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pp. 393-399

Dynamic Simulation of a Free-Piston Linear Alternator in Modelica

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Abstract

This paper presents the modeling and simulation of a novel development of a free-piston engine in Modelica. The investigated concept is a combination of a combustion process and a linear alternator designed to provide clean, efficient energy in a compact engine. To study the features of free-piston engines a Modelica library is outlined containing basic and advanced component models. Detailed sub-models are investigated in order to design and improve hardware components. Control strategies are developed and dynamically tested within the Modelica simulation. Dymola/Modelica was found to be the best tool to examine the dynamic system behavior.
Keywords: free-piston engine, linear alternator, power electronics, control strategies

1 Introduction

The free-piston linear alternator proposed by the German Aerospace Center (DLR) - Institute of Vehicle Concepts (IFK) combines a two stroke combustion engine with a linear alternator. An adjustable gas spring is used to reset the piston assembly (Figure 1). The engine is designed to enable new degrees of freedom for advanced optimization of the combustion process. In contrast to conventional crankshaft engines the free-piston design offers mainly three degrees of freedom to improve engine performance:

- variable stroke
- variable compression ratio
- variable piston velocity

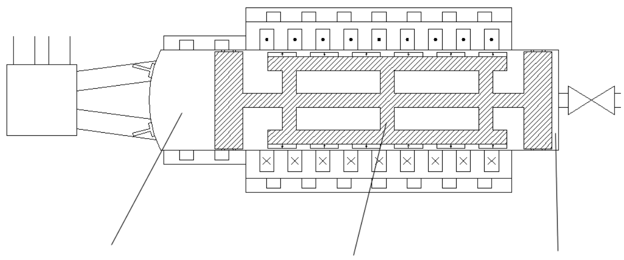

Figure 1: The free-piston linear alternator concept

These key features allow for designing a combustion process with low emissions and development towards homogenous charge combustion ignition (HCCI). The variable stroke and variable compression ratio can be used to optimize the combustion process for part load conditions. The goal is to achieve a compact electric power engine with high efficiency and reduced emissions at low costs. The free-piston linear alternator aims towards automotive application as auxiliary power unit as well as power generator in hybrid electric vehicles.

2 Modeling Objectives

At IFK a hardware demonstrator is currently being built to investigate the functionality of the free-piston linear alternator. In parallel to the hardware components a dynamic simulation model of the complete system is developed using Modelica. A Modelica library is outlined with the following objectives:

- specify hardware components
- develop control strategies
- analyze the combustion process
- evaluate operation modes

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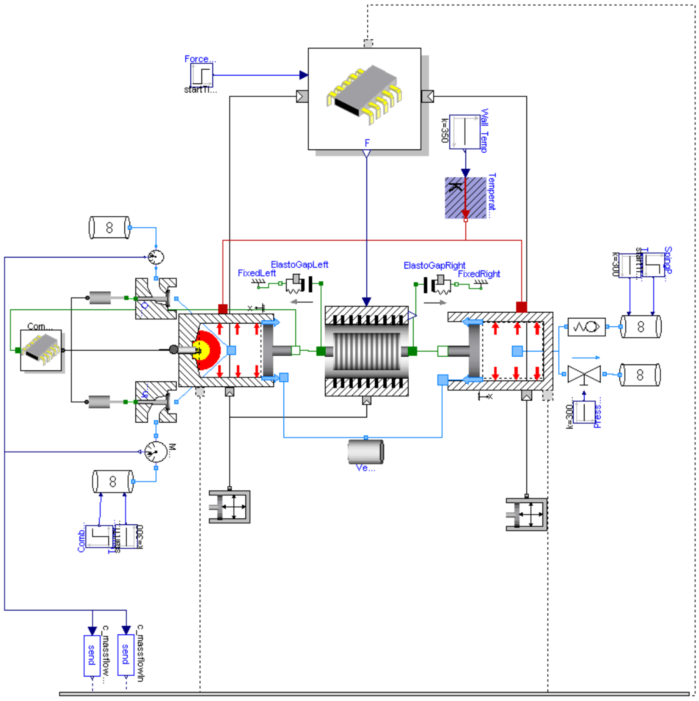

Figure 2: Modelica assembly of free-piston linear alternator

- design dynamic system behavior

The investigation of the operation modes and their dynamic transitions are of special interest since knowledge of system reaction on changes in the parameters is not available. Due to Dymolas dynamic modeling capability parameter influence on stroke, compression ratio and piston motion are a simulation focus.

