combustion process and the generator force which means that both of these must be taken into account. However, a simplified model of the combustion process will still capture the main translator motion and is therefore sufficient for this study. Several papers suggest these types of simulation models and most approaches are quite similar. In this study the one suggested by [5] is used and described below.

Thermodynamics

The first law of thermodynamics and the ideal gas law are used to derive dynamic equations for pressure and temperature in each cylinder. Assuming the mechanical work done to be volume work the incylinder pressure and temperature can be expressed by

$$\frac{dp}{dt} = \frac{\partial Q}{dt}\frac{p}{mc_vT} - \frac{\gamma p}{V}\frac{dV}{dt} \qquad (2)$$

$$\frac{dT}{dt} = \frac{1}{mc_v}\frac{\partial Q}{dt} + \frac{T(1-\gamma)}{V}\frac{dV}{dt} \quad (3)$$

where V is cylinder volume, T cylinder gas temperature, p cylinder pressure, m gas mass, Q heat, c_v is the specific heat with constant volume and γ is the ratio of specific heats.

Mass fraction burned

When the air/fuel mixture ignites it burns for a while, the mass fraction burned is modeled using a Wiebe function,

$$x_b = 1 - e^{-a\left(\frac{t}{t_d}\right)^{N+1}}, \quad (4)$$

and the heat released during combustion is

$$\frac{\partial Q}{dt} = Q_{in}\frac{dx_b}{dt}, \quad (5)$$

where x_b is the mass fraction burned. Q_{in} is the total heat added during one combustion, t_d is the duration of combustion and τ is the time since combustion started. The constants N and a are used to form the shape.

Ignition delay

The combustion does not start instantaneously when the pressure and temperature in the combustion chamber are high enough, but is delayed until the integral

$$\Delta(\tau) = \int_{t}^{t+\tau} \frac{1}{A} p^n e^{\frac{E_A}{RT}} dt \quad (6)$$

reaches the value one. E_a is a fuel dependent constant, R is the universal gas constant and τ is the time elapsed since fuel injection.

Heat transfer

During combustion not all heat generated is converted into work, losses to the cylinder walls occur in accordance with

$$\frac{\partial Q_{ht}}{dt} = \alpha A(T - T_w) \quad (7)$$

$$\alpha = 130V^{-0.06}\left(\frac{p}{10^5}\right)^{0.8} T^{-0.4}(\bar{U}_p + 1.4)^{0.8}, \quad (8)$$

where T_w is the cylinder wall temperature and $\bar{U}_p$ is the piston mean velocity. This model is valid for regular diesel engines and will overestimate the heat loss in a HCCI engine.

Electrical machine

Almost no power is delivered close to the translator turning points as the velocity, thus the induced electromotive force, reaches zero. Therefore the generator is not loaded around these points. This results in a machine model

$$\begin{aligned} F_{el} &= F_{ref} \; when \; |x| < x_{el} \\ F_{el} &= 0 \quad when \;\; |x| > x_{el}. \end{aligned} \quad (9)$$

The direction of the force is always opposite to the piston velocity. Furthermore, a constant electrical machine efficiency of 94% is assumed.

Translator motion

Finally, the piston motion is described using Newton's second law,

$$m_p \frac{dv}{dt} = F_{el} + A_p(p_1 - p_2). \tag{10}$$

where m_p is translator mass and A_p is piston area.

Control system

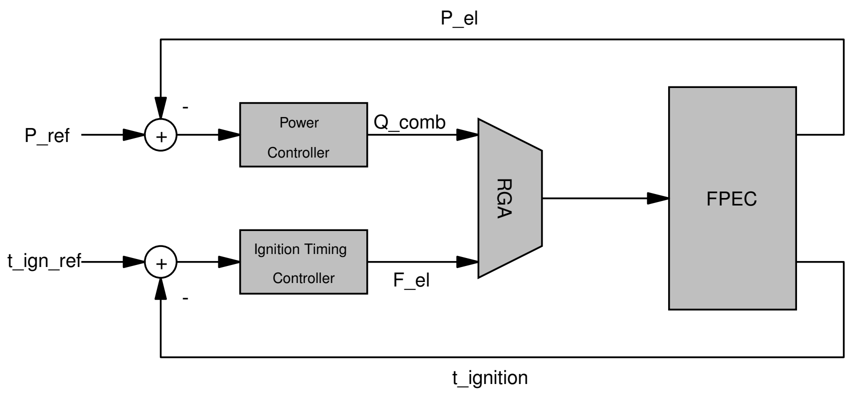

Figure 3: FPEC control system

The HCCI process in combination with the FPEC is a complex, unstable, multiple input multiple output process, challenging to control. In this investigation a simple control system used for initial studies by [1] is utilized.

A block diagram of the control system is seen in Fig. 3. Using generator force amplitude and air/fuel mixture as control signals, two PI controllers control ignition delay and mean power output. The control signals are decoupled using a Relative Gain Array (RGA) with values determined from open-loop simulations. The controller is event trigged using translator direction change. This control system would not be applicable on a real FPEC system since only one sample each stroke is taken which would be too slow for advanced combustion control. However, it is sufficient for this investigation.

FPEC data

The FPEC used in the simulations has a translator weight of 9 kg, a bore of 100 mm and a maximum power of 45 kW.

