

Hybrid Drive Systems for Vehicles

Part I

System Design and Traction Concepts



**LUNDS TEKNISKA
HÖGSKOLA**

Lunds universitet

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Preface

This material is written for the course “Hybrid Drive Systems for Vehicles” given by the Royal Institute of Technology (KTH), Chalmers University of Technology (CTH) and Lund University (LTH) in a joint effort. The material is made to be an introduction into the world of hybrid drive technologies and is intended for students from all traditional disciplines, electrical and mechanical engineers, chemical engineers, physicists etc. It is, if not necessary, at least helpful to have studied fundamental mechanics (Newton’s laws of motion) and fundamental electrical circuit theory to be able to follow the course. Since the material takes extensive advantage of computer simulation in Simulink, it is also helpful to have some experience in using such software.

The ambition of the material is NOT to give exact answers to what technology or system is the best, but to give enough insight and tools for the student to do further evaluation.

The material in this first part of the course is based on ideas developed over years at our department at LTH, and is a compilation of material directly or indirectly developed by Karin Jonasson, Christian Andersson, Bengt Simonsson and Mats Alaküla.

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1. Why study Hybrid Vehicles ?

Transportation is fundamental to societal and economic growth. The prosperity of society is however to a large extent based upon the use of fossil fuels for transportation, heating and generation of other forms of energy like electricity. This is what is called a non-renewable energy source that mankind is depleting at warp-speed compared to the time it took to aggregate the energy stored in oil and coal. We are on an almost daily basis reminded of the price paid for this prosperity, the earth shows clear signs of being irreversibly damaged by us. These reminders have made many aware of the need of change to a sustainable society, where we live on renewable resources. For transportation, this means:

- 1 We need to reduce the emissions related to transportation.
- 2 We need to base the transportation on renewable, and environmentally friendly, fuels.

Both these statements point at a need for further development of the type of transportation means we use today. By improving the efficiency of the various types of engines used, less fuel will be spent. This in turn increases the possibility of actually producing enough renewable fuels to supply everyone's needs.

It is today a known fact that various kinds of energy buffers to support the Internal Combustion Engine can have the effect of improved energy conversion efficiency. It is also evident that the same technology can be used to reduce emissions. These Hybrid Vehicles are a key technology to reduce emissions and simplify the use of other fuels. Completely new energy conversion concepts emerge as well, like the fuel cell technology that may replace the internal combustion engine as the primary energy converter. The fuel cell technology, when based on hydrogen as fuel, is completely clean and environmentally benign. The emission problem is however not entirely solved until the hydrogen is produced from renewable resources. This can theoretically be made today, but there is still no consensus on what method that is best.

Describing how the design and control of a hybrid drive system affect emissions directly is very difficult. Describing how the fuel consumption is affected is less difficult. Since low fuel consumption, and lower demands on the combustion engine dynamics, follows from hybridization it is fair to say that efforts to reduce fuel consumption also can contribute to reduced emissions. The latter statement is however not necessarily always true, the opposite may very well be the case. It will be shown that an effort to reduce fuel consumption only with hybridization means can simultaneously maximize emissions if care is not taken.

The conclusion will be that the maximum success in design and control of a combustion-electric hybrid drive system requires that BOTH the combustion engine control, the electric drive control and the systems level control are taken into serious account.

In the next few chapters, the details of how to design and control hybrid drive systems for vehicles are studied with focus on reduced fuel consumption. However, the reader must keep in mind that it is not only the fuel consumption that is important. The same tools that are taught here can be used to control emissions, but that possibility is related to other combustion engine control aspects like valve timing, turbo charging, variable compression etc. To take advantage of those possibilities requires much more knowledge on the combustion process than intended to follow this material. For the skilled combustion specialist, this material will however give a good insight into new possibilities for improvement of combustion engines that reach beyond reduced fuel consumption.

As the fuel cell based traction system is becoming a highly relevant alternative, it is also studied in comparison to the more conventional internal combustion engine hybrids.

2. Traction systems

This chapter is about the systems used to actuate linear movement of rolling ground vehicles, henceforth just called vehicles. Fundamental energy aspects will be discussed related to the linear movement, primary energy conversion, intermediate energy storage and efficiency. Only the linear movement is discussed, i.e. aspects of stability and road handling are not included. The chapter starts with an ideal vehicle, and then gradually adopts real system components with the ambition to explain the properties of different traction systems.

2.1. The ideal vehicle

The ideal vehicle is able to convert all primary energy into tractive work, i.e. into the energy needed to overcome wind and rolling resistance. The ideal vehicle does of course not exist in reality, but is useful in setting the theoretical limit for energy efficiency related to propulsion of vehicles. No real vehicle can be better than the ideal one, but it sets the limit for how good they can get. The ideal vehicle is however not able to regenerate the braking energy, but this option will also be examined.

Structure

The general traction system structure is shown in Figure 2.1. The *primary energy storage* is the conventional “tank” filled with gasoline, diesel, ethanol, and in some cases with e.g. natural gas or even hydrogen. The *primary energy converter* is uni-directional (only one direction of the energy flow) by nature, e.g. the conventional combustion engine. Even the fuel cell engine fits in here, if it is combined with the necessary power electronics and electrical machines needed to realize mechanical work on a rotating shaft. The *transmission* is the mechanical transmission with the gearbox and differential gears between the primary energy converter and the wheels. The *Newton’s mechanical dynamics* etc. is the mechanical dynamics of the vehicle, i.e. the mass of the vehicles with the forces acting upon it. These are the tractive force from the energy converters, the friction braking forces and the wind and roll resistance braking forces from the road.

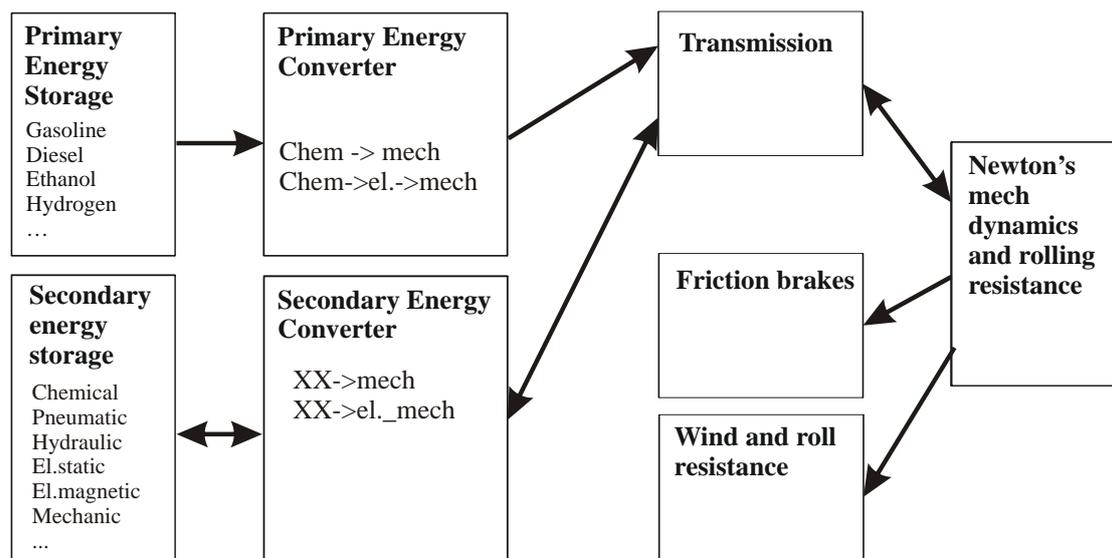


Figure 2.1 Generic traction system structure. Note the arrow directions, indicating possible energy flow.

The *secondary energy storage* is the energy storage used to buffer energy converted by the primary energy converter or energy regenerated from braking (not friction braking). The *secondary energy converter* is bi-directional in nature and converts energy to/from the secondary energy storage.

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One example is the power electronically driven electrical machine that is most common in electric hybrid vehicles.

In the ideal vehicle, all components have 100 % efficiency in energy conversion, with two restrictions:

- The air and rolling resistance represent the friction forces acting on the vehicle, and these forces are modeled to equal reality.
- The primary energy converters are limited in maximum tractive force.

Air and rolling resistance

The braking force acting on the vehicle is in this context modeled as the sum of an air resistance term and a roll resistance term. The equation describing these braking forces acting upon the vehicle is given by equation (2-1) and Figure 2.2.

$$F_f = \left(C_r M_v g + \frac{1}{2} \rho_a C_d A_v v^2 \right) \quad \text{Equation 2-1}$$

P_r = resistance power, C_r = rolling resistance, M_v = vehicle mass, g = gravity, ρ_a = air density, C_d = air resistance, A_v = vehicle front area, v = vehicle speed

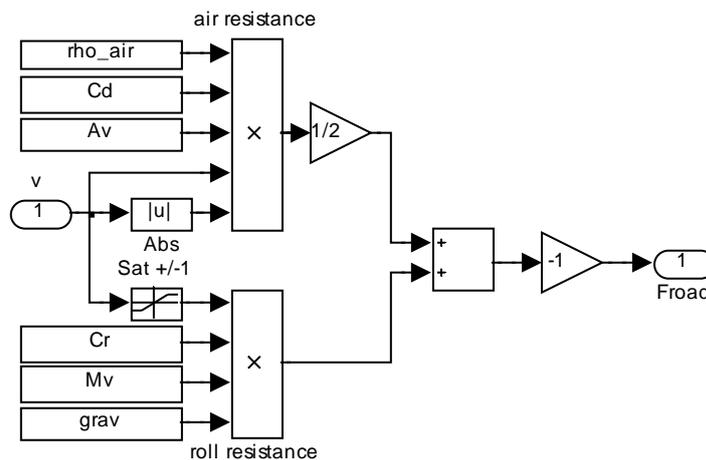


Figure 2.2 Braking forces acting on the vehicle, expressed as a Simulink diagram.

The air resistance is regarded as proportional to the square of the speed, the air density, the vehicle frontal area and the air resistance factor (the C_d -value). The roll resistance is regarded as constant and proportional to the vehicle weight, the gravitation and the roll resistance factor (the C_r -value) of the tires. At very low speeds the roll resistance is also proportional to the speed, however, this is not represented in equation (2-1), but accounted for in Figure 2.2 where the roll resistance is scaled with speed below 1 m/s.

2.2. Simulation of ideal vehicles

In this section, the energy consumption of an idealised vehicle, a private car, is studied. The private car is as similar to a Toyota Prius generation II as possible. Detailed specifications of the Toyota Prius can be found in Appendix 1. The vehicle is simulated with the Simulink program "Ideal". This program is available on the disc or homepage related to this material. You can use the simulation program yourself. The code is full of explanations to facilitate understanding.

One example of the simulation results is shown in Figure 2.3. Note that drive torque is the torque on the wheels produced by the traction system, and the break torque is the torque on the

wheels produced by the mechanical friction breaks. The road torque is the breaking force due to rolling and air resistance represented as a torque on the wheels. All torques are expressed as acting upon one wheel, but in reality they would of course be applied to at least two or four wheels.

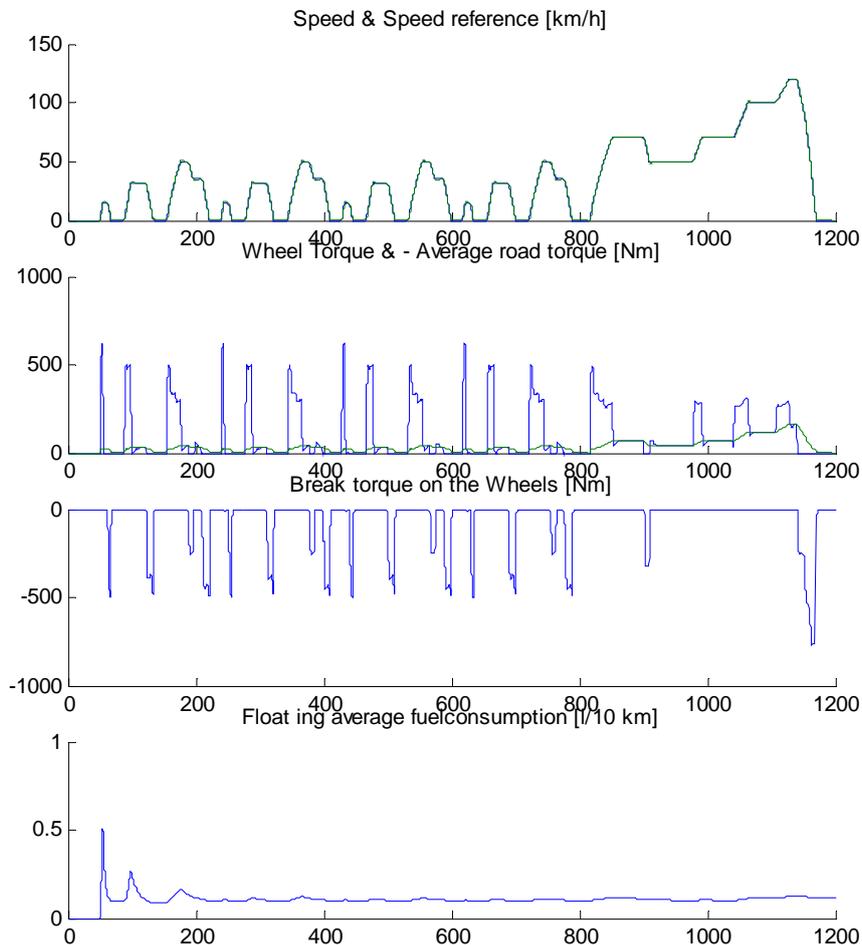


Figure 2.3 Simulation of ideal private car in the EUDC cycle.

Note in Figure 2.3 that the vehicle is able to follow the speed reference. Note also that the drive torque exceeds the road torque (=rolling and wind resistance) when the vehicle accelerates, but is zero when the vehicle decelerates. In deceleration, it is instead the friction brakes that excite the torque on the wheels. The fuel consumption in Figure 2.3 is calculated as the energy used for wheel torque (excluding friction breaks) divided by the traveled distance and the energy density of gasoline. The primary energy converter and the transmission is thus regarded as having no losses.

The complete set of results is, in terms of energy use, summarized in Table 1. There are three energies to be defined:

- *Road Energy.* The road energy is the roll and wind resistance multiplied with speed and integrated.
- *Break energy.* The brake energy is the brake force multiplied with speed and integrated.

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- *Fuel Energy.* This is the energy used by the primary energy converter to propel the vehicle. It contains the energy needed to overcome friction (road energy) and to accelerate the mass. The energy needed to accelerate the mass is returned to the brakes when reducing the speed. Thus the fuel energy corresponds to the road energy and the braking energy.

Table 1 Fuel consumption for two different drive cycles with a private car. The parameters of the car equals a Toyota Prius generation I. See Appendix A for details about the vehicle and the driving cycles.

Case	EUDC	US06
Private car		
Fuel energy used [Ws]	4.13e6	15.5e6
Road energy [Ws]	2.49e6	10.1e6
Breaking energy [Ws]	1.64e6	5.3e6
Gasoline consumption [l/10 km], friction braking.	0.12	0.19
Gasoline consumption, with 100 % regeneration of braking energy [l/10 km]	0.07	0.13

In Table 1 the fuel consumption is calculated as the gasoline volume corresponding to the fuel energy, assuming that 100 % of the fuel energy is converted to useful work (= road energy+brake energy). Friction braking means that all braking energy is dissipated in the brakes. Regenerative braking means that all braking energy is regenerated to the primary energy source. Note that regenerative braking has the potential to recuperate almost half the fuel energy in city traffic (ECE15) but about 1/3rd of the fuel energy in highway traffic (US06). See appendix A about the EUDC and US06 driving cycles.

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3. Non ideal vehicle components

The vehicle analyzed in section 2.2 is not possible to accomplish in reality, but it indicates the theoretical limit for the fuel consumption of this specific vehicle, i.e. around 1-2 deciliter/10 km. If the friction coefficients, the weight and the frontal area of the vehicle in equation (2-1) can be reduced, the abovementioned theoretical lower fuel consumption limit will be reduced correspondingly. However, this context is not dealing with such possibilities, merely with those related to improvement of the traction system. It should also be emphasized that the vehicle modeled, the Toyota Prius, represents a serious effort by a leading vehicle producer to minimize the parameters of equation (2-1) whilst keeping a practically useful vehicle.

To understand the fundamental energy conversion limitations, realistic models of the different energy conversions taking place in a real vehicle must be introduced in the model. In doing so, the possibilities to reach the theoretical limits of fuel consumption by hybridization means can be analyzed.

3.1. Primary energy storages

The primary energy storage is in this context regarded as the system that contains energy not aggregated on the vehicle, but elsewhere like in a refinery or an electrolysis system, and then transferred to the vehicle.

Fluid storage

Fluid energy storages are the conventional gasoline tank. This has an energy density of about 32000 kW/liter and a storage efficiency of 100 %.

Gas energy storages

Because the hydrogen used as fuel has a low energy density per volume, as much hydrogen as possible must be available to ensure a practical vehicle range. At the same time packaging considerations dictate that as little storage space as possible must be taken up by the fuel tanks.

A modern example is the Honda FCX that utilizes a high-pressure hydrogen tank with a three-layer construction composed of an aluminium liner, carbon fibre, and glass fibre, for strength and corrosion resistance, to achieve a filling capacity of up to 350 atmospheres. Two of these tanks are employed to secure a 156.6L fuelling capacity. This large capacity plus improved fuel consumption results in a vehicle range of 355km. Fuelling time at a high-pressure fueling station is only three minutes, for a level of convenience comparable to that of a gasoline-powered vehicle. Figure 3.1 shows the layout of the storage tank and the way two such tanks are located in a vehicle.

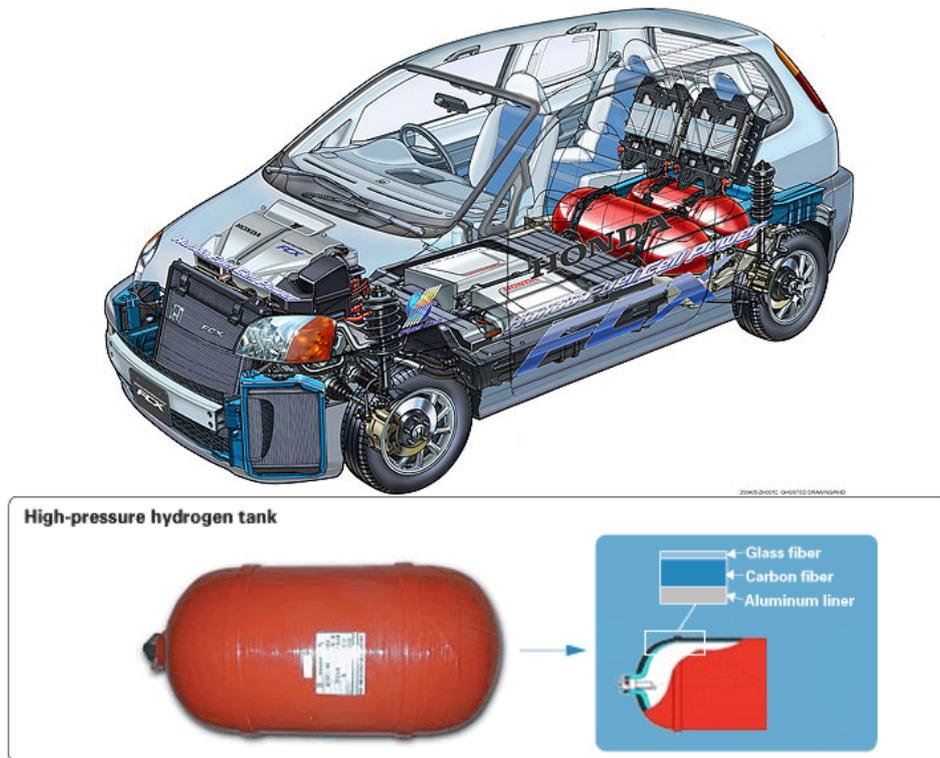


Figure 3.1 Hydrogen storage tank in Honda FCX.
 (<http://world.honda.com/news/2004/4041220.html>)

3.2. Secondary Energy storages

The secondary energy storage is in this context regarded as the energy storage that handles energy consumption variations, like absorbing braking energy or supporting the primary energy converter with additional power, e.g. in heavy acceleration. In most cases this energy storage is electrochemical (=conventional batteries), but it can just as well be of the other types discussed below.

Electrochemical storage¹

This group of energy storage systems contains the conventional batteries, even though the term battery formally can be given a wider interpretation. Some common types of electrochemical energy storage systems are discussed below. The traction battery is the "fuel tank" of the electric vehicle, which is where the energy needed for driving is stored. It is also the most critical component of the vehicle. The principle of a battery is at a superficial level very simple: between two different materials (electrodes) immersed in an electrolyte solution a potential difference will occur. Numerous battery types have been developed, only a small number of these can be taken into consideration for traction purposes.

The following table gives an overview of the different battery types. The cycle life and cost data are estimates, except for lead-cadmium, which are commercial products.

¹ This section is to a large extent copied from (<http://www.aveve.org/working/en/traction.html>).

Table 2 Overview of different electrochemical energy storage types

	Wh/kg	W/kg	Cycle life	Cost ECU/kWh
Lead-acid	35	110	600-1000	150
Nickel-cadmium	50	175	1500 - 2000	600
Nickel-Metall Hydride	70	200	1500	250
Sodium-Sulphur	107	100	600	250
Sodium-Nickel Chloride	90	110	1000	250
Zinc-Bromine	70	100	1000	250
Zinc-Air	180	125	400	125
Lithium	100-200	1000	1000	250

The energy density (Wh/kg) allows a relationship to establish between battery weight and energy content. The power density (W/kg) is a measure for the maximum power (or the maximum current) the battery can deliver, and thus for the performances (acceleration, maximum speed) of the vehicle.

The cycle life of the battery is expressed in number of cycles. The number of discharge/charge cycles a battery can sustain depends on many factors, like the power level at which the battery operates, the temperature, the depth of discharge. One and the same battery can sustain 1 000 000 cycles at 5 % DOD (Depth Of Discharge) but only 2000 cycles at 80 % DOD. A cycle is a charge followed by a discharge; the life cycle is considered as terminated when the battery capacity falls under a predefined value (e.g. 70% of nominal capacity).

Through the years, several battery types have been developed to be used in electric vehicles; the most important types was in the 80's the lead-acid battery and in the 90's the nickel-cadmium battery, but but since the end of the 90's the nickel-metal hydride has dominated advanced vehicles and now most future projections indicate that the lithium type of batteries will dominate.

The Lead-Acid Battery

The lead-acid battery was invented by Gaston Planté in 1860. In the end of the 19'th century and in the first decade of the 20'th century, battery operated vehicles were dominating. Around 1900, there were twice as many electric vehicles as combustion driven ones in USA. The battle against the ICE was however lost due to the same reasons that has made pure EV's questionable in latter years – short driving range, high cost, and long recharging time. Today, it is the most widely used traction battery for electric vehicles, if these include fork lifts and golf vehicles etc. In modern road EV's and HEV's however, other types dominate. The Lead Acid battery is not the most powerful, but definitively the cheapest. Since the 1950's the performance of a Lead Acid battery is doubled AND the price reduced by a factor of 50!

In its basic form, the lead-acid battery consists of a negative plate made from lead metal and a positive plate made from brown lead dioxide, submerged in an electrolyte consisting of diluted sulphuric acid.

- *Flat plate batteries* The best known example of such a battery is the SLI battery (Starting, Lighting, Ignition), that is an ordinary car battery. Car batteries are designed to deliver high current bursts for cranking; to this effect, their plates are very thin to obtain a large active surface and a large current. A car battery is not designed for repetitive deep cycling (charge/discharge) needed in an electric vehicle, as it will not last for long.

Flat plate batteries for electric vehicle purposes have thicker plates and withstand deeper discharges. Such batteries are called "semi-traction" batteries.

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Their energy density is quite high, and they are cheaper than real traction batteries with tubular plates. Their cycle life is rather limited (500-800 cycles); their use is recommended for less strenuous applications.

- Tubular plate batteries In this type, the positive plates consist of tubes made from a porous fabric and filled with lead dioxide. A central lead spine serves as current conductor. These are the genuine traction batteries and are recommended for heavy-duty industrial purposes. Their cycle life can be up to 1500 cycles, with an energy density of 28-30 Wh/kg. The most advanced cells on the market give up to 33 Wh/kg. It should be stated however that "tuning-up" the energy density of a battery in most cases decreases the cycle life.

The disadvantage of the tubular plate battery is its relatively high internal resistance compared to the flat plate battery, which leads to a lower power density.

Both flat plate and tubular plated batteries need regular maintenance: topping up with distilled water. The consumption of water is due to the electrolysis of the electrolyte during charging.

- Maintenance free batteries. As its name implies, the maintenance free battery does not require any maintenance, which makes these batteries very popular for electric road vehicles. Most electric vehicles on the market now come with specially designed batteries.

They are more expensive however, and their cycle life is shorter (600-800 cycles).

Furthermore, they are sensitive to deep discharges and surcharges. They may only be used with specially designed battery chargers.

The Nickel-Cadmium battery

This battery has also been in existence for a long time: it was invented by Thomas Alva Edison. In this battery, the positive electrode is made from nickel oxide and the negative electrode of cadmium. The electrolyte consists of a potassium hydroxide (lye) solution.

Also in the nickel-cadmium battery, water consumption takes place through electrolysis of the electrolyte. This occurs on a larger scale than with the lead-acid battery; the water consumption will thus be higher.

Compared with a lead-acid battery, the nickel-cadmium battery has a higher energy density and above all a much higher power density, which makes it particularly suitable for traction applications. It can be charged rapidly and will stand deep discharges (up to 100%). Its energetic efficiency is lower, which means higher energy consumption on the grid and more maintenance (topping up).

The main disadvantage of the nickel-cadmium battery is the toxicity of Cadmium, which is the main reason why NiCd batteries are abandoned.

The Nickel-Metal Hydride Battery

This type of battery is strongly akin to the nickel-cadmium battery; it also uses an alkaline electrolyte. Cadmium is not used however, which is an added environmental benefit on one hand and a cost benefit for large scale production on the other hand, as cadmium is only available in limited quantities. This type is used in the 2nd generation of Toyota Prius.

The Sodium-Sulphur Battery

This battery is essentially different from the previously mentioned types: it has liquid electrodes and a solid electrolyte, and its operating temperature is much higher: about 300°C! The battery, constituted of a large number of individual cells, is mounted in a thermal enclosure.

Problems concerning cycle life and safety still inhibit the commercialisation of this type of battery.

The Sodium-Nickel Chloride Battery

This battery, also known as the "ZEBRA" battery, is very much akin to the sodium-sulphur battery; the negative electrode consists of sodium however and the positive of nickel-chloride.

This positive electrode is solid and is connected to the solid electrolyte through a molten liquid electrolyte (NaAlCl₄). The fixed electrolyte also consists of ceramic material.

The sodium-nickel chloride battery can not be considered as a commercial product either; its perspectives for the future seem a bit brighter than for the sodium-sulphur battery however.

The Zinc-Bromine Battery

The zinc-bromine battery is a complex electrochemical system built up around a central reaction cell, the so-called "stack", and a circulated electrolyte. The electrolyte is stored in separate tanks and consists of a zinc solution on one part and a complex bromine compound on the other.

The zinc-bromine battery is being manufactured on an experimental basis as its complicated structure (reservoirs, circulation pumps, ...) and the toxic character of the bromine are drawbacks for its commercial development.

The Zinc-Air Battery

This battery is particular: unlike all other batteries, it can not be recharged directly from the electric network. After discharge, the zinc electrodes have to be regenerated through an electrochemical process (which actually uses electricity) in a special plant to prepare the battery for a new cycle.

In practice, the vehicles will be fitted with a battery exchange system and discharged battery packs will be dispatched to a central processing facility.

The practical feasibility of such a battery is considerably burdened by the heavy logistics involved; however an experimental example of such batteries was performed by the German Post Office.

The relative performances of different electrochemical couples are shown in Figure 3.2.

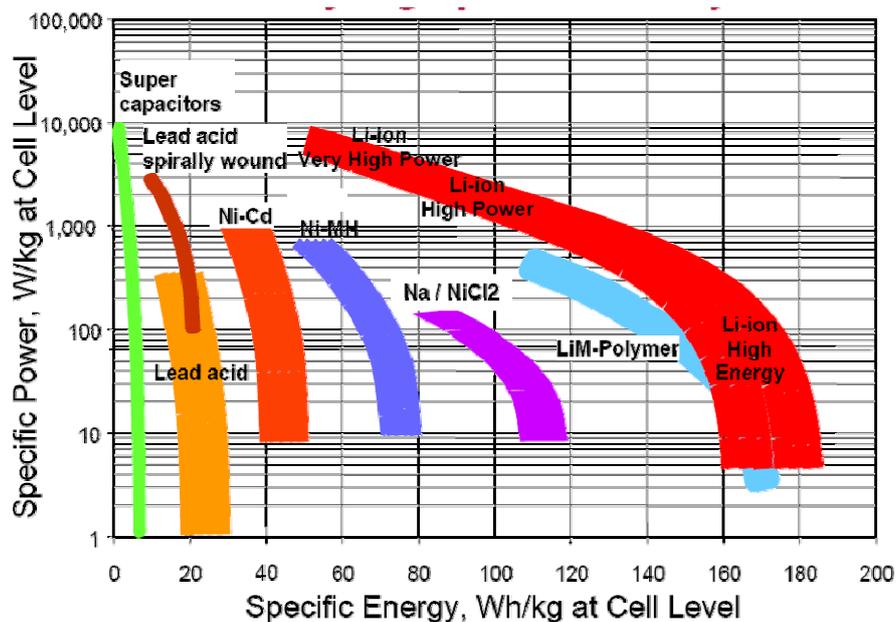


Figure 3.2 Energy as a function of power for the most common traction batteries.

Battery simulation model

The battery model represents the battery losses that are dissipated both during charge and discharge. A battery model can be made very complex, since there are numerous parameters that depend on the SOC (State Of Charge), the temperature, current, age (SOH – State Of Health) and history of the cells etc. A simple, but useful for comparative studies like in this context, model is an emf in series with a resistance, see Figure 3.3.

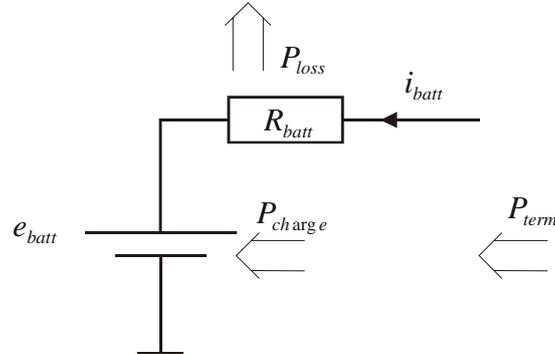


Figure 3.3 The figure shows a schematic model of the battery used in the simulation model.

Both the emf e_{batt} and the resistance R_{batt} are assumed to be constant. The terminal power P_{term} is the power supplied to the connection terminals of the battery. Note that motoric references are used, i.e. positive terminal power charges the battery. The efficiency as a function of the power level can be calculated as follows.

$$P_{term} = (e_{batt} + R_{batt} \cdot i_{batt}) \cdot i_{batt} = e_{batt} \cdot i_{batt} + R_{batt} \cdot i_{batt}^2$$

$$i_{batt} = -\frac{e_{batt}}{2 \cdot R_{batt}} \pm \sqrt{\left(\frac{e_{batt}}{2 \cdot R_{batt}}\right)^2 + \frac{P_{term}}{R_{batt}}}$$

$$P_{loss} = R_{batt} \cdot i_{batt}^2$$

$$P_{charge} = P_{term} - P_{loss}$$

$$\eta_{batt} = \frac{P_{charge}}{P_{term}}$$

Equation 3-1

The battery model is based on physical data originating from the Toyota Prius 1st generation, when such have been available. Supplementary data have been used from battery measurements. These data are mould together into a look-up-table with efficiency (η_{batt}) as output and terminal power (P_{term}) as input, see Figure 3.4.

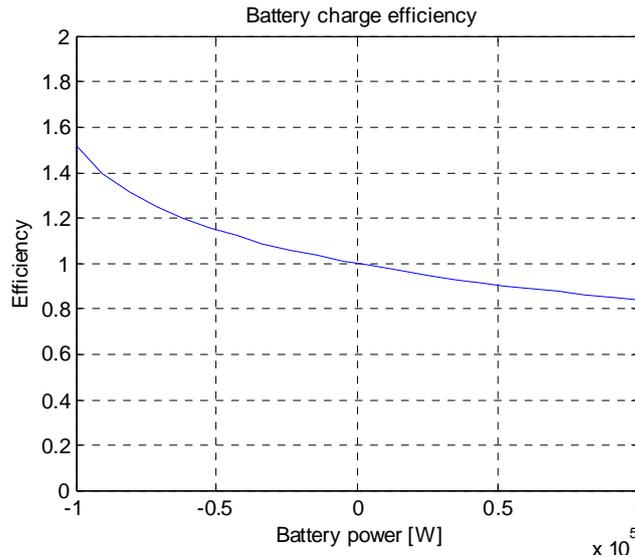


Figure 3.4 Battery efficiency as function of P_{term} .

Note that the efficiency higher than one with negative charging power (= discharging) shall be interpreted as more energy than extracted from the battery terminals is actually removed from the energy storage, as some is dissipated in losses. Note that the charging/discharging efficiency drops significantly at high powers but that, in a Prius, the peak power for the secondary energy storage is around 60-70 kW, and the average power P_{term} is significantly less, thus indicating that the battery efficiency usually is in the range 80-90 %.

It must be emphasized here that the suggested model is almost the simplest possible. Still it represents the losses rather well in comparative studies like the ones made in this material. Note also that since the battery terminal voltage does vary with load, and in a real battery also with state of charge, a power electronic converter is sometimes used to adapt the battery to a fixed “system” voltage used by other traction system components.

Electrostatic energy storage.

This type is usually referred to as the “Super Capacitor” or the “Ultra Capacitor”. These are capacitors with very low maximum voltage, only 2-3 Volts, but with an (for capacitors) unusually high capacitance. The low voltage makes it necessary to series connect many cells in order to reach the voltage levels that are normally used for tractive energy storage in vehicles. This creates a new problem – a charge distribution system must be applied to guarantee that an individual capacitor in a series connection does not exceed its maximum voltage. A simple way to accomplish this is to parallel connect the capacitors with resistors.

The most attractive capability as compared to electrochemical batteries is a high power density. A Super Capacitor system in the size of a cabin bag has energy content in the size of 100’s of kilowatt-seconds² [kW_s], but a maximum output power of 10’s of kW.

