Linear Permanent Magnet Electric Generator for Free Piston Engine Applications

C. A. Oprea, L. Szabó, C. S. Marţiş

Abstract – **As a response to the major climatic changes due to global warming and the foreseen oil shortages once the natural reserves will perish, most vehicle manufacturers began research programs on alternative fuel vehicles. The Hybrid Electric Vehicles, as an intermediate step to full electric vehicles, can incorporate Free Piston Engine – Linear Electric Generator systems to produce the required electric energy. A novel six-side, 3 phase, linear generator with permanent magnets on the translator is proposed. For designing the generator a different approach is used: geometric dimensions and electric parameters are determined based on an Equivalent Magnetic Circuit implemented in National Instruments' LabVIEW. Based on these values a three dimensional finite elements analysis model of the linear generator is created to validate the method.**

Index Terms—**permanent magnet machines, linear electric generators, free piston engine**

I. INTRODUCTION

The beginning of this millennium is marked by the decision of virtually all major car manufacturers to invest in the research of electric and hybrid electric vehicles as an alternative to conventional fossil fuel-powered units. Two major concerns determined this approach: the predicted petrol shortages and the greenhouse effect due to high pollution.

The extreme climatic phenomenons that occurred worldwide in the last decades are generally considered to be caused by the global warming. A look at the multiannual average temperatures shows a constant increase since the middle of the 20th century, with record temperatures in the second part of the 1990's. It is generally accepted that the main cause of the greenhouse effect is the high concentration of CO_2 and other gases (CH_4, NO_2 and water vapors) in the atmosphere. 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 the majority of those are because of road transportation; two thirds of these are produced by small vehicles [1].

Most recent studies indicate that at the current fossil fuel consumption rate the natural reserves will last for another 20 to 30 years (given that no major deposits are discovered). Solutions for replacing the fossil fuels were developed, (mainly the renewable energies), but with the available technology these cannot be applied to vehicle applications. Different solutions were proposed, including compressed air, hydraulic engines or electric motors, all involving specific problems, the biggest being finding a solution to store the energy required to power the drive train. Considering the fact that the electrical machines and power electronics are mature fields compared to the others and that an electric power supply can be found almost anywhere, 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 [2]. A recent study shows that an investment in such an electric vehicle would not pay off, because of the high acquisition cost and the need of periodic battery replacement [3].

There are several solution used to combine the power generated by the combustion engine and the electric motor inside a hybrid electric vehicle [4]:

- *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;
- *series hybrid* – only the electric motor powers the drive-train, while the internal combustion engine is used to power an electric generator to recharge the batteries; also uses regenerative braking;
- *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.

Most of the series hybrid vehicles are using a conventional internal combustion engine directly connected to a rotating generator that would provide the required electric energy. A more radical solution was proposed, that would involve higher initial costs but would offer higher efficiency over the entire life cycle: a Linear Electric Generator mechanically integrated into a Free Piston Engine. For propulsion of the vehicle two or four in-wheel electric motors could be used.

II. TECHNICAL BACKGROUND

A. Free Piston Engines

A combustion engine is referred to as a "Free Piston" if the linear movement of the pistons is not transformed into rotational motion by using the crankshaft. There are two types of FPE: internal combustion engine, where the

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combustion takes place inside the cylinders and external combustion engines, where a working fluid is heated in an external source and then flows through the cylinder (such as the steam engine or the Stirling engine) [5].

The original Internal Combustion Free Piston Engine was patented in 1928 by R.P. Pescara and was initially used for air compressors. Other manufacturers like Junkers in Germany, SIGMA in France, General Motors and Ford Motor Company in USA also showed their interest in this type of engines, but 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 [6].

The absence of a crankshaft brings the advantage of fewer moving parts and reduced friction between the piston and the cylinder walls, but also requires an additional device that would store the mechanical work produced by the piston during the power stroke and return some of that to prepare the system for a new cycle. This rebound device could be a mechanic spring, a compressed air cylinder or an electric linear device. Depending on the number of piston and their position there are several possible topologies:

Single piston – uses only a combustion chamber and a rebound device to store part of the energy generated during the combustion stroke. Such a system is shown in Fig. 1 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;

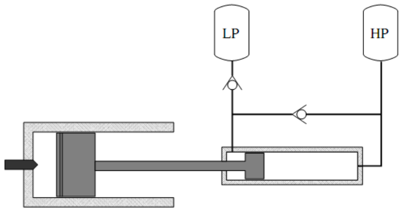


Fig. 1. Single piston FPE

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. 2. 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.

