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Adaptation and optimization of a linear generator for a hybrid vehicle concept

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Abstract

This publication deals with the optimization of a linear generator (LG) intended for use in a hybrid power train design for a vehicle. The system in which the LG is integrated is called free-piston linear generator (FPLG). The free-piston linear generator is able to convert chemical energy into electrical energy by using a combustion process. By optimization of the LG it is possible to reduce the fuel consumption significantly. 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 and optimization of the linear generator to the system. After this the way of the optimization and adaptation process is pictured. It is based on a 2-D and a 3-D FEA model which is controlled by a database software. After the presentation of the calculated results a comparison between the calculation and a physically existing linear generator is presented. In the next chapter the expected fuel consumption based on a systemsimulation is illustrated. At the end of the publication a summary is given.

Keywords: Alternator, free-piston linear generator, linear alternator, linear generator, permanent magnet generator

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1. Introduction

Efficiency improvements in order to reduce the production of CO2 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 energy stored 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] and [3], the high degree of efficiency of the free-piston linear generator at all load points 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 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 technologies and fuel cell technology. Particularly since both of these technologies supply electric current 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. The system free-piston linear generator

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

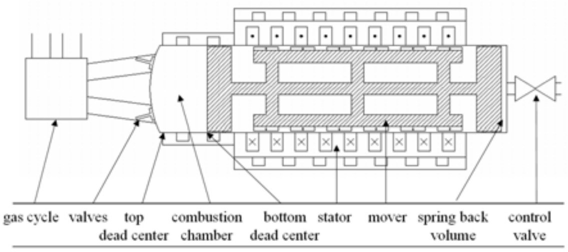

Fig 1 Illustration of the principle of the free-piston linear generator

2.1 Construction

The free-piston linear generator in Fig 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 the combustion chamber. The mass of gas in the gas spring can be adjusted by means of a control valve which allows the spring stiffness of the gas spring to be regulated. The combusted gas is scavenged out and the unburned gas taken in by way 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 plastic 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 make up the linear generator discussed in this paper.

2.2 Operation

At the start of the load cycle the double piston is at the top dead centre (TDC) and a flammable mix 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. 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 (BDC) 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 scavenged between bottom dead centre and top dead centre and unburned gas is introduced. When the unburned gas is compressed and the double piston has arrived at TDC, the next load cycle can begin. The variation in the output power is achieved by adjustment of the stroke, which is determined by the mass of gas in the gas spring. The mechanical frequency of the double piston system is kept constant.

3. Adaptation to the surrounding system

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 majority of the cars used in Europe.

TABLE 1 Vehicle data used as a basis for the design

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

Taking into consideration the acceleration processes resulting from the New European Driving Cycle, the electrical outputs required as illustrated in Fig 2 were determined with the help of a simulation. The model used in the simulation depends on the boundary conditions listed in TABLE 1. A 80 kW electric motor was implemented to realize the traction torque. 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. 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. Given a stroke of 80 mm and assuming that the LG permanently have a constant force with alternating signs. This corresponds to a force of 5000 N at a frequency of 50 strokes/second.

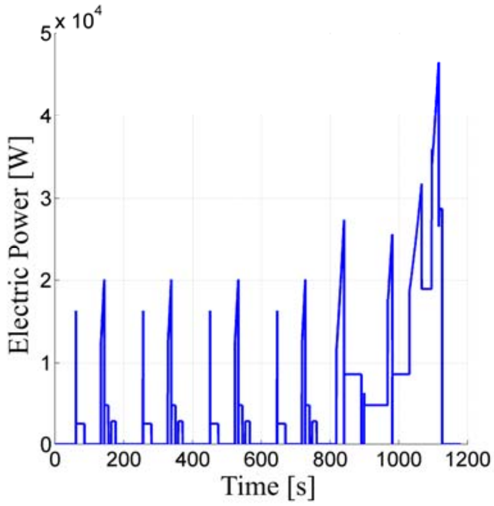

Fig 2 Illustration of the electrical power required in the New European Driving Cycle

For kinematic reasons the weight of the mover must be kept as low as possible. The LG permanently must have a constant force. To reach this aim it is possible to use a short stator arrangement or a long stator arrangement.

In the case of a short stator arrangement, a portion of the magnets in the mover overhangs the stator and thus no longer contributes to the generation of force. This results in a decrease of force and with it a decrease of output power. 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 makes the force independent of the mover position. As the current with assumed constant force in the long stator arrangement is on average lower than the current in the short stator arrangement, the copper losses arising are lower.

