A Review on Design and Development of Free Piston Linear Generators in Hybrid Vehicles

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Abstract. The rapid exploitation of fossil fuels due to their indiscriminate use has brought us to a situation when we cannot sustain the use of fuels like petrol and diesel for more than 30 years from now. Governments and energy companies around the world are looking for some alternative source of energy to power the vehicles. A lot of research is being carried out in this field and many researchers have concluded that hybrid vehicles can be a boon to eradicating the dependence on conventional fuels and move towards battery-aided power trains for running the vehicles. Today, there are a few electric vehicles on roads but in the near future the roads are going to be flooded by them. To propel them, we need batteries which should be charged at some intervals. In absence of battery charging stations, we would need range extending devices on the vehicles itself. A Free Piston Linear Generator (FPLG) is an electric generator which produces electricity by virtue of oscillation of a free piston in a cylinder and it can be used as a range extending device and alternative energy converter in a hybrid vehicle. Using an FPLG will be a new approach to optimize combustion process and thus it can not only help in low exhaust emissions but also in using new renewable fuels due to their capability of variable compression ratios. This paper is a review on the design and development of FPLG system for hybrid vehicles as an inevitable source of energy in near future.

Keywords: Control Systems; Free Piston; FPLG; Hybrid Vehicles; Range Extenders

1. Introduction

Fossil fuels like petroleum and coal fulfil about 66.67\% of the energy required by the world. Their limited reserves and unequal distribution have outcome in the cost of fuel to raise many folds in the last two decades [1]. To prevent the serious social and economic inferences of global decline in oil production the 2005 Hirsch report [2] suggested the need to discontinue the practice of using petroleum over the peak time i.e. ten to twenty years from then. Depletion of petroleum reserves has encouraged many researchers to work on alternative fuels [3] and therefore, various alternative fuels such as compressed natural gas, hydrogen gas, bio-diesels, bio-gas, alcohol etc. are being considered as alternatives for conventional fuels and to reduce exhaust emissions [4] while keeping other features
and behaviors of an engine within limits [5-11]. Besides renewable fuels, electric vehicles (EVs) [13–15] can also be a logical step towards sustainable, efficient and environment friendly transportation.

These EVs are broadly categorized as: pure electric types, hybrid electric types, and fuel cell types. Although pure electric vehicles create no emissions, the cost of battery, its management and maintenance create a hold-up in their use. The fuel cell vehicles have a lot of latent qualities for future vehicles [16] but the cost of their technology and refuelling system are still in early development stage [13]. In a few years from now, the pure electric vehicles could be accepted by a few niche markets, such as for community transportation and the place where electricity is cheap and accessible. The hybrid electric vehicles could have a niche market for the people wanting a long driving range [14] and this is where FPLGs can be a boon i.e. in the area of long extended ranges. They can also be used as an alternative energy converting devices for such hybrid vehicles.
2. An FPLG System

The system in which an electrical generator is linked with an internal combustion engine piston without any aid of a crank is called a free piston linear generator (FPLG) system. It converts the stored energy in the fuel into electricity by using combustion process. A lot of research and investigations are being done in the area of their practicability and feasibility. One such systems as shown in the figure 4 is being studied at the German aerospace center (DLR) [18].

The complete system consists of three main parts namely, the combustion unit, the return unit and the generator. The combustion takes place in one end of the cylinder can have arrangements for inlet and exhaust valves, the fuel injectors and ignitors. It forms the site for energizing the fuel. The opposite end of the cylinder creates an adjustable gas spring (rebounding device) which helps the piston to come back for the second cycle. The spring constant of the gas spring can be adjusted by adjusting the amount of air inside the chamber. A generator is positioned between the combustion chamber and gas spring and it produces electricity due to the relative motion between the magnets mounted on the connecting rod and the stationary coils arranged on the cylinder. A cooling system enclose the cylinder has a very important role to sustain the magnetic properties of the magnets. [18]. The amount of electromotive force (emf) generated at the end of the coil can be given by Faraday’s law as

\[
emf = -N \frac{d\Phi}{dz} \frac{dz}{dt}
\]

Where,
N = Number of turns in the coil
\(\Phi\) = Flux passing in each turn in real time \(t\)
\(dz/dt\) = Relative speed between magnet and coil
Z = Total movement of the magnet
3. Possible Engine Types

3.1 Based on Piston Arrangement

3.1.1 Single Piston
While comparing with the other free piston configurations, the main advantage of this configuration is its simple design with a good controllability. The gas spring gives an opportunity to accurately control the stroke length and compression ratio amount by controlling the energy input to compress the combustion gas.[19][20]

3.1.2 Dual Combustion Chamber
This configuration can eliminate the need for a gas spring which allows a more compact device with a higher power to weight ratio[19] and it is possible because the combustion process in one cylinder which drives the compression in the other. But the fact cannot be ignored that any small variation in the combustion in any one of the combustion chambers can subsequently distort the combustion process in the complete engine. The problem associated with this configuration is controlling the piston motion, in particular the stroke length and the compression ratio which have proved difficult due to the fact that Achten, [22] in his review calls it a challenge for the control system. A good control is required for optimizing its efficiency and emissions.