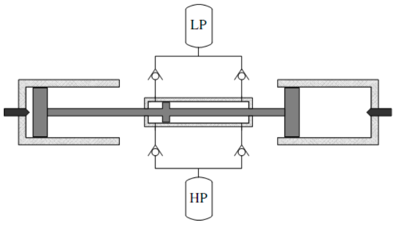


Fig. 2. Dual piston FPE

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. 3. Each piston requires a rebound device on the free shaft end and the load (the electric generator) may be mounted on each side [6].

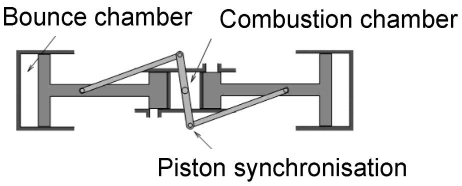


Fig. 3. Opposed piston FPE

A Linear Electric Generator directly connected to a dual piston FPE is shown in Fig. 4. Such a system would require complicated control of the intake and exhaust ports in order to obtain higher efficiencies and lower NO_X and CO_2 emission levels than in conventional IC engines.

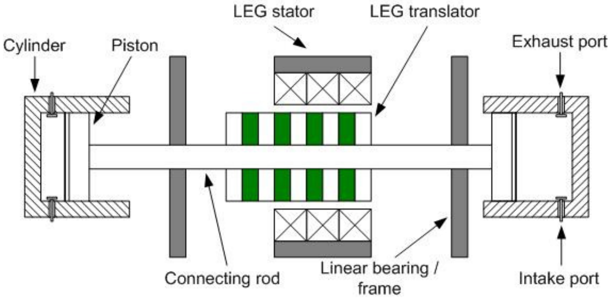
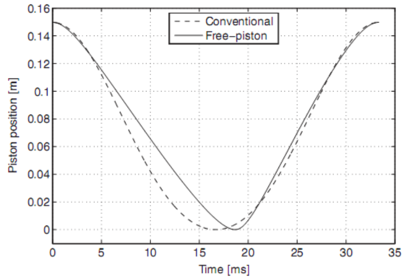
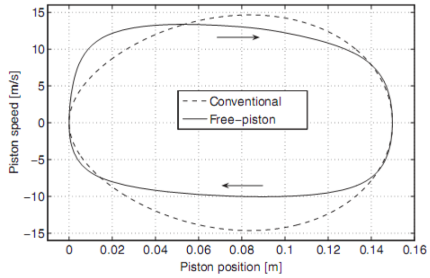


Fig. 4. Free Piston Engine – Linear Generator System

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. 5 presents the piston motion profile and the speed profile for a free piston engine and a conventional engine working at similar frequencies [7]. 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) Piston motion profiles



b) Piston speed profiles

Fig. 5. Piston dynamics of a conventional and FPE [7]

B. *Linear Electric Generators*

Numerous papers were published on this topic in the last years, proposing several electrical machine topologies: PM synchronous machines, PM variable reluctance machines, TFM, hybrid Vernier machines, air-cored machines and moving coil machines [8-14], each of them providing advantages and disadvantages. Several specific aspects must be considered when choosing a linear machine for FPE electric generation system:

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

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;

Mover mass must be kept as low as possible, in order to obtain higher oscillating frequencies. To reach linear speeds similar to those in conventional rotating generators the Free Piston Engine – Linear Electric Generator must work at frequencies of 25-30 *Hz*;

Rare-earth permanent magnets should be used to obtain high power densities, for a smaller, easier to fit inside the vehicle generating system.

Based on these requirements and the experience in designing a four-sided PM linear generator [15], a three phase generator with 6 stators was considered. The translator is made of permanent magnets mounted between iron poles, forming a sandwich-like structure, presented in Fig. 6. The permanent magnets are axially magnetized and mounted alternatively. Since the shaft is nonmagnetic the magnetic flux produced by the PM is forced through the air gap towards the stator.

