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Modelling of Hybrid Electric Vehicles in Modelica for Virtual Prototyping

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Modelling of Hybrid Electric Vehicles in Modelica for Virtual Prototyping

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Abstract: This paper presents a Modelica library made for the simulation of Hybrid Electrical Vehicles (HEVs). The library consists of vehicle models, component models and models of surrounding systems. An overview of the models within the library is given and some models are described more in detail. The major purpose of the vehicle models is to predict vehicle characteristics, especially fuel consumption, for a given vehicle and driving cycle. Modelica has been found useful for the simulation of HEVs.

1 Introduction

Environmental concerns and the decrease in cost of electrical components make *Hybrid Electrical Vehicles (HEVs)* more and more competitive. The major difference between conventional vehicles and HEVs is the presence of a buffer for temporary storage of energy in HEVs. The buffer enables regenerative braking and makes the *Primary Power Unit (PPU)* more or less decoupled from the wheels. This gives a potential for reducing fuel consumption and emissions.

Prototyping is necessary for the design and evaluation of HEVs. It is very expensive and time consuming to build real prototypes. Virtual prototyping (computer simulation) is therefore an almost necessary complement. The aim of this paper is to describe a library, developed in Modelica, whose purpose is to evaluate HEVs. In the future, the library can be extended with more components and configurations.

Modelica [1] is a language for modelling physical systems. It is a standard proposed by an international association. Modelica can handle problems in different areas, e.g. mechanics, electricity, chemistry, fluid dynamics and control theory.

The total system of an HEV is very complex. To achieve reasonable computation time, fairly simple models should be used. Another reason for using simple models is that fewer parameters are needed. It will be easier to update models in the future if fewer parameters are used. A rule of thumb when modelling is to use a model that is as simple as possible but still sufficiently accurate.

2 Modelling of different HEV configurations

HEVs can be configured in numerous ways. The arrangement, type and size of components result in a huge number of combinations. The most common way to categorize HEVs is by using the definitions of series and parallel HEVs. In series HEVs, there is no mechanical connection between the PPU and the wheels. In parallel HEVs, a part of the engine torque affects the wheels directly. This nomenclature is not always easy to adopt, however, because some driveline configurations are neither clear series nor parallel ones. For example, the classification of split HEVs is debatable.

The library includes four different types of HEVs. The arrangements are illustrated on a large scale in Figure 1.

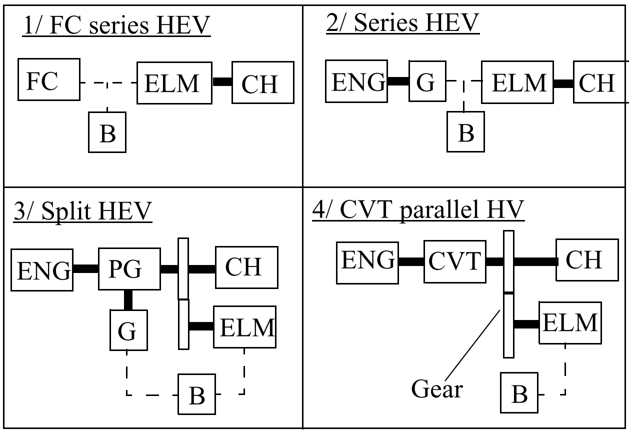

Fig. 1: HEV configurations. Acronyms: *ENG* engine, *FC* fuel cell, *B* buffer, *G* generator, *ELM* electric machine, *CH* chassis, *PG* planetary gear and *CVT* continuous variable transmission. Dashed lines represent electrical connections and continuous lines represent mechanical connections.

The reasons for choosing these HEV types are:

- They are subject to industrial projects. For example, the first HEV ever built for the public market, Toyota Prius, is a split HEV.
- The configurations allow the engine to work at its optimal line.

The reason why a series HEV can work at its optimal line is explained by the fact that the PPU is totally decoupled from the wheels. In other configurations, such as the parallel CVT and split hybrid, a transmission between the engine and wheels makes the engine speed controllable.

The relation between the vehicle and the surrounding systems is illustrated in Figure 2. The environment emits a driving cycle, i.e. speed and slope as functions of time. The driver controls the vehicle in such a way that the desired speed is managed. Figure 3 shows the implementation of a split HEV in Modelica.

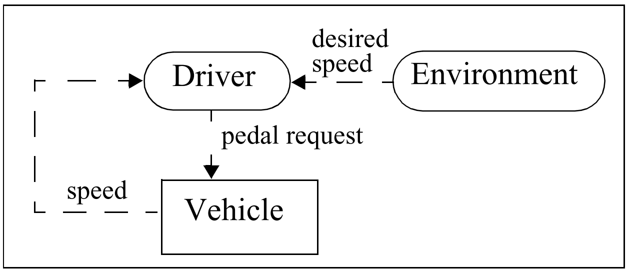

Fig. 2: The relation between the vehicle and the surrounding systems.

