Ensuring Steady Operation of Free-Piston Generator

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ABSTRACT

This paper describes Free-Piston Generator (FPG) model and its control for achieving steady operation. A FPG is a special type of combustion engine representing a new approach concerning the conversion of the chemical energy of hydrocarbon fuel into electrical energy. Unlike conventional engines, this type of engine does not use a crankshaft, and generates electric energy directly by a linear movement of pistons.

Keywords: Combustion engine, free-piston engine, HEV, combustion engine control.

1. INTRODUCTION TO FPG PROBLEM

The FPG presented here is a two-stroke, two cylinder combustion engine. Unlike conventional combustion engines, the FPG has no crankshaft (often the name "free piston engine" is used for such conception). The FPG moving part consists only of two rod-connected pistons, which move from one side to another. There exist also another configurations of free piston engines, e.g. with only one cylinder and the spring on opposite side. Also four-stroke cycle (at least 4 cylinders are necessary in this case) or diesel cycle can be used. These configurations are not discussed in this paper.

The disappearance of the crankshaft has beneficial aspects. The friction losses associated with the crankshaft, the conventional connecting rod, and their accessories are eliminated and the lubrication is also simplified. Piston friction is reduced, as it is no longer under the influence of an angular loading. The system also becomes more robust, as the number of moving parts is reduced to one. As the engine compression ratio is now no longer fixed, at least theoretically, multi-fuel operation is enabled. Variable compression operation for the same fuel type could also be achieved. A modular design approach with several distributed units would also become possible, offering redundancy and improved reliability.

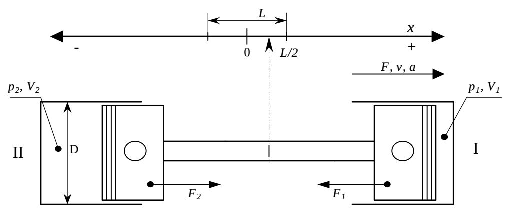

Fig. 1. Simplified FPG diagram - constants and variables definition

During FPG operation, the pistons are accelerated by a combustion mixture and move from one side to the opposite side. The released energy is partially used to compress the fuel mixture in the opposite cylinder. This action is repeated periodically. The difference between the energy released by the combustion mixture and the energy consumed by mixture compression and mechanical losses is drained from the system as electric energy by a linear motor-generator which is also used as a starter during the start of FPG. Finally, the motor-generator also allows the prevention of the FPG from stopping when a misfire occurs.

Because the motion of a moving part is not constrained by a crankshaft, the controller must provide precise control of a moving part's position in order to avoid collision between the piston and the cylinder head. The controller must also detect possible misfires and intervene appropriately, so it works analogical to a flywheel. This represents a key problem related to the feasibility of the FPG. The control features should also maximize the electric energy drained from the FPG.

The main drawbacks of a conventional two-stroke engine (e.g., high emissions of pollutants and irregularity at low speed) could be partially eliminated by the use of a precise fuel mixture system (e.g., air assisted fuel injection). The main application of the FPG is in so called hybrid vehicles.

A number of papers, which examine a combined linear alternator and combustion engine system, have been published; however, most of these works concern the coupling of a linear alternator and Stirling engine [3]. A configuration with two opposed cylinders and two-stroke cycle is described in [1] and [2], but these works are focused mainly on simulation, but control is not considered. Another configuration with one piston and spring is discussed in [4] and in [5]. This configuration also allows the use of a four-stroke cycle, but in this case external electric energy is needed for steady operation.

real model of FPG

The FPG prototype employs two 50ccm cylinders with the direct fuel injectors. The linear motor-generator is a product of VUES Company and is driven through the 3-phase power bridge with IGBT transistors. Picture of the FPG is shown in figure 2.

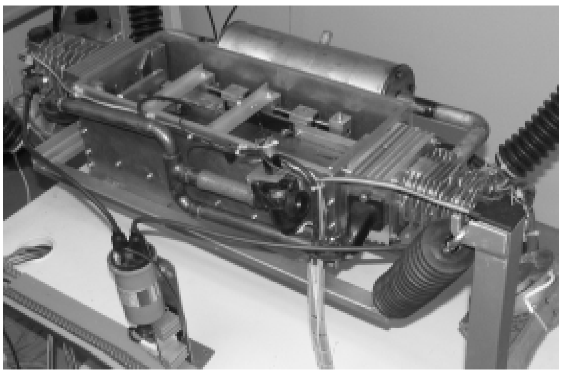

Fig. 2. Picture of real FPG model

The industrial incremental magnetic sensor is used for position measurement. The maximum measured speed is 5 m/s with accuracy 100 μm. The pressure sensor is used to measure the intake air pressure. The current transducers sense currents flowing through the motor-generator windings.

