Modelling of Components for Conventional Car and Hybrid Electric Vehicle in Modelica

Master's thesis
performed in **Vehicular Systems**

by
Johanna Wallén

Reg nr: LiTH-ISY-EX-3489-2004

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Titel Modellering av komponenter för vanlig bil och hybridbil i Modelica

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Sammanfattning
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Hybrid electric vehicles have two power sources — an internal combustion engine and an electric motor. These vehicles are of great interest because they contribute to a decreasing fuel consumption and air pollution and still maintain the performance of a conventional car. Different topologies are described in this thesis and especially the series and parallel hybrid electric vehicle and Toyota Prius have been studied.

This thesis also depicts modelling of a reference car and a series hybrid electric vehicle in Modelica. When appropriate, models from the Modelica standard library have been used. Models for a manual gearbox, final drive, wheel, chassis, air drag and a driver have been developed for the reference car.

For the hybrid electric vehicle a continuously variable transmission, battery, an electric motor, fuel cut-off function for the internal combustion engine and a converter that distributes the current between generator, electric motor and internal combustion engine have been designed.

These models have been put together with models from the Modelica standard library to a reference car and a series hybrid electric vehicle which follows the NEDC driving cycle. A sketch for the parallel hybrid electric vehicle and Toyota Prius have also been made in Modelica.

Developed models have been introduced into the Modelica library `VehProLib`, which is a vehicle propulsion library under development by Vehicular Systems, Linköpings universitet.

Nyckelord
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Acknowledgment

This is so far the largest challenge during my education! It has been very exciting to do something completely of my own and without distinct answers, but sometimes also very frustrating and difficult. Therefore I would like to express my gratitude to everyone who has assisted and encouraged me during this work. First of all thanks to my examiner Lars Eriksson, who let me perform the work with the master's thesis at Vehicular Systems. My supervisor Anders Fröberg has also been very helpful and has guided me through difficulties. Thanks to Jonas Biteus for valuable help with LaTeX. Thank you, Otto Montell, for all discussions about Modelica and modelling problems and also my other room mate Daniel Claesson for a nice atmosphere in "Skrubben". Also thanks to my opponent Magnus Nilsson for interesting questions, Jan Karlsvärd for discussions about modelling principles, Anna Ighe for valuable comments on my English and my friends and my family for supporting me and showing interest in my work.

Last but not least, I have felt very welcome at Vehicular Systems and the joint breaks have been joyful and with many interesting discussions. The time here has meant a lot to me and I will remember it with joy. Thank you all for many hearty laughs, pleasant moments, your kindness and helpfulness!

Future, here I come!

Contents

Chapter 1

Introduction

1.1 Background to Hybrid Electric Vehicles

The population in the world is growing and also the number of people that can afford a car. One of our biggest environmental problems to solve in the future is to avoid a huge increase in environmental pollutions and the greenhouse effect. Many new ideas and concepts need to be developed, because vehicles driven by fossil fuel are one of the largest contributors to today's air pollution [32]. Another serious problem is the oil which will not be enough for our needs in the future. Therefore we need new developed, different mechanical solutions and also another main energy source, for example vehicles driven by fuel cells or natural gas. These new technologies are yet under development but will not be a commercial alternative for a number of years. In the meantime, or as a good solution, the hybrid electric vehicle, HEV, is an alternative to the conventional car driven by fossil fuel. But why are not the pure electric vehicles, EVs, used to a larger extent? The technique is developed and ready to use! An answer to this question is the limited distance range of an EV. The battery of today has not a storage capacity large enough to make a satisfying travel distance. For example a modern EV can be driven about 40 miles (approx. 65 km) without charging the battery again. With advanced battery technologies as Nickel metal hydride, NiMH, the travel range is expected to increase to 80–100 miles (approx. 130–160 km) [2]. Many believe that when we have improved the storage of the electric energy in the battery, the EV is ready to be used. Others think that the HEV, that was created as a temporary solution to the problem with short trips with the EV, still is one of the best alternatives for improving the increasing fuel economy and greenhouse gas emissions [26].

How do you know that a certain car is a “hybrid”? Well, a hybrid vehicle combines at least two sources of power. A familiar hybrid is the old type of moped, which actually is a combination of power from the engine and the pedals driven by the rider. Submarines are also hybrid, some of them have their energy sources from nuclear and electric power, others from diesel and electric power [24]. A HEV is a cross between a conventional car powered by an internal combustion engine, ICE, and an EV. They are more fuel-efficient than conventional cars and therefore they reduce the air pollution. The main idea is to reduce the fuel consumption, but maintain the performance of the car.

An example is the parallel HEV, which is a combination of an ICE in parallel with an electric motor, EM, and a battery. The ordinary ICE is inefficient at low speeds because the engine runs mostly at idle, where it consumes fuel without driving the vehicle forward. It is then better to use the EM alone at low speeds and at starts and stops. Over let us say 30 km/h the ICE is turned on and runs at a fuel-efficient combination of engine speed and torque. If there is extra energy that is not needed at the time, it is saved in the battery. When extra power is needed, a combination of both the EM and the ICE is used. By this design, you utilize both the advantages of the EM and the ICE and combine them to a more fuel-efficient vehicle.

A HEV has many advantages over an conventional car. The first is the ability to store energy temporary in a battery to be able to use when the need is larger. The ICE can also be used more efficiently at higher loads and therefore contribute to a better usage of the fuel.

Another important thing is that the ICE combined with another power source makes it possible to use smaller ICEs, thus decreasing the fuel consumption and air pollution. Smaller engines are more efficient because they run more often at the combination of high load and speed, which is the most efficient working point. The car also consumes less fuel because it does not have to transport a heavy engine.

The concept of regenerative braking also improves the efficiency, where the EM acts as a generator that brakes the car and converts some of the kinetic energy into electric energy which charges the battery. A HEV must not always have the ICE turned on, when it is not needed the engine can be turned off and save some fuel. Use of the continuously variable transmission, CVT, also contributes to a better environment. It is used instead of a conventional step transmission and makes it possible to choose a suitable continuous gear, which makes the engine able to run at the most efficient operating point all the time [32].

Many of the HEVs today also use advanced aerodynamics to reduce the air drag, use low-rolling resistance tyres and lightweight materials [24]. All this makes a HEV of today able to operate nearly two times more efficient than a conventional car with ICE [2].

1.1.1 Why Modelica in this Thesis?

The modelling language Modelica has a big advantage compared to for example Simulink — it is non-causal and the data flow can take place in both directions. In Simulink the blocks have a predetermined data flow from inputs to outputs [8].

At Linköpings universitet a Modelica library, *Vehicle Propulsion Library* also called `VehProLib`, is yet under development. The aim of the library is to model and analyse powertrains of different configurations. Because vehicle powertrains are multi domain with mechanical, electric, hydraulic, thermodynamic and control systems, Modelica is a very suitable language to use for the library. The library is intended to be usable for both engineers, who want to have a platform for collaboration and component models, and students to learn more about how a powertrain functions and the difference between structures with a set of basic components.

1.2 Purpose of the Thesis

This thesis studies object oriented driveline modelling in Modelica. The purpose is to model a reference car, develop components for a HEV and put them together in a vehicle. The vehicle models shall follow the New European Driving Cycle, NEDC. The components shall be developed according to existing library `VehProLib` and the Modelica standard library can be used when appropriate.

1.3 Thesis Outline

Chapter 2 describes the modelling and simulation tools Modelica and Dymola. The structure and contents of the library `VehProLib` is also presented.

Chapter 3 deals with the modelling of a reference car. Each component of the car is first depicted and if there is no suitable Modelica standard model, the component is modelled in `VehProLib`. All component models are then connected to a reference car, which is tested with the NEDC driving cycle.

In chapter 4 four different hybrid topologies are described, which is followed by a presentation of Toyota Prius and Honda Insight. The components needed for modelling HEVs in Modelica are then depicted and modelled.

Chapter 5 describes modelling of the series HEV, determining of the working point and the control strategy.

In chapter 6 the parallel HEV model in Modelica is presented and modelled, which follows by a Modelica model of Toyota Prius viewed in chapter 7. Some conclusions and proposals for future work are described in chapter 8.

1.4 Sources

The material when learning Modelica, working with the models and writing this thesis have been found mostly on the Internet and in the library. Many articles about Modelica are found on the homepage of the Modelica organization, www.modelica.org. Articles about different hybrid vehicle topologies have mostly been found on the internet site www.elsevier.com/locate/jsaerev, in the SAE article base. The search tool Google has also been frequently used during the work. As a base for this thesis, Nobrant's master's thesis [25] and Strömberg's master's thesis [32] have been used.

1.5 Limitations

In the development of new components and controlling the whole vehicle, it is difficult to find a balance between model accuracy, simulation complexity and available working time. The aim with the modelling work in this thesis has been to concentrate on the qualitative behaviour, avoid the most complicated theories and try to create models with comparable complexity. The models can therefore be more developed and even more complex and dynamic, but in this work the borderline is to model the most important behaviours in a satisfactory way that characterizes the main properties.

The HEV components in `VehProLib` have model limitations. The ICE with fuel cut-off mode is only adjusted to the HEV requirements. The use in an ordinary car when fuel cut-off is wanted is not investigated in this thesis. The zero speed case in the fuel cut-off mode is not either fully verified. The two battery models have no physical state of charge, SOC, limit and therefore the controller needs to remain the SOC level within 0 % to 100 %. The table battery is charged with positive current and the physical battery is charged with positive voltage. The batteries need to be connected and treated differently and they are not replacable with each other. The physical battery is not fully tested because of shortage of time.

Although three HEVs have been modelled, only the series HEV has been controlled to follow the NEDC driving cycle.

The reference car and the series HEV are also assumed to only drive forward with $v \geq 0$ and is unable to turn.

Chapter 2

Modelica

Modelica is a very young language used to model physical systems. The language is object-oriented, non-causal[1] and the models are mathematically described by differential algebraic equations, DAE[2] [6]. The language suits modelling of large and complex systems and its design also supports a development of libraries and exchange of models [25]. With Modelica it is possible to both model in high levels by composition (use icons that represent models of the components, connect them with connectors and set parameter values in dialogue boxes) and at a much more detailed level by library component modelling with equations [8].

The design work with Modelica started in September 1996 by a small group of about fifteen persons who had experience of modelling languages and DAE models. A year later the first version of Modelica was released, but the first language definition came in December 1998. Modelica version 2.0 has been used in this thesis. It was available in December 2000 and is developed by the non-profit organization Modelica Association [6] with seat in Linköping, Sweden.

2.1 Dymola

Dymola is developed by Dynasim in Lund, Sweden, and the name is an abbreviation for *Dynamic Modelling Laboratory*. The tool is designed to generate efficient code and it can handle variable structure Modelica models. It finds the different operating modes automatically and the user does not have to model each mode of operation separately. Dymola is based upon use of Modelica models, which are saved as files.

[1] The equations are expressed in a neutral form and consideration of computational order is not necessary [8].

[2] A DAE equation is a system of differential equations and algebraic (static) equations of the form $F(\dot{z}, z, u) = 0$ where u is the input signal [21].

The tool contains a symbolic translator for the Modelica equations and the compiler generates C-code for the simulation. When needed the code can also be exported to Simulink. The features of Dymola are experimentation, plotting and animation.

Dymola has two different modes; the modelling and the simulation mode. In the modelling mode the models and model components are created by “drag and drop” from the Modelica libraries and equations and declarations are edited with the built-in text editor. The simulation mode makes it possible to do experiments on the model, plot results and animate the model behaviour.

In order to simulate the model, Dymola uses Dymosim, *Dynamic Model Simulator*. It is an executable, which is generated by Dymola and is used to perform simulations and compute initial values. It also contains the code that is required for continuous simulation and handling of events. Model descriptions are transformed into state space descriptions by Dymola and these are solved by the integrators in Dymosim. The result of the simulation can in turn be plotted or animated by Dymoview. Dymosim can be used in other environments too, though it is especially suited in combination with Dymola.

The work in this thesis is made with Dymola 5.0. The information above and more details about Dymola can be found in [5].

2.2 Translation and Simulation of a Modelica Model

At the homepage of the Modelica organization, www.modelica.org [6], the way from a Modelica model to the simulation is described. The model with its physical description and equations is translated into a model described with hybrid[3] DAE equations. The simulation starts by a numerical integration method to solve the DAE. If- and when-clauses and discrete variables are kept constant, so the solution is a continuous function of continuous variables. During the following integration, the integration is halted if some of the relations change their values. At that event, the DAE is a set of algebraic equations which is solved for the real, boolean and integer unknowns. Then the numerical integration of the DAE is restarted again.

2.3 Modelica Standard Library

Modelica standard library contains pre-defined components in several fields. It also contains constants, connectors, partial models, model

[3]A hybrid DAE may have discontinuities, variable structure or is controlled by a discrete-event system [6].

components and `type` and `interface` definitions in order to facilitate the own modelling design. The library is, as a part of the ordinary language revision, improved and revised. Modelica Association expects that many informal standard base classes and libraries will be developed in many different fields and these will later on be a part of the Modelica standard library. For example the libraries `VehProLib` by Eriksson [10], `VehicleDynamics` by Andreasson [19] and `Hevlib` by Hellgren [13] are under development. The Modelica package of today, which is free, can be downloaded from the website of Modelica organization, http://www.Modelica.org/library/library.html.

2.4 VehProLib

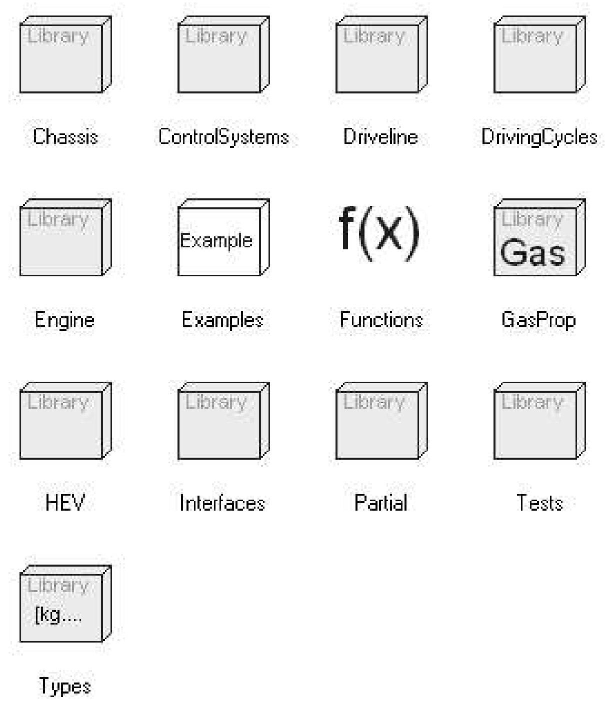


Figure 2.1: *The structure of the Modelica library `VehProLib`, developed at Linköpings universitet.*

At Vehicular Systems, the Department of Electrical Engineering at Linköpings universitet, the Modelica library `VehProLib` is yet under development under the direction of associate professor Lars Eriksson.

The aim of the library is to provide functionality to study and analyse the performance of different powertrain configurations [10]. The models cover a wide range from zero dimensional in-cylinder models[4] to longitudinal models for complete vehicles.

The present structure with directories and subdirectories in `VehProLib` can be viewed in figure 2.1. The content in each directory is shortly described below.

`Chassis` contains models for the air drag, chassis and also a wheel model with slip curve from a table.

- `Data` contains tables used by models in the Chassis directory.

`ControlSystems` The models for engine and vehicle control are collected in this directory. An engine control unit, λ-controller and idle controller are the present models.

- `Components` Component models used by ControlSystem models.

`Driveline` contains a final drive, ideal differential, gearbox and a driver built as a PI-controller.

- `Components` Component models used by the Driveline models.

`DrivingCycles` Tables for driving cycles. At present it only contains the NEDC driving cycle during 600 s. Other cycles, as the US06 or FTP75 cycle, can be added if desired. The tables contain requested vehicle speed, gear and clutch signal.

`Engine` contains different subdirectories with components which covers the range from single cylinder components and single cylinders to mean value, MVEM, engines.

- `Cylinders` contains whole cylinder models; both single cylinder models with valves and MVEM cylinder models.
- `Data` collects cylinder parameters used by the cylinder models and also engine data for Toyota Prius, Saab 9-5 and Volvo S40.
- `Examples` contains different engines ready to use. A thermodynamic engine, different engines with single cylinders or multi cylinders and also MVEM engine models.
- `Functions` Functions used by the engine models, as for example Vibe to describe the engine combustion and Woschni to calculate the heat transfer in the cylinders [14].

[4] A single zone cylinder model leads to a zero dimensional cylinder model. There is no separation of the gases within the single zone cylinder. You cannot interpret the volume because the content is regarded as the same everywhere, therefore the cylinder model has a zero dimensional volume.

- `Mechanical` contains pure mechanical components used by the engines as a crank, piston and cylinder geometry.
- `Partial` contains different models used by the complete cylinder and engine models as cylinder flows, pins and an engine data base.
- `Restrictions` Here standard, linear and isentropic restrictions are collected together with throttle and valve models.
- `Sources` Models used as sources by and in combination with the engines as a flow source, tank and ambient conditions like temperature and pressure.
- `Volumes` contains different control volumes and open cylinder models.

`Examples` The example models show the behaviour and connection between different models, like a reference car and a test bench for the MVEM engine.

`Functions` Functions used by the library models.

`GasProp` contains different gas models which is used by the MVEM engines.

- `GasData` Here datas for the gases are collected.
- `Partial` contains a base class for gas properties and a base model for calculations of the gas properties.

`HEV` contains different models used by HEVs like battery, EM and converter.

- `Components` Component models used by the HEV models.

`Interfaces` Interfaces used by different models in the library.

`Partial` Partial models used by the library.