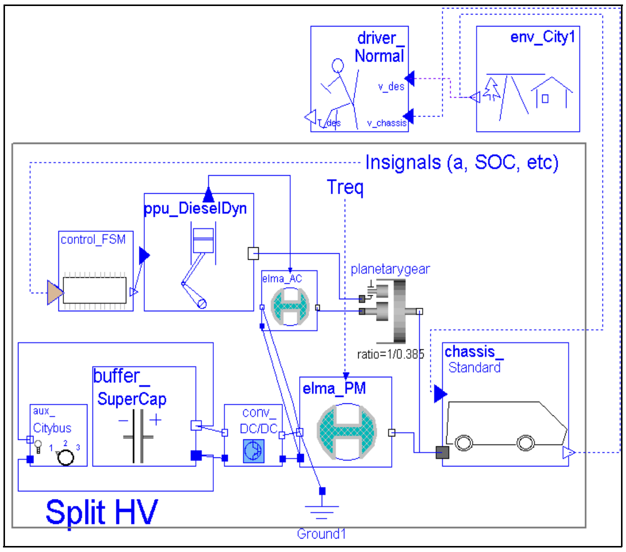

Fig. 3: Modelica model of a split HEV.

2.1 Example of simulation of an HEV

This section presents an example of a simulation of a series HEV. The vehicle has a fuel cell as the primary power unit and a super capacitor as the buffer. A city bus is chosen as an example. Information about the component sizing is given in Table 1 and the layout is illustrated in Figure 4. It is interesting to note that the required PPU size, expressed as maximum power, is about half that of a conventional bus. This is explained by the fact that the buffer assists in heavy accelerations. When the vehicle decreases in speed, power is regenerated into the buffer. The buffer might seem to be oversized with respect to power. The explanation is that the specific energy of the super capacitor is crucial with regard to sizing. The driver controls the target torque of the electric motor. If the driver demands braking, the desired motor torque will be negative. If the desired torque exceeds the torque limit of the motor at braking, a mechanical brake in the chassis will assist. The mechanical brake also assists when the vehicle stands still.

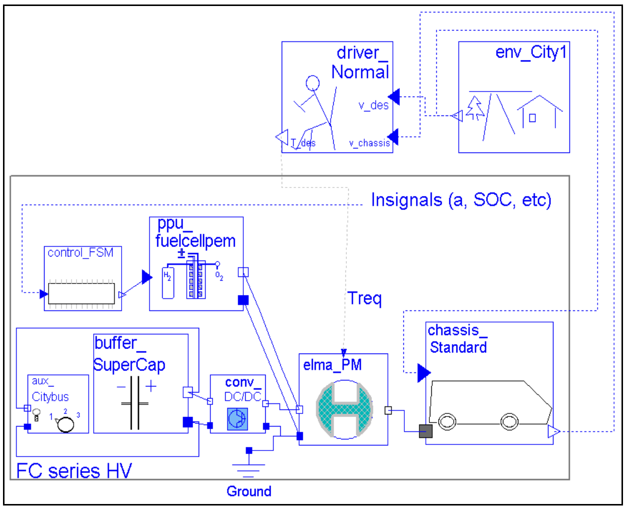

Fig. 4: Modelica model of a fuel cell HEV.

Table 1: Component sizes in the fuel cell HEV.

COMPONENT	SIZE; MASS	MAX POWER; ENERGY
Chassis (with propulsion units)	6; 17600 kg	
Fuel cell	2; 200 kg	100 kW; -
Motor	5; 200 kg	250 kW; -
Super capacitor	8; 500 kg	900 kW; 7.5 MJ

The driving cycle is a part of an urban city bus route and is plotted as speed as a function of time in Figure 5. Figure 6 also shows the cycle but with speed versus position instead of time. Many starts and stops are characteristic for the driving cycle. This makes an HEV more interesting. In this case, the vehicle manages to follow the desired speed almost exactly. Figure 7 shows how *State Of Charge (SOC)* in the buffer and motor temperature change during the driving cycle. It can be seen that the SOC increases at braking and decreases at acceleration. Figure 8 reflects the control of the PPU by comparing the power from the PPU to the power demand from the chassis. According to the simulation, the fuel consumption is 0.2 kg hydrogen/km (the energy density of hydrogen is three times higher than the energy density of diesel). This result is valid for this particular combination of vehicle and driving cycle.

The HEV model in Figure 4 uses 287 variables, 12 states and 80 parameters. This reflects the complexity of the model. Examples of states are: vehicle speed, SOC, temperature of the electric machine and power from the fuel cell.

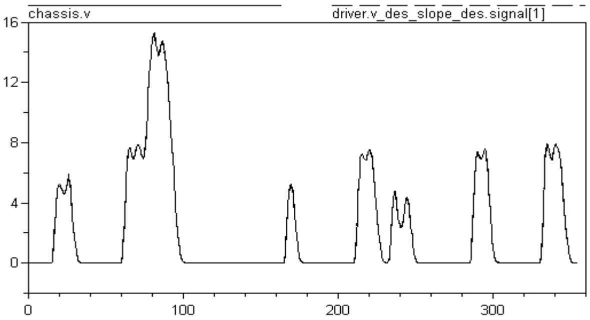

Fig. 5: Driving cycle. Speed [m/s] versus time [s].

