Implementation of Hybrid Electric Vehicles using the VehicleInterfaces and the SmartElectricDrives Libraries

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Abstract

In this paper different configurations of hybrid electric vehicles summarized in the *SmartHybridElectricVehicles* library were examined and simulated. The presented simulation models and results were created and achieved with *Modelica* using *Dymola*. The models represent different kinds of electric and hybrid electric vehicle configurations. Furthermore, different strategies for operating the hybrid electric vehicles energy sources are provided. The parameters needed for parameterization of the vehicle models were, in case of the electric vehicle, taken from real measurements on the vehicle and vehicle components. For all other models parameters were assumed due to a lack of measurement data. In the library three *Modelica* packages specifically designed for modeling systems including mechanical components, electrical components and control components have been used. These are the *SmartElectricDrives* library, the *VehicleInterfaces* library and the *PowerTrain* library. Due to the object oriented architecture of these libraries all necessary components needed for the implementation and simulation of electric and hybrid electric vehicle configurations are provided and can be reused. Hence, the efficiency optimization of such configurations gets eased by these libraries.

Keywords: simulation, modeling, hybrid electric vehicles, optimization, fuel consumption, operating strategy

1 Introduction

In this contribution a simulation library, the *SmartHybridElectricVehicles* (SHEV) library, will be presented. This library is developed by *arsenal research* with focus on automotive applications, such as electric and hybrid electric vehicles (HEV). The SHEV library is written in *Modelica* language [1] and simulated using the *Dymola* simulation environment. The library is implemented on the basis of the *VehicleInterfaces* (VI) library [2]. Therefore compatibility with all other libraries based on the VI library is ensured. For simulations of the electrical components the *SmartElectricDrives* (SED) library [3] is used. The *StateGraph* library, included in the *Modelica Standard Library* (MSL), has been chosen for modeling the operating strategies of the included vehicles. All mechanical components, such as the power train including transmissions, differentials, axles, etc. are provided by the *PowerTrain* library.

2 Electric Vehicle

An electric vehicle using the above mentioned libraries was modeled as depicted in figure 1. This configuration consists of a front axle modeled in the `driveline` model, a transmission (`trans.`) with one gear and an electric machine (`MG2`). Attention is paid to the energy consumption during a simulated drive cycle. Therefore the quasi stationary model of an electrical excited DC machine with integrated converter and control system, including voltage and current limitation as well as flux weakening from the SED library is used here. For powering the vehicle, an energy source (`battery`) is modeled using a simple idealized battery model included in the SED. This battery model consists of a constant capacitor and a constant internal resistor only. All mechanical components, such as `brakes`, `chassis` and `driveline` are taken from the *PowerTrain* library. They are provided there as ready to use models. For controlling the vehicle velocity (acceleration pedal and brake pedal position) a virtual `driver` model taken from the *PowerTrain* library was adapted. In the controller model (`control.`), different operating strategies are implemented.
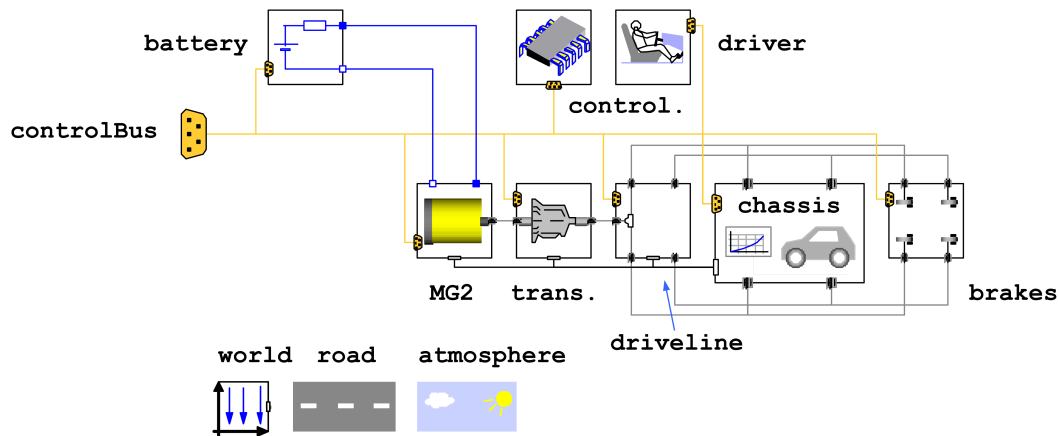
Figure 1: The *Modelica* simulation model of the electric vehicle

