Integrated Free-Piston Generators: An Overview

Waqas M. Arshad, Thomas Bäckström, Peter Thelin and Chandur Sadarangani

Abstract—**The free-piston generator is an energy conversion device that integrates a combustion engine and an electrical generator into a single unit. Thereby the intermediary crankshaft stage present in conventional hybrid topologies is eliminated. This has benefits in efficiency, weight reduction, robustness, variable compression operation and multi-fuel possibilities. This paper presents the free-piston generator concepts, along with the expected benefits and drawbacks. A literature survey is provided. Results from a simplified combustion modeling process are presented in terms of piston motion profiles. These have implications upon the dimensioning and selection of an appropriate electrical machine. Specifications for the electrical machine are outlined. Some distinct electrical machine solutions are presented and discussed. An application of the free-piston generator in a series hybrid vehicle is also proposed.**

Index Terms—**Free-piston generator, Hybrid-electric vehicles.**

I. INTRODUCTION

The hybrid vehicle concept is environmentally friendly, highly efficient, and is gaining popularity by the day. This drives most vehicle manufacturer to have a share in the emerging hybrid vehicles market. The resulting competition among vehicle manufacturers in turn stresses the engineers and researchers working with alternative vehicles to find even newer and better propulsion solutions. Common demands are high specific performance, increased system efficiency, reduced number of system components, etc. The free-piston generator concept is one of the relatively new (and still emerging) hybrid vehicle concepts that could offer good solutions to some of these demands.

II. THE FREE PISTON CONCEPT

The free-piston generator integrates a combustion engine with an electrical generator. This is shown in Fig. 1. The rod that connects the two oppositely placed combustion chambers also acts as a prime mover for the generator. The reciprocating, ignition and compression processes, in the two chambers cause the connecting rod to have an oscillating motion. Now, if this rod is placed in a magnetic field (containing coils), and if the movement of the rod causes a disturbance of the field, an electromagnetic force (EMF) will be induced in the coils. This is the principle of the free-piston generator, producing electricity directly from the linear motion of the pistons. The crankshaft, which is normally required in conventional hybrid concepts, is therefore eliminated.

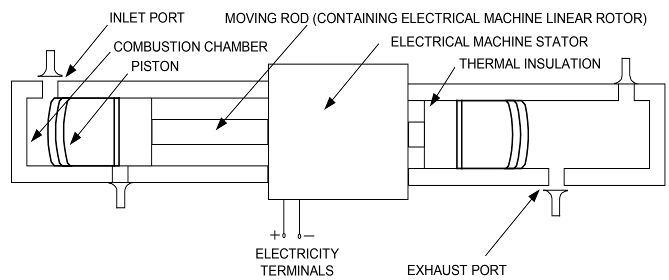

Fig 1: The integrated engine-generator.

The disappearance of the crankshaft has beneficial aspects. The friction losses associated with the crankshaft, the conventional connecting rod, and their accessories are eliminated. 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, allowing an application in military or other operation critical vehicles [3].

Uncertainties associated with this concept are the thermal insulation between the combustion chamber and the generator portions, the excessive and repetitive forces that act on the moving rod, high expectations upon reductions in system costs and improvements in the specific performance. Much of these uncertainties are expected to vanish in the near future, with the maturity of the free-piston concept technology.

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III. Literature Review

Some solid and very informative work on the free-piston concept already exists. This is evident from the long list of related patents that exists today [12]. However, much of the work that has been carried out was intended for use with Stirling engines and for space or remote applications. The Stirling engines operate on an external combustion process. These engines, as compared to internal-combustion engines, are quite heavy and hence, cannot be used in conventional vehicles. Some of the most interesting and relevant literature is reported below:

A. Nasar & Boldea [11] have suggested a permanent-magnet linear motion generator, intended for integration with a Stirling reciprocating engine.

B. The center of electromechanics, University of Texas, Austin [3] is working on the design, construction and testing of a free piston engine-generator, employing an induction-type alternator. The induction generator uses an extension of the piston skirt as the armature instead of the more conventional permanent magnet mover, making the device robust and compact. The device however has low specific performance, but a distribution of a number of these units at convenient places overcomes this drawback. The primary target for their development is military and other operation critical vehicles.