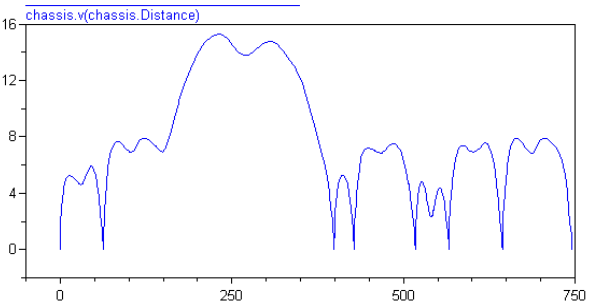

Fig. 6: Driving cycle equal to driving cycle in Figure 5 but with speed [m/s] versus position [m]

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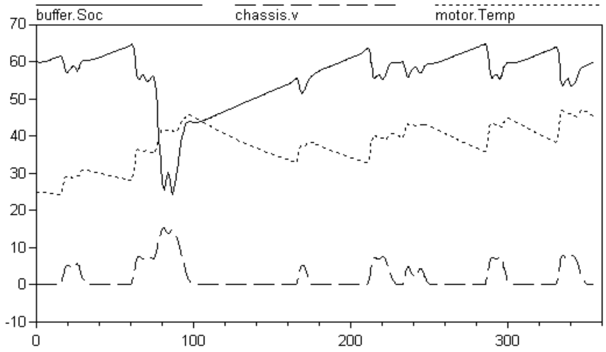


Fig. 7: SOC [%] (continuous line), motor temperature [Celsius] (dotted line) and vehicle speed [m/s] (dashed line) versus time [s].

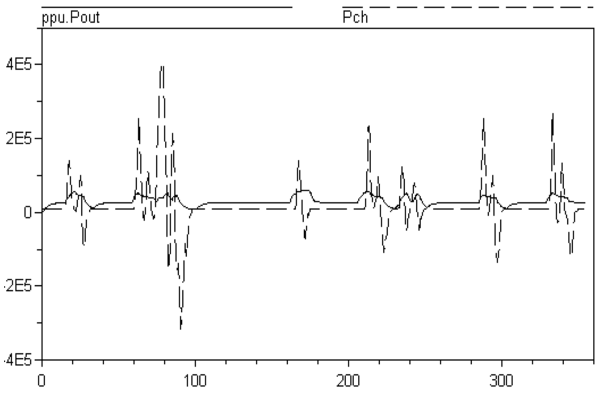


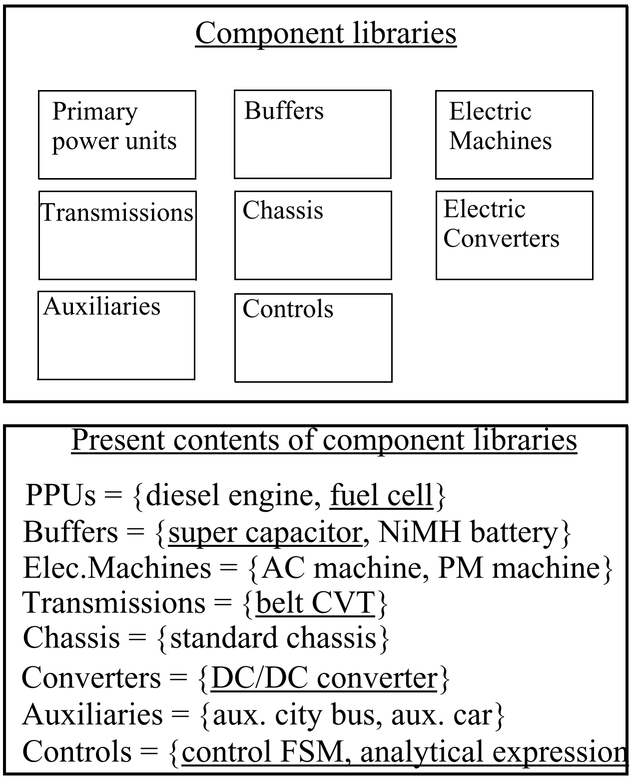
Fig. 8: Power from PPU [W] (continuous line) and power demand from chassis [W] (dashed line) versus time [s].

3 Modelling of components in HEVs

One major principle in modelling a component has been to make it as simple as possible to change its size. This is achieved by a SIZE parameter, which is included in most components. A change of the SIZE parameter affects some of the other parameters in a component model such that the component model behaves as though it has another size. When the SIZE parameter in a component model is changed, the total mass of the vehicle is changed automatically. Another principle has been to use physical parameters and to tune them in such a way that the model behaves similarly to an existing component. For example, the inner resistance in the battery model is defined such that the efficiency of the battery model is similar to a real battery.

Some component models are described more in detail in this paper (underlined in Figure 9). In the described component models, parameters (constant during simulation) are in upper case letters and variables (changing during simulation) are in lower case letters.

Figure 9 shows the structure of the component model library. The library can be expanded to include more models in the future. The graphical interface makes it very easy to replace a component model in a vehicle model, e.g. replace a battery model with a super capacitor model. This is done by a “drag and drop procedure”.