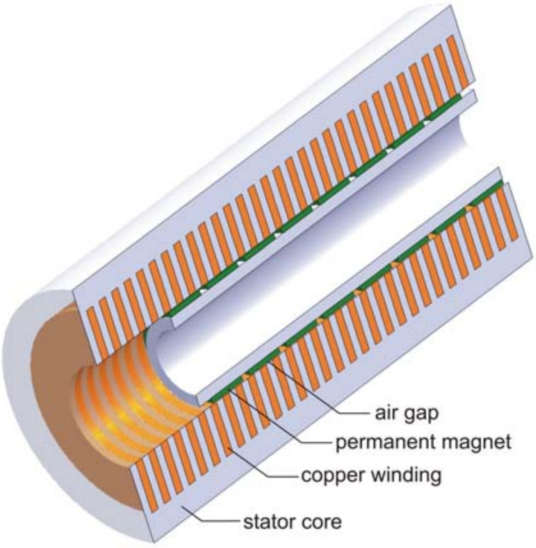

Fig 3 Example of an long stator design for the linear generator

The long stator arrangement (see Fig 3) thus has a better efficiency and is therefore the arrangement used in the free-piston linear generator.

4. Optimization

There are three aims to be achieved by the optimization of the 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 condition explained in chapter 3.

The second aim is to reduce the cogging force of the LG. This is important for the durability of the LG.

The third aim is to reduce the weight of the mover. This is important to get an optimal free oscillating system.

The base of all these optimizations is the FEA-tool Ansys. By using this tool it is possible to calculate 2-D and 3-D FEA results for different types of LG. The implemented models allow the variation of all important geometric parameters. The principle of this optimization is to calculate the axial force by varying one of the important parameters while the other parameters are fixed.

When the maximum axial force is found the result for this parameter is taken to the set of parameters and the next important parameter is varied. During this process it is necessary to hold on the interconnections of the parameters.

4.1 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 earn a higher mechanical power. The higher mechanical power Pmech leads to a higher efficiency η as shown in (1). To get a optimal efficiency it is also possible to reduce the losses Pv. In this paper the main focus is on finding the optimum 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 simulation are represented in TABLE 2

TABLE 2 Base parameters

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

As illustrated in Fig 4 every important geometry parameter 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.

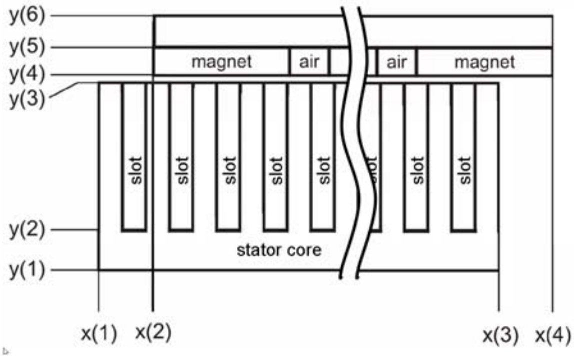

Fig 4 2-D FEA Model

Fig 5 - Fig 7 exemplarily show the calculation results when varying some of the most important geometric parameters. Fig 5 shows the effect of an increase of the air gap. The axial force degrease while the air gap increase. The reduction of the axial force depends on the increasing magnetic leakage flux and the decreasing magnetic permeance of the magnetic cicuit.