The ignition unit is capacitor type and has only one ignition coil. A spark is always simultaneous on both spark plugs, but the combustion process can start only in a cylinder with the fuel mixture.

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All described hardware is connected with the dSpace via an interface board, which provides a voltage level conversion and a protection of all dSpace inputs and outputs.

2. CONTROL OF FPG

The control problem is multi-level. Generally, we consider three levels (in case of FPG use in hybrid vehicles). The top level is an energy management of the vehicle, which determines the use of on-board energy sources – batteries (or supercapacitors) and hydrocarbon-electricity converter (FPG in this case). This level is not considered at this time. The middle level controls the amount of the fuel-air mixture to burn according to the power demands. It is done by controlling the fuel injectors, throttle, and spark position. It is also responsible for emissions and keeping the lambda ratio equal to 1 (approx.). The bottom level controls the movement of rod-connected pistons by keeping the energy drain max efficient. It is done by adequate control of IGBT power bridge. This level is also responsible for overcoming misfires (prevent stopping of FPG due to a misfire) and avoiding collisions between pistons and cylinder heads. Note, that the linear movement has no limits, in comparison to the conventional combustion engine. So the key problem is the collision avoiding. The on-system measured variables are position of the connecting rod, velocity of the rod, intake air pressure, intake mass airflow, and currents flowing through motor-generator coils.

Control system HW description

In this case, for bottom and middle control level is used a powerful Motorola PowerPC based system produced and supplied by DSPACE Company. The modern, high-level design methods utilize Real Time Workshop, Matlab and Simulink for a precise real-time control. Main advantage of this high level approach is a short implementation time of control algorithms in comparison to “C” or assembly language based development. Control algorithms, which are tested on the Simulink model, can be also used directly for the prototype control.

The Dspace DSP board contains analog and digital inputs and outputs. An additional hardware had been constructed to provide an interaction with a real model. Block diagram of this hardware is shown in figure 3.

The DiTech technology injectors with the air assisted fuel injection method (product of Aprilia Company) are used in the FPG. The fuel injection has two phases served by the electromagnetic valves. At first, the proper amount of the fuel is prepared in the small chamber. In the second phase compressed air is used to atomize fuel mixture into the combustion chamb

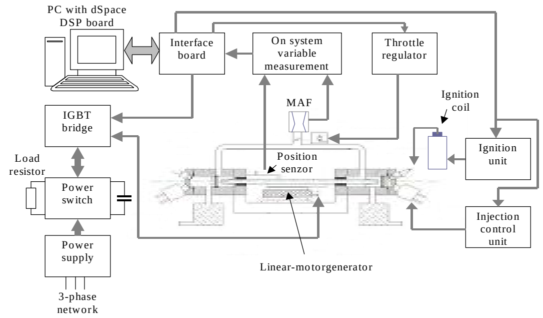

Fig. 3. Block diagram of extension hardware

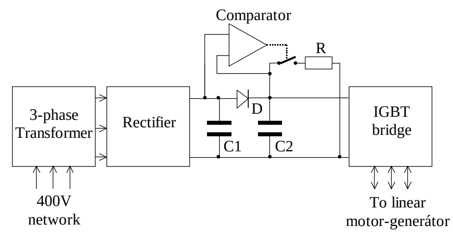

Fig. 4. Block diagram of power switch

For experimental phase of development a power switch is used instead of accumulator with corresponding power management. Main function of this circuit is to recognize and control an electric energy flow. 3-phase power bridge (driven from dSpace) is powered through the rectifier and the diode D (figure 4). Whenever the linear motor-generator is in the generator mode, the voltage on the capacitor C2 is higher than the voltage on C1. To avoid the increase of voltage on C2 over its surge voltage, the load resistor is used. If the voltage difference UC2-UC1 exceeds adjusted limit, the energy is routed to this resistor. Power dissipation on it is equal to the power gained from FPG.

Control algorithm

Currently we consider only the control of the linear motor-generator and the combustion engine operates only in one mode at the constant speed. Therefore the parameters like spark position, fuel-air mixture ratio etc. are set to the constant values, which are based on the experimental system identification. Motor-generator control provides keeping of the pistons in some limits and thereby the steady operation of whole FPG prototype.