2.1 Operating strategies

Three different operating strategies are implemented in the controller of the electric vehicle. These strategies are modeled using the *StateGraph* library of the MSL. All operating strategies control the reference torque of the electric machine. In the first case reference torque of the electric machine is limited between maximum machine torque and zero. The reference torque is restricted to be positive only. In this first operating strategy, only the drive mode of the electric machine is active, no recuperation occurs.

The second operating strategy includes the basic functionality of the first operating strategy with an additional recuperation mode. When the virtual driver actuates the brake pedal, the electric machine is driven in generator mode and the battery is recharged. The reference torque of the electric machine is directly proportional to the brake pedal position. Additionally, vehicle deceleration occurs by mechanical braking.

The third operating strategy is split into two braking mode levels. During the first stage, vehicle deceleration occurs by electrical braking and recuperation only. The battery is charged. If the demanded reference braking torque exceeds the electric machines maximum torque, additional mechanical braking occurs.

In the last two strategies electrical braking and hence electrical recuperation only occurs if the battery state of charge decreases beneath a certain limit. By reaching the upper set limit, electrical braking is switched off to prevent overloading and damaging the battery.

The model of the electric vehicle in figure 1 was simulated with all three operating modes in the *New European Drive Cycle* (NEDC). The state of charge (SOC)
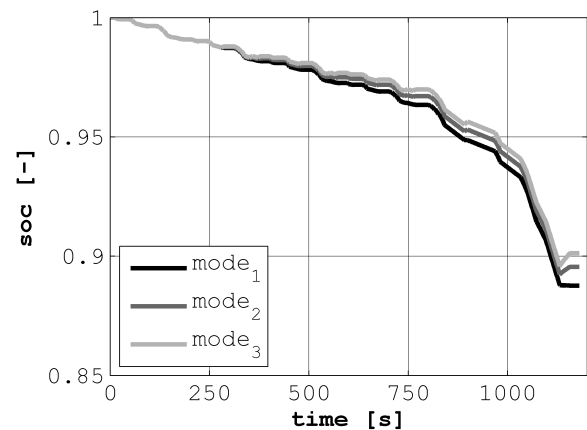

Figure 2: Simulated state of charge of the battery during different operating strategies

of the battery was compared and is shown in figure 2. $mode_1$ represents the first operating strategy without recuperation, $mode_2$ the second operating strategy with proportional recuperation and mechanical braking and $mode_3$ the third implemented operating strategy. Due to a high recuperation ratio $mode_3$ is the strategy with the lowest energy consumption and the highest recuperation potential, respectively. Mainly electrical braking occurs and therefore the battery is recharged more than in any other implemented strategy.

3 Series Vehicle

The series hybrid electric vehicle depicted in figure 3 is modeled based on the electric vehicle model. It contains an additional internal combustion engine (ICE),
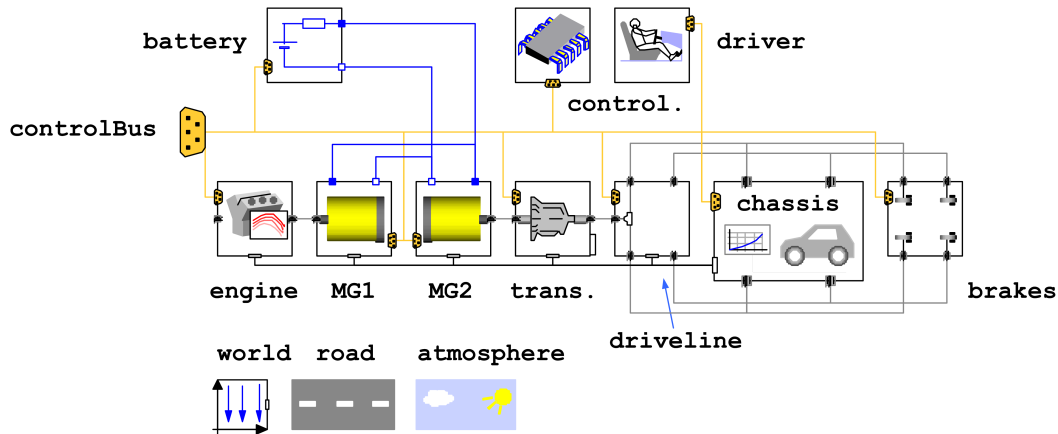
Figure 3: The *Modelica* simulation model of the series hybrid electric vehicle