`Tests` This directory is used during the development of the library. The models shall be used to control if new changes in the library still give working models.

`Types` contains types used in the library.

Chapter 3

Modelling the Reference Car

The driveline converts the combustion energy to kinetic energy to propel the vehicle and it is desirable to do it as efficient as possible in order to decrease the fuel consumption and increase the performance of the car. Therefore it is important to be able to build models of drivelines, simulate the behaviour and test new ideas in a simpler way than with a vehicle prototype [25].

To be able to compare different HEV topologies to each other and see if they are more fuel-efficient than an ordinary vehicle, a reference car is needed. The aim is to model a car like SAAB 9-5.

3.1 Components

The components come many of them from Nobrant's master's thesis, see [25] for a more detailed description. When possible, models from Modelica standard library have been used. In order to facilitate the description of the different driveline components and how they interact with each other, see the modelled reference car in `VehProLib` in figure 3.1.

3.1.1 Internal Combustion Engine — `VehProLib.Engine.Examples.MvemEngine`

The power source in the vehicle is the ICE and it is controlled by the driver by the gas pedal. As output you have the torque as a result of the combustion and the angular rotation in radians.

During the work, the decision has been taken not to use Nobrant's engine model, because in `VehProLib` there are already different de-

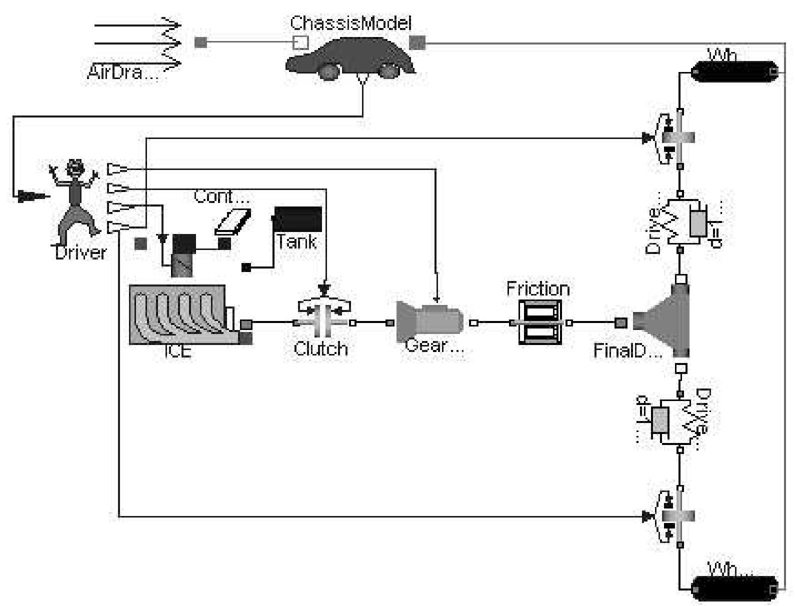


Figure 3.1: *The reference car modelled with components from Modelica standard library, Nobrant's master's thesis [25] and models developed in `VehProLib`.*

veloped engine models, which are more accurate. The MVEM engine `VehProLib.Engine.Examples.MvemEngine` is used instead of the multi cylinder model[1] because the vehicle follows the NEDC driving cycle during 600 s. Here the qualitative behaviour is being studied and the MVEM engine is good enough for this purpose, it also facilitates a faster simulation.

A tank, developed by Montell [22], is connected to the engine in order to measure the fuel consumption. The `MvemEngine` also contains an idle controller and λ-controller, both developed by Montell.

In figure 3.2 it is shown how the `MvemEngine` is fundamentally coupled to other components. The step symbolizes the driver who first is driving the car at idle and after 100 s with full gas. The tank coupled to the engine measures the fuel consumption and the inertia is coupled to the engine because otherwise any torque would be produced by the engine.

[1] A multi cylinder model describes the combustion in every single cylinder and supplies the cycle-to-cycle variations, thus the simulation takes a much longer time. The MVEM engine computes a mean value for the whole combustion and does not take the incylinder variations into account.

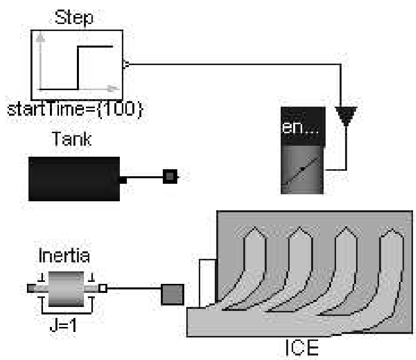


Figure 3.2: *Modelica model of* `MvemEngine` *and how it basically is related to other components.*

Figure 3.3 shows the engine speed in revolutions per minute. First at idle running, the speed decreases from the initial value of 3000 rpm because of the zero gas. The idle controller controls the speed to be about 800 rpm. At time 100 s when there is full gas, the speed increases fast up to a maximum value of approximately 8000 rpm.

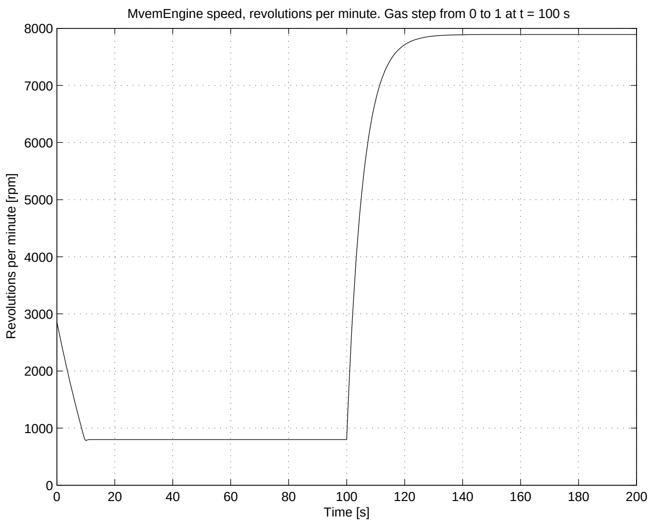


Figure 3.3: `MvemEngine` *speed, revolutions per minute, the initial value is 3000 rpm. The gas is zero at the beginning and the engine speed is decreasing. The engine then performs idle running due to the idle controller. At time 100 s there is full gas and the speed increases to a maximum value.*

The torque produced by the `MvemEngine` is presented in figure 3.4. In the beginning there is a negative torque because the engine speed is decreasing by having no gas and the produced work becomes negative due to friction and pumping losses. At time 100 s, when the engine is running at full gas, the torque increases very fast and then levels away when the vehicle reaches the maximum speed.

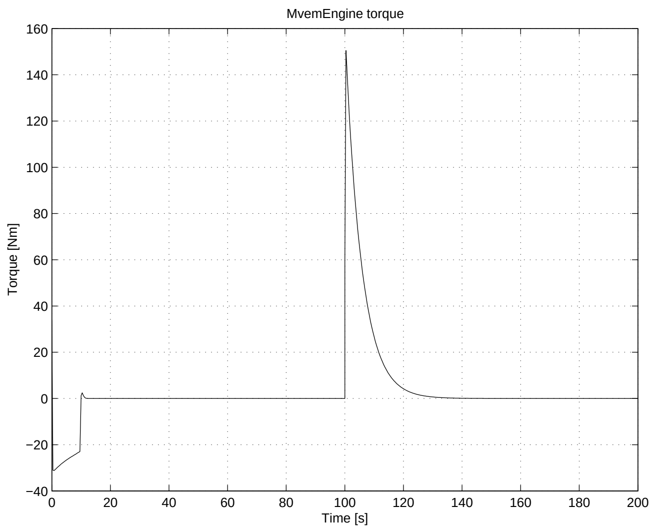


Figure 3.4: *The torque produced in the* `MvemEngine`*. From time 0 to 100 s there is no gas, from time over 100 s there is full gas.*

3.1.2 Clutch — `Modelica.Mechanics.Rotational.Clutch`

The clutch is used in order to connect and disconnect the engine to the remaining driveline parts, which are fastened together with the gear box.

The Modelica standard library clutch, `Modelica.Mechanics.Rotational.Clutch`, is a friction clutch. The clutch disc connects the flywheel of the `MvemEngine` and the gear box input shaft and the driver controls the clutch via data from the NEDC driving cycle. See [25] for verification of the Modelica standard clutch.

3.1.3 Manual Gear Box — `VehProLib.Driveline.Gearbox`

Use of a gear box in the vehicle makes it possible to change the gear ratio r between the engine and the wheels and by that expand the working range [25]. Input signal to the gear box model is the torque T_e and angular velocity ω_e from the engine via the clutch. Output from the gear box is $T_{gearbox} = rT_e$ and $\omega_{gearbox} = \frac{1}{r}\omega_e$.

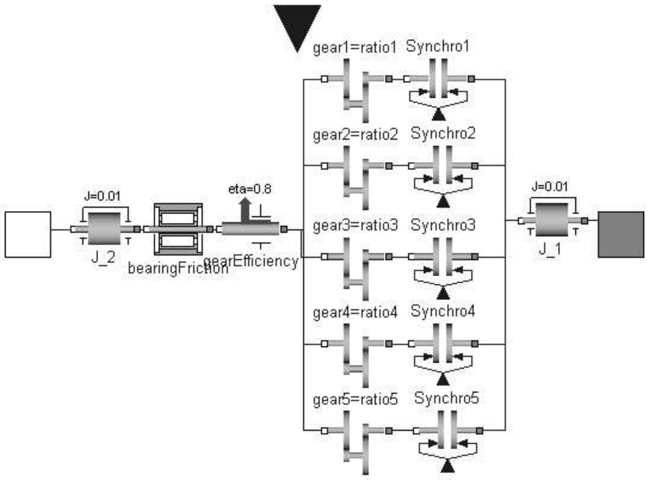


Figure 3.5: *The manual gear box model* `VehProLib.Driveline.-Gearbox`.

In this thesis, Nobrant's model has been used, see figure 3.5. It models the changing gear ratio and tries to describe the effects of the synchronization between the different gears, see [25]. He has also made some simplifications in order to get lower complexity and faster simulation, for example the same gear efficiency and bearing friction for all gears.

The signal into the gear box from the NEDC table is shown in figure 3.6.

3.1.4 Propeller Shaft

The purpose of the propeller shaft is to transmit the rotational energy from the driveline to the drive shaft. Ideally it is stiff, but in reality the propeller shaft is an elastic connection between the gear box and the final drive. According to Nobrant [25] the assumption has been made that the propeller shaft is stiff in comparison with the elasticity in the drive shaft. It means that the torque from the gear box is the same

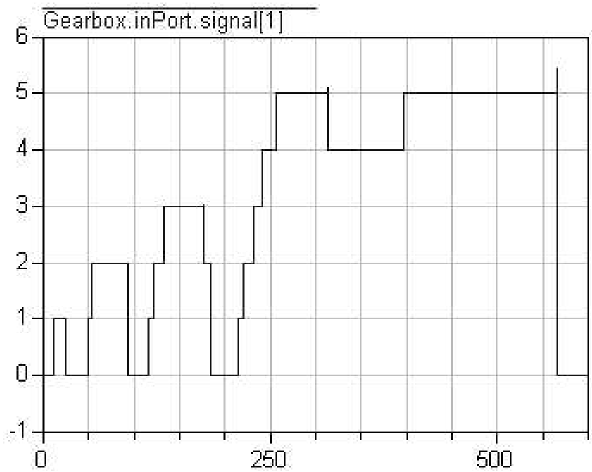


Figure 3.6: *Signal into the gear box from the NEDC driving cycle. X-axis shows time [s] and y-axis the gears.*

as the torque out from the propeller shaft. The gear box and the final drive can therefore be directly connected.

3.1.5 Final Drive — `VehProLib.Driveline.FinalDrive`

The final drive transmits the power to the wheels and slows down the rotational speed of the transmission [23]. It also permits the driven wheels to have different speeds, although they are connected to the same driveline. This is for example very useful when the vehicle drives in a curve and the inner wheel drives a shorter distance and therefore also has a lower speed compared to the outer wheel [25].

The final drive modelled by Nobrant consists of an automotive differential combined with the ideal gear `Modelica.Mechanics.Rotational.IdealGear` from Modelica standard library, see figure 3.7. With the differential `VehProLib.Driveline.IdealDifferential` equal torque is applied to both wheels. The gear ratio gives the relation between the turning angles of the wheels. See [25] for evaluation and tests of the final model.

3.1.6 Drive Shaft — `Modelica.Mechanics.Rotational.SpringDamper`

The drive shaft is the connection between the final drive and the wheels. It is often the part of the driveline that is the weakest, because it is

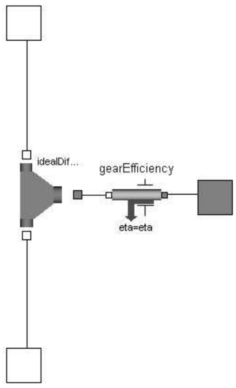


Figure 3.7: *Final drive modelled from Nobrant's master's thesis [25] with an ideal differential and a gear.*

relatively easy and cheap to repair. Therefore it has a flexibility which gives driveline oscillations and the drive shaft cannot be considered as stiff. As in [25] the drive shaft has a stiffness k and an internal damping c and the assumption that there is no friction has been made. The drive shaft is modelled with Modelica's spring and damper from the standard library, `Modelica.Mechanics.Rotational.SpringDamper`.

3.1.7 Brake — `Modelica.Mechanics.Rotational.Brake`

In order to be able to stop the car, it is equipped with brakes. Nobrant has used Modelica's standard brake, `Modelica.Mechanics.Rotational.Brake`, so is also done in this thesis. The brake is a disc brake, where the brake blocks are pressed against the disc and the braking friction torque increases. See [6] for a full description and [25] for verification of the brake.

3.1.8 Wheel — `VehProLib.Chassis.Wheel`

The wheel has contact with the ground and the purpose is to convert the rotational motion to translational motion. Modelling the tyre is very complex and in this thesis a rather simple wheel and tyre model is used, developed by Nobrant [25]. The torque from the brake acts as an input signal into the wheel and output signals are position and force of the wheel.

The wheel is modelled with rolling condition, rolling resistance, longitudinal slip and longitudinal forces. The longitudinal force is a function of the longitudinal slip, in this wheel model implemented as a slip table. There are model limitations, for example are no lateral forces described and the model covers no steering, which makes the vehicle unable to turn [25].

When modelling the rolling resistance, Nobrant has used the model

$$F_{roll} = c_0 + c_1 v \quad \text{where } c_0 = 11 \text{ and } c_1 = 0.3604 \tag{3.1}$$

It is not described how c_0 and c_1 are computed and a split of the constants into known parts is desirable. In order to describe the rolling resistance more precisely, the model [11]

$$F_{roll} = \frac{mg}{2}(f_{fr0} + f_{fr1} v) \tag{3.2}$$

can be used. m and g describes the vehicle mass (1520 kg in this example) and acceleration of gravity respectively. f_{fr0} is the rolling resistance at zero speed, typically about 0.01, and f_{fr1} is a speed dependent component of the rolling resistance, typically about 0.005. This model has two wheels and therefore each wheel only has half of the gravitational force. Equation (3.1) together with equation (3.2) gives

$$\begin{aligned} c_0 &= \frac{mg}{2} f_{fr0} \\ c_1 &= \frac{mg}{2} f_{fr1} \end{aligned}$$

but

$$\begin{aligned} 11 &\neq \frac{1520 * 9.81}{2} * 0.01 \approx 75 \\ 0.3604 &\neq \frac{1520 * 9.81}{2} * 0.005 \approx 37 \end{aligned}$$

Nobrant [25] has not used equation (3.2).

The reference car has too low fuel consumption and the first thing to do is investigating the rolling resistance. During the NEDC driving cycle, the reference car drives 8000 m. With Nobrant's rolling resistance model in equation (3.1), the vehicle consumes approximately 0.459 l fuel during the drive and the fuel consumption becomes quite low with $\frac{0.4592}{0.08} = 5.74$ l/100 km. Using equation (3.2) instead the car consumes 12.2 l/100 km, which is too high, a reasonable result is 7-8 l/100 km. The fuel consumption has a too large change to make it realistic. Investigation of the force components in the wheel shows that the rolling force is far too high — the vehicle reaches a maximum velocity of just 80 km/h when it should drive with 120 km/h. The speed dependent component of the rolling resistance is too large and brakes the car. In [29] the rolling resistance is modelled as a quadratic function and the force lies within a small band. The rolling resistance modelled in equation (3.2) is therefore approximated with $f_{fr1} = 0$ and gives the constant model

$$F_{roll} = \frac{mg}{2} f_{fr0} \tag{3.3}$$

This gives still a too low fuel consumption of 6.34 l/100 km. A possible reason is that the models and components in the reference car can be too ideal and there are more losses in reality. But this fuel consumption is better than 5.74 l/100 km when equation (3.1) was used and therefore equation (3.3) is used in the wheel model.

3.1.9 Chassis — `VehProLib.Chassis.ChassisModel`

There are many different definitions of a car chassis, but in this thesis the chassis just describes the inertia of the vehicle. As described in [25] the sufficient chassis model for a longitudinal driveline model is to consider the chassis to be a sliding mass following Newton's second law and neglect the gravitational force. The sliding mass `Modelica.Mechanics.Translational.SlidingMass` has been used.

3.1.10 Air Drag — `VehProLib.Chassis.AirDragModel`

When driving a car, the air drag brakes the car and for example more fuel is needed to reach the desired vehicle speed. Therefore an air drag model is needed in order to simulate a "real" behaviour during the drive.

In [25] the wind velocity v_s in the expression of the braking force from the air drag

$$F_{air} = c_D A \frac{\rho}{2} (v_{vehicle} - v_s)^2$$

has been neglected due to the fact that the influence from the wind is small compared to the vehicle speed $v_{vehicle}$. c_D is a dimensionless aerodynamic coefficient, A is the front area of the vehicle and ρ describes the air density. Compared to [25], where all the constants together are described by the constant c_2, this model has separated the constants.