3 Modelica Architecture

A Modelica library was outlined to provide basic and advanced components for free-piston engine modeling. A major scope is the compatibility with Modelica standard libraries and with future standards of thermodynamic modeling.

The free-piston linear alternator model can be built from library components. Figure 2 shows the simulation setup. The control systems, the thermodynamic models of combustion cylinder and gas spring are shown. The electrical system consists of the linear alternator and the power electronics. On a sub-layer the physical effects are modeled in detail: The mass flows into and out of the cylinders can be observed, the combustion process is modeled, heat transfer effects are investigated and the thermodynamic properties describe the state of the cylinders.

The `FixedShape` from the `Multibody` library is extended to visualize the motion of the piston assembly. The cylinder pressures are visualized by changing the cylinder color. Figure 3 shows the 3D representation of the free-piston linear alternator. The combustion cylinder is shown on the left, changing color during combustion. The linear alternator is shown in the middle next to the gas spring cylinder on the right. The animation is not only helpful for presentation purposes but also enables the developer to analyze the dynamics of the free-piston linear alternator model.

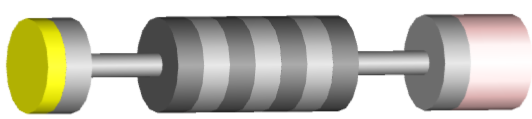

Figure 3: Modelica visualization of free-piston linear alternator

3.1 Interfaces

Modelica provides connector definitions for most physical domains. However, a common thermodynamic connector is not yet available. Thus, pressure and temperature are the two potential variables, mass flow rate as well as heat flow rate are chosen to be the flow variables. Additionally, to satisfy multi-phase flow conditions, the mass fraction for each species is added. From this information all necessary thermodynamic properties can be calculated. A code fragment of the connector definition is shown below:

```
connector CombustionGas
 parameter FKLG.Types.NumberOfSpecies nX;
 SI.MassFraction X[nX] "Mass fraction";
 SI.Pressure P "Gas pressure";
 SI.Temperature T "Gas temperature";
 flow SI.MassFlowRate mdot "Mass flow rate";
 flow SI.HeatFlowRate Hdot "Heat flow rate";
end CombustionGas;
```

For an ideal gas for example, the number of species equals one and the mass fraction is consequently unity.

Complex models tend to exchange a fair amount of information leading to components with several connectors and connections. To reduce the connection complexity a bus system is defined as an assembly of other connectors. Defining a bus currently becomes tedious since every signal has to be added by hand. The following code fragment shows the bus implementation for combustion, gas spring and linear alternator:

```
connector Bus
  import SI = Modelica.SIunits;
  import MoIn = Modelica.Blocks.Interfaces;
// Combustion
MoIn.RealSignal c_pressure (redeclare
 type SignalType = SI.Pressure);
MoIn.RealSignal c_temperature (redeclare
 type SignalType = SI.Temperature);
MoIn.RealSignal c_position(redeclare
 type SignalType = SI.Position);
MoIn.BooleanSignal c_burning;
...
// Gas Spring
MoIn.RealSignal s_pressure(redeclare
 type SignalType = SI.Pressure);
MoIn.RealSignal s_temperature(redeclare
 type SignalType = SI.Temperature);
MoIn.RealSignal s_massflowOut(redeclare
 type SignalType = SI.MassFlowRate);
...
// Linear Alternator
MoIn.RealSignal force(redeclare
 type SignalType = SI.Force);
end Bus;
```

3.2 Base Models

Defining base models for components enables the user to implement further models with the same external connections but different content. Such a base model may contain variable declarations, connectors and common equations. Another benefit from this declaration is the use of selection boxes in higher level models to switch between all models extended from the base model. In that way the user can change the setup of complex models by simply selecting different components from a list. At this time gas properties, fuel models, heat transfer models and combustion models are implemented using the base model approach.

4 Thermodynamical System

The free-piston linear alternator model is divided into the sub-models of combustion cylinder, linear alternator, gas spring and controls. These components are built from basic thermodynamic components, like control volumes, valves and pipes. Detailed sub-models concerning heat transfer and piston blowby are added to the cylinder model. The gas spring model is validated with experimental data. Both, heat transfer and blowby model are successfully obtained using other simulation software.

