A Powerflow Control Strategy to Minimize Energy Losses in Hybrid Electric Vehicles

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Abstract

This work considers control of powerflow and energy storage in a Hybrid Electric Vehicle (HEV). The performance of a HEV, such as fuel consumption and emissions, depends not only on the individual components but also on how the components are controlled. Control in this case is to determine operating points for the components during driving, while control on the machine level, such as speed and torque control, is not an issue. A model of a series HEV has been developed. A number of different performance indices have been applied to the model and evaluated using methods from optimal control. These methods allow us to define simple specifications such as minimizing fuel consumption and to put constraints on emissions. The resulting controller is impossible to implement since it is open loop and needs information about the future. A controller that captures the behaviour of the optimal controller has been synthesised and tried on the model with satisfying result.

The developed controller has also been implemented on a full scale experimental platform, similar to the hybrid busses in Stockholm. The experimental and theoretical results show good agreement. A reduction in fuel-consumption of about 10% seems possible when the results are compared with the busses in Stockholm.

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Contents

1

Introduction

The pollution problems of internal combustion engines (ICE) have been the focus of public interest for a long time. The Clean Air Act in California is well-known and has forced the development of alternative transportation systems. Electric cars - zero emission vehicles - have been thought of as a natural alternative to ICE cars. Still the real obstacle for the electric vehicles to become a success is their operating range. This problem is even more accentuated for large vehicles like busses, that cannot possibly carry the amount of batteries that is needed for their operation. Despite the fact that enormous costs have been devoted to battery research, the energy storage is still the real problem.

To overcome these limitations hybrid-electric-vehicles (HEV) have been considered a viable alternative, as they try to reach a compromise. In a series hybrid vehicle the car is powered by an electric motor, connected to batteries, charged by an ICE. The ICE will be operated only at favourable operating points, both with respect to the emissions and the fuel economy. Its size does not need to reach the peak power required of the system. The hybrid design can solve the problem of the operating range as well as that of the emission. The overall problem to be solved is the total cost and efficiency, since the system includes both an ICE, batteries and an electric motor, together with power electronics and control equipment.

1.1 Motivation

The design of hybrid vehicle drive trains are too often made without considering operation and control. The control structure is something that is added, once the design is finished. Control of the power flow should be affected by the design of the system such as size of battery, zero emission operating range, total energy efficiency, how and how much the batteries should be charged/discharged.

In this work the interaction between system design and control design has been particularly considered.

1.2 Contribution of the Thesis

By formulating the control as an optimisation problem there is a systematic way to find the best possible driving strategy. No prior assumptions have to be made for the drive system operation, such as pre-determined operating points. Instead, the control is given by design specifications such as emission limits and minimisation of fuel consumption. This has the advantage that no possible control strategy is excluded.

1.3 Outline of the Thesis

An introduction to hybrid vehicles is given in Chapter 2. Modelling of a hybrid vehicle for the purpose of energy minimisation is treated in Chapter 3. Evaluation of vehicle operation requires some sort of comparison to be made. What and why to compare is discussed in Chapter 4. Chapter 5 describes how to analyse the model and how to achieve optimal performance. The experimental setup is described in Chapter 6 and the experimental results obtained from the setup are described in Chapter 7. Chapter 8 finally summarises the results.

2

Hybrid Vehicles an Overview

Hybrid vehicles are vehicles that have *at least* two different energy sources. The most common combination today is an internal combustion engine and electric batteries. This is probably why they were given the name hybrids because they are neither conventional vehicles nor pure electric vehicles. Even though it is not required, a hybrid vehicle often means that one of the energy sources, usually the batteries is re-chargeable during driving. Energy sources under consideration for hybrid vehicles today are: gas turbines, fuel cells, flywheels, ultra capacitors and pressure accumulators. Even electric-electric hybrids can be considered, these vehicles have ordinary batteries to provide the base energy and ultra capacitors for the power peaks.

2.1 Why Hybrids?

Hybrid vehicles are inherently more complicated and expensive than conventional vehicles. The reason for developing them is that it is possible to make them, in some aspect, better than conventional vehicles. Today, the focus is on environmental impact and better is often defined as lower emissions and lower fuel consumption. Other considerations are that the vehicles should be as easy to handle as conventional vehicles and that they don't require a whole new infrastructure for fuel distribution. This last item has ruled out trams and trolleybusses for public transport. Although very friendly to the environment they have a high fixed cost for the overhead wires and tracks, they have furthermore the disadvantage that they are tied to this infrastructure. Opening a new line is therefore very expensive since it will require a lot of investments in infrastructure. To compensate for this disadvantage combined busses have been tried, resembling both a trolleybus and a conventional bus.

These busses are however as complicated as hybrid busses and not necessarily better. Another approach is to have pure electric vehicles but then the charging problem has to be solved. An interesting concept was made by the Swiss company Oerlikon in the early fifties which built gyro-electric busses, for use in the city of Yverdon, Switzerland. These busses were like ordinary electric vehicles except that the battery was replaced with a flywheel and an electric machine. The idea was that it should be easier and quicker to charge these busses, since flywheels have higher peak power than electric batteries. Poles for charging were erected at several places along the routes and a new route would only require some additional poles. Unfortunately, he charging time was still too long and the system was quickly abandoned.

2.2 The Series Hybrid

The series hybrid is easiest described as a pure electric vehicle fitted with onboard electricity generation. Merits of this configuration are that placement

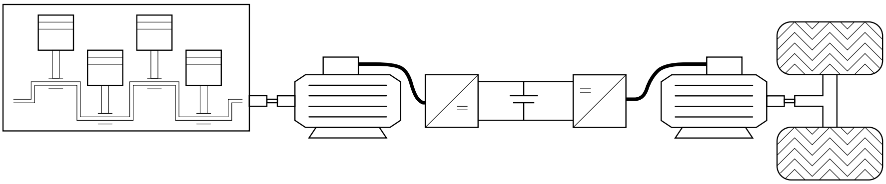

Figure 2.1 Series hybrid

of the components might be easier as there are no mechanical couplings and that, given sophisticated power electronics, the system acts as an electric continuously variable transmission (CVT). This allows the system to be operated at maximum efficiency at all powers. Drawbacks are that they need several electric machines and thus becomes heavy. The machine connected to the wheels must also be able to deliver the maximal power that is needed. Series hybrids are considered most suitable for heavier vehicles like city busses or small cargo trucks. They are also the only alternative today if a high speed primary energy source such as a gas turbine is to be used.

Series hybrids without batteries are not hybrids in the proper sense but this topology has been used since the late forties in the railway industry. These locomotives are known to be robust and reliable. Both diesel engines and gas turbines are used as primary energy sources with sizes up to a few MW.

2.3 The Parallel Hybrid

If the series hybrid is described as a pure electric vehicle with onboard generation facilities then the parallel is best described as a conventional vehicle fitted with an extra electric machine. Advantages with this configuration

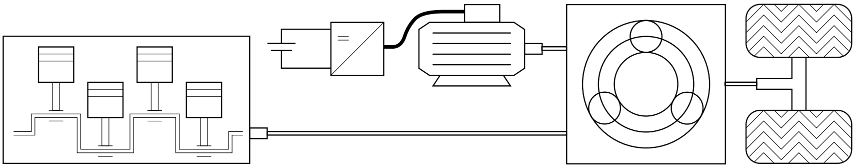

Figure 2.2 Parallel hybrid

are that neither of the machines have to provide the maximal output power alone. One drawback is that some kind of mechanical power-split device is needed, with at least one automatic operated clutch. Parallel hybrids are considered well suited for normal cars.

2.4 Series-Parallel Hybrids

The series-parallel hybrid is as the name suggests a combination of a series and a parallel hybrid. This type of hybrids have several possible ways to route

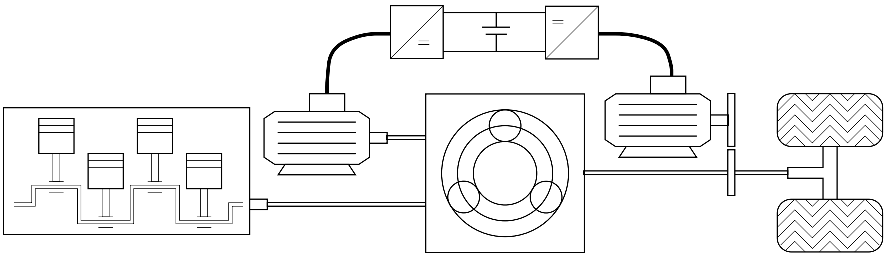

Figure 2.3 Series–parallel hybrid

the power to obtain satisfactory efficiency and driveability. Several different layouts are possible see for example [Mayrhofer et al., 1994], [Dietrich, 1997], [Stridsberg, 1998]. The most well-known hybrid of this type today is probably Toyota's Prius, [Sasaki et al., 1997]. The use of this kind of hybrid seems to be directed to normal cars. An interesting exception is found in [Bullock and Hollis, 1998] where the vehicle is not only a bus, but it also have several different energy storages.

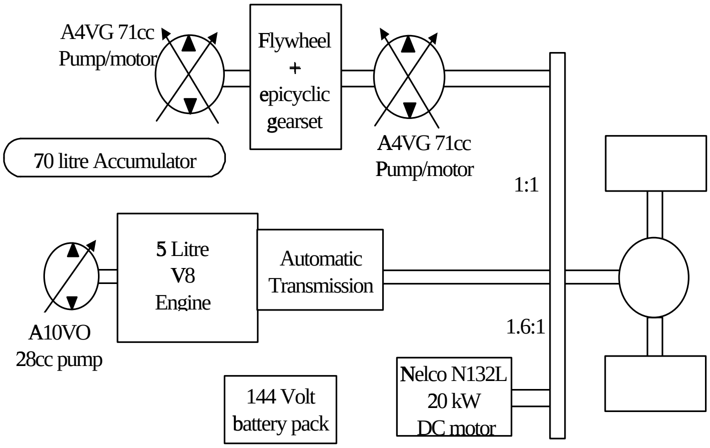

Figure 2.4 The layout of the hybrid bus in [Bullock and Hollis, 1998].

3

Modelling

A hybrid vehicle is a complex system to model. The dynamics of the different components in the system range from μs in the power electronics to months for the aging of batteries. This is not an acceptable time span to encapsulate in one model.

The purpose of the modelling is to achieve a model of a hybrid vehicle that is well suited for calculation of power flows. Accuracy should of course be as good as possible but an error in the fuel consumption or battery loss of a few percent is tolerable as long as this behaviour is consistent.

When looking at powerflows in a bus it is not interesting to look at dynamics that is much faster than the dynamics of the bus, thus the lower limit for the dynamics is about one second. If the aging of batteries is neglected, nothing is slower than half an hour. This is for the components in the vehicle, a hilly route for example, influences the vehicle with a time which is the time for a round trip.

The vehicle to be modelled in this chapter is a series hybrid with an inverter on the generator (Figure 2.1).

3.1 Genset

The genset consists of the internal combustion engine (ICE) together with the generator and power electronics. The genset is modelled with a static model, and the reasons for this are:

1. The dynamics during one combustion-expansion cycle is fast (ms), power electronics even faster (μs) compared to vehicle dynamics, and thus not interesting in this case.

2. The emission control equipment on modern engines is not good at handling transients. One of the main goals with a hybrid vehicle is to reduce emissions which requires slow response of the ICE. When the operating points of the ICE are changed slowly (a few seconds), emissions from static measurements are accurate enough.

3. Neither equipment nor methods for transient emission measurements were available, which makes verification difficult.

The ICE is described with maps that give for example efficiency, NO_X, HC and CO emissions as functions of speed and torque. Some of the data for the ICE have been collected in a Masters Thesis ([Olsson, 1990]). These experiments were redone and extended to complete a few white areas in the maps.

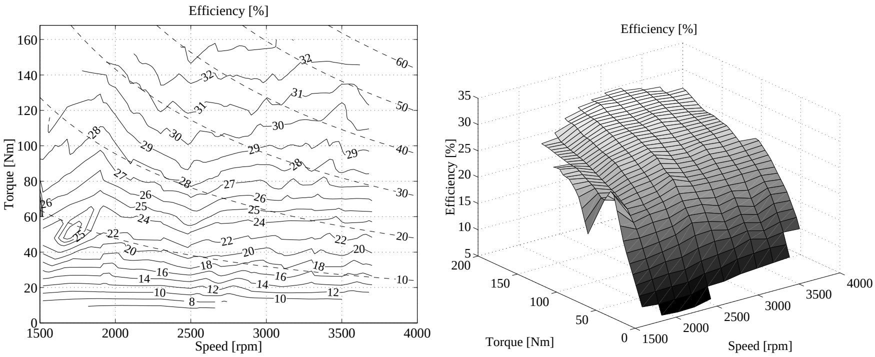

Figure 3.1 Efficiency of the ICE. Dashed lines indicates constant power.

The generator and power electronics were assigned a constant efficiency of 80% because it was impossible to perform the required measurements at the modelling instant. Luckily, this was a rather good guess, since the results from the experiments showed an efficiency between 75%–88%. This includes a fan mounted on the generator shaft.