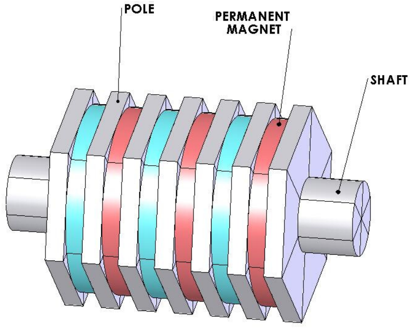


Fig. 6. Linear generator translator

A six-side structure offers the advantage of eliminating the radial attraction/repulsion magnetic forces and at the same time the possibility to generate a three phase voltage system by mounting the 2 opposed stators that correspond to each phase with an offset equal to one third of the pole pitch. A simplified image of the structure is presented in Fig. 7, with the translator in the leftmost position. Since there is no magnetic flux passing through the coils on the right side, these are not producing energy, but instead act as a supplemental load (since all the coils are connected in series). To eliminate this problem the coils that are inactive should be disconnected using an appropriate control. Another solutions is to build a longer translator, so that the coils would be active at all times, at the expense of a higher moving mass, with negative influence on the FPE performances.

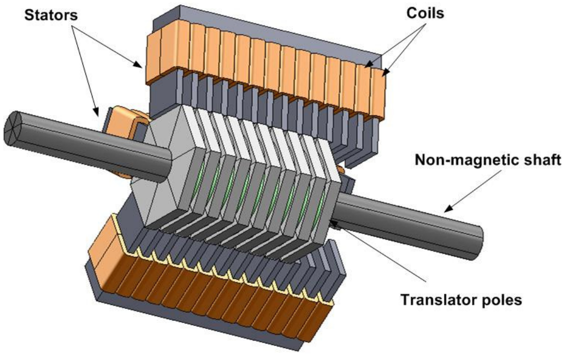


Fig. 7. 3D model of the six-side linear generator

III. LINEAR ELECTRIC GENERATOR DESIGN

A. *Design Procedure*

Based on information published by different authors [16], a 100 mm stroke length was considered at a frequency of 10 Hz (values of up to 30-40 Hz were reported for working FPE prototypes in no-load conditions). For these values the average linear speed can be computed using (1):

$$u_{av} = 2 \cdot l_{stroke} \cdot f \tag{1}$$

The average force developed by the electrical machine can be determined using (2), based on the rated power, efficiency and the average linear speed; an estimated value for the mechanical losses is considered (P_{mec}).

$$F_{av} = \frac{(P_N / \eta) - P_{mec}}{u_{av}} \tag{2}$$

The generated phase voltage is given by:

$$V_{RMS} = B_c \cdot u_{av} \cdot N_c \cdot l_c \tag{3}$$

where: B_c is the average magnetic flux density passing through the coil , N_c is the number of turns/phase and l_c is the average length of one coil turn.

The total number of turns for one phase depends on the number of turns in one coil, n_t, number of coils/stator, n_c and the number of stators connected in series, n_s, 2 in the case of a 3-phase six-side stator.

$$N_c = n_t \cdot n_c \cdot n_s \tag{4}$$

The average length of the coil can be determined using

$$l_c = 2 \cdot (t_l + t_w + \pi \cdot \frac{c_w}{2}) \tag{5}$$

if the geometrical dimensions of the stator tooth are known, using (5). The following notations were used: t_l - tooth length, t_w - tooth width and c_w - coil width.

For determining B_c the no-load simplified magnetic equivalent circuit (MEC) presented in Fig. 8 was used.