An important difference when comparing Super Capacitors with Electrochemical batteries is that the voltage varies strongly with the energy content. A capacitor with the capacitance C (expressed in Farad [F]) stores energy according to equation (3-2).

² Kilowatt-seconds will be used to some extent in this book, since this relates rather well to the practical operation of a vehicle. The power level is usually in the range of 1-100 kW and regarding the secondary energy storage it is usually acting in the range of seconds rather than hours.

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$$W_c = \frac{1}{2} C \cdot u_c^2 \tag{Equation 3-2}$$

where u_c is the voltage across the capacitance. Note that when capacitors are series connected the capacitance of the series connection (C_{system}) is calculated from the single capacitors capacitance (C_{unit}) as

$$C_{system} = \frac{1}{\sum_{\#units} \frac{1}{C_{unit}}} \tag{Equation 3-3}$$

As an example, if you series connect 100 capacitors with the individual capacitance 10 F, the series connection will have the capacitance 0.1 F. Since the system voltage is 100 times higher for the series connection than for the individual capacitor, and the energy content is proportional to the square of the voltage, the energy content of the system will still be 100 times the energy content of the single capacitor, in spite of the lower system capacitance.

Since the energy is proportional to voltage squared, Super Capacitors need to be connected to the drive system with power electronics that adapt the varying capacitor voltage to the system that feeds energy to the traction motors (secondary energy converter in Figure 2.1). It is usually not meaningful to let the capacitor voltage drop lower than half its maximum voltage, since only a quarter of the energy is left when the voltage is halved. In addition, the maximum power is based on the maximum current allowed in the conductors of the capacitor, which means that if the voltage is reduced to half, then the maximum power is also reduced to half.

An example of data for a single capacitance and a system is given in Table 3. Maxwell (a large super capacitor producer) has a design tool on the Internet page <http://www.maxwell.com/ultracapacitors/support/worksheet.xls>) that is helpful in system design.

Table 3 Data for a Super Capacitor from Maxwell

	
Size	22 liter / 15 kg
Capacitance	145 Farads
Max electric specs	50 V / 600 A
Power density	2900 W/kg
Energy density	2.3 Wh/kg

Electro mechanic energy storage

This type of energy storage is also called a flywheel. The idea is to spin a wheel and thus store kinetic energy in the rotating mass. The energy stored in a spinning wheel is expressed as

$$W_{mech} = \frac{1}{2} J \cdot \omega_{wheel}^2 \quad \text{Equation 3-4}$$

where ω_{wheel} is the angular speed (expressed in [rad/s]) of the rotating mass and J is the inertia (expressed in [kgm²]). Since the aim is to store as much energy as possible, such wheels are designed with Kevlar fiber reinforced masses and encapsulated in steel domes for safety in case the flywheel explodes. To transfer energy back and forth between the energy storage and the secondary energy converter (if electric), an electric machine is mounted on the shaft of the rotating mass, and power electronics is used to feed energy in and out of the electric machine and thus the rotating mass.

In analogy with the super capacitors, there is a limit on the torque that the electrical machine can apply to the rotating shaft, which limits the power transfer so that at half maximum speed the power is also reduced to half (since power=speed*torque). Also in analogy with the super capacitors the energy is proportional to speed squared and thus it is not meaningful to reduce the speed below half maximum speed, since there will only be 25% of the energy left at only half the maximum power.

An example of commercial (Magnet Motors) flywheel energy storage is given in



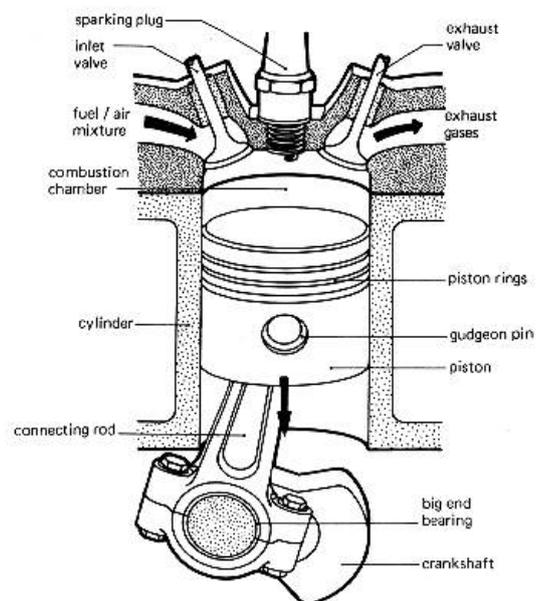
Figure 3.5 Three flywheel energy storages. The peak specifications are 80 MJ / 5 MW for the biggest and 80 MJ / 2.5 MW for the medium sized. The smallest is not known at the time of writing.

3.3. Primary energy converters

The goal of this section is to describe the most common primary energy converters used in present commercial and some prototype vehicles.

The Internal Combustion Engine - types

The most common internal-combustion engine is the piston-type engine used in most automobiles, generally called a *reciprocating engine*. The cylinders can be arranged in one of three ways: a single row (in-line) with the centerlines of the cylinders vertical; a double row with the centerlines of opposite cylinders converging in a V (V-



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engine); or two horizontal, opposed rows (opposed, pancake, flat, or boxer engine). In each cylinder a piston slides up and down. One end of a connecting rod is attached to the bottom of the piston by a joint; the other end of the rod clamps around a bearing on one of the throws, or convolutions, of a crankshaft; the reciprocating (up-and-down) motions of the piston rotate the crankshaft. The number of crankshaft revolutions per minute is called the engine speed. The top of the cylinder is closed by a metal cover (called the cylinderhead) bolted onto it.

The cylinder head has at least two openings/ports, one used for the inlet of air only or an air/fuel mixture and one used for exhaust outlet. The flow through these ports is controlled with valves mounted in the ports. There may be multiple of ports for the same purpose to improve the gas flow in and out of the cylinder. Modern combustion engines in private cars use 4 ports, two for inlet and two for outlet. That is why a 4-cylinder engine often is referred to as a 16-valve engine. In addition to the gas flow ports, there may be a port where a spark plug is mounted, that is used to initiate the combustion with the help of an electric spark. Another possible port is one used to inject fuel into the combustion chamber. A pipe runs from each intake port to an injector, the pipes from all the cylinders joining to form a manifold; a similar manifold connects the exhaust ports with an exhaust pipe and noise muffler.



Another type of internal combustion engine is the *rotary engine*. The most successful rotary engine is the Wankel engine. Developed by the German engineer Felix Wankel in 1956, it has a disk that looks like a triangle with bulging sides rotating inside a cylinder shaped like a figure eight with a thick waist. Intake and exhaust are through ports in the flat sides of the cylinder. The spaces between the sides of the disk and the walls of the cylinder form combustion pockets. During a single rotation of the disk each pocket alternately grows smaller, then larger, because of the contoured outline of the cylinder. This provides for compression and expansion. The engine runs on a four-stroke cycle.

The Wankel engine has half the number of parts and about a third the bulk and weight of a reciprocating engine. Its main advantage is that advanced pollution control devices are easier to design for it than for the conventional piston engine. Another advantage is that higher engine speeds are made possible by rotating instead of reciprocating motion, but this advantage is partially offset by the lack of torque at low speeds, leading to greater fuel consumption.

The Internal Combustion Engine – Combustion principles

Gasoline (Otto) Engines

In gasoline engines, gasoline (am. eng.) or petrol (br. eng) is used in an air fuel mixture with gasoline in proportions of weight varying from 11 to 1 at the richest to a little over 16 to 1 at the leanest. The composition of the mixture is regulated by the throttle, an air valve in the intake manifold that varies the flow of fuel to the combustion chambers of the cylinders. The mixture is rich at idling speed (closed throttle) and at high speeds (wide-open throttle), and is lean at medium and slow speeds (partly open throttle). The mixture is ignited by means of a ignition system, using a spark plug mounted in one of the openings to the combustion chamber. It can thus be argued that the power output of gasoline engines is controlled with both the quantity of fuel and the quality of the air-fuel mixture. A modern version of this engine inject the fuel directly into the cylinders, referred to as GDI - Gasoline Direct Injection, and thus the inlet ports only conveys air into the combustion chamber.

Diesel Engines

The other main type of reciprocating engine is the diesel engine, invented by Rudolf Diesel and patented in 1892. The diesel uses the heat produced by compression rather than the spark from a sparkplug to ignite an injected mixture of air and diesel fuel (a heavier petroleum oil) instead of gasoline. The diesel fuel is injected directly into the combustion chamber, like in the GDI gasoline engine. Diesel engines have no throttle and thus the power output is regulated with the quantity of fuel only – there is more air than needed for full combustion present in the combustion chamber. Diesel engines are heavier than gasoline engines because of the extra strength required to contain the higher temperatures and compression ratios. Diesel engines are most widely used where large amounts of power are required: heavy trucks, locomotives, and ships.

The increased fuel economy of the diesel over the petrol engine means that mile-for-mile the diesel produces less carbon dioxide (CO₂). The possible development of biofuel alternatives to fossil fuels could lead to an effective zero emission of CO₂, as it is re-absorbed into plants that are then used to produce the fuel.

Diesel engines can produce black soot from their exhaust. This consists of unburnt carbon compounds. Other problems associated with the exhaust gases (high particulates, nitrogen oxide, sulfurous fumes) can be mitigated with further investment and equipment.

The addition of a turbocharger or supercharger to the engine greatly assists in increasing fuel economy and power output. The higher compression ratio allows a diesel engine to be more efficient than a comparable spark ignition engine, although the calorific value of the fuel is slightly lower at 45.3 megajoules/kilogram to gasoline at 45.8 megajoules/kilogram.

The lack of an electrical ignition system also improves the reliability.

The Internal Combustion Engine – Combustion cycles

The Four-Stroke Cycle

In most engines a single cycle of operation (intake, compression, power, and exhaust) takes place over four strokes of a piston, made in two engine revolutions. When an engine has more than one cylinder the cycles are evenly staggered for smooth operation, but each cylinder will go through a full cycle in any two engine revolutions. When the piston is at the top of the cylinder at the beginning of the intake stroke, the intake valve opens and the descending piston draws in the air-fuel mixture.

At the bottom of the stroke the intake valve closes and the piston starts upward on the compression stroke, during which it squeezes the air-fuel mixture into a small space at the top of the cylinder. The ratio of the volume of the cylinder when the piston is at the bottom to the volume when the piston is at the top is called the compression ratio. The higher the compression ratio, the more powerful the engine and the higher its efficiency. However, in order to accommodate air pollution control devices, manufacturers have had to lower compression ratios.

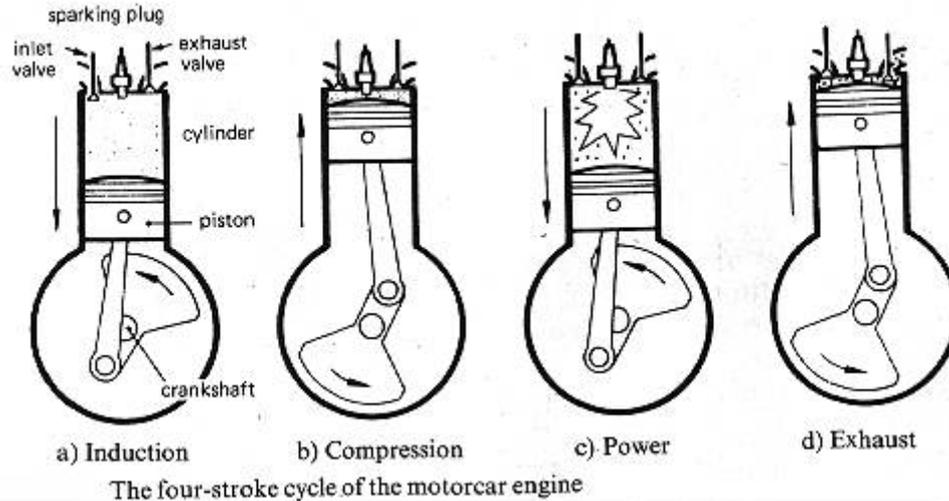


Figure 3.6 The 4 stroke cycle

Just before the piston reaches the top again, the spark plug fires, igniting the air-fuel mixture (alternatively, the heat of compression ignites the mixture). The mixture on burning becomes a hot, expanding gas forcing the piston down on its power stroke. Burning should be smooth and controlled. Faster, uncontrolled burning sometimes occurs when hot spots in the cylinder preignite the mixture; these explosions are called engine knock and cause loss of power. As the piston reaches the bottom, the exhaust valve opens, allowing the piston to force the combustion products—mainly carbon dioxide, carbon monoxide, nitrogen oxides, and unburned hydrocarbons—out of the cylinder during the upward exhaust stroke.

The Two-Stroke Cycle

The two-stroke engine is simpler mechanically than the four-stroke engine. The two-stroke engine delivers one power stroke every two strokes instead of one every four; thus it develops more power with the same displacement, or can be lighter and yet deliver the same power. For this reason it is used in lawn mowers, chain saws, small automobiles, motorcycles, and outboard marine engines.

However, there are several disadvantages that restrict its use. Since there are twice as many power strokes during the operation of a two-stroke engine as there are during the operation of a four-stroke engine, the engine tends to heat up more, and thus is likely to have a shorter life. Also, in the two-stroke engine lubricating oil must be mixed with the fuel. This causes a very high level of hydrocarbons in its exhaust, unless the fuel-air mixture is computer calculated to maximize combustion.

Modelling internal combustion engines in hybrid vehicle applications

In stationary operation at nominal conditions regarding temperature, humidity etc. an internal combustion engine can be described with maps, e.g. an efficiency map. Such a map describes the engine power output relative to the fuel power input as a function of the engine speed and shaft torque. Figure 3.7 shows slightly idealised maps for a gasoline engine and a diesel engine.

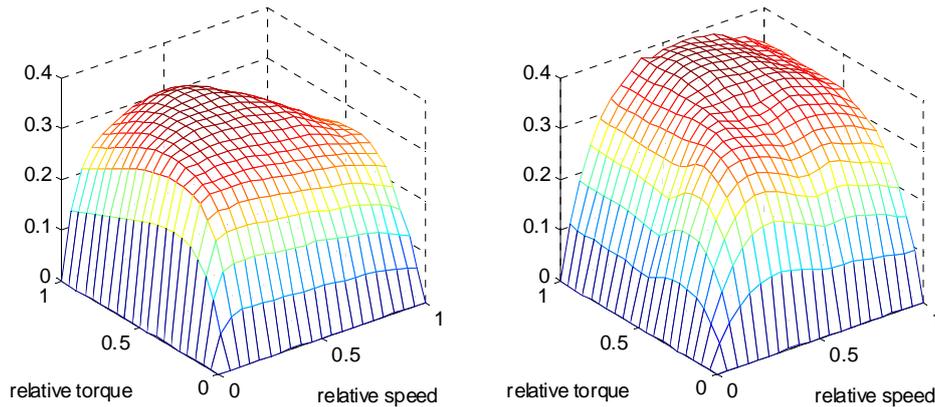


Figure 3.7 Efficiency map for a gasoline engine (left) and a diesel engine (right). Both maps are derived from measurements made on modern engines for private cars. The maps are artificially extended down to zero speed and slightly smoothed.

Maps similar to the one in Figure 3.7 can also be used to describe various emissions. As can be seen from Figure 3.7, the peak efficiency of the diesel engine is significantly higher than for the gasoline engine. In addition, it can also be seen that the diesel engine efficiency map has a flatter plateau telling that the diesel engine is able to operate at higher efficiency in a wider operating range.

In the operation of a vehicle, the power requirements vary with time. Power (P) is the product of speed (ω) and torque (T) according to equation (3-5).

$$P = \omega \cdot T \quad \text{Equation 3-5}$$

The same power can thus be extracted at a large number of combinations of speed and torque. With the gearbox we are limited to a few combinations, of which usually only two or three are possible since extreme speeds or torques must be avoided. For each power level, there is a specific speed-torque-combination that gives the highest efficiency. If those speed-torque-combinations are plotted against the shaft power level, the result for a gasoline and a diesel engine is shown in Figure 3.8.

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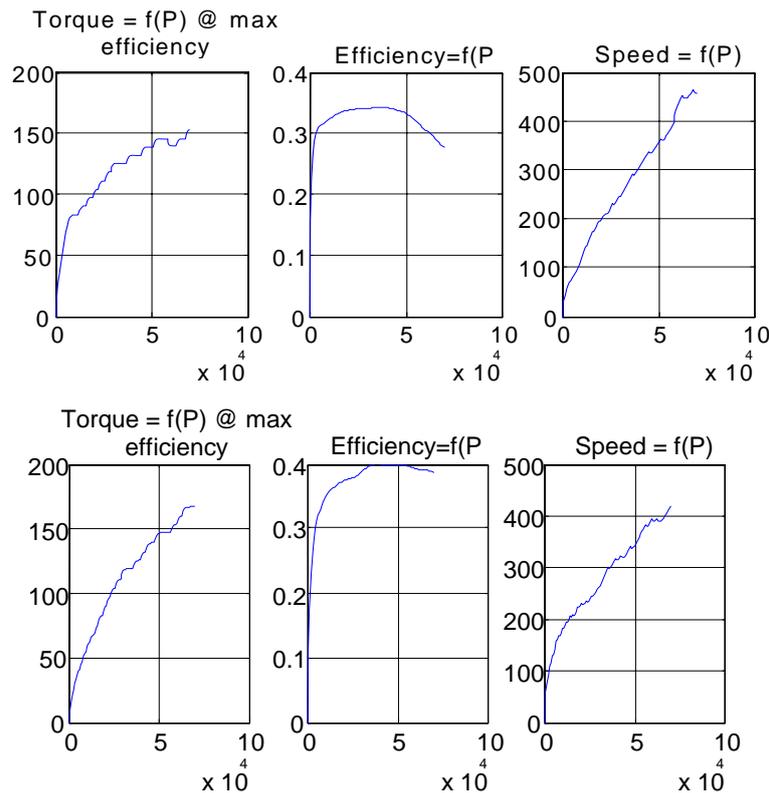


Figure 3.8 Torque (left), Efficiency (middle) and speed (right) as a function of power level for best operating point of a gasoline engine. Otto-engine on the top row and Diesel-engine on the bottom row.

Note that a high efficiency (e.g. >30% for a gasoline engine) can be reached at rather modest power levels, but it requires that a relatively high torque be applied even at low power requirements. In a conventional (not hybrid) vehicle this means that the highest possible gear position should be used. We are usually reluctant to drive the vehicle in such a way, since the margin for higher power is thus limited. Anyone who tries will however find that the fuel consumption goes down.

Dynamic operation of Internal Combustion Engines

When the power requirements vary, so do the operating point. Since the map is a description of the combustion engine performance in stationary operation, it is not self evident that the same map is valid in the transient transition when changing from one stationary operating point to another. There are several physical phenomena related to change of operating point:

- Air and exhaust gas flow changes means that the “plug” of these gases must accelerate/decelerate to the new stationary speed, which takes time.
- When more/less fuel is injected phenomena like wall-wetting can occur, i.e. some of the injected fuel is initially condensed to the inlet manifold walls thus reducing the amount of fuel that initially reach the combustion chamber. After some time a new balance is again reached.

Phenomena like these can to some extent be compensated for by the motor control system. If the rate of change of operating point is limited via the means of a 1st order time constant, then a time constant of 1 second allows the operation of the internal combustion engine to avoid dynamic effects. This is an understatement in gasoline engines, where the motor control system is able to guide the engine through a transient faster, but more true for diesel engines.

If an internal combustion engine is used with limited dynamics like discussed above, e.g. with a 1-second time constant, then the stationary maps can be used to describe the engine operation at any time instant. If faster dynamics is required, the more advanced models are required to account for the transient effects on efficiency and emissions. In the following, the internal combustion engine is described with maps for efficiency and in some cases emissions. The motivation is that the intended use in a hybrid vehicle in a natural way allows limitation of the operation dynamics.

Fuel cell systems

In principle, a fuel cell operates like an electrochemical energy storage, a “battery”. Unlike a battery, a fuel cell does not run down or require recharging. It will produce energy in the form of electricity and heat as long as fuel is supplied.

A fuel cell consists of two electrodes sandwiched around an electrolyte. Oxygen passes over one electrode and hydrogen over the other, generating electricity, water and heat.

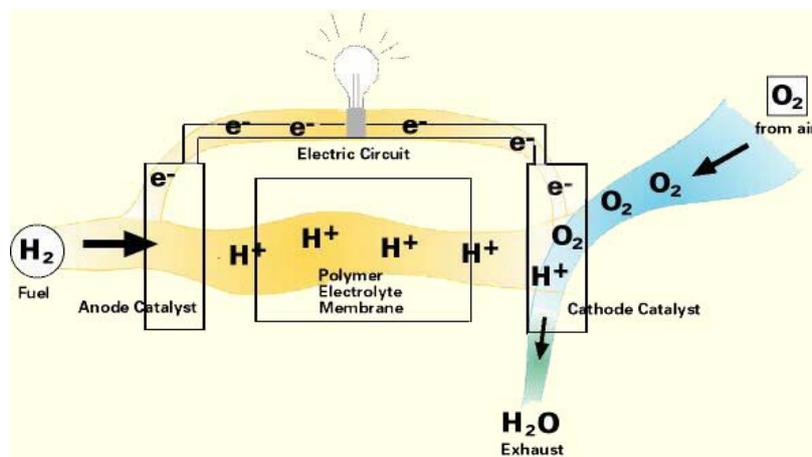


Figure 3.9 The principle of a fuel cell

Hydrogen fuel is fed into the "anode" of the fuel cell. Oxygen (or air) enters the fuel cell through the cathode. Encouraged by a catalyst, the hydrogen atom splits into a proton and an electron, which take different paths to the cathode. The proton passes through the electrolyte. The electrons follows a separate current that can be utilized before they return to the cathode, to be reunited with the hydrogen and oxygen in a molecule of water.

A fuel cell system which includes a "fuel reformer" can utilize the hydrogen from any hydrocarbon fuel - from natural gas to methanol, and even gasoline. Since the fuel cell relies on chemistry and not combustion, emissions from this type of a system would still be much smaller than emissions from the cleanest fuel combustion processes.

The Fuel Cell System in a Hybrid Vehicle is in need of additional system components to be able to propel the vehicle. The output voltage of the fuel cell stack varies some with load and must usually be conditioned to adapt to the system voltage, just like the secondary energy storages also must. When thus conditioned, the electric power is again converted to be fed to the electromechanical energy converter that finally feeds the mechanical power into the transmission system to the wheels. Figure 3.10 shows the system structure of a Toyota hydrogen fuel cell system.

System Configuration of a Fuel Cell Vehicle

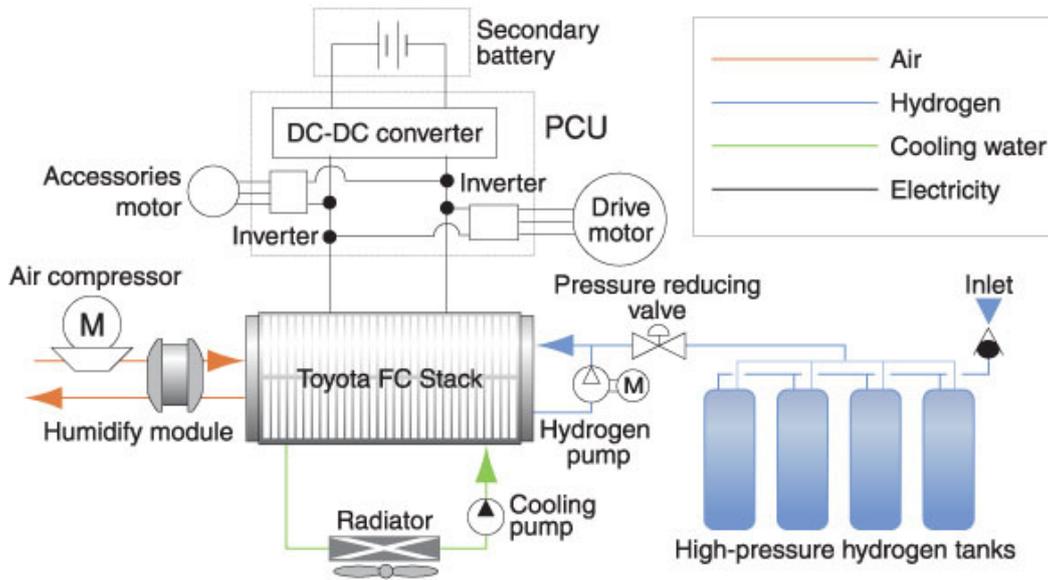


Figure 3.10 Fuel Cell system structure. (http://www.toyota.co.jp/en/special/fcbv/fcbv_3.html)

Figure 3.11 shows the efficiency of a fuel cell system with a methanol reformer as fuel processor and a hydrogen stack including air compressor etc. The “Fuel processor” curve shows the efficiency in extracting hydrogen energy from the methanol to clean hydrogen gas suitable to use in the fuel cell stack. The “FC stack with aux system” is the FC stack efficiency compensated for the power consumption of the support systems like the air compressor used to feed air into the fuel cell stack. The “System” curve shows the whole fuel cell system efficiency from methanol energy to electric output power.

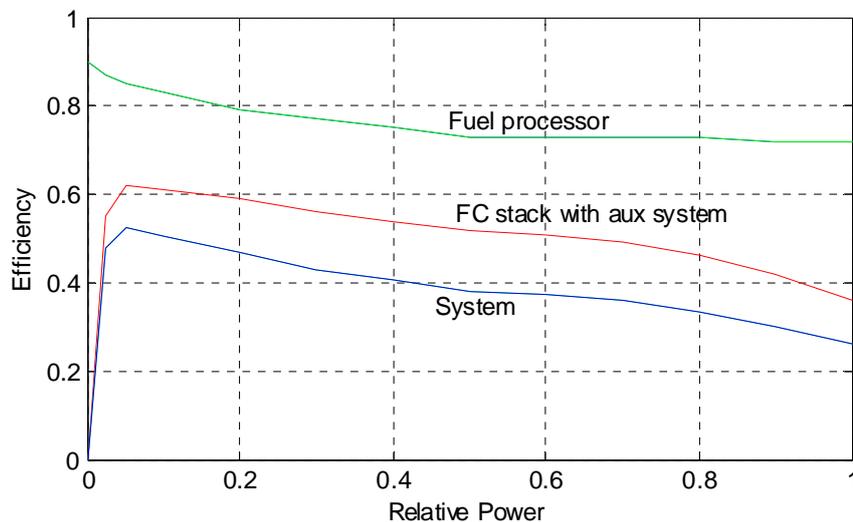


Figure 3.11. Efficiency as a function of power for a fuel cell system including a methanol reformer.

The “System efficiency” curve above will be used as a model for the fuel cell system in simulations of various vehicle configurations.

Power Electronic Converters

There are several power electronic converters used in the traction system of a hybrid vehicle. Almost any electrical machine, whether it is used as a generator or a motor, is power electronically controlled. In addition, secondary energy storages like batteries; super capacitors and fuel cell systems are usually adapted to a common dc link voltage via a power electronic converter.

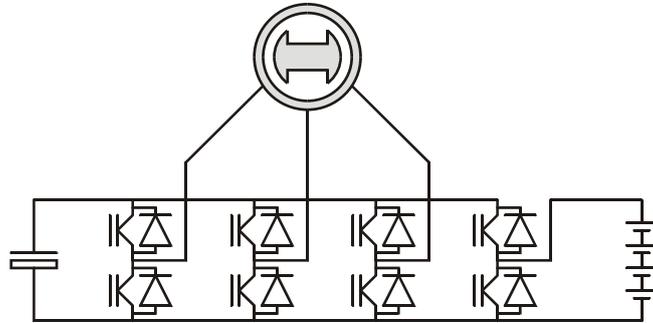


Figure 3.12 Converter controlled electrical machine and secondary energy storage, both adapted to a common dc link voltage via power electronic controllers.

Such power electronic converters have a relatively high efficiency, often with a peak at 97-98 % and even higher. The losses are mainly commutation losses and conduction losses. The commutation losses occur when any of the power electronic components are switching, and these components for a short moment in time operate with a high voltage drop and high current simultaneously. The conduction losses occur when the converter current flows through any of the power electronic components that exhibit a voltage in the range of a few volts. The converter losses depend very little on the current, but rather much on the ratio between the voltage to be converted and the DC link voltage, e.g. the DC/DC converter between secondary energy storage and the DC link in Figure 3.12 has an efficiency between 95 and 98 % for any normal operating voltage of the fuel cell system, however increasing as the fuel cell system voltage increases.

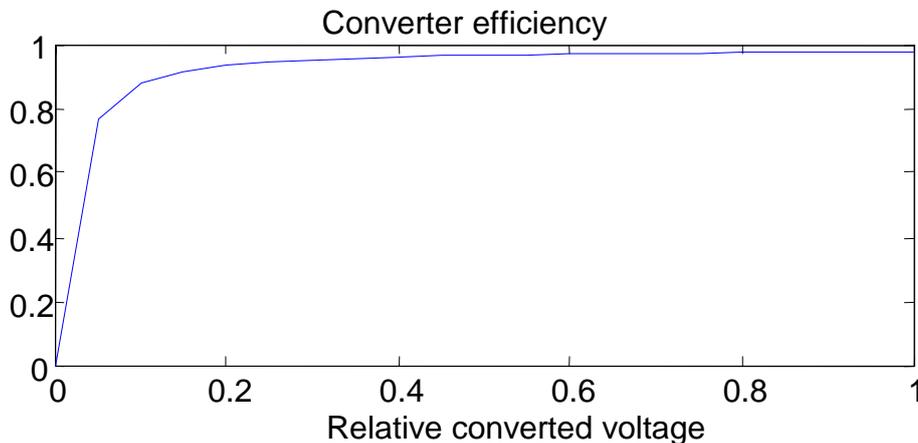


Figure 3.13 Converter efficiency relative to the converted voltage

Due to the almost constant nature of the power electronic converter efficiency it is not a big mistake to represent the converter losses with a fix value, e.g. 97 % that describes most well designed power electronic converters.

Electrical machines

The traction system of an electric vehicle involves at least one electrical machine, and often several. A basic parallel hybrid has only one, a series hybrid has two, and it is possible to consider having four, one on each wheel. The requirements on these machines are usually to have high

torque density, i.e. the maximum torque should be high, at least at low speed. That gives good starting properties. An Integrated Starter Generator (ISG) must be able to start the ICE, usually with at least 200 Nm of starting torque, and must not occupy more than a few centimeter of physical space approximately where the clutch is located. Assume that the ISG was able to produce that much torque continuously over the entire speed range of the ICE, e.g. $< 6000 \text{ rpm} = 600 \text{ rad/s}$. In that case the maximum power would be $200 \cdot 600 = 120 \text{ kW}$, i.e. as much or more than the power of the ICE itself. This is not realistic, and the truth is that the maximum torque at low speed is only maintained up to a certain speed, called the base speed. Above that speed, the maximum torque is gradually reduced such that the maximum power is limited.

How electrical machines work

The types of electrical machines most often used in the traction system of vehicles utilize the interaction between an electric current and a magnetic field, the so called “Lorenz force”, to create torque. The machine is built with a rotor and a stator. These can be concentric cylinders with a small air gap in between or radial plates with an axial airgap in between, see Figure 3.14 for two schematic drawings.

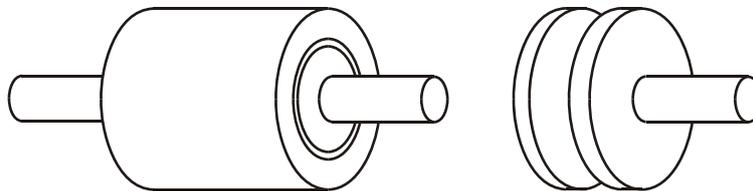


Figure 3.14 Rotor and stator in radial and axial air gap machines.

The magnetic field is often accomplished with the help of permanent magnets. Such machines are called permanent magnet machines. A permanent magnet machine with the magnets on the rotor is shown in Figure 3.15.

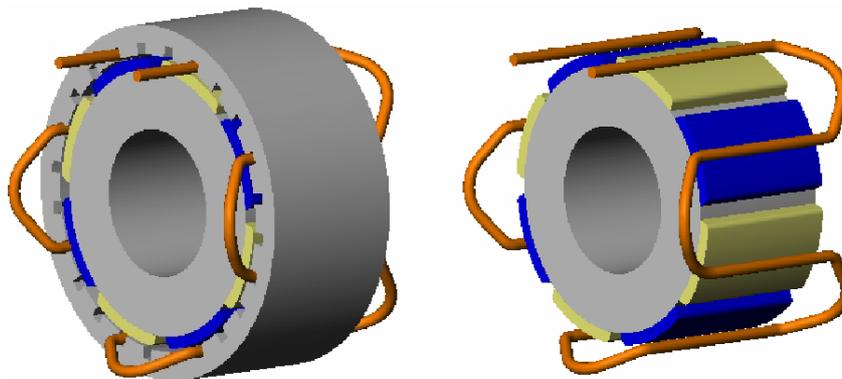


Figure 3.15 8-pole permanent magnet machine with radial air gap. Note that only a fraction of the stator winding is shown for clarity.

The torque is accomplished when currents are forced through the windings in such a way that the current is flowing in one direction in front of permanent magnets of one polarity and then in the other direction in front of permanent magnets of the other polarity. There are several methods to make the currents flow in front of the magnets in the described manner, and these different methods have given the names to some of the electrical machines:

DC machines use a mechanical switch to move the currents in the conductors in such a way that the currents have the right position relative to the magnets when the rotor rotates. The current is fed to the machine as a DC current and then distributed to the winding via this mechanical switch, also called the commutator.

AC machines have a winding split into several, usually three, phase windings that are power electronically fed to the individual windings. By feeding the phase windings with AC currents of

the right amplitude and phase, the result is that the current flows in front of the magnets in the desired manner, and thus the torque is accomplished.

The physical design of electrical machines are done in such a way that the magnetic flux from the magnets almost saturates the iron part of the magnetic core material in the machine. The core material constitutes basically everything that is not air, permanent magnets or windings. From this magnetic flux follows two fundamental properties common to all electrical machines:

- 1 The voltage required to run the machine is proportional, or almost proportional, to the speed of the electrical machine multiplied with the magnetic flux from the magnets.
- 2 The torque is proportional, or almost proportional, to the current supplied to the machine multiplied with the magnetic flux. In the AC machine case it is also required that the phase of the currents is correct.

At low operating speeds the voltage requirement is correspondingly low, and the torque is only limited by the limitations for the current. This means that as long as the voltage is not a limitation, a maximum constant torque can be accomplished. At high speeds, the voltage required is higher than the voltage that can be supplied. This is handled by reduction of the magnetic flux to such an extent that the product of speed and flux is slightly less than the voltage that can be supplied, also called field weakening. Since the flux is reduced, and torque is a product of flux and current, the maximum torque is also reduced. Since the flux is reduced inversely proportional to the speed as the speed increases and thus the torque is inversely proportional to the speed as the speed increases, and since power is torque*speed, the power is constant in the field weakening range. These two operating regimes are referred to the constant torque region and the field weakening region or the constant power region.