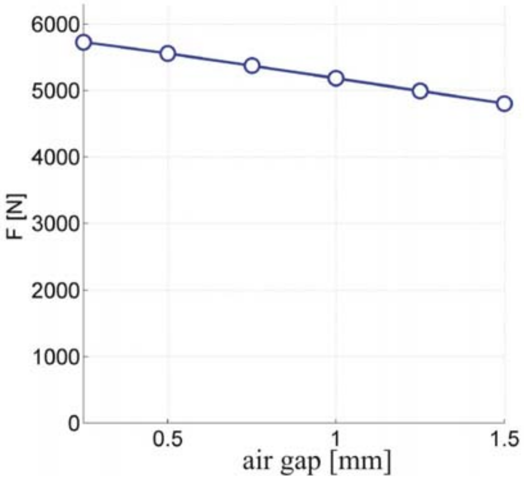

Fig 5 Axial force in dependency of the air gap height

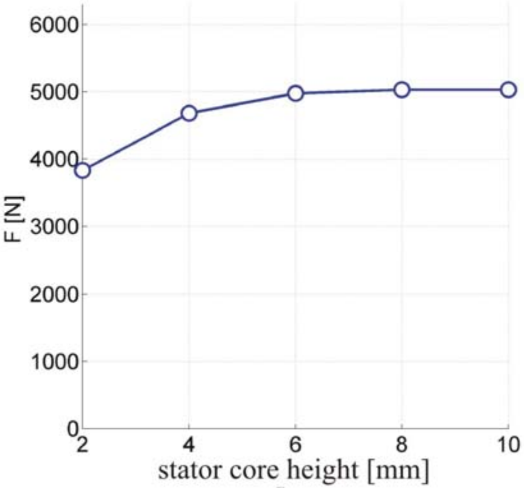

Fig 6 Axial force in dependency of the stator core height

The characteristic of the graph in Fig 6 is due to the effect (see [2]) that the magnetic flux can pass the back iron more easily if there is a bigger back iron area Afl. After a height of 4 mm the growth rate decreases because of the increasing of the magnetic resistance Rm which base on the longer way lfl for the magnetic flux.

$$R_m = \frac{A_{fl}}{l_{fl}} \qquad (2)$$

In Fig 6 the variation of the cumulative magnet height is illustrated. The axial magnetic force increases with the rising height of the integrated magnets. Before the optimization the slot width was fixed at 5 mm. The result of this fixed parameter is that in the flux density in the stator tooth begins to saturate with finally no more flux lines can infiltrate into the stator iron. So it is important to decide an optimum between the weight of the mover, the system costs and efficiency.

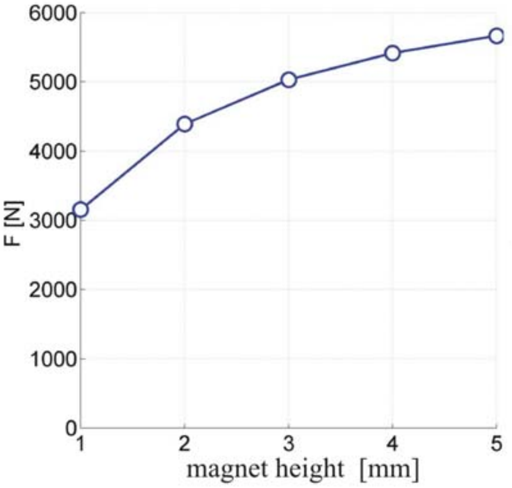

Fig 6 Axial force in dependency of the magnets height

The results of the variations are presented in TABLE 3

TABLE 3 Results of the variation

Parameter	value	unit
air gap	0.75	mm
magnet height	3	mm
magnet width	30	mm
slot width	5	mm
slot height	30	mm
back iron	6	mm
tooth width	5	mm

4.2 3-D FEA

In the 2-D calculation the cogging force, which is a result of effects at the ends of the lineargenerator and the slots turns out to be at an unacceptably high level about 900 N. At a working frequency of 50 Hz the generator would be destroyed after short time because of the cogging force based vibrations.

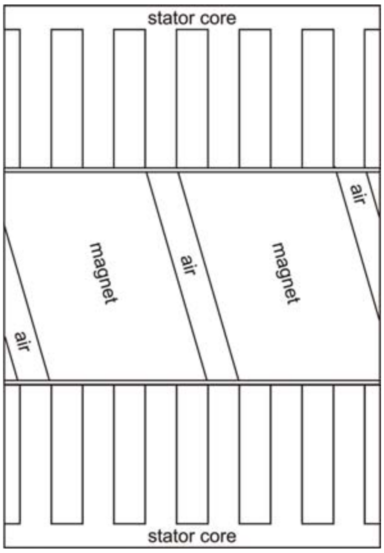

Fig 7 Cut trough the 3-D FEA model

To reduce them a 3-D model was build up. With this model (principle see Fig 7) it is possible to calculate the effect of diagonal built- in magnets. Based on the simulation results, the mover geometry is changed. The 3-D model of the LG is reduced to a minimum number of poles this is necessary to reach an acceptable calculation time.

