Simulation of Hybrid Electric Vehicles

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Abstract

In this work the fuel consumption of two vehicles is compared. For investigating the fuel consumption a whole vehicle simulation is developed with the *SmartPowerTrains* library and the *SmartElectricDrives* library. Both librarys are written in *Modelica* language. As a reference vehicle a conventional vehicle with manual transmission is modeled. A parallel hybrid electric vehicle with a starter/generator and two transition machines at the front and rear drive train wheels is compared with this reference vehicle. The operating strategy of the hybrid electric vehicle is explained. Furthermore, an analysis for finding the optimal sizes of the electric machines for the parallel hybrid electric vehicle using the developed simulation tools and the developed operating strategy is presented. The practical operation modes of the parallel hybrid electric vehicle are considered with regard to the implemented drive train configuration. A dynamic operating method is developed to determine the optimal power split between the internal combustion engine and the electric energy sources. The computer simulation results show the improved fuel consumption of the hybrid electric vehicle.

Keywords: hybrid electric vehicle; operational strategy; drive train configuration; optimization

1 Introduction

The focus of this paper is to compare the efficiency and the fuel consumption of a conventional vehicle and hybrid electric vehicles (HEVs) with scaled electric components. The *SmartPowerTrains* (SPT) library focussing on hybrid electric vehicle concepts is used for the presented investigations. The SPT library was developed at Arsenal Research. It is written in *Modelica* language [1]. All mechanical components of a vehicle are modeled with the SPT library. The electrical components in the HEV concepts are implemented using the *SmartElectricDrives* (SED) library. The used components of the SED library are electric machines, power sources, measurement devices, modern electric drive control algorithms and power electronics.

Compatibility with other *Modelica* libraries such as, the new SED library, the new *VehicleInterfaces* library [2], the *Modelica* standard library and the *Modelica.Thermal.FluidHeatFlow*, can be guaranteed to the user due to proper interfaces harmonization thoughout the development process. This compatibility gives rise to the development of simulation models with the potential to be expanded to hybrid- and fuel cell configurations of automotive vehicles and electric drives of vehicle auxiliaries [3]. The SPT library is developed to determine the energy flow in the entire vehicle including the energy consumption of electrical- and mechanical components. Furthermore, the fuel consumption and the exhaust emissions of the vehicle and the internal combustion engine (ICE) can be calculated and determined by using SPT library components.

An intelligent operation strategy for optimizing the fuel consumption is essential in HEV concepts. A control signal exchange between the energy sources, energy consumers and all other components of the HEV is facilitated by the implemented bus concept of the SPT library. The energy flow in the HEV can be regulated and optimized independently of the drive mode of each component.

2 The *SmartPowerTrains* library

The SPT library, shown in Figure 1, is developed under the framework of Arsenal Research. This library provides components for modeling and simulating conventional vehicles and HEVs. The electrification of conventional vehicles and vehicle components such as the water pump, the cooling fan and air condition system give rise to higher efficiency compared to conventional vehicle designs. Mild and full electric vehicles are expected to have the highest efficiency. The simulation of the entire vehicle is needed to find the optimal drive strategy of an HEV. Particularly, the coexistent simulation of the mechanical components and electrical components of the vehicle is crucial. Such simulations are possible with the developed SPT library, the SED library and the *Modelica* standard library respectively.

In the following the function and the structure of the package components of the SPT library are explained:

1. *AuxiliaryComponents:* This package contains the basic components and partial models. Rotational and translational mechanical friction models are included in this package. With the blocks and the models of this package it is possible to implement the vehicle parts such as the friction of the bearing, the clutch and the rooling resistance of the vehicle.
2. *Chassis:* The *Chassis* package includes different chassis models with drive resistances such as rolling-, aerodynamic-, climbing-, and accelerating resistance.
3. *DriveTrains:* Models of belt drives, mechanical and automatical gear box concepts, differentials, power split devices, cardan shafts, chain drives, clutches, etc. are designed in this package.
4. *Electricals:* The electric components such as the starter/generator (SG), the battery and the traction machines can be found in this package. All components of this package are implemented using the the SED library.
5. *Engines:* The *Engines* package contains components of the ICE and the interpolation tables of the fuel consumption and the exhaust emissions. Only mechanical components of the ICE are modeled in this package.
6. *Environments:* Two sub-packages are included in this package: the *Cycle* package providing different cycle models for the determination of the operation cycle and the *Ambient* package with different ambient models. The cycle models are implemented with interpolation tables.
7. *Examples:* This package contains the different concepts of vehicles.