3.1.3 Opposed Piston
This design makes the engine completely balanced and free from vibration which saves space and reduces complexity [18]. In the absence of any cylinder head, heat transfer losses are highly reduced and this can also allow single-flow scavenging for a high scavenging efficiency but to achieve this, there is a need for a piston synchronization mechanism [19]. Scientists at the German Aerospace Center (DLR) working on this configuration have claimed that they have developed a control system to control piston movement accurately to within one tenth of a millimeter and at the same time to recognize fluctuations in the combustion process and it compensates for them [24].
3.2. Based on Shape of Generator

3.2.1. Tubular Type
The tubular type linear generators can give greater efficiency and because of their structural merits [25], when compared to the flat type generators [26]. The electrical characteristics remain unaltered with the rotation of the piston besides this, the amount of the leakage flux is very less [17]. But the challenges regarding the manufacturing and assembly of the magnetic ring, lamination stacked stator and the windings have to be conquered. Another constrain is the sectional area of the surrounding windings which are controlled by the diameter of the ring magnets.

3.2.2. Flat Type
Qing-feng et al [23] gave a contradicting result when compared to the tubular type generators to show that even if there are structural drawbacks in a flat type generator, they are more efficient with more specific power, output current and voltage and hence they are much suitable for the FPLGs.

4. Advantage of FLPG System

4.1. Low loss due to friction
There is no crank to translate the linear motion into a rotational motion and therefore, it eliminates the losses due to friction in the crankshaft bearing, and an entirely linear motion leads to a very low side-loads on the piston. A few moving parts in the free piston linear generators turn down the frictional losses and hence reduces the lubrication requirements of the system.

4.2. Low fuel Consumption
As shown in figure 8 obtained by Frank Rinderknecht [27], fuel consumption of a vehicle obtained in the simulation of an integrated free piston engine versus that of a conventional car of the same class can be compared and there is a possibility of reduction of about 28% in fuel consumption by using an FPLG integrated vehicle.
4.3. Higher Efficiency
Cosic et al. [17] when comparing the total efficiency of a truck HEV running on a conventional combustion engine and an FPLG found that when a conventional combustion engine is replaced with an FPLG, the total efficiency increased by 25%, this is shown in figure (9).

4.4. Ability to use alternate fuels
It is a well-known fact that the thermal efficiency of an engine depends on the compression ratios, therefore, many variable compression ratio mechanisms have been developed [28][29][30]. But the earlier attempts on this approach required making of entirely new engine design. An FPLG in not constrained by a crankshaft and therefore its compression ratio can be varied without any constructional changes in the engine design [20] and therefore an appropriate fuel supply system can allow us to use different fuels like conventional fuels such as petrol, diesel [31,32,33], and alternative fuels such as natural gas, benzene, alcohol, hydrogen gas, etc. [34].

4.5. Compactness
When compared to conventional engines, FPLGs are small in size and have low weights which can provide more compact power trains and hence overall lighter vehicles.
4.6. Reduced maintenance costs and increased life

Maintenance cost is highly reduced due to the presence of a few moving parts and by the virtue of low friction which in turn increases the life of these engines.

5. FPLG control system development

There are many requirements for the FPLG engines to be viable. Control systems are needed to meet these requirements and bring them in operation. Controlling of piston motion accurately represents one of the biggest challenges. The Top Dead Centre (TDC) position of the piston should be controlled within tight limits [35] and the reason is that, any overshoot may lead to some mechanical contact between the piston and the cylinder head and this can be fatal for any engine. Engine speed control is required because by synchronizing multiple engines, vibrations can be minimized [20]. Besides these, combustion, misfiring, frequency of oscillation, starting the engine, load on piston, power output, etc. need to be controlled. Many researchers have tried answer these issues through their research.

5.1. Piston motion control

Chi Zhang et al. [36] briefs us about three conventional control strategies which are the trajectory tracking control [37-42], specifying a reference current profile [43-46] and regulating the load factor and combustion parameters for balancing energy flow [47-52]. For achieving compression ratio control, Kigezi et. al. [53] developed a model-based procedure to control the two dead centers thus controlling the motion of the piston towards the required compression ratio.