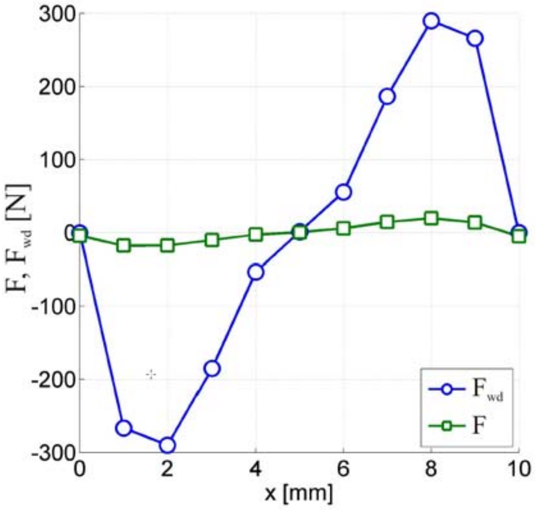

Fig 8 Cogging force reduction

The result of this optimization is shown in Fig 8. F is the force without diagonalisation and Fws is the force with diagonalisation of the magnets. The diagonalisation of the magnets is realized with a tooth width multiplied by two. With this method the cogging force is reduced by 94 % by only loosing 15 % of the usable axial force.

4.3 Weight reduction

To get an optimal freely oscillating system at a high frequency it is necessary to reduce the weight of the mover [2]. The first designed mover has an weight of 15 kg. By using an FEA with an optimization algorithm it was possible to reduce the weight to 10 kg. To be sure to get no problems with the natural frequency of the mover a modal analysis was simulated. The result of this design process is pictured in Fig 9

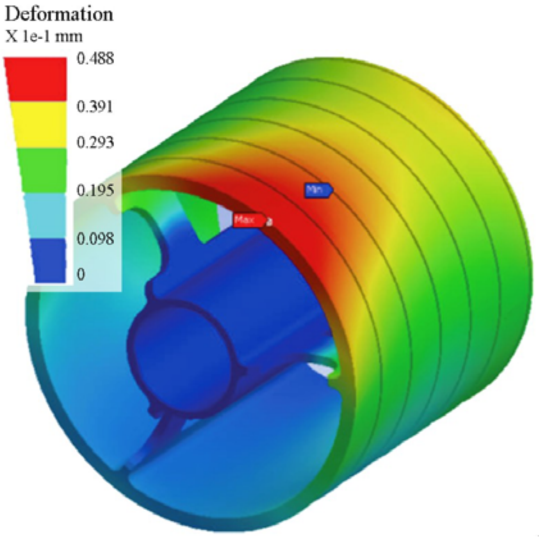

Fig 9 Mover optimization

5. Comparison calculation and real generator

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. The main size with cooling is an external diameter of 360 mm and a length of 320 mm. The used air gap of 1.5 mm and the fragile magnets reduce the expected maximum axial force to 2500 N.

5.1 Static results

An calculated axial force graph Fcal and the measured force Fmeas is plotted against the electric loading a in Fig 10. This characteristic was measured on the installed prototype linear generator. This was done by

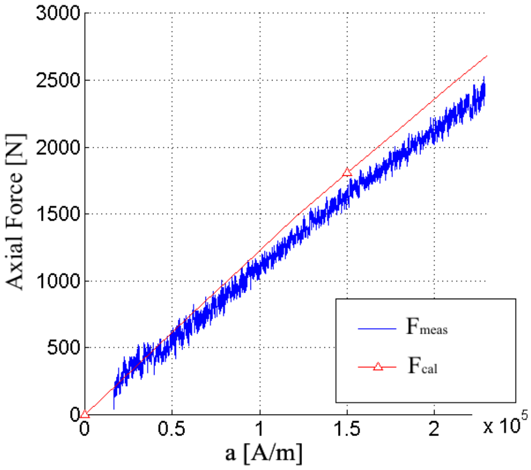

Fig 10 Measured and calculated axial force

fixing the mover at one point and continuously increasing the force-generating cross current. The numerically calculated force differs from the measured force by an average of 3.8 per cent. The discrepancy can be explained by the values for the induction generated by the permanent magnets not being known accurately. The good correlation of the simulation and the physically built up LG verifies the quality of the used approach, models and tools.

5.2 Dynamic Results

The axial force Fmeas is plotted against the stroke (st) in Fig 11. The dither of the measured axial force base on the test-environment which use an high dynamic hydraulic cylinder to realize the movement of the mover.