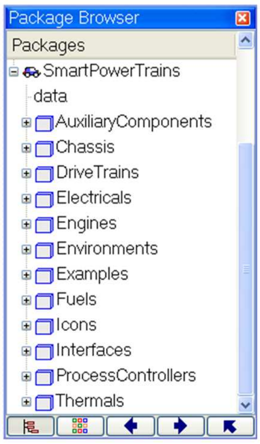

Figure 1: The package browser of the *SmartPowerTrains* library in *Modelica*.

8. *Fuels:* In this package the fuels are defined.
9. *Interfaces:* The *Interfaces* package groups the *Modelica* standard bus connectors, *VehicleInterfaces* bus connectors and advanced bus connectors.
10. *ProcessControllers:* This package contains the different blocks und models for implementing the necessary control algorithms such as the virtual driver, the operating strategy for vehicles, etc.
11. *Thermals:* The *Thermals* package includes the thermal models of the thermal management such as for instance the cooler, the pipeline, the water pump, etc.

The communication between the SPT and SED libraries as well as the independent control of each component allow the highest flexibility in the design of HEV concepts. In the SPT library, the components of the power train and the remaining vehicle components are implemented by algebraic and differential equations whereas the ICE is implemented by characteristic curves. All parameters of the algebraic differential equations are defined by geometrical data of the specific components.

3 The *SmartElectricDrives* library

The SED library uses basic models of electric machines which already exist in the *Modelica* standard library [4]. However, without suitable drive control blocks, these machine models cannot be utilized in a resourceful and easy way. Based on the machine library, the SED library facilitates the modelling of dif-

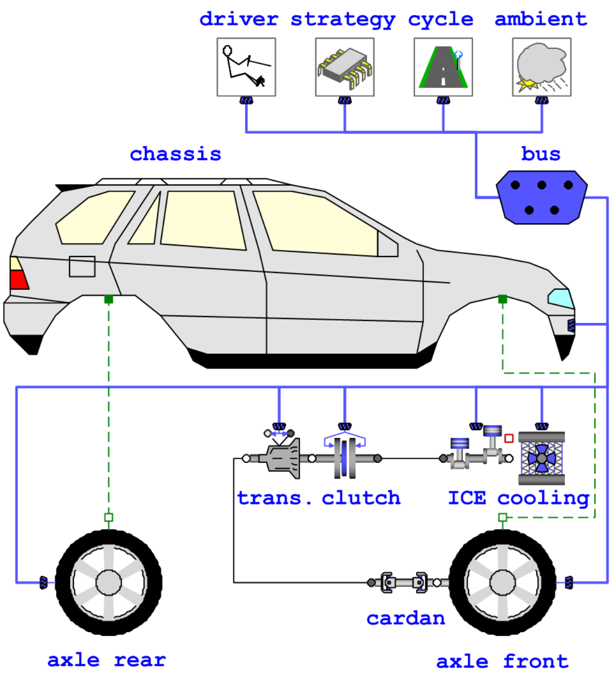

Figure 2: Model of a conventional vehicle.

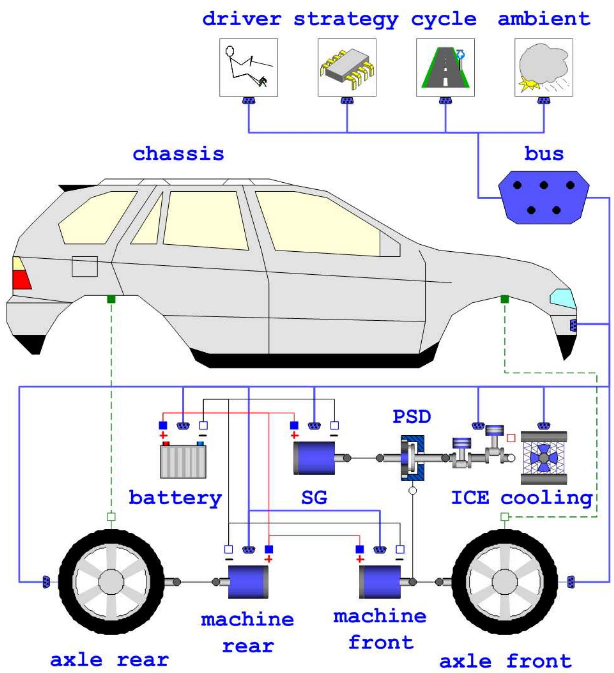

Figure 3: Model of a HEV.

ferent control structures and control strategies. Power electronics and energy storage models are included as well [5].