4.1 Combustion Modeling

Generally, the simulation of combustion is a highly complex process involving several disciplines such as thermodynamics, heat transfer, chemical kinetics, and fluid motion.

Since the compression ratio and the stroke of the free-piston alternator is not constant through out the operation, a major task is to define an appropriate combustion model. To describe the operation modes of the combustion process it can be divided into several combustion processes with differing strokes and compression ratios. In other words the free-piston linear alternator contains several conventional combustion cylinders with the same diameter but varying stroke and compression ratio. The challenge is to find a representative physical process that best describes the combustion behavior with a minimum of input parameters since experimental data is not yet available. Thus, a rough approximation of the combustion process is needed. As a starting point the combustion components presented by Tiller [2] can be used. The cylinder gas is modeled as a single phase ideal gas leading to a straightforward formulation of all connected components such as valves and pipes for the gas exchange. This is not a truly satisfying solution yet and a more detailed combustion model is currently under construction.

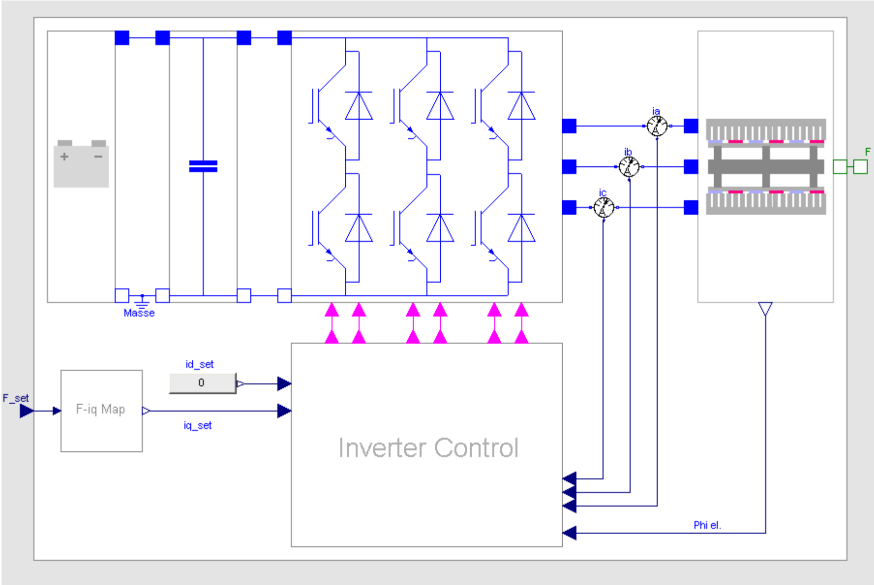

Figure 4: Electrical system of linear alternator

4.2 Medium Models

Three property models for perfect air, ideal air and an air/exhaust gas mixture were implemented as base layer for the gas spring and combustion components using Modelicas `replaceable` notation. The air/exhaust gas properties use the correlations by Zacharias [4]. To reduce computation time the property model was transferred into Modelica.

4.3 Heat Transfer Models

As described in section 3.1 the cylinder wall heat loss models are extended from a base heat transfer model. Two basic approaches for the wall heat loss are available. The first handles the cylinder heat loss for idle running engines based on the approach by Huber [1]. Secondly, for a firing engine, the approach by Woschni [3] is implemented.

4.4 Orifice Flow Models

A general orifice flow model using the isentropic flow formulation found in textbooks is extended for valve modeling.

Commonly, a small gas leakage between piston and cylinder exits the cylinder. This blowby gas flow is based on the orifice flow model. The effective area is implemented as a parameter and is validated using experimental data in case of the gas spring.

5 Mechanical System

The mechanical system is represented by the piston where the equation of motion is solved. Additionally, a spring-damper system mechanically prevents the piston from reaching the cylinder heads or the cylinder pressure from rising above a critical value.

6 Electrical System

The electrical system consists of the battery, the intermediate circuit, the power electronics module and the electromechanical model for the linear alternator.