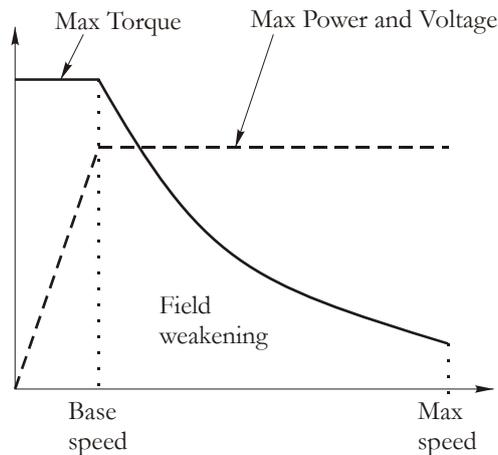


Figure 3.16 Maximum torque in the two operating regimes of electrical machines.

Note that the power delivered by the machine, when disregarding losses, can be expressed both in electrical and mechanical quantities, see the following equation (3-6)..

$$P = \text{speed} \cdot \text{torque} = \text{voltage} \cdot \text{current} = \text{flux} \cdot \text{speed} \cdot \text{current} \quad \text{Equation 3-6}$$

In the constant torque regime, the voltage increases with speed and the maximum current is constant – thus the power increases. In the field weakening regime, the voltage and the current is constant and thus the power is constant.

There are several types of losses appearing in electrical machines. The most important are the copper losses, that are the result of the winding currents flowing in the windings, and the iron losses, that are the result of the magnetic flux moving in the core material. The copper losses are proportional to the currents squared, and since currents and torque are proportional the copper losses are proportional to the torque squared. The iron losses are proportional to the flux

squared and the speed squared. Expressed as a function of torque and speed, the efficiency can be calculated from these losses and one example is shown in Figure 3.17.

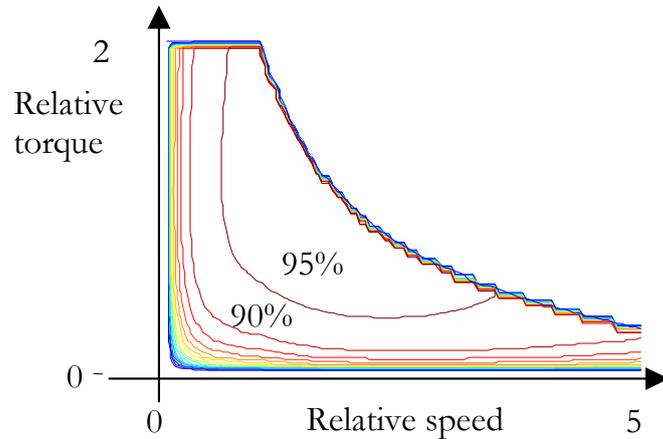


Figure 3.17 Efficiency of an electrical machine as a function of speed and torque for a machine designed to run up to five times the base speed, and up to two times the nominal torque.

3.4. Transmissions

The transmission is used to adapt the speed and torque requirements of the driving wheels to the speed and torque capabilities of the primary energy converter. The transmission ratio should always be selected to allow the primary energy converter to produce the required power for the driving wheels at the torque-speed combination that is the most suitable, e.g. for maximum efficiency.

A mechanical transmission is present in all conventional and most hybrid vehicles. However, it is not necessary in a hybrid. It is possible to design a vehicle with electric motors in the wheels, thus having no need for a mechanical transmission. Still, such a vehicle has a transmission, but it is electric instead of mechanic. Commercial systems with wheel motors exist on the market. The most relevant transmissions that are involved in both conventional and hybrid vehicles are discussed in the following sections.

Manual shift transmission

A manual transmission is built with three axes, one primary that is connected to the combustion engine via a clutch, one secondary that is connected to the driving wheels via a differential gear and one intermediate (layshaft). Figure 3.18 shows a principal drawing of a 5-speed gearbox.

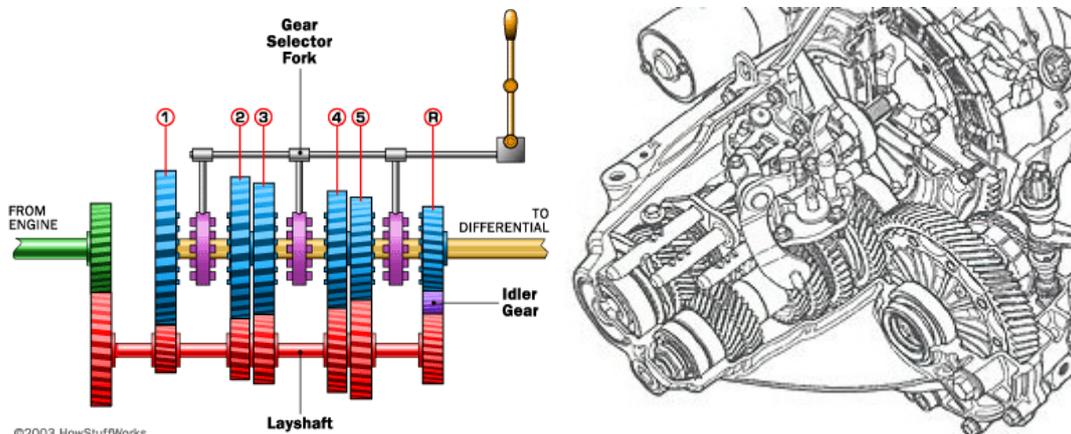


Figure 3.18 Principal drawing of a 5-speed gearbox. (HowStuffWorks) and detail of the corresponding gearbox in a Honda Insight.

All gears are in operation at the same time, i.e. all wheels rotate at the same time, but only one is connected to the main shaft by the help of a “dog clutch” with splines that connect one of the gear sets on the main shaft to the main shaft. A set of synchronization rings are used to facilitate the mechanical connection.

The number of gear ratios that is possible is increasing with time. The T-ford had two gear ratios, in the 60’s there was normally three or four gear ratios and today the most common gearboxes have 5 gear ratios, but 6-speed manual shift is becoming more common. Heavy vehicles have many more.

The transmission of a manual gearbox exhibit losses related to friction when the involved components rotate in oil. Expressed as efficiency, a realistic figure is 96%. In the following an efficiency of 96 % is used in simulations.

Automatic transmission.

An automatic transmission can be accomplished in several ways. The traditional solutions use a hydraulic torque converter that essentially replaces the function of a clutch. The torque converter consists of a turbine (from the ICE), a stator and a pump (to the gears) closely assembled and connected with a transmission fluid, the control of which allows more or less slippage between the turbine and the pump wheels. Apart from the torque converter, a set of planetary gears, bands and clutches are used to accomplish a number of different gear ratios. The key difference between a manual and an automatic transmission is that the manual transmission locks and unlocks different sets of gears to the output shaft to achieve the various gear ratios, while in an automatic transmission, the same (planetary) set of gears produces all of the different gear ratios, with the help of the bands and clutches. The slippage that takes place in the torque converter increases the losses of this type of gearbox compared to the losses in a manual shift transmission. In the following an efficiency of 87% is used in simulations.

Another possible transmission is the Continuously Variable Transmission (CVT). This is also an automatic transmission, but mechanically designed to facilitate an infinite number of gear ratios. The continuous gear ratio can mechanically be accomplished by e.g. the following two methods:

Two sets of double conical pulleys with a steel belt in between. Variable diameter pulleys are a variation in the theme. Two 20° cones face each other, with a v-belt riding between them. The distance from the center that the v-belt contacts the cones is determined by the distance between them; the further apart they are, the lower the belt rides and the smaller the pitch radius. The wider the belt is, the larger the range of available radii, so the usual 4L/A series belt is not often used in this way. Often special belts, or even chains with special contact pads on the links, are used.

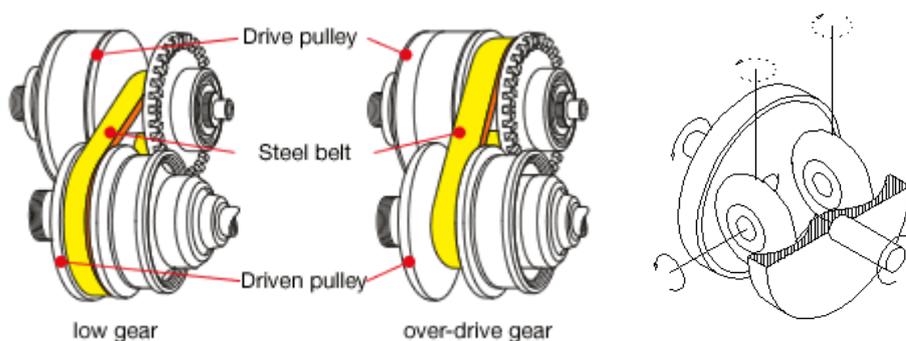


Figure 3.19 Principle and alternate principle design of a CVT

Variable diameter pulleys must always come in pairs, with one increasing in radius as the other decreases, to keep the belt tight. Usually one is driven with a cam or lever, while the other is

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simply kept tight by a spring. Variable diameter pulleys have been used in a myriad of applications, from power tools to snowmobiles, even automobiles

Another CVT involves two coaxial disks bearing annular grooves of a semi-circular cross section on their facing surfaces. The spacing of the disks is such that the centers of the cross sections coincide. Two or more (in patent-speak, "a plurality of") idler wheels, of a radius equal to the radius of the cross sections of the grooves, are placed between the disks such that their axes are perpendicular to, and cross, the axes of the disks.

In Figure 3.19, the speed ratio is varied by rotating the wheels in opposite directions about the vertical axis (dashed arrows). When the wheels are in contact with the drive disk near the center, they must perforce contact the driven disk near the rim, resulting in a reduction in speed and an increase in torque. When they touch the drive disk near the rim, the opposite occurs. This type of transmission has the advantage that the wheels are not required to slide on a splined shaft, resulting in a simpler, stronger design.

The CVT solution offers efficiency around 90 %, i.e. right in between a traditional automatic gearbox and a manual transmission.

3.5. Simulation of non ideal standard vehicles

In this section, we will convert the ideal vehicle of section 2.2 to a more realistic vehicle of conventional type. This will in turn be gradually converted into various hybrid vehicles.

To be able to study and compare the properties of a number of vehicles with different traction systems, otto or diesel engines, various hybrid systems, various energy storages etc, there must be a common denominator in the choice of designs. In this context, the vehicle model is based on technical data for the Toyota Prius, generation II as well as possible. The idea is to:

- 1 Have the same installed total tractive power, in all vehicles to be compared. Numerically, this seems to be close to 120 kW, but this cannot be used simultaneously. Instead about 82 kW is the highest available as a combination of the different engines/machines. A 100 kW total installed tractive power will be the guide in selection of drive train properties. This does not mean that the maximum combined power will be 100 kW, just that the sum of all maximum power will be 100 kW.
- 2 Have the same energy storage in all comparisons, except for those cases when the energy storage itself is studied. This storage will be the one used in Toyota Prius, generation II. This corresponds to 4.7 MWs. Thinking of it as 47 kW in 100 seconds gives an intuitive understanding of the amount of energy available.
- 3 To use the same, or at least as similar as possible, control strategies for the power flow. Since one of the goals with a hybrid vehicle is to keep the traction battery at a suitable State Of Charge (SOC), the control principles of a hybrid vehicle will in the following be referred to as a Charge Control Strategy (CCS). Later in this chapter, the CCS of series and parallel hybrid topologies will be thoroughly discussed.

Apart from the sub systems discussed in the previous sections, it is necessary to have models for the driver and a gear shifting strategy for manual gearboxes. These models are discussed in the following two sections.

Driver Model

The driver is designed as a simple *PI*-controller with anti-windup on the integrator to prevent saturation in the actuator. The necessary amount of torque to achieve the requested vehicle

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speed is calculated with equation (3-7). The requested speed is given by drive cycles as look-up-tables.

$$F_{vehicle}^* = K \left((v^* - v) + \frac{1}{sT_i} (v^* - v) \right)$$

$$T_{wheel}^* = F_{vehicle}^* \cdot r_w$$

Equation 3-7

$F_{vehicle}^*$ = total requested force, T_{wheel}^* = total requested torque and r_w = wheel radius

To set the parameters of the “PI-driver”, a closed loop speed control, system with this driver is studied and the poles of that system are placed at the limit to oscillatory poles, which gives rather good dynamic performance without an oscillatory behaviour.

Assuming that the wheel torque source is infinitely fast, the speed controller can be written as a block diagram in Figure 3.20.

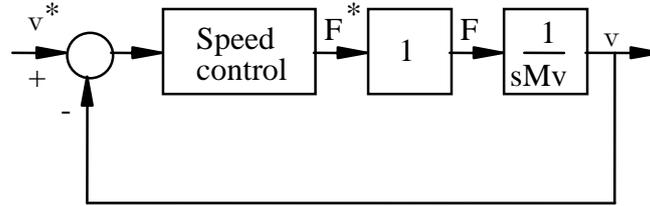


Figure 3.20 The speed control system.

With a PI controller, the system will contain two integrators. It is possible to place the poles of that controller arbitrarily. Assume that the speed controller has the gain K_v and integration time constant T_i . The closed system transfer function will then be

$$\frac{\omega(s)}{\omega^*(s)} = \frac{K_v (s \cdot T_i + 1)}{M_v T_i s^2 + K_v T_i s + K_v}$$

The poles to the system will be

$$poles = -\frac{K_v}{2J} \pm \sqrt{\frac{K_v^2}{4J^2} - \frac{K_v}{JT_i}}$$

By placing the poles at the limit to oscillatory poles, the gain of the speed controller can be related to the integration time constant.

$$K_v = \frac{4M_v}{T_i}$$

Thus the gain is proportional to the vehicle mass. This seems reasonable – a heavier vehicle needs more wheel torque to accelerate at a certain rate. The integration time constant has to be selected, and is here selected as $T_i=3$ s for a 1000 kg vehicle and then proportional to the vehicle weight for heavier vehicles such that it becomes 10 seconds for a 10 000 kg vehicle. These figures are selected to be a fraction of the acceleration time to 100 km/h that can be expected.

Gear shifting strategy

When using a manual transmission, it is necessary to have a gear shifting strategy. In the model used in the simulations in this book, the strategy used is as follows:

The ideal gear ratio, based on optimal choice of operating point is calculated from the data describing the ICE-model see Figure 3.8. Since the speed and torque of the driving wheels is known (torque from the drivers model), the tractive power is also known (speed*torque), and since the optimal ICE operating point (Figure 3.8) is known for the same ICE power, then the ideal gear ratio can be calculated from the vehicle speed and the ideal ICE speed.

Out of the available gear ratios, the closest to the ideal is selected. Simultaneously, the necessary torque of the ICE is calculated for all available gear ratios. If the ICE torque needed for the selected gear ratio is higher than the ICE maximum torque, then the next lower gear ratio is used instead.

Selection of the most ideal gear ratio means in reality at least one gear lower than most drivers use. The reason may be that using the best gear ratio also means using a rather high torque, which in turn means that the margin for additional torque is small. When a need of acceleration appears, it is likely that the gear position must be reduced.

To compensate for the way that many drivers handle vehicles, an algorithm has been added to the gearshift strategy in the simulation programs. It works as follows:

- As long as the ICE speed reference is low, a one gear ratio lower position than ideal is selected.
- When the ICE speed increases, the “one gear down” strategy is abandoned when the speed passes 85 % of maximum ICE speed rpm, but reengaged when the speed drops below 55 % of the ICE speed.

This addition makes the engine run a bit faster and at lower torque most of the time, but still avoids exceeding maximum allowed speed of the ICE.

Case 1: A conventional gasoline or diesel driven vehicle

Based on the ideal vehicle studied in section 2.2, a more conventional vehicle is here built by extending the ideal vehicle with the more realistic models discussed in chapter 3. Figure 3.21 shows a schematic diagram of the traction system in the vehicle.

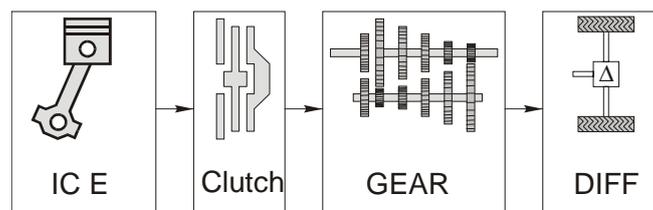


Figure 3.21. The traction system of a conventional vehicle described with a block diagram

The simulation model used is available in the folder marked “Parallel”. This folder contains everything needed to simulate a conventional or parallel hybrid vehicle (the parallel case will be studied later). It is useful to study the simulation model before continuing reading this section. The Simulink program is filled with comments to help understanding the way the program works.

The ICE model used is the one discussed in section 1, a look up table for efficiency. The clutch is just modeled as a lower limitation of the speed signal addressing the look up tables for ICE efficiency, i.e. when the ICE torque requirement, and possibly the speed is zero, the machine is assumed to be idling without connection to the wheels – just what a clutch is doing.

The gearbox is a 6-speed automatically shifted manual gearbox with gear ratios distributed evenly in an interval limited by the following line of thought:

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- The lowest gear is defined by the ICE reaching maximum speed at 1/5'th of the maximum vehicle speed.
- The highest gear is defined by the ICE reaching maximum speed when the vehicle reaches maximum speed.

The other three gear ratios are evenly distributed in between the lowest and the highest.

The differential is not modeled, i.e. the losses and gear ratio related to the differential is assumed to be incorporated in the gearbox.

Prior to running the simulation it is needed to define the vehicle in the "InitiateParallel"-file. Table 4 shows the main parameters and settings of the simulated vehicle:

Table 4 *Conventional 6-speed vehicle data*

Property	Variable name	Setting
Fuel type	Fuel type	1 and 2, both gasoline and diesel are studied below.
Peak ICE power	Pice_max	100 kW
Peak ICE speed	Wice_max	6000 rpm for Otto and 4500 rpm for Diesel
Min ICE speed	Wice_min	700 rpm
Peak ICE torque	Tice_max	= Max power divided by the speed for max efficiency
Vehicle weight	fordonsvikt	1575 kg
Wheel radius	hjulradie	0.3 m
Air resistance	Air_resistance	0.26
Rolling resistance	roll_resistance	0.008
Front area	Front_area	2.57
Air_density	Air_density	1.29
Maximum vehicle speed	Vmax	160 km/h
Max gear ratio (First gear)	Utvx_max	(vmax/5)/hjulradie
Min gear ratio	Utvx_min	vmax/hjulradie
Transmission efficiency	EtaGEAR	0.96
Hybrid control parameter	Hybrid	0 (means no hybrid)

This vehicle is run through the two different drive cycles (EUDC and US06, see appendix A), using both Diesel and Otto engines. Figure 3.22 shows the results.

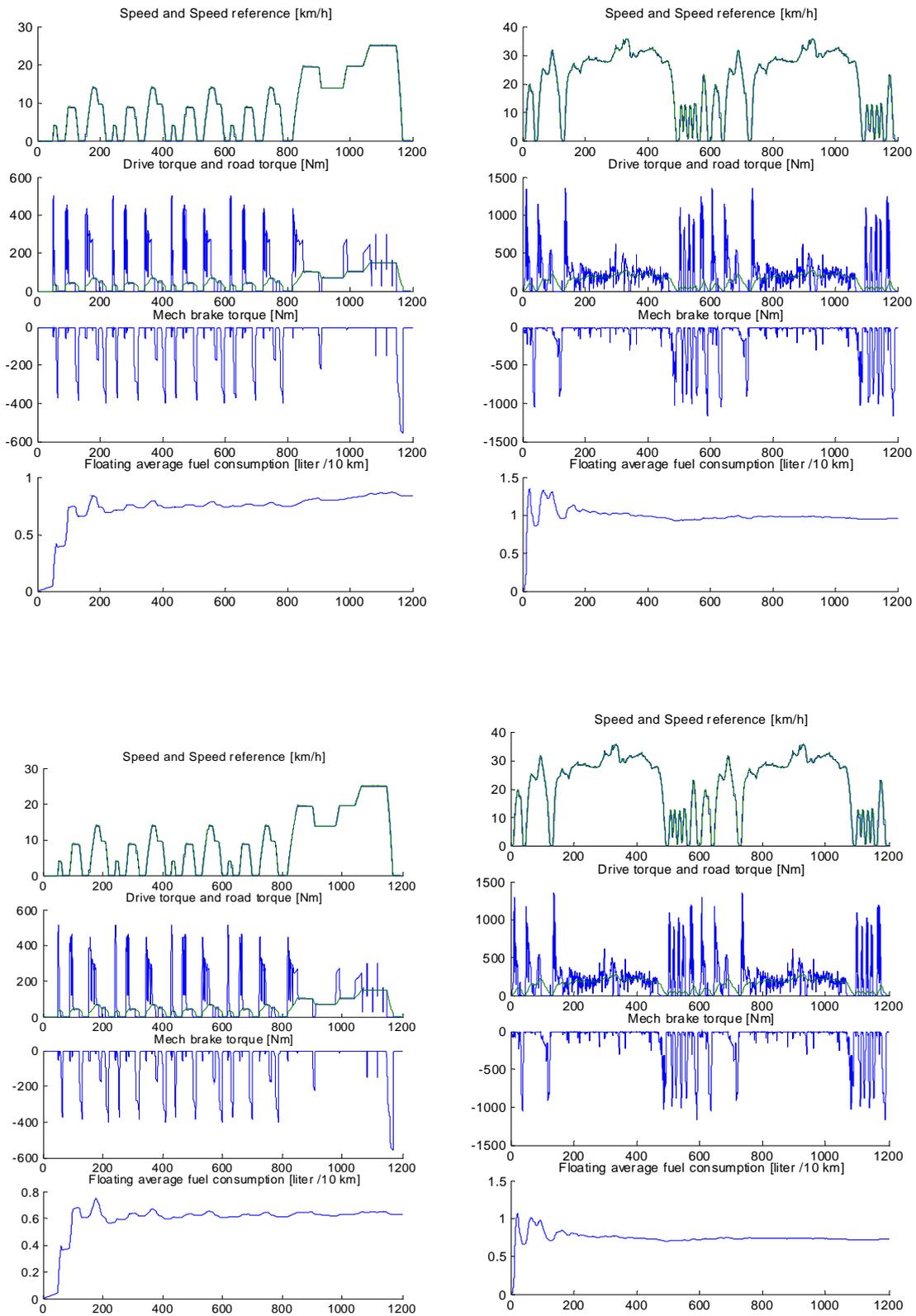


Figure 3.22 Representative simulation results from a vehicle running two different driving cycles (left column EUDC and right column US06) with two different engines (upper row Otto engine and lower row Diesel engine). The quantities shown are the same as in Figure 2.3.

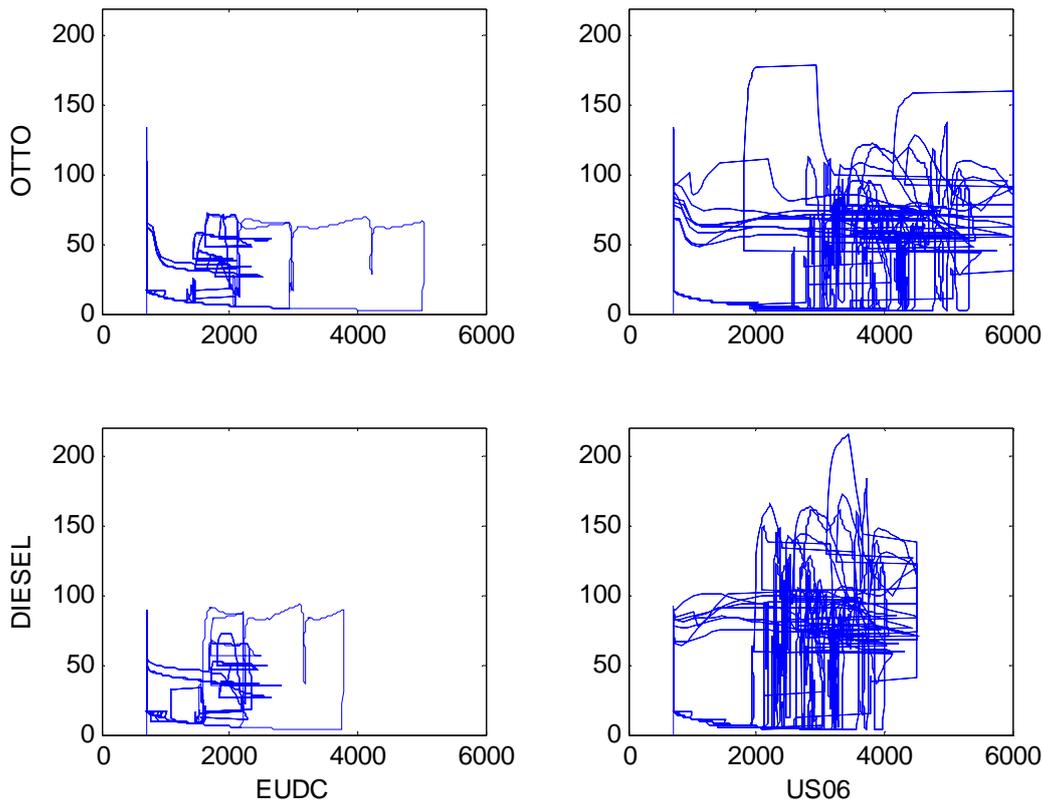


Figure 3.23 ICE torque [Nm] vs. speed [rpm] a vehicle running two different driving cycles (left column ECE 15 and right column US06) with two different engines (upper row Otto engine and lower row Diesel engine). The curves show the ICE torque vs. speed loci.

Note in Figure 3.23 that, in spite of the peak torque of the Otto engine being 200 Nm and of the Diesel engine 265 Nm, the way that these vehicles are driven use the entire speed range, but not the torque range. Looking back on Figure 3.8 showing the efficiency of an ICE as a function of speed and torque, it is evident that the way the ICE is used in these simulations does not utilize the operating points with the best efficiency. Table 5 shows the fuel consumption for the four trips simulated. Note that the diesel engine consumes significantly less fuel, however with less reduction in highway traffic than in city traffic. This is due to the fact that highway traffic is more demanding and thus forces the operating points onto higher torque levels which is beneficial for efficiency. Since the Diesel engine has a somewhat “flatter” efficiency map it has easier to reach high efficiencies even in city traffic.

Table 5 Simulated fuel consumption of a Otto and Diesel “Prius”-like conventional vehicle with a 100 kW ICE running the ECE15 city driving cycle and the US06 highway driving cycle

Fuel consumption [l/10 km]	ECE15	US06
Otto	0.91	0.99
Diesel	0.64	0.65

Case 2: Optimization of operating point

In this section we will study the consequences of being able to run the ICE at its best efficiency under all conditions, independent of the actual operating point. This is unrealistic, but valuable

to understand the potential in hybridization of vehicles. It can easily be accomplished if the ICE efficiency in the simulation program is replaced with the highest possible efficiency of that particular motor type.

In the Otto engine the highest efficiency is 34 % and in the Diesel engine it is 40.0%. Table 6 shows the results of such simulations.

Table 6 Fuel consumption in a realistic driving case and in a case with the ICE always on maximum efficiency.

	Otto		Diesel	
	EUDC	USO6	EUDC	USO6
Real fuel consumption	0.91	0.99	0.64	0.65
Fuel consumption with max efficiency	0.52	0.66	0.35	0.44
Reduction	-43%	-33%	-45%	-32%

Note that the fuel consumption savings are great, in the order of 30-40 %. It is often stated that with hybrid vehicles it should be possible to reduce the fuel consumption to half. Optimization of operating point is however not enough. The indicated savings in Table 6 are purely theoretical. The systems that can be built to realize those savings are non ideal and in reality the potential of moving the operating point is likely to be in the range of 15...25 % rather than 30-40 %, but it is still a lot! In combination with other possibilities, like regeneration of braking energy, more efficient combustion, lower rolling resistance etc., the total potential for reduction of the fuel consumption is still in the range of 50 %.

Case 3: Driving style

In this section the driving habits are studied, i.e. how much the degree of aggressive driving affects the fuel consumption. On page 29 about the gear switching strategy, it was discussed that most drivers tend to use a lower gear than would have been the most optimal, and that an algorithm to compensate for this was engaged in the gearshift strategy. Here, we will disengage this compensation and study the resulting impact on fuel consumption. Figure 3.24 shows the gear positions used in the “optimal” and more realistic gear shift strategy with a 5 speed gearbox running USO6. Table 7 shows some results.

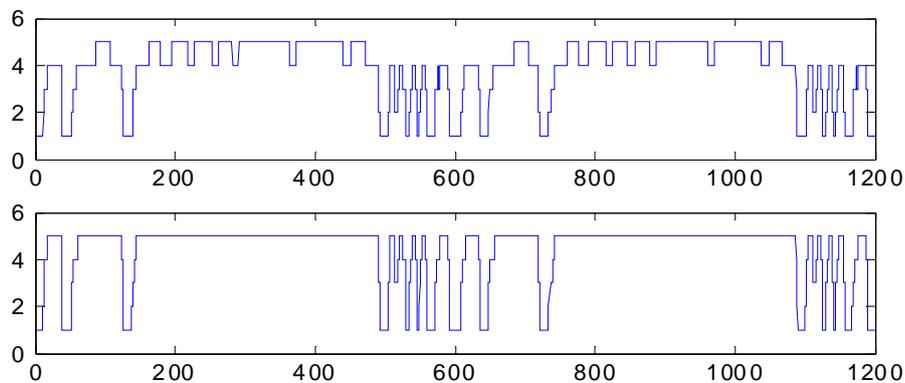


Figure 3.24 Gear shift position for optimized driving (lower diagram) and for a driving style prioritizing one-step lower gear position most of the time (upper diagram).

Table 7 Fuel consumption of a conventional vehicle using the gear shift strategies of Figure 3.24, using an Otto engine.

	EUDC	US06
Near optimal gear shift strategy	0.76	0.86
More aggressive gear shift strategy	0.91	0.99

Note that the potential for fuel saving is larger in the city traffic cycle, since the engine runs at operating points further from the “plateau” on the efficiency map and a gear selection in the wrong direction thus has a higher impact.

Case 4: Regeneration of braking energy

In this section we will study the purely theoretical prospects of being able to return the energy dissipated in the brakes back into the fuel “tank”. The purpose of such a study is to understand the potential in having secondary energy storage to really take care of the regenerated energy.

In all four simulations in Figure 3.22, the braking energy, i.e. the heat dissipated in the friction brakes, is calculated. Table 8 shows the results, together with the fuel consumption data.

Table 8 Fuel saving potential if all friction braking energy dissipated in 4 cases similar to the simulations in Figure 3.22 could be regenerated.

	Otto		Diesel	
	EUDC	US 06	EUDC	US 06
Fuel consumption [l/10 km]	0.74	0.82	0.63	0.63
Distance	11.1 km	25.9 km	11.1 km	25.9 km
Sum fuel [liter]	0.82	2.12	0.70	1.63
Braking Energy [Ws]	1.624e6	5.263e6	1.624e6	5.263e6
ICE ave eff	19.4 %	22.4 %	20.0 %	24.4 %
Equivalent fuel	0.26	0.73	0.25	0.67
Relative reduction	-31 %	-34 %	-35 %	-41%

Note from this table that the theoretical relative reduction of the fuel consumption if all braking energy could be regenerated is in the range of 30...40 %. In reality, all this is not possible to accomplish, since limitations in energy converters and energy storage power limits the ability to absorb the regenerated energy. However, even if half is possible, it is still a great opportunity and together with operating point optimization this will be the most valuable asset of a hybrid vehicle.

Summary on fuel consumption

The simulations made in this chapter show the following aspects of fuel consumption of conventional vehicles:

- 1 The selection of operating point greatly affects the fuel consumption. The use of an optimal operating point has a potential of 30-40% reduction of the fuel consumption.

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- 2 The energy wasted in the friction brakes represents a potential saving of about 30-40% if it can be regenerated to a secondary energy storage.

These are significant reductions. Next chapter of this book deals with the systems and methods used to reduce the fuel consumption along the possibilities indicated in this chapter.

3.6. Alternative drive trains

The drawback of the conventional vehicle studied in the previous chapter, is the inability to always reach the best operating points of the engine and the inability to regenerate the energy stored in the moving mass as the vehicle decelerates. The operating point can to some extent be chosen, by the help of the gearbox, but it must in terms of power equal the instantaneous driving power. In other words, if the car runs a low load (e.g. slowly on flat ground) then the power level is low and it is not possible to reach the more efficient operating points without increasing the power, but then there is nowhere to store the excess energy converted.

To get around this problem, it is necessary to equip the vehicle with an energy storage that can absorb the difference between the instantaneous driving power and the power converted by the primary energy converter. If this is done, the same secondary energy storage can be used for other purposes, like

- Running the AC compressor or other loads even if the primary energy converter is turned off.
- Running the vehicle with limited performance with the primary energy converter turned off. The motivation to do this may be emissionfree operation or silent operation.

The energy storage needed to facilitate such functions can theoretically be of many types, e.g. hydraulic, pneumatic, mechanic, electric etc. The electric/electrochemical energy storage has emerged as the most useful solution, for several reasons:

- It is safe. Electrical systems are highly developed regarding safety and due to that the fundamentally hazardous technology is used everywhere in society.
- It is flexible. Electrical energy can easy and with high quality be converted into many other energy forms, e.g. mechanical energy for traction or electrical/electrochemical energy for energy storage. The energy transfer does not need a stiff mechanical transmission, but can use soft cables, which allows packaging of vehicles in a more free way than other methods.
- It is cheap. The components used with electric energy conversion are usually produced for a vast number of applications and thus cheap.

For these reasons, hybrid electric vehicles have been developed and are still under intense development with all vehicle manufacturers of the world. It is not only road bound vehicles, but also aircrafts, boats, bicycles, motorcycles and other vehicles never heard of before.

The tractive system of a hybrid electric vehicle includes both an ICE or FC and, at least, one electric machine for propulsion of the vehicle. There are many ways of combining the included components and consequently the number of possible hybrid topologies is very large, considering the combinations of electric machines, gearboxes, clutches etc. The two main solutions, series and parallel hybrid, can be supplemented in a numerous amount of combinations, each one with its pros and cons. The topology efficiency is depending on the chosen vehicle solution with its unique characteristics and the actual working condition.

