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52062 Aachen

The Design Requirements of a Linear Generator Integrated in a Free Piston Engine for Range Extender Application

Un-Jae Seo, Björn Riemer, Rüdiger Appunn and Kay Hameyer

Institute of Electrical Machines, RWTH Aachen University, Schinkelstr. 4, Aachen, Germany
email: UnJae.Seo@iem.rwth-aachen.de

Abstract

The free piston linear generator is a new range extender concept for application in a full electric vehicle. The free piston engine driven linear generators can achieve high efficiency at part and full load which is suitable for the range extender application. This paper presents requirements for designing a linear generator deduced from a fundamental analysis of a free piston linear generator.

1 Introduction

A range extender is an auxiliary power source of an electric vehicle (EV) to increase travel-distance. A free piston linear generator (FPLG), shown in Fig. 1, is a potential efficient power source for the range extender application. There is no crankshaft mechanism which facilitates variable stroke length and a piston can be controlled on each stroke by appropriate fuel injection timing. Unlike conventional engines that the piston motion is determined by the crank system, the piston motion of free piston engine is determined by the instantaneous force balance on the mover, which the piston motion may vary for different operating conditions. Numerous linear generators for integration in the free piston engine have been analyzed [1-2]. However, the linear generator may operate in wide operation range and each operating point has a different velocity profile. This paper conducts system level simulation in order to facilitate the design of the linear generator. This allow the design at a system level, taking account of the vehicle.

2 Simulation of Range Extender Vehicles

A series hybrid electric vehicle is the simplest configuration of hybrid electric vehicles. The electric motor is the only mean to provide the power to the vehicle's wheel which is demanded by the driver. The power delivered to the electric motor is combined power of the range extender and battery. We first choose one reference battery electric vehicle (BEV) and compared the analytical stored energy, which can be delivered to the electric motor, to possible range extender vehicles assuming such energy difference between the range extender (REX) and BEV is proportional to the difference of travel-distance. The required battery capacity, fuel tank of the range extender electric vehicle (REX-EV) to travel K times more distance than the BEV in same mass condition is revealed by the analytical mean enhanced by the results of vehicle's power management simulation.

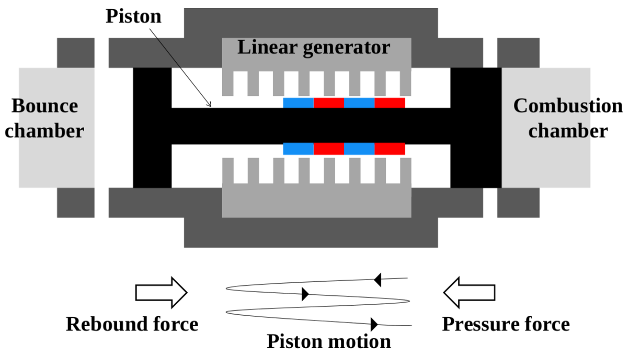

Figure 1: Schematic of a free piston linear generator

2.1 *Delivered energy to the electric motor*

There is two driving modes in a REX-EV, charge depleting (CD) mode which deplete the battery energy driving pure electrically and charge sustaining (CS) mode which sustain the state of charge (SOC) of the battery at reference level by the REX. The energy delivered to the electric motor in CD mode is,

$$E_{cd} = n_{dis}(n_{ch}E_d^- + E_b) \tag{1}$$

where $E_d^-, E_b, n_{dis}, n_{ch}$ is negative demand energy from the electric motor due to breaking, battery energy, discharging and charging efficiency of the battery respectively. The energy delivered to the electric motor in CS mode is followed by,

$$E_{cs} = n_{dis}n_{ch}E_d^- + \alpha\hat{n}_{rex}E_f \tag{2}$$

where α is a controller coefficient, which will be discussed in a later section, and $\hat{n}_{rex}$ is the peak efficiency of REX and E_f is fuel energy. Only CD mode can be applied in case of the BEV. By assuming that REX-EV can deliver K times more energy than demand energy, the energy ratio of REX-EV and BEV for two modes are,

$$K_b = \frac{E_b}{E_B},\ K_f = \frac{\alpha\hat{n}_{rex}E_f}{n_{dis}E_B} \tag{3}$$

The discharging and charging efficiency is assumed as same for both vehicles and operating modes. The energy can be represented using energy density coefficient and mass as follow.