The control unit demands a specific force from the linear alternator. This signal is mapped into a set-value *iq* for the inverter control. The inverter control generates PWM-signals for the IGBT-B6-Modul using the *dq*-transformation. The IGBT is modeled as a diode and a switch. The free wheeling diode is put in parallel to the IGBT. The diode itself is described with 3 characteristic curves, a straight line for the negative branch, a 3rd grade polynomial equation for the forward characteristics and a straight line for describing the system beyond the normal operation area.

The linear alternator is described with maps for the flux linkage and the inductance matrix for every position. This data is impressed on the equivalent circuit of a permanent magnet machine, composed of a resistor, an inductance and a voltage source for the induced voltage for all 3 phases.

The generated force is calculated after a *dq*-transformation of the real currents with the inverse F-iq map described in the beginning. As a result the linear alternator force is simulated under dynamic conditions including all time constants influencing the over-all system. In addition the Modelica inverter control model will be used in combination with the dSPACE box for controlling the constructed hardware. The power electronics are mainly modeled using the `Modelica.Electrical` and `Modelica.StateGraph` packages.

7 Control System

Disconnecting the piston from the crankshaft requires a new approach to system control since the continuous shaft motion is not available. In fact developing control strategies is the most challenging task in the free-piston linear alternator design process.

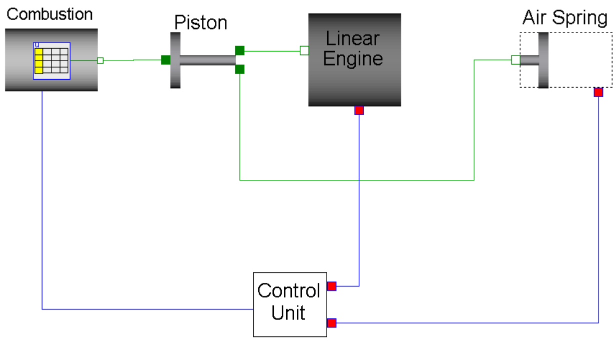

Figure 5: Simulation setup for co-simulation

In conventional engines it is needless to mention that the crankshaft returns the piston to the starting point of a cycle. In a free-piston engine the piston not necessarily returns to the same point. The piston position is strongly dependent on the states in the cylinders and the energy converted by the linear alternator. A piston motion control is developed by adjusting the converted energy of the alternator such that the piston returns to its starting point. To account for all losses occurring during the cycle the cylinder pressures are taken as calculation basis. It should be noted that the linear alternator can be actively used to control the piston motion. Hence, the linear alternator control can accelerate or slow down the piston to either influence the combustion process or prevent the piston from crashing.

In order to level the power output the energy released by the combustion process is converted by the linear alternator partly in the expansion phase and partly in the compression phase. Thus, the gas spring is used as temporary energy storage. This ”force split strategy” also effects the piston motion depending on the amount of energy converted in each phase. The simulation results presented in this paper are based on an equal energy conversion in expansion and compression phase. Extracting the energy in both, compression and expansion phase also reduces the linear alternator size and consequently piston weight. The

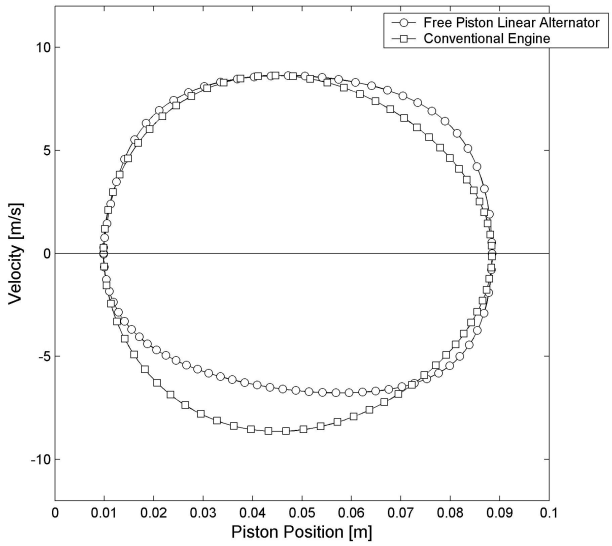

Figure 6: Comparison of piston velocities for crank shaft engine versus a free-piston linear alternator

variable volume of the combustion cylinder demands for flexible valve and ignition timing. An ”electronic camshaft” needs to be implemented to control valve and ignition timing according to the operation mode. For that purpose a virtual camshaft angle is introduced to coordinate the timing issue.