3.2 Battery

Battery dynamics are not yet understood by other than perhaps chemists. There are some good models of batteries [Bernardi et al., 1985] and [White and Fan., 1991]. The problem is that these models are often closely tied to

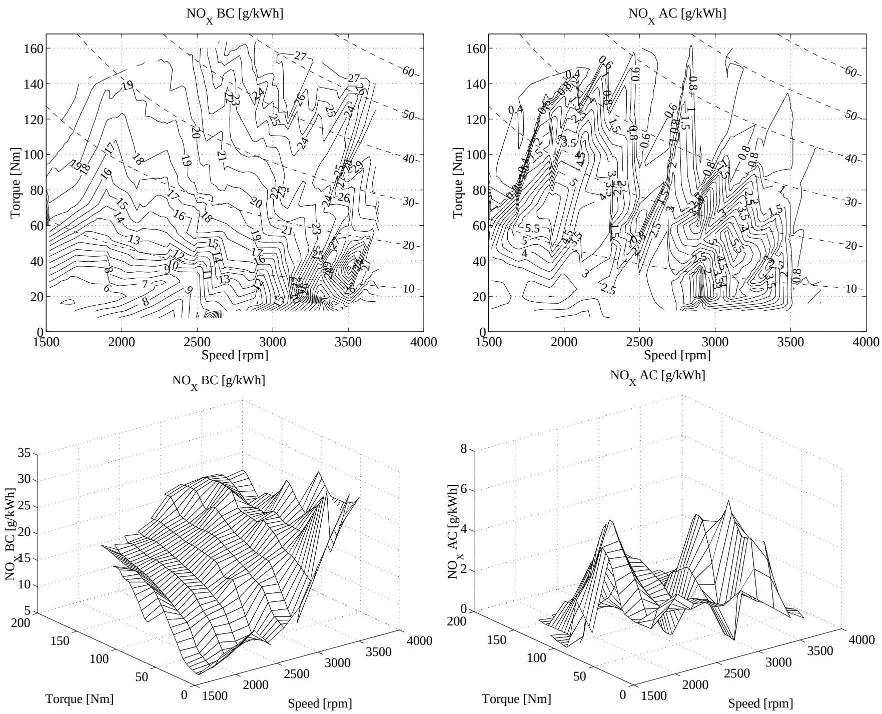

Figure 3.2 NO_X emissions before (left) and after (right) catalyst, note the different axes. Dashed lines indicates constant power.

one specific battery and not very easy to adopt to another size of the battery and of course not to other types of batteries. Unfortunately, most models concerning NiCd batteries are for sealed batteries, whereas the batteries used in the project were of open type. The large amount of research that has been put into developing models of sealed batteries is due to their widespread use in space and consumer industries. The power per cell in these cases is also low compared to those in traction applications. These models are partial differential equations (PDE) that describe diffusion in electrolytes, changing structure of electrodes and a lot of other phenomena. These models are also hard to tune for a non-expert and difficult to understand. Most non-chemists prefer some type of electric equivalent of a battery, made of voltage sources and passive components (Figure 3.3). The equivalent models still need a lot of tuning and the values of the components change with state of charge (SoC) and temperature. The impedance in Figure 3.3 is often divided

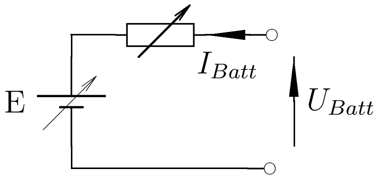

Figure 3.3 Generic battery equivalent. Voltage and impedance depends on SoC, temperature and history.

into smaller parts describing different phenomena in the battery. A simple model that captures the dynamics in the minute range is seen in Figure 3.4. The capacitance is fixed and the resistance is allowed to change its value.

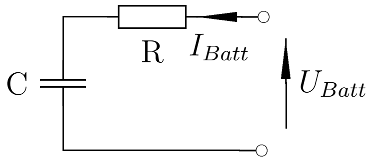

Figure 3.4 The used battery model.

This model has successfully been used for lead-acid batteries ([Bengtsson and Kjellsson, 1991]). The model works best when the battery is neither fully charged nor completely discharged. The size of the capacitor is determined from the rating of the battery in Ah and the voltages when the battery is full and empty. The capacitance in the simulations was 3 kF and the resistance was fixed to 1 $m\Omega$ per cell giving a total resistance of 0.27 Ω.

Battery Estimator

One advantage with this simple model is that it is easy to make an observer for the battery, estimating capacitor voltage and resistance from measurements of current and voltage. A Kalman filter based on the model in Figure 3.4 was used in the experiments. Let the battery be described by the following model

$$\begin{bmatrix} E(k+1) \\ R(k+1) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} E(k) \\ R(k) \end{bmatrix} + \begin{bmatrix} \frac{h}{C} \\ 0 \end{bmatrix} I_{Batt}(k) + \begin{bmatrix} v_1(k) \\ v_2(k) \end{bmatrix}$$

$$U_{Batt}(k) = \begin{bmatrix} 1 & I_{Batt}(k) \end{bmatrix} \begin{bmatrix} E(k) \\ R(k) \end{bmatrix} + e(k)$$

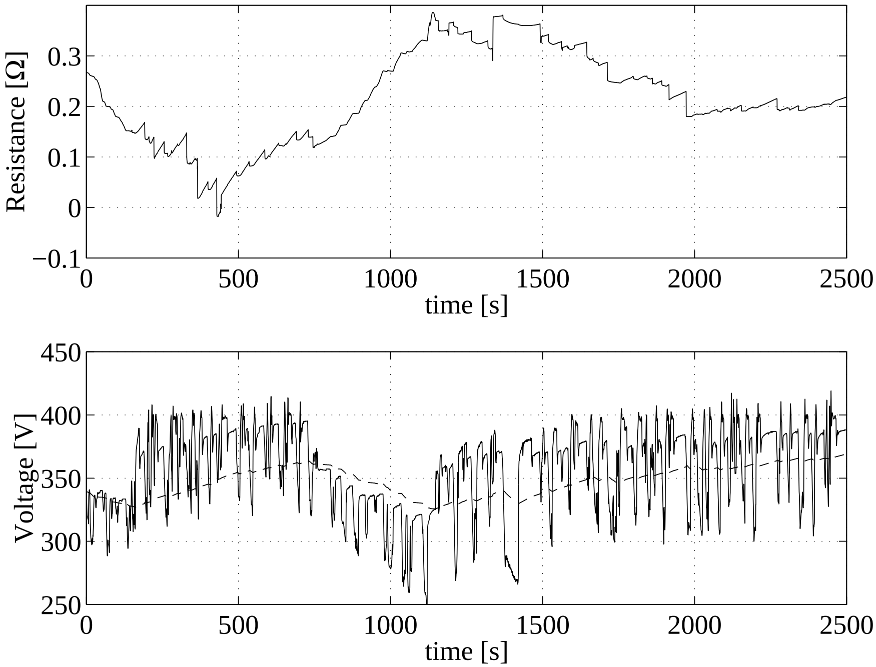

Figure 3.5 Estimated internal resistance (top), the bottom graph shows battery voltage (solid) and estimated capacitor voltage (dashed).

where E is capacitor voltage and R is internal resistance, C is the capacitance and h is the sampling interval. The variables v_i and e are discrete-time Gaussian white-noise with zero mean value and

$$E[v(k)v^T(k)] = R_1$$
$$E[v(k)e^T(k)] = R_{12}$$
$$E[e(k)e^T(k)] = R_2$$

the noise parameters are regarded as "tuning" parameters for the filter. Especially the size of the elements in R_1 (process noise) is artificial. R_2 is easier to estimate as it is the covariance matrix of the measurement noise, often diagonal[1] in the case of several outputs. R_{12}, the cross-coupling between

[1]The noise in each output is independent of the other outputs.

process noise and measurement noise is often neglected. The system is more conveniently expressed in matrix notation as

$$
\begin{aligned}
x(k+1) &= \Phi x(k) + \Gamma u(k) + v(k) \\
y(k) &= C(k)x(k) + e(k)
\end{aligned}
$$

The state estimates are now given by

$$
\begin{aligned}
\hat{x}(k+1|k) &= \Phi \hat{x}(k|k-1) + \Gamma u(k) + K(k)\left[y(k) - C(k)\hat{x}(k|k-1)\right] \\
K(k) &= (\Phi P(k) C^T(k) + R_{12})(R_2 + C(k)P(k)C^T(k))^{-1} \\
P(k+1) &= \Phi P(k) \Phi^T + R_1 - K(k)(R_2 + C(k)P(k)C^T(k))K^T(k)
\end{aligned}
$$

where $\hat{x}(k+1|k)$ denotes the state estimates at the next sampling instant $k+1$ given measurements up to time k. $P(k)$ can be interpreted as the covariance matrix of the estimation error $x - \hat{x}$.

When the energy loss was calculated from the estimated model there was a difference of about 20% compared to measurements. This was without extensive tuning of the model. In order to get even better estimates it is possible to compute $\hat{x}(k|k)$. This was however not considered worth the extra computational cost. Another possibility is to also try to estimate the size of the capacitance, which can be done with an Extended Kalman filter,[Ljung and Söderström, 1983]. This approach was abandoned because of stability problems.

The purpose of the estimator was initially to justify the use of the simple model by monitoring the states and the output of estimator. Slowly varying states and a small output error tells us that the model is good enough for our purpose. When trying to get better and better results from the estimator one must not forget that the model is only some kind of simplified electrical equivalent. Finding a limit on how good the model can perform is therefore difficult.

3.3 Vehicle & Drive system

There are several ways of modelling a vehicle, from the simplest rigid body motion models to models covering effects of suspension etc ([Wältermann, 1996]).

The goal when simulating a vehicle is that the model should follow a predetermined speed profile. This can be accomplished in two different ways:

- The model is driven by a driver. This requires a model of a driver which might not be that easy. The advantages with a driver is that he will take care of things that are difficult to know à priori, like the vehicle weight. This depends on:

  - Fuel consumption (probably not very important)
  - Passengers entering and leaving, described by a stochastic process

  One drawback with this approach is that the behaviour of the complete system (with driver) will change when the vehicle is changed, unless the driver is re tuned. It may thus be hard to determine whether it was the changes in the vehicle or the poorly tuned driver that caused the differences in the result.

- The other approach is to use the model "backwards", that is given the speed calculate the required torque and propagate through the drive system until the point where the unknown power enters the system. The speed profile is now converted to a power profile. The advantage with this is that the speed profile will always be correct *if* the system manages to deliver the calculated power. If the system can't deliver the required power this will show up as a complex battery (DC) current. Drawbacks are that it is impossible to compensate for disturbances that are unknown à priori. If the system is changed all the calculations have to be redone, which can be time consuming.

The latter method was chosen. The main reason was, that many parameters about the system were unknown but there existed measurements of tractive power from the municipal busses in Stockholm. The measurements gave a power profile directly without modelling. The drawback is that it is impossible to investigate how the system changes if for example the batteries are exchanged, since there is no model.

3.4 Complete Vehicle

A model of a complete vehicle was formed from the three described subsystems. The static model of the ICE & generator can be considered as a power source. Inputs to this power source are torque and speed, which are used in the lookup tables for efficiency and emissions. This is possible because of the inverter on the generator which allows full torque at all speeds. A model for the busses in Stockholm would have been more complicated. Similarly, the chosen bus model can also be described as a power source. The complete vehicle is now formed by connecting the three components. Since the battery is an electric component it makes sense to model the ICE and the bus as electric power sources. In a series hybrid the components are connected in parallel, which implies that the model of the power source is a controlled current source.

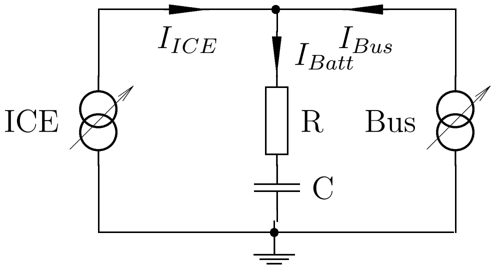

Figure 3.6 Electric model of a series hybrid vehicle.

The model described above is derived for a series hybrid. If the inputs to the bus are changed from power to torque and speed it is also valid for a parallel hybrid. Depending on how the ICE, generator and wheels are connected there will be some extra requirements on the system, for example that the speed of the ICE and the wheels must have a fixed ratio.

4

Selecting Performance Criteria

or

How to make Hybrids Better

The main reason for doing research on hybrid vehicles is to make them better than conventional vehicles. Unfortunately, "better" is in the eye of the beholder. When comparing different designs it is important to clearly state what to compare and why before the experiments are made. Making an adequate performance index is complicated because it will almost certainly end in comparing quantities that are not comparable on equal basis.

4.1 General Considerations

Several things have to be considered when selecting a performance index. Some of them belong to one category such as:

- operational costs,
- capital costs,
- environmental impact,

while other things can belong to several categories. Some factors are very hard to compare or put a price on like different kinds of noise, or if the vehicle behaves as a vehicle should behave, ease of handling.

Batteries or the energy storage is a vital part of a hybrid vehicle. They are initially a capital cost but will probably need replacement during the lifetime of the vehicle and can therefore also be considered as an operational cost. The lifetime of the battery is heavily dependent on how it is charged–discharged which in turn depends on the size and type of battery, size and treatment of the ICE and the power control strategy for the vehicle. The lifetime of batteries expressed in number of charge–discharge cycles can vary from several thousand cycles to less than hundred cycles. Batteries that are badly treated are thus likely to show up as a huge operational cost. The battery influences the environment in several ways, and in a hybrid vehicle it will help to reduce the emissions. On the other hand they often contain metals such as lead, nickel or cadmium which should be taken care of when the batteries are scrapped. The cost for this as well as mining of the metals are assumed included in the price of the batteries.

Emissions are today regarded as a fixed cost. The cost is included in the price of the ICE, as the ICE has to fulfil the legislations. Once the ICE has passed the typing tests it is free to be used in any vehicle. It is unlikely that this will persist and several different future scenarios are possible. One possibility is that the emissions may be subject to a charge depending on the amount of emissions per kilometre or hour. For a hybrid vehicle there will now be several possibilities to obtain low emission costs:

- By using a good (and expensive) ICE that produces low emissions in all driving conditions.
- By assuring that the ICE only will run at favourable operating points and perhaps optimise the ICE for these points.

There is a problem to describe emissions as a running cost. It is hard to verify the emissions during the whole lifetime of a vehicle, since it is unlikely that there will be emission measuring equipment onboard all vehicles. There might also be problems with assuring that the ICE always operates as intended. This is probably extra cumbersome for cars that have very different operating conditions (city, highway) compared to city busses.