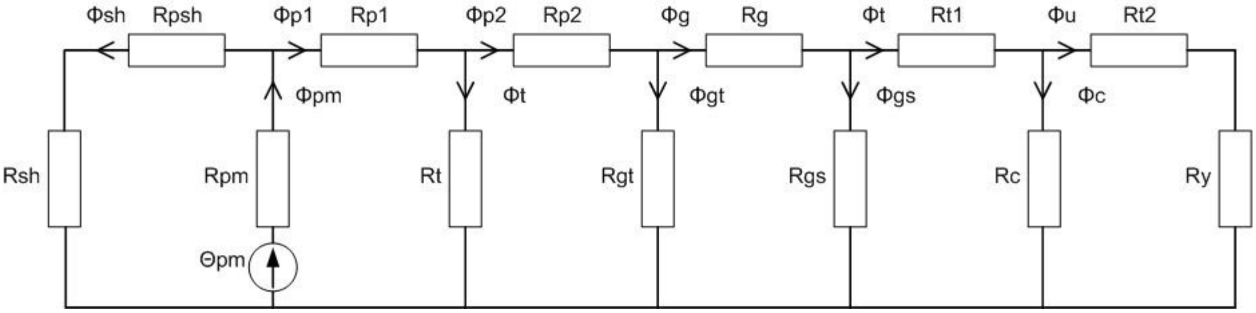


Fig. 8. Equivalent magnetic circuit

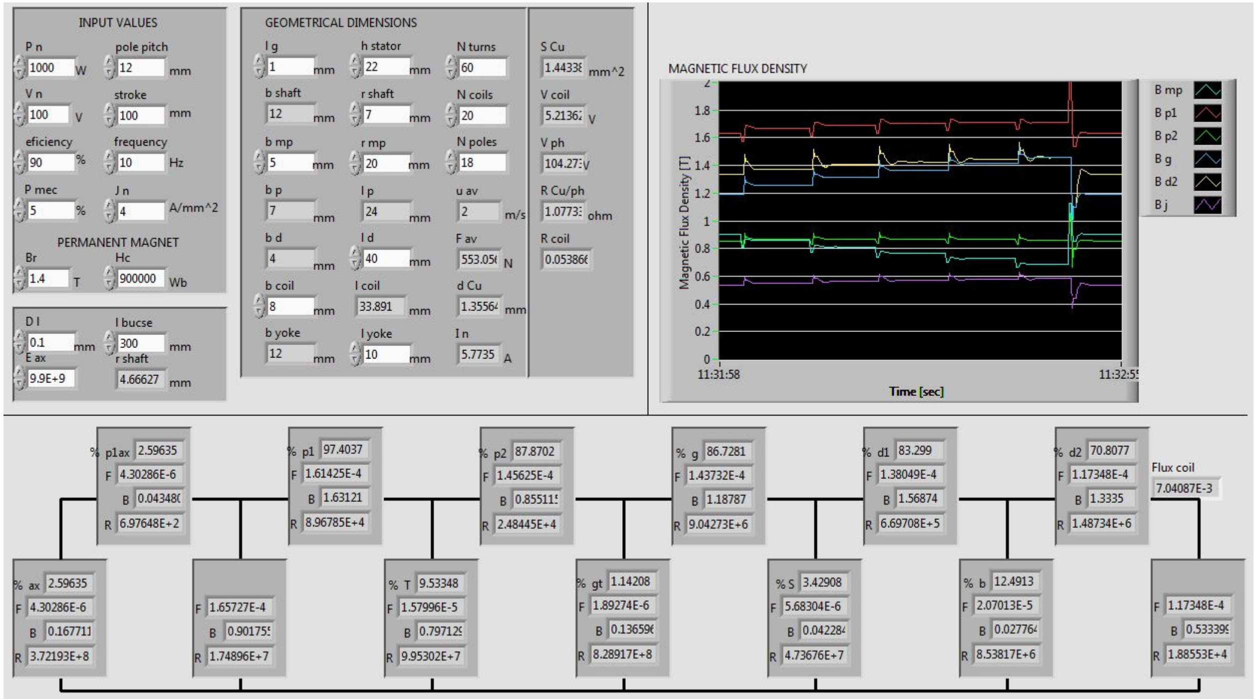
In Fig. 8 the following notations were used: R_x - reluctance of various parts of the generator, Φ_x - the magnetic flux trough the parts of the generator. The *x* subscript has the following meaning in the different cases: *sh* – the shaft, *psh* – translator pole area near the shaft, *pm* – the permanent magnet, *p1* – translator pole in the area situated between the permanent magnets (with curved flux lines), *t* – the air between the translator poles, *p2* – translator pole area near the air gap (parallel flux lines), *gt* – a thin air gap region near the translator, *g* – the air gap, *gs* - a thin air gap region near the stator, *t1* - the stator tooth near the air gap (in the area with no coils in the slot), *c* – the slot (through the coil), *t2* – the tooth in the coil area, *y* – yoke, Θ_{pm} – permanent magnet MMF.

Based on the geometric dimensions of the structure the MEC can be solved and the magnetic flux density that passes the coil can be determined, providing a faster method than FEM to evaluate the electrical machine structure. Since the geometric dimensions are not determined in this stage of the design process a different approach is considered, presented in the following paragraph.

B. Results

Starting from the desired value of the generated voltage, the magnetic flux density in the stator tooth can be determined with (3). Using an interactive, graphical programming software, National Instruments LabVIEW [17], the MEC components are calculated for different values of the geometric dimensions of the generator, allowing the user to determine the structure that would produce the desired voltage.

