APPLICATION OF A FREE-PISTON GENERATOR IN A SERIES HYBRID VEHICLE

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Abstract - **This paper deals with an investigation of different control strategies for a series hybrid electric vehicle (SHEV). Another discussed issue is the application of a free-piston generator. By replacing a conventional combustion engine with a free-piston generator it is possible to increase the total efficiency of the system. The object of investigation is a 12-ton truck, mainly used in urban areas. The drive system has been built up and simulated in a MATLAB Simulink environment. It follows from the investigation that the application of a free-piston engine in a SEHV can increase the efficiency by 25 percent compared to the conventional engine.**

Key words -**SHEV, HEV, Free-piston generator, SOC**

1. INTRODUCTION

In order to reduce the fuel consumption of a vehicle, many manufacturers are doing big efforts to find new and better solutions compared to the most common ones today. One of the interesting solutions today is a hybrid electric vehicle (HEV).

There are many different solutions for the system. To mention some, there are series hybrid electric vehicles (SHEV) and parallel hybrid electric vehicles (PHEV) which today are the most common ones. In this paper the first mentioned one is going to be discussed in more detail.

To put an electrical motor "in series" with the conventional combustion engine means that the energy needs to be converted from, mechanical to electric and back again, which of course implies bigger losses due to several energy conversions. One way to improve the efficiency of the SHEV system is to replace the conventional engine by another energy source, in this case a linear combustion engine. In order to convert a linear motion of the piston into electric energy, a special linear electric generator has been investigated [1]. One of the demands of the electric generator is very high power density.

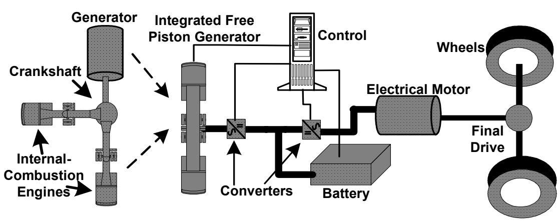

Figure 1.1. A free-piston generator fed series hybrid vehicle.

2. MODEL

The object for this study is a 12-ton distribution truck with the data presented in table 1

TABLE 1 VEHICLE DATA FOR THE 12-TON TRUCK

Vehicle data		
Curb weight	5.5	ton
Payload	6.5	ton
Gross vehicle weight	12	ton
Mean weight	8.75	ton
Front area	8	m^2
Rolling radius	0.421	m
Drag coefficient	0.6	---
Rolling coefficient	0.01	---

The truck is mainly used in urban areas for distribution of e.g. groceries to stores. During the simulations the mean weight has been used. The reason is the assumption that the truck in the beginning of the drive cycle is fully loaded while it is empty in the end of it.

In this study a model has been built up in a MATLAB Simulink environment. Eight separate modules, as can be seen in figure 2.1, represent the whole system.

The first module calculates the power, torque and angular speed demands from the FTP-72[1] drive cycle. The calculations in the module are based upon the vehicle technical data that is shown in table 1.

The total power demand of the vehicle at the final drive can be calculated as follows

$$P = \frac{v \cdot \left(\frac{1}{2} \cdot k_1 \cdot \rho_{air} \cdot A \cdot v^2 + k_2 \cdot m \cdot g + m \cdot \frac{dv}{dt} \cdot j\right)}{\eta} \quad (2.1)$$

where P is the vehicle power demand, v is the vehicle speed in, k_1 coefficient of air drag, ρ_{air} is air density, A is the front area of the vehicle, k_2 is the coefficient of the rolling resistance, m is the mass of the vehicle, η is the transmission efficiency and j is the mass factor which includes the effect of inertias.

[1] Federal Test Procedure drive cycle

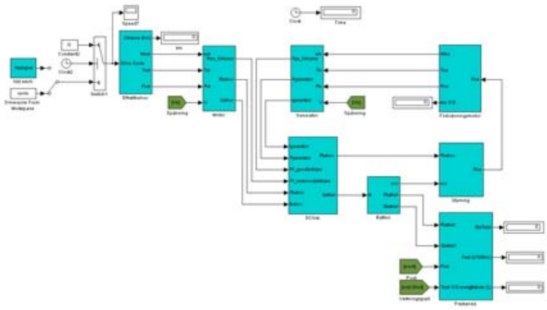

Figure 2.1. SEHV system built in a MATLAB Simulink environment.