3.1.11 Driver — `VehProLib.Driveline.Driver`

In order to drive the car, a driver is needed. This driver consists of a table over a driving cycle with data about the reference speed, gear and clutch signal with respect to time and also a PI-controller with parameters $K_i = 0.1$ and $K_p = 0.3$. Input signal to the model is the actual speed. With respect to the desired speed, the PI-controller controls the output gas pedal or brake pedal signal and the output lies between -1 and 1. When the PI-controller computes a negative value, the car brakes and if the value is positive, there is a signal to the gas pedal. Other output signals are gear and clutch signals.

The largest difference between this driver and a "real" driver is that this driver is a PI-controller that only measures and controls with respect to an actual speed difference. A human being can plan the driving and adjust before the speed difference occurs. See [25] for more details about the driver.

3.2 Reference Car —`VehProLib.Examples.Reference_car`

Now the different parts of the vehicle powertrain can be put together in order to model a vehicle, see the reference car in figure 3.1. The model has only two driving wheels. As described in [25] it does not affect the behaviour of the car during acceleration, but braking gives only half the braking force, because normally the car brakes with all four wheels. The car is also modelled without starter motor and the ICE starts at 3000 rpm.

The vehicle has been driven with half of the NEDC driving cycle and the actual vehicle speed is given in figure 3.8. The difference between desired speed from the NEDC driving cycle and the actual speed is shown in figure 3.9. The large differences occur when shifting between gears and also during the beginning of the braking phase. When the clutch has disengaged the driveline during gear shifting, the driving torque becomes unused for a moment and the vehicle loses speed.

Figure 3.10 views how the number of revolutions per minute changes during the NEDC driving cycle. When the car stands still, the speed reaches a minimum of 800 rpm due to the idle controller. Without the controller, the engine speed would reach zero engine speed and stop the simulation because the `MvemEngine` does not handle negative speed.

One problem with the `MvemEngine` is the low fuel consumption of 6.34 l/100 km. A first check in the engine model is to investigate the air flow into the throttle — an air flow of 4 g/s through the throttle during idle running is reasonable. Figure 3.11 shows the air mass flow through the throttle during the NEDC driving cycle. As can be seen, the air mass flow is low with a value of approximately 0.25 g/s during idle running. This thesis does not however try to find the reason why the `MvemEngine` has too low fuel consumption.

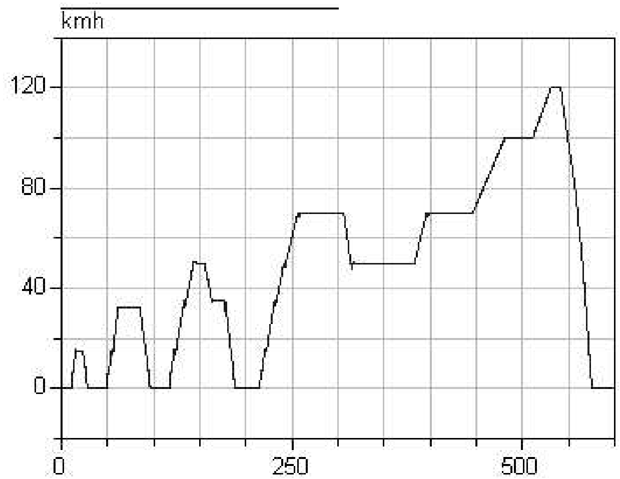


__Figure 3.8:__ Actual speed for the reference car during the NEDC driving cycle. X-axis shows time [s], y-axis vehicle velocity [km/h].

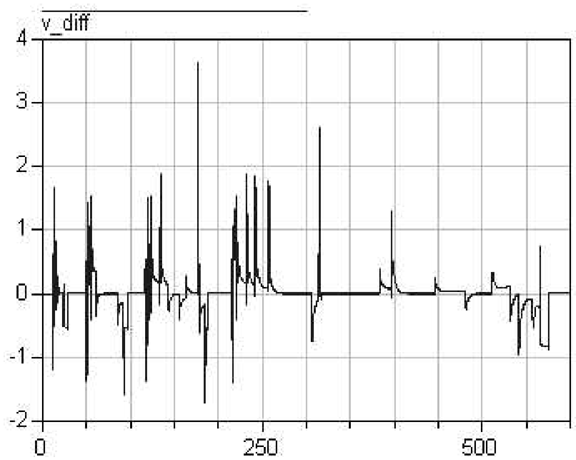


__Figure 3.9:__ Difference between NEDC speed and vehicle speed during the driving cycle. The differences depend on gear shifting and the beginning of the braking phase. X-axis shows time [s] and y-axis shows velocity [km/h].

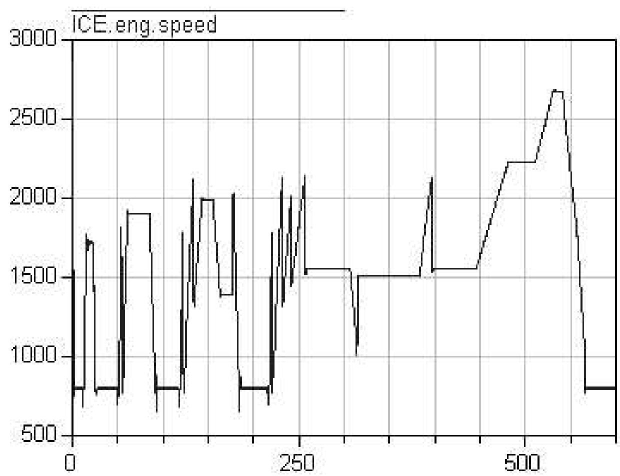


Figure 3.10: *Engine speed in the reference car. X-axis is time [s], y-axis is engine revolutions per minute [rpm].*

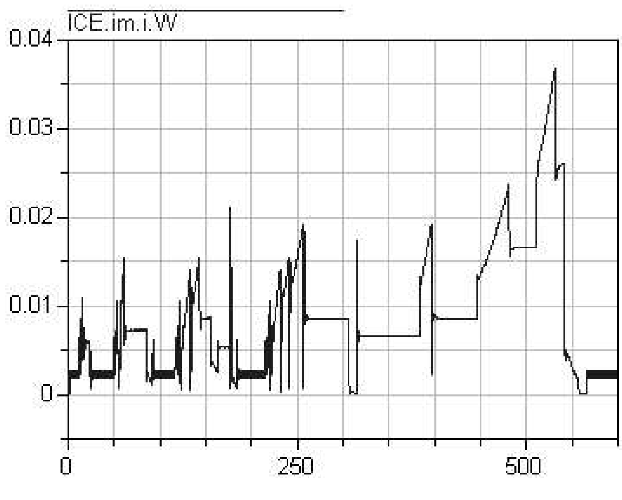


Figure 3.11: *Air mass flow through the throttle in the* `MvemEngine` *during the NEDC driving cycle in the reference car [kg/s]. X-axis shows time [s], y-axis shows air mass flow [kg/s].*

Chapter 4

Modelling Hybrid Electric Vehicles

4.1 Different Topologies

The HEVs in this thesis consists, as mentioned before in section 1.1, of an internal combustion engine, ICE, in co-operation with an electric motor, EM. There are different strategies for how to combine the ICE and the EM and four essential topologies are a series hybrid, a parallel hybrid, a series-parallel hybrid and a complex hybrid [7]. These topologies are described in more detail in this section.

4.1.1 Series Hybrid

A series HEV has the ICE in series with a generator and the EM. The main idea is to have the ICE running at an optimal point and store the energy in the battery via the generator, as presented in figure 4.1 and by Strömberg [32]. The power during driving is taken from the EM and the battery supplies it with energy. When the state of charge of the battery is at a predetermined minimum, the ICE is turned on to charge the battery. The ICE turns off again when the battery has reached a desirable maximum state of charge. In a series hybrid there is no mechanical connection between the ICE and the chassis.

The advantage with this configuration is that the ICE is running at its optimal combination of speed and torque all the time, thereby having a low fuel consumption and high efficiency. But, since there are two energy conversions during the transportation of the energy between the ICE and the wheels (ICE – generator and generator – EM), much energy is lost because of inner resistances and friction [32]. The series HEV has the worst power path compared to other topologies and by that the

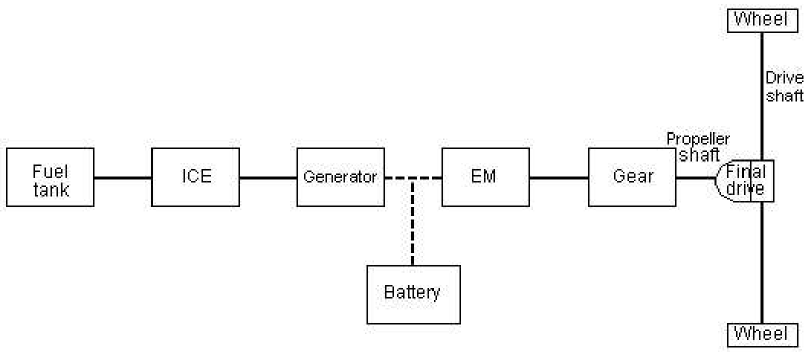


Figure 4.1: *A schematic figure of a series HEV where the ICE is placed in series with a generator and an EM [32]. The solid lines represent a mechanical connection and the dashed lines an electric connection.*

largest losses [17]. Another drawback is that the regenerative braking technique[1] cannot be used to save energy [20]. According to [17] and [7] all HEVs can use the regenerative braking technique conceptually, the reason why series HEVs cannot use the technique [20] can be that it requires special hardware and electronics that maybe not is available in all HEVs. The only advantage over the parallel configuration is that the series HEV creates less harmful emissions than the other topologies [20].

4.1.2 Parallel Hybrid

A vehicle with the parallel configuration has both the ICE and the EM mechanically connected to the wheels. Compared to the series HEV, the parallel HEV only needs these two propulsion devices [7]. A schematic figure of the parallel hybrid is shown in figure 4.2. The vehicle can be driven with the ICE or the EM or both of them at the same time and therefore it is possible to choose the combination freely to give the required amount of torque at each time.

In the parallel HEV topology, there are many ways to combine the use of the ICE and the EM. One strategy is to use the EM alone at low speeds where it is more efficient than the ICE, and then let the ICE work alone at higher speeds. When only the ICE is in use, the EM can function as a generator and charge the battery. The drawback with this excluding strategy is among other things that the battery will be discharged during long periods of very slow driving and the ICE has to be used for low speeds where it is less efficient [32].

[1] The regenerative braking technique makes the vehicle slow down by letting the wheels use the EM as a generator and contribute with power to the battery [30].

Another way to vary the power split between the ICE and the EM is a mixed strategy [32]. The EM is then used alone when the power demand is low as in the excluding strategy and at ordinary driving, when the power demand is between let us say 6 kW and 50 kW, only the ICE is used. At a power demand over 50 kW, for example at accelerations and high speeds, the EM is used as a complement to the ICE in order to give extra power when needed [30]. This speed limit as deciding parameter varies of course between different vehicles and strategies.

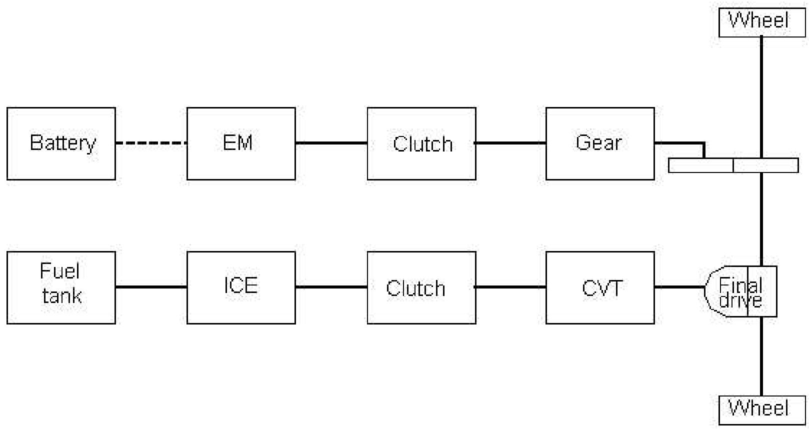


Figure 4.2: *A schematic figure of a parallel HEV. The vehicle consists of three possible combinations of the two propulsion devices EM and ICE; only use the battery in series with the EM, only use the ICE or use a combination of them [32]. The solid and dashed lines means a mechanical and electric connection respectively.*

A parallel vehicle can have a continuously variable transmission, CVT, instead of a fixed step transmission. With this technique it is possible to choose the most efficient operating point for the ICE at given torque demands freely and continuously [32]. The result is lower fuel consumption, because the fuel is used more efficiently. Energy is also saved thanks to the regenerative braking technique. The advantage with the parallel configuration is that there are fewer energy conversions compared to the series vehicle and therefore a lesser part of the energy is lost. The parallel hybrid has the lowest losses compared to the other topologies [17].

4.1.3 Series-Parallel Hybrid

The series-parallel HEV is a combination of the series and the parallel hybrid. In some literature it is called strigear hybrid, the name is an abbreviation for *sequentially run, triple gearbox connected engine/motor hybrid* [17]. There is an additional mechanical link between the generator and the EM compared to the series configuration and an additional generator compared to the parallel hybrid, see figure 4.3. With this design it is possible to combine the advantages of both the series and the parallel configuration, but the series-parallel hybrid is relative to them more complicated and expensive [7].

There are many possible combinations of ICE and EM, but two major groups can be identified — electric-heavy and engine-heavy. The electric-heavy vehicle indicates that the EM is more active than the ICE for the propulsion and in the engine-heavy case the ICE is more active. The two groups have in common that the EM is used alone at start and the ICE is turned off. During normal driving the ICE alone propels the vehicle in the engine-heavy case and both the ICE and EM in the electric-heavy case. When acceleration is needed, the EM is used in combination with the ICE to give extra power similarly in both groups. During braking or deceleration the EM is used as a generator to charge the battery and in stand still the ICE can maintain running and charge the battery via the generator in both cases if needed.

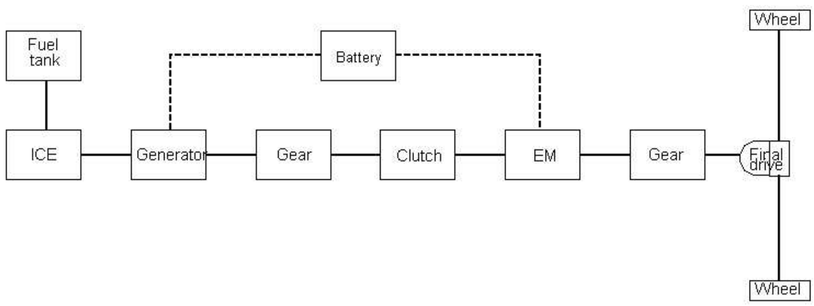


Figure 4.3: *The series-parallel hybrid schematically presented. There is an additional mechanical link compared to the series hybrid and an additional generator compared to the parallel hybrid [7]. The mechanical connection is described by the solid lines and the electric connection by the dashed lines.*

4.1.4 Complex Hybrid

The complex HEV is also called power split hybrid, combined hybrid or dual hybrid in some literature [17]. It is another combination of the series and parallel hybrid, see figure 4.4, although not so distinct and clear as in the series-parallel hybrid. This topology includes a planetary gear box, which connects the ICE, EM and generator. The ICE speed can be controlled by varied speed from the two planetary gear pinions connected to the EM and the generator.

The ICE is possible to switch off and then the vehicle is propelled just electrically, but at most of the operating points the energy flows both as in a parallel hybrid (from ICE via the gear box to the wheels) and as in a series hybrid (from generator and EM to the wheels) [17]. The proportion between these two energy flows depends on the speed — sometimes it may act as a pure parallel hybrid, but most of the time it is partially a series and partially a parallel hybrid.

The complex hybrid has, as the series-parallel hybrid, higher complexity and costs [7]. It is also difficult to create a complex hybrid which is more effective than a parallel hybrid [17].

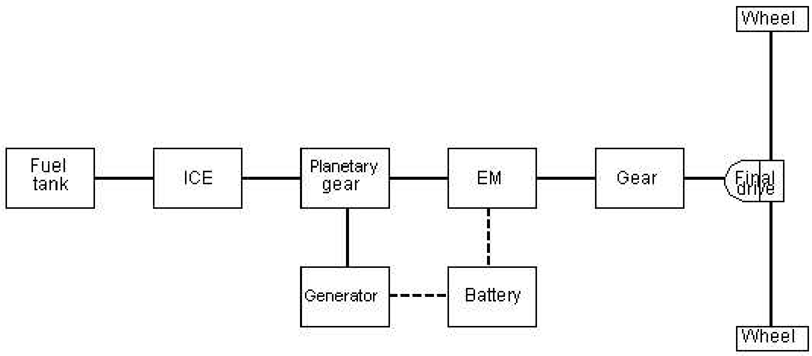


Figure 4.4: *A schematic figure of the complex hybrid. It can drive as in a parallel hybrid with the energy flow from the ICE, via the gear box to the wheels, or as in a series hybrid with the energy flow from the generator and EM to the wheels [17]. Solid lines means a mechanical connection and dashed lines an electric connection.*

4.1.5 Hybrid Models on the Market

The hybrid vehicle market is growing and many companies in the motor industry have concept HEVs under development. In this context DaimlerChrysler, Fiat, Ford, GM, Mitsubishi and Nissan can be mentioned [32]. In this section, the first HEV on the market, Toyota Prius, and the early competitor Honda Insight are described.

Toyota Prius

Toyota Prius, see figure 4.5, is a very interesting car, because it was the first mass-produced HEV on the market and a breakthrough[2] in many ways [26], presented at Tokyo Motor Show in 1995 [34].