The topologies chosen in this work are discussed in the following sections 3.7 - **Fel! Hittar inte referensälla..**

3.7. Series

The series hybrid has no mechanical connection between the ICE and the wheels. The ICE working point, i.e. speed and torque, can be chosen freely, but at the expense of many energy conversions. The thermal energy is converted into mechanical energy in the ICE, and thereafter, in the generator, turned into electric energy. The generator charges the battery that in its turn supplies the electric traction motor(s). On its way the energy also passes power electronics twice. These many energy conversions affects the system efficiency in a negative way.

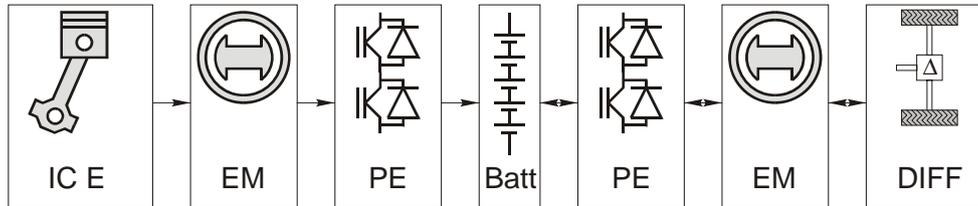


Figure 3.25 Series hybrid topology

The electric machine to the right in Figure 3.25, i.e. the traction motor, has to be designed for peak power and the generator (the EM to the left) is designed for the ICE power. The simplest series hybrid vehicle is an electric vehicle, equipped with a range extender.

An advantage with the topology is that the ICE can be turned off when the vehicle is driving in a zero-emission zone. Yet another merit of the topology is that the ICE with the generator can be mounted separately from the traction motor. This gives a possibility to distribute the weight of the vehicle drive system and in buses an opportunity to use low floor, the latter since no mechanical transmission has to be present under the bus floor like in conventional buses.

Charge sustaining control of a series hybrid vehicle

The traction system consists of only one motor. The control law of that motor is thus simple, the wheel torque reference value defined by the driver is recalculated into a torque on the shaft of the traction motor, according to equation (3-8) where gr_2 is the gear ratio in the final gear of the drive train.

$$T_{em2}^* = \frac{T_{wheel}^*}{gr_2} \quad \text{Equation 3-8}$$

The ICE and generator are used to supply electric energy to the vehicle traction drive. Several strategies can be considered when doing so, amongst where two are fundamentally different:

- **Charge sustaining.** With this strategy the ICE is involved as often as feasible to compensate deviations in battery charge level, thereby minimizing these deviations. The motivation is that the battery is expensive and must be kept as small as possible. With small deviations in battery energy, less battery energy is needed and consequently a smaller battery.
- **Charge depletion.** With this strategy the vehicle is allowed to run in pure electric mode until the battery SOC hits a minimum limitation when the ICE is started and used to charge the battery up to a maximum limitation where the ICE is turned off, and the procedure is started again.

A vehicle can switch between these two strategies when in use, depending on the amount of battery energy storage installed. The rest of this section assumes a charge sustaining strategy.

A fundamental consideration is that the dynamic operation of the ICE must be limited. It can be argued that an ICE consumes fuel and generates emissions out of proportion when making

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changes of operating point faster than a certain rate, compared to the fuel consumption and emissions in stationary operation, see page 20.

The simplest way to limit the dynamic operation of the ICE is to low pass filter the power requirement for the ICE. The power requirement is in this context based on the assumption that the ICE must provide all energy used by the vehicle. The ICE power reference is thus a composite of the tractive power and the power needed to supply charge to the batteries, see Figure 3.26. This power reference is low pass filtered. The time constant of the filter must be selected to ensure quasi-stationary operation of the ICE. The ICE power requirement is thus given by equation (3-9) .

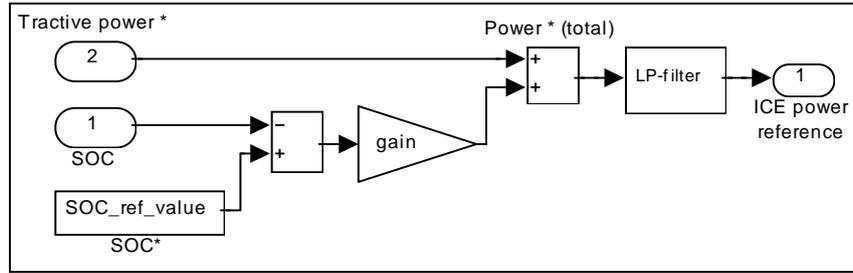


Figure 3.26 A generalized view of the part of the power distribution block in the simulation models that handles the calculation of ICE power reference.

$$\frac{dP_{ice}^*}{dt} = \frac{P_{tractive} + P_{aux} + k_{soc} \cdot (SOC^* - SOC) - P_{ice}^*}{\tau_{ice}} \quad \text{Equation 3-9}$$

In equation (3-9), $P_{tractive}$ is the instantaneous tractive power, P_{aux} is the power consumed by auxiliary devices like the AC or the 12 volt system, k_{soc} is the gain in the proportionally controlled charge control loop and finally τ_{ice} is a time constant to limit the dynamics of the ICE output power. The selection of the parameters of the ICE power reference calculation in equation (3-9) can be done as follows:

$$k_{soc} = \frac{W_{max}}{400 \cdot \tau_{charge}} \quad \text{Equation 3-10}$$

where τ_{charge} = A time constant suitable to guarantee quasi-stationary operation of the ICE. In this context 1 second is used. Once the power level of the ICE is determined by the help of equation (3-9), the most suitable combination of speed ($\omega_{ice,OPT}^*$) and torque ($T_{ice,OPT}^*$) that can provide this power must be selected. The easiest way is to use a look up table like the one in Figure 3.7, which represents the torque of best operating point as a function of the ICE power level. Once the torque is known, the speed reference can also be calculated. In addition to the control law of equation (3-9), an efficiency limitation is also used according to the following:

$$T_{ice}^*, \omega_{ice}^* = \begin{cases} 0,0 & \text{if } \eta_{ice} \leq \eta_{iceOFF} \\ T_{ice,OPT}^*, \omega_{ice,OPT}^* & \text{if } \eta_{ice} \geq \eta_{iceON} \end{cases} \quad \text{Equation 3-11}$$

In equation (3-11), η_{ice} is the best efficiency that can be reached at a certain power level, i.e. the efficiency for the optimal operating point [$T_{ice,OPT}^*, \omega_{ice,OPT}^*$]. The limits for switching the ICVE on and off are control parameters, the value of which can be adjusted to optimise fuel consumption.

Now, assume that the speed and torque reference for the ICE is known. The next step is to use the combination of the ICE and generator on the same shaft. The ICE control system is given

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the ICE torque reference, and the speed reference is used in a speed controller to calculate the torque of the generator, according to equation (3-12).

$$T_{em1}^* = k_s \cdot (\omega_{ice}^* - \omega_{ice}) - T_{ice}^* \quad \text{Equation 3-12}$$

where k_s = speed control gain. In control terms, equation (3-12) is a pure proportional speed controller with feed forward of the load torque. The gain parameters of this speed controller should be selected according to equation (3-13).

$$K_s = \frac{J_{genset}}{4 \cdot T_x} \quad \text{Equation 3-13}$$

In equation (3-13), J_{genset} is the inertia of the ICE+generator rotating parts together, and T_x is a time constant that should be the longest of the sampling time of the control system used to control the speed or the time constant of the filter used to measure the speed. This setting of K_s , or a lower value, guarantees stable operation.

Braking is made with the traction motor to the limit of its abilities. If the traction motor is not able to provide the braking torque need, the friction brakes fills in.

Charge depleting control of a series hybrid vehicle

In addition to the charge strategy discussed in the previous section, the charge depletion control model requires an additional law to govern when to switch the ICE on and off.

Based on the charge strategy for the charge sustaining series hybrid, the following addition needs to be made:

$$P_{ice_depletion}^* = \begin{cases} 0 & \text{if } SOC > SOC_{max} \\ P_{ice_depletion}^* & \text{if } SOC_{min} < SOC < SOC_{max} \\ P_1 & \text{if } SOC < SOC_{min} \end{cases} \quad \text{Equation 3-14}$$

Now, P_1 can be either the power determined by equation (3-9), or a selected constant power. On the later case with a constant power, the power corresponding to the highest efficiency of the ICE is normally selected.

Simulated example of a series hybrid

The traction motor of the series hybrid vehicle has to be designed to provide enough power to sustain the highest speed as well as enough torque on the wheels to allow good take off acceleration. To estimate the torque and power needed, assume that the vehicle simulated must accelerate from standstill to 100 km/h in 10 seconds. This corresponds to the linear force and corresponding wheel torque

$$\begin{aligned} F &= m \cdot a = 1300 \cdot (100/3.6)/10 = 3600 \text{ N} \\ T_{wheel} &= F \cdot r_{wheel} = 3600 \cdot 0.3 = 1000 \text{ Nm} \end{aligned} \quad \text{Equation 3-15}$$

To reach such torque levels it is reasonable to use a gear box with a fix gear ratio. In this case the gear ratio $gr_2=5$ is proposed. The traction motor torque requirement is thus $1000/5=200$ Nm. To be able to keep the maximum speed anticipated, the tractive power can be calculated from equation (3-16). With the parameters of the vehicle used in this context (see appendix A), the tractive power at max speed is calculated with equation (3-16).

$$P_{vehicle_max} = \left(C_r M_v g + \frac{1}{2} \rho_a C_d A_v v_{max}^2 \right) \cdot v_{max} = 59.7 \text{ kW} \quad \text{Equation 3-16}$$

Based on this fact, a maximum power for the traction motor is selected to be 60 kW. To keep the previously stated ambition to have 100 kW installed power on the vehicle, the combustion engine and the generator should be selected to have the maximum power 20 kW each. That will turn out to be a too low power for the US06 driving cycle (highway driving) that has an average tractive power between 20...25 kW. Thus, the ICE and the generator power is selected to be 25 kW each, just barely enough to sustain the battery charge in the heavy US06 highway cycle.

Table 9 shows a summary of the parameters and settings used with the simulated series hybrid.

Table 9 Vehicle data for a series hybrid

Property	Variable name	Setting
Fuel type	Fuel type	1, Otto
Peak ICE power	Pice_max	30 kW
Peak ICE speed	Wice_max	6000 rpm for Otto and 4500 rpm for Diesel
Min ICE speed	Wice_min	800 rpm
Peak ICE torque	Tice_max	= Max power divided by the speed for max efficiency
Vehicle weight	Mv	1600 kg
Wheel radiud	rw	0.3 m
Air resistance	Cd	0.26
Rolling resistance	Cr	0.008
Front area	Av	2.55
Air_density	rho_air	1.2
Maximum vehicle speed	vmax	165 km/h
Peak generator power	Pem1_max	30 kW
Peak generator torque	Tem1_max	1.2*Tice_max to facilitate speed control
Peak generator speed	Wem1_max	Wice_max
Final gear ratio	gr2	5
Peak motor power	Pem2_max	60 kW
Peak motor torque	Tem2_max	200 Nm to facilitate speed control
Peak motor speed	Wem2_max	vmax/rw*gr2
Charge time constant	Tau_charge	1 s
Charge control gain	ksoc	18000
Genset speed control, gain	kgenset	Jgenset/4/0.05 = 0.5
Power electronics efficiency	EtaPE	0.97

Figure 3.27 shows the power levels from each of the three main energy converters when running the ECE15 city driving cycle. Note that the ICE and the generator power are almost opposites, only the sign and the losses of the electrical machine and the power electronic converters is the difference. Note also that the generated electrical power seems to follow the driving power quite well. Still the dynamics of the ICE are limited by the 1-second time constant Tau_charge that of course cannot be seen in the timescale of Figure 3.27.

The same figure also shows the loci of the operating points of the energy converters. Note that the ICE operates along a narrow band in the speed-torque characteristic. It is the previously described method of selecting the operating points for the best efficiency that picks these operating points.

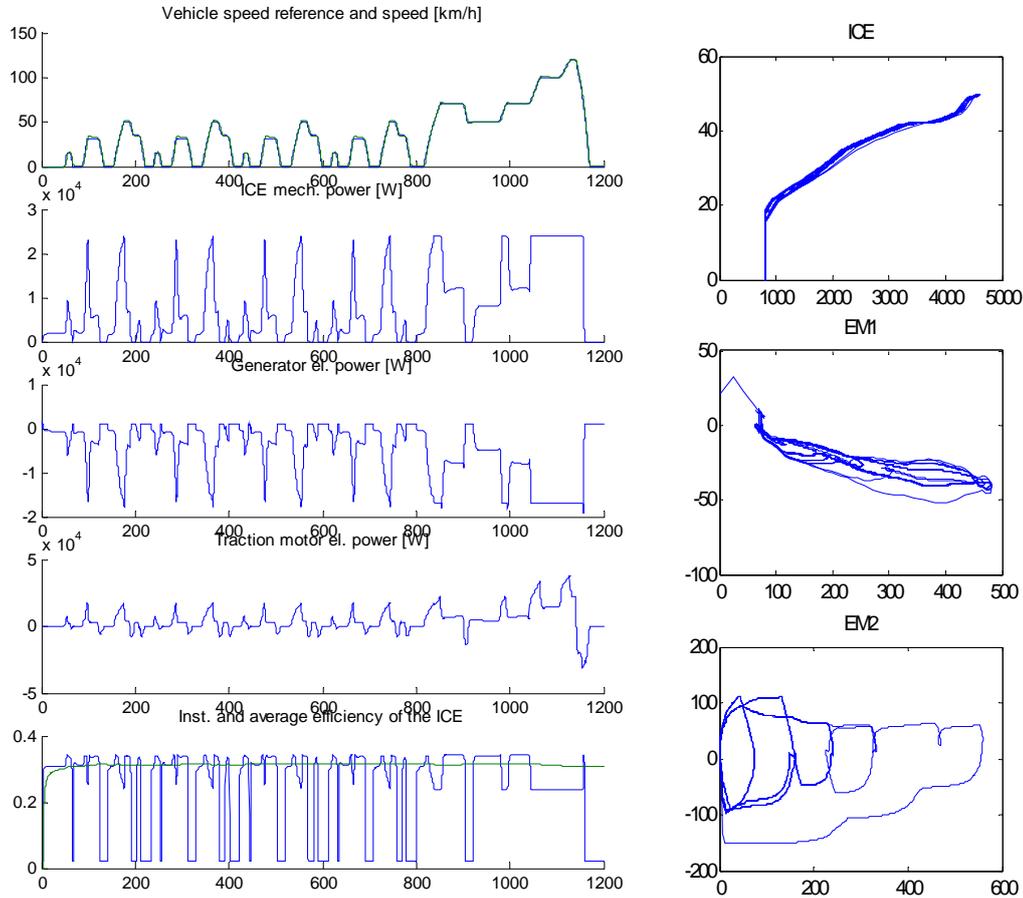


Figure 3.27 Power levels of the main energy converters and speed-torque loci for the same converters when running the vehicle through the ECE15 city driving cycle

Note also in Figure 3.27 that the average efficiency is close to 30 %. Given the fact that this is an Otto engine with a peak efficiency around 34 %, this is a very good result. The hybrid system is apparently able to run the ICE at the best operating points.

It is sometimes argued that a series hybrid benefits of the ICE having the possibility to operate at a constant operating point. This is very different from the way the ICE operates in Figure 3.27. To evaluate this argument, a simulation is made with a charge depleting strategy. The battery SOC is allowed to vary in a wide interval, 40..90%, the ICE starts and runs at optimal power (the power that gives optimal efficiency) when SOC hits 50 % and the stops when the battery SOC hits 90 %. In addition, if the battery SOC keeps dropping below 50 %, then the ICE power is increased proportionally with k_{soc} . Figure 3.28 displays the results.

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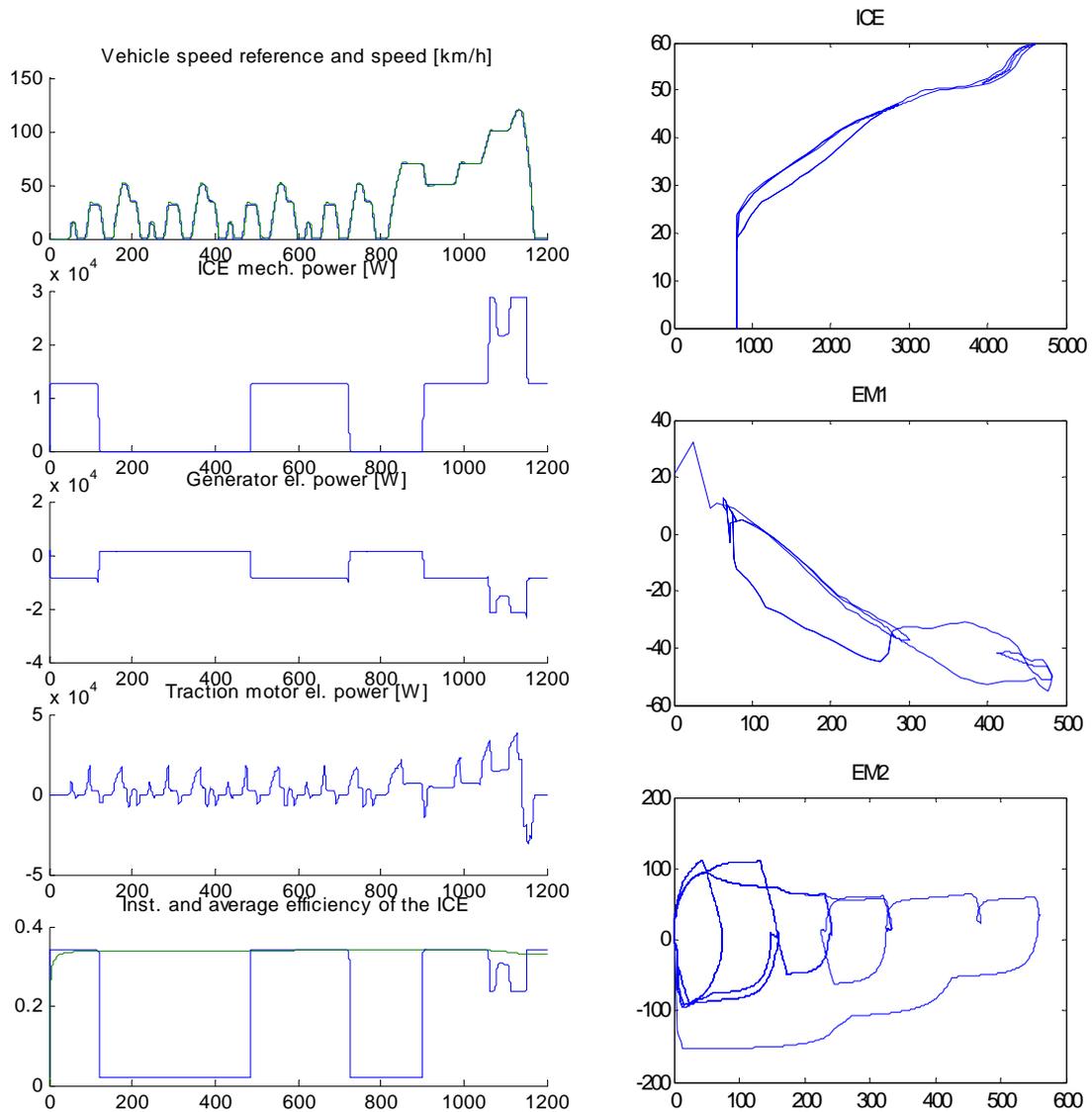


Figure 3.28 The same simulation as in Figure 3.27, but with a charge sustaining strategy.

Note from Figure 3.28 how the ICE changes operating point, basically between two fix levels. Since the ICE does not follow the quickly varying power to the traction motor, the difference between the produced electrical power and the consumed electrical power must be supplied from the battery. This means that the battery has to work harder which shows in the SOC. Figure 3.29 shows the SOC for two simulations, one with $\tau_{charge}=1$ s and the proportional control described by equation 3-9 and one with the additional charge depletion strategy, corresponding to the two cases in Figure 3.27 and Figure 3.28.

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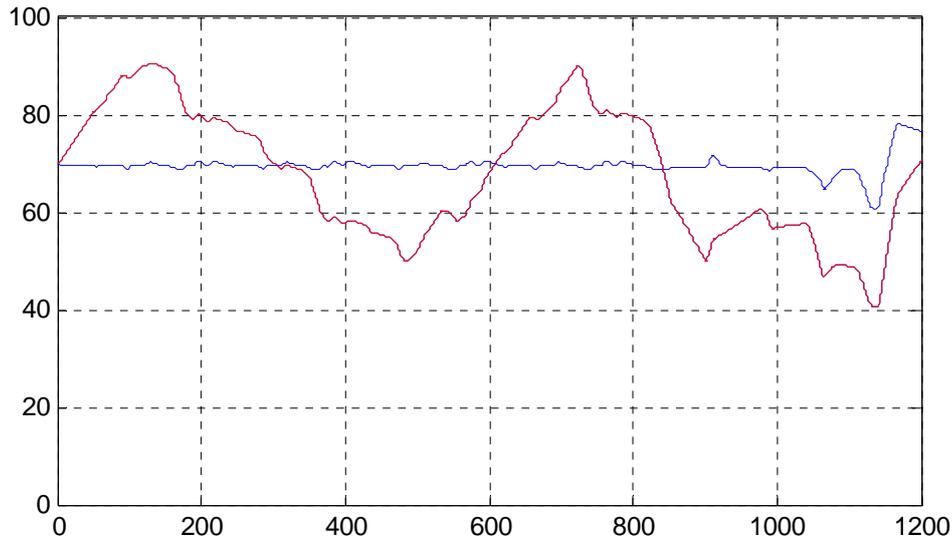


Figure 3.29 SOC with $\tau_{charge}=1$ second in the charge sustaining strategy and the charge depletion strategy when running the EUDC driving cycle with a series hybrid powered with and Otto engine.

Note from Figure 3.29 the big difference in the variations in SOC entirely depending on how fast the ICE follows the tractive power variations. The smaller the SOC deviations are, the smaller the traction battery can be.

If the fuel consumption is studied in detail, it shows that with the short time constant the fuel consumption is 0.87 l/10 km, and with the ON/OFF strategy it is 0.84 l/10 km. Thus, it is shown that the series hybrid has a potential for lower fuel consumption since the ICE can be operated at the best operating points. There is however another aspect that needs to be taken into account, before drawing to quick conclusions from this difference. The cycling of the battery is significantly deeper with the depleting mode, and thus the battery cost is likely to eliminate the benefits with depletion mode. As will be discussed later in a section on “Plug In” hybrids, this comparison is very much depending on what way the batteries are recharged.

Table 10 shows the fuel consumptions for both the Otto and the Diesel engines running both the EUDC and the US06 driving cycles. In all cases the charge time constant is $\tau_{charge}=1$ s.

Table 10 Series hybrid fuel consumption [l/10km]. Pure combustion driven vehicle within paranthesis.

	EUDC	US06
Otto	0.87 (0.74)	1.26 (0.82)
Diesel	0.58 (0.63)	0.68 (0.63)

Note that the series hybrid may have a fuel consumption advantage in city traffic, but it is small. In highway traffic, the small ICE of this design has to work a lot at its highest power, which does not give the best fuel efficiency, and correspondingly the fuel consumption is way to high. This particular design is not suitable for highway traffic. A different design, with a bigger ICE would give better results, but would then loose in city traffic instead. The conclusions of the simulations so far are:

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- 1 The ICE should be allowed to operate with as high dynamics as possible, since the power drawn from the batteries thus is minimized. This allows for the use of a smaller battery, which is attractive due to the relatively high battery costs.
- 2 The many energy conversion of a series hybrid eliminates most of the advantages of this type of drive train topology. Series hybrids are most suitable for city traffic.

The main alternative to the series hybrid is the parallel hybrid. The main advantage compared to the series hybrid is that a large fraction of the power converted by the primary energy converter is delivered to the wheels via the mechanical transmission, minimizing the number of energy conversions. Next chapter describes this topology.

3.8. Parallel

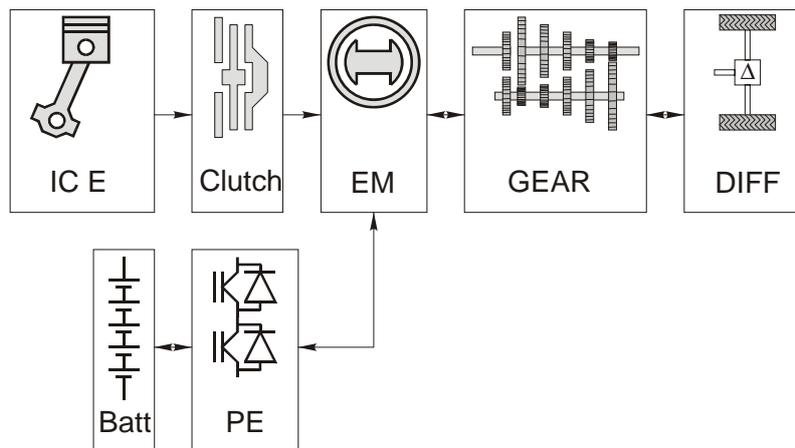


Figure 3.30 Parallel hybrid topology with one optional electric traction motor.

The parallel hybrid is a combination of two drive systems. The ICE is mechanically connected to the wheels via a gearbox. The gearbox can be manual, automatic, a CVT or an automatically controlled manual gearbox. It is this latter type that will be used in the simulations that follows below. The differential is assumed to have a gear ratio 1:1 and the gearbox thus represents the total gear ratio of the mechanical transmission.

The working point of the hybrid can be chosen relatively freely with the help of the electrical machines, i.e. the speed of the ICE is chosen with the gearbox and the torque with the electric machine(s). There are three options available: pure electric operation, pure ICE operation and a combined operation when the electric drive absorbs or delivers power to improve the ICE operating point. To achieve peak tractive power, both the ICE and the electric machine are used.

There are several locations to put the electrical machine, not only next to the clutch as in Figure 3.30. An extreme is to have the traction motor built into the wheels. Formally, they are still located as in a parallel hybrid, with some differences related to transmission losses. In this context, the topology of Figure 3.30 is used to represent the parallel hybrid.

Charge sustaining control of a parallel hybrid

The charge control of a parallel hybrid is identical to the one used on a series hybrid. The ICE power is even in this case based on the tractive power, the power needed to level the battery charge and the auxiliary power. There are however two main differences:

- 1 The operating point cannot be chosen freely, since the ICE is mechanically connected to the wheels, and thus dependent on the vehicle speed. The gearbox allows adaptation of the ICE speed in steps. A CVT offers more freedom in selection of ICE speed, but a five

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speed gearbox gives enough possible gear ratios to allow finding one that is close to the ideal gear ratio.

- 2 The electric machine does not have to brake the whole ICE power as the generator of the series hybrid, nor does it have to drive the whole vehicle alone. The electrical machine only provides the difference between the ICE power and driving power. This is helpful in acceleration and regenerative braking, but also in charging the batteries.

The control algorithms are repeated here, the charge control and the control parameters for charge control.

$$\frac{dP_{ice}^*}{dt} = \frac{P_{tractive} + P_{aux} + k_{soc} \cdot (SOC^* - SOC) - P_{ice}^*}{\tau_{ice}} \quad \text{Equation 3-17}$$

τ_{charge} = A time constant suitable to guarantee quasi-stationary operation of the ICE. In this context 1 second is used.

$$k_{soc} = \frac{W_{max}}{400 \cdot \tau_{charge}} \quad \text{Equation 3-18}$$

In addition to this control algorithm, additional algorithms are needed for selection of most suitable gear ratio, and for selection of the electrical machine torque. The gear ratio (g_r) selection was discussed on page 29, and will not be repeated here. The control law for the electrical machine is give by equation (3-19).

$$T_{em}^* = \frac{T_{wheel}^*}{g_r} - T_{ice}^* \quad \text{Equation 3-19}$$

Equation (3-19) says that the electrical machine must provide the part of the required wheel torque that the ICE does not. The reason why the ICE does not provide the required torque can be several:

- 1 A sudden change of operating point may prevent the ICE to follow, as the strategy is to limit the ICE dynamics.
- 2 The operating point of the ICE may give so low efficiency that it instead is turned off.
- 3 The ICE may not be able to provide the requested torque, like during a heavy acceleration, or in braking mode.

For any or several of these reasons, the electrical machine will support the ICE.

Braking works in a similar way as with the series hybrid. If the ICE and the electrical machine together cannot supply the negative torque needed for braking, then the friction brakes fills in the missing negative torque. The energy spent in the friction brakes can of course not be regenerated to the battery.

Charge depletion control of a parallel hybrid

Similarly as with the series hybrid, a parallel hybrid can run in charge depletion mode, i.e. with the ICE turned off. The limitation in the electric traction system power limit the performance, unless the ICE is allowed to step in only when the EM is not enough. The additional control laws required when running the vehicle in charge depletion mode are:

$$P_{ice_depletion}^* = \begin{cases} 0 & \text{if } SOC > SOC_{max} \\ P_{ice_depletion}^* & \text{if } SOC_{min} < SOC < SOC_{max} \\ P_{ice}^* & \text{if } SOC < SOC_{min} \text{ or } P_{em,max} < P_{tractive} \end{cases} \quad \text{Equation 3-20}$$

The last line of equation (3-20) indicates that the ICE is expected to step in in case the EM is not able to provide the tractive power by itself.

Simulated example of a parallel hybrid

The traction system of a parallel hybrid has one combustion engine and one electric machine, at least. In the specification of the vehicle, the tractive power is an important design parameter that greatly affects the way the vehicle handles on the road, and beyond that, who buys the vehicle. In the case that is studied in this context, it is already decided that the total installed power shall be 100 kW. This is of course a rough parameter when making traction concepts comparable, but it is reasonable to assume that there is a “price/kW” and that traction systems with the same power represents about the same cost. The electric traction system is probably more expensive, at least due to the fact that ICE based traction systems for vehicles are made in several orders of magnitude higher numbers than electric traction systems for vehicles.

Since there are two main energy converters, the ICE and the EM, the proportion in power rating between these two must be set. There can be several different philosophies behind this choice:

- 1 A large ICE and a small EM can be motivated by the fact that the EM drive is more expensive. A big EM drive also need a large energy storage if it is going to be useful, and energy storage is also expensive. Another argument for a small EM is that the ICE development continuously widens the plateau of the efficiency map and thus reduces the need for a supporting machine at less efficient operating points.
- 2 A small ICE and a large EM can be motivated by the fact that gasoline is expensive compared to electric energy bought from the power grid. A vehicle with a large battery and a big EM has the ability to store and use enough energy to eliminate the need for ICE traction for several 10's of kilometres. This implies the use of the charge depletion strategy for the parallel hybrid. Since most private cars only are used for rather short distances most of the time, like commuting to work, a vehicle equipped like this would use very little gasoline if recharged from the power grid regularly. This type of vehicle is referred to as a “plug in hybrid”. The main drawback of such a design is the cost of the large battery.

For the simulation example in this context, a design along philosophy 1 above will be made. The 100 kW-installed powers are split into 80 kW ICE and 20 kW EM. The ICE is then big enough to support the vehicle alone in case of emergency. A malfunction of the EM drive must not endanger the vehicle handling, e.g. when accelerating onto a highway it may turn out very dangerous if the EM drive suddenly fails. The 20 kW EM drive is still strong enough to allow pure electric drive at low speeds, e.g. silently moving in a residential area at night or emission free operation in a garage, even acceptable handling in city traffic

Table 11 shows a summary of the parameters and settings used with the simulated parallel hybrid.

Table 11 *Vehicle data for a parallel hybrid*

Property	Variable name	Setting
Fuel type	Fuel type	1, Otto
Peak ICE power	Pice_max	80 kW
Peak ICE speed	Wice_max	6000 rpm for Otto and 4500 rpm for Diesel
Min ICE speed	Wice_min	800 rpm
Peak ICE torque	Tice_max	= Max power divided by the speed for max efficiency
Fordonsvikt	Mv	1600 kg
Hjulradie	rw	0.3 m
Air resistance	Cd	0.26
Rolling resistance	Cr	0.008
Front area	Av	2.55
Air_density	rho_air	1.2
Maximum vehicle speed	vmax	165 km/h
Peak generator power	Pem_max	20 kW
Peak generator torque	Tem_max	200 Nm to facilitate ICE starting
Peak generator speed	Wem_max	Wice_max
Final gear ratio	gr2	1
Gear ratios (wice/wwheel)	gr1	15.4224
	gr2	9.6588
	gr3	6.0491
	gr4	3.7885
	gr5	2.3727
Charge time constant	Tau_charge	1 s
Charge control gain	ksoc	22500
Power electronics efficiency	EtaPE	0.97

Figure 3.31 shows the power levels of the two main energy converters when running the EUDC city driving cycle.

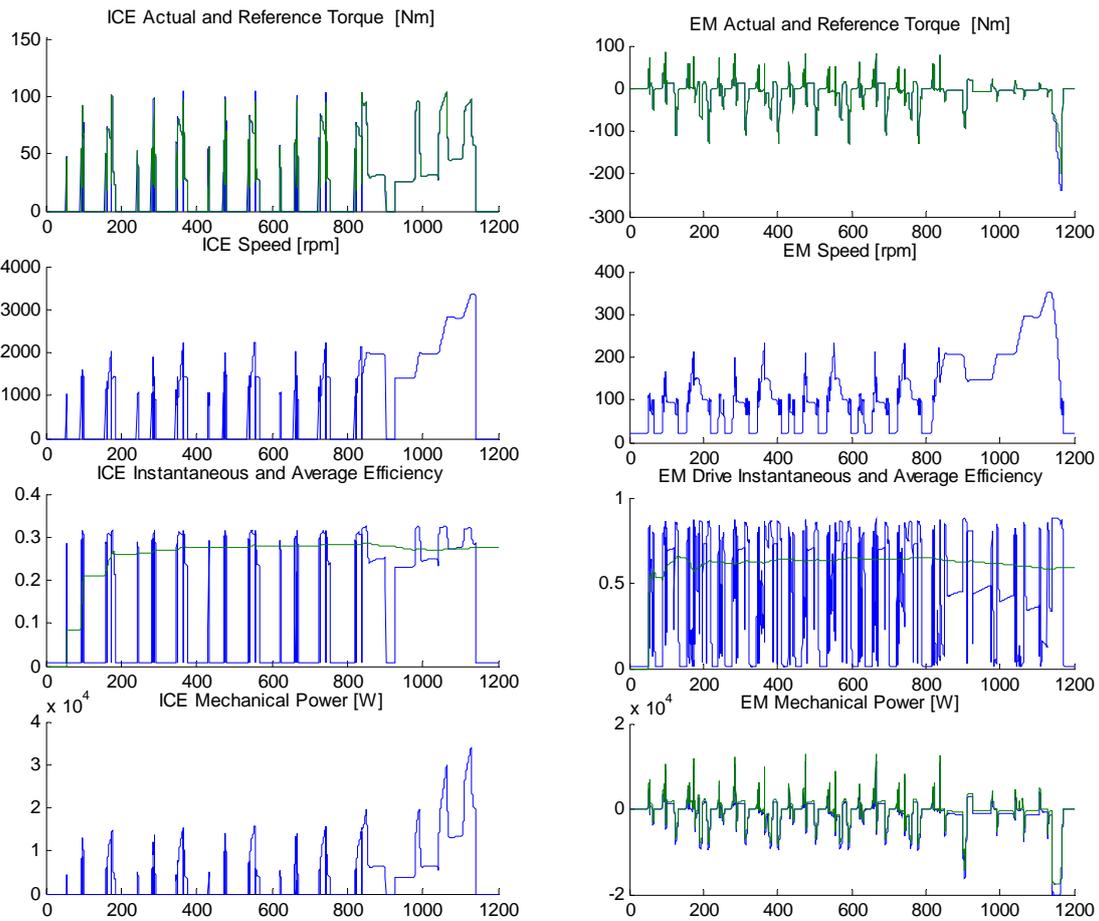


Figure 3.31 Power levels of the two main energy converters when running the parallel hybrid vehicle through the EUDC city driving cycle.