The second module represents the electrical machine. Torque, power and angular velocity are used as an input to this module. In order to calculate the electrical and the mechanical losses simplified equations has been used. To keep the system efficiency high, only permanent-magnet electrical machines are considered. It is assumed that the electrical machine has an efficiency of 95 percent. The generator module is similar to the motor module.

The combustion engine module is determining the instantaneous fuel consumption of the vehicle by means of look-up tables. The input to the module is the power that is controlled by the control module.

The purpose of the control module is to keep the power balance in the system at any moment in time. Another important thing with the control module is that it has to keep the battery state of charge (SOC) level within the predefined borders.

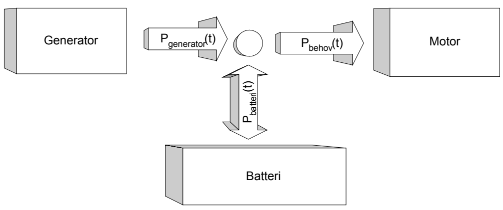

Figure 2.2. Power balance in the SEHV system.

The battery module represents a lithium-ion battery. A lithium-ion battery has been chosen due to its high power density that makes it very suitable for hybrid applications. The battery model is based upon a Zimmerman model [2]. The Zimmerman model was from the beginning supposed to represent a NiCd battery. Later it has also been shown that, with slight modifications, the model is suited even for lithium-ion batteries. Figure 4 shows an equivalent electrical circuit that represents the lithium-ion battery.

Due to the complexity of batteries one need to take many different aspects into consideration. Usually the different battery models take charging and discharging times, SOC and the temperature into consideration. In this model the attempt is made to derive an equivalent electrical circuit where the different components are current-, voltage- and temperature-dependent.

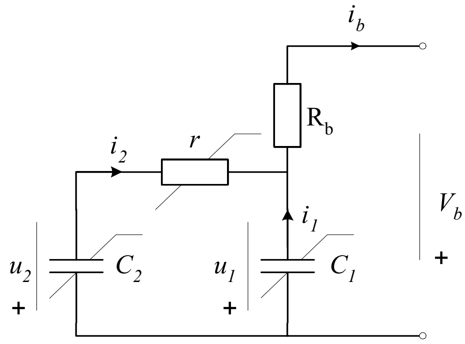

Figure 2.3. Equivalent electrical circuit of a lithium-ion cell.

Equations 2.2, 2.3 and 2.4 represent capacitances, which are dependent upon the voltage. The coefficients A_1, B_1, u_1, u_{M1}, A_2, B_2 and u_{M2} are temperature and current dependent and can be found in [2] and [3]. For simplicity, the battery temperature has been kept constant during the simulations.

$$C_1(u_1) = A_1 \cdot e^{\left(-B_1 \cdot (u_1 - u_{M1})^2\right)} + A_2 \cdot e^{\left(-B_2 \cdot (u_1 - u_{M2})^2\right)} \quad (2.2)$$

$$C_2(u_2) = \frac{D_0}{2} \cdot \left(1 + erf\left(u_2 - u_E\right)\right) \quad (2.3)$$

$$C_2(u_2) = D_0 \cdot \left(u_M - u_2\right) \quad (2.4)$$

Equation (2.3) is valid for $0 \le u_2 \le 4.1$V and equation (2.4) for 4.1V$< u_2 \le u_M$.

The last two models are the DC-link and the performance module. The DC-link module is quite simple and its task is to connect the generator, the motor and the battery module.

In the performance module the fuel consumption per 100 km is calculated as well as the total efficiency of the system. Equation 1.5 is used to calculate the total efficiency of the vehicle,

$$\eta = \frac{W_{needed}}{W_{fuel} - \Delta W_{battery}} \quad (2.5)$$

where W_{needed} is the energy required to force the vehicle a certain distance, W_{fuel} is the total amount energy in the fuel, consumed by the vehicle, and $\Delta W_{battery}$ is the difference in the battery stored energy in the beginning and in the end of the simulated drive cycle.

3. STRATEGIES

The efficiency of the system is in high order dependent upon the control strategy. In this paper three different strategies has been suggested and investigated.

3.1. Strategy 1

The aim of this strategy is that the combustion engine will work in its optimal point, which means its highest efficiency. The battery supplies the power demanded by the traction motor. The battery's SOC level is allowed to vary between 40% and 70%. When SOC has reached the

40% level the combustion engine will start and it will run until the battery's SOC level has reached 70%. The combustion engine will then stop and the same procedure is repeated again and again.