Figure 4.5: *Toyota Prius, a picture from [24].*

It has been difficult to determine to which topology Toyota Prius belongs. It has a configuration similar to the electric-heavy series-parallel system [7], according to Hellgren [13] it is a split HEV, but own comparisons and [2] shows that Toyota Prius is a complex hybrid. The energy flows sometimes like a series HEV, sometimes like a parallel HEV and the proportion between these two energy flows is speed dependent. The vehicle is large with seats for five persons. It is also powerful with a 1.5-liter four-cylinder engine which has the Atkinson/Miller high-expansion principle[3], coupled with an EM of 40 horse powers [20]. The EM is powered by a battery where the energy is produced in 40 NiMH batteries connected in series. Toyota Prius is a "full" hybrid, which means that the car sometimes turns off the ICE and only is powered by the battery and EM [33]. The car is designed to reduce emissions in urban areas and Toyota Prius meets California's super ultra low emissions vehicle standard, SULEV [24].

Due to the regenerative braking technique, approximately 30 % of the energy that normally is lost in friction brakes is here converted to current stored in the battery [33]. As can be seen in the principial figure 4.4 of the complex hybrid, Toyota Prius has a planetary gear

[2]Toyota Prius has regenerative braking, light and small engine, better fuel efficiency, lower emissions and is more aerodynamic than a family sedan [26].

[3]The mechanical compression ratio is about 9:1, the virtual compression ratio is 14:1 [34].

box, which also acts as a CVT. Prius is the forerunner to Toyota Hybrid System, THS. This system is used by Toyota in further developed HEVs and in the THS the gear box has been replaced by a clever planetary-gear-type power-split device, which also is an electric CVT, which is called THS-CVT [34].

The early Toyota Prius on the american market and in Japan is smaller compared to the vehicle in Europe. There is a difference in for example motor size and the european vehicle is also heavier. The difference is quite small and the essential design is the same. It has been very hard to analyse which articles and facts that refer to the different sizes of the vehicle. This thesis has tried to separate the models and use the facts from the bigger european vehicle when possible, and has also used other facts from Toyota Prius even if it has not been certain to which vehicle they refer.

Honda Insight

An example of a simplified parallel hybrid vehicle is Honda Insight, see figure 4.6. Honda names this hybrid the Integrated Motor Assist system, IMA, which includes the ICE, EM and transmission [24]. IMA uses the EM to assist the ICE, which means that the ICE must be running during the whole drive in order to drive the vehicle and the EM is only used when extra power is needed. The vehicle was introduced in early 2000 in the United States and it is not designed to reduce emissions as Toyota Prius, but to get best possible mileage. Honda Insight is a “soft” hybrid, which means that it is the ICE which propels the vehicle primary and the extra power is provided with the EM when needed. The Honda Insight has a conventional five-speed manual gear box, but now is the car Insight CVT with continuously variable transmission also available [24].

Figure 4.6: *Honda Insight, the picture comes from [24].*

Honda Insight has a large improvement in the fuel economy owing to the car's overall design with for example air drag[4] and lighter vehicle (aluminium frame, smaller engine) that leads to that a smaller engine can fulfil the requirements. The car uses a 3-cylinder 1.0-liter petrol engine together with a 10 KW (and about 13 horse powers at 3000 rpm) EM [33]. The car is small, has a low weight and has only room for two persons [24].

Comparison Toyota Prius versus Honda Insight

In table 4.1 a small comparison between Toyota Prius and Honda Insight is made.

Characteristics	Toyota Prius	Honda Insight
Topology	Complex	Simplified parallel
Design issue	Reduce emissions	Improve mileage
Petrol engine	1.5-liter 4-cylinder 70 hp at 4500 rpm	1.0-liter 3-cylinder 67 hp at 5700 rpm
Electric motor	Max 40 (44) hp	Max 13 hp
Weight	1255 (1645) kg	862 kg
Drag coefficient	0.29	0.25

Table 4.1: *Comparison between Toyota Prius and Honda Insight. The values in parenthesis refer to the bigger european model of Toyota Prius [24].*

4.2 Hybrid Components

In this section components necessary for modelling HEVs is described. They are all developed in `VehProLib`.

4.2.1 Internal Combustion Engine — `VehProLib.Examples.MvemEngineFuelCutOff`

In for example the series hybrid it is sometimes desirable to be able to cut off the ICE and run the vehicle with only battery and EM. From aspects of modelling it means that the engine must be able to run with no fuel and thereby without producing driving torque. This is called fuel cut-off[5] and is implemented in the MVEM engine `VehProLib.-`

[4] Honda Insight has an aerodynamic drag coefficient of 0.25. With this it places the vehicle among the best of the cars available today [33].

[5] In an ordinary car, like the reference car, the fuel cut-off behaviour does not mean exactly the same as here in the HEV case. Here, in the HEV case, the fuel

`Engine.Examples.MvemEngineFuelCutOff` and the cylinder `VehPro-Lib.Engine.Cylinders.MvemCylinderFuelCutOff`. This model has the `MvemEngine` without λ-controller as a basis, because it is impossible to control the λ-value when the fuel mass flow is reduced to zero. The fuel cut-off is made as a "fuel factor" as ingoing signal to the ICE, which rescales the effects of the fuel. For example a fuel factor of 0.5 means that only half of the energy in the fuel is used and therefore only produces half of the indicated mean effective pressure IMEP[6] in the expression $BMEP = IMEP - PMEP - FMEP$, where $BMEP$ is the work actually produced by the engine when the friction work $FMEP$ and pumping work $PMEP$ have been taken into consideration. BMEP is related to the produced work per cycle by $BMEP = W_{per\ cycle}/V_d$. When total fuel cut-off is wanted, the fuel factor is zero and the engine should produce no work, that is $IMEP = 0$ and there are only braking torque from the friction and pumping work.

The ICE in a HEV should be able to be turned on and off during driving when required. Because the engine models are not modelled to manage zero and negative speed, many simulation and modelling problems appear when trying to model the fuel cut-off as to slow down the engine speed to zero and then spin up the engine again when it is needed to produce a driving torque. The case with low and zero speed in the engine models is not finished, either is this thesis. It would require much time and more detailed knowledge about the engine models and Modelica. For example the air mass flow per revolution should remain nonzero in order to avoid problems when for example computing the λ-value. At zero engine speed the mass of fuel from the tank into the cylinders, m_f, is zero, but the mass of air in the cylinders, m_a, has to be nonzero. Another problem is the friction model. The friction should behave like a singularity around the zero point and the model should require reaching a certain engine speed in order to overcome the friction threshold and give a driving torque. Ideas how to implement a wider model of for example $FMEP$ in the `MvemEngine` can be found in Modelica's own example of how friction is modelled in `Modelica.-Mechanics.Rotational.Examples.Friction`. The special case when the angular velocity ω is zero is of great interest.

One solution to the problem with zero speed in the engine model

cut-off shall simulate the behaviour of an engine which actually is turned off, thereby producing no driving torque and consuming no fuel, but maybe produce a braking torque because of the friction and pumping work. In the reference car case, fuel cut-off means that when driving in for example a slope, it is desirable to turn off the engine and thereby consuming no fuel. When the torque reaches the lowest possible value (approximately 800 rpm) where it is risk that the engine stops, the idle controller controls the engine speed again and the engine is turned on.

[6] $IMEP$ = (Gross) indicated mean effective pressure means the work delivered to the piston over the compression and expansion strokes of the cycle, divided by displaced volume V_d [14].

that has not been verified in this thesis would be to have two different ICE models to switch between during the simulation. One model for the ordinary driving and a simple model, like a flywheel mass, for the zero speed case.

Another way, which is implemented in `MvemEngineFuelCutOff`, to avoid the most difficult complexity in the fuel cut-off mode described above is to keep the engine away from reaching zero speed. When the main vehicle controller wants the ICE to run in fuel cut-off mode, the controller steers the torque to zero. The engine slows down because the idle controller is uncoupled in this mode. When the speed reaches for example 1 rpm, the speed remains constant, but the mass of fuel m_f is set to zero. Thus the engine does not stop, but it has a very low speed, consumes no fuel and produces no torque. When the torque is zero, the engine is disengaged from the driveline in order to simulate the behaviour of having no effects on the vehicle drive. When the vehicle controller wants a driving torque from the ICE again, a starter motor speeds up the engine and the engine is connected to the driveline, "ignites" and starts to consume fuel again when it reaches a minimum speed, in this work 100 rpm.

When the engine runs with fuel cut-off, it should use no fuel and the amount of consumed fuel per second $\dot{m}_f$ should be zero. In `MvemEngineFuelCutOff` the energy flow Q_{in} becomes zero. By letting the incoming amount of fuel into the cylinders be zero, no fuel will be delivered from the tank when the fuel factor is zero. See figure 4.7, which shows a test of the behaviour of the `MvemEngineFuelCutOff` when starting from speed equal to 1 rpm.

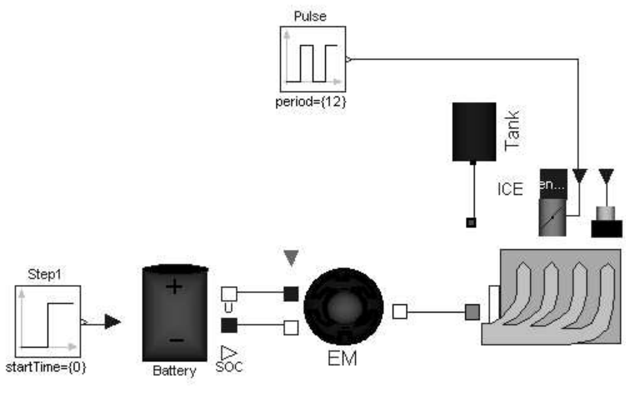


Figure 4.7: *Test of `MvemEngineFuelCutOff` when starting from speed 1 rpm.*

In figure 4.8 the ICE speed during the test is plotted. The ICE runs at fuel cut-off until it reaches a certain speed, in this test 100 rpm, and the engine “ignites”. Then the starter motor is disengaged, the idle controller is activated and the ICE consumes fuel. First at time 3 seconds, there is full gas, so at the beginning the idle controller adjusts the speed to the idle speed 800 rpm. At time 9 seconds the gas goes down to zero and the idle controller adjusts the speed again to 800 rpm. Figure 4.9 shows the consumed fuel during the fuel cut-off mode. As desired, the ICE consumes no fuel when it is in fuel cut-off mode. At time 0.041 seconds the engine has reached the speed 100 rpm, it “ignites” and starts to consume fuel. This test shows that the `MvemEngineFuelCutOff` manages to start from 1 rpm, the idle controller is activated when the engine is in driving mode and the engine consumes no fuel in the fuel cut-off mode.

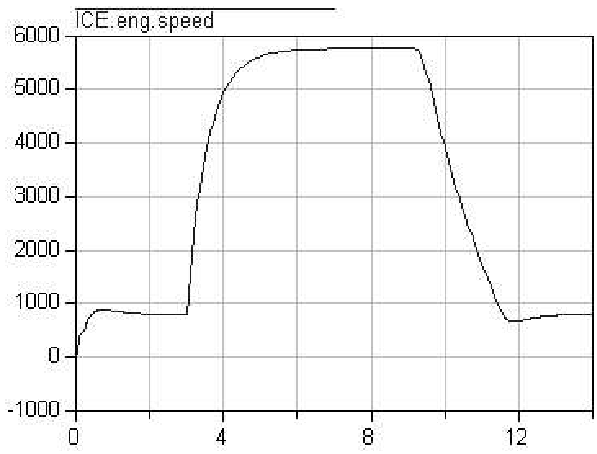


Figure 4.8: *Test of starting the* `MvemEngineFuelCutOff`*. The engine starts at speed 1 rpm. At 100 rpm (approximately at time 0.041 s) the engine “ignites” and the idle controller adjusts the speed to 800 rpm. At time 3 s there is full gas and at time 9 s, there is no gas, resulting in the speed is controlled down to 800 rpm again. X-axis shows time [s] and y-axis shows engine speed [rpm].*

In the fuel cut-off mode before the start and stop phases, the speed changes fast and the engine accumulates energy because of the mass inertia (the acceleration and deceleration energies). This thesis does not take this into account. As long as the start and stop phases only occupy a maximum of 1 % of total driving time, this simplification does not affect the simulation results too much. If it is over 1 %, the model needs a dynamometer that speeds up and down in order to model the mass inertia.

During driving the ICE in fuel cut-off mode, it is desirable to disconnect the ICE from the remaining driveline. In this thesis both disconnecting the EM and using a clutch between the ICE and EM have been tested without success. The reason is unfortunately not yet understood.

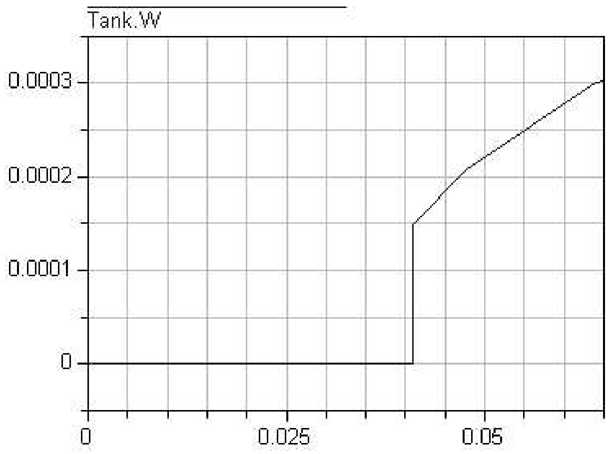


Figure 4.9: *Test of starting the* `MvemEngineFuelCutOff`*. At the beginning, the starter motor speeds up the engine, which is in fuel cut-off mode. At 100 rpm and time 0.041 s the engine changes to driving mode and the engine starts to consume fuel. X-axis shows time [s], y-axis shows consumed fuel per second [kg/s].*

4.2.2 Continuously Variable Transmission

The CVT is like an automatic gear box which gives an infinite number of gears. The large advantage with this technique is that it is possible to choose a gear ratio that makes the engine work at its optimal combination of speed and torque due to the environment [32]. In modelling the HEV, there are two choices of how to model the CVT. Either it can be simple and just model the ratio between required ICE and wheel angular velocity, or be more complex using a planetary gear. In this section both ways are described. None of them are verified in a vehicle model.

CVT
— `VehProLib.Driveline.CVT`

The CVT, named `VehProLib.Driveline.CVT` is based on the equation [32]

$$CVT_{gear\ ratio} = \frac{w_{ICE,\ required}}{w_{wheel,\ required}}$$

and the relations between rotational angle φ and torque T from the ideal gear `Modelica.Mechanics.Rotational.IdealGear` in Modelica standard library

$$\begin{aligned}\varphi_{ICE} &= CVT_{gear\ ratio}\varphi_{gear}\\ 0 &= CVT_{gear\ ratio}T_{ICE} + T_{gear}\end{aligned}$$

$w_{ICE,\ required}$ will be given by a look-up table and is chosen so the engine has as low fuel consumption as possible for a given torque. When $\omega_{wheel,\ required} = 0$ the gear ratio $CVT_{gear\ ratio}$ has a default value of 0.

Planetary Gear
— `Modelica.Mechanics.Rotational.IdealPlanetary`

Toyota Prius has the Toyota Hybrid System, THS, and uses double pinion types of the planetary gears [9]. The term "double pinion types" is still confusing, since it cannot be found in any literature. Instead the CVT in this Modelica model of Toyota Prius is described with following equations [18]

$$\begin{aligned}T_{EM} &= \frac{1}{1+p}T_{ICE}\\ T_{generator} &= \frac{p}{1+p}T_{ICE} \quad \text{where} \quad p = 0.385\\ T_{driveshaft} &= \left(\frac{1}{1+p}T_{ICE} + T_{EM}\right)\eta\\ w_{ICE} &= \frac{p}{1+p}w_{generator} + \frac{1}{1+p}w_{EM}\end{aligned}$$

where η describes the ratio of the reduction gear between the ring and the drive shaft, $T_{driveshaft} = T_{ring}\eta$. The reduction gear is the same as the ideal differential in the final drive, where the gear ratio is the same as η. p is the ratio between number of teeth of the sun gear and the ring gear. Compared to the equations describing the ideal planetary gear in Modelica standard library, `Modelica.Mechanics.Rotational.IdealPlanetary`, the generator shall be connected to the sun gear, the ICE to the planet carrier and the EM to the ring gear in order to fulfil the equations above for Toyota Prius [24]. The connection between the ratio for the `IdealPlanetary` and p is $ratio = \frac{1}{p}$. The driving torque T_o in Toyota Prius is according to [27]

$$T_o = (T_d + T_{EM})\,\eta \quad \text{where}$$
$$T_d = T_{ICE}\frac{p}{1+p}$$

T_{EM} and T_d fluctuate constantly during the drive in order to get an optimal combination.

The planetary gear in Toyota Prius also acts as a CVT and the gear ratio is chosen by changing the input from two of the three pinions, that is the $CVT_{gear\ ratio}$ and the gear wheel speed is determined by the wheel speed ω_{wheel}.

4.2.3 Battery

The battery stores the energy electrically, supplies the EM with current and is an important part of the vehicle. It must be efficient, be able to charge current enough to drive the car an appropriate distance and have a long lifetime. The Nickel Metal Hydride battery, NiMH, is used in both Toyota Prius and Honda Insight [24] and is also the most common type of battery in HEVs today [32], therefore this thesis models this type of battery. The advantages of a NiMH battery is its high specific power (stored energy per weight unit) and long lifetime.

In this section two models of a NiMH battery is described. The first model contains the basic relations and behaviours according to Strömberg [32], the second model is Hellgren's NiMH battery model in `Hevlib` [13]. This model is more advanced and covers a greater part of the complex characteristic behaviours. The battery model can be even more complex if all the dynamics is captured in the model.