engine, and an electric machine acting as generator, MG1. The generator is driven by the ICE and is used to charge the battery. The operating maps and the fuel consumption of the ICE are taken from a *Toyota Prius*, according to [4]. The basic drive modes for the MG2 are taken from the electric vehicle. Additionally, different operating strategies for the ICE and the MG1 have been implemented. With the disabled recuperation mode of the MG2 and a disabled generator MG1, the behaviour of the series vehicle is the same as the electric vehicle. For operating the MG1 a shift of the ICE operating point is implemented. It is dependent on the demanded electrical power and, hence, the required torque and speed of the generator. The input value for this operating strategies are the measured motor power and the current generator power, respectively. During a change of the demanded generator power the strategy calculates the most efficient operating point of the ICE regarding fuel consumption. In figure 4 the shifting between two operating points with different demanded generator power is depicted. τ_{max} is the maximum torque and τ_{min} is the drag torque of the ICE. These two operating points of the ICE are those with the highest efficiency and the lowest fuel consumption, respectively. The operating strategy is modeled in the controller (control.) block and based on different control algorithms that will not be described here in detail. The control is independent of size and type of the electric machine as well as of the size of the ICE, which means, that any kind of ICE or machine can be included in the model. Currently the user can choose between two engines and various transient and quasi stationary electric machines in different power classes.
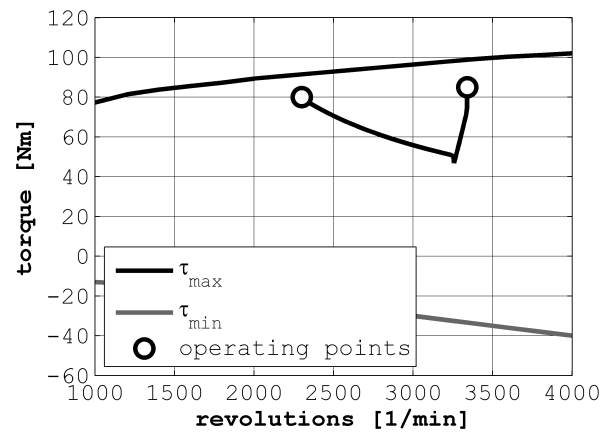

