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FREE PISTON ENGINE DRIVEN LINEAR GENERATOR FOR HYBRID ELECTRIC VEHICLES

BY

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Abstract. In the last decade the world became aware of the climatic changes due to the greenhouse effect caused by CO_2 emissions and began seeking solutions to reduce the industry's negative impact on the environment. Major efforts are focused on developing alternative energy sources and improving the efficiency of all energy consuming systems; in this context the hybrid electric vehicles emerged, and numerous solutions for powering them became of interest. A relatively new proposal is to use Linear Generator driven by Free Piston Engines, with superior performances compared to the system using rotating engines/generators.

Key words: linear generator; free piston engine; hybrid vehicle.

1. Introduction

Most of the extreme climatic phenomenon that occurred worldwide in the last few years can be accounted on the global warming. The multiannual temperature reports show that the temperature is constantly rising since the 1950's, culminating with the highest recorded temperatures in the second part of the 90's. There is a close correlation between the temperature rise and CO_2 and other gasses emissions: ever since the industrial revolution in the 18^{th} century

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the CO_2 concentration has been rising constantly until the middle of the 19th century, when it erupted, rising with almost 15% in only 50 years (Schwartz, 2005).

Besides CO_2 other gases are accounted in different percentages for the greenhouse effect namely: CH_4, NO_2 and water vapours. Since the CO_2 has the highest concentration it is important to determine its sources: 27% of the total CO_2 are due to transportation and 55…99% of those are because of road transportation; two thirds of this are produced by small vehicles (OECD, 2002). Considering these facts most of the car manufacturers founded research programs focused on non-polluting electric vehicles, with hybrid vehicles as an intermediate step.

The major problem concerning the full electric vehicles is the electric power storage system, mainly batteries (lead–acid, NiMH, Li–ion, NiZn or NiCd) or ultracapacitors, offering various storage performances and different number of charge – discharge cycles (Khaligh & Zhihao, 2010). Because of the poor performances of the storage system an electrical vehicle such as the plug-in General Motors' Volt is not going to be a major success: at a cost of approximately $40,000 you get a fuel reduction over the entire life cycle of the vehicle that would not justify the initial investment and the required battery replacement (Ross, 2010).

There are several solution used to combine the power generated by the combustion engine and the electric motor inside a hybrid electric vehicle namely

a) *parallel hybrid* – both power sources are connected to a mechanical transmission and simultaneously transmit power to drive the wheels; the hybrid can use regenerative braking to charge the battery pack;

b) *series hybrid* – only the electric motor powers the drivetrain, while the internal combustion engine is used to power an electric generator to recharge the batteries; also uses regenerative braking;

c) *power-split hybrid* – or series-parallel hybrid systems combine the advantages of the two basic types: the series hybrid are more efficient at low speed and the parallel configuration is better at high speeds.

While most of these systems use rotating motors and engines, our focus is on a more radical solution: using an Electric Linear Generator connected directly to an Internal Combustion Free Piston Engine in order to produce and store energy in a battery pack. The vehicle traction is made by using two or four wheel-mounted electric motors. Though this system seems more complicated and implies some major modifications of the vehicle, the overall system efficiency is better than in other hybrid systems.

2. Free Piston Internal Combustion Engines

In the category of "Free Piston" Engines fall all systems that do not use a rotating crankshaft to transform the linear piston motion into rotating motion. The original Free Piston Engine (FPE) was patented in 1928 by R.P. Pescara and was initially used for air compressors. Until the Second World War the FPE was exclusively used for producing compressed air and latter was abandoned for a while; the first system using it with a linear electric generator is reported in 1959. Reported internal combustion engine systems use both two-stroke and four-stroke combustion cycles, depending on the application. Depending on the number of piston and their position there are several possible topologies

a) *Single piston* – uses only a combustion chamber and a rebound device that stores part of the energy generated during the combustion stroke, enough to compress the cylinder for the next working cycle. Such a system is shown in Fig. 1 *a*, where the rebound device is at the right. This device allows the control of the system frequency and stroke by controlling the low and high pressure valves.

b) *Dual piston* – eliminates the need of a rebound device during functioning because the combustion stroke of one piston coincides with the compression stroke of the second piston (Fig. 1 *b*). An external force needs to be applied when starting the engine, a force that can be produced by the linear electrical machine. The high vibration levels produced by such a system can be eliminated by using two or more systems that would work in anti-phase, requiring precise control.

c) *Opposed piston* – the two pistons share the same combustion chamber and a mechanical synchronization part that assures that the pistons move simultaneously is needed, like the one shown in Fig. 1 *c*. Each piston requires a rebound device on the free shaft end and the load (the electric generator) may be mounted on each side (Mikalsen & Roskilly, 2007).