Two control loops are used to control the movement of the linear motor-generator. The outer loop provides tracking of the desired trajectory. The output value of this regulator is a desired force, which should be generated by the linear motor-generator. This force is dependent on the actual currents through the motor-generator coils, therefore another regulation loop is necessary to provide the appropriate current control (motor-generator is supplied by the voltage from the PWM modulator).

Current control loop

Because there are dependencies between individual phases of the 3-phase motor-generator, the feedback is implemented only for two phases to avoid antagonistic conflicts in the regulator and the last signal is calculated from these two.

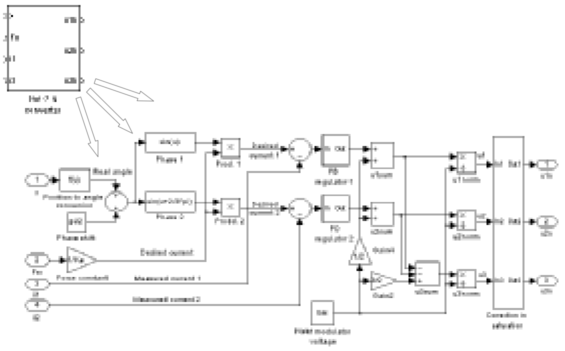

Fig. 5. Current control loop

At fist the real angle (the angle of the analogical rotary machine) is calculated from the real position of the connection rod according to the motor-generator geometry (pole pitch, number of windings etc.). The desired force is divided by the motor-generator constant K_a to obtain desired current.

$$I = \frac{F}{K_a} \qquad (1)$$

Two PD regulators are used for the tracking of the desired currents. For the better approximation of the derivation FIR filter is used. The output voltage of the regulator is normalized to the values from 0 to1 (it is necessary for the PWM modulator block). Third phase is derived from another two according to the equation:

$$\sin(j) = -\sin\left(j + \frac{2}{3}p\right) - \sin\left(j - \frac{2}{3}p\right). \qquad (2)$$

Position control loop

This controller must provide the following functions:

- Collision avoiding between the piston and the cylinder head
- Maximization of drained electric power in each cycle
- Prevention of the FPG from stopping when a misfire occurs
- Starting of the FPG (with respect to a actual FPG state)

From the character of the system clearly implies, that it can't be forced to move with exact frequency, because there is some stochastic part in the behavior of the combustion engine. Therefore the reference trajectory must be adapted to the actual system state. The regulator structure is in figure 6.

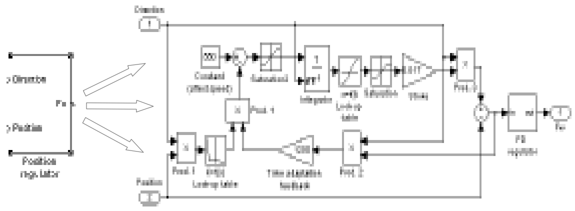

Fig. 6. Position control loop

A ramp signal (created by integrator) is used as the input for the look-up table, which affects trajectory of the FPG movement. At this time it contains the grooving part of the sinusoidal signal, but generally it can contains also the different trajectory. Multiplication by 1 or -1 provides the proper reference trajectory for the both directions. This trajectory is very similar to the sinusoidal, but there are discontinuities caused by the impreciseness in the determination of the real direction. The constant at the input of the integrator sets the desired FPG speed. A simple PD regulator is used for tracking of the reference trajectory (the output is the force). As in the previous case, the FIR filter is used for the approximation of the derivation.

For an adaptation of the reference trajectory an additional feedback is used. It provides adapting of the time scale according to the actual regulation error. Because only the position of the dead centers is important, we can allow more freedom to the system after combustion, but trajectory near the dead center must be strictly forced. For this feature there is another look-up table, which represents a dependency of the time adaptation constant on the real position.

For proper function of the previous controller, the real direction must be derivate from the position sensor. This is provided by the block "Commutator", with a structure in figure 7. Another important function is the initialization of the controller and the encoder for the incremental position sensor. The input "Ref. Mark" is connected to the real sensor on the prototype. Its value is 0 for the left side position of the connecting rod and 1 for another case. It allows starting of the FPG movement in the right direction. The velocity is obtained as the filtered derivation of the position. Starting of the FPG is detected as the first occurrence of the non-zero velocity. After the each start, a short pulse is generated on the direction output, to reset integrators in the regulator and models. The position encoder is reset only once after the start (S-R flip-flop is used for this purpose). The relay function enables the direction changing only after the spark position (protection against the incorrect direction changing due to a noise in the position signal).