Figure 4: Operating point shift of the internal combustion engine

4 Parallel Vehicle

The parallel HEV, figure 5, contains an ICE, engine, and an electric machine acting as starter/generator, MG1 with two shaft ends. This electric machine is used for starting the ICE, for boosting during driving mode and for recharging the battery. The electric machine, MG1, is coupled on one side with the ICE by a mechanical clutch, C1, and on the other side with the transmission by a mechanical clutch, C2. The mechanical clutch, C2, is embedded in the transmission model (trans. + C2). Using this kind of power train configuration, it is possible to switch between more driving modes. Potential driving modes are driving with the electric machine only, driving with engine and electric machine (ICE and boosting electric machine), start/stop operation of the ICE, load point shifting of
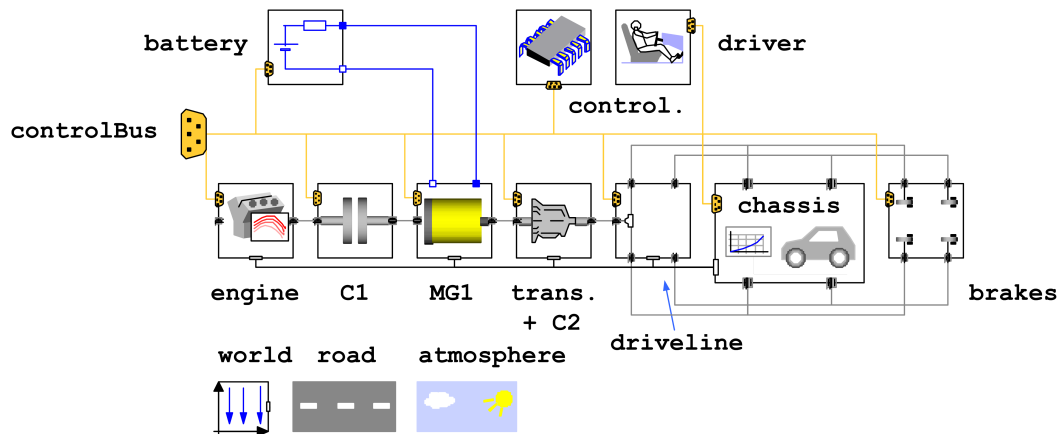
Figure 5: The *Modelica* simulation model of the parallel hybrid electric vehicle

the ICE and recuperation during vehicle deceleration. Exemplarily, two operating strategies for the ICE and the starter/generator are simulated and shown here. The first operating strategy demonstrates the basic operating strategy of a conventional vehicle, only driven by the ICE without recuperation or start/stop operation. The second operating strategy manages the start/stop driving operation of the ICE and the starter/generator. The comparison of the fuel consumption of the ICE is depicted in figure 6, where $\Sigma_{conventional}$ is the fuel consumtion of conventional driving and $\Sigma_{start/stop}$ is the fuel consumption during start/stop operation, respectively. Both vehicle models are simulated in an NEDC operating cycle. The SOC of the battery is balanced in both models at start and end of the simulation, figure 7. One can see, that the state of charge of the conventional vehicle remains unchanged, because no electrical driving or boosting occurs. By contrast the SOC during start/stop operation shows slight changes. During standstill the engine is switched off. By activating the acceleration pedal, the engine is started by the electric machine. While accelerating the engine, the SOC decreases until the engine has reached idle speed. Then the electric machine switches to recuperation mode and the battery is recharged to the upper set limit. Due to a fuel saving during standstill, the vehicle with start/stop operating mode shows a slightly lower fuel consumption as the conventional vehicle.

5 Electric Vehicle Validation

For validation of the HEV models and the SHEV library the electric vehicle was used in a first step, be-
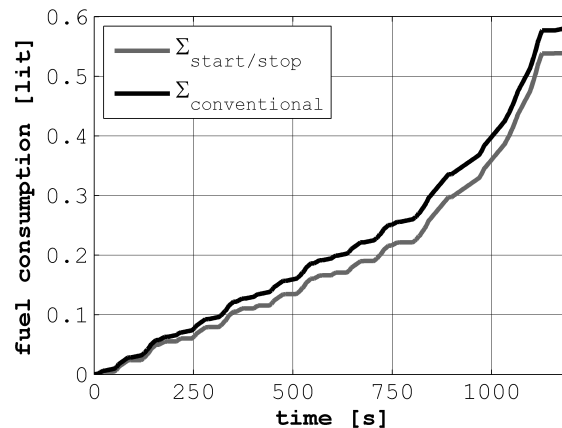

Figure 6: Comparison of the fuel consumption of conventional and parallel hybrid electric vehicle
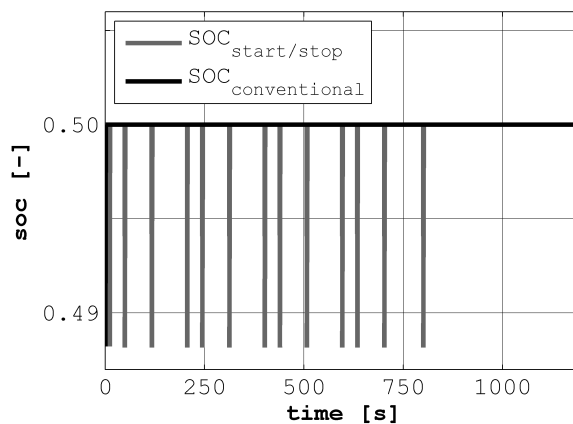