4 The example of a conventional vehicle

Figure 2 shows a conventional vehicle concept with front axle drive. All vehicle components are connected by a expandable bus connectors. These bus connectors are extended models based on the *VehicleInterfaces* connectors [2]. The mechanical connection of rotational components is indicated with solid lines and circled flanges. The dashed lines show the mechanical connection between the translational components.

In the block `driver` the behaviour of a virtual driver is implemented. The virtual driver controls the state of the following variables: the gas padel position, the brake pedal position, the clutch pedal position and the gear ratio of the transmission. The block `cycle` and the block `ambient` define the desired vehicle velocity and the state of the environment temperature, the pressure, the density, etc. The entire control unit of the vehicle is implemented in the `strategy` block.

The drive train is realised using a conventional `ICE` with a simple `cooling` circuit, a `clutch`, a conventional manual transmission, marked as `trans.`, a `cardan` and the front axle. Both axles include two tire models considering slip, two brake models and a differential model considering losses. The vehicle handling is implemented in the `chassis` model.

5 The example of an HEV

The model of the HEV is based on the *Toyota Lexus* concept. In this HEV concept three electrical machines are used. One electrical machine is used as the starter/generator, indicated as `SG` in Figure 3, the two other machines are traction machines (`machine front` and `machine rear`). The `SG` is coupled with the sun shaft of the power split device (`PSD`) and the `ICE` is coupled with the carrier shaft respectively. The `machine front` is coupled with the `axle front` via the front differential input shaft and the `machine rear` is coupled with the `axle rear` via the rear differential input shaft, respectively.

A `battery` model taken from the SED library is used as the energy source for the electrical components of the HEV model. The intelligent operational strategy is implemented in the `strategy` block. The operational strategy is implemented using the *Modelica_LinearSystems* library. All other components and models of the HEV are the same as in the conventional vehicle simulation.

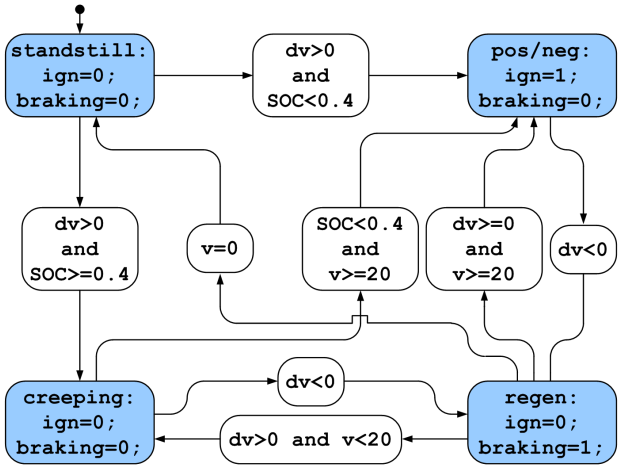

Figure 4: Bubble diagram of the operation strategy

6 The operational strategy of the HEV

For the optimization of the energy consumption of an HEV concept an intelligent operational strategy is essential. The operation of energy sources (ICE, SG and traction machines) in an HEV drive train is monitored and controlled with the intelligent operation strategy. Each energy source is regulated independently based on the state of the entire HEV system.

6.1 Operation modes

In this HEV concept the operation modes of the ICE and the brake is defined as a state algorithm in the intelligent operation strategy. In this HEV concept the operation strategy is implemented using a state algorithm that defines the main operation modes determined by the state of the ICE and the state of the brake. The following variables effect the ICE state and the brake state: the vehicle velocity, the vehicle acceleration and the state of charge (SOC) of the battery. Figure 4 represents basically the switch logic between the possible modes [6]. This operation strategy has four main modes: the `standstill` mode, the `creeping` mode, the `regen` mode and the `pos/neg` mode. In each mode the ICE state, indicated as `ign` (ignition), and the brake state, indicated as `braking` is defined. The switching between the main modes is shown in Figure 4. The variable `v`, with the non-SI unit km/h, is the vehicle velocity and the variable `dv` is vehicle acceleration.

Standstill mode

If the vehicle is in *standstill*, the vehicle velocity is zero and the ignition of the ICE is off. If the SOC of the battery is low, or the battery and the ICE need to be warmed up, the ignition of the ICE is on and working near the idle speed to facilitate the charging of the battery.