An important task of the control system is covering of the variation of the batteries SOC level. If the SOC level start to decrease despite the combustion engine is working in its optimal point the combustion engine must in that case start to work at its maximum point of operation until the SOC level again is 70%.

A more sophisticaded strategy would be that instead of delivering the maximum power, the combustion engine delivers as much power as the traction motor requires and also some extra power to charge the battery. However, for simplicity it will be sufficient if the SOC level is kept within the certain limits during all operating conditions.

3.2. Strategy 2

In this strategy one will minimize the use of the battery. In the beginning of the drive cycle, in the previous strategy, the battery supplies the whole power demand. When the battery's SOC level has reached 40% a combustion engine is then started.

During a period of high power demand from the traction motor, the battery needs to supply a high current that will cause high losses inside the battery. In order to reduce the high stress, of the battery the combustion engine will in this case start to operate at a point where the power demand from the traction motor exceeds the optimum operating point of the combustion engine. The combustion engine will then run with its maximum efficiency.

The peak power that has to be delivered by the battery is by that means reduced. This will also reduce the losses in the battery. To be able to operate the combustion engine in realistic way a time control function has been included in the control system. Without the time control function there is a risk that combustion engine in some cases would work for very short time periods. Too many starts and stops of the combustion engine will cause increased fuel consumption (and emissions) thereby reducing the total efficiency of the system.

3.3. Strategy 3

There is a similarity between this strategy and strategy number 2. Only difference is that the combustion engine will now operate within an interval instead of at its optimum point. The combustion engine will follow the optimum line that has been derived from its 3D-map (i.e. efficiency versus torque and speed). In that way the peak power that has to be delivered from the battery is decreased even further.

4. IMPROVED EFFICIENCY

To improve the efficiency of a SEHV-system a free-piston engine can replace the conventional combustion engine. To simulate this, the combustion characteristic (efficiency curve) of a conventional engine is here replaced by those of a free-piston engine by up-scaling the same. Figure 4.1, shows this possible improvement in system efficiency for a 17 kW engine. Due to the unavailability of free-piston data for bigger engines, it is assumed that this improvement is also prevalent for bigger engines (though this may not be correct in reality).

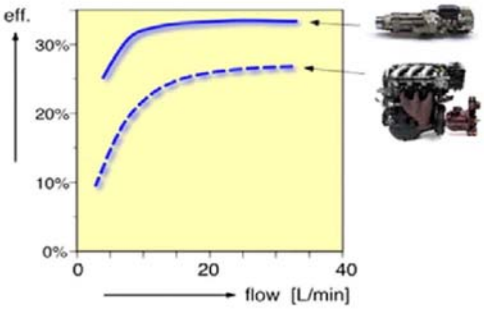

Figure 4.1. Overall efficiency of a free-piston engine pump compared to the efficiency of a comparably sized conventional diesel engine piston in-line pump [2].

As can be seen in figure 4.1 the difference in the efficiency is larger at the lower powers. Since the figure represents the total efficiency of the system there can be several different causes behind that.

To upscale the efficiency of the conventional combustion engine it is assumed that the free-piston engine has at least 20 percent lower fuel consumption over the full operational range. The original and up-scaled efficiency curves of the combustion engine are illustrated in figure 4.2.

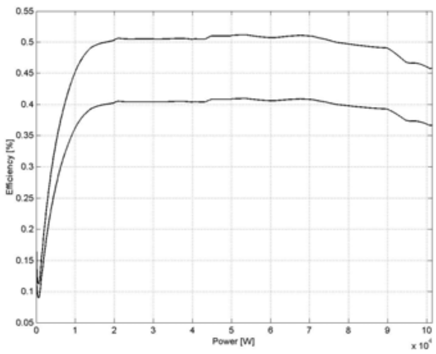

Figure 4.2. Original and up-scaled efficiency curves of the conventional combustion engine. The upscaling is done to simulate a free-piston engine.

5. SIMULATIONS AND A DRIVE CYCLE

During the simulations the start and stop losses of the combustion engine have not been considered. Simulations of the system are based on FTP-72 drive cycle. FTP-72 is a part of a FTP-75 drive cycle, which is the one used in Sweden during a prescribed exhaust testing. In the beginning of the drive cycle the batteries SOC level has been put to 70 percent.

In order to do a simple analysis of the system performance different parameter has been varied. Variables that have been varied are the time interval and the power limit where the combustion engine should start to operate. These variables are considered to have most influence on the system efficiency.