$$K_b = \frac{m_b}{m_B},\ K_f = \frac{\alpha\hat{n}_{rex}(a_f m_f)}{n_{dis}(a_b m_B)} \tag{4}$$

where m_b is mass of the battery of REX-EV, m_B is those of BEV, m_f is fuel mass, a_f is fuel energy density, which is 12.5 kWh/kg in case of diesel and a_b is battery energy

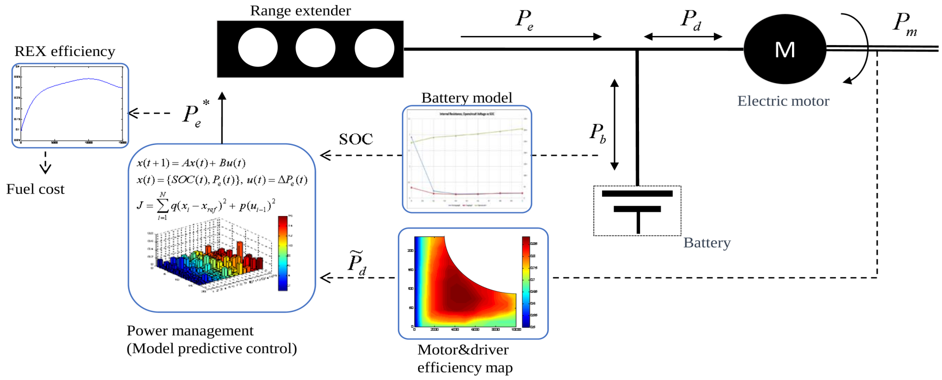

Figure 2: Simulation architecture of the REX vehicle.

Table 1: EV simulation parameters

Quantity	Value
Mass	1480 kg
Drag coefficient	0.35
Rolling coefficient	0.015
Electric motor peak power	80 kW
Battery capacity(usable)	18.5 kWh

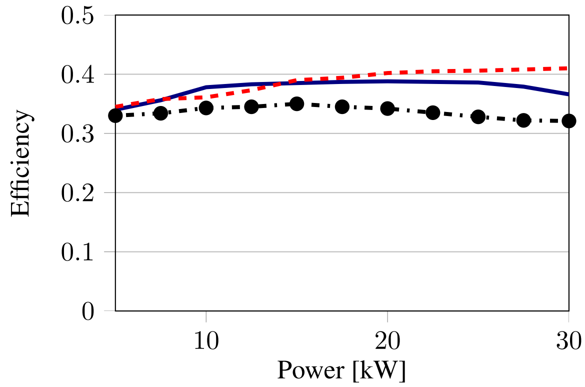

Figure 3: Conventional vehicle engine efficiency curves

density, 0.11 kWh/kg. The energy ratio between BEV and REX-EV is combined of (4) that is same to the travel distance ratio. The mass condition for BEV and REX-EV is,

$$m_B = m_f + m_b + m_{rex} + m_{sys} \quad (5)$$

where m_{sys} is mass of the fuel tank system and set to 25 kg.

2.2 Required maximum power of range extenders

The demand power of electric motor becomes high when a vehicle climbs up a hill. In this case, both battery and REX deliver power to the electric motor, depleting the battery energy continuously. Once the SOC of battery reaches it's minimum boundary, discharging the battery becomes restricted, hence the velocity of vehicle becomes reduced as only range extender can not fulfill the demanded power. As higher maximum power of the range extender and larger battery capacity, longer distance for climbing up a hill is possible before output of the battery is restricted. The required force to climb up a hill with constant speed is,

$$F = fmg + c_d v^2 + mg\sin(\theta) \quad (6)$$

The range extender has to deliver its maximum output power to the electric motor.

$$P_{rex\_max} + \frac{P_{battery}}{n_{dis}} = \frac{Fv}{n_{motor}} + P_{auxiliary} \quad (7)$$

We have calculated the maximum output power of range extender by following manner.