8 Simulation Results

In the remainder of this section two simulation approaches are shown investigating the potentials and challenges of a free-piston engine.

8.1 Step 1: Co-Simulation

In a first step the combustion process is simulated externally and the combustion thermodynamics are loaded into the free-piston linear alternator model (see Figure 5). In an iterative process the result is then used to re-simulate the combustion process until convergence. In that way the combustion process can be simulated in detail with a well validated programm. Due to unknown inlet and exhaust measures only the high-pressure part of the combustion cycle is investigated.

Figure 6 compares the piston velocity of a free-piston linear alternator in respect to a conventional crank shaft engine. As a result of the degrees of freedom of a free-piston alternator the piston velocity is a function of the system states.

The fundamental advantage of the proposed free-piston engine over a conventional engine is emphasized by Figure 7. In the left figure a comparison of the engines at full load conditions is displayed. Both processes show about the same performance. However, in part load conditions, shown in the right figure, the conventional engine keeps its stroke and compression ratio and the maximum pressure is quite low. Due to the variability of the free-piston linear alternator the stroke is lowered and the compression ratio is adjusted such that the cylinder pressure reaches a sufficiently high value. The performance in part load conditions of the free-piston linear alternator is consequently higher. This first approach shows the potential of a free-piston linear alternator in terms of combustion enhancement.

8.2 Step 2: Dynamic Simulation

A transient simulation is performed applying the Modelica model shown in Figure 2 and described in the sections above. Similar to many simulation tasks using DAE-solvers the free-piston linear alternator simulation needs solid start values. A solution to this task is to define a starting sequence where the linear alternator actively follows a fixed path for a few cycles before switching to a general operating mode. In the starting sequence the linear alternator simulates the piston motion of a crankshaft engine. During operation the system depends on the states in the cylinders and the energy converted by the linear alternator as well as the combustion process. The operation mode, e.g. the power output, can be changed by adjusting the system variables during the simulation process. The dynamic change in the system variables directly influence the operation mode. Figure 8 displays the change of operation mode from full load to part load conditions. The piston stroke is reduced and the compression ratio rises while the power output decreases as expected.

9 Conclusions

Examining the concept of a free-piston linear engine two main fields of interest for simulation are detected: Firstly, the development and testing of solid control of the free-piston system before applying it to hardware. On a second level the components involved in the system, namely the gas spring, the linear alternator and the combustion process can be studied in the free-piston context.

The dynamic simulation shows promising results. The system behavior as well as the cylinder conditions can be investigated, even when changing the operation mode. Developing control strategies is found to be a challenging task since solid piston control and an electronic camshaft are needed to ensure principle functioning of the free-piston assembly. Control models have been implemented and tested successfully.

Hardware components, such as valves and injectors, naturally have dead times which effect their reaction time. A predictive control to time the events in advance will be a focus of further development. Additionally, future efforts will be made to extend the free-piston linear alternator model in order to form a solid model to be built into a hybrid electric vehicle.

In order to implement a complex model of the free-piston linear alternator in the different levels of detail, subcomponents and components were modeled using Modelica. The system analysis was performed using Dymola. Both, the language formulation of Modelica and the powerful capabilities of Dymola were found to meet the expectations.