Another difficulty with emissions is where they attain their minimal value. The controlled emissions today, hydrocarbons (HC), carbonoxide (CO) and nitric oxides don't attain their minimal values at the same operating point, and although these points are quite close to the maximal efficiency of the ICE they are not equal. The complexity of this problem will increase with the number of controlled emissions. The relative weighting between different components is also a problem, for example if NO_X is more dangerous than CO, but this is more a problem for the legislature

Start and especially cold start of an ICE suffers from poor emissions. The efficiency of a cold engine is also lower than for a warm one. It is possible to compensate for this by preheating the catalytic converter (if any) and the engine itself. However, the preheating consumes extra energy which has to be supplied by the onboard energy-storage. An operating strategy which has many starts and stops of the ICE should take this into account.

Maintenance should probably not be very different between different designs.

Fuel is naturally a running cost. The cost depends on type of fuel as well as the handling of the ICE. The emissions depend on both the type of fuel and the type of engine.

Genset The cost of the genset depends on the type of the components and their size. Once installed they are intended to remain with the vehicle for its whole lifetime.

Performance It is quite obvious that increased performance will increase the cost of the components. However, even if decreased performance will make the components cheaper, a bus might not be able to keep the timetable. Then the operator can choose between having a more sparse timetable, bye larger busses or to use more busses. A decrease in performance may thus require extra busses and drivers.

4.2 Discussion

A performance index can be formed by summing all the relevant costs over the lifetime of the vehicle. The big challenge is how to weight the different costs against each other. Is there an easy way to tell how the battery degrades depending on treatment? How is performance evaluated? How to compare efficiency with emissions? And how to quantify things such as driveability

The loss function that is used in the following chapters only considers energy losses, that is losses in the genset and the battery. The battery losses may also be considered as a form of battery treatment cost.

5

Control

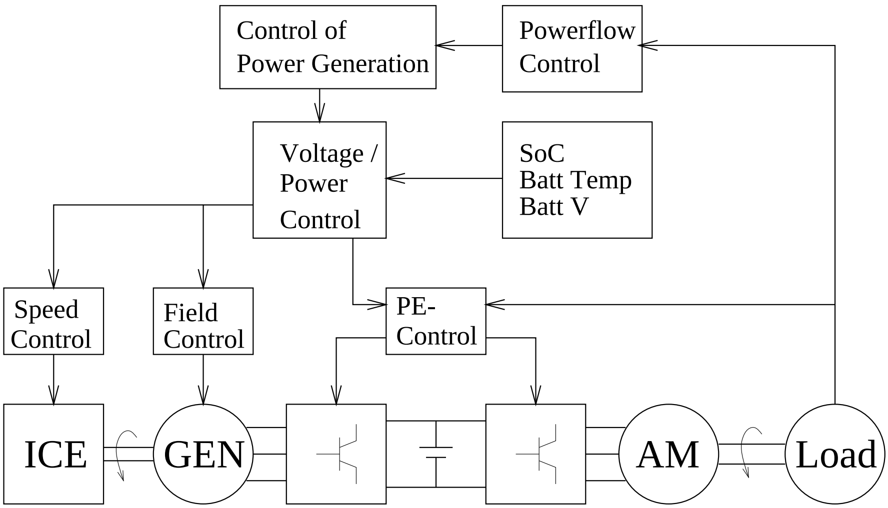

Figure 5.1 Layered control scheme for a series hybrid.

Control of a hybrid electric vehicle can be divided into several layers. From emission control of the ICE, via speed and torque control of the machines to power planning and supervision of the drive train. On the lowest level there are systems for emission control and speed control of the ICE. There are also field and stator current controllers for the generator and the traction motors. These parts of the control system are often embedded and hard to change unless they are developed in-house.

On the middle level there are controllers for ICE-generator torque and vehicle speed, here called voltage/power control. This level also contains overvoltage and temperature protection.

The main objective with the power planning is to assure that there will always be power and energy[1] available, and to minimise the operational costs. This is done by controlling the setpoints of the ICE, generator and traction inverter. The middle layer is the tool to accomplish smooth transition between the different operating points required by the powerflow controller. This chapter will only deal with the powerflow control.

5.1 Powerflow Control –General Solutions

When trying to minimise the running costs it makes sense to find the absolute minimum, given a loss function and a driving cycle. Even if it is impossible to implement this strategy it is useful to know the minimum for comparisons.

There exist many ideas on how to realise powerflow control. The ideas are closely connected to what kind of vehicle that is under consideration and its intended use. Some things that affect the control are:

- Emission free driving or acceleration support,
- Size of car, city use or all-round use,
- Autonomous operation or not,
- City-bus, distribution truck compared to cars,
- Type of hybrid, series, parallel or series–parallel,

Acceleration support with minimal losses is treated in [Sweet and Anhalt, 1978]. On-off operation is discussed in [Burke, 1993], [Hochgraf et al., 1996] and [Pelkmans et al., 1997]. The strategies used in [Wallentowitz and Ludes, 1994] and [Mazzucchelli et al., 1998] do not explicitly state what they are trying to achieve. A comparison between different strategies is found in [Mierlo et al., 1998].

5.2 Powerflow Control Based on Optimization

Powerflow control based on optimization is found in [Vollmer et al., 1998], [Seiler and Schröder, 1998], and [Zoelch and Schröder, 1997]. All of these deal with integrated drivetrain and powerflow control.

[1] Energy is only for emission free driving.

The theory of optimal control offers a way to investigate the system and its sensitivity to parameter variations in the loss function in a systematic way.

Consider a loss function that describes the power losses

$$L(T,\omega,t) = \underbrace{P_{mech} \cdot \frac{1-\eta_{ICE}(T,\omega)}{\eta_{ICE}(T,\omega)}}_{\text{ICE losses}} + \underbrace{P_{mech} \cdot (1-\eta_{Gen}(T,\omega))}_{\text{generator losses}} + \rho(\mathbf{X}) \underbrace{R\, I_{Batt}^2}_{\substack{\text{battery}\\ \text{losses}}} \tag{5.1}$$

where $P_{mech} = P_{mech}(t) = T(t) \cdot \omega(t)$ is mechanical power on the shaft, η_{ICE} denotes the ICE efficiency from chemical energy to mechanical energy, η_{Gen} is generator and inverter efficiency from mechanical to electrical power and ρ is a weighting factor between battery losses and genset losses. It makes sense to make ρ dependent on a number of parameters $\rho = \rho(\mathbf{X})$, in this way it is possible to incorporate extra information about battery treatment. One example is that some batteries can not be charged and discharged with the same power. By making ρ large for positive currents and small for negative currents this behaviour is captured in the loss function.

To be able to apply this loss function to the model derived in Chapter 3 the battery current has to be known. The power into the battery in Figure 5.2 is:

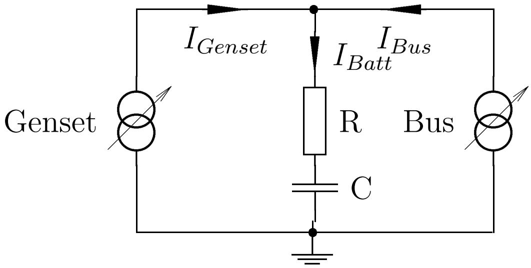

Figure 5.2 Electric model of a series hybrid.

$$\begin{aligned} P_{Batt}(t) &= P_{Gen}(t) + P_{Bus(t)} \\ &= U_{Batt}(t)\, I_{Batt}(t) \\ &= R\, I_{Batt}^2(t) + U_0\, I_{Batt}(t) + \frac{I_{Batt}(t)}{C} \int_0^t I_{Batt}(\tau)\, d\tau \end{aligned} \tag{5.2}$$

where U_0 is the initial capacitor voltage, or more conveniently expressed in state space form

$$\dot{Q} = I_{Batt} \tag{5.3}$$

$$\dot{Q} = -\frac{1}{2\,R}\left\{U_0 + \frac{Q}{C} - \sqrt{\left(U_0 + \frac{Q}{C}\right)^2 + 4\,R\,P_{Batt}}\right\} \tag{5.4}$$

We want to minimise the loss over one driving cycle,

$$W = \int_{t_{start}}^{t_{final}} L(T, \omega, \tau)\, d\tau \tag{5.5}$$

which can be interpreted as the total energy loss over the driving cycle. In order to be able to compare different loss functions and to make autonomous operation (no charging from the mains) possible, the net charge on the battery must be zero at the end of the driving cycle. Another possibility is to discharge the batteries by a small amount for each trip so that they are almost empty at the end of the day and then charged from the mains during the night. This will probably affect the control as the battery losses increase when the battery is being discharged. The optimisation should then be performed over the whole day which is computationally impossible today.

The condition for autonomous operation can be written as

$$Q(t_{start}) = Q(t_{final}) \tag{5.6}$$

There are also constraints on the inputs

$$0 \leq T \leq T_{max} \tag{5.7}$$

$$0 \leq \omega \leq \omega_{max} \tag{5.8}$$

Additional constraints can be added, for example on emissions.

$$\int_{t_{start}}^{t_{final}} HC(T, \omega)\, d\tau \leq HC_{max} \tag{5.9}$$

Minimising the loss thus requires us to determine T and ω as functions of time, an infinite dimensional problem. This problem is too complicated to be solved analytically since it is both nonlinear and time-varying, but it can be solved numerically. The resulting T and ω are then not functions but time-series. A classic reference on optimal control is [Bryson and Ho, 1975]. The most common methods to solve this today are to discretisize the controlled variables (T, ω) or to use splines. It should be noted that the different values of T and ω are not independent. Instead, a change in one time step will influence the variables in all the other steps. Some software packages for solving optimal control problems are: RIOTS (Recursive Integration Optimal Trajectory Solver) by [Shwartz, 1996], DIRCOL (Direct Collocation method) by [von Stryk, 1997] and PAREST (Parameter Estimation) by [Heim, 1996]

5.3 Results

The loss function (Equation 5.1) was tried with different values on ρ, with and without limits on the total amount of HC emissions during one driving cycle. Some of the results are seen in table 5.1 and Figures 5.3 and 5.4.

To reduce the complexity of the calculations and to avoid chattering in the power reference to the genset, the time-axis was divided into blocks of five to ten seconds, making the problem finite dimensional. It is however still a large problem. The driving cycle is 1250s long with 10s long blocks which gives 250 variables to determine. Depending on model parameters, computer and accuracy this has taken from eight hours to 15 min. Because of the discrete behaviour of the signals it will be impossible for the genset to follow them. A not too short discretization step will assure that the genset reaches the reference within that step and is able to stay there for some time before it is time to change operating point.

	no HC constraints			HC constraints		
	$\rho = 0$	$\rho = 1$	$\rho = 50$	$\rho = 0$	$\rho = 1$	$\rho = 50$
Fuel Consumption (l)	3.85	3.84	3.86	3.94	3.93	3.93
loss function W/10^7	9.76	9.95	18.35	10.03	10.25	21.74
Genset losses (kWh)	27.12	27.11	27.34	27.87	27.82	27.81
Battery losses (kWh)	0.565	0.525	0.472	0.626	0.658	0.651
HC emissions (g)	54.1	52.9	49.7	45.0	45.0	45.0

Table 5.1 Comparison between different values of ρ when the loss function (5.1) is used.

Interpretation of the Results

From the Figures 5.3 and 5.4 it can be seen that the genset power should follow the tractive power as close as possible but not be below 20 kW ($\rho = 1$). This is because the efficiency of the ICE drops quickly when the power is

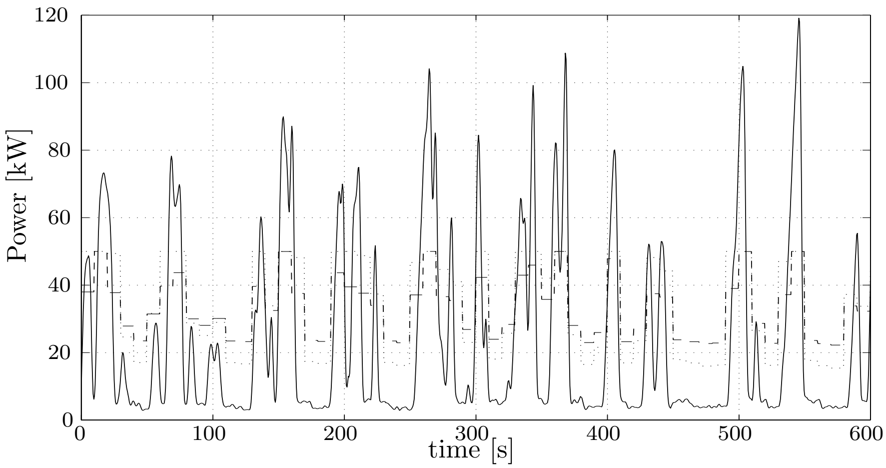

Figure 5.3 ICE power for two different values of ρ, $\rho = 1$ (dashed) and $\rho = 50$ (dotted). The solid line is tractive power.

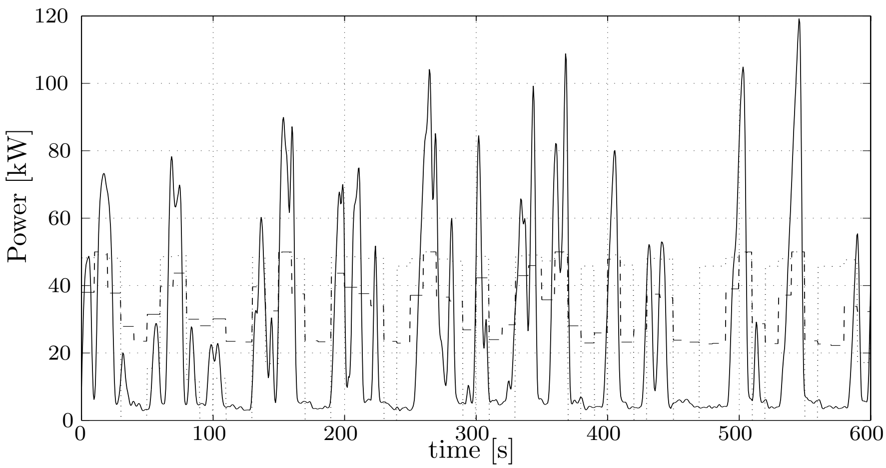

Figure 5.4 ICE power without limitation on HC emissions (dashed) and HC emissions reduced with 15% (dotted), $\rho = 1$. The solid line is tractive power.