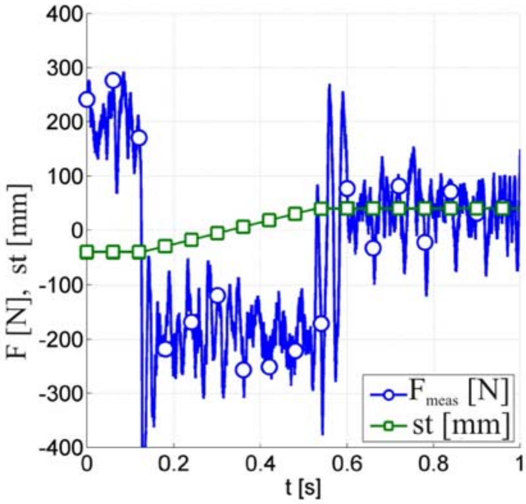

Fig 11 Dynamic measuring of the real cogging force

The calculated maximum cogging force of the realized generator should be at a level of about 40 N. The dither of the measured force is about 100

N so it is not possible to find the cogging force. To make a more exact measurement a different test-environment had to be build up. The optimization of the cogging force is successful.

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 Fig 12. 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 Fig 13.

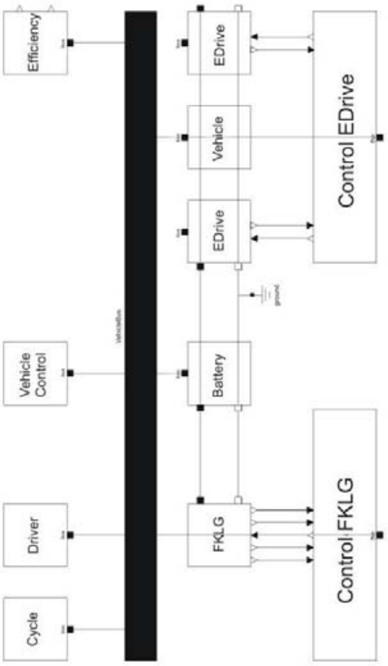

Fig 12 Model of the system simulation

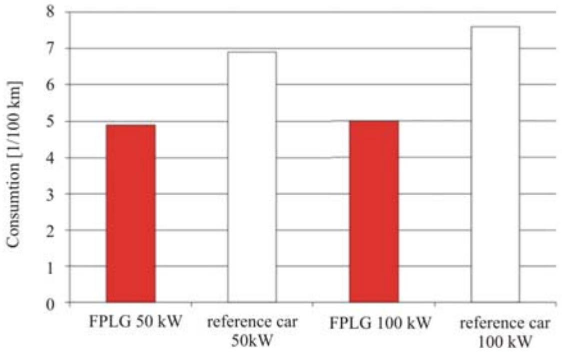

Fig 13: Fuel consumption

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 %.

7. Conclusion

By using a 2-D and a 3-D simulation model the lineargenerator was optimized to fulfill the requirements of an FPLG application. The maximum force, the lowest possible cogging force, the resulting maximum of efficiency, the reduction of the mover mass and the adaptation to the FPLG environment have been accomplished. With the demonstrated optimization of an LG all aims are achieved. The main system objective to reduce the fuel consumption of an FPLG based car compared with a conventional car is achieved. A reduction of fuel consumption about 28% seems to be possible.

References

[1] B. Metz, O. R. Davidson, P. R. Bosch, R. Dave and L. A. Meyer, *Climate Change 2007: Mitigation of Climate Change*, Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change IPCC, Cambridge, Cambridge University Press, 2007.

[2] S.-E. Pohl, *The free-piston linear generator - theoretical consideration of the complete system and experimental studies in the subsystem of the gas spring*. Ph.D. dissertation, Deutsches Zentrum für Luft und Raumfahrt, 2007.

[3] Markus Gräf, Peter Treffinger, Sven-Erik Pohl, Frank Rinderknecht, *Investigation of a high efficient Free Piston Linear Generator with variable Stroke and variable Compression Ratio*, WEVA Journal Volume 1, 2007.

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Frank Rinderknecht was born in Sindelfingen, Germany, on June 7, 1974. He completed his Masters Degree (Dipl.-Ing.) in electrical engineering at the University of Stuttgart, Germany, in 2002. Since 2002 he has been working at the German Aerospace Center, Insitute of Vehicle Concepts. F. Rinderknecht has been a consultant on various projects in the field of electrical drive and storage systems. He is responsible for the linear generator in this project. He has been leader of the Energy Converter team since January 2010.

Hans-Georg Herzog studied Electrical Engineering at Technische Universität München, Munich, Germany, where he got his Diploma Degree in 1991 and his Doctoral Degree in 1999, respectively. From 1998 to 2002 he was with Robert Bosch GmbH, Leinfelden and Gerlingen, in the field of dynamic simulation of power trains. In 2002 he joined Technische Universität München as an associate professor for energy conversion technology. His main research interests are energy efficiency, energy management and advanced design methods.