The linear generator as integral component of an energy converter for electric vehicles

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Abstract: *The system in which the linear generator (LG) is integrated is called free-piston linear generator (FPLG). He is able to convert chemical energy into electrical energy by using a combustion process. The FPLG can be used as alternative energy converter for hybrid cars. By optimization of the LG it is possible to reduce the fuel consumption of a vehicle significantly. This publication deals with the calculation of a linear generator, the measurement of the reached LG efficiency and the expected fuel consumption of a FPLG based midrange car. In this publication the function and the characteristics of the free-piston linear generator will be explained first. Then the surrounding system and its effect on the FPLG and the linear generator will be pictured. This is important for the understanding of the adaptation of the linear generator to the system. After this the way of the calculation process is pictured. It is based on a 2-D FEA model. After the presentation of the calculated results a comparison between the calculation and the measured results of a physically existing linear generator is presented. The next chapter represents the outcome of the efficiency measurement. At the end of the publication the actual situation of the expected fuel consumption of a midrange car system based on a simulation is represented.*

Keywords: Alternators, free-piston linear generator, linear motors, linear alternators, linear generators, permanent magnet generators, synchronous generators.

1. Introduction

Efficiency improvements in order to reduce the production of CO_2 are required in all technical areas of life to limit the anticipated climate changes [1] to an extent sustainable for humanity. Current approaches in the field of transportation cover both increasing the efficiency of conventional drives and the development of hybrid, battery, fuel cell and range extender concepts, and combinations of these.

The aim of every alternative power train design is to transform the stored energy into a useful form of energy with the greatest possible efficiency. This requirement is met particularly well by a free piston linear generator. It is capable of transforming chemical energy into electrical energy by means of a combustion process. As explained in [2], the high degree of efficiency of the free-piston linear generator at all load levels is inherent in its design. This is achieved by keeping the system frequency constant and adapting to the power demanded by variation of the stroke and compression. Furthermore, these system characteristics mean that the free-piston linear generator can be operated with both conventional fuels such as petrol, diesel and gas and with alternative fuels such as sun fuel, synthetic fuel, hydrogen etc. In the development of scenarios for the introduction of alternative power train concepts the free-piston linear generator can be seen as a bridging technology, between conventional power train technology and fuel cell technology. Particularly since both of these technologies provide electric energy at their energy interface. The linear generator discussed in this paper is a component in the free-piston linear generator having the task of transforming mechanical energy into electrical energy.

2. Free-piston linear generator system

The principle of the free-piston linear generator will be described in this section in order to assist in the understanding of the boundary conditions acting on the linear generator.

A Construction

The free-piston linear generator in Figure 1 is based on a double piston system (hatched) built into a cylinder. At one end of it is the combustion chamber for the combustion of a liquid or gaseous energy carrier. An adjustable gas spring is built into the end opposite of the combustion chamber. The volume of gas in the gas spring can be adjusted by means of a control valve which allows the spring rate of the gas spring to be regulated.

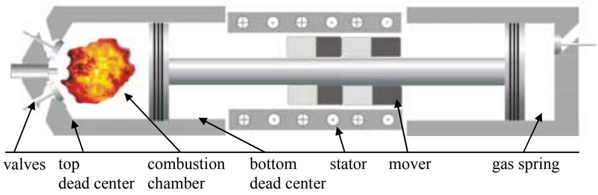

Figure 1: Illustration of the principle of the free-piston linear generator

The combusted gas is scavenged out and the fresh gas brought in of electrically actuated valves in the cylinder head of the combustion chamber.

The mover is mounted between the two pistons of the double piston. Permanent magnets are glued to the mover and additionally secured by a fibre-glass reinforced bandage. The mover with the permanent magnets is enclosed by a stator with integrated generator winding and the necessary cooling system. The mover and the stator together compose the linear generator discussed in this paper.