None of the models has a limit for the allowed SOC level. Therefore the controller needs to take this into consideration and avoid the SOC level to reach values outside the interval from 0 % to 100 %. Neither the batteries have limits for the output current and voltage.

Table Battery
— `VehProLib.HEV.Battery`

`VehProLib.HEV.Battery` is a battery model which covers the fundamental behaviours of the NiMH battery and the decrease of efficiency during discharging. It is based on Strömberg's master's thesis [32] and can be seen in figure 4.10. Input to the battery is the battery gas signal from the driver, output is the battery voltage, current and the battery state of charge, SOC. As figure 4.10 shows, the battery is modelled as a look-up table for the connection between SOC and battery output voltage with interpolated values from [16]. The effect of aging on the efficiency is not taken into account in the model.

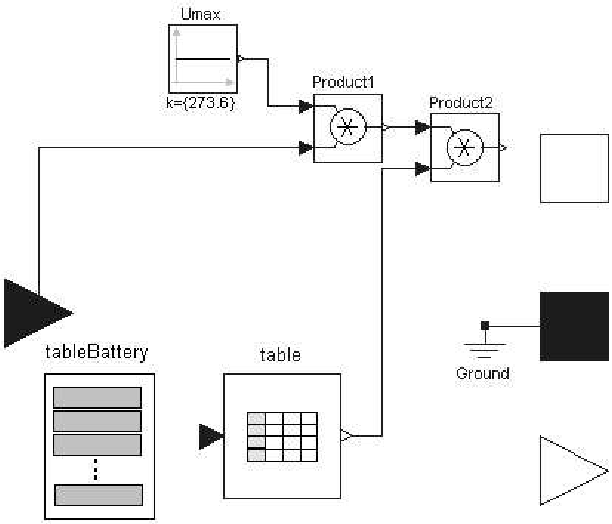


Figure 4.10: *The `VehProLib.HEV.Battery`. The battery is modelled as a look-up table for the connection between SOC and battery output voltage.*

The SOC of the battery is described by the equation

$$SOC = SOC_{init} + \frac{1}{Q_{max}} \int_t i(\tau) d\tau$$

where SOC_{init} is the initial SOC value, in the model 60 % according to [32]. The minimum battery SOC before the battery need to be charged is 20 %, the maximum battery SOC level is 80 % as default values in this thesis. The battery is charged when the current $i(\tau)$ is positive. Q_{max}, the maximum charge, is calculated from a storage capacity of 6.2 Ah to

$$Q_{max} = 6.2 * 60 * 60 = 22320 \text{ C}.$$

The connection between the battery charge $Q(t)$ and SOC [15] is

$$\frac{\partial}{\partial t} Q(t) = i_{batt}$$
$$SOC = \frac{1}{Q_{max}} Q(t)$$

The battery output voltage U_{batt} is calculated by

$$U_{batt} = U_{max} S_{acc} f(SOC)$$

from [32]. U_{max} is the maximum battery output voltage and S_{acc} is the signal from the gas pedal. $f(SOC)$ describes how the SOC influences the battery output voltage by a look-up table. The battery voltage has a nonlinear dependency of the SOC, described by a table according to [16]. The table "Open circuit voltage" with the 25°C data has been used.

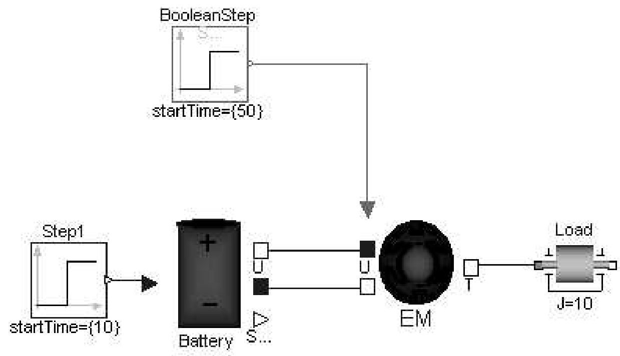


Figure 4.11: *Test of the table battery in combination with the EM.*

Test of the battery in combination with the EM is shown in figure 4.11. In the first test the EM circuit is closed and therefore the motor produces a torque due to the battery voltage. The driver uses the gas at time 10 seconds and as can be seen in figure 4.12, there are no current from the battery and no torque from the EM before that time. The value of SOC also remains unchanged, see figure 4.13. When there is full gas, the current and the torque become very high. The test illustrates how the battery works together with the EM and no current limiter has been used. Because there are no braking current and braking torque in the test model for the battery in combination with the EM, the EM reaches its speed and retains it. The current and torque therefore sink to zero again after the high output.

Figure 4.14 shows a test where the battery is discharged and then charged again. The change of SOC is presented in figure 4.15(a) where it can be seen that first, when the torque is zero, the battery is discharged. When the torque is nonzero, the battery becomes charged. The change in battery current can be seen in figure 4.15(b). The battery is discharged when the current is negative and becomes charged with positive current.

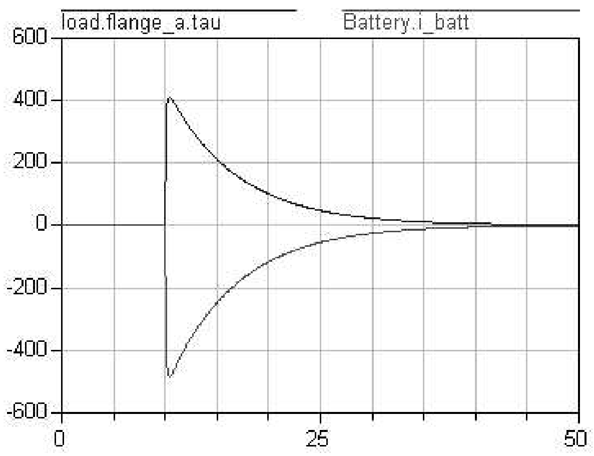


Figure 4.12: *Test of battery and EM with EM circuit closed. Before time 10 s the driver does not use the gas pedal and therefore there is no current from the battery and no torque from the EM. At time 10 s there is full gas, this rises the current and the torque to very high values. After a while the values goes down to zero again because the engine reaches its speed and there is no braking torque in the model. X-axis shows time [s] and y-axis shows torque [Nm] for* `load.flange_a.tau` *and current [A] for* `Battery.i_batt` *respectively.*

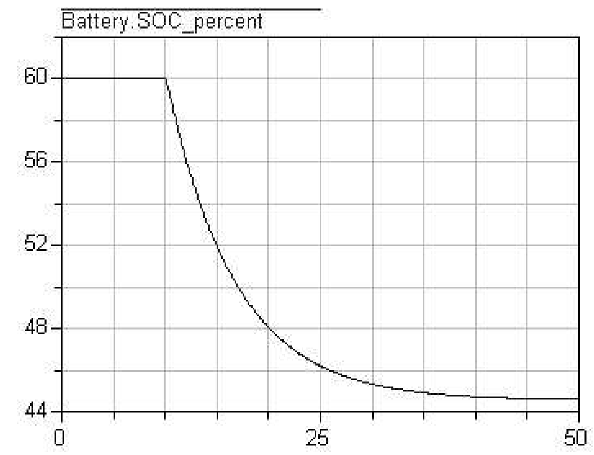


Figure 4.13: *Test of battery and EM with EM circuit closed. Before time 10 s there are no change in SOC, because the driver does not use the gas. At time 10 s there is full gas and the battery discharges. X-axis shows time [s], y-axis shows battery SOC [%].*

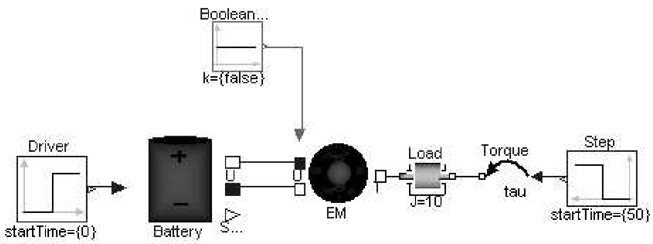
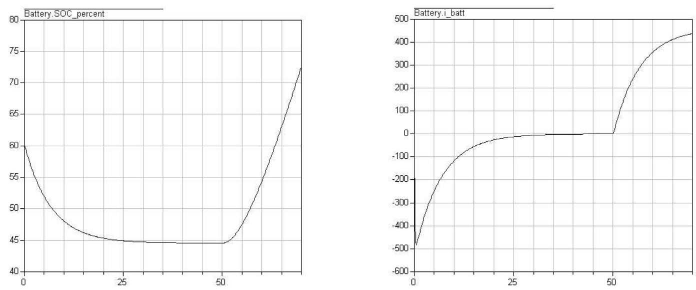


Figure 4.14: *Test of discharging and charging the battery. The torque shall symbolize an ICE.*



(a) The battery SOC. When the producing torque is zero, the battery is discharged. With an "engine torque" the battery charges. X-axis shows time [s], y-axis shows battery SOC [%].

(b) The battery current. Negative current discharges the battery at the beginning. Then the positive current due to the producing torque from the "engine" charges the battery. X-axis shows time [s], y-axis current [A].

Figure 4.15: *Results of the test when discharging and charging the battery. The torque component symbolizes an engine producing torque.*

Physical Battery

There is also a battery model which describes a NiMH battery more completely, see figure 4.16. The battery comes from Hellgren's model `Hevlib.components.buffers.buffer_NiMHbattery`, developed in his library `Hevlib` [13]. The model is a mathematical description of the Panasonic NiMH battery (HHR650D) used in Toyota Prius. Nonlinear battery elementary charging and discharging characteristics and the variation of SOC are modelled. This battery is charged with positive voltage Vcb. U is the voltage in a single battery cell, $I_{cellPos}$ and $I_{cellNeg}$ model the current in the cell from the two battery contacts. The leakage current is determined by the resistance R_p. The inner resistance R is SOC dependent — a nearly empty or almost fully charged battery results in a very high inner resistance due to the R_{overch} parameter in the model. The battery pack consists of modules and the number of battery cells within each module define the voltage of the battery pack. The parameter $SIZE$ represents the size of the pack, because it sets the number of modules in parallel. For a wider description, see [13].

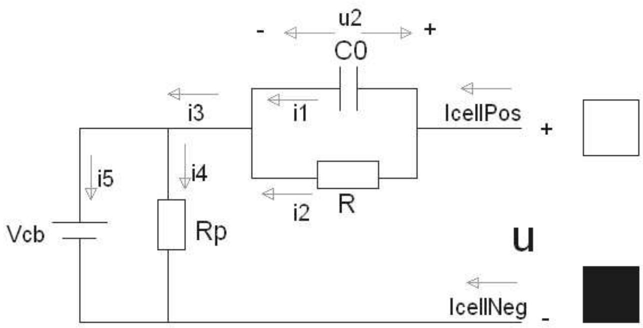


Figure 4.16: *Model of a NiMH battery from Hellgren [13].*

To limit the output current (and output voltage) from the battery, a limiter consisting of a PI-controller and a variable resistance can be added outside of the model, see section 4.2.4.

The idea is to use this battery as a complement to the former table battery. Due to time requirements, the function of this battery has not fully been investigated and tested. Unfortunately it is impossible to change between the two different battery models without doing some changes in the HEV models developed in `VehProLib`. The table battery is somewhat like an ICE with a "gas pedal" which gives a specified output battery current dependent of the gas. This physical NiMH battery gives the amount of current and voltage which is determined from the other parts of the test or vehicle model.

4.2.4 Current Limiter —`VehProLib.HEV.Components.CurrentLimiter`

In order to limit the output current from the battery a limiter is desirable. As an example of a proper current limit, the battery by Strömberg [32] limits the current to ±80 A. Many approaches as if-clauses and controllers have been tested, but an ideal current limiter has not been able to model in Modelica due to time requirements. The wish is to just cut off the current when it reaches its limits, but how should the non-causality in Modelica be taken care of? An ordinary if-clause has been tested, but it has a predefined "inport" and "outport" and how shall the problems be solved in Modelica when the current is calculated from the output-side to the input-side?

The current limiter in `VehProLib` is modelled with a PI-controller which controls a variable resistor `VehProLib.HEV.Components.VariableResistor`, see figure 4.17. Because the limiter is built with a PI-controller, it cannot control too fast changes, which is bad. But, as can be seen in figure 4.18, the limiter manages to control the current from a sine curve with amplitude 200 A, when tested in a simple circuit. As default values, the proportional parameter $K_p = 0.5$ and the integral parameter $K_i = 0$, otherwise the PI-controller controls the current worse due to integrator wind-up.

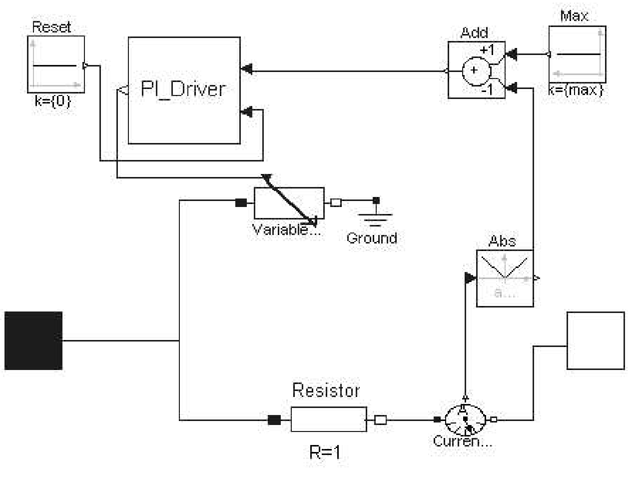


Figure 4.17: *The current limiter `VehProLib.HEV.Components.CurrentLimiter` with a PI-controller and a variable resistor.*

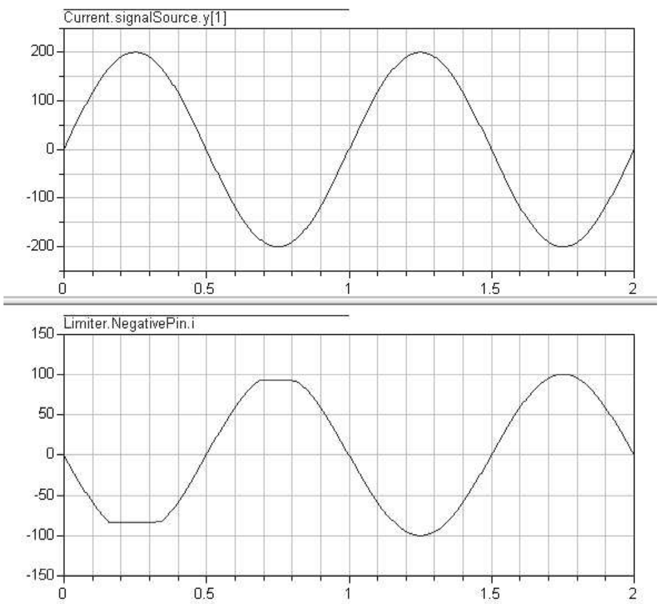


Figure 4.18: *The current limiter manages to control the current from a sine curve with amplitude 200 A. The current is allowed to be between -80 A and 80 A. X-axis is time [s], y-axis is current [A].*

4.2.5 Electric Motor — `VehProLib.HEV.PM_motor`

The electric motor, EM, is one of the two sources of power in an HEV and it is supplied with energy from the battery. The EM also acts as a large starter motor which spins up the ICE and the vehicle during the start phase. Unlike the ICE, the EM provides full torque at low speeds. It is, as in Strömberg [32], modelled as a conventional DC-motor with a permanent magnet[7], see figure 4.19. Input to the EM is voltage U_{EM} and current i_{EM} from the battery and the boolean switch signal, output is torque T_{em} and rotational angle φ.

The equations describing the EM according to Strömberg [32] are

$$T_{EM} = i_{EM} k_{EM}$$

$$L_{EM} \frac{\partial}{\partial t} i_{EM} = U_{EM} - R_{EM} i_{EM} - \omega_{EM} k_{EM}$$

[7]Another name is permanent magnet synchronous motor [15]. The magnetic field is created by a permanent magnet, in opposite of a “common” DC-motor where an electric energy source creates the magnetic field. This type of EM is used in Toyota Prius.

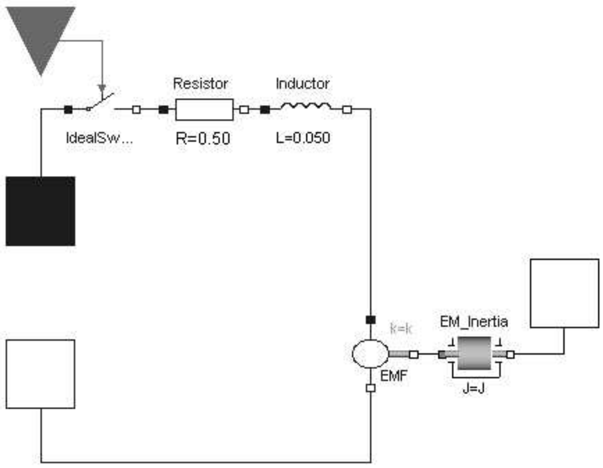


Figure 4.19: *The EM modelled as a DC-motor with permanent magnet.*

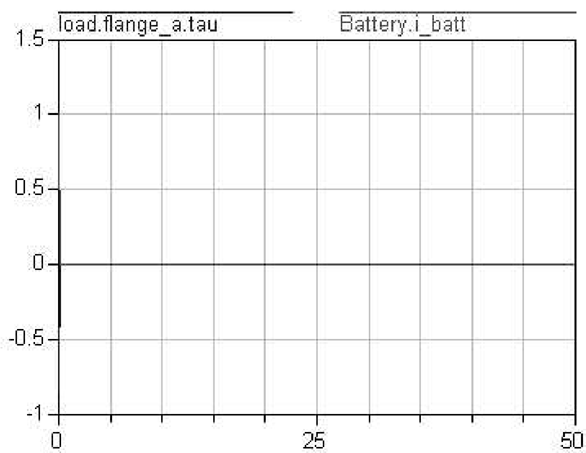


Figure 4.20: *Test of battery and EM with EM disconnected. At time 10 s there is full gas, but because the motor is disconnected, the circuit has no current and produces no torque. X-axis shows time [s], y-axis shows torque [Nm] for* `load.flange_a.tau` *and current [A] for* `Battery.i_batt` *respectively.*

k_{EM} and ω_{EM} is the EM magnetization and the actual EM speed respectively. L_{EM} and R_{EM} are inner inductance and resistance. In order to choose reasonable parameter values, [28] in combination with data about Toyota Prius [17] have been used. The inner resistance R_{EM} is varying and a function of SOC, for simplicity a constant resistance value is used in this work. The EM magnetization k_{EM} is chosen after tests of how to reach and control the predetermined working point in the series HEV, see section 5.1. $k_{EM} = 0.85$ was required in order to reach the working point of 105 Nm and 1250 rpm.