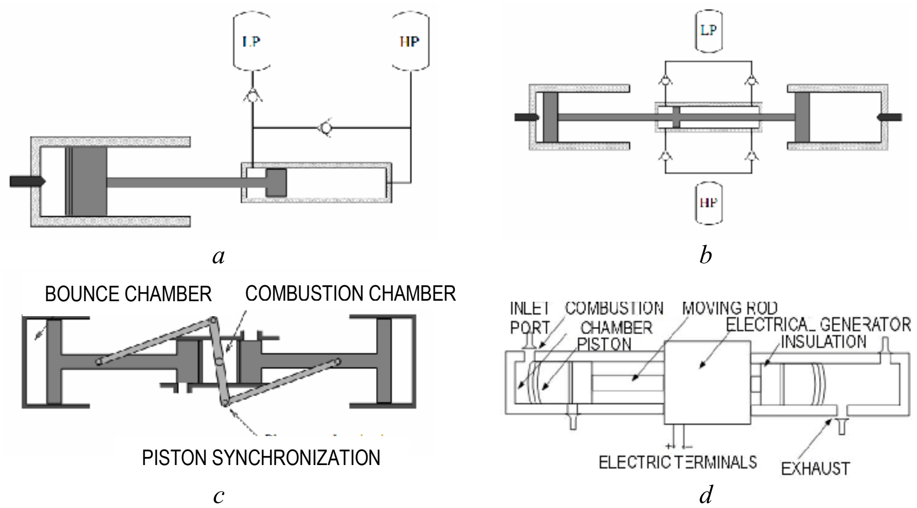
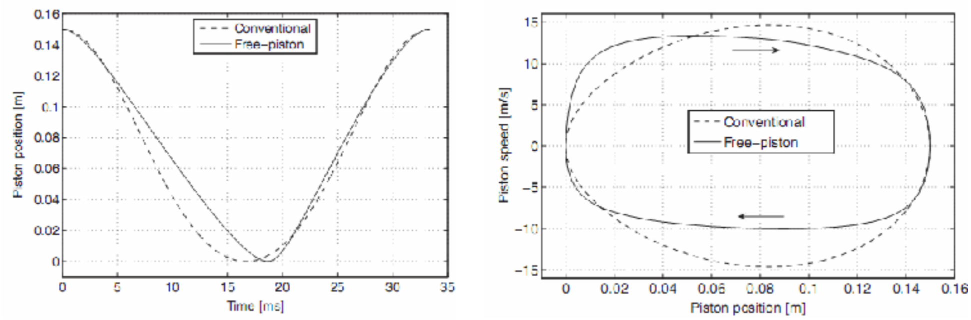


Fig. 1 – Free piston engine configurations: *a* – single piston; *b* – dual piston; *c* – opposed piston; *d* – engine-generator system.

Fig. 1 *d* presents an integrated electric generator – free piston engine system with two pistons mounted an each side of the generator shaft. The high temperature values must be considered and proper insulation mounted between the internal combustion engine and the electric generator (Arshad *et al.*, 2002).

Free piston internal combustion engines provide better dynamic profiles compared to conventional crankshaft internal combustion engines, can work at variable compressed ratio and, by limiting the temperatures inside the combustion chamber, produce less pollution. Fig. 2 present the piston motion profile and the speed profile for a free piston engine and a conventional engine working at similar frequencies (Mikalsen & Roskilly, 2009). During the combustion stroke the expansion of the free piston is faster compared with a conventional engine and the time spent around the TDC (Top Dead Centre) is shorter, meaning the speed is also higher around TDC.



a *b*

Fig. 2 – Piston dynamics of a conventional and free piston engines: *a* – piston motion profiles; *b* – piston speed profiles.