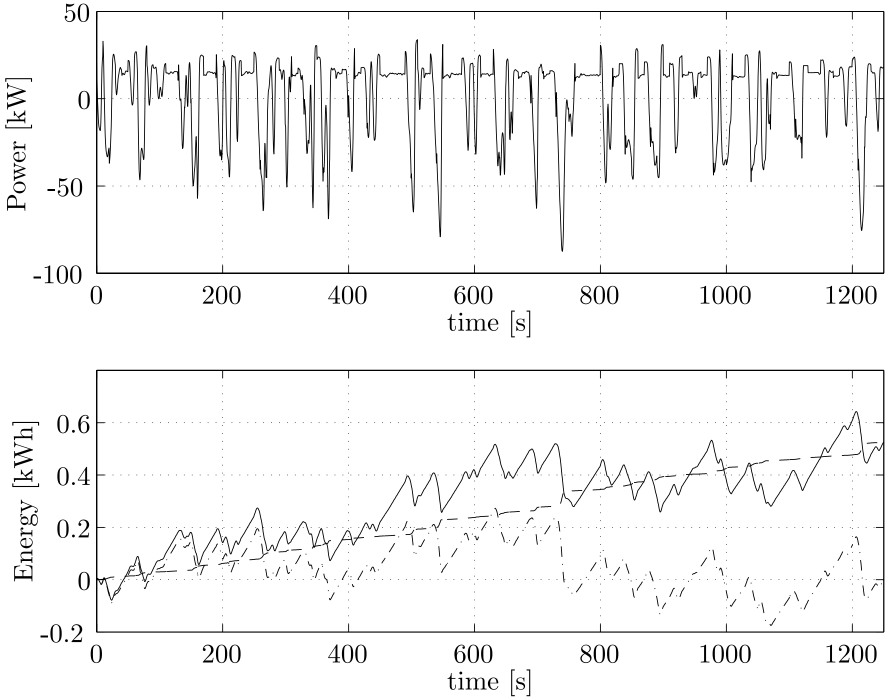

Figure 5.5 Battery power (top), positive power means charging. Battery energy (bottom),total battery energy (solid), loss energy (dashed) and chemical energy (dashdotted).

less than 20 kW. For 20 kW and upwards it is always possible to obtain an efficiency above 30%. This is achieved because of the inverter on the generator which makes torque and speed independent of each other and independent of the battery voltage.

The conclusion is that as long as the ICE efficiency is good enough and approximately constant, it is no use to charge or discharge the batteries because of the extra energy losses that will be caused. In Table 5.1 it is seen that a decrease in emissions is followed by an increase in fuel consumption.

From Figures 5.5 and 5.6 one can draw the conclusion that the battery only provides power support when the vehicle operates in hybrid mode. The energy stored in the battery is thus only needed *if* emission-free driving

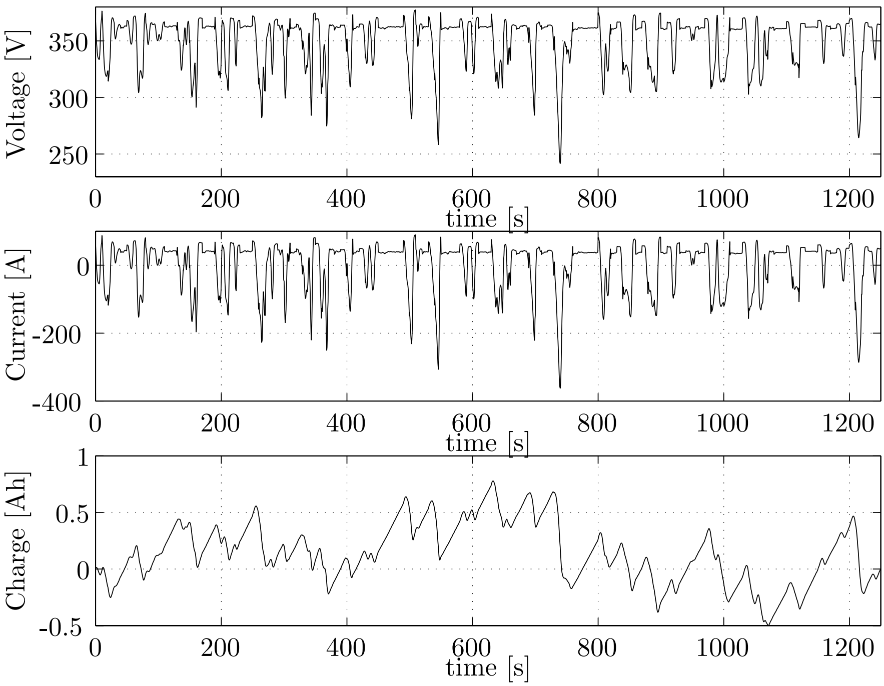

Figure 5.6 Battery voltage (top), battery current (middle) positive current means charging and battery charge (bottom).

is required. With the batteries that are available today specific power and energy go more or less hand in hand so that high power batteries also contain a lot of energy. Alternative storages such as flywheels or ultracapacitors can therefore be of interest for pure hybrids, where energy is not an issue.

5.4 Implemented Controller

Implementing the results from the previous section is not an easy task. This is because the result from the optimisation is open loop control and is thus only valid for the driving cycle that was used for the optimization. A feedback controller is necessary to compensate for disturbances. There are methods, like receding horizon, to find some sort of feedback controller but they are computationally heavy. Solving for the optimal return function (the feedback controller) is probably impossible in this case.

Another idea is to train a neural network to mimic the behaviour of the optimal controller. As always with neural networks there are a number of parameters that have to be chosen ad hoc, like number of hidden neurons, number of input neurons, training algorithm etc. Because of these limitations, it was decided not to use the neural networks.

The implemented controller is a low-pass filter with alarms, where the input to the filter is the drive-system power via a limiter. Pseudo code for the implemented controller is seen in Listing 5.1. As the alarms restarts the filter this means that the filter does not have a fixed time constant. The idea with the alarms is that when the cumulated error between input and output of the filter has become sufficiently large, the filter is restarted. In order to limit the number of alarms the error has to be larger than the normal drift or noise level of the signal, which is defined by the parameter ν. Since it is the size of the cumulated error that determines the alarm there is no fixed alarm time. A large error will give a short alarm time while a small error

Listing 5.1 Pseudo code for the implemented controller. u_k is the input and θ_k is the output, ν_i are drift parameters and h_i are alarm levels.

ε_k	$=$	$u_k - \theta_{k-1}$	% prediction error
g_k^1	$=$	$\max(g_{k-1}^1 + \varepsilon_k - \nu_1, 0)$	% update cumulated error if $\varepsilon > \nu$
g_k^2	$=$	$\max(g_{k-1}^2 - \varepsilon_k - \nu_2, 0)$	
if $(g_k^1 > h_1$ **or** $g_k^2 > h_2)$ **then**			% alarm
$g_k^1 = 0$			% reset cumulated error
$g_k^2 = 0$			% and
$\theta_k = u_k$			% restart filter at input value
else			
$\theta_k = \lambda\,\theta_{k-1} + (1-\lambda)u_k$			
end			

$\lambda \in [0, 1]$
$\nu_i > 0, \quad h_i > 0$

will give a long alarm time. These times are crucially dependent on the drift (ν) and alarm (h) levels.

Fuel Consumption (l)	4.08
loss function $W/10^7$	10.58
Genset losses (kWh)	28.88
Battery losses (kWh)	0.508
HC emissions (g)	52.7

Table 5.2 Values for one of the implemented controllers. When this controller was tried on the model it resulted in a charge of 1.46 Ah, corresponding to 0.5 kWh at the end of the driving cycle. The energy content (heating value) of one litre of gasoline is 9.4 kWh.

Improvements

- The controller described above does not take the state of the battery into account, which can result in a completely discharged battery. This is easiest compensated for by adding an offset, that depends on battery state, to the output of the controller.
- Power to the drive system is input to the controller. This signal is often rate limited, so when this signal is low-pass filtered it will lag the desired output even more. Feed-forward from the accelerator should improve the behaviour.
- Busses in some cities are equipped with a system that informs the passengers on where they are, which stop is next etc. It would be beneficial if signals from this system could be used by the controller, like knowing “it is going to be uphill very soon, I will need a lot of power”.

6

Experimental Setup

Hofstadter's Law:

> *It always takes longer than you expect, even when you take Hofstadter's Law into account*

The laboratory setup is intended to mimic one of the hybrid busses in Stockholm. The ICE and the generator are the same as in the busses. The main difference is that the generator in the lab is equipped with a self commutated inverter whereas the generators in the busses are equipped with diode rectifiers. The drive system of the bus is replaced with a thyristor inverter which is connected to the grid. This setup allows us to mimic the power consumption of the busses, even regenerative braking, without the trouble of having a complete drive system with braking machines or eddy current brakes.

6.1 Components

ICE

The ICE is a SAAB 2.3 litres normally aspirated four cylinder four stroke gasoline-engine from 1992 with a peak efficiency of about 32%. It is equipped with standard ignition and emission control and a catalytic converter. It is further equipped with a speed governor. Extra measurement sensors are: lambda sensor, fuel measurement, inlet pressure and thermocouples. Exhaust emissions have been measured for a number of operating points and are normally not measured during the experiments .

The speed governor is made by Heinzmann and is some kind of standard governor, probably of PID type. It has been hard to tune this governor

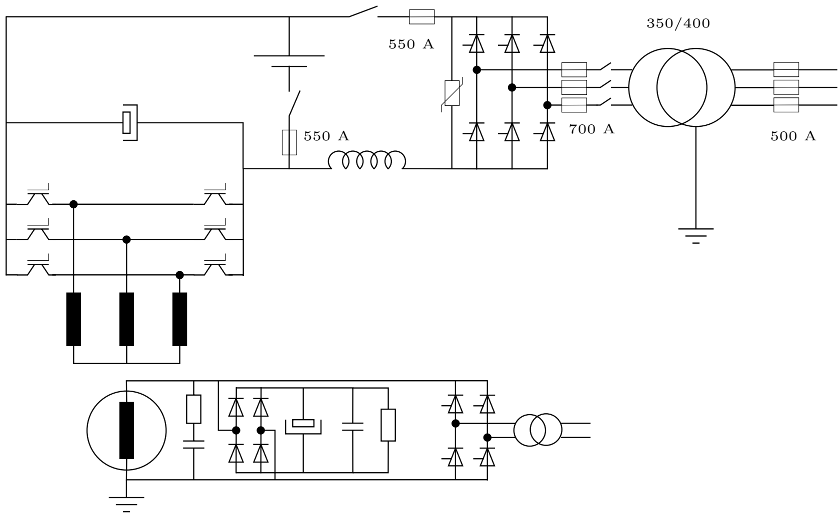

Figure 6.1 Schematic of the electrical layout in the lab. The fuses to the left of the transformer are fast thyristor fuses. The fuses to the right of the transformer are ordinary fuses.

to work satisfactory in all speed ranges. This is probably due to that the governor is originally intended for constant speed operation. The reason for using this governor is that it is used in the busses.

The lambda sensor is of wide band type, and is only used for the measurement system to assure that the ICE control system is working correctly.

Fuel consumption is measured with a Flowtronic 206 which measures volumetric flow. Outputs from the signal conditioner are volumetric flow and total consumption.

The following temperatures are measured with thermocouples: oil, water, gasoline, inlet and exhaust.

Generator & Power Electronics

The Generator is a synchronous generator made by EME, is rated 40 kVA at 3500 rpm and is a multi-pole 400 Hz machine. The generator was originally equipped with a rotating exciter. This is a good and robust construction which is well suited for the harsh environment in the busses. But since the exciter is designed to work at nominal speed it does not fit our purpose to

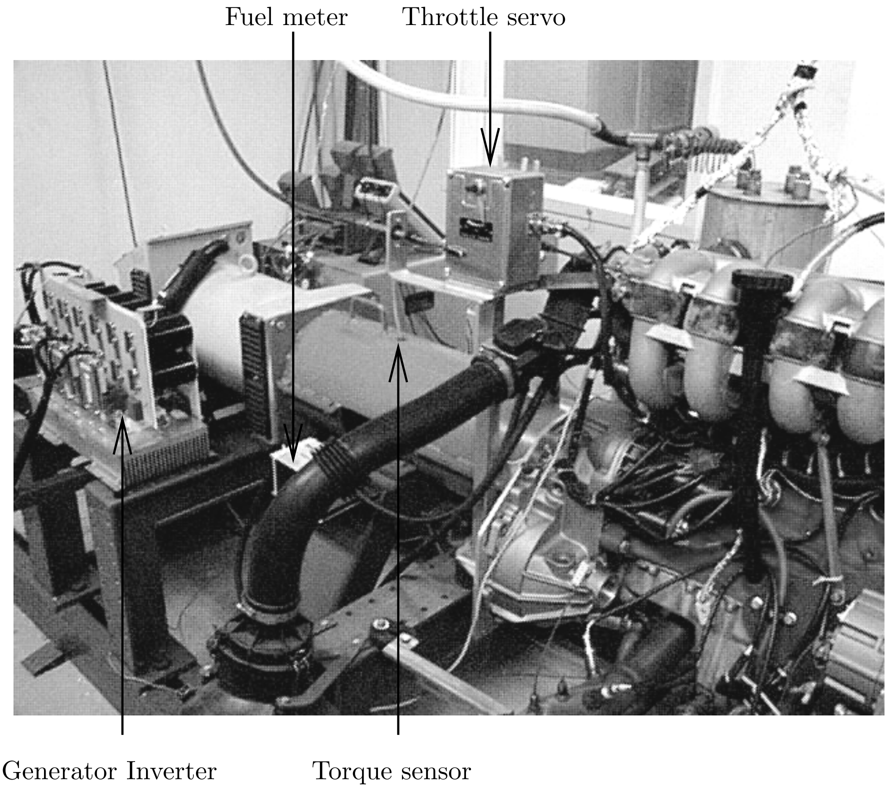

Figure 6.2 Genset part of the lab, the batteries are behind the wall.

run at low speed and high torque, thus the generator has been converted to be excited by sliprings. After this conversion it was noted that one side of the rotor-winding was in some way connected to the housing of the generator. This is the reason why there is a transformer between the mains and the field inverter. The field inverter is a thyristor inverter that has current as lead-value.