B Operation

At the start of the load cycle the double piston is at the top dead centre (TDC) and a flammable mixture previously introduced into the combustion chamber is ignited by a spark plug. The double piston with its integrated mover begins to move towards the gas spring (bottom dead centre BDC). The movement of the magnets induces a voltage in the coils of the stator which drives a corresponding electric current. Half of the energy released in the combustion is captured between top dead centre and bottom dead centre in this way. The other half is stored in the gas spring and extracted by the linear generator on the return stroke of the double piston (BDC-TDC). The gas remaining in the combustion chamber is actively flushed out between bottom and top dead centre and fresh gas is introduced. When the fresh gas is compressed and the double piston has arrived at TDC, the next load cycle can begin. The variation in the power to be output is achieved by adjustment of the stroke, which is determined by the volume of gas in the gas spring. The mechanical frequency of the double piston system is kept constant.

C Integration in a vehicle

The FPLG is planned to be integrated as energy converter in the vehicle structure as shown in Figure 2. It is possible to combine multiple FPLG modules. The effect of this combination is the possibility to adapt the numbers of used modules to the requested electrical power for the traction.

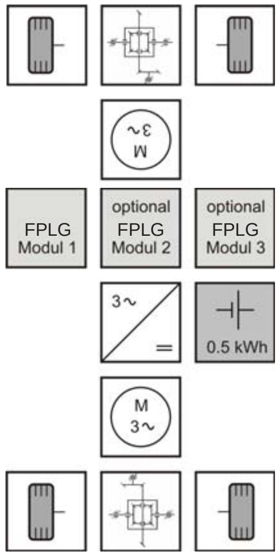

Figure 2: FPLG integrated in a 4 WD hybrid vehicle

By using this operation strategy it is possible to reduce the system losses and the fuel consumption of the vehicle in comparison to an conventional hybrid vehicle. It is also possible to manufacture small vehicles with one integrated module or large vehicles with more then one FPLG module. In both vehicles the same module size can be used.

3. Boundary conditions

A Output

The design of the output to be provided from the linear generator is based on the speed profile in the New European Driving Cycle. A mid-range car with the values listed in Table 1 is assumed as the vehicle. This class of car was selected as it represents a great deal of the cars used in Europe.

parameter	value	unit
c_w	0.325	-
A	2.2	m²
c_r	0.0115	-
m	1750	kg

Table 1: Basic data for the vehicle used as a basis for the design

Taking into consideration the acceleration processes resulting from the New European Driving Cycle, the electrical outputs required as illustrated in Figure 3 were determined with the help of a simulation. Both the parameters listed in Table 1 and also the output for the 80 kW electric motor required to provide the traction and a battery-based buffer contributed to the simulation model.

The outcome of this simulation is that a maximum electrical output of 50 kW is assumed for the design of the linear generator.

In Figure 4 the power as a function of the vehicle speed measured in [10] is shown. The information of this graph is that it is possible to reach a constant speed of 170 km/h by using an electrical generator power of 50 kW. In this operation mode the generated power goes direct to the traction motor without using any additional energy storage.

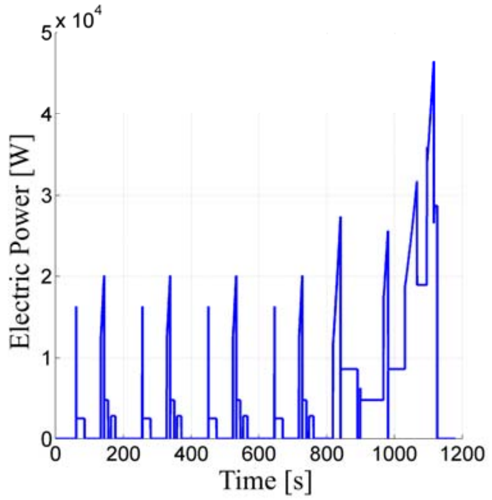

Figure 3: Illustration of the electrical power required in the New European Driving Cycle

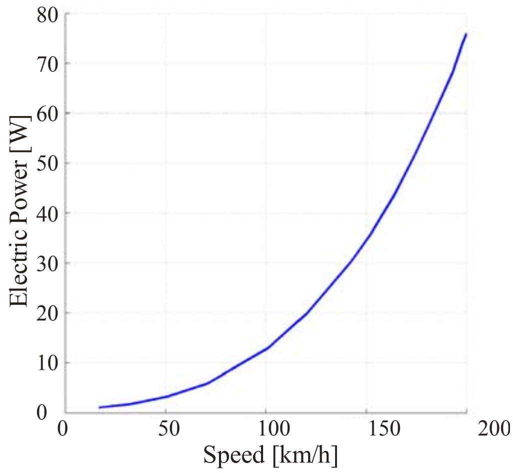

Figure 4: Required power for constant maximum speed

As the free-piston linear generator must have two systems running in opposition to one another to balance the masses in motion, the electrical output per linear generator is 25 kW. This corresponds to a power of 5000 N at a frequency of 50 strokes/second.