After the synchronous DC-motor circuit there is an inertia in order to try to model affects due to the motor mass like acceleration and deceleration [32]. But it is desirable that the EM does not tie too much rotational energy, therefore the inertia is small with $J = 0.01$.

The EM can be switched off with the ideal boolean switch. A true value means an opened switch and also an opened circuit in the EM, thereby it is possible to disconnect the EM and run the ICE without torque to or from the EM/generator. A false value means a closed switch and circuit and the EM works as usual. Figure 4.20 shows the battery and EM test result when the EM is disconnected, that is the circuit is open. At time 10 seconds the driver uses full gas, but because the EM is disconnected, there is no current in the circuit and the EM produces no torque. In figure 4.21 the battery SOC when the EM is disconnected can be viewed. A reason to the small variation in SOC can be calculation error in the integration.

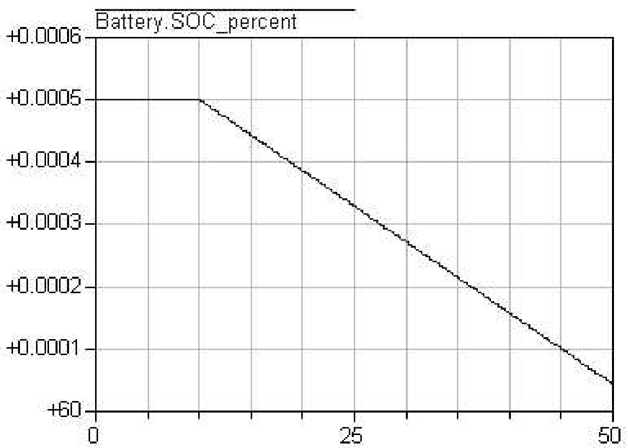


Figure 4.21: *Test of battery and EM with EM disconnected. A reason to the small variation in SOC can be calculation error in the integration. X-axis shows time [s], y-axis shows battery SOC [%].*

4.2.6 Generator

The generator is an EM which converts mechanical energy to electric energy. The EM works as a motor when the input is voltage and current, like a generator when the input is torque and rotational angle.

4.2.7 Converter —`VehProLib.HEV.Converter`

The converter distributes the current between the EM, the generator and the battery and is placed between the three components. The positive electric pins have the same voltage, as also the negative electric pins. The currents are principially calculated according to $i_{battery} = i_{EM} + i_{generator}$. This converter is ideal and has no losses. As can be seen in figure 4.22 the currents are calculated as follows

$$i_{battery} = -(i_{drive} + i_{charge}) \tag{4.1}$$

$$i_{EM} = i_{drive} + i_{extra} \tag{4.2}$$

$$i_{generator} = -(i_{charge} + i_{extra}) \tag{4.3}$$

Modelica takes care of the positive and negative signs due to the flow direction, but the negative signs in 4.1 was necessary when testing the converter. The currents $i_{battery}$, i_{EM} and $i_{generator}$ are the currents delivered to or from the battery, EM and generator respectively. i_{drive} is the current from the battery to the EM which drives the car according to the driving requirements. i_{charge} is the current needed to spin up the ICE through the generator. If the EM wants more current than is available, it can get some extra current from the generator if the ICE is on and charges the battery. Some of the charging current goes then directly to the EM instead of to the battery.

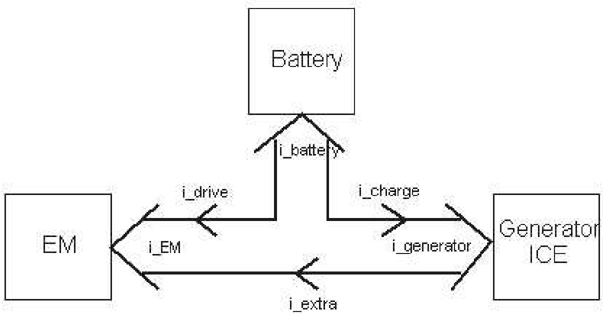


Figure 4.22: *The currents in the converter to/from the generator, battery and EM.*

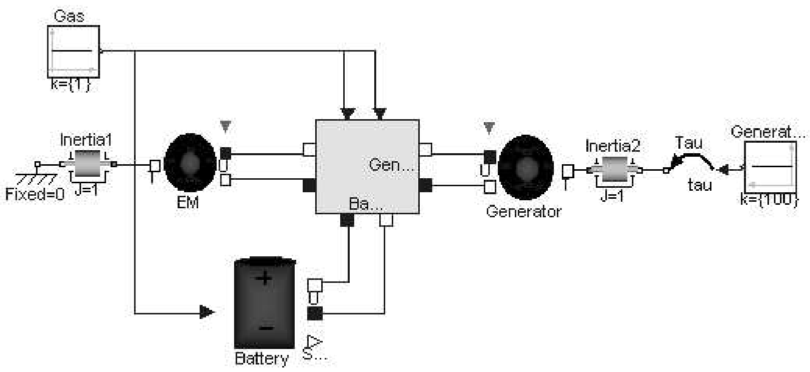


Figure 4.23: *The battery is connected to the EM through the converter and the generator is disconnected.*

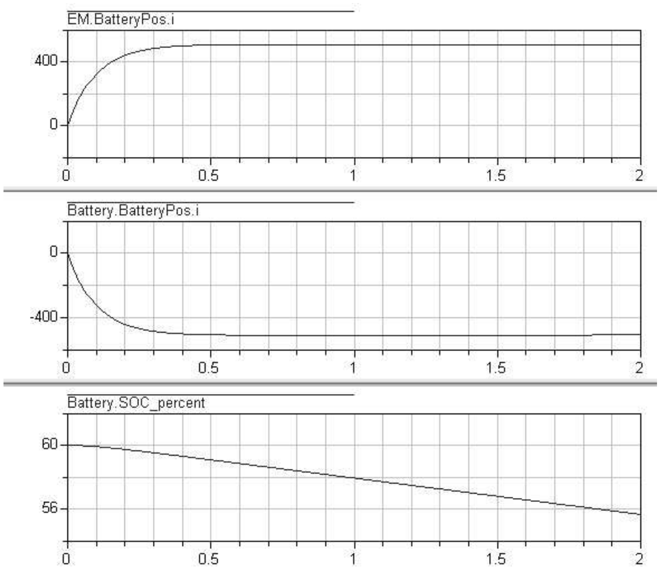


Figure 4.24: *The currents flowing out from the battery* `Battery.BatteryPos.i` *to the EM* `EM.BatteryPos.i`*. Because the generator is disconnected, it does not add something to the current sum. X-axis shows time [s], y-axis shows current [A] and SOC level [%] respectively.*

Figure 4.23 shows how the battery is driving the EM with a negative current and is discharging the battery. The converter is used and the generator is disconnected. The current from the battery to the EM is shown in figure 4.24 and also the battery SOC level. Because the generator is disconnected, the current from it is zero. As can be seen, the equation $i_{battery} = i_{EM} + i_{generator}$ is fulfilled. The opposite signs is because the current is flowing out from the battery into the EM according to the Modelica sign convention. The same results are given when the battery is directly connected to the EM without a converter between them, as expected.

The results when the generator is connected to the converter is presented in figure 4.25. The torque in figure 4.23 represents an engine torque. First the generator works as an EM to spin up the inertia to give the defined torque. After a while, the inertia has the required speed and the generator can convert the torque to current to charge the battery. Therefore the battery has a larger negative current at the beginning (discharging the battery faster), and then a smaller negative current because the generator can manage to deliver some energy. As can be seen in figure 4.25, the current `Battery.BatteryPos.i` is the sum of the currents `EM.BatteryPos.i` and `Generator.BatteryPos.i`. A positive value means that current is flowing into the component, a negative value describes that current is flowing out.

Figure 4.26 shows a test when the `MvemEngine` is used. The engine starts at 1 rpm and the generator has to spin up the engine. The results are presented in figure 4.27, compare them to figure 4.25.

The "gas inports" to the converter exist because the converter needs to determine the current requirements from the EM and the generator separately. The converter treats the current flow differently if only the EM wants current from the battery or both the EM and the generator wants current. The latter case appeares when the ICE has been turned off and then is spinned up by the generator at the same time as the battery propels the car forward. Looking at the figures, it however seems as if the different distributing modes nevertheless have been taken care of. For example the generator spins up the ICE even if the gas inports are the same. This has not been investigated further.

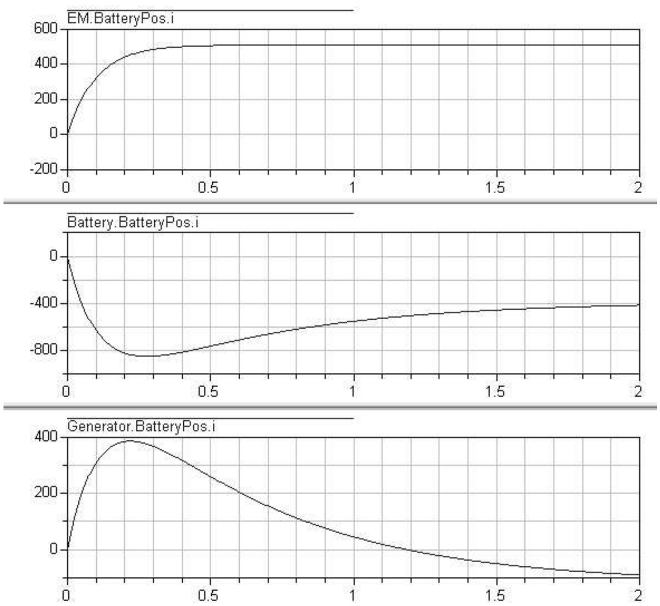


Figure 4.25: *Test of the converter with battery and connected EM and generator. The battery current is the sum of the currents from the EM and the generator, as expected. At the beginning the generator works as a starter motor for the predefined torque and discharges the battery. After a while the inertia has reached its speed and the generator charges the battery. X-axis is time [s], y-axis is current [A].*

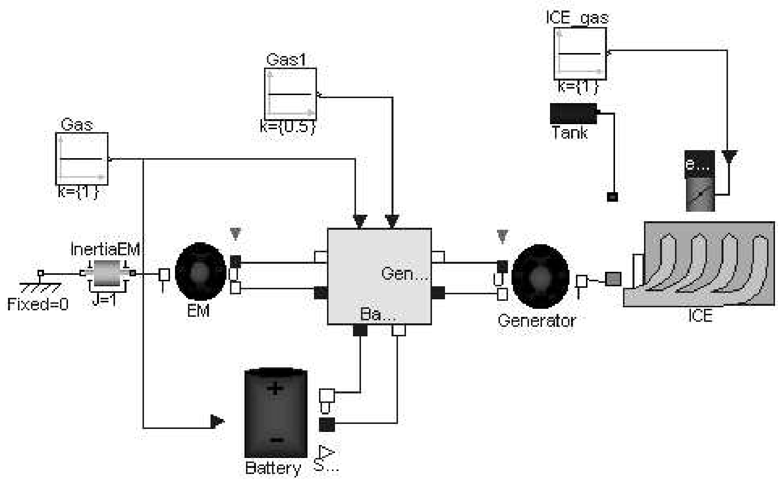


Figure 4.26: *Test of the converter with battery, EM and ICE.*

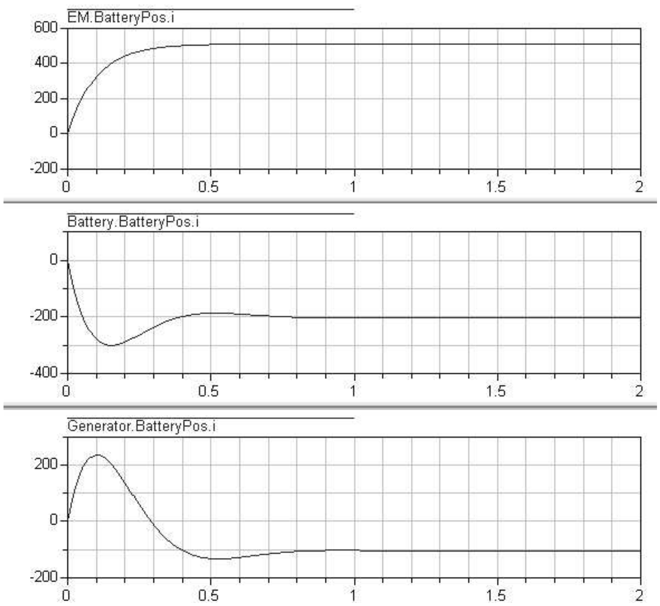


Figure 4.27: *Test of the converter with an* `MvemEngine` *connected which starts at 1 rpm. The generator acts as a starter motor and spins up the engine before it charges the battery. X-axis shows time [s], y-axis current [A].*

Chapter 5

Series HEV

The model of a series HEV presented in figure 5.1 is made with hybrid components developed in `VehProLib` combined with models from Modelica standard library. See the similarities between the fundamental construction of the series HEV in figure 4.1 and the vehicle model shown in figure 5.1.

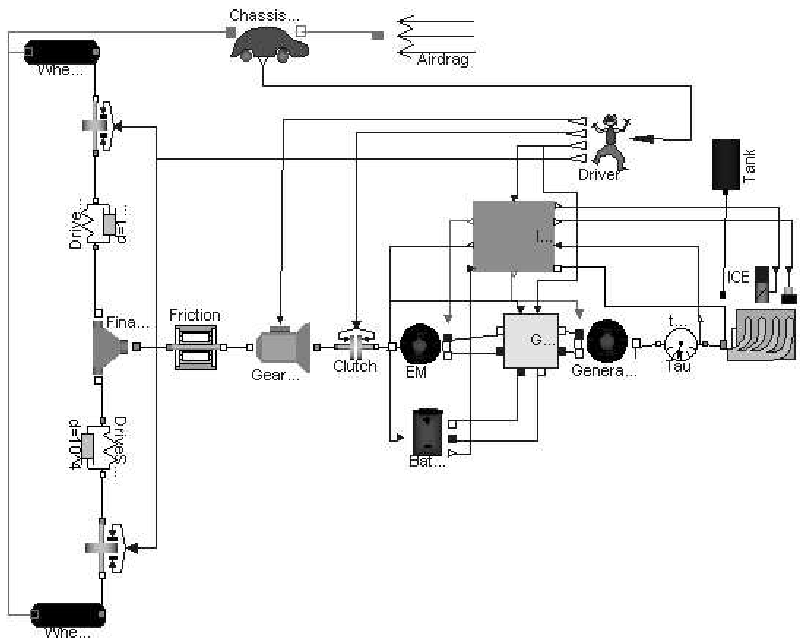


Figure 5.1: *The series HEV in* `VehProLib`.

5.1 Determining and Controlling the Working Point

In order to decide the working point for the ICE, Toyota Prius engine size has been used in combination with the program ADVISOR[1] to decide the point from collected data. In figure 5.2 from ADVISOR you can see that every point over a fuel efficiency of 0.45 is good. In this thesis the ICE has been chosen to do a 105 Nm torque at the engine speed of 1250 rpm. Figure 5.3 shows how to control the ICE in order to reach the working point. The reference values of the torque (105 Nm) and speed (1250 rpm) are compared to the actual values from the ICE and the PID-controller controls the output signal so the desired values are reached. The PID-controller fulfils the requirements with only P- and I-part[2] and gives an output signal between 0 and 1. Figures 5.4(a) and 5.4(b) show the controlled ICE speed and torque.

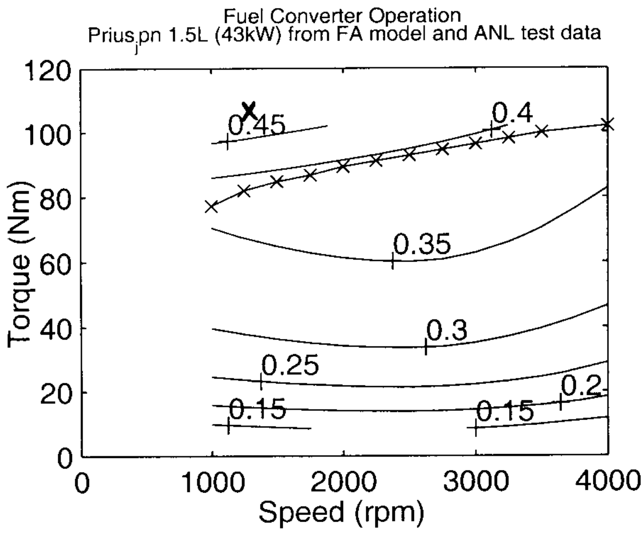


Figure 5.2: *Determination of the working point. The cross in the figure shows the determined working point with torque 105 Nm and speed 1250 rpm. The data from Toyota Prius model from Japan are collected and presented in ADVISOR.*

[1] ADVISOR *Advanced Vehicle Simulator* simulates and analyses conventional, advanced, light and heavy vehicles in a MATLAB/Simulink environment [12]. It also provides collected measured data from existing vehicle models.