Note in Figure 3.31 how the ICE is using increased torque rather than increased speed to reach the power levels needed to drive the vehicle. Note also that the EM seems to have almost zero average power. The EM is really only handling the deviations between the driving power and the ICE power. Even though the ICE dynamics are slightly reduced compared to a conventional vehicle, it is still able to do most of the tractive work. Figure 3.32 shows the corresponding situation with the much more demanding US06 highway driving cycle.

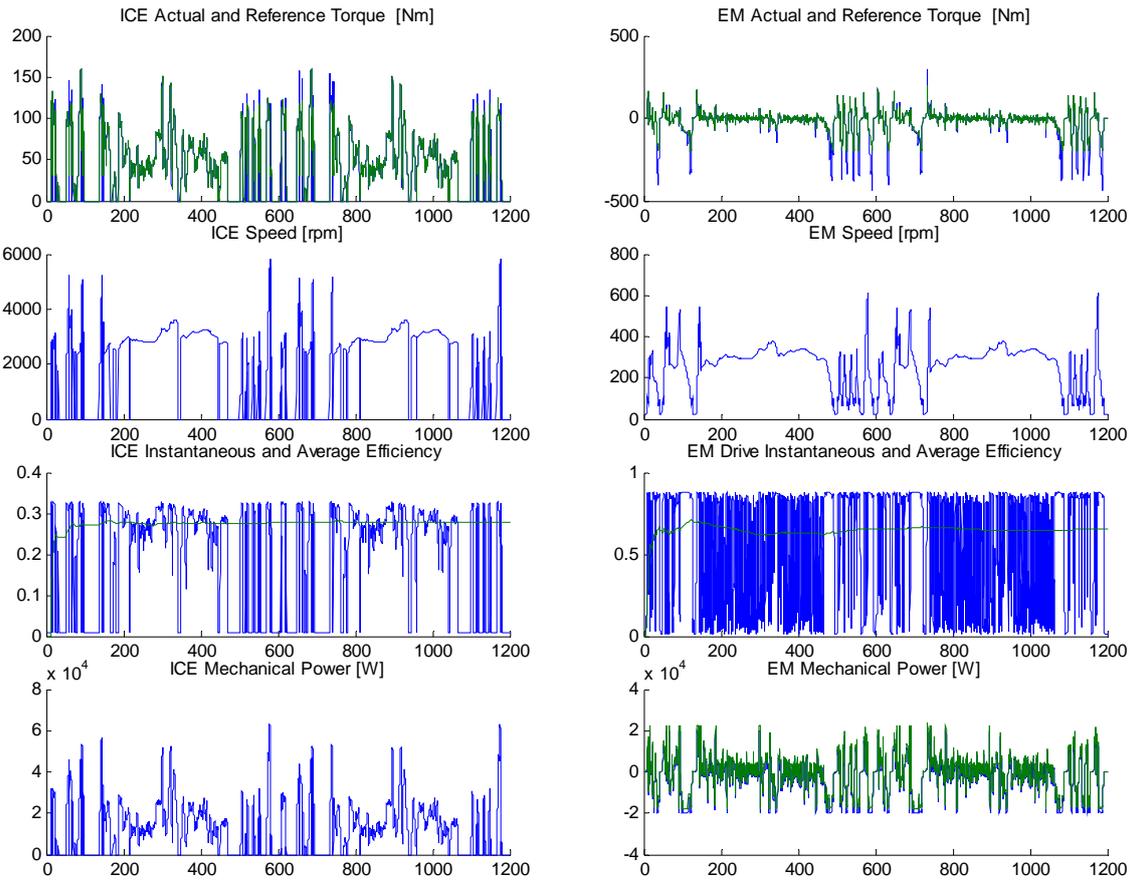


Figure 3.32 Power levels of the two main energy converters when running the parallel hybrid vehicle through the US06 highway driving cycle.

Note from Figure 3.32 that the ICE even more clearly in this case use high torque rather than high speed when higher power is needed. Compare to Figure 3.23, upper right, that is the same case for a conventional vehicle.. Note also that as the speed increases, the EM torque is strongly limited, due to field weakening. This is the consequence of having a high torque at low speed but not a correspondingly high power at high speed. If the peak torque (200 Nm) would have been available at the highest speed (628 rad/s) then the EM power would be 126 kW, an EM far bigger, heavier and more expensive than the 20 kW machine used here.

Table 12 shows the fuel consumptions for both the Otto and the Diesel engines running both the ECE15 and the US06 driving cycles. In all cases the charge time constant is $\tau_{charge}=1$ s.

Table 12 Parallel hybrid fuel consumption.

	EUDC			US06		
	Conv.	Series	Parallel	Conv.	Series	Parallel
Otto	0.74	0.87	0.45	0.82	1.26	0.64
Diesel	0.63	0.58	0.36	0.63	0.68	0.49

Note from Table 12 that the parallel hybrid has the significantly lowest fuel consumption in comparison with the conventional and the series hybrid. This can be explained with the low number of energy conversions. The primary energy is supplied to the wheels with a minimum of conversions, the worst operating points are avoided and the breaking energy is fed back to the batteries.

The conclusions about the parallel hybrid is that it is a very competitive design regarding fuel consumption, it is easy to control and has a redundancy regarding traction system that is appealing. In the case of an EM drive failure, the vehicle is still able to continue its operation, with only slightly reduced performance.

3.9. Power Split

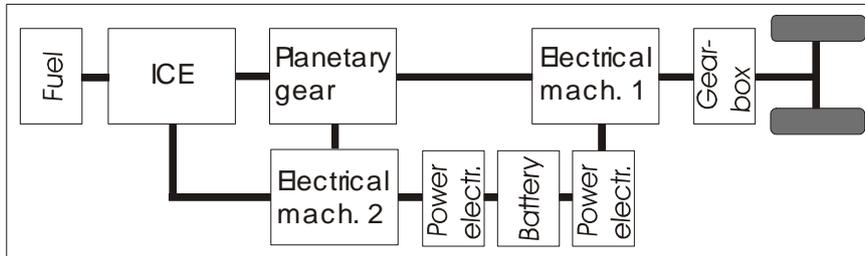


Figure 3.33 Power split hybrid topology.

A transmission that must be mentioned is the Power Split Hybrid (PSH) that can be regarded as a mix between the series and parallel hybrid state. The PSH is even called complex, combined or dual hybrid vehicle. This is the type of transmission used in e.g. Toyota Prius.

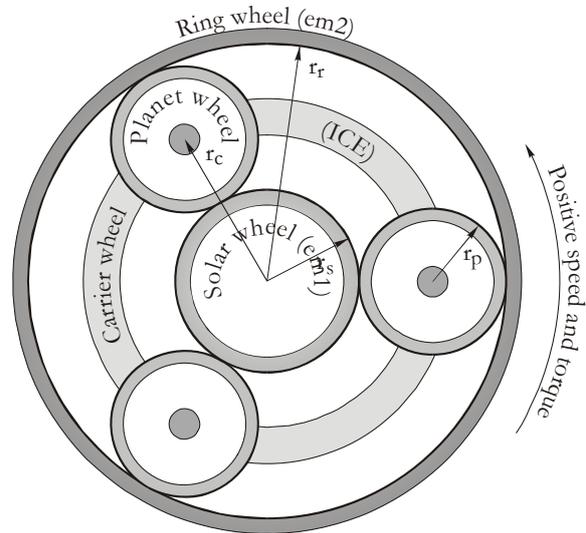
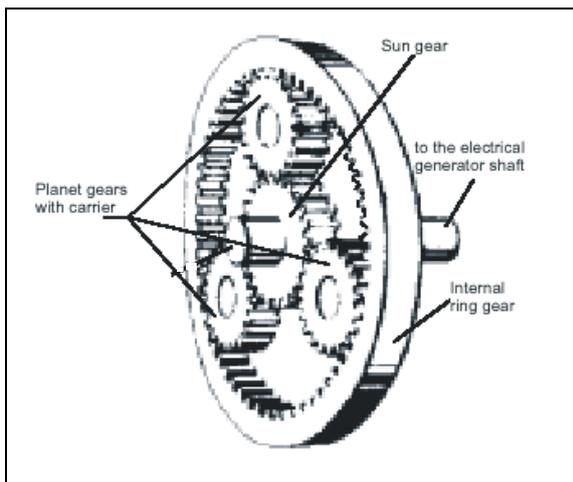


Figure 3.34 Planetary gear

A planetary gearbox connects two electrical machines and the ICE. One electric machine is connected to the solar wheel; one to the ring wheel and the ICE is connected to the carrier wheel. The ring wheel is finally driving the differential gear to the tires. To understand the fundamental principle of this hybrid, the following may be helpful:

- 1 The ICE applies a torque to the ring wheel by moving the planets wheels relative to the solar wheel.
- 2 Thus, the solar wheels must set up a torque in proportion to the ICE torque = the carrier wheel torque.
- 3 By adjusting the solar wheel speed, the speed of the carrier=ICE can be varied with respect to the ring wheel speed=the vehicle speed.
- 4 The solar wheel speed can be either positive (to allow increased ICE speeds relative to the vehicle speed) or negative (to allow reduced ICE speeds relative to the vehicle speed). As the solar wheel electric drive applies a torque in opposition to the ICE torque, i.e. a torque of mostly one sign, and the solar wheel speed can have any sign, the solar wheel

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electric machine provides electric power flow in both directions, i.e. works either as a generator or as a motor.

- 5 The ring wheel electric machine can help the ICE with driving the vehicle and thus work as a motor, but just as well brake the vehicle and thus work as a generator. It is the combined effort of the solar wheel electric machine and the ring wheel electric machine that determines whether the battery is charged or discharged in a certain situation.

Fundamental torque relations

The fundamental ratios between the torques on the three axis can be derived in the following way:

Solar wheel / carrier wheel system

Assume that T_{ice} is applied to the carrier wheel. What torque T_s does that correspond to on the solar wheel? Use force balance with the ring wheel as a fix point.

$$\begin{aligned} \frac{T_{ice}}{r_c} \cdot (r_r - r_c) &= \frac{T_s}{r_s} \cdot (r_r - r_s) \\ r_c &= \frac{r_r + r_s}{2} \\ T_{ice} \cdot \left(\frac{r_r}{r_c} - 1 \right) &= \frac{T_s}{r_s} \cdot (r_r - r_s) = T_{ice} \cdot \left(\frac{2r_r}{r_r + r_s} - 1 \right) \quad \text{-Equation 3-21} \\ T_{ice} &= \frac{\frac{T_s}{r_s} \cdot (r_r - r_s)}{\left(\frac{2r_r}{r_r + r_s} - 1 \right)} = \frac{\frac{T_s}{r_s} \cdot (r_r - r_s)}{\left(\frac{2r_r}{r_r + r_s} - \frac{r_r + r_s}{r_r + r_s} \right)} = T_s \cdot \left(\frac{r_r}{r_s} + 1 \right) = T_s \cdot (1 + k_{pl}) \end{aligned}$$

For stationary operation, the ICE torque must be balanced by a torque from the solar wheel electric drive (em1) equal to:

$$T_{em1} = - \left(\frac{T_{ice}}{1 + k_{pl}} \right)$$

Ring wheel / Carrier wheel system

Assume that T_{ice} is applied to the carrier wheel. What torque T_r does that correspond to on the ring wheel? Use force balance with the solar wheel as a fix point.

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$$\frac{T_{ice}}{r_c} \cdot (r_c - r_s) = \frac{T_r}{r_r} \cdot (r_r - r_s)$$

$$r_c = \frac{r_r + r_s}{2}$$

$$T_{ice} \cdot \left(1 - \frac{r_s}{r_c}\right) = \frac{T_r}{r_r} \cdot (r_r - r_s) = T_{ice} \cdot \left(1 - \frac{2r_s}{r_r + r_s}\right)$$

$$T_{ice} = \frac{\frac{T_r}{r_r} \cdot (r_r - r_s)}{\left(1 - \frac{2r_s}{r_r + r_s}\right)} = \frac{\frac{T_r}{r_r} \cdot (r_r - r_s)}{\left(\frac{r_r + r_s}{r_r + r_s} - \frac{2r_s}{r_r + r_s}\right)} = T_r \cdot \left(\frac{r_s}{r_r} + 1\right), \text{ i.e.}$$

$$T_{r(of\ ice)} = \frac{T_{ice}}{\left(1 + \frac{r_s}{r_r}\right)} = T_{ice} \cdot \frac{\frac{r_r}{r_s}}{\left(1 + \frac{r_r}{r_s}\right)} = T_{ice} \cdot \frac{k_{pl}}{(1 + k_{pl})}$$

Equation 3-22

Ring wheel / Solar wheel system

How does the torques on the ring and solar wheel, resulting from a torque on the carrier wheel, relate? Combine the two equations 3-22 and 3-21.

$$T_s \cdot \left(\frac{r_r}{r_s} + 1\right) = T_r \cdot \left(1 + \frac{r_s}{r_r}\right)$$

$$T_r = T_s \cdot \frac{\left(\frac{r_r}{r_s} + 1\right)}{\left(1 + \frac{r_s}{r_r}\right)} = T_s \cdot \frac{\left(\frac{r_r + r_s}{r_s} + \frac{r_s}{r_s}\right)}{\left(\frac{r_r + r_s}{r_r} + \frac{r_s}{r_r}\right)} = T_s \cdot \frac{r_r}{r_s} = T_s \cdot k_{pl}$$

Fundamental speed relations

The speed relations are derived from superposition, by considering first the carrier wheel fixed and then the ring wheel fixed and calculate the solar wheel movement as a function of the other two axis movements.

$$\begin{cases} \frac{d\theta_r \cdot r_r}{r_p} = -\frac{d\theta_s \cdot r_s}{r_p} \\ \frac{d\theta_c \cdot r_c}{r_p} \cdot 2r_p = d\theta_s \cdot r_s \end{cases} \Rightarrow$$

$$d\theta_s \cdot r_s = -d\theta_r \cdot r_r + 2 \cdot d\theta_c \cdot r_c$$

Equation 3-23

$$\begin{cases} \omega_s \cdot r_s = -\omega_r \cdot r_r + 2 \cdot \omega_c \cdot r_c \\ r_c = \frac{r_s + r_r}{2} \end{cases} \Rightarrow$$

$$\frac{\omega_s - \omega_c}{\omega_r - \omega_c} = -\frac{r_r}{r_s}$$

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Charge sustaining control of a complex hybrid

The charge control of a complex hybrid is identical to the one used on a series or parallel hybrid. The ICE power is even in this case based on the tractive power, the power needed to level the battery charge and the auxiliary power.

The control algorithms are repeated here, the charge control and the control parameters for charge control.

$$\frac{dP_{ice}^*}{dt} = \frac{P_{tractive} + P_{aux} + k_{soc} \cdot (SOC^* - SOC) - P_{ice}^*}{\tau_{ice}} \quad \text{Equation 3-24}$$

τ_{charge} = A time constant suitable to guarantee quasi-stationary operation of the ICE. In this context 1 second is used. In this context 1 second is used.

$$k_{soc} = \frac{W_{max}}{400 \cdot \tau_{charge}} \quad \text{Equation 3-25}$$

Based on this instantaneous power, a torque and speed reference for the ICE is obtained. There are now two separate control issues to take care of:

- 1 To set the speed of the ICE, the solar wheel motor is used for speed control, just like with the series hybrid, with the only difference that there is a gear ratio between the ICE (= carrier wheel) and the EM1 (=solar wheel electric drive)
- 2 The ring wheel drive will be used to set the total torque on the drive shaft to the wheels of the vehicle, just like in a parallel hybrid. The difference is that there is a gear ratio between the ICE (=carrier wheel) and the EM2 (= ring wheel).

ICE speed control

Now, assume that the speed and torque reference for the ICE is known. The ICE torque reference is given to the ICE control system and the ICE speed reference is used in a speed controller to calculate the torque of the solar wheel electric machine (em1), according to Equation 3-21

$$\begin{aligned} \frac{d}{dt} (J_{genset,eq} \cdot \omega_{ice}) &= T_{ice} + T_{em1} \cdot (1 + k_{pl}) \\ \omega_{ice} &= \frac{\omega_r}{(1 + k_{pl})} + \int \frac{T_{ice} + T_{em1} \cdot (1 + k_{pl})}{J_{genset,eq}} \\ T_{em1}^* &= \frac{1}{(1 + k_{pl})} \cdot (k_s \cdot (\omega_{ice}^* - \omega_{ice}) - T_{ice}^*) \end{aligned} \quad \text{Equation 3-26}$$

where k_s = speed control gain. In control terms, equation (3-26) is a pure proportional speed controller with feed forward of the load torque. The gain parameters of this speed controller should be selected according to equation (3-27).

$$k_s = \frac{J_{genset,eq}}{4 \cdot T_x} \quad \text{Equation 3-27}$$

In equation (3-27), $J_{genset,eq}$ is the inertia of the ICE+generator rotating parts together reflected to the ICE side of the gear ratio solar/carrier, and T_x is a time constant that should be the longest

of the sampling time of the control system used to control the speed or the time constant of the filter used to measure the speed. This setting of k_s , or a lower value, guarantees stable operation.

Wheel torque adjustment

Knowing both the wheel torque requested by the driver, and the ICE torque set by the operating point optimization algorithm, the ring wheel electric drive is used to complement the ICE torque to the level of wheel torque requested. The control law for the ring wheel electric drive is give by equation (3-28).

$$T_{em2}^* = \frac{T_{wheel}^*}{g_r} - T_{ice}^* \cdot \left(\frac{k_{pl}}{1 + k_{pl}} \right) \quad \text{Equation 3-28}$$

where g_r in this case is the final gear ratio between the ring wheel and the wheels.

Simulated example of a complex hybrid

The following example will show a Prius generation II simulated and compared to the other hybrid drive systems with as similar conditions as possible regarding the components used, the assumptions on efficiency etc.

Table 13 Vehicle data for a complex hybrid

Property	Variable name	Setting
Fuel type	Fuel type	1, Otto
Peak ICE power	Pice_max	57 kW
Peak ICE speed	Wice_max	6000 rpm
Min ICE speed	Wice_min	800 rpm
Peak ICE torque	Tice_max	= Max power divided by the speed for max efficiency
Fordonsvikt	Mv	1600 kg
Hjulradie	rw	0.3 m
Air resistance	Cd	0.26
Rolling resistance	Cr	0.008
Front area	Av	2.55
Air_density	rho_air	1.2
Maximum vehicle speed	vmax	165 km/h
Peak EM1 power	Pem1_max	30 kW
Peak EM1 torque	Tem1_max	38 Nm
Peak EM1 speed	Wem1_max	868 rad/s
Peak EM2 power	Pem2_max	50 kW
Peak EM2 torque	Tem2_max	300 Nm
Peak EM2 speed	Wem2_max	536 rad/s
Final gear ratio	gr2	1
Charge time constant	Tau_charge	1 s
Charge control gain	ksoc	22500
Power electronics efficiency	EtaPE	0.97

Figure 3.35 shows the power levels of the three main energy converters when running the EUDC city driving cycle.

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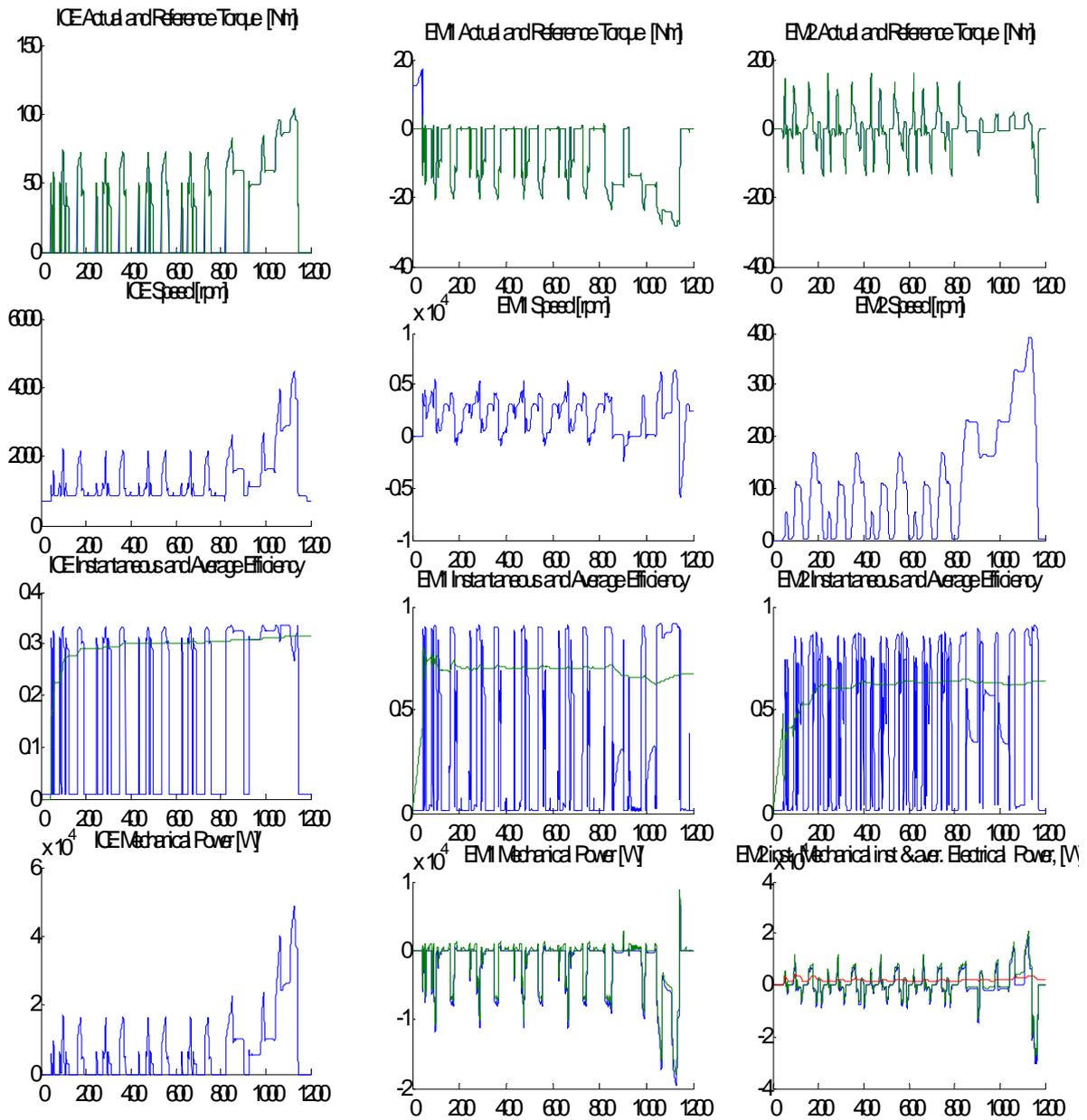


Figure 3.35 ICE, EM1 and EM2 quantities for a complex hybrid in the EUDC driving cycle.

Note from Figure 3.35 in particular that the EM1 torque mostly is a negative scaled version of the ICE torque, but that the EM1 speed varies in a quite different way as it is used to set the most suitable operating point of the ICE. Note also that EM1 most of the time operates as a generator, the reason why Toyota refers to this machine as the generator.

Table 14 shows the fuel consumptions for the Otto engine running both the EUDC and the US06 driving cycles. In all cases the charge time constant is $\tau_{charge}=1$ s.

Table 14 Parallel hybrid fuel consumption.

	EUDC				USO6			
	Conv.	Series	Parallel	Complex	Conv.	Series	Parallel	Complex
Otto	0.74	0.87	0.45	0.58	0.82	1.26	0.64	0.71

Note from Table 14 that the Complex hybrid does not show the lowest fuel consumption of the four, it is still the parallel hybrid. The reason for this is that the Complex hybrid generically has more energy converters, which is detrimental for system efficiency. The drawback of not being able to adjust the speed freely but in steps with a parallel hybrid and a fixed step transmission, is not as important as the drawback of having to circulate some of the power via four (2 el. Machines and 2 power electronic converters) extra energy converters in the complex hybrid.

A way to illustrate this is to plot the difference between the power flowing to the two electric drives. The sum of these powers represent the power flow to the battery, and the difference represents the circulating power.

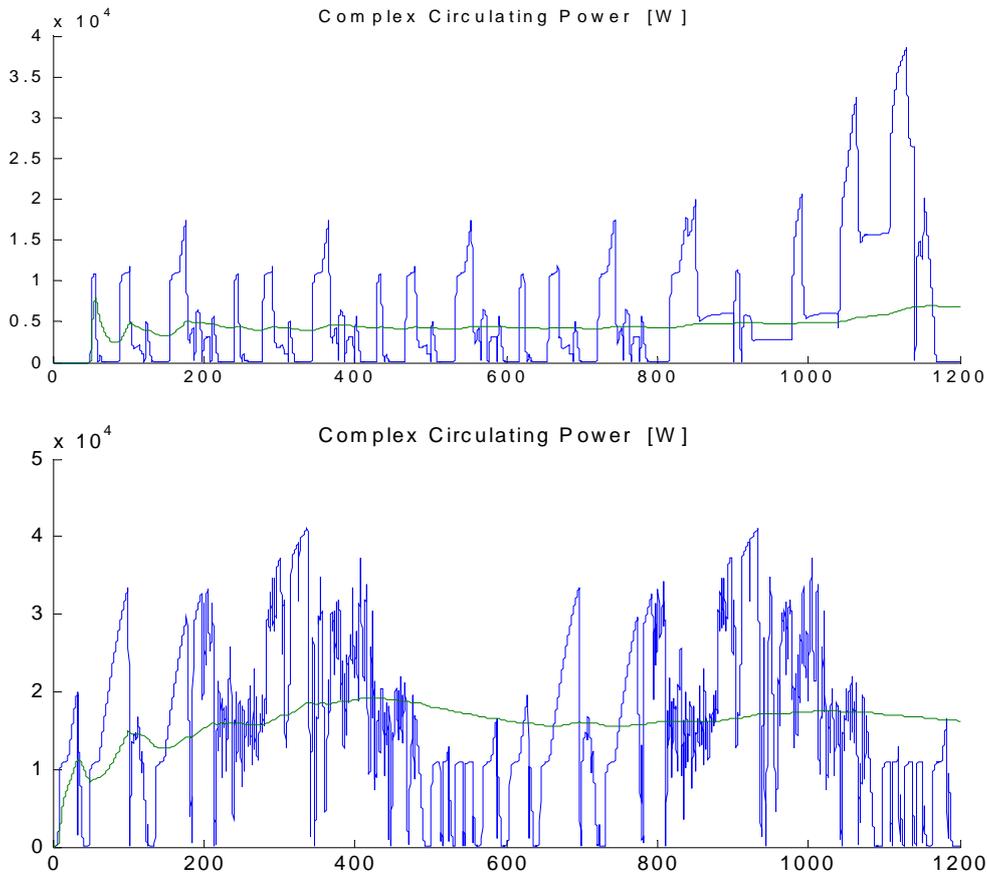


Figure 3.36 The electric power circulating between the two electric drives in a complex hybrid transmission

Note in Figure 3.36 how about 5 kW in the EUDC cycle and 15 kW in the US06 cycle circulates this way. Even assuming 97 % efficiency of one of the electric drives, there are four of them, corresponding to 88 % efficiency or 12 % losses. This corresponds easily to 5..10 % of the fuel efficiency.

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3.10. Fuel cell

A serious and promising alternative to the combustion engine hybrids is the fuel cell based traction system that currently is the subject of intense development.

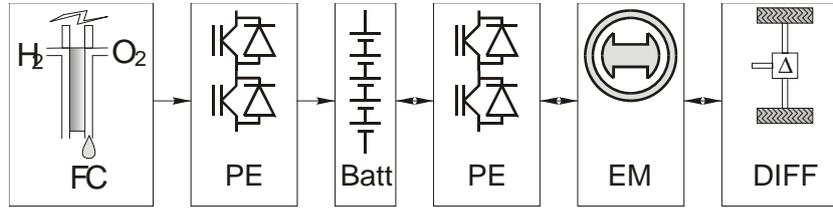


Figure 3.37 Fuel Cell hybrid drive system

The drive system topology of this vehicle is a series hybrid. There is no consensus yet, as of what fuel cell system technology to use. The main issue is related to the fuelling infrastructure. Hydrogen is the preferred fuel, but it is difficult to distribute to the vehicle. Having a reformer on board allows using a more easily handled fuel like methanol, but the reformer adds to complexity and cost. It is still a secret of the future what system will emerge as the best solution. In this context, a methanol reformer based fuel cell system is modelled with a look up table for efficiency as discussed in the section about fuel cells on page 21.

Control of a fuel cell hybrid vehicle

The traction system control law is the same as with the series hybrid vehicle, repeated her:

$$T_{em}^* = \frac{T_{wheel}^*}{gr} \quad \text{Equation 3-29}$$

The charge control algorithm is also the same, repeated here:

$$\frac{dP_{fc}^*}{dt} = \frac{P_{tractive} + P_{aux} + k_{soc} \cdot (SOC^* - SOC) - P_{fc}^*}{\tau_{charge}} \quad \text{Equation 3-30}$$

The selection of the parameters of the FC power reference is also done in the same way as with a series hybrid, repeated here:

τ_{charge} = A time constant suitable to guarantee quasi-stationary operation of the FC. In this context 1 second is used.

$$k_{soc} = \frac{W_{max}}{400 \cdot \tau_{charge}} \quad \text{Equation 3-31}$$

A non linear method to avoid low efficiency operating points, similar to the one proposed for the ICE series hybrid is also used:

$$P_{fc}^* = \begin{cases} 0,0 & \text{if } \eta_{fc} \leq \eta_{ifcOFF} \\ P_{fc}^* & \text{if } \eta_{ice} \geq \eta_{ifcON} \end{cases} \quad \text{Equation 3-32}$$

Where η_{fc} is the efficiency of the desired power level.

Braking is made with the traction motor to the limit of its abilities. If the traction motor is not able to provide the braking torque need, the friction breaks fills in.

Simulated example of a fuel cell series hybrid

Since the fuel cell hybrid in most aspects is identical to the ICE series hybrid, similar power levels as in chapter 37 can be used. The electric traction motor is selected to be 70 kW. The fuel cell system power is selected to be 30 kW, just barely enough to sustain the battery charge in the heavy US06 highway cycle.

Table 15 shows a summary of the parameters and settings used with the simulated fuel cell series hybrid.

Table 15 Vehicle data for a fuel cell series hybrid

Property	Variable name	Setting
Fuel type	Fuel type	Methanol
Peak FC power	Pfc_max	30 kW
Fordonsvikt	Mv	1300 kg
Hjulradie	rw	0.3 m
Air resistance	Cd	0.35
Rolling resistance	Cr	0.008
Front area	Av	3
Air_density	rho_air	0.6
Maximum vehicle speed	vmax	200 km/h
Final gear ratio	gr2	5
Peak motor power	Pem2_max	70 kW
Peak motor torque	Tem2_max	200 Nm to facilitate speed control
Peak motor speed	Wem2_max	$v_{max}/r_w * g_{r2}$
Charge time constant	Tau_charge	1 s
Charge control gain	ksoc	18000
Power electronics efficiency	EtaPE	0.97

Figure 3.38 shows the some quantities when running the ECE15 city driving cycle with the vehicle of Table 15.

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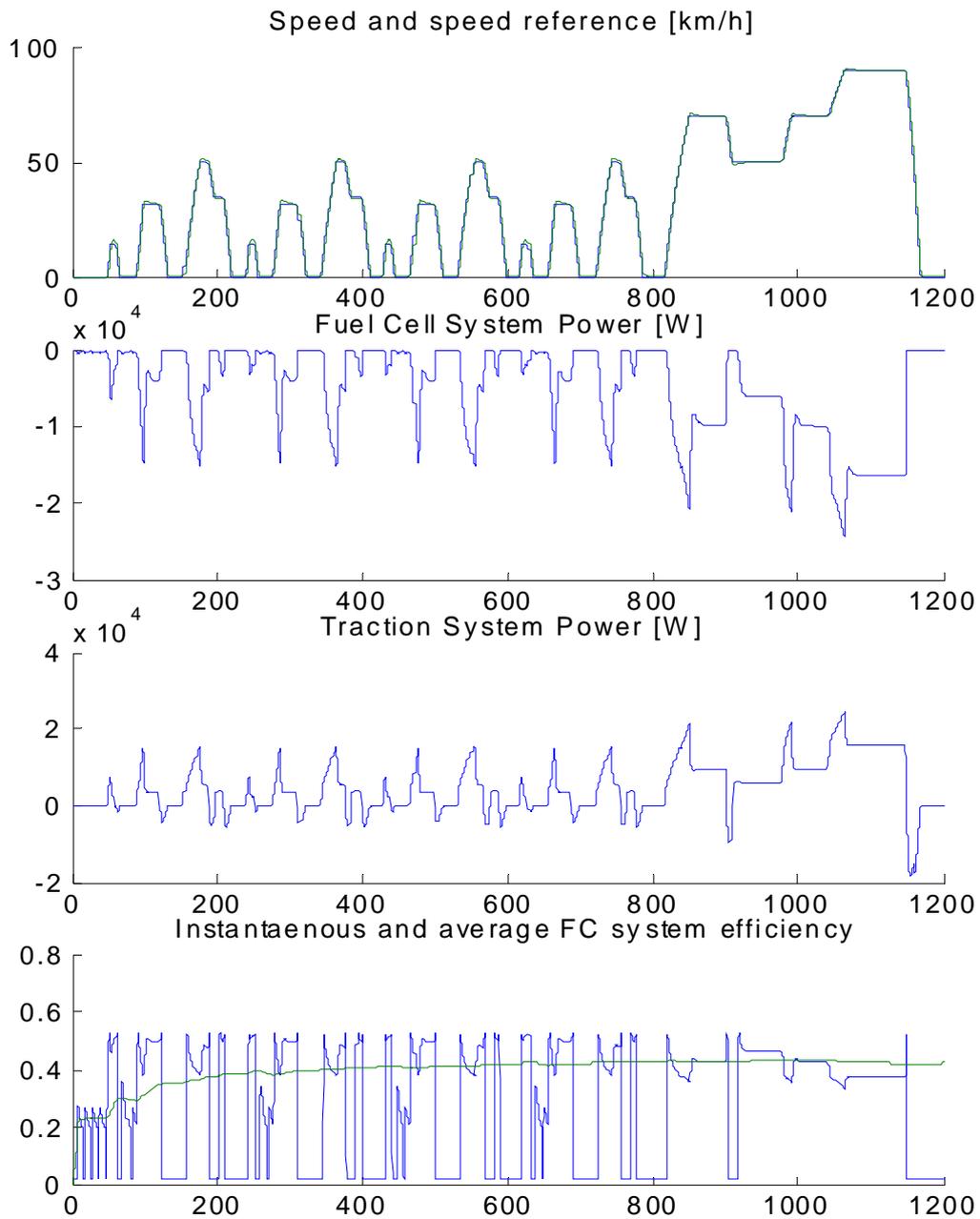


Figure 3.38 Vehicle speed, speed reference, Fuel cell system power, Traction system power and FC system efficiency when running the ECE 15 city driving cycle with the FC powered vehicle of Table 15

The most important to deduce from the simulation in Figure 3.38, is the efficiency of the fuel cell system. The average efficiency is slightly over 42 %. That is in level with the peak efficiency of the Diesel engine and over the peak efficiency of a Diesel motor with a generator in a series hybrid.