The Front Panel of the program is presented in Fig. 9.



INPUT VALUES
P n 1000 W
pole pitch 12 mm
V n 100 V
stroke 100 mm
eficiency 90 %
frequency 10 Hz
P mec 5 %
J n 4 A/mm^2

PERMANENT MAGNET
Br 1.4 T
Hc 900000 Wb

D l 0.1 mm
l bucse 300 mm
E ax 9.9E+9
r shaft 4.66627 mm

GEOMETRICAL DIMENSIONS
l g 1 mm
h stator 22 mm
N turns 60
b shaft 12 mm
r shaft 7 mm
N coils 20
b mp 5 mm
r mp 20 mm
N poles 18
b p 7 mm
l p 24 mm
u av 2 m/s
b d 4 mm
l d 40 mm
F av 553.05 N
b coil 8 mm
l coil 33.891 mm
d Cu 1.3556 mm
b yoke 12 mm
l yoke 10 mm
I n 5.7735 A

S Cu 1.4433 mm^2
V coil 5.2136 V
V ph 104.27 V
R Cu/ph 1.0773 ohm
R coil 0.05386

% p1ax 2.59635
F 4.30286E-6
B 0.04348
R 6.97648E+2

% p1 97.4037
F 1.61425E-4
B 1.63121
R 8.96785E+4

% p2 87.8702
F 1.45625E-4
B 0.85511
R 2.48445E+4

% g 86.7281
F 1.43732E-4
B 1.18787
R 9.04273E+6

% d1 83.299
F 1.38049E-4
B 1.56874
R 6.69708E+5

% d2 70.8077
F 1.17348E-4
B 1.3335
R 1.48734E+6

Flux coil 7.04087E-3

% ax 2.59635
F 4.30286E-6
B 0.167711
R 3.72193E+8

F 1.65727E-4
B 0.90175
R 1.74896E+7

% T 9.53348
F 1.57996E-5
B 0.79712
R 9.95302E+7

% gt 1.14208
F 1.89274E-6
B 0.13659
R 8.28917E+8

% S 3.42908
F 5.68304E-6
B 0.04228
R 4.73676E+7

% b 12.4913
F 2.07013E-5
B 0.02776
R 8.53817E+6

F 1.17348E-4
B 0.53339
R 1.88553E+4

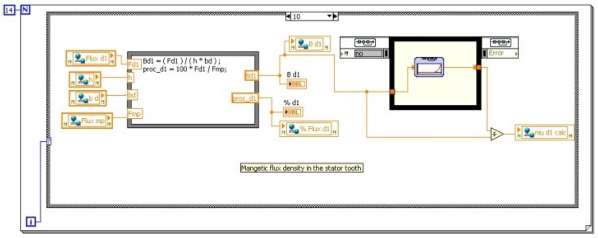
Fig. 9. LabVIEW Front Panel interface

The Front Panel includes 3 distinct zones: in the upper left zone the rated values are defined and the geometric dimensions of the linear generator model can be adjusted. The results of the calculations performed by the program are shown in the middle section: average force, average speed, induced voltage in one coil and in the entire phase, the required Copper section and diameter and the coil and one phase resistance. The graph shows the computed magnetic flux density in various zones of the model. If, for example, the radius of the permanent magnet is varied from 20 to 25 mm using 1mm increments and then back to 20mm, the values of the magnetic flux densities are modified accordingly (as it can be noticed on the graph it takes a few iterations for the system to stabilize).

The bottom part contains a sketch of the magnetic equivalent circuit presented in Fig. 8. For each branch of the circuit the magnetic flux value, magnetic flux density and reluctance are displayed; the percentage represents the amount of the permanent flux that passes trough that area.

LabVIEW was preferred for this application because it offers all the required tools for solving such a complex problem (linear equation systems solver, look-up table, formula node, etc.) combined with the advantages of graphical programming and the possibility of creating sequences of operation, and feed-back loops. In addition to these, if any of the various parameters of the generator is modified the results are instantaneous updated on the graphical interface, so the best values can be easily determined. Once the optimum is reached the results are exported in text files or directly to CAD programs for building bi or tridimensional models of the structure.

As an example, fig. 10 shows the Block Diagram used for determining the magnetic flux density in the stator tooth, using the magnetic flux values determined in the previous step; based on this value a new magnetic permeability is obtained that will be used in the solving the magnetic equivalent circuit in the next step, taking into account the nonlinear magnetization characteristic of the materials used (implemented using a Lookup Table block).