Simulation and results

The system is modeled using Matlab/Simulink. Simulations using the eight different force profiles are performed until the system reaches steady state. The power control reference is set to 20 kW. The simulation results are presented in Table 1.

Table 1: Simulation results

	1	2	3	4	5	6	7	8
P_{peak} [kW]	28.5	25.5	33.2	30.9	43.6	44.4	46.8	39.0
F_{peak} [kN]	2.9	5.0	3.4	3.4	4.3	4.5	5.9	5.4
v_{peak} [m/s]	10.6	10.6	10.5	10.7	10.9	10.9	9.9	11.2
f_{power}. [Hz]	65.0	65.0	64.0	65.0	64.0	64.0	61.0	67.0
$Work$ [J]	329.0	328.0	332.0	328.0	330.0	330.0	339.0	312.0

Typical position, speed and acceleration curves from simulation can be seen in Fig. 4. Note that the velocity over time resembles something between a sinusoid and trapezoid which was the motivation for the high efficiency profiles 5 and 6.

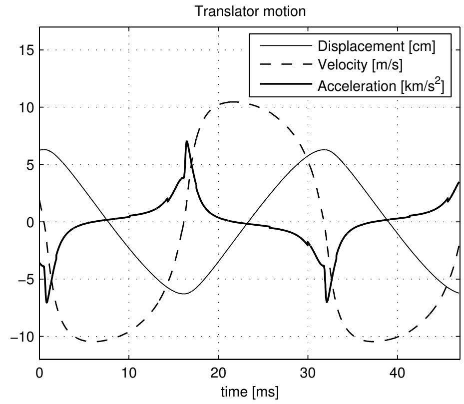

Figure 4: Typical free piston displacement, velocity and acceleration from simulation.

The peak current is assumed to be proportional to the peak force. As relative values are more interesting for comparison, the achieved simulation results are normalized. That is the peak power level, peak current, and work from each simulation case is divided with the corresponding result from the rectangular profile. A barchart of the normalized values is presented in Fig. 5.

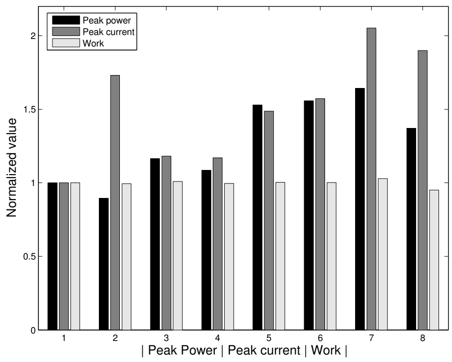

Figure 5: Normalized peak power amplitude, peak current, and work.

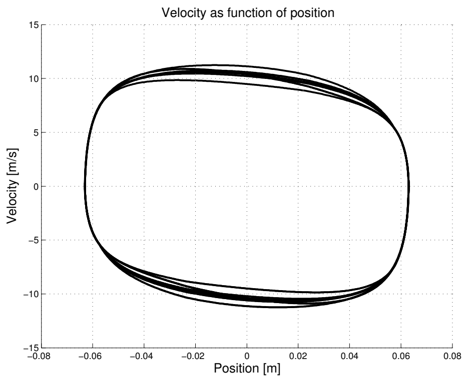

Figure 6: Translator velocity as a function of position.

The velocity as a function of translator position in steady-state can be seen in Fig. 6. Six of the curves are essentially the same but two extreme cases, corresponding to the triangular force profiles 7 and 8, occur. In these two cases the total work done differs slightly from the other simulation cases. The peak velocity is 10% lower with only 3% higher work done for the early load force profile. For the late load case, the peak velocity has increased by 5% decreasing the work by the same amount. Increased frequency with lower load and vice versa is consistent with the work presented in [10].

Loading the translator early or late in the stroke seems to have more effect on the translator dynamics than other load strategies. However, looking at the peak current demand for these two profiles in Fig. 5 almost twice the peak current compared to the rectangular case is needed and the power pulsations have high amplitude.

It can also be seen in Fig. 5 that the inverse velocity force (profile 2) results in the lowest power pulsations but 70% higher peak current demand compared with a constant force. Thus power pulsations can be somewhat reduced by generator force control, again at the price of a large peak current.

As expected, a constant force (profile 1) demands the lowest current, and it also results in quite low power pulsations.

Conclusions

Simulation results shows that the generator force has major influence on power pulsation amplitude. When choosing force control strategy this must be taken into account since large pulsations will require large components. Moreover, goals like reduced power pulsations or improved translator control can be fulfilled but at the price of a high peak current demand.

This study has not covered combustion issues. Translator motion and position relative to ignition will affect the combustion process and thus emissions and efficiency. Furthermore, when using a high bandwidth control system, which updates several times during a stroke and considers both combustion and translator motion, an exact force profile can probably not be chosen in advance. But the control signal could still end up in a profile similar to the ones investigated here.

To conclude, the results provided here give an insight into how force control strategies will affect necessary performance of converter, electrical machine and energy storage. High peak current demands and power pulsations can be coped with, but it is important to consider them when designing the system to achieve an efficient system with a reasonable size and cost. This is especially important if the FPEC is placed in a vehicle application, as low cost and weight are key parameters for the automotive industry.

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