Figure 7: Comparison of the battery SOC of conventional and parallel hybrid electric vehicle

description	value	unit
vehicle mass	1625	kg
front area	2.653	m²
wheel radius	0.285	m
inertia of electric machine	0.2	kgm²
final gear ratio	7.35	-
aerodynamic resistance coefficient	0.407	-
rolling resistance coefficient	0.0144	-

Table 1: Parameters of the chassis model and driving resistances derived from measurements

description	value	unit
nominal armature voltage	162	V
nominal armature current	110	A
nominal excitation current	12.5	A
nominal rotor speed	1340	rev/min
maximum rotor speed	6500	rev/min
warm armature resistance	0.069	Ω
armature circuit inductance	0.00169	H
warm excitation resistance	9.47	Ω
excitation circuit inductance	0.0947	H

Table 2: Parameters of the electric machine according to the Peugeot Partner data sheet

cause measurements on and electric vehicle could be accomplished easily. A *Citroën Belingo electrique* vehicle was chosen for validation, according to [5]. After determination of the component parameters, all single components and the entire electric vehicle model were parameterized. Afterwards simulation results were gathered and compared with measurement results of the real vehicle.

5.1 Parameterization

Every component of the electric vehicle model needs a set of parameters which have to be determined prior to the simulation. They have been derived from numerous measurements on all mechanical and electrical components and data sheets. The data sheet for the electric machine is taken from a *Peugeot Partner Electric* vehicle which has the same as the *Citroën Berlingo Electrique*, according to [6]. For the parameterization of the chassis model and the driving resistances, freewheeling curves of the electric vehicle were determined. Out of these measurements parameters listed in table 1 were calculated and used for the simulation.

For a detailed battery simulation a dynamic battery model was developed at arsenal research, whereas for the simulation and validation of the entire electric vehicle power consumption the more simplified idealized model was used. The parameterization of both battery models, linearized and dynamic, is based on measurements on the real vehicle battery using a standardized charging/discharging test cycle. Throughout this investigation it was possible to determine the parameters of the battery.

The electric machine as described in the data sheet according to [6] was parameterized with the values listed table 2.
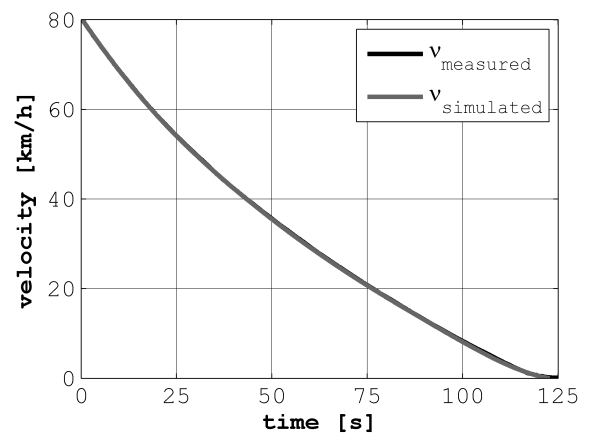

Figure 8: Comparison of the measured and simulated freewheeling curve of the electric vehicle

5.2 Model Validation

The validation of the electric vehicle model was executed first on component level and then regarding the complete vehicle. All mechanical and geometrical parameters, the electrical parameters of the electric machine and the battery as well as the overall power consumption of the entire electric vehicle were determined. The vehicles driving resistances such as aerodynamic and rolling resistances have been calculated based on the measured freewheeling curve. For validating the electric vehicle resistance model the simulated freewheeling curve is compared with the measured one in figure 8. The very small difference between the real measured and the simulated freewheeling curve allows the assumption, that the driving resistances have been chosen in an accurate way.