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Bd1 = ( Fd1 ) / ( h * bd );
proc_d1 = 100 * Fd1 / Fmp;
```

Fig. 10. Block Diagram for computing the magnetic flux density

Besides the computation of magnetic and electric parameters of the generator presented above, some geometrical constrains were implemented to check if the distance between two adjacent stators allows the mounting of the coils. Another important aspect to be considered is the mechanical dimensioning of the shaft to withstand the forces that appear between the translator and the stators. Even though the symmetric structure of the linear generator should compensate these forces, in the case of an air gap unbalance due to manufacturing tolerances important forces could appear. The required shaft section was determined using (6).

$$S_{sh} = \frac{l_b \cdot F_{sh}}{\Delta l \cdot E_{sh}} \tag{6}$$

Where: l_b is the distance between the two linear bearings, F_{sh} is the force applied to the shaft, Δl is the maximum allowed deformation of the shaft and E_{sh} is the elasticity constant of the shaft material.

Based on the results obtained using LabVIEW a 3D model of the generator was created and simulated in a finite elements analysis (FEA) software, JMAG Studio. Only one sixth of the structure was considered and symmetric boundary conditions were imposed. To further reduce the simulation time only 5 coils and 7 translator poles were considered. The magnetic flux density distribution (an axial cut plane was considered through the middle of structure) is presented in Fig. 11, with values similar to those obtained using the equivalent magnetic circuit approach.

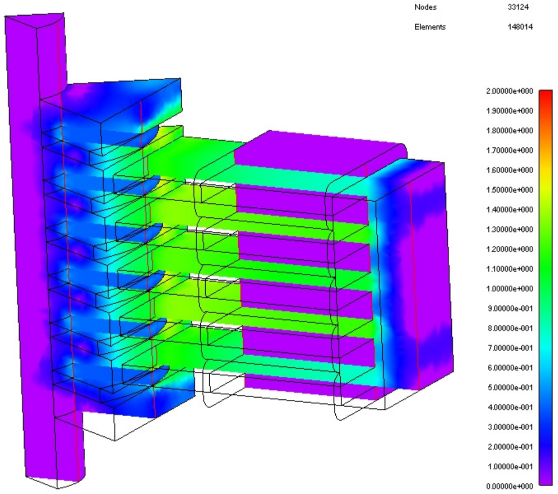

Fig. 11. Magnetic flux density repartition

Once the magnetic flux densities obtained using the EMC were confirmed using FEM the next step was to verify if the voltage equation is correct. A dynamic simulation was considered, with the translator moved at constant speed for a stroke equal to two pole pitches. To eliminate the end effects only the voltage induced in the middle coils was considered; the voltage wave form is presented in fig. 12. The values obtained using the tridimensional model confirms the results calculated in LabVIEW.

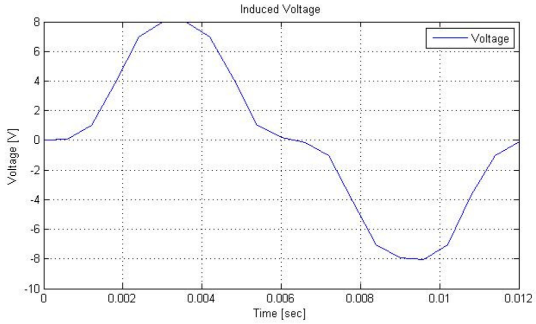

Fig. 12. Induced voltage

IV. CONCLUSIONS

Basic information regarding the Free Piston Engine structure and principle were presented and a motivation was presented for using a FPE – LEG system for producing electric energy for a hybrid vehicle. A linear generator suitable for such a system should have a low weight translator, a multiphase structure and high power density values that could be obtained by using rare-earth permanent magnets

A novel six-side, 3 phase, permanent magnet linear generator was considered and a different approach for determining the geometric dimensions was considered: starting from some geometric and electric constrains the magnetic equivalent circuit of the generator was solved using an interactive program implemented in the software LabVIEW.

Based on the computed dimensions a three dimensional model of the generator was implemented in a FEM software and the magnetic flux density values in the structure were compared to the values obtained in LabVIEW. The induced voltage values were also compared, confirming that the simplified EMC model is accurate and can be used for further design and optimization of similar structures.

V. REFERENCES