PPUs = {diesel engine, fuel cell}
Buffers = {super capacitor, NiMH battery}
Elec.Machines = {AC machine, PM machine}
Transmissions = {belt CVT}
Chassis = {standard chassis}
Converters = {DC/DC converter}
Auxiliaries = {aux. city bus, aux. car}
Controls = {control FSM, analytical expression

Fig. 9: Structure of component library. *AC* stands for alternating current, *PM* stands for permanent magnet and *DC* stands for direct current. When possible, a component uses sub-models that are included in the standard Modelica library.

Table 2: Number of internal states and number of parameters in the component models.

COMPONENT MODEL	**NUMBER OF INTERNAL STATES**	**NUMBER OF PARA-METERS**
AC machine	5	27
Auxiliaries	0	1
Chassis	2	20
CVT	3	10
DC/DC converter	0	2
Diesel engine	2	6+data map
Fuel cell	2	16
NiMH battery	3	26
PM machine	5	30
Super capacitor	3	12

Table 2: Number of internal states and number of parameters in the component models.

3.1 Model of fuel cell

A fuel cell is an electrochemical device that combines hydrogen fuel and oxygen from the air to produce electricity, heat and water. Fuel cells operate without combustion, so they are virtually pollution free. In theory, a fuel cell can operate at much higher efficiencies than internal combustion engines, but auxiliary systems such as pumps and compressors reduce the efficiency. The efficiency of a fuel cell is approximately 50%. The fuel cell itself has no moving parts, and the fuel cell is thus a quiet and reliable source of power. Individual fuel cells are normally combined into a *stack*. The number of fuel cells in the stack, i.e. the number of cells in series, determines the total voltage. Major disadvantages of fuel cells are high capital cost and difficulties in handling the fuel. For example, hydrogen, gasoline and methanol are proposed as fuel.

Figure 10 illustrates the major idea of the model. Three efficiencies have been defined: the efficiency of fuel delivery η_{fuel}, the internal efficiency of a fuel cell η_{cell}, the efficiency related to parasitic losses and electrical conversion η_{elsyst}. The model is strongly influenced by [2]. The SIZE parameter represents the number of stacks in the system. The transient performance, i.e. how fast the fuel cell can change power, is expressed by low pass filtering the desired power

P_{des}. The total power output from the fuel cell system is P_{out}.

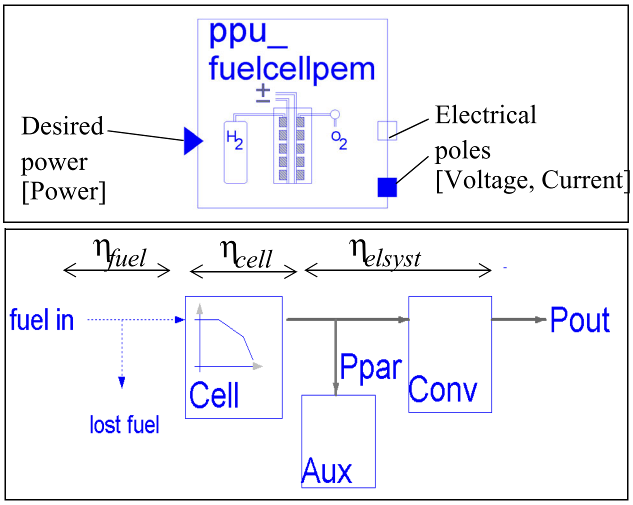


Fig. 10: Model of fuel cell. *Aux* represents auxiliary systems and *Conv* represents a DC/DC converter.

Eq. 1 to Eq. 4 describe how total power output P_{out}, desired power P_{des}, power produced in one cell P_{cell} and normalized power p are calculated and related to each other.

$$P_{out} = filter(P_{des}) \tag{EQ 1}$$

$$P_{out} = P_{cell} \cdot N_{SER} \cdot N_{STACKS} \cdot \eta_{elsyst} \tag{EQ 2}$$

$$P_{cell} = U_{cell} \cdot I_{cell} \tag{EQ 3}$$

$$p = \frac{P_{cell}}{P_{NOMCELL}} \tag{EQ 4}$$

The voltage in a cell U_{cell} decreases with p according to Eq. 5 and Eq. 6.

$$U_{cell} = \eta_v \cdot E_{CELL} \tag{EQ 5}$$

$$\eta_v = \left(1 + \sqrt{\left(1 - \frac{p}{PPC}\right)}\right)^2 \tag{EQ 6}$$

The calculation of the instantaneous fuel consumption Fc [g/s] and total efficiency of the system η_{tot} are described by Eq. 7 to Eq. 14.

$$Fc = \frac{P_{out} \cdot H_{FUEL}}{\eta_{tot}} \tag{EQ 7}$$

$$\eta_{tot} = \eta_{cell} \cdot \eta_{fuel} \cdot \eta_{elsyst} \tag{EQ 8}$$

$$\eta_{cell} = \eta_v \cdot \eta_{MAX} \tag{EQ 9}$$

$$\eta_{fuel} = U_{FUEL} \cdot \eta_{REF} \tag{EQ 10}$$

$$\eta_{elsyst} = \eta_{EL} \cdot \eta_{par} \tag{EQ 11}$$

$$\eta_{par} = \frac{P_{out}}{P_{out} + P_{par}} \tag{EQ 12}$$

$$P_{par} = \alpha_1 \cdot P_{TOT} + \beta_0 \cdot P_{TOT} \cdot p \tag{EQ 13}$$

$$P_{TOT} = P_{NOMCELL} \cdot N_{SER} \cdot N_{STACKS} \tag{EQ 14}$$

Table 3: Notations for the fuel cell model.