The converter is an IGBT converter made by Semikron. It has two parallel modules of type `SKM 150 GB 122D` in each leg, each module is rated 150 A at 85° C.

The power electronics control is designed and built at the Department and based on the ideas from [Alaküla, 1993]. It provides control for current in the d and q axes. There is no resolver on the generator, instead rotor position is estimated in the power electronics control.

Battery

The Battery pack consists of 270 cells of type L 306-2 from SAFT-NIFE. This is a wet cell of open type. It is unfortunately not the same type of cells as in the busses. The cells in the lab have a greater capacity than those in the bus but are not intended for traction purposes.

The Batteries are located in a room adjacent to the ICE and the generator. There are two other ICEs, which are mainly used for education, in this room too. The room is very well ventilated and the temperature has never been above 30° C during the tests.

Thyristor Inverter & Transformer

The inverter is a four quadrant inverter type 590/4 made by Eurotherm Drives. It is rated 450 A continuously and 900 A peak during a few seconds. The continuous rating is perhaps a little bit too low but the large powers that requires large currents have a duration of typically 10 seconds.

The transformer has a ratio of approximately one and is inserted to make the whole system floating with respect to ground. This will also prevent some circulating earth-currents which can cause very confusing measurements.

Between the inverter and the batteries there are some choking coils. This is to make it possible to connect the batteries to the grid as the batteries and the grid always have different voltages. These coils are not needed in the real bus.

6.2 Measurements

A large and widespread setup like this offers excellent measurement problems. The large number of components and equipment makes it hard to do correct grounding and shielding. Sorting most things out was a great challenge. More than one time it was discovered that the whole system was grounded via the ethernet or the computer I/O cables.

A VME-bus based computer is used for measurement and control. It is supplied with a real time kernel developed at the Department of Automatic Control, LTH. This computer is equipped with two I/O cards providing 16 inputs and 8 outputs. The I/O cards are connected to an external I/O interface. This interface provides galvanic isolation and anti-alias filtering. Additional signal processing is carried out in the VME-computer and all the measured values, as well as setpoint values are sent over the ethernet

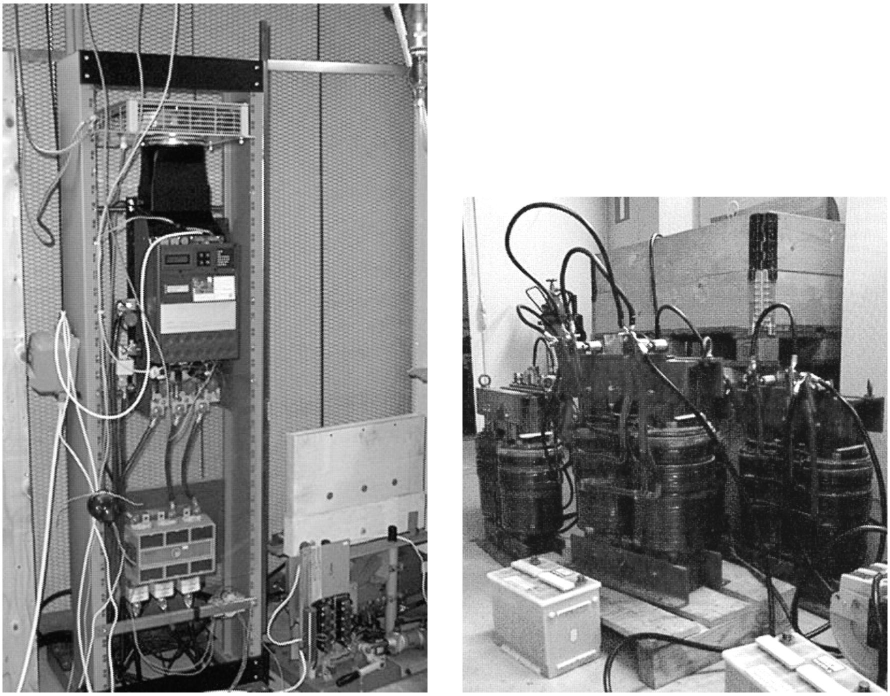

Figure 6.3 "Bus" inverter with DC contactor (left). The choke coils that makes it possible to connect the batteries to the "bus" inverter (right).

directly to a UNIX workstation. On the workstation the measurements are fed directly to a MATLAB session for visualisation and analysis (Figures 6.5 and 6.6). MATLAB is also used to download the drive cycles.

Temperature

Temperatures are measured with thermocouples. The low output from the thermocouples together with the large voltage and current derivatives caused by the generator inverter give rise to big noise problems. The signals from the thermocouples are first amplified in instrumentation amplifiers. This removes a lot of the common mode noise. After this the signals are low pass filtered. The amplifiers are placed as close to the thermocouples as possible.

In the beginning of the project it was noticed that the thyristor inverter caused some very strange errors on the temperature measurements.

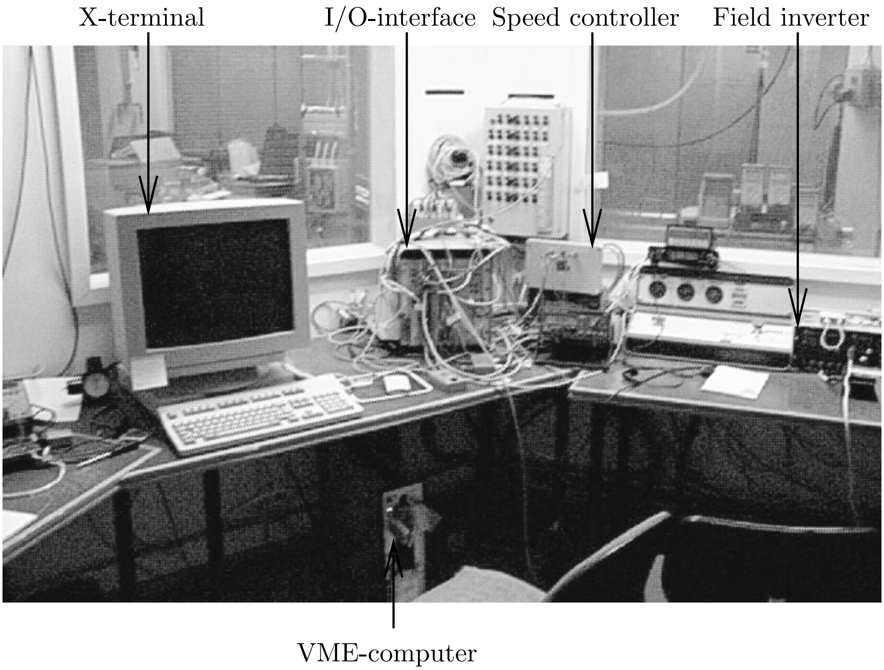

Figure 6.4 Control room

As seen in Figure 6.7 the noise seems to be "single sided". The noise was probably caused by circulating earth-currents. The strange thing was that the thyristor inverter only had to be connected to the grid, with the noise being independent of the current. The problem disappeared when the transformer between the mains and the thyristor inverter was inserted.

Battery Voltage, Current & Power

Measuring current and voltage at high frequencies is a non-trivial task, especially when there is a need for galvanic isolation. The equipment for these measurements were developed as a part of a master thesis [Palm and Östergren, 1996] and is capable of measuring voltage and current up to several tens of kHz.

The battery voltage is galvanicly isolated from the measurement system via a linear opto-coupler (CNR 200 from Hewlett-Packard). This opto-coupler has a very high bandwidth, while the bandwidth of the voltage meter is limited to 80 kHz.

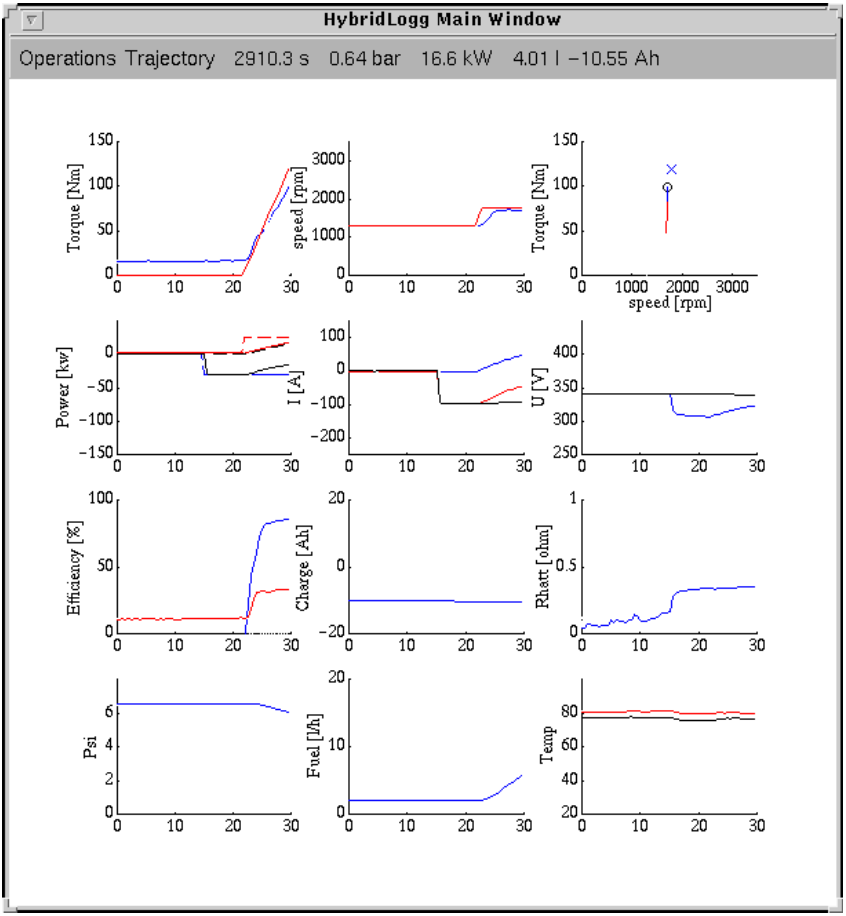

Figure 6.5 Screenshot of measurement visualization in Matlab.

The currents from the generator inverter to the battery and the current to the thyristor inverter are measured with LEM-modules and thus also galvanicly isolated. These modules are quite fast and have a bandwidth of a few kHz. If the bandwidth of these modules is too low it is possible to use shunts instead. Isolation is achieved with the same optocoupler as for the voltage measurements.

Electric power is calculated by multiplying the instantaneous values of voltage and current in an analog multiplier. This signal is later lowpass filtered.

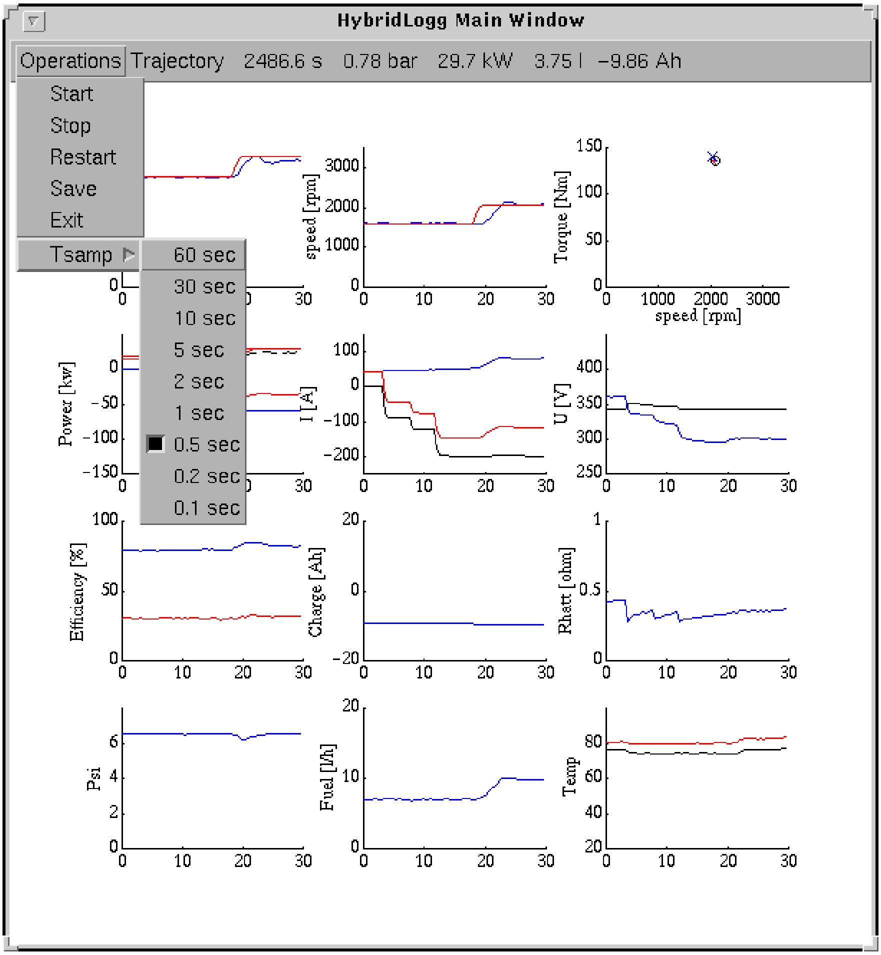

Figure 6.6 The graphical user interface.