References

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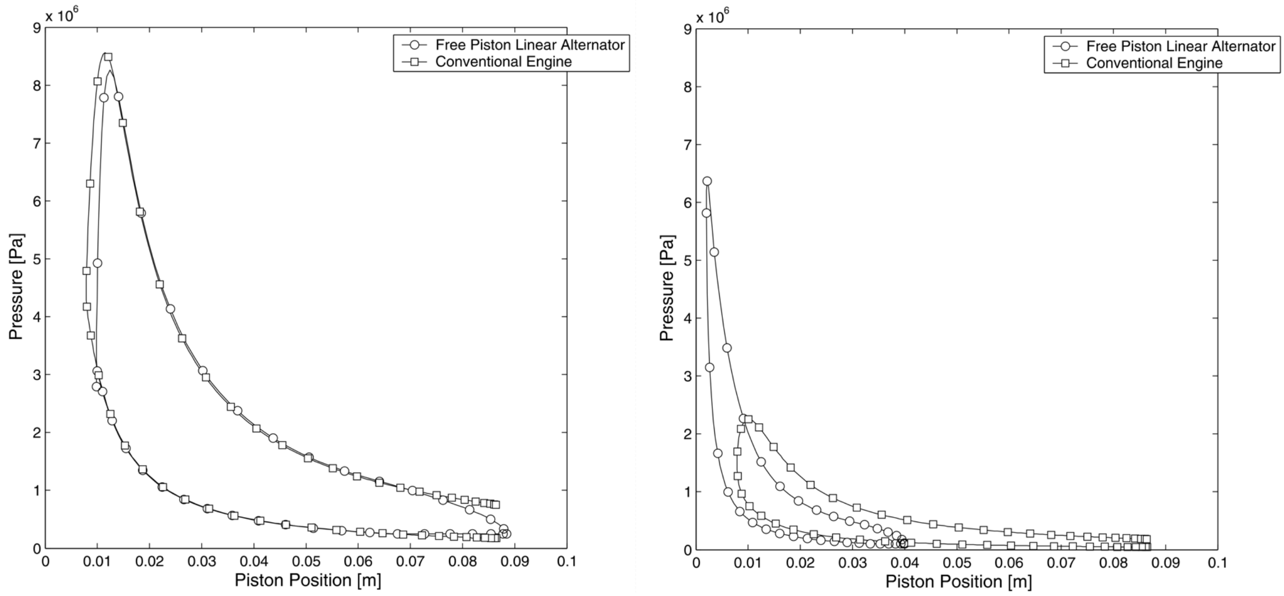

Figure 7: Comparison of combustion pressure at full (left figure) and part (right figure) load conditions for a crank shaft engine versus a free-piston linear alternator

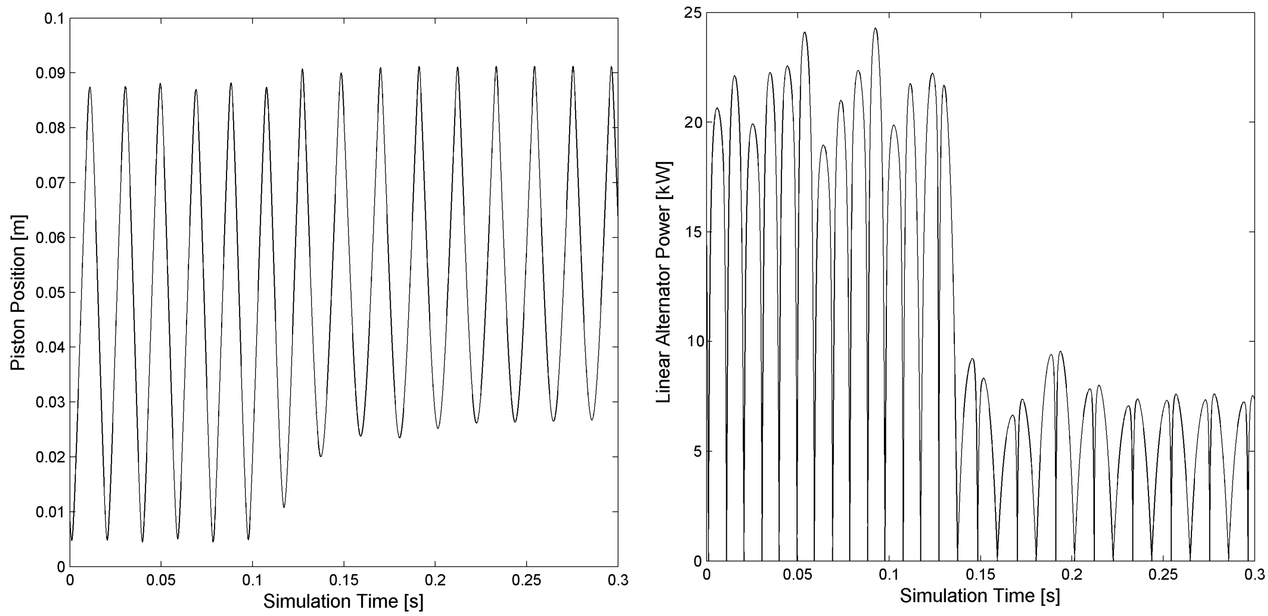

Figure 8: Piston position (left) and power output for dynamic Simulation