NOTATION	DESCRIPTION
α_1, β_0	Parameters that determine parasitic losses
E_{CELL} [V]	Maximal voltage in a cell
η_{EL} [-]	Efficiency of converter
η_{MAX} [-]	Maximal efficiency in one cell
η_{REF} [-]	Efficiency of reformer
H_{FUEL} [g/J]	Mass of hydrogen to achieve one Joule of energy
U_{FUEL} [-]	Amount of hydrogen utilized
N_{SER} [-]	Number of cells in series
N_{STACKS} [-]	Number of stacks
$P_{NOMCELL}$ [W]	Nominal power from a cell
P_{par} [W]	Parasitic losses
PPC [-]	Part of maximal theoretical power that is used in cell
P_{TOT} [W]	Nominal power from fuel cell system
U_{cell} [V], I_{cell} [A]	Voltage and current in a cell

The model is general and fairly simple and can therefore easily be adjusted to imitate almost any fuel cell system by changing the parameters. The system presented here meets the targets set by DOE (the Department Of Energy in USA) [3]. The targets are an efficiency of 44% at full load, an efficiency of 55%

at part load and a response time of three seconds. Part load is defined as 25% of full load and response is defined as how quickly power is changed from zero to maximal load. Figure 11 compares the model with the DOE targets.

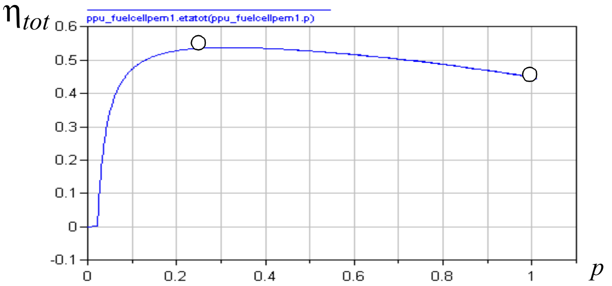


Fig. 11: Efficiency (η_{tot}) versus normalized power p. The continuous line represents the model and the circles represent DOE targets.

3.2 Model of DC/DC converter

The task of a DC/DC converter is to adjust the output voltage of an electrical device. In an HEV the operating voltage of the buffer may be different from the voltage range desired in the electrical machine. This is an example of a situation in which a DC/DC converter becomes useful. DC/DC means that a direct current is transformed to a direct current with another voltage and current. Unfortunately, this power transformation is related to losses. The power losses in a DC/DC converter are accurately described in [4]. The model takes into account the dominant losses according to [4].

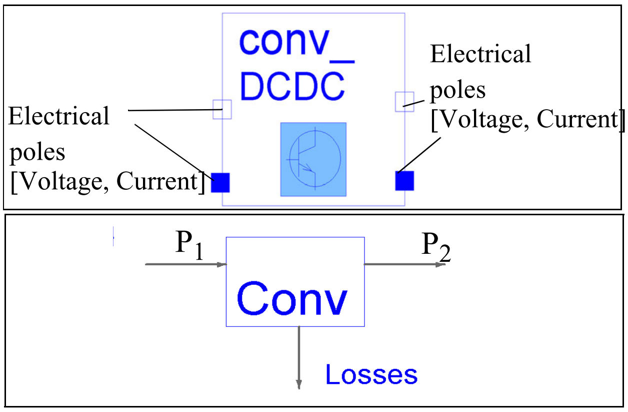


Fig. 12: Model of DC/DC converter.

Eq. 15 to Eq. 18 describe the model. Eq. 16 and Eq. 17 imply that a higher quotient between voltage on outside and inside results in a lower efficiency η.

$$P_{losses} \approx (1-\eta) \cdot P_1 \qquad \text{(EQ 15)}$$

$$d = \left| 1 - \left| \frac{v_2}{v_1} \right| \right| \qquad \text{(EQ 16)}$$

$$\eta = \eta_{MAX} - d \cdot KD \qquad \text{(EQ 17)}$$

$$P_2 = \begin{cases} P_1 \cdot \eta & (P_1 > 0) \\ \dfrac{P_1}{\eta} & (P_1 < 0) \end{cases} \qquad \text{(EQ 18)}$$

Table 4: Notations for the converter model.

NOTATION	DESCRIPTION
d	Ratio of switching
P_{losses} [W]	Total losses in the converter
η_{MAX}, KD	Parameters determining the efficiency of the converter
P_1, P_2 [W]	Power in and power out from the converter
v1, v2	Voltage on outside and inside

The parameters in the model are adjusted in such a way that the efficiency is close to 95%.