$$P_{rex\_max} = \frac{Fv}{n_{motor}} + P_{auxiliary} - \frac{n_{dis} 3600 E_b \Delta SOC}{t_d} \quad (8)$$

where E_b ΔSOC is the available kWh battery energy and t_d is the travel time before the SOC reach minimum boundary. The travel time, t_d, is equal to the travel distance divided by the velocity, which is restricted to

$$P_{battery} t_d \leq 3600 E_b \Delta SOC \quad (9)$$

2.3 Vehicle simulation with power management control

The algorithm employed in this paper is a model predictive control (MPC) referred by [3], as the exact knowledge of a range extender efficiency map is not necessary in the MPC. We used Rint model for the battery and reference operating point of controller is its highest efficiency point of the REX efficiency curve. The simulation structure is shown in Fig. 2. The CS and CD mode simulation on Artemis driving cycles [4] was performed with the vehicle parameters presented in Table.1. Since a real free piston engine for measurement is not available, we referred [5] for different engine efficiency curves as shown in Fig.3. The maximum output power was scaled as half, which is originally 60 kW. The vehicle power management simulation results are shown in Table. 2. The efficiency curve having 34% peak efficiency shown in Fig. 3 was used for

Table 2: Artemis driving cycle simulation results

Operating mode	Criteria	Driving cycle		
		Urban	Rural	Motor way
CD	Battery energy consumption per km (kWh/km)	0.15	0.16	0.24
	Average Discharging/Charging efficiency	0.95/0.96	0.93/0.95	0.88/0.94
CS	Average REX efficiency	0.31	0.33	0.32
	Average Discharging/Charging efficiency	0.95/0.94	0.93/0.93	0.93/0.92

Table 3: Calculated controller coefficient

Reference power	Urban	Rural	Motorway
15 kW	0.9	0.93	0.92
20 kW	0.89	0.92	0.96
30 kW	0.86	0.89	0.95

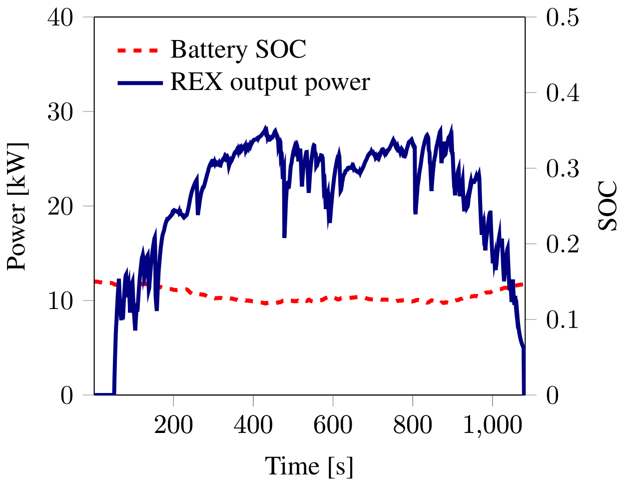

Figure 4: The output power of REX and SOC of battery on the Motorway cycle

the CS mode simulation. The output power profile of the REX on the motorway driving cycle is shown in Fig. 4.

The previous three efficiency curves were applied to estimate the controller coefficient in (4). The each reference operating point of the MPC was differed by each REX efficiency curves. The simulation results on three Artemis driving cycles are presented in Table. 3. The controller coefficient is highly depends on differences between the average demand power of driving cycle and reference operating point of the MPC where the highest efficiency point lies.

2.4 *Requirements of REX vehicles with a free piston linear generator*

The requirements of the REX-EV with the free piston linear generator to travel 2.5 times more distance than the reference BEV have been analyzed, which means the combined of (4) is 2.5. The specifications of the free piston linear generator are 34% peak efficiency and 0.34 kW/kg power density [6]. The battery efficiency and controller coefficient is assumed as 93% and 0.9 respectively to solve

Table 4: Requirements of the REX-EV with FPLG

Quantity	Value
Curb weight	1400 kg
Battery capacity	11 kwh
Fuel tank	12 ℓ
REX Maximum output power	28 kW
Driving distance	270 km

(4). The required power of the REX is calculated by (8) with conditions that 5 km distance, 90 km/h velocity, 3% available battery energy and 3% grade hill. The driving distance of reference BEV was assumed as 109 km (0.17 kwh/km) and REX-EV can travel 2.5 times more distance. The REX-EV specification for the free piston linear generator is shown in Table. 4.