Speed & Torque

The speed signal is taken from the speed governor. The signal is a pulse-train with varying amplitude and frequency, and where the engine speed in rpm corresponds to the signal frequency in Hz. The signal is created by a cog wheel and an inductive sensor. This signal is fed to a frequency-to-voltage converter and then fed to the measurement system. Torque is measured by

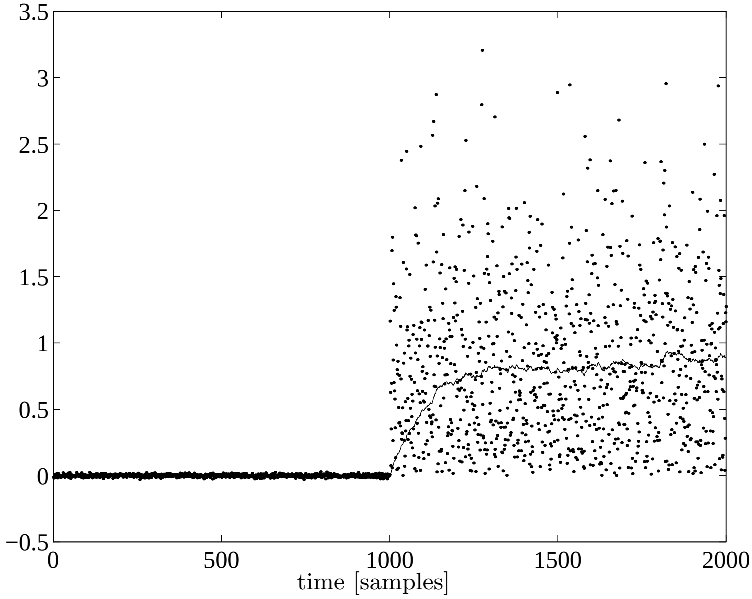

Figure 6.7 A typical measurement signal subject to noise, before corrective actions had been made. Power electronics are turned on at t=1000. The solid line is a low-pass filtered version of the signal.

a torque transducer made by Vibrometer. The transducer is mounted on the axle between the generator and the ICE and has a range from -500 to 500 Nm. A carrier frequency amplifier, HBM MVD 2555, is connected to the transducer. This amplifier has built-in filtering capabilities.

6.3 Disturbances

IGBT inverter

Some disturbances have already been discussed but the largest disturbance came from the IGBT inverter. The disturbances from this inverter didn't affect the measurements as much as it affected its own control. When first used the mean time between failure (MTBF) was approximately 10 s, the failure was that one or several phases tripped. Various shielding of the power cables were tried but any increase in MTBF was not noticeable. A closer investigation of the data sheets for the IGBT driver showed that the driver trips not only if both transistors in a leg are turned on, but also if the supply voltage falls below 13 V from nominally 15 V. The driver consumes maximum 160 mA. This together with long and thin wires might have been the source of the problem.

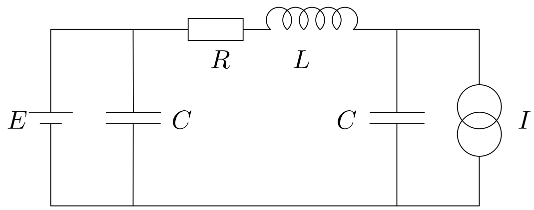

Figure 6.8 Model of flatcable. E supply voltage, I IGBT driver.

C	$46\ pF$
L	$2.64\ \mu H$
R	$0.1\ \Omega$

Table 6.1 Parameter values for the flatcable.

The wire is modelled as in Figure 6.8 with parameter values taken from ordinary flatcable. The current source symbolises the IGBT driver. The impedance as seen from the driver is

$$Z(s) = \frac{s\,L + R}{s^2\,LC + s\,RC + 1} \tag{6.1}$$

As seen in the Bode diagram, Figure 6.9, and in the step response, Figure 6.10 (top), it is sufficient with a current step of 10 mA to make the supply voltage lower than 13 V. This undesired behaviour was compensated for by inserting a 10 μF capacitor between the supply voltage and ground at the driver end of the wire.

To make the control signal wires more noise insensitive a kind of low-pass filter (Figure 6.11) was added to the wire. The idea with this filter is to low-pass filter the signal so that the energy of "bouncing" signals should be dissipated in the resistors. The values were chosen to give a rise time of 1 μs, $R_l = R_f = 100\ \Omega$ and $C_f = 1$ nF. That this compensation was successful is seen in Figures 6.13 and 6.14.

As an extra precaution the blanking time was increased from 2.8 μs to 5 μs. These changes to the system made it work very well and it is now quite rare that the phases trip.

Field inverter

Another thing that was severely affected by the IGBT inverter was the field inverter. In a synchronous generator there is a strong magnetic coupling

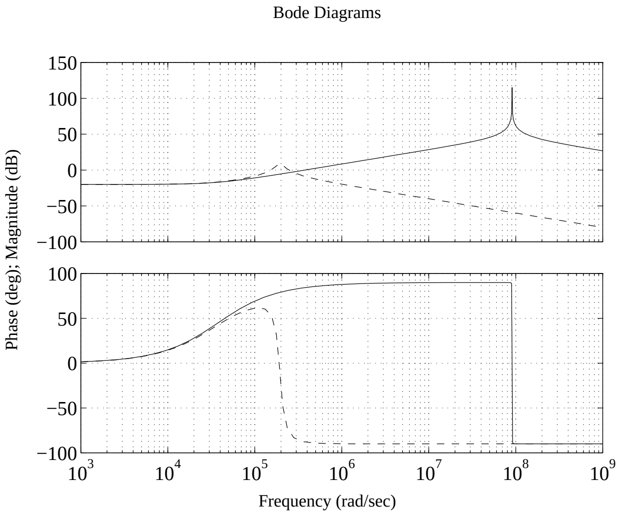

Figure 6.9 Bode diagram for $Z(i\omega)$ (equation 6.1), uncompensated wire (solid), and compensated with 10 μF (dashed).

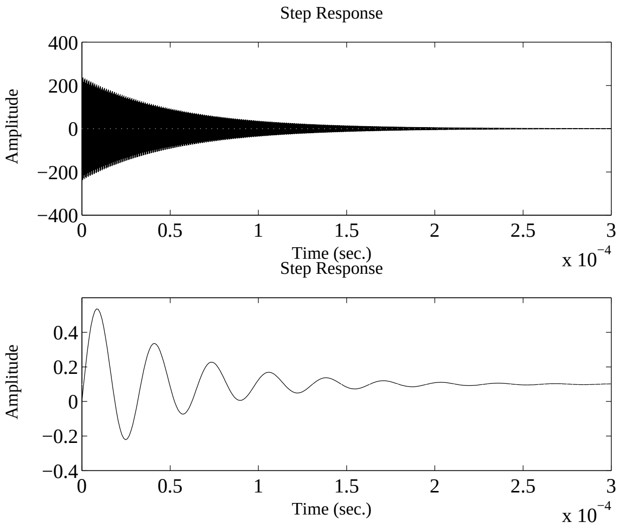

Figure 6.10 Voltage at the IGBT driver caused by a 1 A step. Uncompensated wire (top) and compensated with 10 μF (bottom).

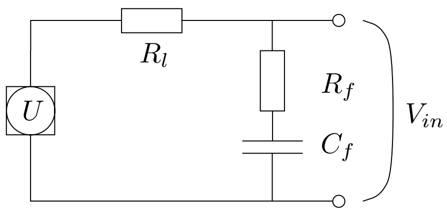

Figure 6.11 The low-pass filter for the signal wire.

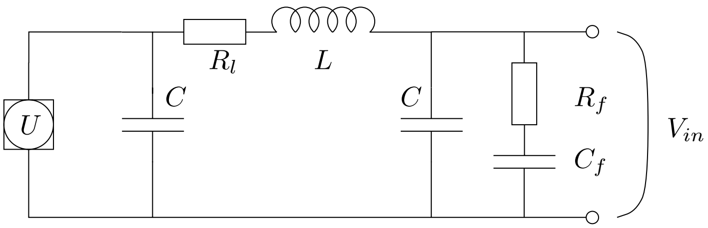

Figure 6.12 Wire with low-pass filter.

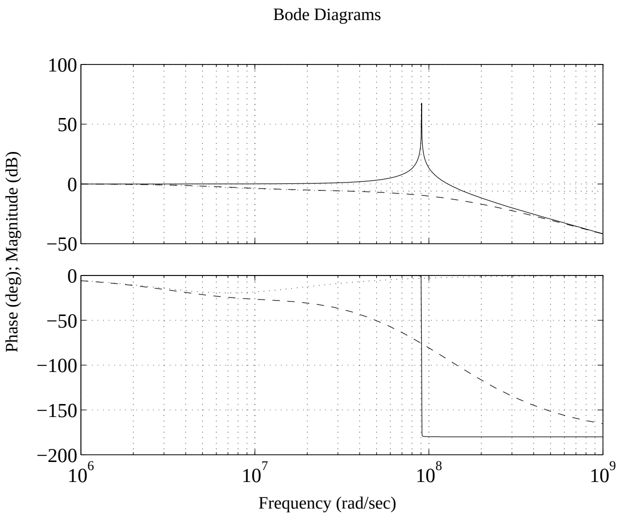

Figure 6.13 Bode-diagram for $V_{in}(s)$. Uncompensated wire (solid), low-pass filter (dotted),wire with filter (dashed).

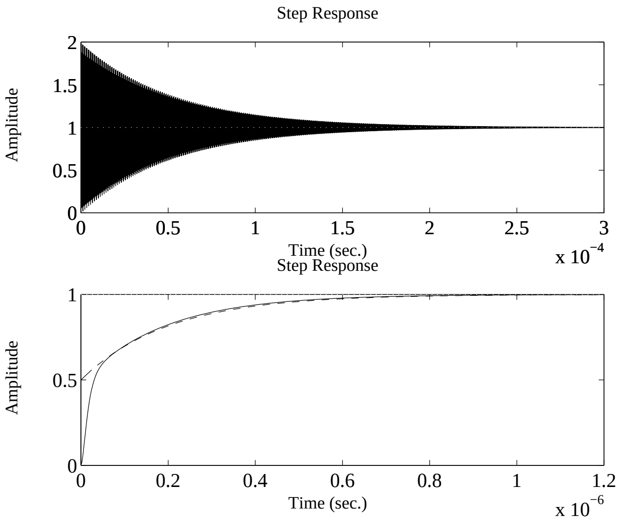

Figure 6.14 Step-response of $V_{in}(s)$, top, uncompensated wire, bottom, low-pass filter (dashed) and wire with filter (solid). Notice the different time scales.

between the stator-winding and the rotor-winding. The ratio between the windings is also quite high. In normal operation, the stator current rotates with the same frequency as the rotor, thus the rotor only sees a constant magnetic flux. In an inverter fed machine however, there is always a ripple current which is not synchronous with the rotor. The high frequency of this ripple current together with the strong magnetic coupling caused over-voltage at the field inverter. This is why the "snubber" is used on the field inverter in Figure 6.1.

6.4 Control

Control of the individual components ICE, generator and "bus" are described in this section. It does not deal with the calculation of the ICE reference power, P^*_{ICE} in Figure 6.15.

ICE & generator

The main objective for the ICE and generator control is to keep the genset at a specified operating point regardless of what the traction system does with the

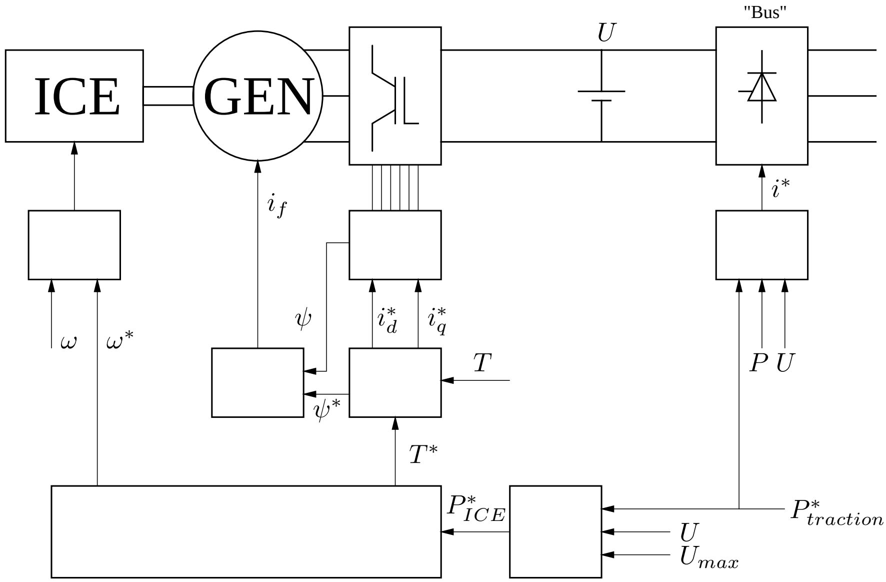

Figure 6.15 The controllers in the system. Stared symbols * denotes setpoint values.

battery voltage. A secondary objective is to prevent battery overvoltage. In the case of regenerative braking, the overvoltage protection has to be shared between the ICE control and the traction control. In this case however it is purely a matter for the ICE control.