B Force diagram

Figure 5 shows, by way of example, one of the force graphs specified in [2]. The force shows the same development at the other operating points. Only the amplitude is varied. Figure 5 shows that it must be possible to decouple a constant force over the complete stroke with the linear generator. The short or long stator designs arise from this requirement as possible design principles for the linear generator.

This requirement must, however, take into account the fact that the weight of the mover must be kept as low as possible for kinematic reasons. This is the case if the length of the mover is selected such that the maximum required force can be decoupled by all the magnets being covered by the stator coils.

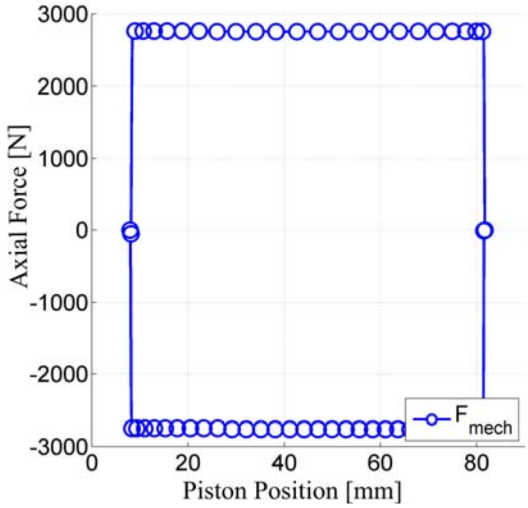

Figure 5: Force curve pictured in [3]

In the case of a short stator arrangement, which meets the requirement explained above, a portion of the magnets in the mover exits the stator and thus no longer contributes to the generation of power. This results in the power decreasing. This drop in force can be counteracted by increasing the current which results in higher electrical losses and reduces the efficiency of the linear generator.

In the case of the long stator arrangement, the mover is permanently inside the stator, which leads to a constant force given a constant current. As the load-independent current with assumed constant force in the long stator arrangement is on average lower than the load-independent current in the short stator arrangement, the copper losses arising are less.

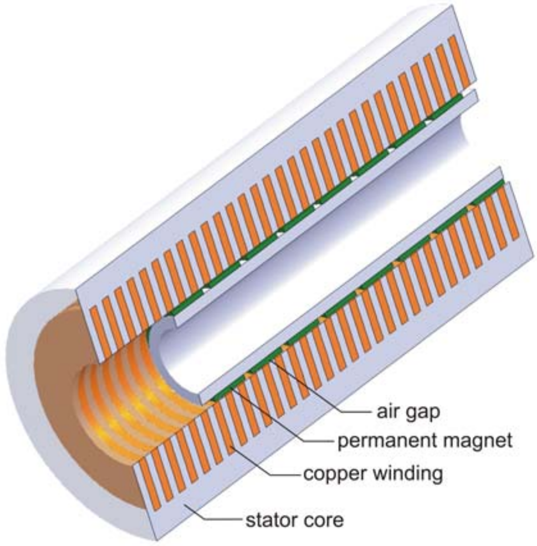

Figure 6: Stator design for the linear generator

The long stator arrangement (see Figure 6) thus has a better degree of efficiency and is therefore the arrangement used in the free-piston linear generator.

C Production costs

To keep the costs down, the development of the linear generator must aim for a low number of different parts, modular construction, a reduction in the complexity of manufacturing the components and a design for the parts that is susceptible to automated manufacturing. These requirements are expressed in the selection of a waste-free sheet metal cut-out, among other factors. If the teeth and the slots are given the same width, as illustrated in Figure 7, the part can be cut from sheet metal with practically no waste.

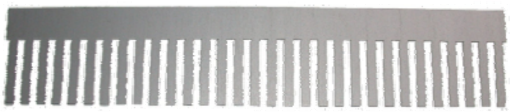

Figure 7:Practically waste-free sheet metal cut-out with identical width of tooth and slot

4. Calculation

There are three aims to be achieved by the calculation of the linear generator (LG). The first aim is to get a maximum electrical power. To reach a maximum of electric output power it is necessary to develop a LG with maximum axial force. So it is important to find a geometric structure which guarantees a maximum of axial force under consideration of the boundary conditions explained in chapter 3.