[2] A D-part could be used in this test, but when used in the HEVs, it may be necessary to change the working point. An abrupt change in the reference value gives a high derivative, which causes a large D-part and a bad controller. The D-part makes the controller more sensitive to changes and when the system contains abrupt and large changes, the D-part is undesirable.

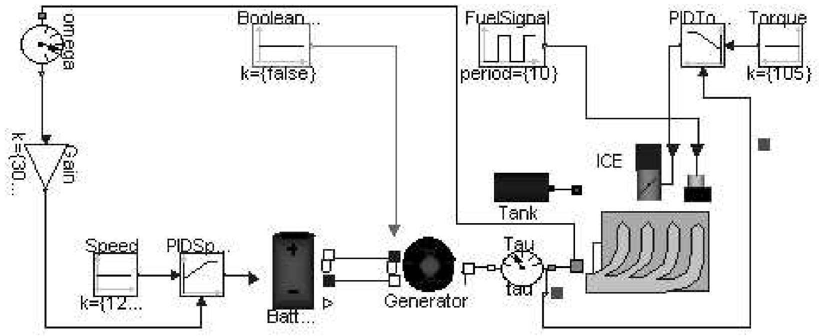
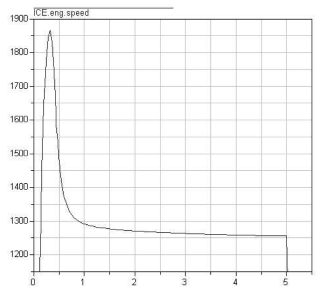
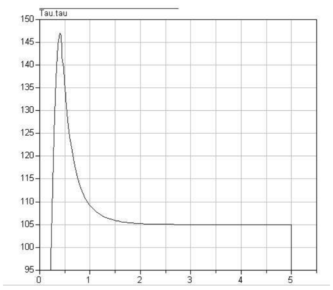


Figure 5.3: *Model to test how to control the engine to a torque of 105 Nm and a speed of 1250 rpm. The system controllers have P- and I-part.*



(a) Outcoming speed controlled to a value of 1250 rpm. X-axis shows time [s], y-axis shows engine speed [rpm].

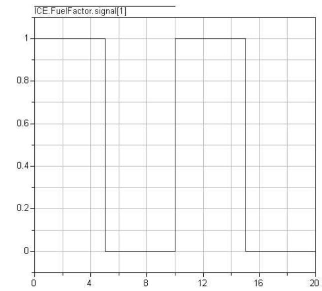


(b) Outcoming torque controlled to a value of 105 Nm. X-axis shows time [s], y-axis shows torque [Nm].

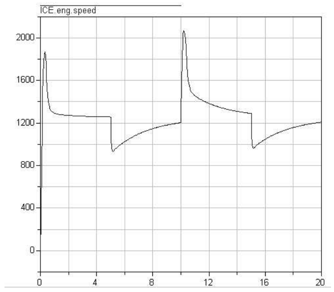
Figure 5.4: *Speed and torque from ICE controlled to the working point 1250 rpm and 105 Nm. At time 5 s the ICE is in fuel cut-off mode and the PID-controllers do not affect the ICE.*

During the test the generator circuit is closed, because otherwise the test would fail as described previously in section 4.2.1. It is however desirable that the ICE is disconnected to the remaining driveline when it is in fuel cut-off mode.

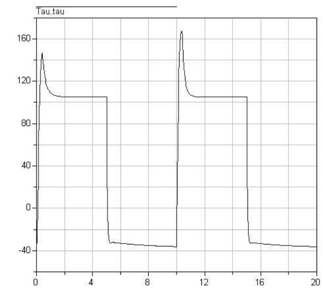
As can be seen in figure 5.5(a) the fuel factor changes during the test. The speed is first controlled to 1250 rpm because the fuel factor is 1, see figure 5.5(b). When the fuel factor changes to 0, the speed decreases. The torque has the same behaviour during the test. First it is controlled to 105 Nm, then it is decreasing due to the battery discharging, as in figure 5.5(c).



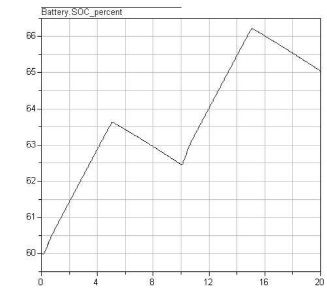
(a) The fuel factor signal during the test of controlling the ICE towards the working point. A value of 1 means that the ICE is running in normal mode with fuel consumption, a value of 0 means that the ICE is in fuel cut-off mode and no fuel is consumed. X-axis shows time [s], y-axis shows fuel factor signal.



(b) The ICE speed during the test. The initial value is 1 rpm, then the controller manages to control the speed to the working point 1250 rpm because the fuel factor is 1. When the fuel factor changes to 0 the speed changes due to battery discharging. Next time the fuel factor changes to 1, the speed is controlled to 1250 again. Wen the ICE is in fuel cut-off mode, it is driven from the generator because it is not disconnected and the ICE becomes some speed. X-axis is time [s], y-axis is engine speed [rpm].



(c) The ICE outcoming torque during the test. When the fuel factor is 1 the torque is controlled to 105 Nm. When the fuel factor is 0, the torque is decreasing due to the battery discharging. The generator is not disconnected and when the ICE is in fuel cut-off mode, some torque is produced from the generator to the ICE. X-axis shows time [s], y-axis shows engine torque [Nm].



(d) The battery SOC. When the fuel factor is 1, the ICE is running and charging the battery. When it is changed to 0, the battery is discharging. X-axis is time [s], y-axis is battery SOC [%].

Figure 5.5: *The test sequence of controlling the working point and switching between fuel mode and fuel cut-off mode. The generator circuit is closed all the time and driving the ICE from behind when it is in fuel cut-off mode, giving the behaviour with ICE speed and torque when the fuel factor is 0.*

The battery SOC level is presented in figure 5.5(d). First the battery is charging because the ICE is running. When the fuel factor changes to 0, the battery discharges.

The behaviour of the speed and torque when the ICE is in fuel cut-off mode can be explained by the closed generator circuit during the whole test. When the ICE is in fuel cut-off mode, it is driven from the generator and some torque and speed are received.

5.2 Control Strategy

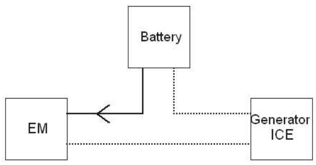
The main control design for the series HEV is to let the ICE work at the optimal combination of torque and speed, charge the battery and propel the car by the EM. The ICE is only running when the battery needs to be charged and is otherwise turned off, which is done by the fuel cut-off function in this model.

The intended control strategy is as follows. The limits of the battery in the series HEV is 20 % to 80 % [31]. At the beginning of the drive, the EM starts the vehicle. Because the initial SOC value is 60 %, the ICE starts in fuel cut-off mode with speed 1 rpm. Both ICE and generator is disconnected to the driveline by the switch in the generator. When the SOC level reaches the minimum limit, in this thesis 20 %, the ICE is turned on by the generator as starter motor and is controlled by PID-controllers to the predetermined working point (here with torque 105 Nm and speed 1250 rpm). The ICE produces extra torque that is converted to electric energy by the generator and can be stored in the battery. This model of the series HEV has no regenerative braking implemented.

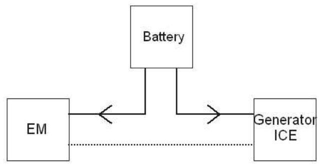
The converter `VehProLib.HEV.Converter` is a distributor between the battery, EM and generator. The voltage between the components is the same, but the current must be distributed differently according to the driving conditions and requirements. When only the EM is driving the vehicle, all current from the battery goes to the EM, see figure 5.6(a). When fuel cut-off mode is wanted and the generator spins up the ICE, current is distributed from the battery to both EM and generator, as in figure 5.6(b). When EM drives the car, but the ICE produces torque to charge the battery, current from the generator goes directly to the EM. Unused current is charging the battery, see figure 5.6(c). If the requirements are so high that the battery cannot both spin up the ICE and deliver current to the EM, it is more important to fulfil the driving requirements. The EM gets as much current as possible and if some is left, it goes to the generator. If the requirements are too high when the ICE charges the battery, some charging current goes directly to the EM and the battery charges slower, see figure 5.6(d).

An extended control strategy would be to fulfil the EM driving requirements when the SOC level is above a minimum value, for example 5 %. Below this, all necessary current is used for the generator to spin up the ICE so the battery can be charged again.

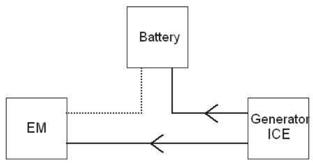
The driver controls the gear, the ordinary clutch before the gear and the brakes as in the reference car.



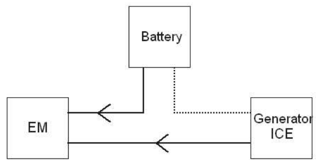
(a) Only the EM is driving the vehicle and all current from the battery reaches the EM.



(b) Fuel cut-off mode is wanted and the battery distributes current to both the EM and the generator to spin up the ICE.



(c) The EM drives the car with current from the battery at the same time as the ICE via the generator charges the battery.



(d) During high driving requirements the charging current from the generator is used directly by the EM as an extra power source.

Figure 5.6: *The distribution of the current between the battery, EM and generator in four different driving conditions and requirements.*

5.3 Driving

Unfortunately the ICE in fuel cut-off mode is not functioning as expected. In the HEV, the ICE should first be controlled down to zero torque and thereafter the ICE should be in fuel cut-off mode. It is desirable that the generator which is coupled to the ICE is switched off, so the torque, if any (due to model and structural errors), should be zero for sure. When this is tested in Modelica, the program crashes and the reason to this is not yet understood. Therefore this vehicle has the generator switched on during the whole drive.

Another problem, also not yet understood, is that Modelica crashes when the torque is tested. The fuel factor shall only change to 0 when the torque has been controlled down to zero (or a small value), but

Modelica cannot handle this condition in the if-sentence.

With all these problems with the components described so far in this thesis and the lack of time, the control and driving is made as simple as possible, just to test the behaviour and if the whole vehicle can function and drive forward. With the ICE replaced by a torque, the series HEV is driving forward as can be seen in figure 5.7. In figure 5.8 the vehicle speed and clutch signal can be viewed. The velocity for the series HEV trying to follow the NEDC driving cycle is shown in figure 5.8, where the vehicle speed can be compared with the NEDC reference speed. The components and parameters in the series HEV are not yet sized to fulfil the driving requirements as perfectly as possible, but in figure 5.8 you can see that the vehicle is able to move forward and follow the NEDC driving cycle fairly.

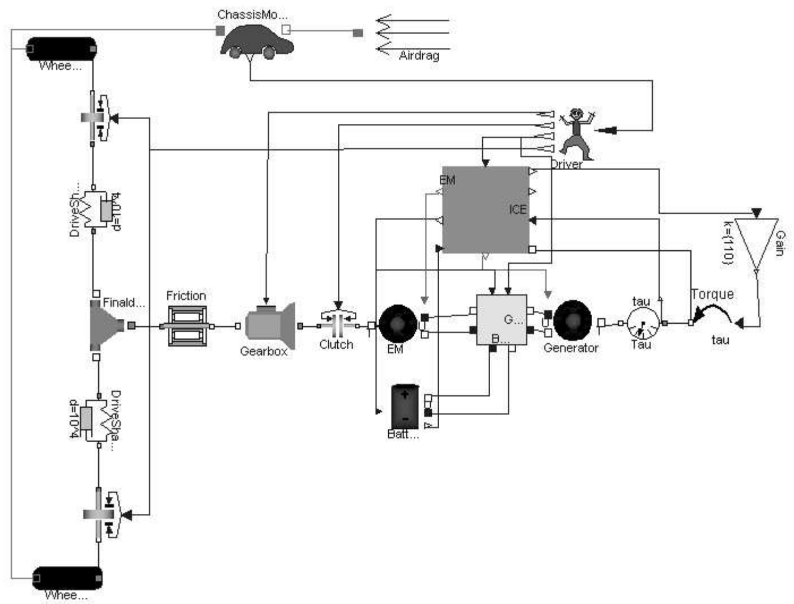


Figure 5.7: *Test of the series HEV with the ICE replaced by a torque.*

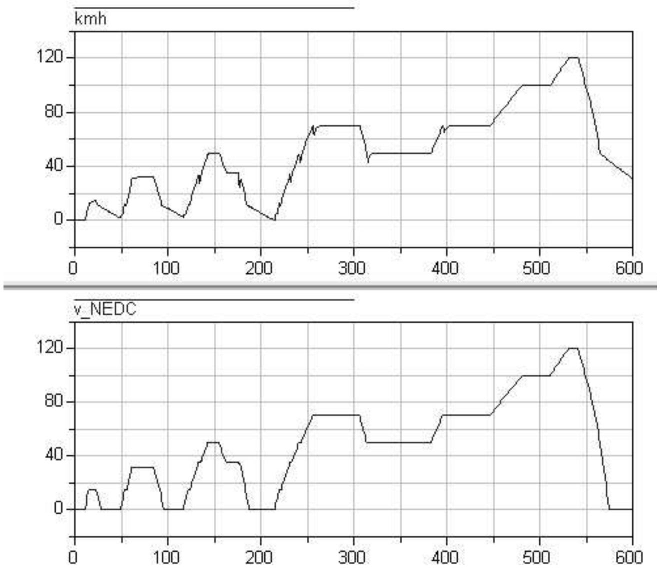


Figure 5.8: *The upper figure shows the vehicle velocity when the ICE is replaced by a torque, the lower figure shows the NEDC velocity. The cuts depend on gear shifting. X-axis is time [s] and y-axis is velocity [km/h].*

Chapter 6

Parallel HEV

As with the series HEV, the parallel HEV in figure 6.1 uses models from both `VehProLib` and Modelica standard library. Compare to the graphic presentation of the parallel HEV construction in figure 4.2. The aim when starting with this thesis was to model a parallel HEV too, control it and compare the results with the series HEV. The expected result is that the parallel HEV has a better efficiency compared to the series HEV because the straightest power path is found in the parallel topology and the series vehicle has more losses due to two energy conversions [17]. The parallel HEV should therefore have the lowest fuel consumption. The two vehicles would yet be difficult to compare because they have different control strategies and the results would maybe not be as clear as desired.

6.1 Intended Control Strategy

Unfortunately lack of time has made controlling the parallel HEV impossible. But in this section nevertheless the contemplated control strategy will be shortly described.

For low speeds the excluding strategy [32] would be used. It means that the EM works alone at low speeds, for example at starts, stops and slow driving in the city. The ICE is turned off and saves fuel at low speeds (where it also is less efficient). At higher speeds, the mixed strategy [32] is used. The ICE is running all the time and the EM is used as an extra power source when needed, for example at accelerations and high speeds. The ICE can be downsized and consumes less fuel, but the vehicle still has the same performance level. The velocity limit where the vehicle changes the strategy can for example be 30 km/h. The four driving modes are according to Jonasson [17] pure EM mode, pure ICE mode, EM operates and the ICE charges the battery and finally ICE operates and the EM provides it with additional peak power.

The EM is used as a generator when the braking energy is charging the battery with the regenerative braking technique. It can also absorb power from the ICE and charge the battery when the output from the ICE is larger than required to drive the vehicle [7]. In this parallel HEV there is a CVT instead of an ordinary discrete gear box. The ICE can for example be controlled to an optimal working point due to the torque and speed combination and if some extra power is produced, it charges the battery.

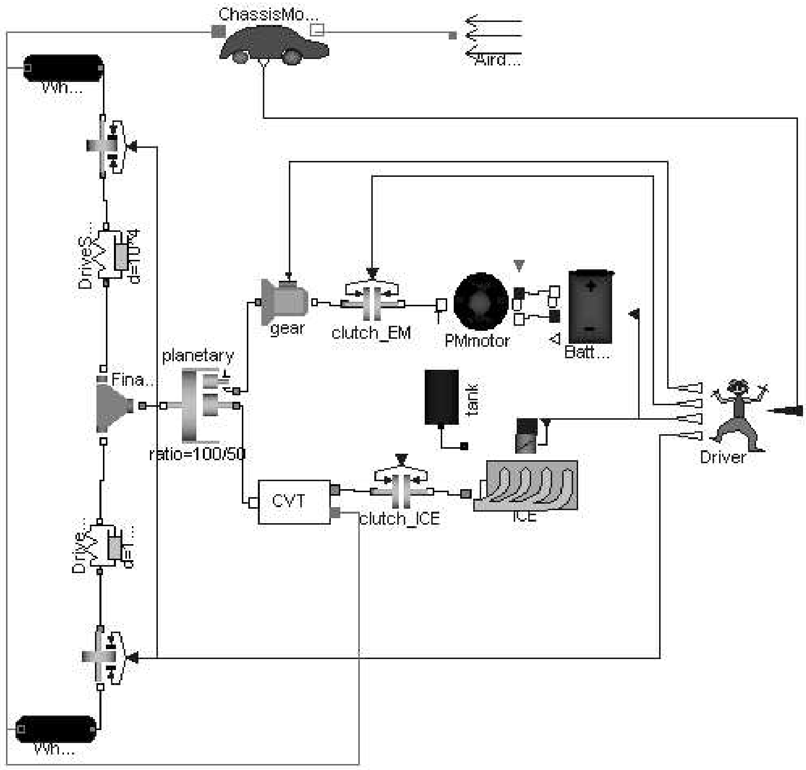


Figure 6.1: *The parallel HEV in* `VehProLib`.