The idea with having a self commutated inverter on the generator is that it should be easy to control torque and speed independently of each other. This is easy to do when the peak voltage of the generator is lower than the battery voltage. Control of the generator takes place in a stator reference frame. For this case we have the relation:

$$i_s = \frac{T}{\psi_s} \tag{6.2}$$

where T is torque, i_s is stator current and ψ is the flux linkage. The flux linkage is given by

$$\frac{d\bar{\psi}}{dt} = \bar{u}_s - R_s \bar{\imath}_s \tag{6.3}$$

Flux linkage estimation is done in the power electronics control, and has not been of any concern in his work. By choosing $I_d \equiv 0$ and controlling the flux linkage with the field current, a torque controller that only depends on i_q is obtained. This controller can have unity power factor. i_q is controlled with a PI controller that has torque as lead-value. The flux control is slow compared to the current control but not slower than the speed control of the ICE. Control principles of synchronous machines and flux estimation techniques can be found in [Alaküla, 1993].

When the battery voltage falls below the peak voltage of the generator the inverter will start to act as a diode rectifier. This will typically happen when the bus consumes a lot of power, thereby lowering the battery voltage, and the ICE is running at a high speed in order to produce as much power as possible. The only way to affect the torque now is to change the flux linkage with I_d or the field current. The strategy in this case is to turn off the integral action of the I_q controller and limit the field current. The bus power and ICE power will not be decoupled but overload of the ICE and generator is avoided. When the battery voltage has increased above the generator voltage there will be a smooth transition back to normal operation and the integral action of the I_q controller will be turned on again.

Flux

The flux linkage is controlled by a PI controller, providing current setpoint to a thyristor inverter. Inputs to the controller are setpoint and flux linkage given by Equation 6.3. The estimated flux is heavily filtered, cutoff frequency 1 Hz, before it is fed to the controller. This is to prevent tripping of the IGBTs. When the flux was not as heavily filtered it was quite common that one of the phases in the IGBT inverter tripped due to large voltage derivatives caused by fluctuations in the flux linkage.

"Bus"

The bus is simulated by a thyristor inverter. The inverter has its own current control so the control system only has to provide a current setpoint, which is obtained as:

$$i^* = \frac{P_{traction}}{U_{batt}}$$

Problems

The ICE has its best efficiency when the throttle is fully opened. Due to oscillations (Figure 6.16) it has however been impossible to run at these

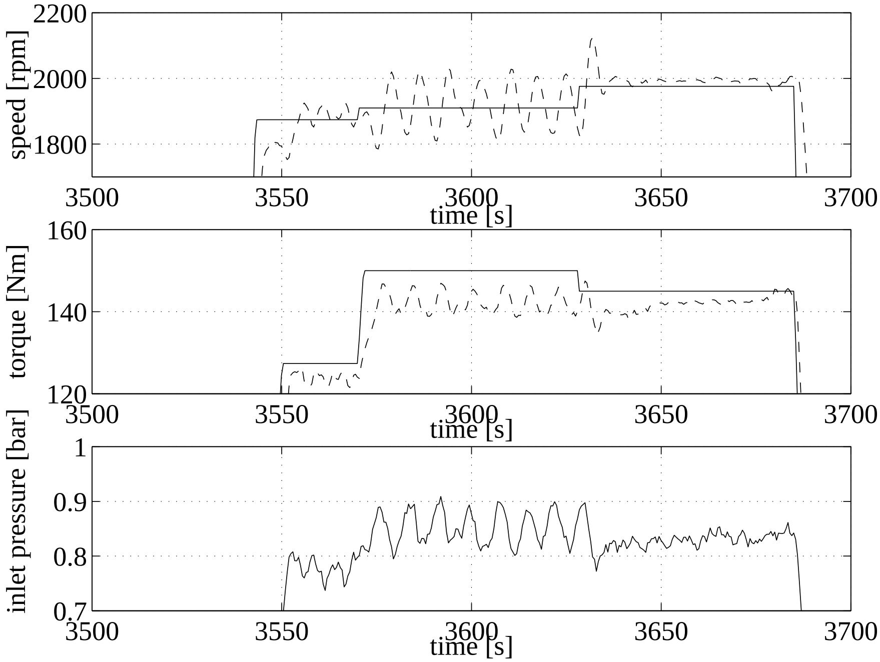

Figure 6.16 Speed and torque oscillations. Solid line is setpoint value in the two upper graphs.

points. The oscillations are probably due to interaction between the speed and torque controllers. The oscillations are probably excited by the fact that when the throttle is fully open, control is lost in one direction.

7

Experiments

This chapter is divided into two parts. In the first part the experimental setup is verified. The second part describes the experiments that were carried out to verify the powerflow control strategy.

7.1 Verification

Load Decoupling

The first and most important feature to verify was the decoupling between mechanical power and tractive power. The fact that this can be achieved for moderate tractive powers is proven in Figures 7.1 and 7.3(e-h). The relatively larger deviation in the error of mechanic power compared to error in tractive power is due to the fact that the tractive power is much faster than the mechanical power. Tractive power settles in about 10 ms whereas the sampling frequency in this example is 2 Hz.

Trajectory Following

The next thing to verify was the possibility to move the ICE between different operating points in a well–behaved way. The difficulties associated with this depends mainly on the required bandwidth of the control system. The problem is addressed in [Bunker et al., 1997], but whereas their goal is to obtain high bandwidth for dynamic testing, the goal here is to slowly move between the operating points.

To simplify the control and tuning, the cross-couplings between ICE and generator were neglected. The resulting system has a speed governor operating on the ICE throttle and a torque controller on the generator. The coupling between speed and torque is seen in Figure 7.3(a-d). At 25s there is a

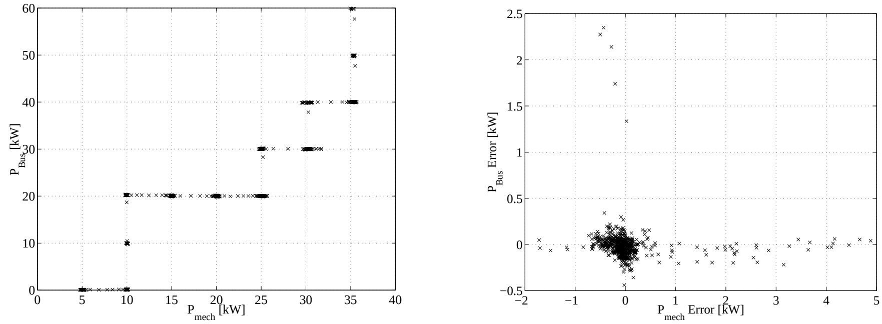

Figure 7.1 Tractive power vs ICE power (left). Error ($P_{ref} - P$) in tractive power vs error in ICE power (right). The powers and errors as function of time are depicted in Figure 7.3.

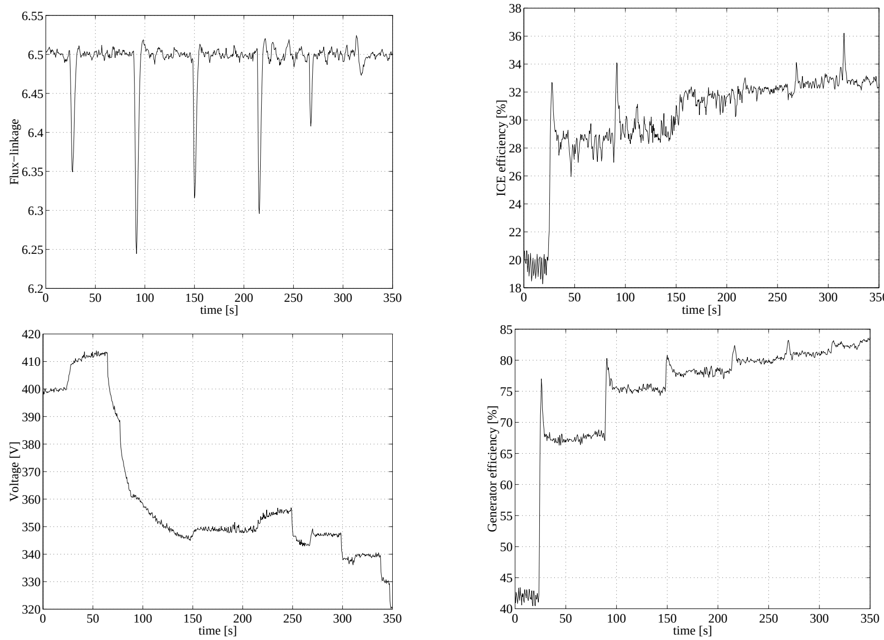

Figure 7.2 Flux-linkage and battery voltage (left), ICE efficiency (top right) and generator plus inverter efficiency (bottom right). The overshoots in generator efficiency are due to different cut-off frequencies for the filters used when filtering mechanical and electrical power.

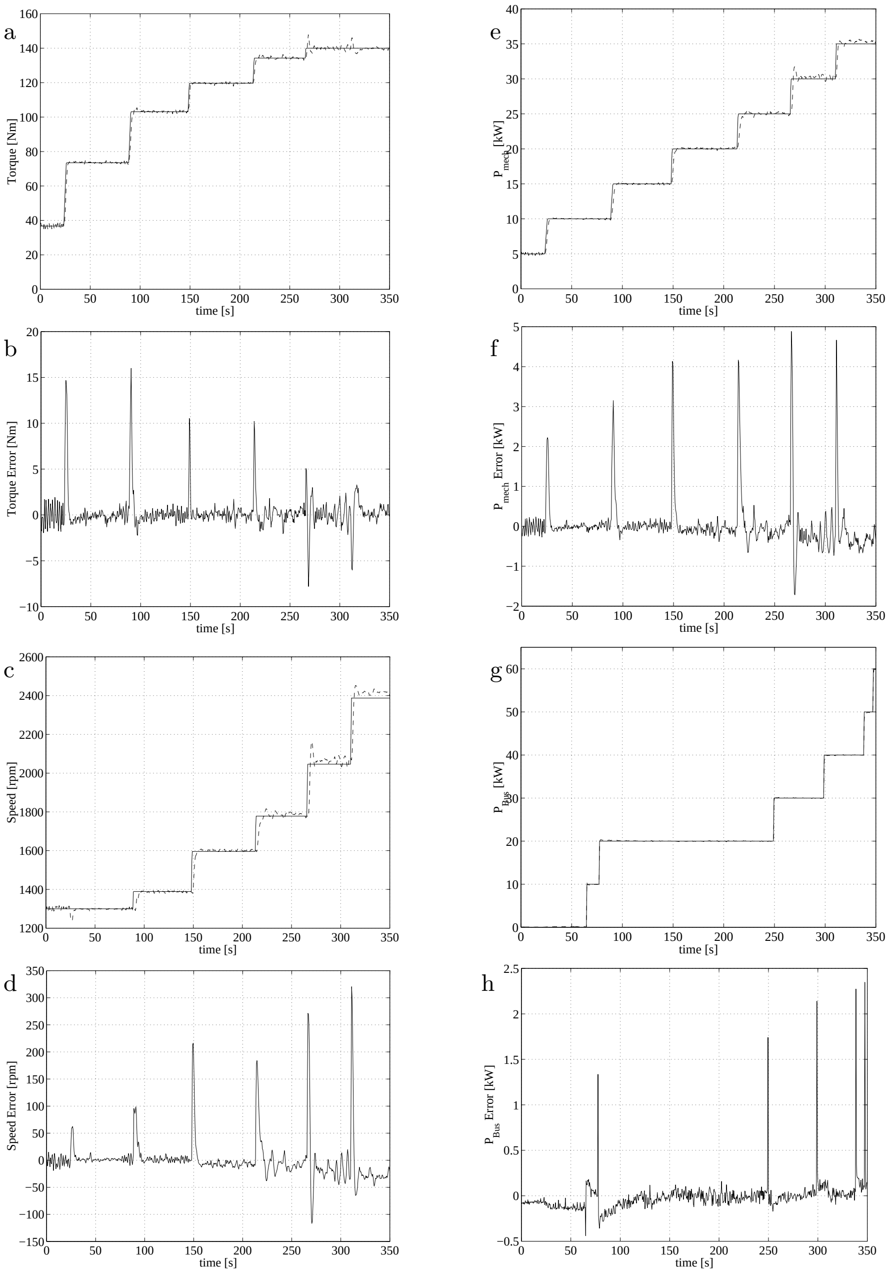

Figure 7.3 Torque and torque error (a,b), speed and speed error (c,d), mechanical power and error in mechanical power (e,f), tractive power and error in tractive power (g,h). Solid lines in (a,c,e,g) are setpoint values, dashed lines are measurements.

torque step that causes a speed error and at 315s there is a speed step that causes a torque error. There is also a coupling between torque transients and flux-linkage which is depicted in Figure 7.2

As seen i Figure 7.3 the genset behaves as desired for small steps in reference power. For large steps the behaviour was not that good when the system had to move from low speed (1300 rpm) and high torque (90 Nm) to a higher torque (140 Nm) and speed (above 2000 rpm). Three possible causes to this behaviour were found.

- The excess torque available is smaller at low speeds. The problem disappeared when the lower speed limit was changed to 1800 rpm.
- The speed governor was not appropriately tuned for this operating region.
- Mismatch in generating torque and speed lead values. If torque increases faster than speed one might reach the maximum torque for this speed; further acceleration is then impossible

One problem that occurs when the throttle is fully open is that it is impossible to increase the output power without first decreasing it. This is because there is no extra torque available to accelerate the genset. In order to increase the mechanical power the load torque first has to be reduced, which reduces the mechanical power, so that it is possible to accelerate the genset. The load torque can then be increased when the genset has reached the desired speed. Running with fully or almost fully open throttle thus makes it difficult to change operating point. This is very unfortunate as the ICE has its best efficiency at these points. Instead of having the ICE speed controlled and controlling the load with the generator it is possible to do it the other way around. This will however not solve the problem of changing operating point at fully open throttle. The generator is then speed controlled and the torque is given by the throttle position. Some extra logic is needed to assure that the powerflow always has the right direction. This is automatically handled with the used strategy.