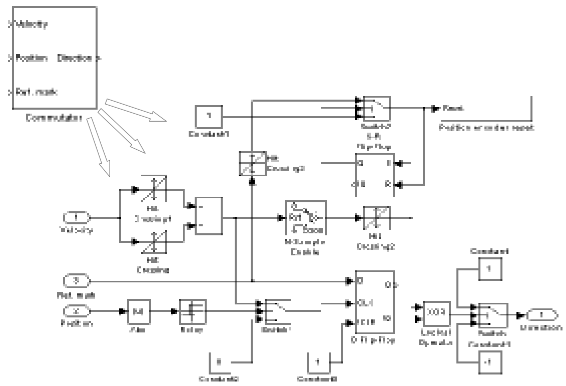

Fig. 7. Block diagram of commutator

All described blocks are combined together in global diagram. It contains also mathematical model of the FPG [6]. Structure allows simple switching between simulation and real-time control.

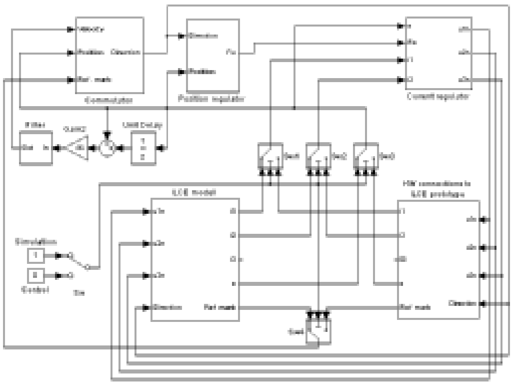

Fig. 8. Global simulation diagram

3. EXPERIMENTAL RESULTS

For the experimental purpose, the pressure sensor was placed directly into the cylinder head. It enables to obtain the p-V diagram and compare it with the simulated one. Unfortunately the p−V diagrams were measured at the time, when the FPG didn't operate steady (the pressure sensor was only lent). Therefore the results from pressure sensor are only informative and don't have correspondence to other results in figures 10-13.
With the new control system described above, a long-term steady operation was achieved. Hence we obtain lot of new experimental results, unfortunately without appropriate equipment we where not able to identify the combustion engine parameters. Therefore the results are concerned mainly on the electric motor-generator and the global behavior of the FPG. In future, we plan to measure the pressure in the combustion chamber and in the chamber under the piston, mass airflow, pressure in intake manifold, fuel consumption and analyze the exhaust gasses. It allows better thermo-dynamical analysis of the combustion engine.
The comparisons between the experimental and simulated p−V diagrams are shown in figure 9. Step of the pressure in the simulated result is caused by an assumption that the exhaust port opens in infinitely short time. The spark position is obvious on the compression curve. Another fact – the limited speed of a flame expansion can be also observed.

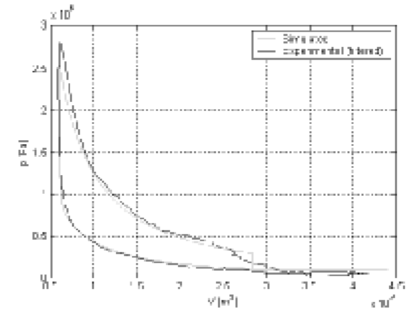

Fig. 9. Simulated and experimental p-V diagram

All the following results are obtained at the same conditions. Speed is approximately 27 Hz (1600 rpm), spark position is $x_z = 15.5mm$ (upper dead center is 18.5 mm) and compression ratio $e \doteq 9$.
Next figure shows the reference and the real trajectory of the connection rod. Discontinuities in the reference trajectory are caused by impreciseness in determination of the real direction. Note, that the reference trajectory shape is not ideal, but it allows the FPG to operate steady and also solves the possible misfire problem.

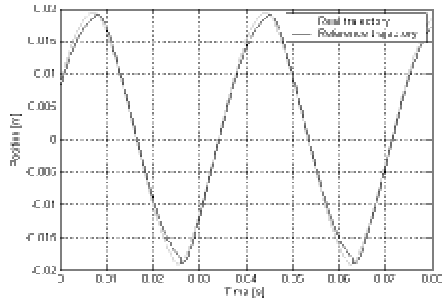

Fig. 10. Reference and real trajectory of connecting rod

More informative is next figure. It shows dependency between the velocity and the position of the connection rod. One cycle of the FPG runs in a clockwise direction. The function of above described regulator is well observable – after upper dead centers there are differences in individual cycles (regulator provides more freedom to the system), but dead centers are achieved very accurately. The crinkles on the experimental data are caused by opening of the intake and exhaust ports (it causes step change of the in-cylinder pressure) and intervention of the regulator to this situation. Note, that the velocity is obtained as a derivation of the position and thus there is also some inaccuracy (the velocity in figure 11 is already filtered by a low-pass filter). By comparing the results with figure 10 is obvious, that a change of the velocity has only very small influence on the shape of the real trajectory.