Creeping mode

If the vehicle speed is lower than 20 km/h, the creping mode is active. In creeping mode the operation strategy is devided into three sub-modes:

1. If the desired torque is not large and the SOC of the battery is not below the lower limit, the desired torque is distributed to both traction machines.

2. If the desired torque is very large and the SOC of the battery is above the lower limit, the desired torque is distributed to both traction machines and the SG.

3. If the SOC of the battery is below the lower limit, the ignition of the ICE is on and the battery gets charged.

Pos/neg mode

In `pos/neg` mode the ICE, the SG and the traction machines are operated such way that maximum fuel economy is achived. Depending on the SOC of the battery and the desired torque, the calculation of the distributed torque can be devided into three different submodes: positive power split, parallel drive and negative power split.

1. *Positive power split:* In this sub-mode, the SG is operated as a generator. If the SOC of the battery is below the lower limit, the battery gets charged. As long as the SOC of the battery is not above the upper limit, the battery gets charged. If the SOC of the battery is between the lower and the upper limit, the distribution of the torque is used to achieve higher efficiency of the ICE.

2. *Parallel drive:* If the *parallel drive* mode is active, the vehicle is driven by both traction machines and the ICE. The distribution of the torque is used to achieve higher efficiency of all power sources (the ICE, the front and rear electric machine and the battery).

3. *Negative power split:* If the SOC of the battery is very large, the SG is operated as a motor. In this case the speed of the SG accelerates in the negative direction and the speed of the ICE becomes much lower. If the vehicle velocity is very large, this sub-mode is active.

Regenerative mode

This *regenerative* mode, indicated as `regen` in Figure 4, is active if the brake pedal is applied or the deacceleration of the vehicle is determined. In this case the ignition of the ICE is off, and consequently, the ICE gets stopped. Both traction machines are operated as generators. If the vehicle is in the *regenerative* mode and the SOC of the battery is below the upper limit the battery gets charged.

6.2 Torque distribution

In each operation mode the desired torque (reference system power, P) is distributed. This torque is defined by the virtual driver and by the power split equation (1). In this equation, ω_{ICE} is the speed of the ICE and τ_{ICE} is the torque of the ICE, ω_{SG} is the speed of the SG and τ_{SG} is the torque of the SG, ω_{FM} is the speed of the front traction machine and τ_{FM} is the torque of the front traction machine and ω_{RM} is the speed of the rear traction machine and τ_{RM} is the torque of the rear traction machine. The behaviour of the power split in a planetary gear, `PSD`, in Figure 3, is extracted from [7].

$$P = \omega_{ICE} \cdot \tau_{ICE} - \omega_{SG} \cdot \tau_{SG} + \omega_{FM} \cdot \tau_{FM} + \omega_{RM} \cdot \tau_{RM} \tag{1}$$

7 Sources data

The ICE of both investigated vehicle concepts is a gasoline engine. The following parameters are taken for modeling and parameterizing the ICE [8]: 1.5 cc displacement, 43 kW maximum power at 4000 rpm, 102 Nm maximum torque at 4000 rpm, four cylinders. The fuel consumption map of this ICE is defined according to [9].

The following parameters are taken for modeling and parameterizing the Ni/MH battery of the HEV concept: 1.2 V cell voltage, 6 cells per module, 38 modules, 273.6 V battery package voltage, 6.5 Ah rated capacity.

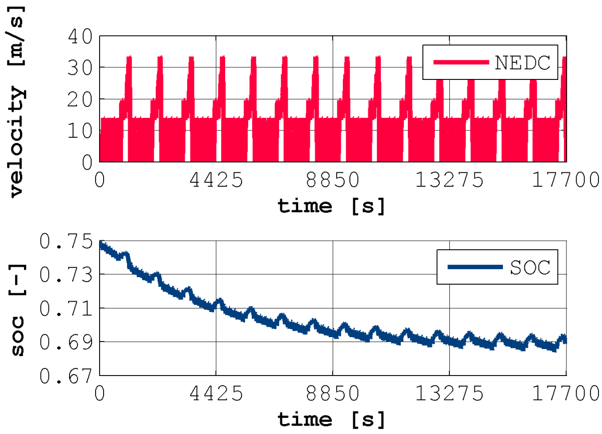

Figure 5: The simulated values of vehicle velocity and battery SOC

Both traction machines are 3 phase alternating current (AC) permanent magnet synchronous machines with an output power of 33 kW. The SG has an output power of 13 kW and is also implemented as an permanent magnet synchronous machine. All electric machines are modeled using the SED library.