The base of these calculation is the FEA-tool Ansys. By using this tool it is possible to calculate 2-D results for different types of the LG.

A 2-D FEA

The efficiency of every electrical motor or generator is a function of several variables including the magnetic force. With a higher magnetic force it is possible to gather a higher mechanical power. The higher mechanical power P_{mech} leads to a higher efficiency η by constant losses as shown in (1). To get a optimal efficiency it is also possible to reduce the losses P_v. In [5] the main focus is on finding the maximum by increasing the magnetic force.

$$\eta = \frac{P_{el}}{P_{mech}} = \frac{P_{mech} - P_v}{P_{mech}} = 1 - \frac{P_v}{P_{mech}} \qquad (1)$$

The base parameters for the calculation are represented in Table 2.

Parameter	value	unit
air gap radius	100	mm
active length mover	270	mm

Table 2: Base parameters

parameter	value	unit
remanent induction	1.32	T
coercivity	1020	kA/m
μ_{rpm}	1.030	
air gap	0.75	mm
active length stator	270	mm
magnet width	24	mm
magnet height	3	mm
slot width	5	mm
slot height	30	mm
tooth width	5	mm
tooth height	30	mm
air gap radius	100	mm
distance between stator poles	30	mm
distance between rotor poles	30	mm
number of pole pairs	3	
number of windings per coil	5.75	
filling factor	80	%

Table 3: The data for the linear generator used in the calculation

As illustrated in Figure 8 every important geometry parameter of the 2-D FEA model can be varied by changing the coordinates x(1)..x(n) and y(1)..y(n). Additional the width of the slot and the magnets can be varied.

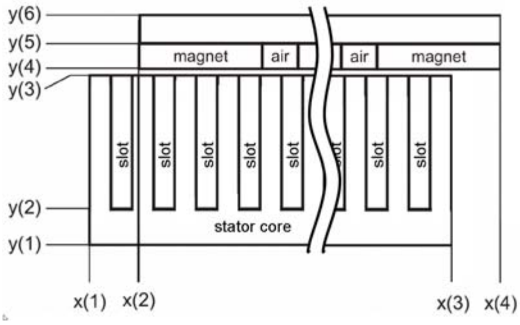

Figure 8: 2-D FEA Model

In Figure 9 the result of the calculation with the geometric parameters in Table 3 is pictured.

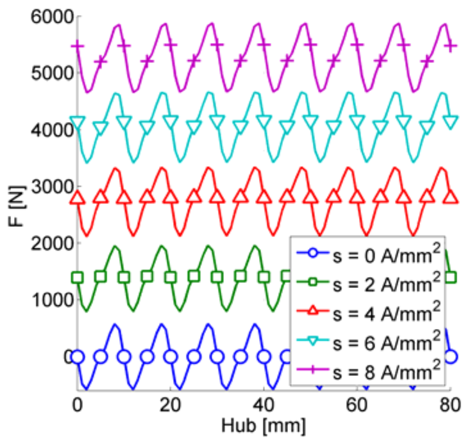

Figure 9: Axial force depending on the movers position (Hub) and the current density

The axial force F depending on the movers position and the current density s. The axial force is not constant because of the cogging force in the LG. How to reduce them is published in [5]. The calculated average force by using a current density of 8 A/mm2 is 5260N.

5. Measurement

In order to be able to make a statement regarding the quality of the calculation results by comparison with reality, it is necessary to undertake a comparison between calculation and measurement on a real, installed linear generator.