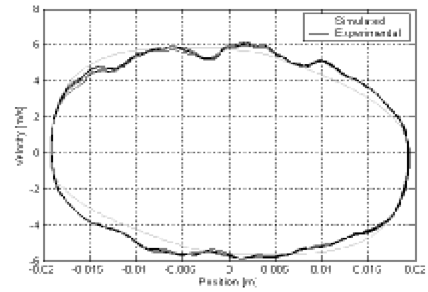

Fig. 11. Velocity as function of position

Because the aim of the project is maximization of the drained electric power (consequently efficiency), the key problem is utilization of the combustion energy in the cycle. Next figure shows on the left axis the reference trajectory x_r (black), real trajectory x (blue) and regulation error $e = x_r - x$ (green). On the right axis there are the actual power (red) and average power from 1000 samples (magenta). Positive value means the electric power delivered in to the system. It is obvious, that the average output power is approximately 350 W. Same value was also measured by an analogue wattmeter directly connected to the load. The actual power depends on the actual regulation error. Ideal case is, when the reference trajectory always foreruns the real trajectory, because the electric power is drained from the system by braking. However if the desired braking force exceeds some limit (depends on the actual velocity and motor-generator constants), an additional electric energy is needed (in our case it happens after the combustion), which is not desired situation. The design of control algorithm, which maximizes drained electric energy, is the key problem of whole project. Here presented solution is not optimal, but provide steady operation of the FPG and can be used as the groundwork for a further research.

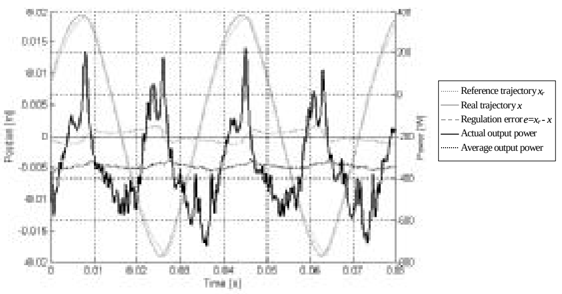

Fig. 12. Actual output power as function of position – experimental data

Last figure shows same variables obtained from the simulation. Shape of the actual power is much more smoother (it is not affected by a measurement noise), but the results are similar. Also the average output power is very close to the value obtained on the real prototype.

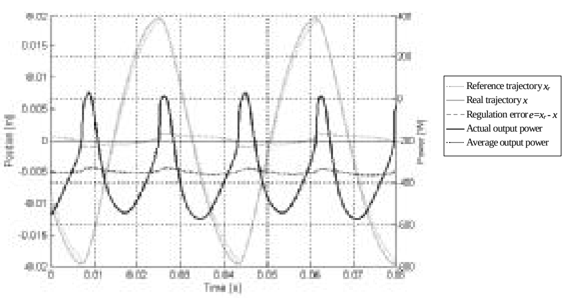

Fig. 13. Actual output power as function of position – simulated data

4. CONCLUSION

Nevertheless simplifications in the model, simulations results show a good correspondence between the model and the real system, but more precise thermo-dynamical identification is necessary for further work.

Although the prototype at this time is very crude, it enables experiments, which are very important for further research. Currently a steady operation of the FPG was achieved, which demonstrates a feasibility of the FPG project. Previous work also indicated problems of the current FPG design. The main problem is in electric motor-generator, because its parameters are not sufficient for draining of energy from the combustion engine. Therefore only poor fuel mixtures can be used (braking force of the motor-generator is not high enough) and it has a negative effect on efficiency of the FPG. The key problem is also the design of the control algorithm, which maximizes drained electric energy and concurrently provides a steady operation of the FPG (also in case of a misfire).

Generally the free piston generator seems to be a perspective device concerning the conversion of the chemical energy of hydrocarbon fuel into the electrical energy. With some essential improvements in the current design it can offer advantages over the traditionally used rotary system.

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6. ACKNOWLEDGEMENT

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