3. Linear Electric Generator

Several linear electrical machines were considered for using with a free piston engine: permanent magnet synchronous machines, permanent magnet variable reluctance machines, transverse flux machines, hybrid Vernier machines, air-cored machines and moving coils machines (Arshad *et al.*, 2003; Xu Z. Chang, 2010; Kim *et al.*, 2007; West *et al.*, 2007; Arof & Arof, 2007). Each of them provide advantages and disadvantages that must be taken into account when designing such a system: the air/cored structure eliminates most of the magnetic forces but requires higher magnetic flux densities to compensate the lack of the stator iron, a moving coil structure has a lighter translator but using sliding contacts or flexible connections could reduce the system reliability, a moving magnet generator offers high air gap magnetic flux density and low moving mass but is sensitive to high temperatures near the combustion chambers and so on.

When selecting the best solution for a free piston engine power generation system some aspects must be considered namely

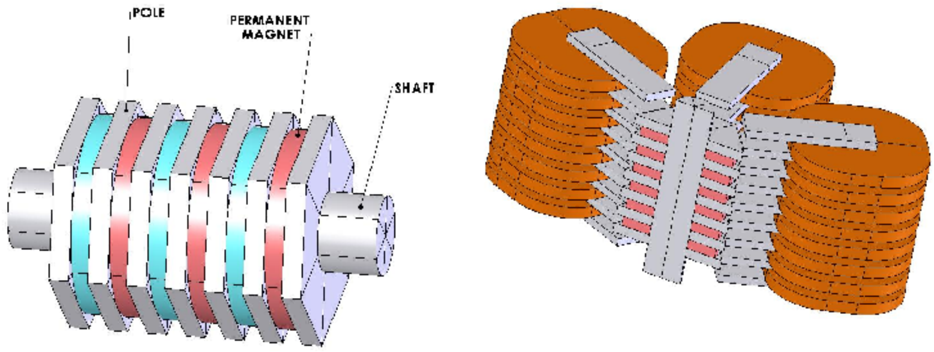
a) *Mover mass* must be kept as low as possible, because it has a negative influence on the entire mechanical system oscillating frequency. In order to reach linear speeds similar to those in conventional rotating generators a frequency of 25…30 Hz must be reached.

b) *Temperature* near the combustion chambers can reach up to 400ºC, so proper insulation must be used, especially if rare-earth permanent magnets are used.

c) *Rare-earth* permanent magnets must be used to obtain high power densities, resulting a smaller, easier to fit inside the vehicle generating system.

d) *For starting* the internal combustion engine the electrical machine must be able to work as a motor, so a multi-phase structure must be used and the developed force must be high enough to compress the working gas inside the cylinder for the first stroke.

Based on the above mentioned requirements we decided to focus our research on a three phase linear generator with permanent magnets mounted on the moving part. The chosen structure has six stators, mounted around the translator; the moving part is made up of NdFeB permanent magnets mounted between steel poles in a sandwich structure, like in Fig. 3. The permanent magnets are axially magnetized and are mounted so that facing magnets have the same magnetic poles. In this case the poles have a double role: they allow the permanent magnets to be mounted and the magnetic flux lines are forced outside trough the air gap. The shaft is made up of a non magnetic material so that the flux leakage trough that area is around 5…10 % of the total flux produced by the magnets.



a *b*

Fig. 3 – Six-sides permanent magnet linear generator: *a* – permanent magnet translator; *b* – six-sides linear generator structure.

In order to obtain a three phase generator the six stators (two for each phase) are mounted with a lag equal to one third of the pole pitch. This way the induced voltages are $2\pi/3$ out of phase and when working as a motor a sliding magnetic field is obtained in the air gap.

When designing the generator some inputs were considered: rated power, rated voltage, rated efficiency, linear velocity provided by the free piston engine, permanent magnet type and others. A major concern was determining the permanent magnet volume correctly, because under-sizing would lead to smaller induced voltage and lower generated power and by using too much magnetic material would increase both the translator weight and production costs. For determining the geometrical dimensions of the generator some relations were used, like

$$F_{\mathrm{med}} = 2B_g k_s l_{\mathrm{med}} p I_N N_{sp}; \tag{1}$$

for determining the required number of turns per coil based on the average produced Force or the air gap magnetic flux density based on the rated voltage

$$U_t = B_g N_{\mathrm{coil}} v_{\mathrm{med}} l_{\mathrm{med}} N_{sp}. \tag{2}$$

Special attention was also paid to correctly dimension the shaft in order to avoid any deformations and eccentricities in the air gap that could cause the appearance of high magnetic forces, leading to generator faults

$$d_{\mathrm{sh}} = \sqrt{\frac{4F_{\mathrm{med}}}{\pi k_1 \tau_{\mathrm{Al}}}}. \tag{3}$$