C. Galileo Research Inc. [8] is undoubtedly the research leader in the free-piston generator technology today. They have developed a commercial unit, which has a single moving component, the piston rod assembly, and is integrated with internal-combustion engines.

D. The department of electrical engineering at University of West Virginia has developed a 500 W free-piston generator [7]. It is now being tested and employs two spark-ignited cylinders to produce reciprocating motion of the piston. The permanent magnets are mounted on the moving piston, and the coils are situated in the stator. In the future it is planned to use a compression ignition process along with a substantial increase in the power rating of the device. The electrical machine's stator is of the air-core type. In the future, an iron core stator is also planned.

E. Mechanical Technology Inc. [4-6,13-16] has been working with free-piston generators for a number of years and already has some patents [12]. The prime mover in all these devices is the Stirling engine. The primary targets for these generators are space and terrestrial power units. Both moving magnets [4-6,13,15] and moving iron [14,16] generators are available, and with a diverse power range. Commercially available units have power ratings of 10, 11 and 350 Watts. Work on a 3 kW commercial unit is in progress for remote applications. For space applications a 12.5 kW unit has been built, and work towards a 25 kW unit is in progress.

F. SunPower Inc. [9] has developed 3 kW high frequency free-piston generators of the diesel fired and Stirling-engine powered types. These are long life, low noise units, built specially for the US Army. The alternator is of the moving magnet type.

IV. The Combustion Process Modeling

In order to find the specifications and design guidelines for the electrical machine, a simplified modeling of the combustion process has been carried out. The force that drives the piston/translator is the expansion force (F_e) of the active chamber. The forces that oppose this motion are; the compression force (F_c) of the inactive chamber, the friction force (F_f), and the counteracting electromagnetic force (F_l) (dependent upon the loading of the electrical machine). The acceleration of the moving unit (of mass m) is thus given by (1).

$$a = \frac{d^2x}{dt^2} = \frac{F_e - F_c - F_l - F_f}{m} \tag{1}$$

The expansion force is of an order higher as compared to the other forces of (1). Thus, the acceleration (and accompanying velocity) of the translator is directly dependent upon the moving mass, which is one of the most critical parameters in the system. Fig. 2 shows the variation of pressure in one combustion chamber for one complete engine cycle. From this the magnitude of the combustion forces and stresses exerted upon the moving unit could be found. Parameters for the combustion process are specified in Table I. Fig 3 shows the motion profiles for the translator (assuming a constant electrical loading of the generator) for one combustion process. It is seen that very high accelerations are involved (due to high combustion force and low moving mass). Hence, special care has to be taken when designing the translator. Problems with high stresses, fatigue and mechanical imbalances will arise. It is also seen from Fig. 3 that the velocity profile is far from sinusoidal, suggesting an induced emf, with a high content of harmonics. This would thus require a greater emphasis on converter and filter circuits for this particular application.

TABLE I
COMBUSTION PROCESS PARAMETERS

Parameter	Value
Required system output	50 kW
Stroke length	100 mm
Average frequency	30 Hz
Piston diameter	90 mm

There will likely be problems associated with heat flow from the combustion chambers to the moving translator of the electrical machine. To counter it, a proper thermal insulation between the pistons of the combustion chambers and the translator of the electrical machine would be required. This will contribute to the moving mass and would further restrict the amount of mass available for the electrical machine translator.

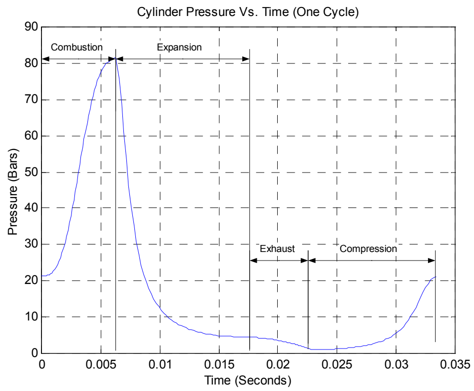

Fig 2: Chamber pressure variation for one engine cycle.