Figure 3.39 shows the same simulation, but with the US06 highway driving cycle.

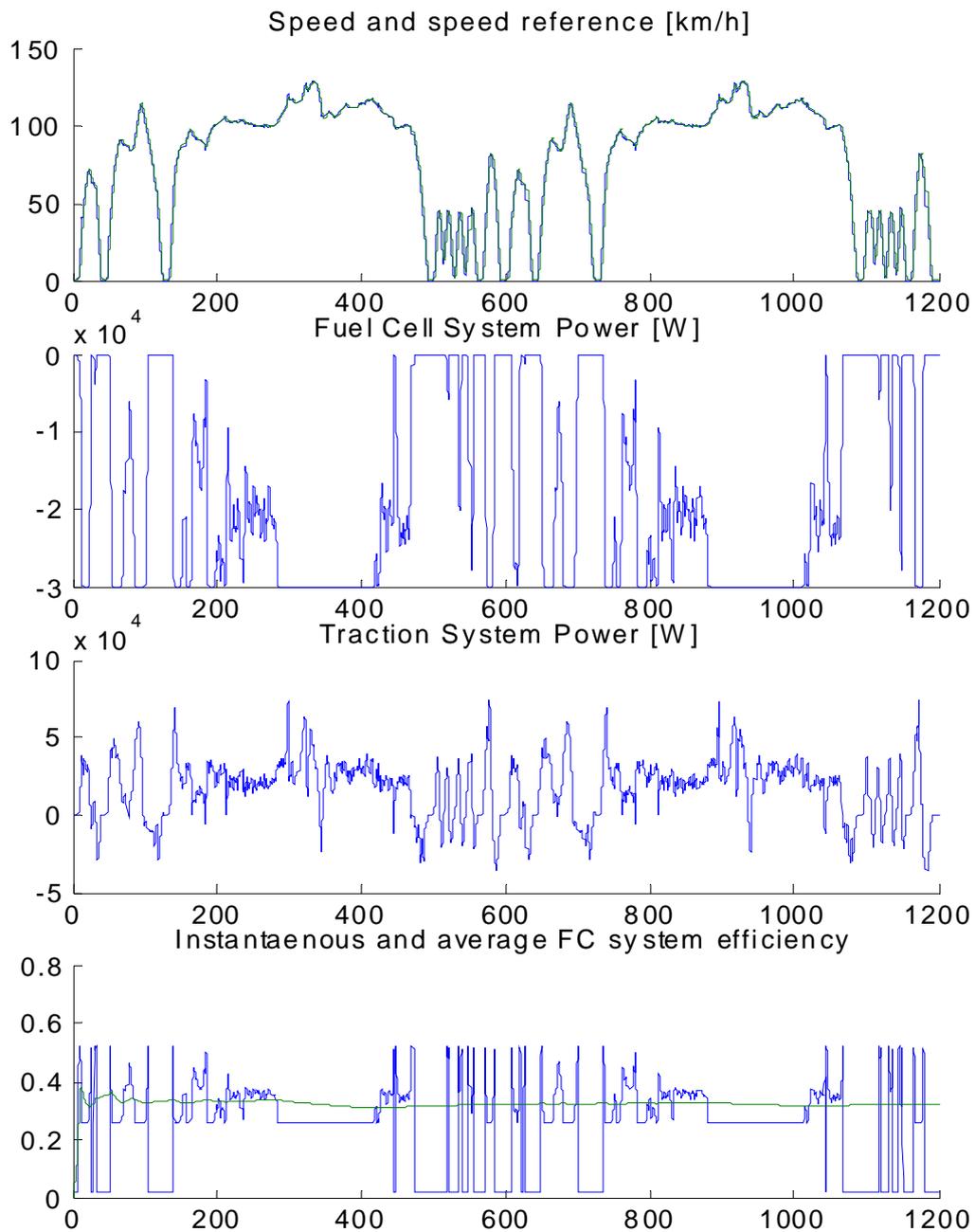


Figure 3.39 Vehicle speed, speed reference, Fuel cell system power, Traction system power and FC system efficiency when running the US06 highway driving cycle with the FC powered vehicle of Table 15.

Compared to the simulation of the ECE15 cycle, the average efficiency is in this case lower. This is due to the fact that the fuel cell system must provide a higher power in the US06 cycle, and at higher power the efficiency is lower, see Figure 3.11.

The conclusion is that a fuel cell vehicle has the potential for high efficiency, but it is possible that the system has to be designed with too high peak power in order to avoid weak operating points at high driving power.

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4. Auxilliary systems

It is not only the traction system on board a vehicle that consumes power. The number of, and diversity of, loads that are used either to just facilitate the operation of the vehicle, or to increase the comfort and usability of the vehicle is steadily increasing. Some of these loads are mechanically driven via a belt from the crankshaft of the ICE, and yet some are electrically driven. In hybrid vehicles, and especially those without an ICE like the Fuel Cell vehicle, it is beneficial or necessary to drive the auxiliary loads with electric power. There are several advantages of doing so:

- 1 The load can be more freely placed within the vehicle since they do not have to be connected to the belt in the front of the ICE. This give both a weight and volume benefit.
- 2 The efficiency can be significantly increased, since the possibilities to control the power consumption is bigger when an electric machine is driving the load. The AC compressor, as an example, can be driven at the optimal speed all the time. In a conventional vehicle the AC compressor is tied hard to the ICE speed which is related to the vehicle speed, not to what is best for the AC compressor.'

Most vehicles consume large amount of energy, generating cost, pollution and limiting operating range, no matter whether the propulsion system is conventional, hybrid or electric. There has been a great deal of research recently into reducing the energy consumption of the driveline, as this is the main energy consumer in most duty cycles. However, in these studies the energy consumption of the auxiliary sub systems, *i.e.* the air condition (AC), cooling fan, air compressor, water pump, servomotor and 12/24 V system, are often neglected or regarded as small energy consumers. The power of the auxiliary sub systems loads will only be less than 10% of the driving power when accelerating. Nevertheless most auxiliary sub systems loads the propulsion system under all driving conditions, leading to a relatively high energy consumption. In urban duty cycles, characterised by low average speed, low maximum speed and many stop-and-go situations, the energy consumption of the auxiliary sub systems will be high compared to the energy consumption of the driveline. In a hybrid electric urban bus equipped with AC the auxiliary sub systems might well consume as much energy as the driveline.

The following section gives an overview of the generic sub systems used in vehicles, including those used merely in heavy vehicles. The next chapter discuss potential energy savings with these systems on a city bus.

4.1. Pneumatic system

Pneumatic systems are used in every commercial vehicle. The purpose is to boost the driver's power for example when braking or open/close doors.

Most commercial vehicles use pneumatic brake systems. Laws and regulation are controlling the number of full brakes that the air tanks should supply. They also control the time compressor needs to refill the tanks.

On busses the suspension system and door open/close is often pneumatic. The pneumatic suspension system maintains the bus at a constant level regardless of load. The system can lower the front boarding step, the whole side or the entire front. Lowering starts when the switch for kneeling is pressed. The largest draw back with the suspension is the efficiency. Pressurized air is released when going down. When going up the suspension is filled with air from the compressor.

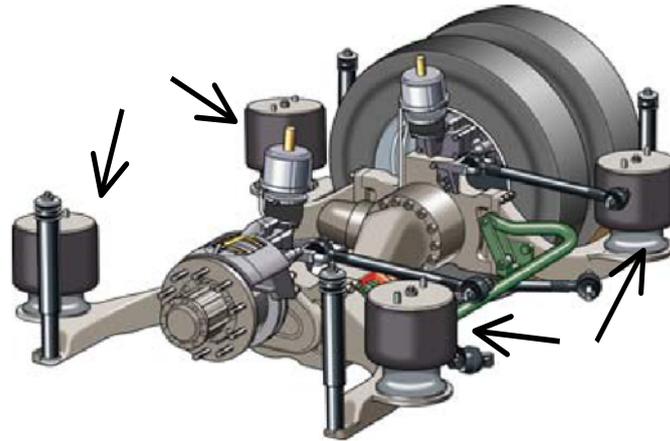


Figure 4.1 Rear bus axis pneumatic suspension system

Other application is EGR-valve and engine valves. The pneumatic controlled engine valves are increasing due to stronger emission regulations.

On a hybrid vehicle a separate electric motor for driving the compressor must be added, if the engine is off. The efficiency of the pneumatic system will become even lower and the complexity will increase for hybrids.

4.2. Air treatment system

The air produced by a compressor must be treated before use in order to protect the entire pneumatic system from freezing and internal corrosion, to ensure the reliable operation of the compressor and increase the overall life. An air dryer is used for keeping the water and other corrosive stuff away. The air dryer has no air space of its own for regeneration. For this reason, an external tank is used for the regenerated air. This smaller tank (4-8 l) is located close to the air dryer. It is the air from the regeneration tank, which is blown back through the desiccant, bringing the moisture out into the open air via the relief valve. Air dryers, pressure regulators, circuit protection valves and pressure limiting valves, ensure the operational safety of pneumatic braking systems.

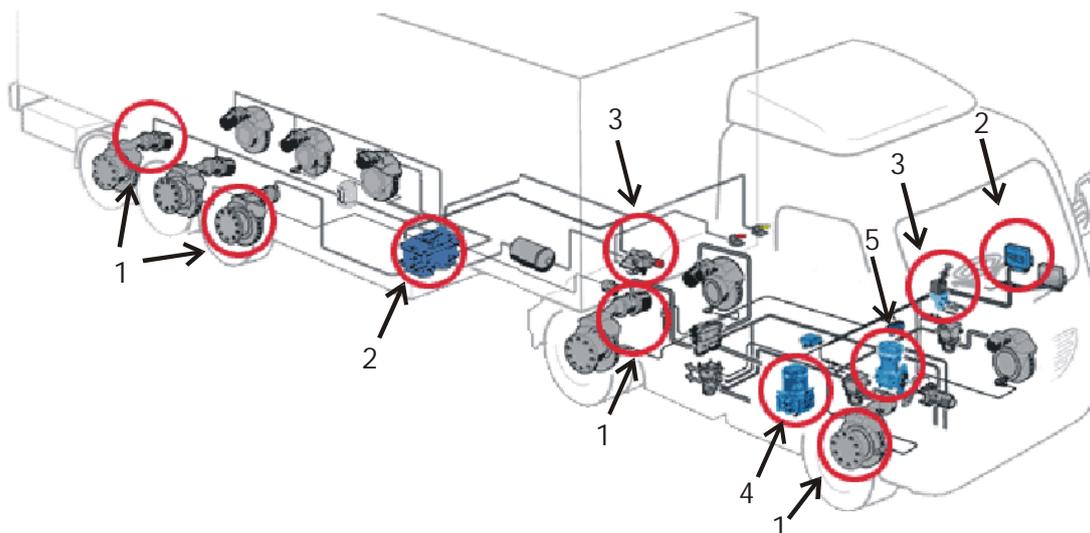


Figure 4.2 Components in the pneumatic system, 1 Brakes, 2 Electronic control system, 3 Valves, 4 Air dryer and 5 Compressor.

4.3. Compressors

The compressor is used to produce compressed air to the pneumatic system. The compressor is usually connected to the engine's crankshaft axle via a belt in a conventional vehicle. The compressor development began in the early 19th. The compressors had slow speed, low efficiency and heavy weight. The first types of compressors were piston compressors. The piston compressor is still very common. The speed and capacity has increased and the weight has been reduced.

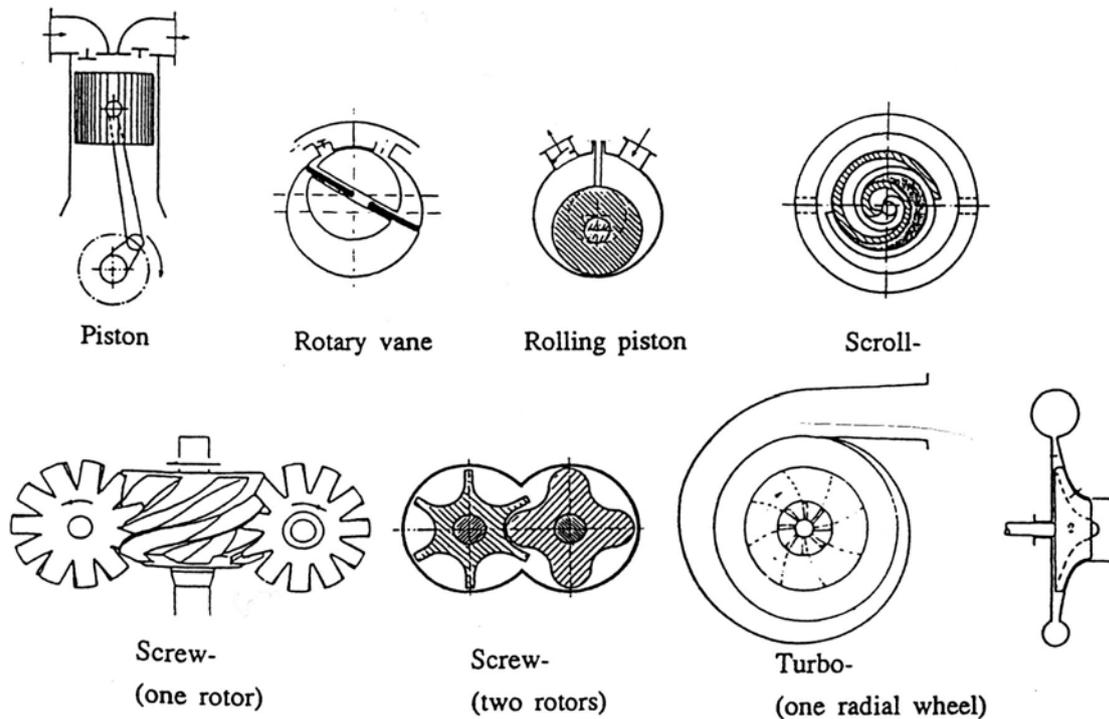


Figure 4.3 Different compressor types.

Compressor principles

- Piston or reciprocating compressor
- Screw compressors
- Rotary (rotary vanes or rolling pistons) compressors
- Scroll compressors
- Turbo compressors

In all compressors, except for the turbo, are positive displacements. This means that a volume of gas reduced during the rotation. Due to the volume reduction, the pressure of the gas will rise, and the gas will be delivered to the high-pressure side. The turbo compressor is a “dynamic compressor”. The pressure is enhanced by the rotating centrifugal field, which is produced by the high-speed impeller.

An important difference between the compressors is the use of valves for controlling the gas flow. The valves are very sensitive and important for the life expectancy.

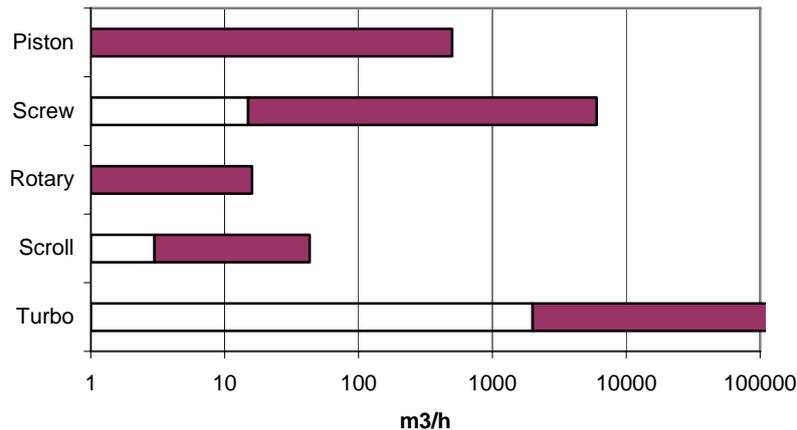


Figure 4.4 Swept volume of different compressor types

The way to define a displacement compressor is the “swept volume”. The swept volume is defined as the volume that geometric is formed to be filled by gas at the inlet of the compressor. It can also be expressed as “swept volume per revolution”. In the SI-system the units for the swept volumetric flow will be m^3/sec .

Different designs of compressors have different application.

Piston compressors are most common but the market are decreasing due to large screw compressors. The flow rates are up to $500 m^3/h$. One of the problems in the vehicle is carbonised coal in the cylinder. It occurs the cylinder to be too hot and the mixture of oil to be too high.

Screw compressors with two rotors from 180 to $6000 m^3/h$, requesting 50 to 1700 kW operating power are available. This type of compressor has high efficiency due to the construction with small compression room that gives high volume metric efficiency. It has low noise level and may be used in vehicles instead of piston compressor in the future. Drawback: high price.

Rotary compressors are used for smaller units to about $15 m^3/h$. The rotary compressor can also be built in as a booster in a two level system. It is very silent, $60 - 70$ dB most noise comes from the cooling air. Te rotary compressor is possible to run without buffer.

Scroll compressor has increased in the last decades and both size and market are expected to grow. The volumetric flow is about 2 to $40 m^3/h$.

Turbo or centrifugal compressors are used for the largest capacities with inlet flows of more than $2000 m^3/h$. with limited pressure.

The compressor in Figure 4.5 is a two-cylinder piston compressor used for supplying the pneumatic system on a truck or bus. The compressor consumes a lot of power when it is off load. To reduce the off load power some kind of energy saving system is used. The energy saving system will reduce the off load power by 50% . When the compressor has filled all the air tanks, a pneumatic valve automatically closes the outlet. This does not open until the system needs filling again. During this relief phase the compressor works with a backpressure in the cylinders and consumes less engine power. If a mechanical clutch were mount between the compressor and the engine it would reduce the off power load to zero. The reason for not mounting the clutch is that the connection torque will be too large. The AC compressor has a mechanical clutch to control the on and off.

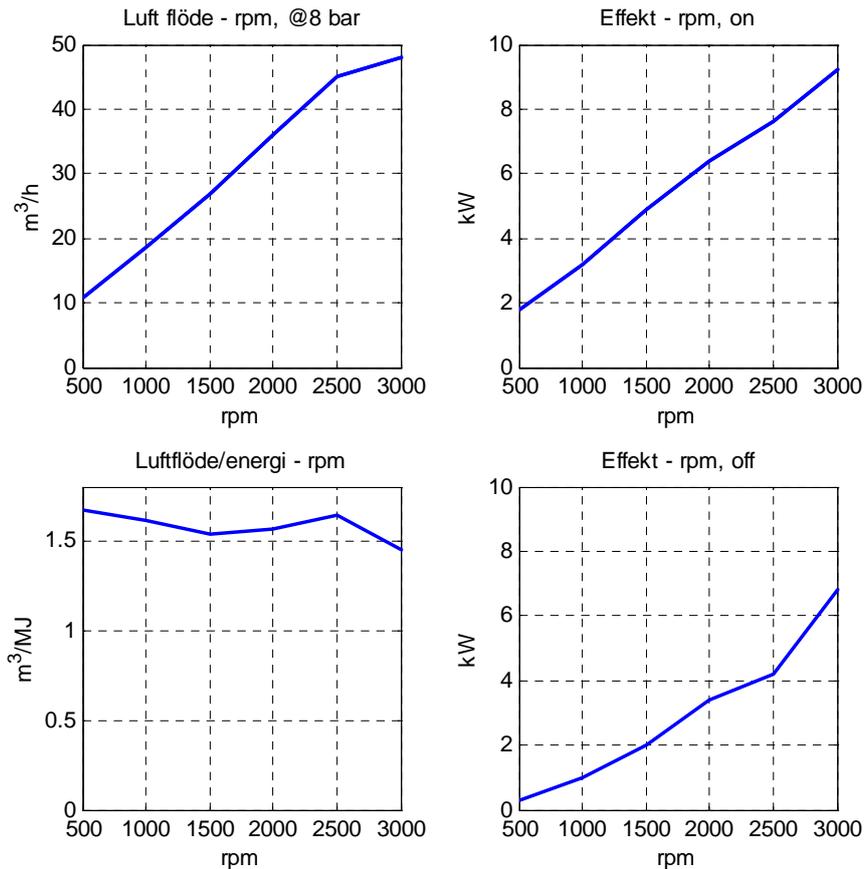


Figure 4.5 The airflow from a two cylinder piston compressor.

4.4. Brake system

The brake system is a part of the vehicles safety. The systems on vehicles are strongly regulated both by individual country laws, EU Directives and ECE and EEC regulations. The European brake directions divide the vehicle into classes and subclasses. The classes depend on weight, number of wheels and passenger.

The brake system includes:

- Service brakes
- Secondary brakes
- Parking brakes
- Retarding system
- Self actuated braking system (on trailer only)

The service brakes should be applied step by step without the hands are realised from the steering wheel. The maximum time to achieve 75 % of the full brake power is 0.6 s. The safety or secondary brake system may use part of the service or parking brake systems and will be applied by one hand on the steering wheel. The power of the safety brake system should be 50 % of the service brake system. If the parking brake is engaged it should hold the vehicle by a gradient of 18 % without the driver present.

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Cars use hydraulic or a boost hydraulic brake system. Commercial vehicles use pneumatic brake systems. One of the drawbacks with pneumatic brakes compared with hydraulic brakes is the response time. The benefits with pneumatic brakes are that the connection between the truck and the trailer is safer and more environmental friendly.

Drum brakes and Disc brakes

The two major brakes used in vehicle are drum and disc brakes. The temperature influences the friction and the lifetime of the brakes. Over heating is a large problem in heavy vehicles. Lager brakes will decrease the brake temperature, but the size is limited for the brakes in vehicles. The dimension of the rim sets the limit of the brake size.

Retarding system

Commercial vehicles are often equipped with alternative brake systems, a retarder or an exhaust brake. These systems may be used for example when going down a steep hill. The retarder and the exhaust brake may be operated in two different ways: with the control lever on the instrument panel or with the brake pedal. The brake pedal function can be disengaged with a switch.

The hydraulic retarder delivers a high braking torque, 3000 Nm. The high braking torque enables the driver to maintain higher speeds on long descents without inflicting wear on the service brakes. The retarder creates a great deal of heat when braking which has to be cooled by the cooling system. The retarder is a compact unit mounted integrally with the rear section of the gearbox.

4.5. Electrical system

The electrical system has a voltage of 12 volt in small cars and 24 volt in commercial vehicles. Most vehicles are equipped with open lead-acid batteries, possible to refill the electrolyte with water. In some demanding application sealed lead-acid (Optima) are used, with higher power density and higher cost. The battery capacity is rated in Ah. In small cars the size of the battery is approximately 50 Ah ($12 \times 50 = 600$ Wh). Commercial vehicles use two 12 volt batteries connected in series. The capacity is usually as high as 200 Ah ($24 \times 200 = 4800$ Wh). The battery must supply the starter motor in a limited duration with sufficient electric energy during all conditions. Critical conditions are outside temperatures and load variations by engine idling. The voltage of the battery should be as stable as possible. The battery voltage varies with the temperature and the charge or discharge current. The load requires as constant load as possible.

Alternators

The alternators are all engine mounted and are driven by a V-belt. The current from the alternator increases with the speed. Important alternator parameters:

- Supply the electric system with enough current and constant voltage during all conditions (low speed - high consumption).
- Robust design, in the aspect of vibration, dirt and high temperature.
- Minimal operating noise.
- Low weight, small dimensions and long service life.
- High efficiency.

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The development has gone from DC generator to alternators. The alternators are cheaper and the weight is 50 % less. The construction vary depending on the application from: claw-pole alternator, compact alternator, salient-pole alternator and alternator without windings. A diode rectifier converts the three-phase alternating current into direct current. The diodes also prevent the battery from discharging when the engine is stopped. Large-scale alternator application becomes feasible with the introduction of cheap, powerful silicon diodes.

In small cars the alternator is air-cooled. An integrated fan or an attached radial fan supplies the alternator with the airflow. In commercial vehicle the entire collector-ring and carbon-brush assembly is usually encapsulated in order to prevent dust, dirt and water. Special application requires liquid-cooled alternators. The liquid-cooled alternator has less noise (no fan), sustainable for higher temperature and it is waterproof. The drawback is of course high costs.

There are always losses when converting mechanical energy to electric. A normal operated alternator has the average efficiency of 50 %. At higher speeds the efficiency falls-away. The losses are: iron losses (hysteresis and eddy current), copper losses (resistance in the windings), friction (bearings) and aerodynamic losses (cooling fan). The relatively high losses are coursed by the lightweight, compact design and low costs. More emphasis should be placed on optimization of the efficiency than on optimization of its mass.

The output current from alternators vary from 80 A ($80 \cdot 14 = 1.1$ kW) in small cars to 300 A ($300 \cdot 28 = 8.4$ kW) in larger busses. Charging capacity at idling speed is 50%. The demand for electric power in vehicles is increasing as more electric accessories are connected in the vehicles.

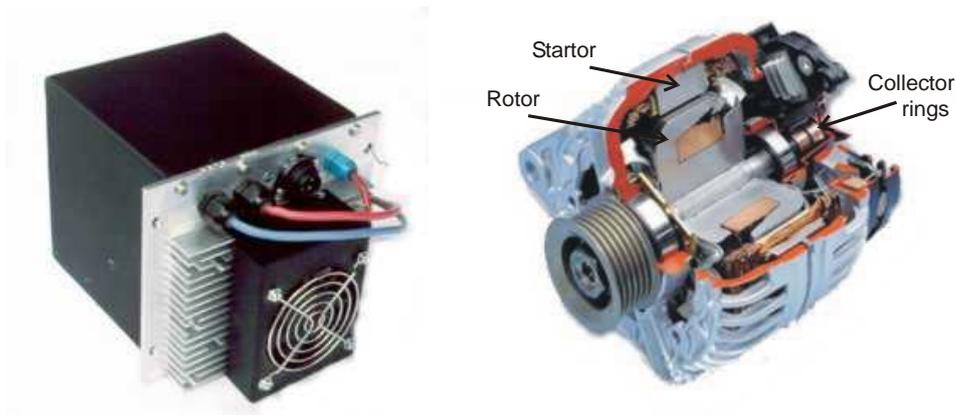


Figure 4.6 DC/DC converter from Brusa and an alternator for small cars from Bosch.

In a hybrid vehicle a DC/DC converter will be used instead of an alternator. A DC/DC converter has no moving parts except for a small cooling fan. All transformations from high voltage to low voltage are done by power electronic components. The efficiency will rise dramatically if it is possible to use a DC/DC converter instead of an alternator. A DC/DC converting power from 500 V to 12 V will have an efficiency of about 90 %.

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Table 16 *Technical Characteristics of a DC/DC converter*

Max. voltage capacity	900	V
Operating input voltage range	250 - 750	V
Output voltage	11 - 14.5	V
Max. output current	125	A
Continuous output current	80	A
Standby power consumption	< 1	W
Degree of protection	IP54	
Efficiency up to	91	%
Weight	3.5	kg

4.6. Steering

The steering system of vehicles is regulated in European Directive. The regulations aspects are:

- Fast response
- Operating force
- Road surface damping
- The steering wheel should go back to neutral position

Steering system has some unique request of the performance quantities:

No playing in the straight position.

- Low friction
- High rigidity.
- Readjust ability

Some of these requests are not so easy to combine; this is the reason why only two types of steering have become established to this date.

Rack and pinion steering

Rack and pinion steering consists of a rack and a pinion (kuggstång och kuggjul). The steering ratio is defined as the number of steering wheel revolutions to rack travel. The number of teeth can be adjusted to change the steering ratio and the force of the steering wheel.

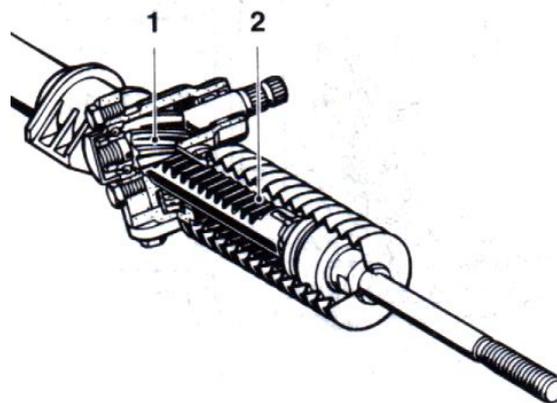


Figure Steering system, Pinion (1) and Rack (2)

Recirculating ball steering (styrnsäck)

Forces generated between steering worm and steering nut are transmitted via low friction recirculating row of balls. The steering nut acts on the steering shaft via gear teeth. The steering box can change the ratio by changing the number of teeth.

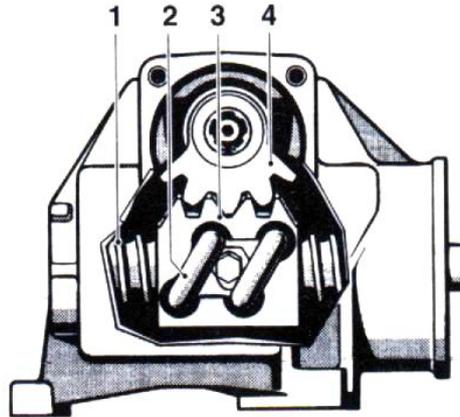


Figure 4.7 Steering system, Steering worm(1), recirculating balls(2), steering nut(3), steering shaft with gear teeth.

European directive defines three types of classifications of steering system:

- Muscular energy steering system, which are only powered by human, used in small vehicles. This system is used in small cars and lighter vehicles.
- Power assisted steering system that uses both the human driver and the source of energy. For example is used in higher speed vehicles.
- Power steering system that uses only the source of energy in the vehicle. This system is not used in vehicles that go faster than 50 km/h.

Hydraulic power assisted steering

A vane (centrifugal) pump powered by the engine or an electric gear or roller pump on smaller vehicles, is the energy source in the system. The pump must be dimensioned so it is possible to turn the steering wheel when the engine is idling. The temperature of the oil in the circuit may not rise above 100 °C. The system also contains oil reservoir, flow regulator and control valves. An electric powered pump is easier to locate in the modular design.

Electric power assisted steering

It is possible with an electric power assisted steering in small and medium sized cars.. The electric servo unit works directly on the pinion of the steering gear. Only the torque exerted on the steering wheel is transmitted via the steering column, intermediate shaft and universal joints. The sensors and torsion bars sit directly on the steering gear pinion. The advantages for the driver, compared to normal hydraulic system, are more precision, improved ride comfort and safety. Other advantages are: 80% power savings compared to standard hydraulic power steering systems, power supply independent from vehicle's engine, no maintenance and depending on the vehicle type various installation alternatives are possible. Additional performance potential is available for larger cars if the vehicle power supply increases from 12 V to 42 V.

The electric power assisted steering will probably be the best solution for a hybrid car.

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Figure 4.8 Pinion electric power assisted steering system

Hydraulic electric power steering

Hydraulic electric power steering is a combination of electric motor driven hydraulic pump instead of engine shaft driven. The steering will not be dependent on the power supply of vehicle engine. Driving characteristics will be as a standard hydraulic power steering system. Power-savings of about 70% compared to standard hydraulic systems. This steering system will also be suitable for hybrid vehicle. Drawbacks: need maintenances and are power consuming.



Figure 4.9 Hydraulic electric power steering.

4.7. Air Condition (AC)

Due to design and aerodynamic modern vehicles are equipped with large windows. The windows size will increase the cooling demand. The AC-system is the largest energy consumer of the auxiliary subsystem. When the AC-system run at full power in a large bus it consumes up to 25-30 kW. In small cars the power demand is lower, approximately 4 kW. This energy consumption of the AC system is also a large part of the total vehicle's energy. When the AC starts working in a small car the idling speed of the engine usually to go down.

The AC system performance is strongly influenced by the efficiency of the compressor. In an AC system the compressor is the most energy consuming part.