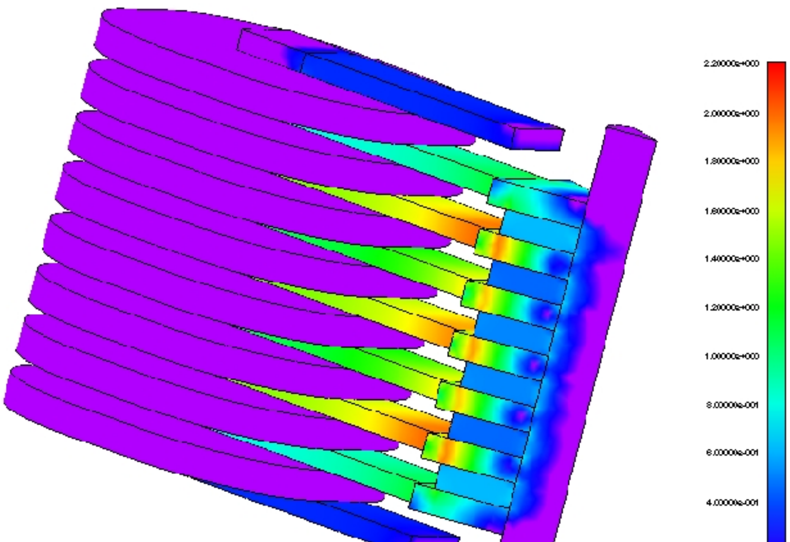


Fig. 4 – Magnetic flux density repartition.

Once the geometric dimensions of the linear generator were determined the structure was simulated using JMAG Studio, a FEM based magnetic field computation software. To reduce the simulation times only one sixth of the generator was modeled and periodic boundary conditions were imposed. The magnetic flux density repartition in the structure is presented in Fig. 4, where high magnetic flux density values are noticed in the translator poles and stator teeth, while the average air gap magnetic flux density is 0.829 T.

For a dynamic simulation at a constant linear speed of 4.5 m/s the obtained induced no-load voltages are represented in Fig. 5, with a rms value of 62.8 V.

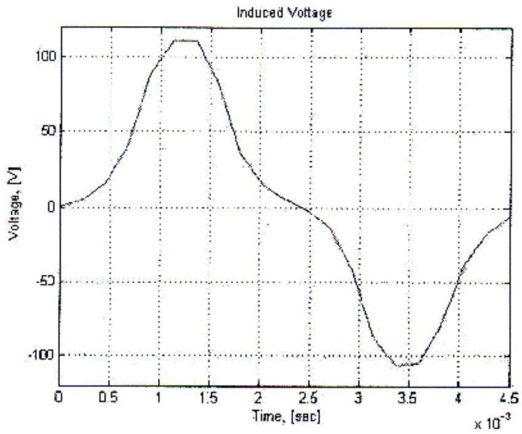


Fig. 5 – No-load generated voltage.

4. Conclusions

Based on the information found in the main publications stream the use of electric linear generators driven by internal combustion free piston engines provides better performances compared to conventional systems. Based on some constrains a three phase, six sides, linear generator was designed and simulated and some results presented briefly. The obtained results using FEM confirm the analytical values obtained during the design process and provide a solid ground for the optimization and building of the prototype.

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GENERATOR ELECTRIC LINIAR ACŢIONAT DE MOTOR CU ARDERE INTERNĂ DE TIP „PISTON LIBER" PENTRU AUTOVEHICULE ELECTRICE HIBRIDE

(Rezumat)

Se face o sumară trecere în revistă a motivelor ce au determinat orientarea producătorilor auto spre autovehiculele electrice hibride, ca pas intermediar spre cele 100% electrice. Sunt prezentate topologiile existente în acest moment făcându-se trecerea spre sistemele formate din generatoare electrice liniare şi motoare de tip „piston liber". După o scurtă prezentare a tipurilor de maşini electrice compatibile cu acest gen de aplicaţii şi a condiţiilor generale impuse de sistem se prezintă generatorul ales, o structură trifazată cu şase statoare. Pe baza dimensiunilor obţinute în proiectare este simulat generatorul, fiind determinate repartiţia inducţiei şi tensiunea de mers în gol.