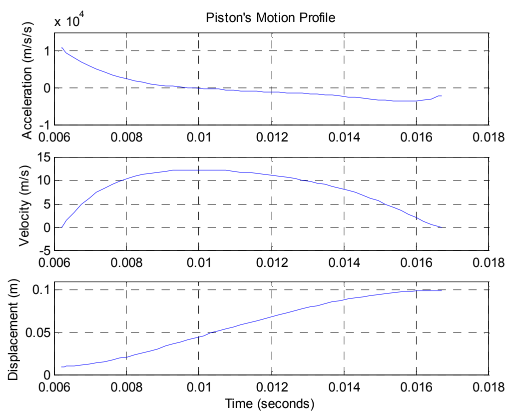

Fig 3: Piston motion profiles for one combustion process.

V. Specifications for the Electrical Machine

For a free-piston generator concept, the electrical machine topology is one of the most critical factors.

TABLE II
SPECIFICATIONS FOR THE ELECTRICAL MACHINE

Parameter	Requirement
Moving Mass	Low
Specific Power	High (>1 kW/kg)
Efficiency	High (> 90%)
Power Factor	High
Mechanical Stability	High

As stated earlier, there are severe restrictions upon the moving mass and the forces that act upon the moving chamber are extremely high and repetitive. The moving rod and its components (e.g. magnets) should therefore be able to withstand the high combustion forces being exerted upon them. Further, a non-sinusoidal motion profile demands a challenging task of working with pronounced harmonics. Besides, the technical limitations there are performance/design constraints due to economic and system constrains. The converter/filter costs are dependent upon the machine's power factor. Thus, it is desirable to have the machine power factor as high as possible. Cogging (common in permanent magnet machines) is not a major problem for a free-piston application because of the high magnitudes of combustion forces involved, when the machine is run as a generator. Even in motor mode (for starting purposes), the machine could be fed with sufficiently high currents to overcome cogging forces (if present at all). Table II provides a listing of the specifications set upon the electrical machine.

VI. Electrical Machine Possibilities

In this section some distinct electrical machine topologies are discussed. Dimensioning and performance details for these various topologies are provided in [1].

A. Moving Coil Designs

In moving coil machines the permanent magnets are stationary and provided on the stator, while the coil reciprocates within the area spanned by the stationary magnets (see Fig. 4). The magnets are located on the inner surface of an iron structure. The inter-poles between the magnets may be of steel or of a non-magnetic material [10]. The magnets could also possibly be located behind a flux concentrating iron pole, in order to focus flux to the coils. The coils may be supported on iron for higher performance. Alternatively, an iron-less structure for the coils may be employed to reduce inertia of the moving piece.

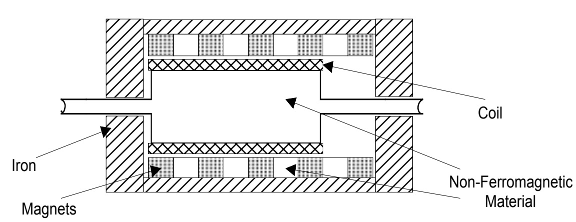

Fig 4: A moving coil electrical machine [10].

The use of moving-coil machines is not feasible in free-piston generators. Problems encountered are requirements of flexible coils, wear out of the coils, high moving masses and problems with heat dissipation from the coils. Due to moving mass restrictions, an iron-less coil structure is preferred, but it would result in a large magnetic airgap and poor machine performance, further aggravating the situation.

B. Moving Iron Designs

The moving iron alternators have only iron as the moving mass. Both the coils and the magnets are provided on the stationary stator. The coils are excited by a variation in flux linkage. This occurs as a result of variations in the permeance along the direction of the motion [2]. Moving iron devices are rugged, cheaper, and easy to manufacture. They also impose less strain upon the thermal design of the moving member, and frequency and impact restrictions required for moving magnet designs can be relieved. The main drawback with the moving iron designs however, is their lower specific performance and a pronounced mass of the moving member. A modern moving iron design is shown in Fig 5. This design has benefits over older moving iron designs, as it facilitates flux reversal in the moving iron and not merely relies upon flux pulsation, a characteristic of the older designs.