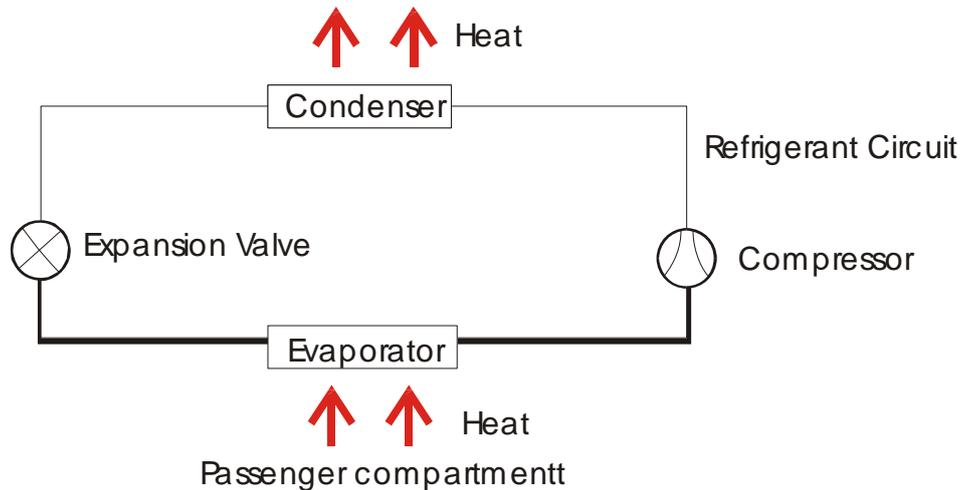


Figure 4.10 AC system

Working principle:

- The evaporator (förångaren) absorbs the heat to the refrigerant circuit and the cools to the air of the compartment. A => B During this phase the temperature is constant and the refrigerant goes from liquid to gas.
- The compressor increases the pressure and the temperature goes up when the refrigerant flows through the compressor. B => C
- The condenser heats the ambient air and cools the refrigerant circuit. C => D The temperature is constant and the refrigerant goes from gas to liquid.
- The expansion valve decrease the pressure and the temperature go down. D => A

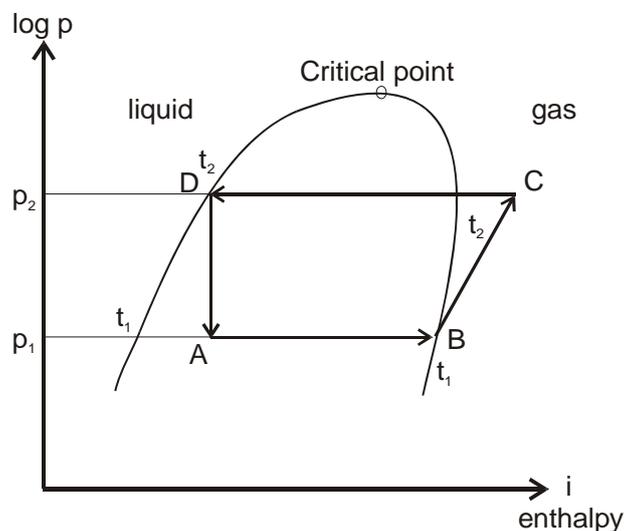


Figure 4.11 Ideal cooling process with evaporation

In the real process there is often a pressure drop in the heat exchanger and an enthalpy increase in the compressor. In a closed system the control cannot be made 100 % between the different temperatures in point D and point B, for all operating temperatures. If the condenser during the cooling phase has further area to cool after media has condensed, the D point will move in the left direction.

If over heating occurs, the B point will move in the right direction. The over heating will decrease the system efficiency, increase the temperature in the compressor exhaust pipe and increase the power consumption. A temperature control unit will control the temperature by

increasing the area of the expansion valve. The pressure and the temperature in the evaporator will increase.

Refrigerant

The gas in the refrigerant circuit should have certain criteria: cheap, safe, non-toxic and have good thermal performances. Today's AC system manufacturer uses "R134a" gas in the refrigerant circuit. Earlier AC systems used gases with more freon. When the system gets old leakages will appear and the compressed gas will leak out. The freon gas brakes down the ozone layer and the global warming will increase. The risk for flames and explosion of the refrigerant may not be too large. In the thermal performance such aspects as reasonable pressures and temperatures in the refrigerator circuit must be considered.

Environmentally friendly refrigerants have been tested in practical application. They do not contribute to the depletion of the ozone layer and have neglected global warming effect. Some examples of these environmentally friendly gases are: R600a (isobutane), R290 (propane), R717 (ammonia), CO₂. The use CO₂ gas in AC system is still in the experimental face. One of the main problems is the high operating pressure that requires expensive installations.

AC compressor

The compressor in the air condition system is used to transfer the vapor between the different pressures in the AC system. It is connected to the engine's crankshaft axle via a belt. The AC compressor is also connected via an electro mechanical clutch, and can be disconnected when the AC compressor is off.

The compressor, used in the AC system, is a rotary piston compressor. Screw compressors have also started series production. The advantages are: moor quiet, needs less maintenance and better efficiency. The strongest draw back is the price.

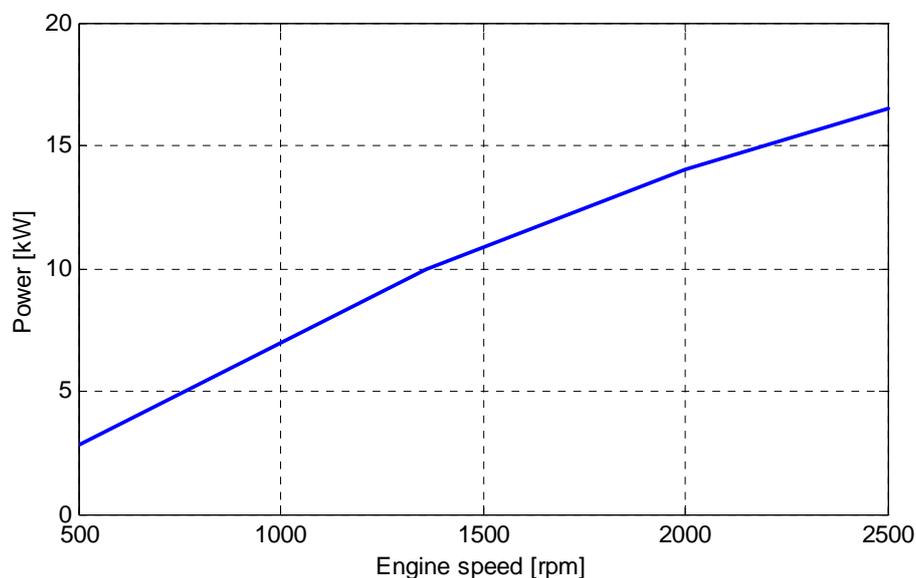


Figure 4.12 Engine speed and Power consumption of an AC compressor.

The compressor in the AC- system consumes large amounts of energy. In Figure 4.12 the power consumption is plotted of a compressor used in medium size busses. In larger busses and busses in warmer areas two compressors are used. The power and capacity is very dependent of the engine speed. It is a problem when the engine is idling for long times. A solution to the idling problem in busses with AC systems is a special engine to drive the compressor, which secures the cooling capacity in all driving points.

Electrical High Voltage Air Condition (HVAC) concept

In the UITP conference, 2003, Madrid Thermo King presented a High Voltage Air Condition (HVAC) system for hybrid or electric busses. It would also be suitable for conventional busses with a special generator. A smaller unit for truck cabins was also presented. The smaller unit used the 24 V system @ 70 A. All parts of the AC system were packed in one-piece rooftop.

The advantages with all in one unit are: independent of engine speed, plug-and-play installation and ideal for high-pressure refrigerant like use of CO₂. The plug-and-play function is important for the bus manufacture. Often the bus manufacture has to hire a special company to do the final refrigerant installation and testing. With one single unit there will be no leakage in pipes and hoses and higher pressure will be possible. The technique with HVAC is well tried in the rail application.

4.8. Cooling system

The cooling demand of the engine is large. It is also very depending on the load and the climate the vehicle are used in. When the engine is producing 100 kW on the crankshaft it also produces approximately 200 kW heat. One part of the heat goes out with the exhaust gases, approximately 100 kW. The rest is directly cooled by the surrounding air and to the cooling system, approximately 100 kW. The size of these shares can of course vary in a large range depending of the working point. All passenger cars and heavy-duty vehicles have water-cooling systems. Antifreeze (glycol) and corrosion inhibitors are added to the water in the coolant mixture. The cooling system consists of: a water pump that makes the coolant circulate in the circuit, coolant radiator, cooling fan, radiator tank that ensures that the coolant is distributed through the blocks. In most vehicles the water pump is connected via a belt to the crankshaft of the engine.

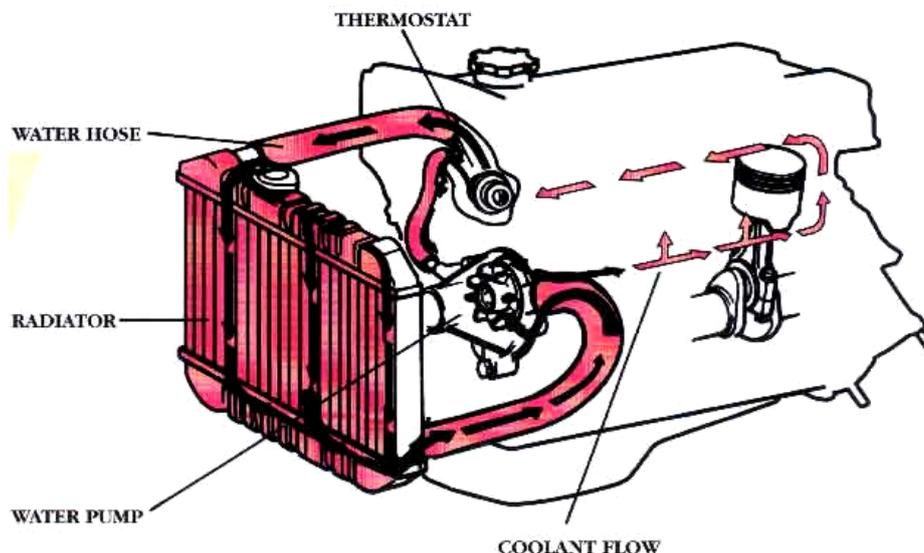


Figure 4.13 The engine cooling system

The design of the radiator is important. The design factors involve minimizing the fan power and aerodynamic drag and maximize airflow to the radiator. If the size of the radiator is increased, the size and power consumption of the fan will decrease. The radiator must provide a reliable thermal transfer discharging of the engines heat to the surrounding air.

The wide range of climate conditions and the fluctuation of the engine load must be constant and remaining in a narrow range. A thermostat incorporated with an expansion element to

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regulate temperature, independent of the pressure variation in the cooling system, does the regulation of the coolant temperature.

The cooling fan supplies the engine with substantial cooling capacity at low speeds, when the force-air ventilation is smaller. Most of time (95%) the air stream is enough to provide a sufficient radiator cooling. In small cars a single-piece injection-molded plastic fan. An electric motor (up to 600 W) is used to drive the fan in small cars. The electric fan is easy to deactivate and than be activated when the temperature reaches a certain level. Due to costs the fan is connected to the engine via a belt in lager cars. In heavy vehicles the fan is often attached directly to the crankshaft and the fan is made of metal. The fan on heavy vehicles can also be deactivated. With a mechanical connection to the engine an electro mechanic clutch or a visco coupling can control the fan. The visco coupling is the most common in heavy vehicles in Europe. The visco coupling slips so the outgoing speed of the fan is lower than the incoming. The visco coupling transmits a torque to the fan that is dependent of temperature in the coolant.

In some heavy vehicles it is not possible to place the radiator and the cooling fan in front of the engine by the crankshaft. This problem may occur in busses. A solution to the problem is to mount a hydraulic driven fan. The hydraulic driven fan is very easy to control. In Figure 4.14 the power of a cooling fan for a medium size truck with mechanic connection to the engine is plotted. The relation between power consumption and speed is cubic. The cooling system normally consumes 3-4 % of the energy output from the engine.

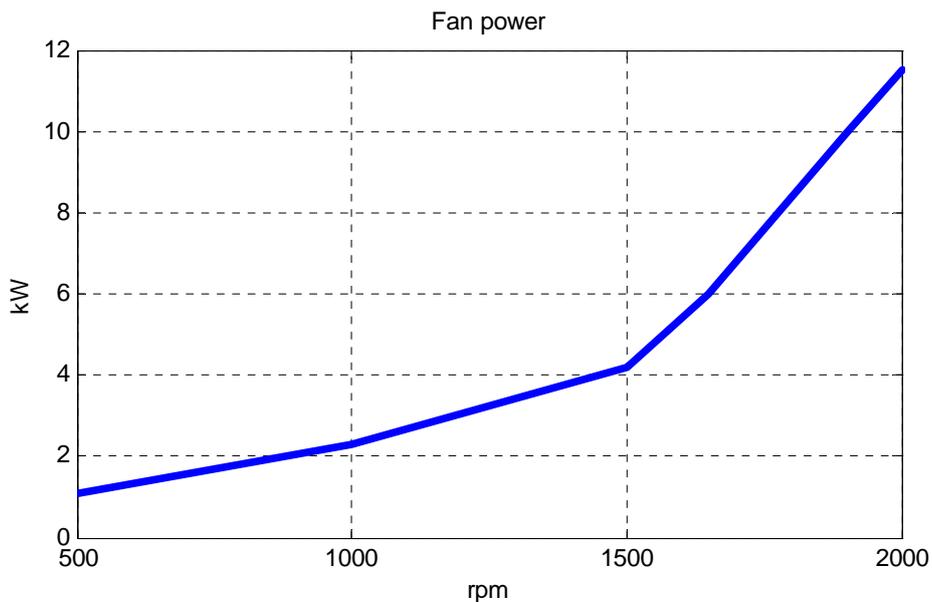


Figure 4.14 The power consumption as a function of speed for the cooling fan.

In a hybrid vehicle there are more than one coolant circuit. The engine or fuel cell has a higher temperature and the electric motor, battery and electronics have separate liquid cooling with lower temperature. All cooling fans in hybrid vehicle can be electric powered when high voltage is available.

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5. Potential to Energy Saving in Auxiliary Systems

To evaluate possible savings with altered designs and control schemes, a simulation model is necessary. Many vehicle simulation programs simulate auxiliary sub systems as a constant parasitic load. This is an often-incorrect simplification as the load is usually strongly dependent on the driving pattern. Using a full vehicle simulation program, extended with a proper definition of auxiliary sub systems, the potential of intelligent 1) technology selection and 2) control has been analysed.

1. Technology selection The auxiliary systems have often low efficiency. A pneumatic system with a compressor in one end and e.g. a bus door-opening piston in the other end has very low energy transfer efficiency. The door opening work could be performed by an electric motor instead. By changing door activation from pneumatic activation to electrically activation considerable energy savings can be obtained.
2. Controlled timing of auxiliary sub system loads can improve propulsion system efficiency. If the auxiliary sub systems are loading the driveline of the vehicle when it is braking, the energy could for example be used for the generator (or DC/DC converter) to charge the 24 V battery or the AC-system to cool down the compartment. If all the auxiliary systems “buffers” were filled up by the braking, this would result in a optimal use of braking energy with high efficiency and less driveline peak power requirement saving a considerable amount of energy. Alone the effect of not letting the braking energy pass the energy buffer before being used for powering sub systems would save 15-20% as the roundtrip efficiency of the energy buffer is 80-85%. A considerable downscale of the energy buffer would be one of the side effects! In conventional vehicles where no regeneration is applied, the energy savings would be even larger, as braking energy is not recovered. Nevertheless some mechanical driven sub systems are not designed for advanced regulation.

5.1. Case study: A Fuel Cell series Hybrid Bus.

The following discussion on potential savings with sub systems are based on extensive measurements and simulations on a fuel cell series hybrid city bus.. There are two main pathways for reducing auxiliary energy consumption, technology selection and control. The following auxiliary sub system improvements have been analysed by use of the new model:

- Technology selection
 - Mechanical to electric.
 - Pneumatic to electric
 - Hydraulic open loop to closed loop
 - Hydraulic to electric
- Control
 - Load shaving (peak power reduction)
 - Intelligent use of braking energy

Some technology selections are more long-term solutions than other as e.g. electrical steering assist for heavy trucks will not be available in the near future. The relevant control strategy, according to our study, would be to prioritise activation of all sub systems during braking and to increase peak propulsion system power demand by deactivating auxiliary sub system loads during acceleration. Energy that is stored in the traction battery has a round trip efficiency of 85% (in

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and out). By direct use of braking energy for auxiliary sub system loads the charge/discharge efficiency losses of approximately 15% are avoided. In a conventional bus the gain of intelligent auxiliary sub system load control would be even larger as the braking energy is not recovered. When the bus brakes and the retarder is used, it only heats the cooling water. Intelligent control of auxiliary loads can reduce the peak power requirement of the propulsion system. In a hybrid vehicle both the peak power requirement for accelerating, and for storing energy regenerated during braking, can be reduced. Combining more loads on each speed-controlled motor could help increasing total sub system efficiency.

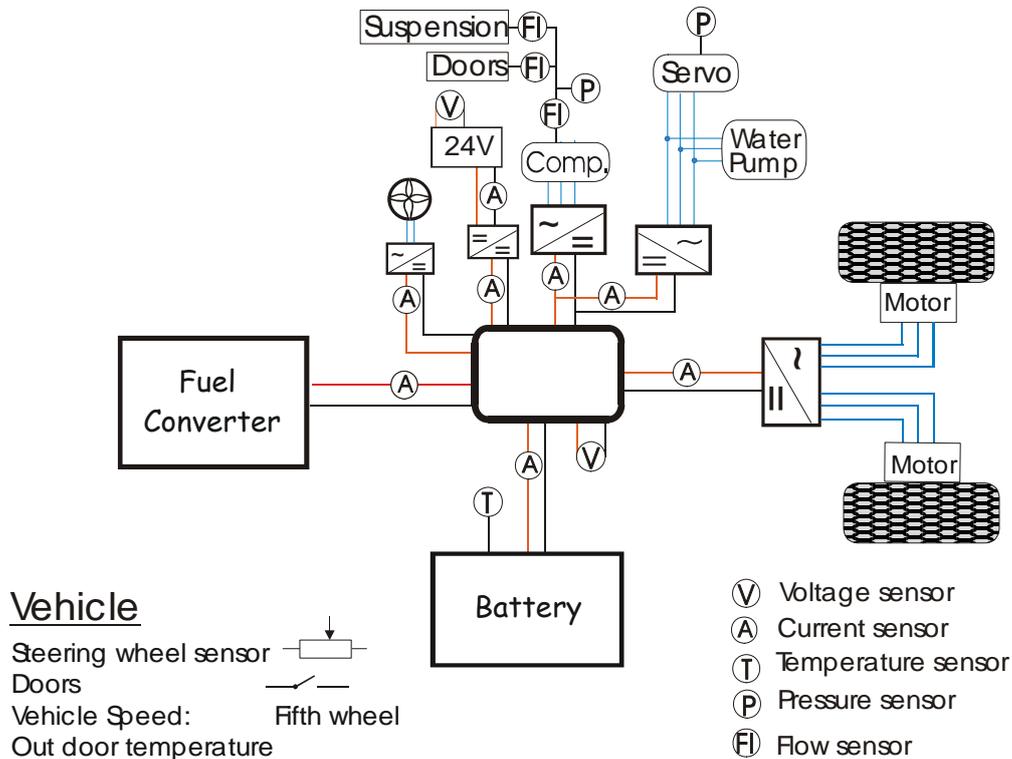


Figure 5.1 The principal layout of the fuel cell bus sub systems. Circles with A and V in them are measurement points for the measurements used to calibrate the simulation model.

The simulation are made on the Braunschweig driving cycle. The duration of the Braunschweig cycle is 1800 s. During this cycle the bus is braking more than 25% of the time. Electric braking power and duration is:

- 20% of the time (or 370 s.) the bus is braking with more than 5 kW
- 16% of the time (or 280 s.) the bus is braking with more than 20 kW
- 6% of the time (or 105 s.) the bus is braking with maximum regenerative power, 90 kW.

Consequently

- In a vehicle with a conventional propulsion system some auxiliary sub systems would run for free 20% of the cycle and all sub systems 16% of the cycle.
- In a vehicle with hybrid electric propulsion system some auxiliary sub systems would run with 15% improved efficiency 20% of the cycle and all sub systems 16% of the cycle.
- In a vehicle with hybrid electric propulsion system the battery requirement with regards to peak charge power can be reduced with approximately 20%.

5.3. Servo steering

Options for reducing servo steering energy consumption:

- Electrical steering unit. Existing for cars but still not ready for heavy trucks and buses. Improves efficiency, reduces noise and makes system architecture much simpler as the whole hydraulic circuit, with its friction losses and risk for oil leakage, can be avoided.
- Speed control of open circuit systems can eliminate idle losses, which counts for up to 80% of the total hydraulic sub system energy consumption. Would work with conventional system architecture!
- Closed circuit hydraulic system where buffer tank can be added. Technology not available yet. Test results indicate that replacement of the current servo steering system with a closed circuit system and buffer tank would save 70% of the energy compared to the current system without speed control, see table 2.

5.4. 24 Volt system

The 24 V charging system is controlled by peak shaving during operation and activation during braking.

Normal 24 V system calculation:

Average consumption: 2900 W

20% (370 s) Braking (>5 kW): 2900 W

9% (160 s) Acceleration(>80 kW): 2900 W

Power from the energy source:
$$\frac{2900 \cdot 1800 - 2900 \cdot 370}{1800} = 2300W$$

Controlled 24 V system calculation:

Average consumption: 2900 W

20% (370 s) Braking (>5 kW): 4000 W

9% (160 s) Acceleration(>80kW): 0 W

Power from the energy source:
$$\frac{2900 \cdot 1800 - 4000 \cdot 370}{1800} = 2080W$$

Total saving: 2300-2080= 200 W or 10% of the DC/DC energy consumption.

Options for reducing the 24 V system energy consumption:

- Peak shaving during operation can lead to more optimal engine/fc operation, 16% of the time in the Braunschweig cycle
- Activation during braking, 20% (370 s) of the time in the Braunschweig cycle at full power (4 kW), which will reduce the energy by 10%.
- Most alternators on the market, both 12 V and 24 V, have very low efficiency, 50 – 60%. On a hybrid or electric vehicle a solution with a DC/DC converter is used offering a high efficiency. A DC/DC has an efficiency of >92%. In the simulation model a 140 A, 24 V DC/DC converter was used.

5.5. Compressor

Our study indicates that a major part of the energy consumed by the pneumatic sub systems can be avoided by replacing pneumatic sub systems with electrical and hydraulic systems.

4.4.1 Doors

Electric assisted doors is in these years replacing the old pneumatic doors in many new urban buses. The change from pneumatic doors to electric doors saves 85% of the energy. The power needed for an electric assisted door is 0,2 Wh (15 A, 24 V, 2 s.) pr door. See table 2.

4.4.2 Suspension

Replacing the pneumatic suspension (down/up), which has very low efficiency, by e.g. an hydrostatic semi active solution would be more energy efficient. The system would be composed of a small hydraulic pump, a 24 V DC motor and hydraulic pistons. All these components are on the market for other applications. This modification would increase the efficiency of this work (down/up) from 6% to 75%. Our results indicate a reduction in energy of 90%. See table 2.

4.4.3 Brakes

For heavy-duty vehicles it is also possible to have an electric controlled parking brake and service brakes can be replaced by electrical/hydrostatic solutions. LONG TERM SOLUTIONS though as e.g. truck industry have to serve millions of trailers with pneumatic brakes. Electric controlled parking brakes are now becoming more standard on luxurious passenger cars. The electric servomotor on the rear wheel, which presses the brake calliper directly onto the brake disc. The controller developed by Siemens VDO[4]. There are projects to replace the ordinary brake system like the eBrake project [5]. It is based on an electric powered controlled friction brake with high self- reinforcement capability. These solutions have a great potential for saving energy and in the end eliminate the use of pneumatics in vehicles as the brake system will typical be the last system to change from pneumatics to alternatives. In the “New” model in table 2 an electric parking brake is used.

Table 2: The auxiliary energy source consumption of Brunschweig cycle (1800 s long), all values are transferred into Watt (mean values). *Present* means the present installation in the bus. *New* means electrically driven loads according to the discussion above, except for steering where “closed loop” is used. *With Control* means that maximum loading is allied to some loads when the bus is breaking, according to the discussion above, and “peak shaving” to avoid extreme peak loads.

System	Present	New	With Control
Doors	230	35	35
Suspension	260	25	25
Parking brake	150	10	10
Steering	560	230	230
24 V system	2300	2300	2080
AC at 50%	8190	8190	6740
Total	11700	10800	9100

5.6. Improvement

The power savings by converting to electric or change the auxiliary sub system will reduce the consumption of the doors, suspension, parking brake and steering from 1200 W to 300 W or 80% reduction. The savings by changing the control of the auxiliary sub system will be around 1.6 kW. The total savings by changing the system and by using the control strategy will be: 11700-9100 = 2600 W. When a vehicle runs 18 hours a day, this will be a considerable amount of energy (18 h x 2.6 kW = 47 kWh). If this energy would be supplied by a diesel engine in an

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urban cycle in a conventional bus (average engine efficiency <20 %) this corresponds to a reduction of 23 litre diesel in the fuel consumption, see equation 2.

$$\frac{\text{Energy consumption}}{\text{Lower heating value} \cdot \text{Density} \cdot \text{Efficiency}} = \frac{47 \cdot 3600 \cdot 1000}{42.5 \cdot 10^6 \cdot 0.85 \cdot 0.20} = 23.4 \text{ litre}$$

5.7. Conclusions

In an urban bus application the auxiliary sub systems consumes large amount of energy. Some of these systems may be changed e.g. from pneumatic to electric and/or controlled with respect to the propulsion system. Examples of such systems in a bus driving an urban cycle is the door openers, suspension, parking brake and steering system. This chapter has shown that such improvements will reduce the energy consumption of these systems by 80%. It has also been shown that a control strategy, to use the regenerated energy when braking and to reduce the power request when acceleration, has a potential to save 15 % on the 24 V and AC system. The proposed control strategy applied to the AC itself gives the largest individual saving (1.6 kW), and combined with the 24 V and the other electrically controlled auxiliary subsystems the total savings amounts to 2.6 kW. This reduces the current energy consumption, which today either causes pollution or limits the range of pure electric vehicles.

6. Auxiliary loads and power system considerations

This chapter is focused on the power supply for auxiliary loads, both traditionally electrical loads and those mechanically driven loads that in many cases may benefit from conversion to electric drive.

6.1. Conventional private car energy supply

The energy stored in the battery of a conventional vehicle should provide power supply to a number of loads like light, ventilation, audio etc. for a reasonable amount of time and still be sufficient to start the ICE. The electric system as a whole, including generator, battery, starter and auxiliary loads is an optimized balance with low weight, size and cost as optimization criteria.

The electric loads of a conventional vehicle are listed in Table 17.

Table 17 *Electrically driven equipment on a conventional vehicle (Bosch Automotive Handbook, 5th edition)*

Load	Power consumption	Average power output
Motronic, electric fuel pump	250 W	250 W
Radio	20 W	20 W
Side-marker lamps	8 W	7 W
Low-beam headlamps	110 W	90 W
License-plate lamp, tail lamps	30 W	25 W
Warning lamp, instruments	22 W	20 W
Heated rear window	200 W	60 W
Interior heating, fan	120 W	50 W
Electric radiator fan	120 W	30 W
Windshield wipers	50 W	10 W
Stop lamps	42 W	11 W
Turn-signal lamps	42 W	5 W
Front fog lamps	110 W	20 W
Fog warning lamp	21 W	2 W
Total		
Installed loads	1145 W	
Average power consumed by loads		600 W

A conclusion from Table 17 is that the generator has to be designed to supply at least 600 W to the electric system to sustain the battery charge in average. This must be related to the energy consumed from the primary energy source. Table 18 shows the drag power consumed by some generic types of vehicles. Now, consider that the power consumed by the electric loads of Table 17 is supplied from a generator with an average efficiency of 50 %. This means that the mechanical load on the crankshaft of the ICE is about twice the average power of the generator, i.e. about 1.2 kW. Compare this figure to the drag powers of Table 18. It is evident that the electric load, in particular in city traffic, cannot be neglected since it represents a significant part of the fuel consumption in particular at low speeds.

Consider also that the directly mechanically driven loads are not included in this perspective, e.g. the power steering pump, the AC compressor, the water and oil pump. These all represent additional auxiliary loads that contribute to a significant energy consumption of the vehicle that is independent of the transportation energy. In the following sections, the most common electrical and non-electrical loads will be discussed in detail.

Table 18 Drag power for some types of vehicles

	Drag coefficient c_d	Drag power in kW, average values for $A = 2 \text{ m}^2$ at various speeds ¹⁾			
		40 km/h	80 km/h	120 km/h	160 km/h
 Open convertible	0.5...0.7	1	7.9	27	63
 Station wagon (2-box)	0.5...0.6	0.91	7.2	24	58
 Conventional form (3-box)	0.4...0.55	0.78	6.3	21	50
 Wedge shape, headlamps and bumpers integrated into body, wheels covered, underbody covered, optimized flow of cooling air.	0.3...0.4	0.58	4.6	16	37
 Headlamps and all wheels enclosed within body, underbody covered	0.2...0.25	0.37	3.0	10	24
 Reversed wedge shape (minimal cross-section at tail)	0.23	0.38	3.0	10	24
 Optimum streamlining	0.15...0.20	0.29	2.3	7.8	18
Trucks, truck-trailer combinations	0.8...1.5	—	—	—	—
Motorcycles	0.6...0.7	—	—	—	—
Buses	0.6...0.7	—	—	—	—
Streamlined buses	0.3...0.4	—	—	—	—

Additional electric loads

As discussed in chapter 4, page 61, there are efficiency, weight and volume benefits to be drawn in converting some traditionally mechanically driven loads to electric operation. In a hybrid vehicle that has a generic ability to provide higher electric power than a conventional vehicle, some “new” loads appear that further increase the load on the electric power system. Table 19 summarize some non-conventional electric loads.

There are lot’s of more loads that could be added to the contents of Table 19. Some examples are GPS Navigation Systems, DVD based Passenger Entertainment Systems, BlueTooth connection for giving brought on Mobile Phones Hands free via the Sound Systems, Detachable Cooling Boxes, Electrically Operated Foldable Cabriolet Roof, Electrically Controlled Suspension and Levelling System, Reversing Distance Sensing System, 230 V/50 Hz outlet for electric power to e.g. electric hand tools or electric grills for tail gate parties, Most of these loads use a relatively low electric power, although electric suspension and mains power outlet must be expected to be in the range of several kW.

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Table 19 *Non-conventional electric loads on a private car*

Load	Traditional load power	Load at electric operation
AC compressor		500 (1500)
Water pump		200 (100)
Oil pump		150 (100)
Catalyst electric pre-heater		2000 (0)
Electric Power Steering		400 (50)
Sum of additional loads		3250 (1750)
Traditional load according to Table 17		1145 (600)
Total electric load	-	4400 (2350)

Note from Table 19 that, even when being incomplete, the electric load is increased by a factor of four compared to the conventional vehicle. This is far more than the claw pole generator of a conventional private car is designed to supply. The ability to provide this electric power, and possibly even more, in a hybrid vehicle depends on the type and size of the drive train. This will be discussed in the following section.

6.2. The Power System Structure of a Hybrid Vehicle

As should be evident from the previous chapters, especially chapter 3.6 ff, a hybrid system can be structured in several different ways, e.g. series or parallel, with combustion engines or fuel cells, with different proportion between the power of the primary energy converter and the power of the secondary energy converter. A Super Capacitor based Parallel hybrid cannot provide rated electric power for more than seconds, whereas a battery supported Plug In Hybrid (i.e. an Energy Hybrid) can provide rated power for 10's of minutes. Any Series Hybrid designed for pure electric operation for at least a few kilometres of city traffic can supply rated power for minutes.

As an example, assume that the Air Conditioning of a hybrid vehicle should be possible to operate with full power for 5 minutes without starting the ICE. A Super Capacitor supported Parallel Hybrid without batteries couldn't do this, but a Plug In Hybrid could. IN the design of a hybrid vehicle, such considerations must be made. What auxiliary loads must be possible to operate on pure electric power without the ICE running, and for how long?

Why not 12 V for everything?

In the early automobiles, the power system used 6 Volts as system voltage, which was mainly used for ignition and lighting. The 6 V starter and generator was introduced in 1912. However, with the introduction of the V8 engines and higher compression, it became more difficult to run the ignition system on 6 V and in 1955 the 12 V system was introduced to meet the increasing need for electric power and the need for higher ignition energies.. Today almost all conventional vehicles of modern standard use a 12 Volt electric power system. As indicated in Table 17 this system consume about 1 kW as a maximum power. The voltage level has several attractive features:

- 12 V can be handled by anyone without risk of electric shock.
- Isolation requirements are modest.
- The braking of fault currents with melting fuses is simple and cheap.

It would be very attractive to continue with the same system voltage when increasing the power level. However, there are several reasons why this cannot be done:

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- The cable area becomes far too big at high powers. A 1 kW load would need 25-mm² cable areas at 50 Centigrade surrounding temperature (Source: Bosch Automotive Handbook, 5th Edition, page 858). Such a conductor is 8 mm in diameter. A 4 kW load would need a cable area about 16 mm in diameter. It is evident that the conductors become unrealistically thick, in particular for the power levels of the traction system energy converters with power levels of 10's of kW.
- The connectors become expensive, since the contact resistance at the high current levels cause significant voltage drops, that cannot be afforded with only 12 Volt system voltage.

Thus, with the seemingly ever-increasing load power it is necessary to increase the system voltage beyond 12 Volts. A first hand solution would be to double the voltage to 24 V, since that is the system voltage used in heavy vehicles, and thus there is already a production of system components for that voltage level. 24 Volts, however, is not enough for the power levels anticipated. In 1994 MIT and Mercedes Benz took the initiative to a tripling of the system voltage, to 36 V. This initiative was supported by Ford, GM, Delphi, Siemens, and others and resulted in a new standard, somewhat illogically called the 42 V Power Net. It is a 36 Volt system, three times the voltage of a 12 Volt system. The reason for calling it a 42 V system is related to the charging voltage that is 14 Volts for a 12 Volt system and consequently 42 Volts for a 36 Volt system. A logotype was introduced for this new voltage level, see Figure 6.1, and it was expected that all big automotive manufacturers gradually should convert to this new voltage level.



Figure 6.1 The 42 Volt logotype

The 42 Volt system has however not turned out to be the success that it was intended to be. Several problems has turned out to be working against the adoption of this new standard:

- Fuses become significantly more expensive. At the higher voltage level, the electric arcs that are created when a fuse tries to break an inductive fault current are difficult to extinguish. Of course such fuses are possible to design, but the price is reported to be unacceptably high.
- The currents are still to high for some interesting power levels in particular in hybrid drive trains.
- The windings of all small electric motors become larger due to the higher number of winding turn with thicker isolation (due to the higher voltage) and thus the electrical machines become larger. This counteracts the ambition to make things smaller and lighter, not bigger and heavier and causes difficulties in e.g. electrically controlled rear mirrors which contain two small motors.
- Filament lamps are also more difficult to make for a higher voltage, since the filaments become thinner at a higher voltage and thus have a shorter lifetime.

The consequence is that the development of 42 Volts systems and components have lost its momentum, and it is likely that a new standard for an even higher voltage will be developed, most likely higher than 100 Volts. Such a high voltage is already a reality in hybrid vehicles, but without a standard. Different producers use different t voltages. The Toyota Prius use a 200 Volt

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Traction Battery, but with a step-up converter to supply up to 500 V to the electrical machines in the drive train.