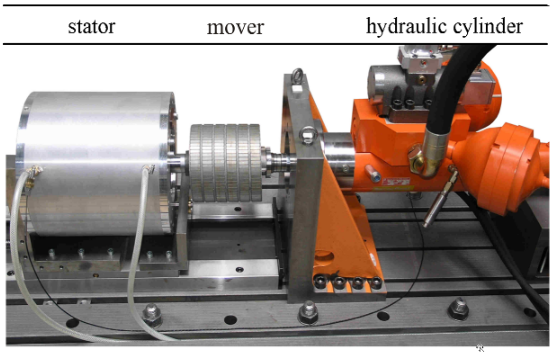

Figure 10: Installed linear generator with hydraulic cylinder

The key dimensions with cooling is an external diameter of 360 mm and a length of 320 mm. The resulting weight is about 80 kg with a reduction potential of 30 percent. The used air gap of 1.5 mm and the fragile magnets reduce the expected maximum axial force to 2500 N. For the results in Fig. 10 the calculation was done again with the parameters depending on the implemented LG.

A Measurement environment

To this end, a hydraulically-powered test bench was developed and constructed (see Figure 10). The hydraulic cylinder built into the test bench, with its model-based control, replaces combustion and the gas spring. The linear generator component can thus be tested and measured without having to construct the other components of the free-piston linear generator system.

B Result Force

An axial force graph Fx(a) is plotted against the

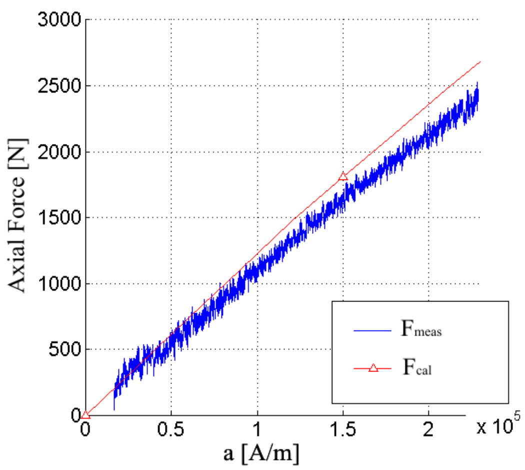

Figure 11: Measured and calculated axial force

electric loading a in Figure 11. This characteristic was measured on the installed prototype linear generator. This was done by fixing the mover at one point and continuously increasing the torque-generating cross current. The numerically calculated force differs from the measured force by an average of 3.8 per cent. This discrepancy can be explained by the values for the induction generated by the permanent magnets not being known accurately. It is thus possible to state that the numerical calculation lead to very accurate results.

B Result Efficiency

One of the FPLG boundary conditions is the variability of the mover's stroke. Because of this additional dimension it isn't possible to use the traditional efficiency graphs in which the force is plotted against the rotation speed.

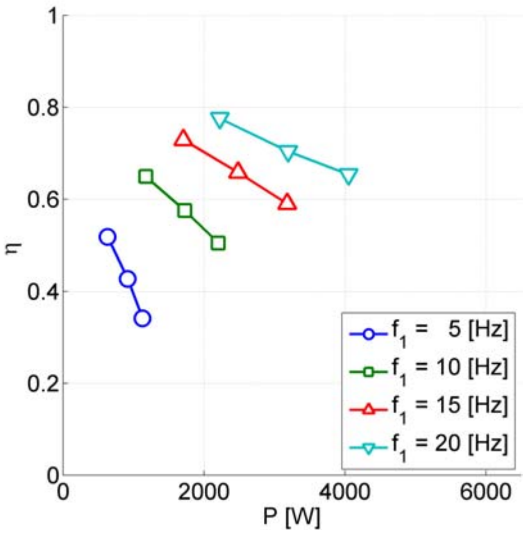

Figure 12: Efficiency LG stroke 40 mm

The solution is one graph for every stroke. In Figure 12 and Figure 13 the efficiency for different frequencies in different load points is pictured. The results in Figure 12 were measured with a mover's stroke of 40 an the results in Figure 13 with a stroke of 80 mm. The maximum frequency was 20 Hz. This is the highest possible frequency for the test bench.

In Figure 13 there is no line for the 20 Hz measurement (mes) because of the enormous mechanical stress for the test bench. The decision was made not to measure the efficiency at this frequency.

The Result of the efficiency measurement is that it is possible to reach high efficiencies. The most important losses are the iron losses in the massive iron mover. To reduce them the mover should be build of laminated metal sheets. The losses in the magnets can be reduced by a segmentation of the magnets. And the current losses can be reduced by the optimization of the current profile especially in the reversal points. Under consideration of this potentials a physically based calculation leads to the conclusion that there is a potential (pot) to reach an efficiency of about 90 percent.