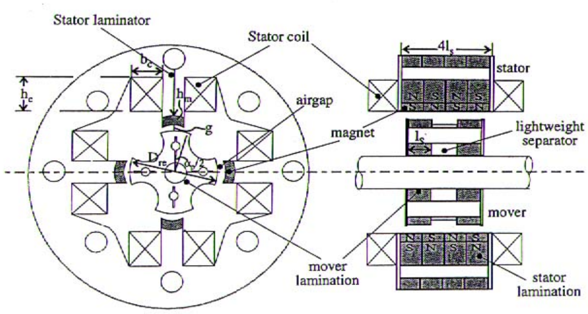

Fig. 5: A modern moving iron design [2].

C. Moving Magnet Designs

In moving magnet designs, the magnets are mounted on the moving member. The magnets may be supported on non-ferromagnetic structures (surface mounted designs, Fig 6) or be used with ferromagnetic-iron pieces (for flux concentration, Fig. 7).

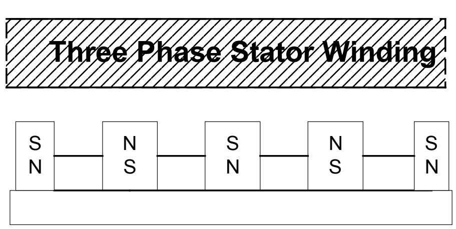

Fig 6: The surface mounted moving magnet design.

These designs provide the highest specific performance and lowest moving masses. Linear equivalents of the different types of permanent magnet rotating machines may be evaluated for a free-piston application. The main problems here are associated with the high and repetitive impact forces, which the magnets may be subjected to, and a proper thermal insulation between the magnets and the combustion chambers.

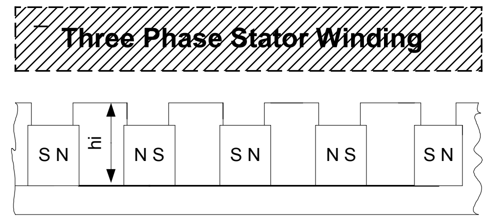

Fig 7: The flux-concentrated moving magnet design.

VII. Application in Series-Hybrid Vehicle

Fig. 8 shows the application of the free-piston concept in a conventional series-hybrid vehicle layout, other concepts have not been investigated. For a qualitative comparison of the free-piston concept with the other existing hybrid-vehicle solutions, demands system simulations. This would require appropriate modeling and dimensioning of all system components shown in Fig. 8. It is expected that, once a proper design for the free-piston concept has been achieved and a suitable driving and energy storage strategy is finalized, such comparisons would not impose considerable difficulties.

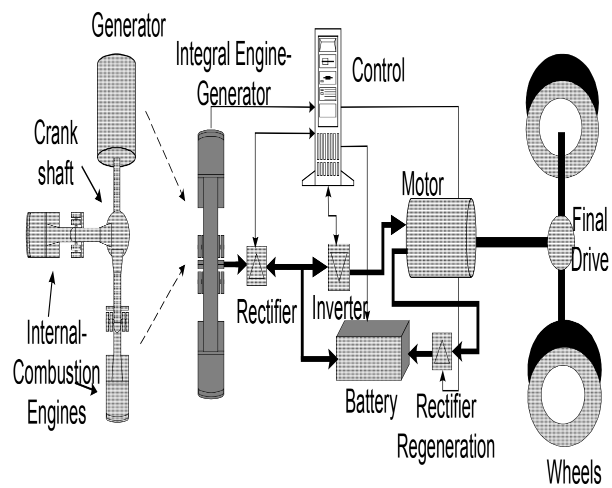

Fig 8: Application of a free-piston generator in a series-hybrid vehicle.

VIII. CONCLUSIONS

An introduction to the free-piston generator is presented, along with a detailed literature survey. Results from a simplified combustion modeling process are provided. These simulations results are required to define some of the constraints set upon the electrical machine design. Specifications for the electrical machine are discussed and different electrical machine topologies are outlined. Finally, a layout suggesting the use of the free-piston generator in a series-hybrid vehicle is presented and discussed briefly.

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