For the strategy 1 there was no need of implementing the time control. In strategy 2 only the time interval has been varied. In strategy 3 both the time interval and the power limit has been varied. Only the best strategy is used for simulations of free-piston implementation in a SEHV system.

6. RESULT OF THE SIMULATIONS

By implementing the time control to the system another problem, battery overcharging, is raised. In this work it is chosen that in the strategy 2 the combustion engine will work at its optimum point during the time interval t_{on} regardless of the system load. In some cases the battery can then be overcharged. It will be a question of priority, battery SOC level on one hand and time interval t_{on} on the other.

One possible solution to avoid battery overcharging is to choose the combustion engine to work in idling position once the power requirement from the road is zero or less than zero (regenerative breaking). Another solution, which has been used in this paper, is to introduce a new charge and discharge SOC limits. When the SOC level of the battery has reached the new high limit (over 70%) then the battery needs to be discharged to a new low limit (in this case 65%). Introduction of new limits is illustrated in figure 6.3.

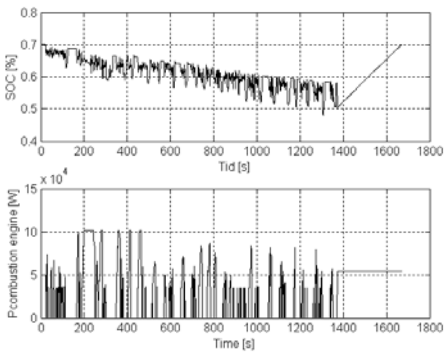

Figure 6.1. Battery state of charge and the power from the combustion engine versus time for strategy 3, without time control.

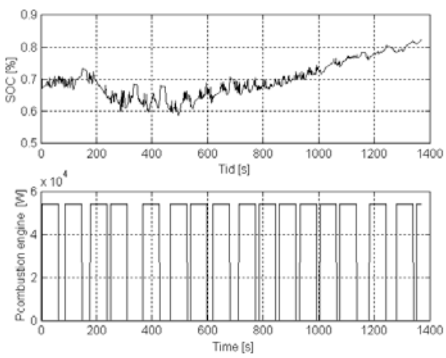

Figure 6.2. Battery state of charge and the power from the combustion engine versus time for strategy 2.

The maximum efficiency of the systems occurs with the control strategy 3 with the time interval t_{on}=70s, t_{off}=10s and P_{limit}=35 kW. The efficiency of the system, according to equation (2.5), is 42 percent. The fuel consumption is 19.3 litres/100km, which is better then the fuel consumption of a conventional distribution truck (25.5 litres/100km [5]). Compared to another hybrid concept; a four-quadrant transducer (4QT) [5] (consumption of 17.9 litres/100 km) a free-piston concept show not as good rsults as (4QT).

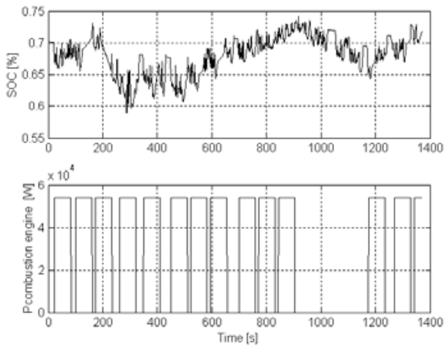

Figure 6.3. Battery state of charge and the power from the combustion engine versus time with introduced new SOC limits for strategy 2.

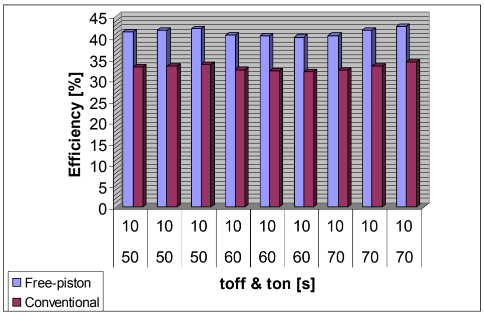

Figure 6.4. System efficiency versus time intervals t_{on} and t_{off} (P_{limit} =20, 28, 35 kW, strategy 3).

7. CONCLUSIONS

In this paper three different control strategies to minimize the fuel consumption of the 12 ton distribution truck has been presented. By implementing a free-piston engine, instead of a conventional combustion engine in the SEHV, it is shown that the efficiency of the vehicle may be improved by up to 25 percent. According to the simulation results too much use of the battery can lead to lower system efficiency.

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