A similar work, to predict TDC, ‘a predictive piston motion controller’ was proposed by R. Mikalsen et al [35]. Boru Jia et al [55] showed that the position of the piston and power output can be predicted from the parameters like stroke length, cross sectional area of the piston, mass of the piston and electrical load. To have better performance, ‘the cascade control’ was proposed [54] to be implemented in the FPEG control system. O Lim, et al [33] investigated the effects of parameters like input caloric value, equivalence ratio, spark timing delay, electrical resistance, and air-gap length on the piston dynamics and electric power output. C. M. Atkinson et al [56] in their numerical modelling of the engine carried out the dynamic analysis for evaluating frictional forces and the alternator load and the thermodynamic analysis for evaluation for process of scavenging, compression, combustion and expansion.

5.2. Load Control

Output power depends on many factors like the in-cylinder initial pressure, the dimensions of FPLG [57, 58,59] and the piston movement characteristic [36].

| Table1. Potential parameters influential to TDC [54] |
|-----------------------------------------------|
| **Input Parameters**                        | **Engine size**                     | **Working Condition** | **Electric Load** |
| TDC                                          | Piston area (A), Half stroke length (Ls), Moving mass (M) | Injected fuel mass (Mf) | Coefficient of load factor (Kf) |
| Engine Operating Frequency                   | Piston area (A), Half stroke length (Ls), Moving mass (M) | Injected fuel mass (Mf) | - |
6. Other FPLG issues

6.1. Detent Force
The attraction between the magnets on the connecting rod and the stator results in detent force [47].
Ahmad M. Eid et al [61] studied the permanent magnet length for reducing detent force in the linear generator. They found that by introducing the slope in the permanent magnet, the detent force decreased and simultaneously, an increment in the voltage developed by the alternator was recorded. Sun-Ki Hong, et al [25] studied the effect of varying the pole pitch to reduce this force besides this achieving sinusoidal output waveform and high output voltage. The dependence of detent force on the pole pitch x and y as shown in figure 10. While modulating the pole pitch, a minimum value of detent force can be achieved.

![Figure 10. Pole pitch modulation for calculating detent force [25]](image)

6.2. Starting
An FPLG can be started either by giving an impulse to the piston sufficient enough for the piston to reach the TDC, or by oscillating the piston with either an electric machine or a hydraulic cylinder until it reaches sufficient compression. The requirement of the former strategy is that the engine should start on the first stroke itself and after that the control system should sustain the to and fro motion [19]. Saiful A. et al [62] investigated the viability of rectangular current commutation and mechanical resonating strategy to start a dual combustion chamber FPLG.

6.3. Combustion
The advantage of adjustable compression ratio in an FPLG can help us to optimize the combustion process which were not feasible in conventional engines [19] but researchers working in this field rouse many questions on combustion efficiency [63-69]. Adjusting the piston motion trajectory can be an answer to this problem [70].

6.4. Misfiring
The piston is capable of oscillating freely between its dead centres and this motion is controlled by the forces applied by the gas and other loads acting on it and any misfiring may cause a problem in the engine since it does not have energy storage machine element like the flywheels in conventional engines which are capable of driving the engine for several revolutions [19]. A good control system can help in overcoming this issue [36].

6.5. Lubrication
Roman Virsik et al. proposed solid lubrication as one possible solution for emission issues [18] in FPLGs with opposed combustion chamber configuration.

7. Fully Developed FPLG Systems-From Concept to Reality
Researchers at West Virginia University have demonstrated a controlled operation of a gasoline fueled, spark ignited, linear engine and a linear generator system [71]. When operating at full load, a maximum of 316 watt power was recorded at 79 volts and at no load, their system operated at a frequency of 25 hertz which generated an open circuit voltage of 132 volts. William R. Cavthorne in his research provided a method to choose a combination of engine and generator [72]. Researchers at UniversitiTeknologi Petronas in partnership with other two universities developed an FPLG to charge batteries for hybrid electric vehicles [62]. A team at Toyota Central R&D Labs have claimed to have been developing a prototype of FPLG[21]. Scientists at the German Aerospace Center have developed the concept of increasing the range of electrically powered vehicles and their researchers claim to have succeeded in operating this system in a stable manner [24].

8. Conclusions
Free Piston Linear Generators have a substantial potential as a range extending device in Hybrid Vehicles. These engines can be classified on the basis of piston configuration and generator shapes. FPLGs have many advantages but they are all futile unless we have a robust control system (for piston and load control). A number of issues like: detent force, starting, combustion, misfiring and lubrication were reviewed and over the past few years, these issues have been addressed by a number of different case studies and the days are not far away when we would see FPLG mounted hybrid vehicles with such control systems that would allow different fuels to be used in the same engine and these hybrid vehicles would move hundreds of kilometers with the aid of these range extenders.

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