3.3 Model of super capacitor

Super capacitors are an energy storage technology ideally suited for applications that need repeated bursts of power for fractions of a second to several minutes. High specific power but low specific energy is characteristic.

The model illustrated in Figure 13 is influenced by [5]. The parameters are taken from the data sheet for an existing super capacitor “PC2500” described more in detail in [6]. The SIZE parameter represents the number of super capacitors in parallel. Due to the definition of a leaking current I_{leak}, the model takes into account that the capacitor is discharged even when no current is requested. R_I is the internal resistance, C is the capacitance, I_{capPos} is the requested current and U_{cap} is the voltage of the capacitor.

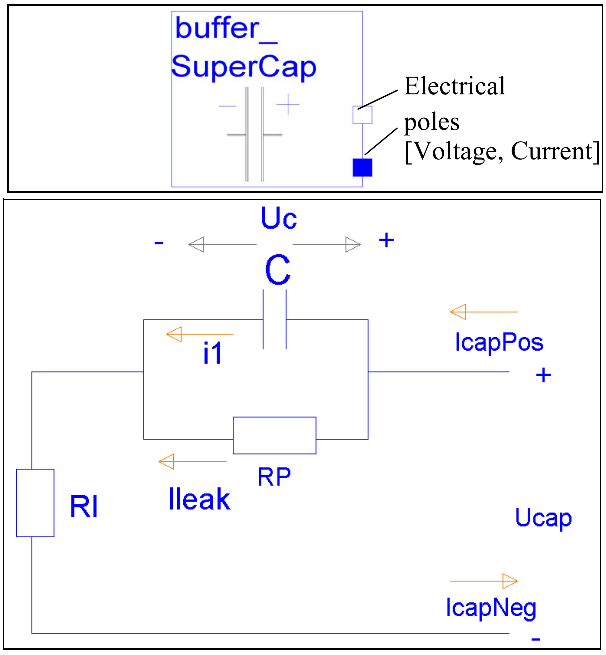


Fig. 13: Model of super capacitor.

Eq. 19 to Eq. 24 describe current and voltage laws for one capacitor. Most of the terms are described in Table 5.

$$I_{capPos} = i_1 + I_{leak} \tag{EQ 19}$$

$$I_{capPos} + I_{capNeg} = 0 \tag{EQ 20}$$

$$U_c = \frac{Q}{C} \tag{EQ 21}$$

$$\dot{Q} = i_1 \tag{EQ 22}$$

$$I_{leak} = \frac{U_c}{R_P} \tag{EQ 23}$$

$$U_{cap} = U_c + R_I \cdot I_{capPos} \tag{EQ 24}$$

The requested power P is positive at discharge and is negative at charge. The following equations define the energy level in the super capacitor *Soc* and the efficiency η:

$$Soc = \frac{U_c - U_{MIN}}{U_{MAX} - U_{MIN}} \cdot 100 \tag{EQ 25}$$

$$\eta = \frac{|P|}{|P| + P_{Losses}} \tag{EQ 26}$$

$$P = U_{cap} \cdot I_{capPos} \tag{EQ 27}$$

$$P_{Losses} = I_{Leak}^2 \cdot R_P + IcapPos^2 \cdot R_I \tag{EQ 28}$$

Table 5: Notations for the super capacitor model.

NOTATION	**DESCRIPTION**
U_c [V], i_1 [A]	Internal voltage and internal current in capacitor
Q [C]	Charge in capacitor
R_P [Ohm]	Resistance determining the leaking current I_{leak}
U_{MIN}, U_{MAX} [V]	Permitted minimal and maximal voltage in capacitor

Figure 14 shows the simulation of a charge process of a super capacitor model. Power is taken from the capacitor and increases with time. The upper curve corresponds to *Soc* starting at 70%. The lower curve corresponds to a start value of 30%. The curves show that efficiency is dependant on *Soc* and decreases with power. The simulated efficiency corresponds to data given in [6].

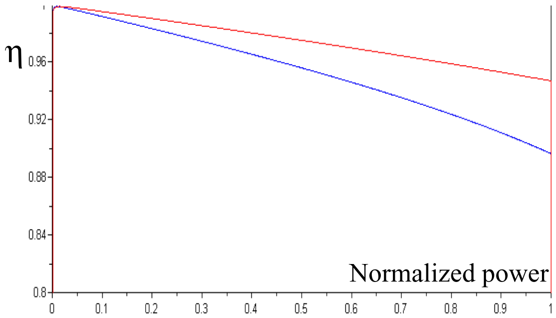


Fig. 14: Efficiency for super capacitor versus normalized power for different start values of Soc. Normalized power is defined as requested power divided by maximum possible power.

3.4 Model of belt CVT

A *Continuous Variable Transmission (CVT)* allows the speed ratio to change in a step less way. This allows the engine to operate on its optimal line. One disadvantage is that a CVT has a lower efficiency than a conventional transmission.