Multi Voltage Systems

No matter what system voltage, higher than 12 V, that is introduced it will not eliminate the need for a 12 V system. It is instead likely that the 12 V system will coexist together with a higher traction system voltage. It is true to say that the electric power system of a modern vehicle is a multi voltage system, a fact that is exaggerated in hybrid vehicles:

- 12 Volts is the standard voltage for instrumentation, low power actuators and low power lighting. The 12 V battery at this voltage level is also called the service battery.
- 5 Volts is used in the many micro processors in various controllers.
- 100-500 V DC link voltage for the traction system. This voltage level may also be used for e.g. electric shock absorbers in the wheel suspension system.
- 36 V used in sub systems designed to comply with the 42 Volt standard.

At least the three first of these voltage levels are a realistic combination, to be expected in a hybrid electric vehicle. It is not an easy task to design such a multi voltage system. The main difficulties are:

- Power bridges are needed between the different voltage levels, at least between the 12 V and the traction system voltage. In a hybrid vehicle the traction battery is charged by means of the hybrid system control, and the 12 V battery is supplied from the traction battery via a DC/DC-converter.
- Due to the high voltage of the traction battery, there must not be any possibility for the normal vehicle user to misuse the connections of the electric power system. Connection of additional equipment like extra headlights, or jumper start of another vehicle, must be practically impossible to do in other ways than the right way.
- A deformation of the vehicle body in an accident may cut through the isolation of wires connected to the traction battery. This short circuit may not cause a hazardous situation, e.g. fire.

Power Bridges

There are power bridges at several locations within a system of electrically driven auxiliary loads and the traction system. The 12 Volt system is normally arranged with negative earth and the chassis of the vehicle is used as the earth definition. With the presence of a traction battery it is necessary to decide how it should relate to the chassis. There are two choices

1. The traction battery can, with negative earth, be connected to the same chassis as the 12 Volts system.
2. The traction battery can be “floating”, meaning that it has no connection to the chassis at all and thus no relation to the 12 Volt battery.

Alternative 1 gives a higher risk for electric shock, since it is enough for a person to touch the positive traction battery conductor and the chassis to be exposed to the full traction battery voltage. In the case that the battery can be charged from the mains, alternative 1 is impossible. This is related to the way that the potentials of a switched charging system varies over time, and will be discussed in more detail in the subsequent section on Line Charging Systems.

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Alternative 2 is the one that is preferred, since it gives a higher degree of personal safety against electric shock, but also because it simplifies line charging. In the following section it is thus assumed that the traction battery is “floating” in potential relative to the chassis of the vehicle.

Figure 6.2 shows the principal structure of a Power Bridge, in particular a DC/DC converter between a traction battery and a 12 Volt battery.

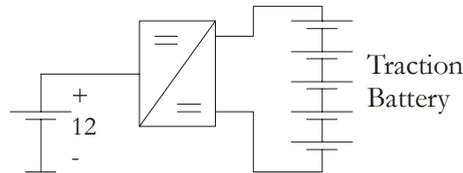


Figure 6.2 A DC/DC converter

The DC/DC converter must thus give galvanic isolation between the 12 Volt service battery and the traction battery. Depending on the specification, this DC/DC converter can be bi-directional or unidirectional, i.e. it can be able to control power flow in one, or in both directions. In e.g. a parallel hybrid with super capacitors, the ICE starting can be based on the traction motor being fed from the super capacitor system. If the vehicle has been out of operation for a longer time, the super capacitor may be discharged and must be recharged prior to a starting attempt of the ICE. The service battery can then charge the traction battery/super capacitor via the power bridge / DC/DC-converter. Figure 6.3 shows a bi-directional DC/DC converter built with two 4-quadrant voltage source converters and a transformer, which is able to provide bi-directional power flow and galvanic isolation. The details on how a 4-quadrant voltage source converter is used are described in a subsequent section of the course material.

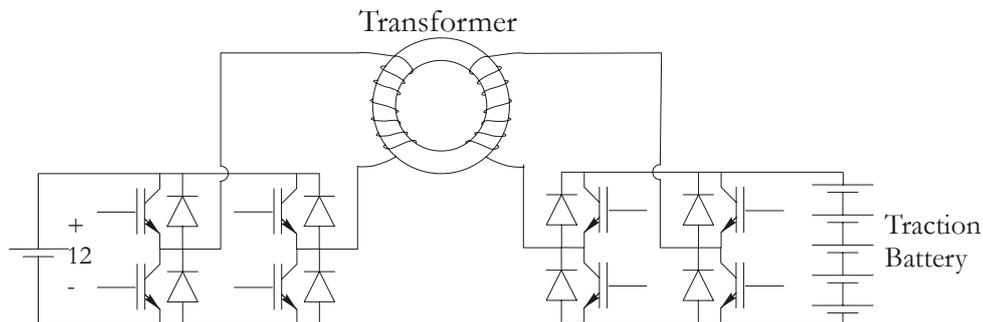


Figure 6.3 A bi-directional Power Bridge

The Power Bridge between the service battery and the traction battery becomes a delicate part of the hybrid vehicle, for more than one reason:

- A loss of operation in the power bridge leads to the loss of charging of the 12 V service battery and subsequently to the loss of all systems supplied by the service battery. The power bridge needs to be redundant.
- As the power bridge between the service battery and the traction battery is controlled with Pulse Width Modulation (PWM) it is a likely source of EMC-problem, since many subsystems are supplied from the service battery. Both the notion of PWM and EMC will be discussed in subsequent sections.

Methods to address the two problems (redundancy and EMC) with power bridges will be discussed in the next sections.

Charge evening systems

A traction battery is a series connection of a number of blocks (e.g. 12 Volt modules), each of them being a series connection of a number of cells, very much like a chain. The saying that a

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chain is not stronger than its weakest link is true also for a battery system like the traction battery of a hybrid vehicle. Each block should be regarded as an individual; some have slightly higher capacity, some slightly lower. This can be due to the blocks being different in age, e.g. if a block is replaced sometime during the service life of the battery pack, or because their different physical location has exposed them to different thermal conditions over a longer time.

Assume a power hybrid that intentionally is designed to be charged from the utility grid.

When charging, the block with the lowest capacity will reach full charge first. If the charging is disrupted at that point, the other blocks will not reach full charge. If charging is continued beyond this point, the block with the lowest capacity will be overcharged which contributed to reduced lifetime of that particular block.

When discharging (i.e. when the vehicle is in operation), the block with the lowest capacity will reach minimum charge level first, whilst the other block still have more energy to supply. If discharging is disrupted at this point the energy in the other blocks will never be used. If discharging is continued beyond this point, the block with the lowest capacity will be depleted which contributed to reduced lifetime of that particular block.

Following this line of thought, it is evident that a traction battery needs a support system that makes it possible to both charge and discharge all blocks to the maximum of their individual abilities. A simple system of that kind use a shunt to bypass charging current when full charge is reached, see Figure 6.4.

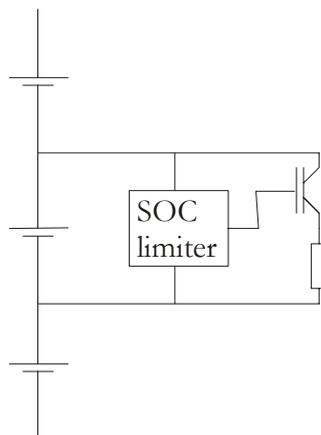


Figure 6.4 A shunt based charge limiter

The system in Figure 6.4 is passive and dissipates the bypassed energy in heat. Furthermore it cannot bypass discharge current. A more advanced system use a small bi-directional power bridges next to each block in the traction battery pack. These power bridges are bi-directional and provide galvanic isolation. One side is connected to an individual traction battery block and one side is connected to the 12 Volt service battery. Figure 6.5 shows the structure of such a system.

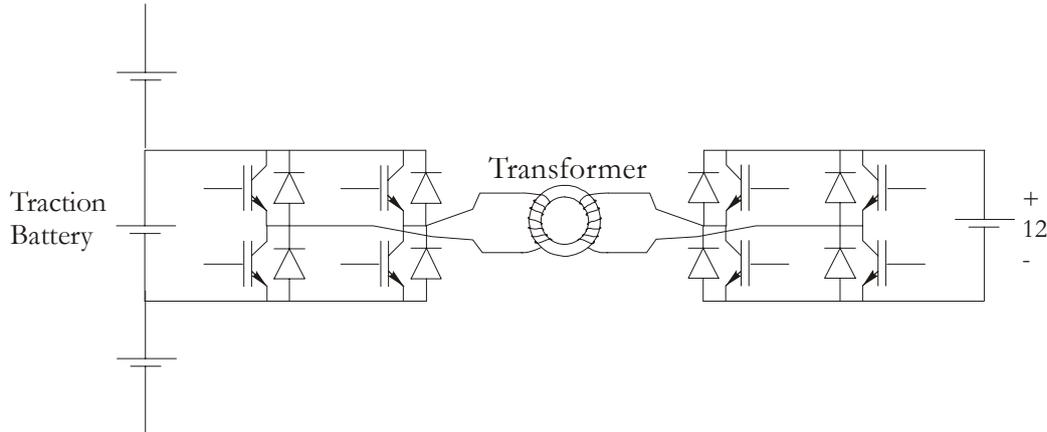


Figure 6.5 A fully bi-directional charge evening system

The unit power of each individual power bridge in a charge evening system does not have to be very high. When charging a battery, the “topping” of charge, i.e. in the end of the charging period is made with relatively modest power compared to the rated power of a battery pack.. Individual differences, however important, are relatively small and the power bridge does not have to be engaged at more than a fraction of the rated battery current.

A fully bi-directional charge evening system has several attractive features:

1. Improvement of the useful charge dynamics of the battery. As discussed, the battery pack can both receive and deliver more energy.
2. A DC/DC converter between the traction battery and the service battery becomes obsolete. Assume a 240 V traction battery made out of 20 12 V blocks. Assume that 5 Ampere DC/DC converters are used in the charge evening system. The total power of the charge evening system is thus $20 \times 12 \times 5 = 1200$ Watt. This is normally more than enough to supply the loads connected to the 12 V service battery. Even if one of the DC/DC converters fails to function correctly, the others are still in operation and guarantees a high degree of redundancy for the transfer of energy between the service and traction battery. Thus, no additional DC/DC converter is needed between the traction and service battery. Remember that the heavier loads like the Air Conditioning are most likely supplied from the traction battery directly.
3. The lifetime of the battery is increased, since none of the blocks is ever exposed to charge or discharge beyond its abilities.

The cost of a charge evening system is balanced by the increased capacity and lifetime of the traction battery. The function of a charge evening system is however based on PWM, and spread over a wide physical area (= the size of the traction battery). It is very important that the design of the individual DC/DC converters as well as the system of these is made with the highest regard to EMC.

EMC

Electro Magnetic Compatibility, abbreviated EMC, means the conditions, regulations and methods used to guarantee that electronic equipment can coexist with other electronic systems without disturbing or being disturbed by the other systems. In automotive applications this means that the various electrical and electronic systems such as the ignition system, the electronic fuel injection, ABS/TCS, airbags, radio car phone, navigation systems etc. must function in close proximity of each other without interfering with each other beyond an allowable level. It also means that the vehicle as a system remains neutral with respect to its surroundings.

These disturbances can be created and transferred via conductive, inductive or capacitive connection between the involved systems.

- **Conductive.** Systems connected to the same galvanic circuit expose each other to signals transferred via the connecting conductors. The frequency range is from zero Hertz up, and the connecting conductors can be both power cables and signal cables, e.g. a communication bus. One example is the generator in a conventional car, where the diode rectifier is a cause of a voltage and current ripple that vary in frequency as the speed of the generator varies with the speed of the ICE. This voltage ripple is transferred via the 12 V system to all loads connected and may e.g. be heard as a whine in the sound system.
- **Inductive and Capacitive.** Systems that are physically arranged in such a way that there is an inductive and/or capacitive coupling that can transfer signals through this coupling. A good example is the cables arranged in parallel in the same bundle. Cables belonging to different subsystems, arranged in parallel like that, exhibit both a capacitive and an inductive coupling

EMC is a scientific field of speciality that is gaining an increased attention as the number of auxiliary loads is increased. The knowledge on how to design equipment with good EMC properties is tightly coupled to good understanding of how electromagnetic fields propagate and interact.

In the context of auxiliary loads there are some facts that must be emphasised.

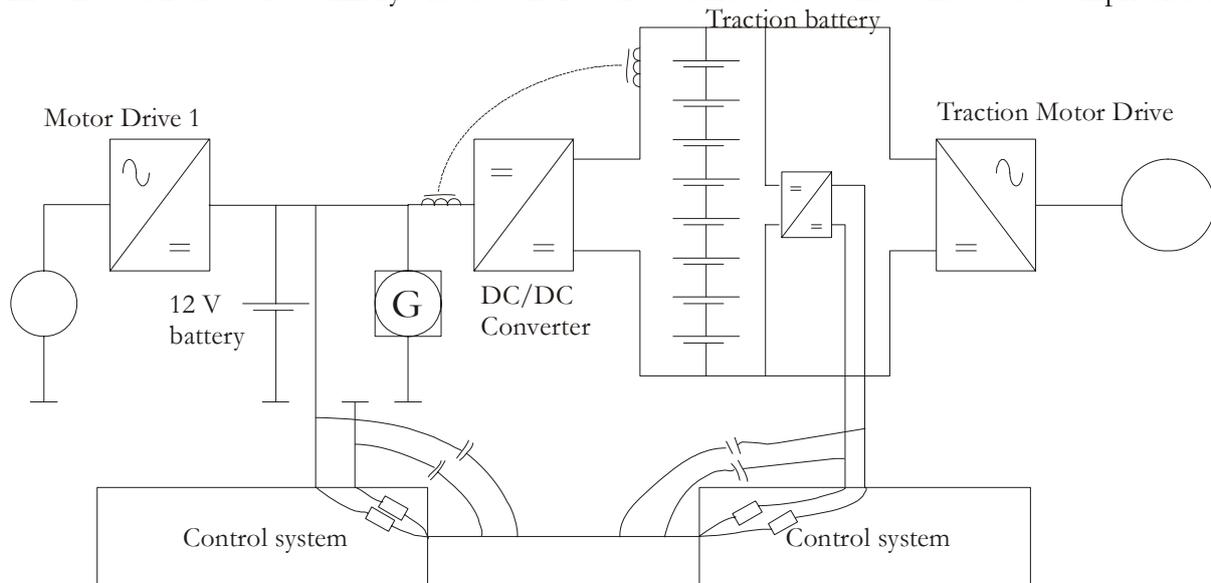


Figure 6.6 shows a system involving the 12 V service battery and one load connected to the 12 V level, a power bridge to the traction battery and a load connected to the traction battery.

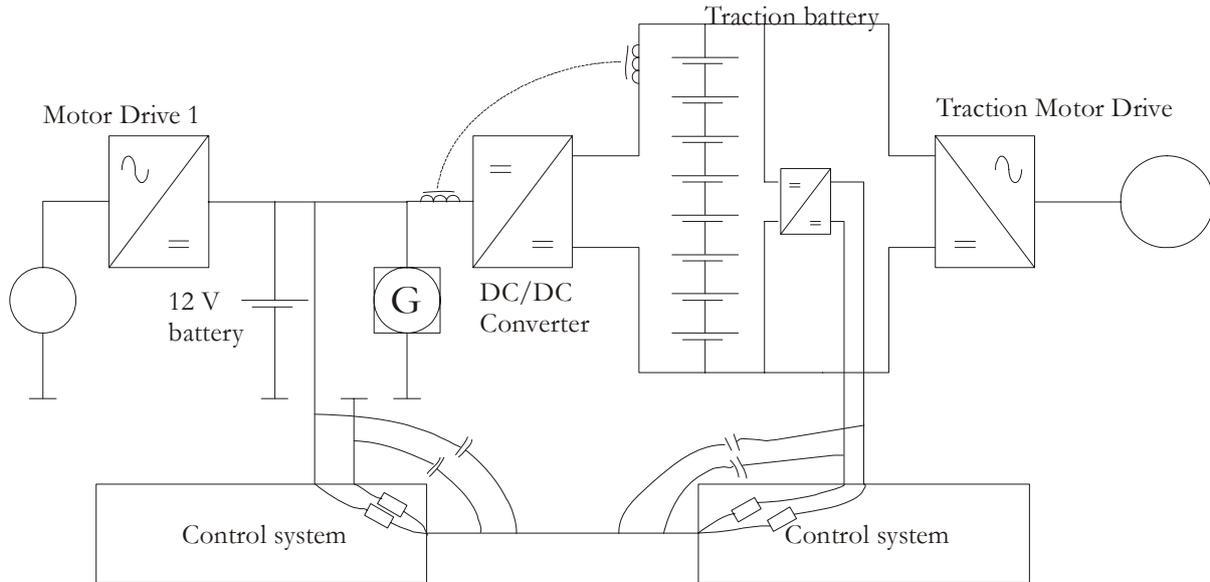


Figure 6.6 A part of the electric power system of a hybrid vehicle.

In Figure 6.6 there is a control system connected to each load, both on the 12 V system level and the traction battery system. Remember that the traction battery is “floating”, i.e. it has no, and should have no, galvanic connection to the service battery. In the figure, some possible causes of EMC problems are indicated. The control systems are most likely connected to the same communication bus.

If there is a resistive or capacitive connection between the power supply and the communication interface of the control systems, then there is also an undesired connection between the service battery systems and the traction battery level.

If the cable to and from the power bridge between the service and traction batteries is drawn in the same bundle, then there is an inductive coupling between these cables, opening another undesired path for EMC problems.

There is no room to go into depth with the important field of EMC as applied to automotive technology in this context. Let the example of Figure 6.6 indicate the importance of making a very thought through design of auxiliary systems, including both the physical layout of the circuit and the connections via both power cables and signal cables.

Line Charging Systems

Plug in hybrids, as discussed in section 3.8, benefit from low electric energy price and short average travelling distance between stops long enough to provide substantial charge to the batteries. Two distinctly different systems may be used for charging these batteries:

1. 1-phase / 10 A supply from consumer level voltage. With a 230 V systems the charging power is thus 2.3 kW. Assume a realistic energy consumption when driving the vehicle corresponding to 1.5 kWh/10 km. Charged this way, the electric utility grid provides no more than 20 km of driving per hour connected. An 8 hour working day would the provide 160 km of driving which is most likely more than the size of the traction battery can accommodate. However, a shorter stop may not provide enough energy to “fill up” the battery. The solution to this is to use a higher power charger.
2. 3-phase / 16 A supply from consumer level 3-pase voltage. With a 400 V three-phase system the charging power level in this case corresponds to 11 kW. Charged at this power level, the

electric utility grid provides up to 70 km of driving distance per hour connected. A one hour lunch break charge time is then probably enough to “fill up” the batteries of such a hybrid.

The circuit diagram of a charger according to alternative 2 is shown in Figure 6.7.. It is tempting to use the internal power electronic converter of the vehicle, i.e. the same converter as is used for propulsion of the vehicle to also perform the charging of the batteries from the utility grid. Done that way, the vehicle carries its own charging system around and can charge itself from any 3-phase power outlet. This contributes to flexibility.

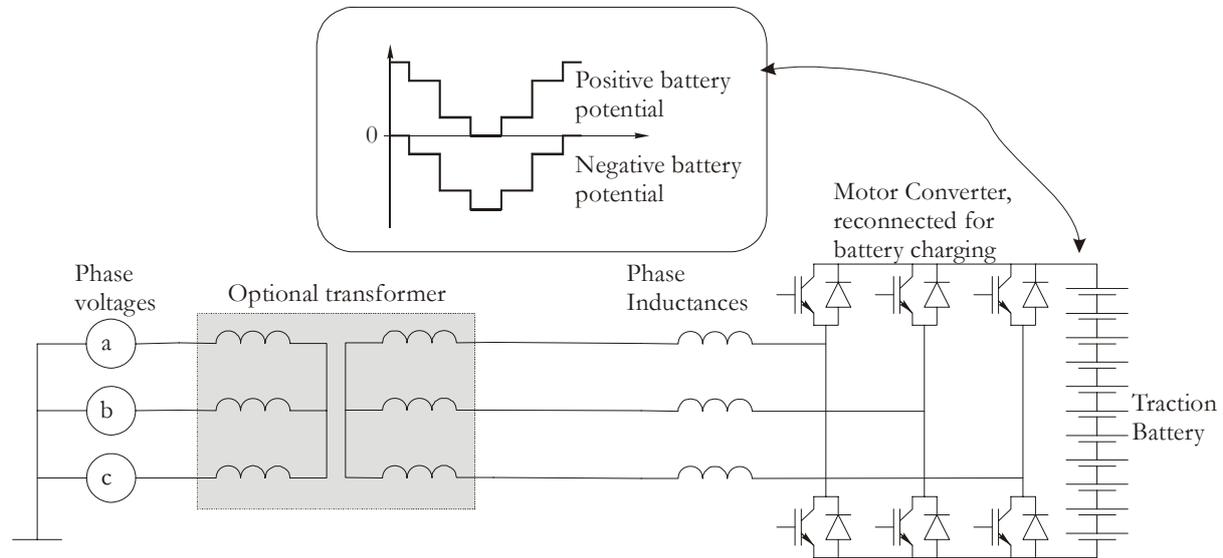


Figure 6.7. A 3-phase charging system

Without the optional power transformer, the potentials of the positive and negative pole of the traction battery will vary with the battery voltage and the modulation frequency of the power electronic converter according to Figure 6.7. This is called a common mode voltage and originates from the modulation of the power transistors. The details of this will be further explained in a subsequent part of this course. The importance here is to realize the consequences of this.

Even if the battery is not galvanically connected to the chassis of the vehicle, there is an unavoidable capacitance between the battery and the chassis of the vehicle. The high voltage and high frequency of the potential variations due to the connection to the utility grid cause large currents, at modulation frequency and harmonics of it, that flows through these undesired capacitances. These currents may also connect inductively to other equipment and is the cause of severe EMC problems.

To alleviate these problems, the optional transformer indicated in the figure is helpful. It separates the grid connection galvanically from the utility grid, and introduces a capacitance between the mid point of the transformer secondary winding and earth. For the common mode voltage this capacitance appears in series with the capacitances between the battery and the chassis and thus suppress the undesired common mode currents substantially.

A simpler charging system for high power can be made where the problem indicated here is less accentuated, but the principle is still the same. Such systems have a high frequency transformer and works like a primary switched power source.

The example indicates again, like in the EMC section, the importance of a thought through design in the energy system on board the vehicle. Physical layout in order to minimize capacitive and inductive couplings is fundamental for high EMC. A complete awareness of the intended as well as parasitic components in the electric power and signalling system is mandatory. The small

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space, high power and diverse systems of a hybrid vehicle will otherwise cause hard to locate and difficult to cure EMC problems.

6.3. Auxiliary Power Unit

A component belonging to the auxiliary system group that has become particularly interesting in the last years is the Auxiliary Power Unit. It is a power converter that is able to generate electricity from a primary energy source and it is separate from the power converter involved in the tractive system. The concept emanates from heavy vehicles used in long distance transportation. The drivers of these vehicles live on the vehicles and need an electric power supply even when the vehicles are standing still, e.g. for the driver to rest/sleep. The vehicles are sometimes so well equipped that there are e.g. washing machines on board that run on electricity. The generator driven by the ICE can generate this electricity. The load power is then so low that the ICE is almost idling, and the efficiency is consequently very low. A separate system that can provide this energy at a higher efficiency is thus attractive. This is what the Auxiliary Power Unit is intended to do.

Two different ways to provide the energy for stand still power supply will be discussed here.

Fuel Cell Based Systems

A Fuel Cell based system may be a small version of the system used in the Fuel Cell Hybrid discussed in chapter 3.10. To reach a high efficiency, the system must be designed for a higher power rating than the anticipated load power, see Figure 3.11. This system requires a separate tank for the fuel used, e.g. hydrogen or methanol.

Combustion Hybrid Based Systems

If the heavy vehicle is equipped with a hybrid drive system anyway, e.g. a parallel hybrid system, then it is possible to use the traction battery to supply the electric power at standstill. The ICE would go on and off to either charge the battery at high enough power to reach a good efficiency, or off when the battery is charged. The following example may serve as an estimation of the size and weight of such a system:

Assume a 400 kW Diesel, with peak efficiency at 44% and able to run at more than 40 % efficiency above 20 kW of output power. Assume an electric drive of 20 kW used in the hybrid system. This is enough to drive the truck in residential areas, for manoeuvring when parking etc, and the electrical machine can be used for generation of up to 20 kW of electric power. Assume a 5 kWh NiMH battery as secondary energy storage. This has a weight of about 50 kg. Assume a 2 kW electric load power at standstill and a 40 % allowed variation of the SOC in the battery. With the ICE off, the battery can provide 2 kW for one hour without starting the ICE and thus dropping the SOC by 40 %. Then the ICE can start to charge the battery with $(20-2)=18$ kW of power, i.e. fill up the battery in 5...10 minutes, and the cycle is closed. The charge efficiency of the battery pack may be 85 % including charging and discharging, resulting in a total efficiency of $40 \cdot 0.85 = 34$ %. This should be compared to the efficiency of the FC-based system that most likely is 10 % higher. On the other hand, the combustion hybrid system is also able to provide hybrid drive functions and operate on the same fuel as the ICE.

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1. (Appendix) Driving Cycles

The simulations made in this context have been made with the US06 and the EUDC cycles. US06 describes a demanding highway driving including aggressive accelerations and high speed driving. The cycle is 12.8 km long and has a mean speed of 77.8 km/h, maximum speed of 130 km/h and a maximum acceleration of 3.24 m/s^2

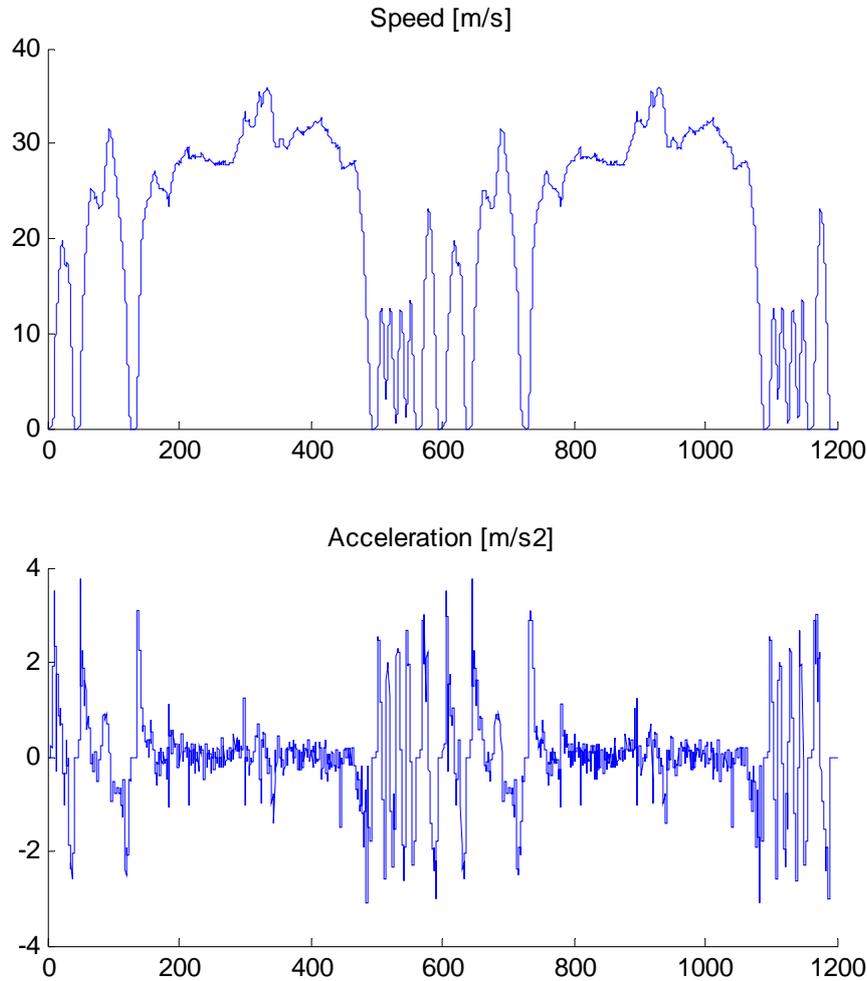


Figure 6.8: Drive cycle US06, speed and acceleration.

The US06 Supplemental Federal Test Procedure (SFTP) is developed to address the shortcomings with the FTP-75 test cycle in the representation of aggressive, high speed and/or high acceleration driving behaviour, rapid speed fluctuations and driving behaviour following start up.

The reason to include the US06 cycle in the survey is that its demanding accelerations expose the transient behaviour in fuel consumption and emission.

The drive cycle EUDC has also been used in the survey to make a fair comparison of the topologies. The EUDC drive cycle is not as demanding as the US06 cycle. The cycle is theoretical and includes relatively low accelerations. The EUDC cycle is an extended urban driving cycle with a short high speed part in the end. It was devised to represent city driving

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conditions. It is characterized by low vehicle speed, low engine load, and low exhaust gas temperature (Dieselnet, 2002).

For light duty vehicle the speed limit is 90 km/h. The cycle is 10.8 km long and its average speed is 33.9 km/h. The accelerations are considerably lower than the US06 with 1.05 m/s^2 .

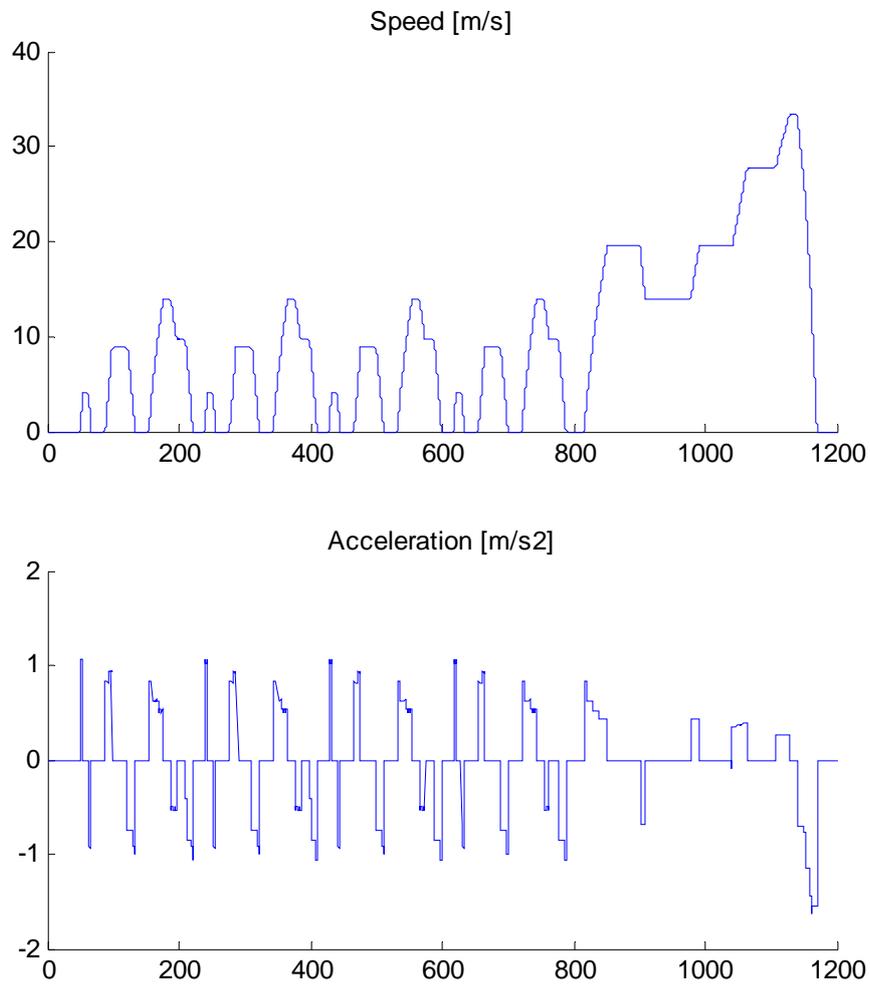


Figure 6.9: Drive cycle EUDC, speed and acceleration.

There is a possible variation of the cycle. For heavy-duty vehicles the top speed is limited to 70 km/h. This affects also cycle distance and average speed.

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Reference Vehicle

To make the survey fair and relevant to a large market segment, a medium sized family car was chosen as simulation input. The specific vehicle became Toyota Prius Generation II, an electric hybrid family car, available on the market today. The advantages with the choice are that input data are accessible and there are measured data available as well. The chosen Toyota Prius is the one marketed in Europe. It is equipped with a larger engine than the ones earlier sold in the USA and at the Japanese market.

As input in the ICE-simulation model data from a SAAB engine has been used. This is due to lack of sufficient detailed information about the Toyota Prius engine.

The SAAB engine is a naturally aspirated gasoline engine, 2.3 l and 16 valves. Its max torque is 212 Nm at 3800 rpm and its max power is 110 kW at 5500 rpm. The engine data used in the model are all measured at Lund University, department of Heat and Power Engineering, Combustion Engines division.

The SAAB engine data is thereafter adjusted through cylinder reduction to suite the size of the Prius ICE (PRIUS, 2004++). Input data in the simulation model are the engine speed and the torque demand. Outputs are the actual torque, the fuel consumption and the emissions. The emission output is derived from scaled emission maps, as based on the SAAB engine measurements.

The sizes of the machines are selected to correspond to the Prius data, as well as possible and adjusted to suit the demands following the single topology. (See

Table 20.) Note that the pure series hybrid has a smaller ICE and a larger em1, with preserved total installed power.

Table 20: Vehicle data.

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2004 & later model	
	
Production:	2004 to present
Class:	Midsize
Body styles:	5-door hatchback
Engines:	Hybrid Synergy Drive Gas: 1.5 L I4 DOHC 16 valve VVT-i 57 kW (76 hp) @ 5000 rpm Torque: 115 N·m (85 lbf·ft) @ 4200 rpm Electric: 500 V 50 kW (67 hp) @ 1200 to 1540 rpm Torque: 400 N·m (295 lbf·ft) @ 0 to 1200 rpm AT-PZEV Hybrid System Net Power: 110 hp (82 kW)
Length:	4450 mm (175.33 in)
Width:	1725 mm (67.97 in)
Height:	1490 mm (58.71 in)
Curb weight:	1325 kg (2921 lb)

Feature		Model code		
		NHW10	NHW11	NHW20
Body style		4 Door Sedan	4 Door Sedan	5 Door Hatchback
First sales		1997	2000	2003
Battery	Modules	40	38	28
	Cells per module	6	6	6
	Total cells	240	228	168
	Volts per cell	1.2	1.2	1.2
	Total volts (nominal)	288	273.6	201.6
	Capacity amp hours	6.0	6.5	6.5
	Weight kg	57	50	45
Petrol Engine	Power kW	43	52	57
	Max rpm	4000	4500	5000
Electric Motor	Power kW	30	33	50
Combined	Power kW	?	73	82