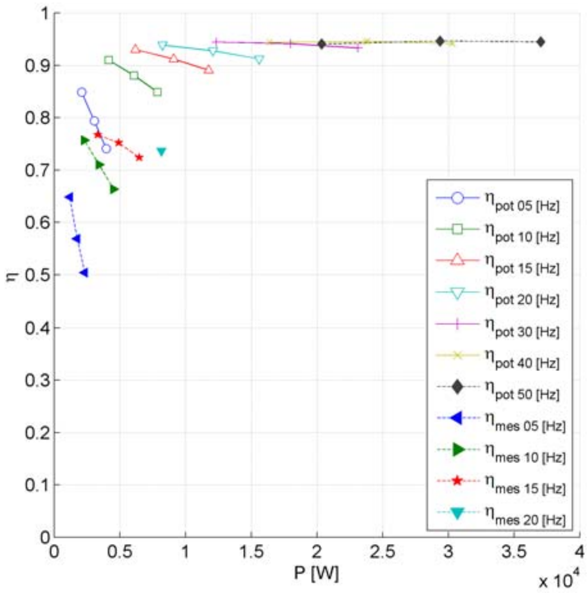

Figure 13: Efficiency LG stroke 80 mm

6. The expected fuel consumption

The results of the linear-generator optimization are base dates for a system simulation of a hybrid car with a integrated FPLG with an permanent power of 50 kW / 100 kW. The main level of the simulation model is shown in Figure 15.

The simulation system includes an electric engine used for the traction with a peak power of 80 kW. To use the recuperated electrical energy a small battery is implemented. The torque of the electrical engine is transformed by a gearbox with a transmission ration of 1:5 to the wheels. Every component is controlled by an special optimized controlunit. As testcycle to compare the FPLG based car with an conventional car the European Driving Cycle (EDC) is selected an implemented.

The simulated fuel consumption of a vehicle with an integrated FPLG versus the fuel consumption of a conventional car of the same class is presented in Figure 14.

The most important result of the system simulation and the comparison with a conventional car is that under use of an 50 kW FPLG the fuel consumption can be reduced by about 28 %.

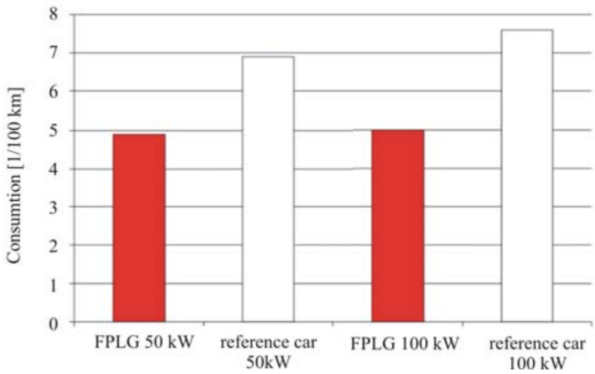

Figure 14: Fuel consumption

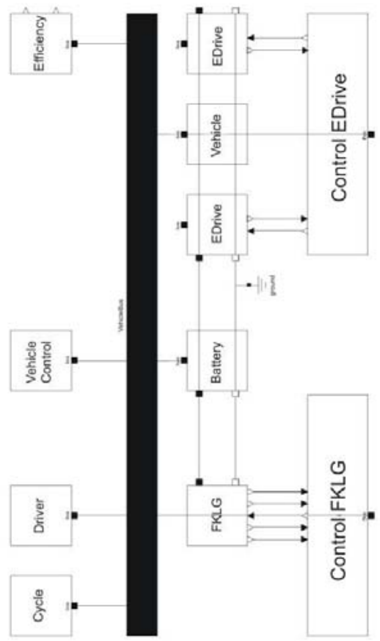

Figure 15: Model of the system simulation

7. Conclusion

It is possible to make an exact numerical calculation of a linear generator. The realized linear generator design based on a 2-D FEA calculation model fulfills the force requirements of an FPLG application. The difference of the measured and the calculated results is below 4 percent. The efficiency of the actual linear generator design is good and it can be increased by reducing the losses especially the iron losses in the mover. The main system objective to reduce the fuel consumption of a FPLG based car compared with an conventional car is achieved. A reduction of fuel consumption about 28% seams to be possible.

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