A belt CVT, illustrated in Figure 16, is used here. The clutch slips when the torque is too high, which results in poor efficiency. The efficiency of the belt η_{belt} is a function of utilized torque, see Figure 15. The SIZE parameter determines the mass and maximum torque capacity T_{MAX} of the CVT.

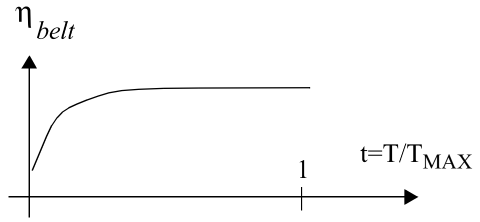


Fig. 15: Efficiency of CVT belt as function of utilized torque *t*.

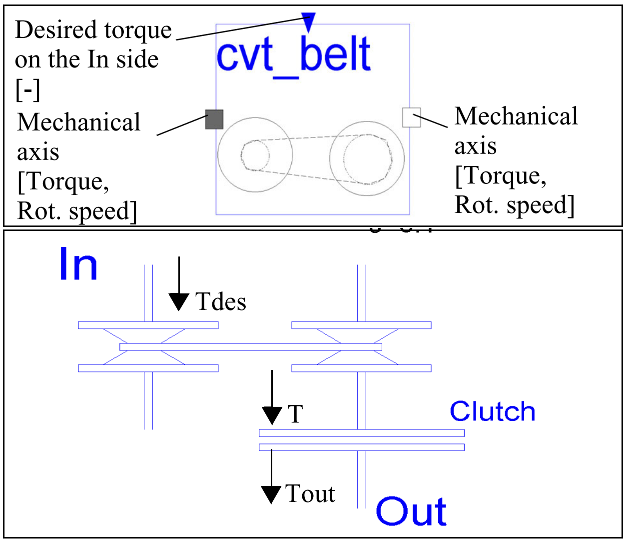


Fig. 16: Model of belt CVT.

Eq. 29 to Eq. 33 describe how the output torque T_{out}, the ratio of the CVT r_{cvt} and the total ratio r_{tot} are calculated and related to each other. The filter function in Eq. 30 reflects the fact that there is a response time in the system.

$$T_{out} = min(T_{MAX}, T) \tag{EQ 29}$$

$$T = filter(T_{des}) \cdot r_{cvt} \cdot \eta_{belt} \tag{EQ 30}$$

$$r_{cvt} = min(r_{MAX}, max(r_{MIN}, r_{tot})) \tag{EQ 31}$$

$$r_{tot} = \frac{w_{In}}{w_{Out}} \tag{EQ 32}$$

$$\eta_{belt} = B + \frac{A - B}{1 + e^{t \cdot C}} \tag{EQ 33}$$

Table 6: Notations for the belt CVT model.

NOTATION	DESCRIPTION
A, B, C	Constants determining the efficiency of the belt
r_{MAX}, r_{MIN} [-]	Maximum and minimum ratio
T_{des} [Nm]	The desired torque at the In side
T_{MAX} [Nm]	The maximum torque that the CVT can transmit
w_{IN}, w_{OUT} [Rad/s]	Speed at IN and OUT side

The parameters in the model are adjusted in such a way that the maximum efficiency is close to 90%.

3.5 Model of chassis

The chassis model takes into account resistance in the longitudinal direction. This resistance is mainly a result of vehicle mass, air and tire rolling resistance. From the SIZE parameter, it is possible to choose chassis models that correspond to the following vehicles: Volkswagen Golf (small passenger car), Volvo V70 (large passenger car), Toyota Previa (minibus), Chassis corresponding to a mini truck, Volvo FL6 (large truck), Volvo B10M (city bus), Volvo FL20 (heavy truck). The brake is necessary to make the vehicle stand still if a slope is present or to assist if the capacity of the electric braking in an HEV is exceeded. The traction force $F_{traction}$ is limited to prevent the wheels from skidding. Figure 17 shows the layout of the chassis. Only components from the standard Modelica library are used. The gear efficiency depends on vehicle configuration. A low gear efficiency corresponds to the use of a differential while a high gear efficiency corresponds to the use of wheel motors.

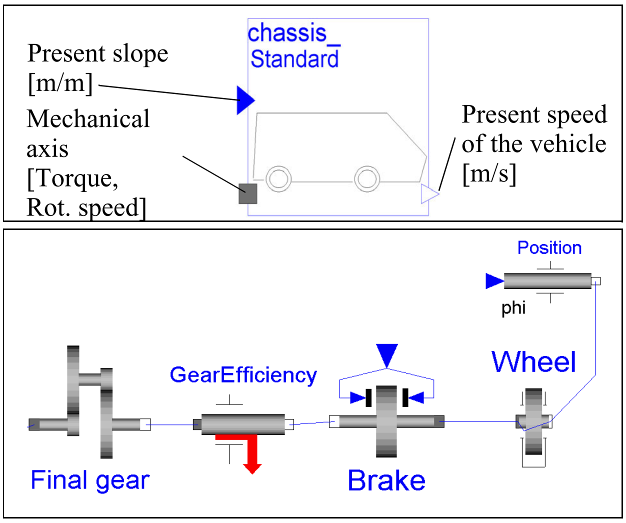


Fig. 17: Model of chassis.