For validation of the vehicles power train, the electrical excited DC machine, the DCDC converter and the battery model are validated. For modeling the electric machine a torque controlled quasi stationary
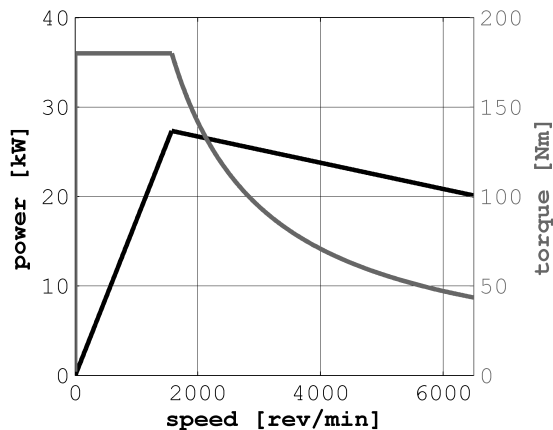
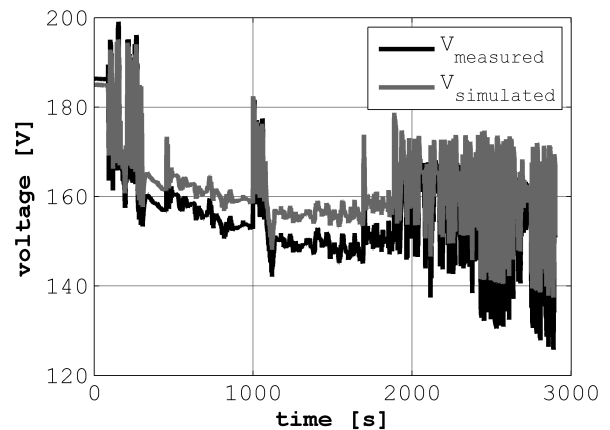Figure 9: Power and torque curves of electric machine

Figure 10: Mesured and simulated battery voltage

model, taken from the SED library, was used. The electric machine is driven by a reference torque and the simulation covers the entire admissible electric machine speed range. The maximum feasible inner electric torque and the mechanical output power in dependence on the electric machine speed is depicted in figure 9. This parameterization is based on the electric machine manufacturers data sheet and shows good congruence with the measured values.

Using measurement results of the voltage, current and temperature gathered during road test procedures, the complex battery model was parameterized. The measurement results were recorded during a ride through the city of Vienna, Austria. For the battery model and the entire electric vehicle validation the measured curents were used as reference signals. The measured, $V_{measured}$, and simulated, $V_{simulated}$, battery voltages are depicted in figure 10. The deviation of the voltages is assigned to the fact that some cells of the real battery were slightly damaged. Though, the overall voltage error of less then 5% is still in an acceptable bandwidth and shows the applicability of the used models.

6   Conclusions

The presented vehicle simulations allow the determination of the energy and fuel consumption as well as the identification of the economic savings potential by integrating alternative vehicle drive train concepts. Using the developed SHEV library different HEV concepts and operating strategies can be analyzed and tested very quickly . Based on the developed vehicle models different potential concepts have been identified and analyzed under different application scenar-

ios. A significant acceleration of the development process of HEV drive train concepts and technologies can be achieved and effort can be reduced. The achievable improvements of a HEV concept highly depend on the specific driving cycle and the boundary conditions, e.g. driving time without recharging possibilities, recharging time during standstill periods, recharging during recuperation, recharging during load point shifting of the ICE operating point, etc. Therefore, these boundary conditions should be defined prior to the simulations to assure simulation results that can match the real system behaviour in a satisfying way. Furthermore, already small changes in the control strategy can have big influence on the overall energy consumption. Also these steps of development can be simulated by means of this library in a rather easy way.

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Definitions, Acronyms and Abbreviations

SHEV	*SmartHybridElectricVehicles*
HEV	hybrid electric vehicle
VI	*VehicleInterfaces*
PT	*PowerTrain*
SED	*SmartElectricDrives*
MSL	*ModelicaStandardLibrary*
NEDC	*New European Drive Cycle*
SOC	state of charge
ICE	internal combustion engine