[1] OECD (Organization for Economic Co-operation and Development), "*Strategies to Reduce Greenhouse Gas Emissions from Road Transport: Analytical Methods*", report, (2002). Available:http://www.internationaltransportforum.org/pub/pdf/02GreenhouseE.pdf

[2] Khaligh, A. Zhihao Li, *"Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art",* Vehicular Technology, IEEE Transactions on Vehicular Technology, Volume 59, Issue 6, pg. 2806 (2010), ISSN: 0018-9545.

[3] Ross, P.E., "*Loser: Why the Chevy Volt Will Fizzle*", IEEE Spectrum special report, Volume 47, Number 1 international, January 2010.

[4] C.C. Chan, *"The State of the Art of Electric Hybrid, and Fuel Cell Vehicles",* Proceedings of the IEEE, Volume 95, Issue 4, pg. 704-718, ISSN : 0018-9219.

[5] Arshad W.M., Backstrom T., Thelin P. and Sadarangani C, "*Integrated Free-Piston Generators: An Overview*", IEEE NORPIE-02 Conference, Stockholm, 2002.

[6] Mikalsen, R, Roskilly, A.P. "*A review of free-piston engine history and applications*", Applied Thermal Engineering 27, (2007): 2339-2359.

[7] Mikalsen, R, Roskilly, A.P., "*The fuel efficiency and exhaust gas emissions of a low heat rejection free-piston diesel engine*", Proceedings of the Institution of Mechanical Engineering, Part A: Journal of Power and Energy, pag 379-386, Volume 223, Number 4 (2009), ISSN: 0957-6509.

[8] Arshad, W.M. Thelin, P. Backstrom, T. Sadarangani, C., "*Use of transverse-flux machines in a free-piston generator*", IEEE Internation Electric Machines and Drives Conference, 2003. IEMDC'03., Volume 3, page 1428, ISBN:0-7803-7817-2.

[9] Zheng, P. Chen, A. Thelin, P. Arshad, W. M. Sadarangani, C., "*Research on a Tubular Longitudinal Flux PM Linear Generator Used for Free-Piston Energy Converter*", IEEE Transaction on Magnetics, Jan. 2007, ISSN: 0018-9646.

[10] Zhaoping Xu Siqin Chang, "*Improved Moving Coil Electric Machine for Internal Combustion Linear Generator*", IEEE Transactions on Energy Conversion, Volume 25, Issue 2, page 281 (2010), ISSN: 0885-8969.

[11] Young-wook Kim Jaewon Lim Ho-Yong Choi Sun-Ki Hong Heesoo Lim Si-Deok Oh Hyun-Kyo Jung, "*Starting mode analysis of tubular-type linear generator for free-piston engine with dynamic characteristics*", International Conference on Electrical Machines and Systems, ICEMS, page 926 (2007), ISBN:978-89-86510-07-2.

[12] Jiabin Wang West, M. Howe, D. La Parra, H.Z.-D. Arshad, W.M., "*Design and Experimental Verification of a Linear Permanent Magnet Generator for a Free-Piston Energy Converter*", IEEE Transaction on Energy Conversion, Volume 22, Issue 2 (2007), page 299, ISSN:0885-8969.

[13] Qing-feng, Li, Jin Xiao, Zhen Huang, "*Flat-type permanent magnet linear alternator: A suitable device for a free piston linear alternator*", Journal of Zhejiang University – Science A, 2009, Volume 10, No. 3.

[14] Arof W. and Arof H., "*Open Circuit Field Distribution and Induced Voltage of a Cylindrical Permanent Magnet Linear Generator",* American Journal of Applied Sciences, vol. 4, no 11, page 912-917 (2007), ISSN: 1546-9239.

[15] Oprea, C. A., Martis, C. S., Biro, K. A., Jurca, F. N., "*Design and testing of a four-side permanent magnet linear generator prototype:*, International Conference on Electrical Machines (ICEM), Sept. 2010, ISBN 978-1-4244-4175-4.

[16] Carter, D., Wechner, E., "*The Free Piston Power Pack: Sustainable Power for Hybrid Electric Vehicles*", Free Piston Power – Pempek Systems,
Available: http://www.freepistonpower.com/FreePistonPowerPack.htm

[17] National Instruments LabVIEW help file and web resource, Available: http://zone.ni.com/dzhp/app/main

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