Eq. 34 to Eq. 37 describe the dynamics of the vehicle in the longitudinal direction. $F_{traction}$ calculated in Eq. 37 affects the wheel component in Figure 17.

$$MASS = MASS_{DRIVELINE} + MASS_{COACH} + MASS_{FRAME} + MASS_{PASSENGER} \quad \text{(EQ 34)}$$

$$F_{traction} = \begin{cases} F_{trnom} & (|F_{trnom}| < F_{TRMAX}) \\ F_{TRMAX} \cdot \varsigma & (|F_{trnom}| > F_{TRMAX}) \end{cases} \quad \text{(EQ 35)}$$

where

$$\varsigma = sign(T_{Wheel})$$

$$F_{trnom} = \frac{T_{Wheel}}{R_{WHEEL}} \quad \text{(EQ 36)}$$

$$F_{traction} = F_{acc} + F_{air} + F_{roll} + F_{slope} \quad \text{(EQ 37)}$$

where

$$F_{acc} = MASS \cdot a \cdot \gamma$$

$$F_{air} = \frac{C_D \cdot A \cdot \rho_{AIR} \cdot v^2}{2}$$

$$F_{roll} = K_F \cdot N \cdot \left(1 - \frac{1}{e^{0.5 \cdot v}}\right)$$

$$F_{slope} = MASS \cdot G \cdot \alpha$$

$$N = MASS \cdot G \cdot \cos(\operatorname{asin}(\alpha))$$

Table 7: Notations for the chassis model.

NOTATION	DESCRIPTION
α [m/m]	Road surface grade
a [m/s^2]	Acceleration of vehicle
C_DA [m^2]	Air resistance of vehicle
$F_{traction}$ [N]	Force between ground and wheel
F_{trnom} [N]	Traction force if vehicle is not skidding
γ [–]	Factor for influence of rotational inertias of driven axle
G [m/s^2]	Constant of gravity
K_F [-]	Coefficient of rolling resistance
MASS [kg]	Total mass of vehicle
N [N]	Normal force between vehicle and ground
v [m/s]	Speed of vehicle

3.6 Model of controller

The controller controls the power from the PPU. How this should be done is debatable and the aim of research. In the simulations presented in this paper, a *Finite State Machine (FSM)* is used as the control algorithm. A more detailed description of how this works is found in [7]. In practice, the control model interprets data maps that contain information on the FSM.

Another candidate to control the power produced in the PPU is to use an analytical expression. Eq. 38 proposes how this power can be calculated. The expression is influenced from [8].

$$\frac{d}{dt}(P_{PPU}) = \frac{(Pch + K(Soc_{tar} - Soc) - P_{PPU})}{\tau} \quad \text{(EQ 38)}$$

Table 8: Notations for Eq. 38.

NOTATION	DESCRIPTION
P_{PPU}	Power requested from PPU
Soc_{tar}	Desired Soc
K, τ	Parameters

4 Modelling of surrounding systems in HEVs

The surrounding systems are more abstract models and are necessary to be able to make the simulation. The driving cycle in particular is extremely important for the result of a simulation.

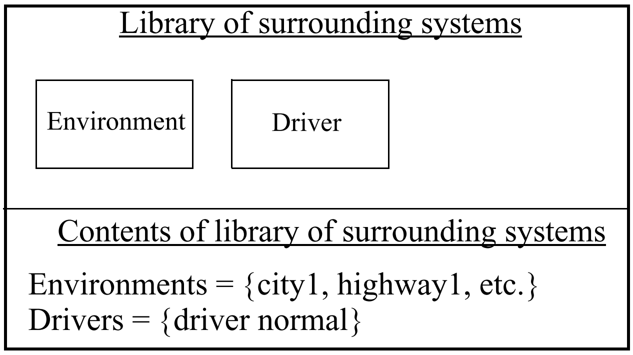


Fig. 18: Library of surrounding systems.

4.1 Model of environment

The environment model interprets data maps that contain the driving cycles. Speed and slope are described as functions of time. Alternatively, speed and slope can be described as functions of position.

4.2 Model of driver

The driver model is simply a PID regulator that forces the vehicle speed to be equal to the desired speed, i.e. the speed that is given in the driving cycle. Desired speed and vehicle speed are inputs and requested traction torque is output.

5 Conclusions and future work

Modelica has been found suitable for modelling and simulating an HEV. Properties such as object orientation, non casual modelling and an equation based syntax have been found useful during the development of the models presented in this paper. Much modelling work would have been saved if more public model libraries for Modelica had been available. Unfortunately there is a lack of such libraries today.

In the future, additional vehicle configuration and component models should be developed. More detailed models that take more phenomena into account should also be developed. Validation of the virtual HEV models towards existing vehicles should also be done.

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NOTATION

NOTATION	DESCRIPTION
CVT	Continuous Variable Transmission
Data map	A set of numbers presented in a vector or matrix
Normalized power	Requested power divided with maximum power that can be delivered to/from the device
Soc [%]	State of charge in an energy buffer