Chapter 7

Toyota Prius

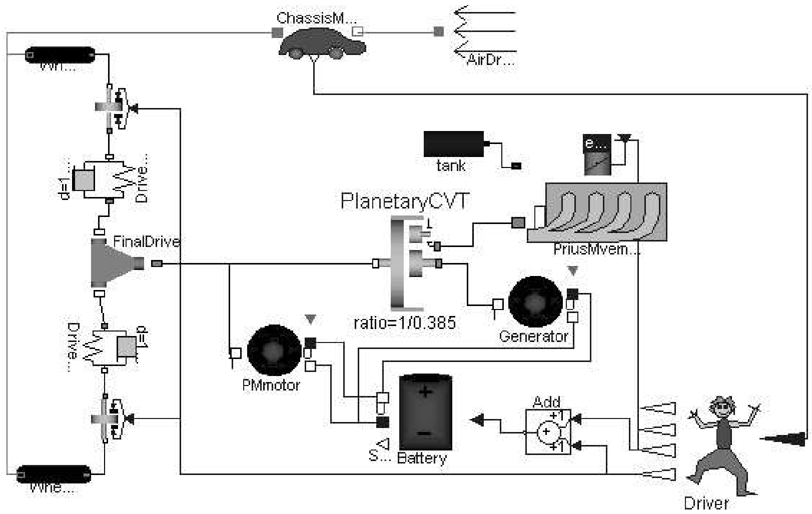


Figure 7.1: *A model of Toyota Prius in* `VehProLib`*.*

Toyota Prius is also modelled with components from `VehProLib` and Modelica standard library, see figure 7.1. Compare to the complex hybrid pictured in figure 4.4. Sometimes it has been hard to find appropriate parameter values for Toyota Prius — other parameters or scaled parameter values for the present engine size have been used. It has also been difficult to separate component values for the smaller japanese Prius and the larger european model. But, because the differences between the values are small and the remaining models are modelled without available measurements, the thesis still models qualitative behaviours. Table 7.1 shows the parameters that has been used in the model of Toyota Prius.

final gear ratio = 5.182 [9]
planetary gear ratio = 1/0.385 [18]
wheel radius = 0.29155 m [4]
front area = 2.52 m^2 [17]
coefficient of air drag = 0.29 [26]
mass of vehicle = 1645 kg [17]

BMEP max = $9.6536 * 10^5$ Pa from the equation
$BMEP_{max} = \frac{2\pi T_{max} n_r}{v_{dtotal}}$ [11]
T_{max} = 115 Nm [17]
stroke = 0.0847 m [3]
bore = 0.075 m [3]
$V_d = 0.001497$ m^3 [3]
mechanical compression ratio $r_c = 13.0$ [4]

$R_{EMinner} = 0.50\ \Omega$ [17]
$L_{EMinner} = 0.050$ H [28]
$J_{EM} = 0.01$ kgm^2 [32]
$U_{battery} = 273.6$ V [15]
$Q_{max} = 22320$ C [32]
$i_{battery,max} = 80$ A [32]

other constants according to [25]

Table 7.1: *Parameters that have been used in the Modelica model of Toyota Prius.*

7.1 Intended Control Strategy

The aim was also here to model and control the Toyota Prius and compare it to the two base topologies series and parallel HEV. It would be very interesting to see if the fuel consumption is better with the parallel HEV than Toyota Prius! The parallel HEV is expected to be more fuel-efficient because this configuration has the straightest power path and the lowest energy losses. But, lack of time has unfortunately made this investigation and development of the control device impossible.

The contemplated control strategy would be done according to [7]. The EM is used alone at startup and driving at light load and the ICE is turned off. At normal driving and acceleration both the ICE and the EM works together and propels the vehicle. At normal driving some of the energy goes directly to the gear box and some goes through the generator and EM to the gear box. At acceleration the same energy flows appear, but now also the battery contributes with some energy to the EM. The planetary gear splits the ICE output between the gear box and the generator directly. When the vehicle brakes or decelerates, the EM acts as a generator and charges the battery and the ICE is turned off. The battery can be charged during driving and the ICE provides some extra power which goes from the generator to the battery. When the vehicle stands still and the battery needs to be charged, all the power from the ICE is transformed to electric energy in the battery. The velocity limits between these different driving modes may be tested, there are no specified limits in the literature.

Chapter 8

Conclusions

8.1 Summary and Conclusions

In this section the modelling work will be summarized and the main problems are shortly discussed. The language Modelica and the simulation tool Dymola will be discussed regarding to experiences and difficulties during the modelling work.

8.1.1 The Modelling Work

In chapter 3 the components for the reference car were developed. As ICE the `MvemEngine` in `VehProLib` was used because this engine model is good enough when studying the qualitative behaviour and it also gives a faster simulation. The Modelica standard clutch and standard brake are used in the reference car model. The manual gear box is developed with some simplifications according to Nobrant [25], for example the same gear efficiency and bearing friction for all gears. The propeller shaft is stiff compared to the elasticity in the drive shaft. No model is needed for the propeller shaft and the gear box and the final drive are directly connected to each other. The drive shaft is as by Nobrant [25] modelled with the Modelica standard spring damper. The wheel is according to Nobrant [25] modelled with rolling condition, rolling resistance, longitudinal slip and longitudinal forces. The model limitation is for example that no steering is covered, which makes the vehicle unable to turn. A constant rolling resistance model gives the most realistic fuel consumption, although it is still low. The chassis is described as a sliding mass following Newton's second law and neglecting the gravitational force according to Nobrant [25]. The air drag model is described by the braking force from the air drag, neglecting the wind velocity because it has a small influence compared to the vehicle speed [25]. The driver is modelled as a PI-controller with reference values from the NEDC driving cycle [25]. The reference car is modelled with these components and it follows the NEDC driving cycle with satisfaction. The small difference between desired speed and vehicle speed depends on gear shifting. When following the NEDC driving cycle, the reference car has a too low fuel consumption — 6.34 l/100 km compared to an expected result of 7-8 l/100 km. A possible reason can be too ideal models and that there are more losses in the reality. The rolling resistance can for example still be too ideal and the neglected wind velocity in the air drag model makes a larger difference than expected, this has however not been verified.

Chapter 4 describes the components necessary for modelling HEVs. As ICE the `MvemEngine` in the reference car is used, implemented with a fuel cut-off mode to be able to turn off the ICE when desired. It is implemented as a "fuel factor" which rescales the effects of the fuel. In fuel cut-off mode when the fuel factor is zero, the energy flow becomes zero. The problem with this fuel cut-off mode is when the ICE reaches zero speed because the model is not developed to handle these low speeds. This is avoided by setting the ICE speed to 1 rpm when it reaches this limit. Another possible way to avoid the problem with the fuel cut-off mode is to switch between different ICE models — the "real" ICE model when driving normally and for example just an inertia when driving in fuel cut-off mode. This has not been verified in this thesis. Another problem with the ICE is when it is disconnected from the remaining driveline. Both to disconnect the generator (open the generator circuit) and to use a clutch between the generator and the ICE have been tested, unfortunately without success. The problem has not been investigated further. Instead of a traditional gear box, a CVT is used. `VehProLib` has two choices, either a simple CVT based on a quotient between required CVT speed and required wheel speed, or the ideal planetary gear in Modelica standard library can be used. In `VehProLib` there is a NiMH battery model. It is based on Strömbergs battery model [32] and is basically a look-up table between SOC and battery output voltage. The other NiMH battery model described in the thesis is made by Hellgren [13] and can be found in his Modelica library `Hevlib`. This model is a mathematical description of a Panasonic NiMH battery. Both battery models have no limits for the SOC level or output current and voltage. The output current can be controlled by the developed current limiter, although it is not tested in the series HEV. The battery based on a look-up table is used in the HEV models because it is easy to grasp and also tested together with the EM. The aim is to be able to switch between the different battery models, but this has not been investigated in this thesis. The EM is modelled as a synchronous DC-motor according to [32], which can be switched off with a boolean switch. The EM can also be used as a generator.

Chapter 5 describes how the vehicle components are put together to a series HEV. Both Modelica standard models and models developed in `VehProLib` are used. The working point is decided from ADVISOR to a torque of 105 Nm and a speed of 1250 rpm. The control strategy is to maintain the battery SOC level within 20 % and 80 %. When the SOC level reaches the lower limit, the ICE is turned on, charging the battery and turned off again when the battery is fully charged. A problem is however when the vehicle is driven with the ICE in fuel cut-off mode. The simulations take unreasonably long time and the vehicle does not move forward. When testing to replace the ICE by a torque, the vehicle can follow the NEDC driving cycle tolerably. The problem with the ICE has unfortunately not been investigated further because of the time limit.

In chapter 6 the parallel HEV can be seen, as the Toyota Prius in chapter 7. The control strategies for these vehicles has not been implemented and verified.

The purpose of the thesis has only partially been fulfilled. The vehicle components have been developed according to `VehProLib` and the reference car follows the NEDC driving cycle satisfactorily. When developing the series HEV, some problems with the ICE appear. When replacing the ICE with a torque, the series HEV manages to follow the driving cycle tolerably, but lots of work remains to solve the ICE problems and improve the control strategy. The reference car can however be used, both to show how the different components in `VehProLib` work together and be an illustrative example of the function of a driveline in an ordinary car.

8.1.2 Modelica and Dymola

During this work, some experiences from the modelling environment in Modelica and Dymola have been made. The Modelica language is very interesting and seems simple to use. The idea with equation modelling and to be able to reuse equations by “drag and drop” components in new models is attractive — just describe your model with a certain number of equations and then connect it with other models and simulate! To summarize, the non-causality, equations describing the models and reuse of the equations seem very good to me.

The non-causality however causes problems and makes the simulation results rather complicated to analyse and compare to each other. A flow variable has a positive sign when it flows into a component and a negative sign when it flows out. This is of course physically correct and a proper way to describe the flow direction. But when simulating, plotting different variables and comparing them to each other, this makes it difficult. You have of course to know the model very well in order to analyse the results, but you also have to know at which end of the components the variable is “seen” and remember the signs. After an intense work with Modelica and Dymola, I still not understand which one of the positive or negative variable that is the “real one” and how to be sure that variables have been chosen that is comparable to each other due to the sign convention. My wish is improved simulation tools that makes the simulation results easier to understand, for example only show variable values comparable to each other (and show all the information when asking for it).

The work has sometimes been very confusing and frustrating due to bugs and simulation problems in Dymola. The tools need to be refined to achieve a simulation environment that is easy to work. The largest problem with Dymola is its sparse error messages. Often it for example only says “DAE with 555 unknown scalars and 559 scalar equations. Check of Model succesful.” Every single submodel must be controlled and no hint of where the extra, unnecessary equations are situated is given. It often requires a lot of time to reduce the number of equations and a good share of luck is needed.

When different models are built without “knowledge of each other” they may interact in a way that causes problems. The idea with connecting models leads to that the person who makes the modelling work has to have great model knowledge. He or she shall have a detailed knowledge about every single model and also a detailed knowledge of how they interact with each other. This may sound like an ordinary requirement in modelling work, but here you shall for example know if a certain variable is computed or indirectly defined and computed in some other submodel or in the combinating process. When the models become larger and more complex, it is hardly possible to be able to know all this information.

8.2 Future Work

HEVs are very exciting and interesting and there is a lot more to do. Unfortunately it requires much more time than has been available. The aim with the different batteries was to have the table battery as a test battery during the development and be able to replace it by the more advanced physical battery. Now there are differences between the two batteries that makes it impossible to use them in the same way and be able to replace them by each other. The first thing to do is to make them charge and discharge in the same manner. Next thing is to control them similarly and then be able to replace the table battery by the physical battery.

One interesting thing to investigate is to add a supercapacitor in the HEV in connection to the battery. The supercapacitor has higher specific energy and can deliver higher power than an ordinary battery.

It is an electrolytic capacitor-device and the energy is stored as electrostatic charge [1]. The current from the battery is sometimes smaller than required. Therefore you can add a supercapacitor that can deliver a higher current during a certain time when it is required and be a "back up" and give extra "power" to the battery. It would be very interesting to compare a vehicle with just a battery with a vehicle with both a battery and a supercapacitor. It is possible to have a smaller ICE and battery when the supercapacitor increases the performance of the car? Smaller components are positive because they give a lighter vehicle with a reduced fuel consumption.

Another idea to work with, is to have different strategies when charging the battery. Is it better to charge the battery only when it has reached the lower limit or should it be charge continuously when a good opportunity appears? What happens to the fuel consumption if the vehicle has an "electric mode button" that makes the driver able to decide only to drive with the EM, for example in cities or sensitive environmental areas?

The fuel cut-off ICE is special designed for HEVs in this thesis. First the problems with disconnecting the ICE and driving in fuel cut-off mode have to be solved. A future work is to enlarge the fuel cut-off ICE with the behaviour that is characteristic for a conventional vehicle with fuel cut-off. Another thing to implement in the model is a restriction of how often the ICE is allowed to turn on and off. Is it a better strategy to allow the engine to turn on (if required) after a certain time after the latest turn off?

One more thing that I would like to do is to model other hybrid cars, for example Honda Insight and Ford's Escape Hybrid and also newer models of Toyota Prius. Which one of the cars seems to have the best topology? Is there a difference between an older version of Prius and the newer one regarded to fuel consumption — progress or negative development? The idea of comparing HEVs with each other is very interesting, because many studies are made separately, but there is a problem when you want to compare them. Are they made similarly or do they have main differences that may influence the comparison?

An improvement of the reference car model is to add an electric starter motor to start the ICE. Other improvements are for example to investigate the rolling resistance in the wheel model deeper and make the vehicle able to turn. Further work is to treat the five gears differently in the gear box and develop a driver that behaves more like a human beeing.

Last but not least it is also important to investigate how components and models in `VehProLib` can be combined with other libraries, for example Andreasson's `VehicleDynamics` [19].

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Notation

Symbols used in the report.

Abbreviations

CVT	Continuously variable transmission
DAE	Differential algebraic discrete equation
EM	Electric motor
EV	Electric vehicle
HEV	Hybrid electric vehicle
hp	Horse power
ICE	Internal combustion engine
IMA	Integrated motor assist system (Honda)
$MVEM$	Mean value engine model
$NEDC$	New european driving cycle
$NiMH$	Nickel metal hydride
rpm	Revolutions per minute
SOC	State of charge
$SULEV$	California's super ultra low emissions vehicle standard
THS	Toyota hybrid system

Variables and parameters

A	Vehicle front area
$BMEP$	Brake Mean Effective Pressure
c	Drive shaft internal damping
c_0	Parameter of wheel rolling resistance
c_1	Speed dependent parameter of wheel rolling resistance
c_D	Aerodynamic drag coefficient
$CVT_{gear\ ratio}$	Gear ratio for the CVT
η	Reduction gear ratio
φ_{gear}	Output gear rotational angle
φ_{ICE}	ICE rotational angle
F_{air}	Air drag force

f_{fr0}	Wheel rolling resistance at zero speed
f_{fr1}	Speed dependent component of the wheel rolling resistance
F_{roll}	Wheel rolling resistance
$FMEP$	Friction Mean Effective Pressure
$f(SOC)$	How SOC influences battery output voltage, a look-up table
g	Acceleration of gravity
i_{batt}	Battery current
$I_{cellPos}$	Positive battery current in a single cell
$I_{cellNeg}$	Negative battery current in a single cell
i_{EM}	Input current to EM
$IMEP$	Indicated Mean Effective Pressure
k	Drive shaft stiffness
k_{EM}	EM magnetization
K_i	PI-controller parameter
K_p	PI-controller parameter
λ	Air-to-fuel equivalence ratio (normalized (A/F))
L_{EM}	EM inner resistance
m	Vehicle mass
m_a	Mass of air in the cylinders
m_f	Mass of fuel from the fuel tank into the cylinders
$\dot{m}_f$	Mass of fuel per second from the fuel tank into the cylinders
mps	Mean piston speed
p	Planetary gear ratio between number of teeth of sun gear and ring gear
$PMEP$	Pumping Mean Effective Pressure
Q_{in}	Energy flow into the cylinders
$\dot{Q}_{in}$	Energy flow per second into the cylinders
q_{LVH}	Lower heating value
Q_{max}	Maximum battery charge
$Q(t)$	Battery charge, time dependent function
R	Battery inner resistance
r	Gear ratio
r_c	Compression ratio
R_{EM}	EM inner resistance
R_{overch}	Extra resistance when battery is overcharged or undercharged
R_p	Resistance in `NiMHbattery`
ρ	Air density
S_{acc}	Gas pedal signal
$SIZE$	Size of the battery pack
SOC	Battery state of charge
SOC_{init}	Initial battey state of charge when simulation starts

T	Torque
$T_{driveshaft}$	Torque to drive shaft
T_e	Torque from ICE
T_{EM}	Torque from EM
T_{gear}	Torque from CVT
$T_{gearbox}$	Torque from gear box
$T_{generator}$	Torque from generator
T_{ICE}	Torque from ICE
T_o	Driving torque in Toyota Prius
T_{ring}	Torque from planetary ring gear
U_{batt}	Battery voltage
U_{cell}	Battery voltage in a single cell
U_{EM}	Input voltage to the EM
U_{max}	Battery maximum voltage
v	Vehicle velocity
$VarR$	Resistance in variable resistor
V_d	Displaced volume in one cylinder
$V_{d,tot}$	Total displaced volume in all cylinders
v_s	Wind velocity
$v_{vehicle}$	Vehicle velocity
ω_e	Angular velocity from ICE
ω_{EM}	Actual angular velocity from EM
$\omega_{gearbox}$	Angular velocity from gear box
$\omega_{ICE,\ required}$	Required angular velocity from ICE
ω_{wheel}	Wheel angular velocity
$\omega_{wheel,\ required}$	Required angular velocity from the wheel
W	Fuel mass flow from tank
$W_{percycle}$	Work per cycle