3 MODELING AND SIMULATION OF A FREE PISTON ENGINE

In order to find the design specifications of the linear generator, the single zone and zero dimensional model is used for the free piston engine simulation. The piston motion is not mechanically prescribed but is rather a result of the balanced in-cylinder pressures, inertia forces, friction forces and the applied load. A dynamic model of the piston motion from Newtons 2nd law can be represented as,

$$m\frac{d^2t}{dt^2} = F_L + F_R - F_e \tag{10}$$

where F_L, F_R, F_e is force from each cylinder and electromagnetic force of the linear generator respectively. The following equation is used to calculate the in-cylinder pressure at each time step [7].

$$\frac{dp}{dt} = \frac{\gamma - 1}{V}\frac{dQ}{dt} - \gamma\frac{p}{V}\frac{dV}{dt} \tag{11}$$

In combustion model, a time based Wiebe function is used to express the mass fraction burned in the combustion process as follow,

$$\chi(t) = 1 - \exp(-a(\frac{t - t_0}{t_c})^{1+b}) \tag{12}$$

$$\frac{dQ}{dt} = Q_{in}\frac{d\chi(t)}{dt} \tag{13}$$

The control objective of a free piston engine is maintaining the top dead center (TDC) and bottom dead center (BDC) at desired position. We referred Milkalsen and

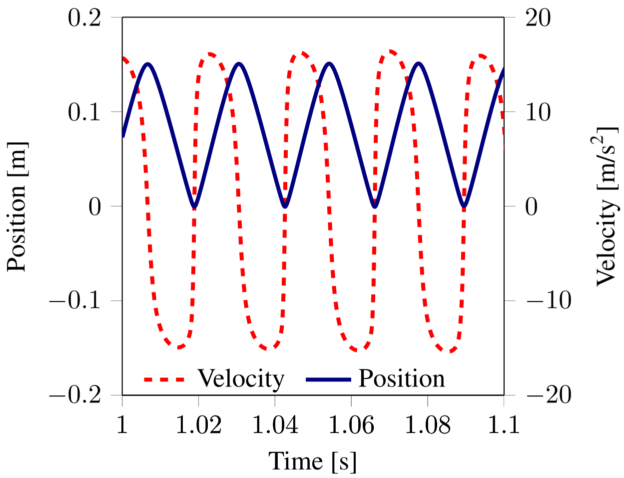

Figure 5: Simulation results of the free piston engine

Roskillys investigation [8]. The control inputs are fuel mass, air mass in bounce chamber and electric load force while output are TDC and BDC position. The simulation results are shown in Fig. 5 which is far from sinusoidal. The obtained speed profile can be used for numerical analysis of the linear generator.

4 Design consideration of a linear generator

The velocity of the translator mounted on the piston is directly dependent upon the moving mass, which is one of the most important parameter in this system. The system should be installed beneath the driver's seat as discussed in [6] to secure sufficient length for the opposed piston FPLG topology. Hence, the generator would be thin and long. The longitudinal stator topology have an advantage of the reduced moving mass while it suffers from increased system mass due to long stator. The possible solution to decrease the mass of longitudinal mover is the ironless mover with Halbach array permanent magnet. It have been discussed that the leakage flux of the Halbach array magnetized permanent without mover back iron is relatively weak due to the virtually self-shielding property [2].

In series HEV, the REX operates only at its most efficient speeds and loads as it is not coupled to the wheels. Thus, the operating points to analyze the linear generator is limited by operating points of it's prime mover. It can greatly reduce the necessary analysis points as fundamental of the free piston engine was analyzed. Unlike the electric motor of the EV, the output of linear generator is governed by the power management algorithm while the output of electric motor directly follows the demand power of driving cycle. As the output power profile of the REX has been obtained, the performance index can be established for the linear generator design process.

5 Conclusions

The numerical simulation for designing the linear generator has been performed. The reference BEV was chosen and the REX-EV with the FPLG to drive 2.5 times more distance than reference BEV in same mass condition have been analyzed. The REX-EV with the FPLG requires 12 ℓ fuel tank, 11 kWh battery to travel desired distance. The output power of the REX has been calculated by the desired climbing-distance, 5 km, when a vehicle climbs up a hill with 90 km/h velocity, 3 % grade and 3 % of available battery energy. The free piston engine has been simulated to find the design specifications of linear generator. The mass of mover is the most important parameter of the linear generator since it determined the velocity of the piston.

The vehicle and prime mover, the free piston engine, has been analyzed to synthetically consider the design requirements of the linear generator. The obtained results can enhance the design of the linear generator as the influence of the linear generator can be simulated in consideration of the fuel efficiency of REX-EV.

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