The parameters of the front axle and the rear axle (brakes, differentials, inertia of rotational parts, etc.) are defined using [10]. Basically, the *Toyota Prius* component data are used to parameterize the HEV components. The only difference between the proposed HEV concept and the *Toyota Prius* is that the proposed HEV concept is featured with one electric traction machine for each axle. Both traction machines have the same rated power.

8 Energy balance

Investigating the fuel consumption of a vehicle it is necessary to assure that the system energy at the start and the end of a test cycle is the same. In this work both vehicle concepts are simulated in the New European Driving Cycle (NEDC). The new NEDC defines vehicle velocity profiles for one urban drive cycle (UDC) as well as one extra-urban drive cycle (EUDC). The simulation time of the HEV simulation is chosen so long that the SOC reaches a steady state. The upper diagram in Figure 5 shows the vehicle velocity of a vehicle concept driving 15 NEDC. The SOC of the battery is represented in the lower diagram in Figure 5. It can be seen that the SOC of the battery is in balance on the last cycle. This value of the SOC is used as the initial value of the SOC for the fuel consumption calculation in one NEDC.

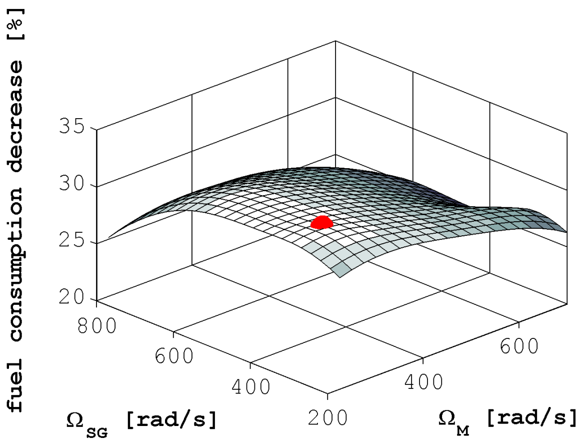

Figure 6: The decrease in the fuel consumption at different nominal speeds of the electric machines in HEV

9 Simulation results

For the optimization of the HEV the nominal operation points of the SG and the front- and rear machine are varied. All other design parameters of this components are kept constant. The nominal speed of the SG, Ω_{SG}, shown in Figure 6, is varied from 200 rad/s to 800 rad/s and the nominal speed, Ω_M, of the front and rear electric machine is varied from 270 rad/sec to 700 rad/s. The size of the used battery is kept constant and the components of the drive train in the HEV are not varied.
Figure 6 shows the simulated results of the HEV with different nominal operation points of the traction machines and the SG. The decrease in the fuel consumption (`fuel consumption decrease`) is given in percent and shows the economic gain compared to the conventional vehicle concept. The possible decrease in fuel consumption is in the range from 20 % to 31.4 % for this varied range of the nominal speeds of the electric machines. The best efficiency of the HEV is at $\Omega_{SG} = 310$ rad/s and $\Omega_M = 298$ rad/s. In this point the decrease in fuel consumption is 31.4 %.
Here the best design point of an HEV concept is calculated and defined. In the simulations a number of NEDCs is used. Therefore, the simulation results can not be applied to other drive cycles. The simulation results are valid for the performed NEDC only.

10 Conclusions

The implemented vehicle simulation allows the determination of the actual fuel consumption and shows evidence of economic savings potential by using alternative drive train concepts – in this case a HEV. Different vehicle drive train concepts and operating cycles can rapidly be analized and tested on fuel consumption and efficiency. Based on the presented results, the design point of the energy sources and the energy consumption of each vehicle component can be calculated and determined. It is shown that the presented libraries can be used to accelerate the design process of innovative vehicle concepts significantly.
This investigation can only be used for the design of vehicles, which are driven in an exact operating cycle such as the exact city drive, the exact reiteration drive, etc.
Based on the calculated decrease in fuel consumption the reduction of energy and emissions of a vehicle on European level can be projected. Focus of the developed process is the realisation of integrated and optimized electric components in autmotive industry. For demonstration purpose selected electrical components such as an SG will be built and integrated in a test vehicle in the near future.

11 Abbreviations

HEV	hybrid electric vehicle
SPT	SmartPowerTrains
SED	SmartElectricDrives
ICE	internal combustion engine
SG	starter/generator
PSD	power split device
SOC	state of charge
AC	alternating current
NEDC	New European Driving Cycle
UDC	urban drive cycle
EUDC	extra-urban drive cycle

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