Overvoltage

The overvoltage protection worked as intended with one exception. The overvoltage protection operates on the ICE power reference-value. When the battery voltage exceeds the limit the protection system will decrease the ICE power reference-value. Torque and speed reference values are not changed instantaneously but ramped, which will lead to some oscillations in

ICE power. However, the voltage will not be above the limit. The maximum overvoltage obtained in all tests and experiments was 5 volts above the preset overvoltage limit.

7.2 Powerflow Experiments

Twelve different experiments were performed. Two of them were with constant ICE power, the others had different parameter settings and different limits on the maximum allowed field-current. To get comparable results from the experiments, they were organised as follows:

Start-up The ICE is started and run until it has obtained correct operating temperature. During the warmup there is time to adjust the batteries to a state from which all experiments should start. Determining that the batteries are at this state is a non-trivial task. All experiments were made during one week, so with this in thought the following assumptions were made: It was assumed that the batteries were in the same state as the previous experiment when the temperature and the open circuit voltage was the same as in the previous experiment. In addition it was also required that the net charge on the batteries should be zero, measured from the previous experiment.

Performance After the Start-up it is time for the real experiment. The powerflow controller and the drive cycle are started and the system is left to itself during the duration of the drive cycle (40 min). Due to problems with a circuit-breaker on the 10 kV side of a transformer the experiments were performed with limited tractive power. The peak power was cut to 80 kW instead of 130 kW. To minimise the effect of this peak power cutting the removed energy was spread out over the whole drive cycle, making the energy in both cases equal. The peak cutting will probably mostly affect the battery losses, since the peak power should have been taken from the batteries. The reduced losses will in turn give a lower fuel consumption.

Finishing After the drive cycle is ended, the genset will, if needed, charge the batteries. This is done to make the results comparable and to make autonomous operation possible. A more advanced controller would include feedback from the battery state and make this step unnecessary. The power used for this charging is 20 kW shaft power corresponding to approximately 16 kW electric power. This power is chosen not for the efficiency, which can be higher, but it offers an operating point that has good efficiency and low ICE speed. Low speed can be translated to low noise levels. Low noise levels are essential since the charging is going to take place at the terminus. A high noise level from a bus at standstill is also a psychological problem. Who wants to step out in front of a bus that sounds as it will run over you any time?

Result

The goal is to have maximum efficiency for every desired operating point. A trajectory that is fairly close to this is seen in Figure 7.4, where the parameters should be $(n_1, T_1) = (1200, 100)$ and $(n_2, T_2) = (1700, 140)$, compare Figure 3.1. To obtain the best efficiency the lower speed limit should be even

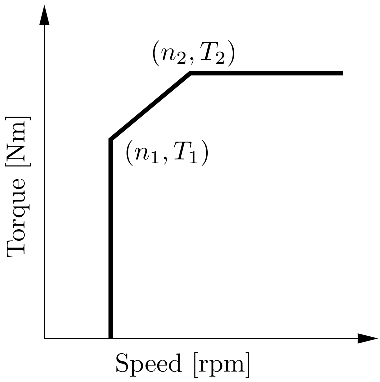

Figure 7.4 Trajectory on which the ICE is operated.

lower but the speed governor didn't manage speeds lower than 1200 rpm. Since the system shouldn't operate at low powers, adjusting the governor was not considered.

The poor behaviour when shifting operating points were solved by increasing the lowest speed (n_1). Thus, the parameters (n_1, T_1) and (n_2, T_2) do not only influence the static behaviour but also the dynamic behaviour of the genset.

The experiments were performed with the type of controller that is listed in Listing 5.1 on page 27. This controller has five parameters, filter time constant λ, drift levels ν_i, and limits on cumulated prediction error h_i. There are also the limits on mechanical power P_{min} and P_{max}. These parameters affect the amount of power that is generated. The main difference between the experiments are different values of P_{min} and P_{max}. The other parameters ν_i and h_i were adjusted so that the behaviour of the controller was approximately equal for all experiments. Different values of (n_1, T_2) and (n_2, T_2)

were also tried because of the poor dynamic behaviour at low speeds of the genset.

The results are summarised in Table 7.1. The reason that the values in this table are about twice as large as those in Table 5.1 on page 23 is that the optimisation was performed over the first half of the drive cycle due to computational time. It should be noticed that the *HC* emissions are calculated by interpolating in a map, describing the static behaviour of the ICE. This works when the transients are negligible. However, if the transients are large the interpolated result may be wrong with several orders of magnitude. The results for the *HC* emissions in the table should therefore be taken with a pinch of salt.

	Fuel Consumption (l)	Total Energy (kWh)	Genset losses (kWh)	Battery energy (kWh)	Battery charge (Ah)	*HC* emissions (g)	Charging time (s)	P_{min}–P_{max} (kW)
30 kW	8.60	80.87	60.20	1.95	0.01	140	930	
35 kW	8.18	76.89	57.09	1.47	0.02	113	23	
1	8.30	78.05	59.04	1.52	0.02	111	370	18-51
2	8.31	78.08	58.31	1.23	0.02	115	304	20-51
3	8.00	75.18	55.37	1.15	0.03	113	173	18-51
3ψ	8.48	79.70	59.80	1.40	0.00	122	600	18-44
4	8.04	75.53	55.75	1.13	−0.09	112	173	18-50
5	8.46	79.55	58.50	2.41	3.24	115	0	23-50
6	8.13	76.43	56.33	1.68	1.34	112	0	20-46
7	8.28	77.84	58.06	1.19	0.03	114	350	18-44
8	8.28	77.80	58.41	1.27	0.03	116	408	18-44
9	8.11	76.27	55.86	1.76	1.68	113	0	22-47

Table 7.1 Result from the different experiments. Total tractive energy is 18.8 kWh and mean tractive power is 27 kW. Charging time is the time that was required to bring the battery back to its original state when the drive cycle had ended.

It should be noticed that three experiments (5,6,9) produced excessive charge. These experiments are thus not directly comparable with the other nine experiments. Experiments 1,2,7,8 had a lower speed-limit of 1300 rpm whereas the lower speed-limit in the other experiments was 1900 rpm. The upper speed-limit varied between 1800-2400 rpm for $n_1 = 1300$ and 2100-2400 for $n_1 = 1900$. It is interesting to see that though the efficiency at low power is lower for $n_1 = 1900$ the fuel consumption over the drive cycle is generally lower.

An interesting observation can be made between the experiments with lowest fuel consumption, experiments 3,4,6 and 9, where experiment 6 and 9 produce excess charge. Experiments 6 and 9 consume about 0.1 litres more gasoline (about 1 kWh) than experiments 3 and 4. Half of his energy is lost in the genset and the other half charges the batteries. The marginal efficiency of the extra fuel consumption is thus 50% from chemical energy to electric energy. Calculating backwards instead, it is known that the total efficiency can't be better than $0.35 \cdot 0.85 = 0.30$, so that 0.5 kWh electrical energy is translated into 1.67 kWh chemical energy or 0.18 litres of gasoline.

If one experiment should be picked as the "best" I would choose experiment number nine. This experiment has a low fuel consumption and produced some excess charge. The excess charge will compensate for the increased battery loss when running the experiment at full power. Some more subjective opinions about this experiment was that it behaved nice concerning noise and transient behaviour.

Notes about the Experiments

30 kW Mechanical power constant at 30 kW, electric power 24 kW. This experiment shows clearly that there is no use to discharge the batteries during driving if they are to be charged from the generator later. Charging power was reduced at the end of the charging because of voltage limitations. This result also indicates that on–off control is a poor strategy for this vehicle from an energy management point of view.

35 kW Battery losses are large with respect to fuel consumption compared to most other experiments.

1 Poor transient behaviour. Generator inverter operated as diode rectifier several times.

2 See 1.

3 Largest difference between $P_{mech_{max}}$ and $P_{mech_{min}}$. The battery voltage reached the limit a few times during the drive cycle. Generator inverter operated as diode rectifier several times.

3ψ Same parameters as in experiment 3 except for maximum field-current that was reduced.

4 Transient behaviour ok. Generator inverter operated as diode rectifier several times.

5 Overvoltage many times during the drive cycle. Upper torque reference set to 155 Nm.

6 Maximum power reference reduced halfways through the drive cycle in order to reduce over-charging. Upper torque reference set to 155 Nm.

7 Transient behaviour better than in 1 and 2 with approximately the same parameters for power generation.

8 Upper torque reference set to 155 Nm.

9 Upper torque reference set to 155 Nm.

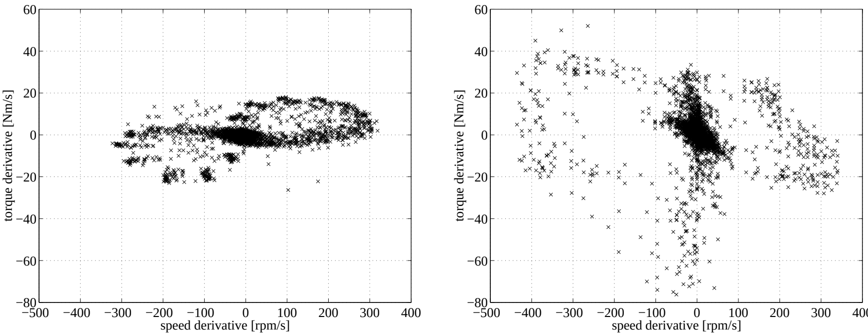

Figure 7.5 Torque derivative vs Speed derivative for experiment 9 (left) and for the real bus (right). The torque for the real bus is estimated from generator power and speed.

Comparisons

The fuel consumption in the experiments varies between 67.8 and 72.9 l/100 km whereas the busses in Stockholm have a fuel consumption of 78.2–91.9 l/100 km. The difference is partly due to the reduced battery losses in the experiments but that alone can't explain the difference. The big advantage should however be reduced emissions due to smoother operation of the ICE, see Figure 7.5. Another comparison is with the bus from which the data was collected. For the used drive cycle this bus used 9.06 litres of gasoline, 76.3 l/100 km, and charged the batteries with 1.29 Ah corresponding to a total change in battery energy of 2.77 kWh. The reason to that the change in energy for the battery in the bus is much larger than in the experiments is because the bus runs on battery power only, for a part of the drive cycle. A large part of the change in battery power is thus due to increased battery losses.

8

Conclusions

Control of power generation and energy management in a series hybrid bus has been studied with methods from optimal control. The objective was to make the losses in the system as small as possible. The optimal control formulation also allows additional requirements to be added as constraints, such as the emission levels must be under a specified limit. It further gives a systematic way to analyse the system and a possibility to investigate parameter sensitivity. For the studied vehicle the following conclusions can be drawn.

- If the vehicle always is to operate in hybrid mode, then the battery size is given by the maximum required power together with the size and operation of the ICE. The smaller and slower operation of the ICE that is required the larger the battery has to be in order to be able to deliver the required power. With the chemical batteries available today a battery with the required power also have a large energy content which is not needed. Batteries with high specific power rather than energy content are thus of vital importance for this kind of operation.
- If emission free operation is required then the size of the battery is given by the energy needed to drive the specified distance. The size of the battery will also be affected by the required performance but it will almost certainly be large enough in the case of a city bus.
- The fuel consumption can be decreased by allowing the genset to use several different operating points. Smooth transitions between these points will also give lower emissions.
- On-off operation of the ICE is not energy efficient. At least two operating points are needed to obtain a high overall efficiency.

A controller that mimics the result obtained by optimal control has been synthesised and used both for simulation and for verification on a full scale experimental setup. Although simple models have been used the agreement between experiments and calculations are satisfactory.

Optimisation of HEVs has traditionally been performed either on the components, such as batteries and size of ICE, given a powerflow strategy or on the *parameters* of a powerflow strategy given a complete vehicle. The used method finds a strategy given a criteria and a complete vehicle but unfortunately not as a feedback controller.

Topics for Future Research

As the experimental results seem to depend strongly on the interaction between the ICE and the generator, the generation of reference values and genset control ought to be investigated. This will require dynamic models of the genset which also should be used in the optimisation. Other kind of hybrids should be investigated, especially multisource hybrids which have several possible ways to route the power. It is possible to recover some of the braking energy in hybrids. This have not been studied at all in this thesis but is a natural continuation of the effort to minimise energy losses. The problem is that braking power often have a short duration but at high power. The question is then if the braking power or ICE power should be used to charge the batteries, since using both sources will probably result in overvoltage. Multisource hybrids with one "energy storage" and one "power storage" like ultra-capacitors or a flywheel might be considered for this purpose.

An obvious continuation on the optimisation is to merge component sizing and powerflow strategy into one problem. This should be possible to do given that it is possible to parameterize components such as battery, ICE and generator. Since the powerflow problem is infinite dimensional, adding some extra parameters, describing the components, does not significantly increase the complexity of the problem. The result from such an optimisation is naturally not better than the model it uses. However, even a simple model should provide a good starting point for more detailed investigations.

9

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A

Experiments

Some results from different experiments are seen on the following pages. The tractive power is only shown once as it is the same drive cycle in all the experiments. All times are in seconds.

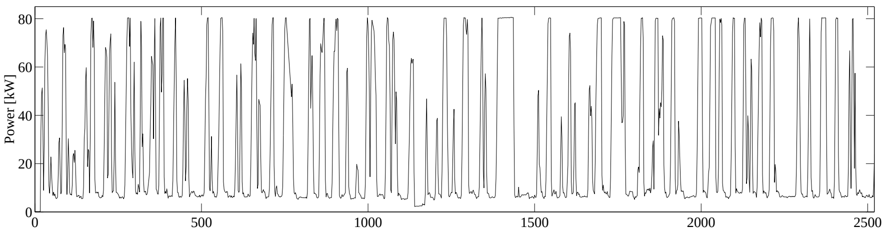

Figure A.1 Tractive power in the experiments.

A.1 Experiment 5

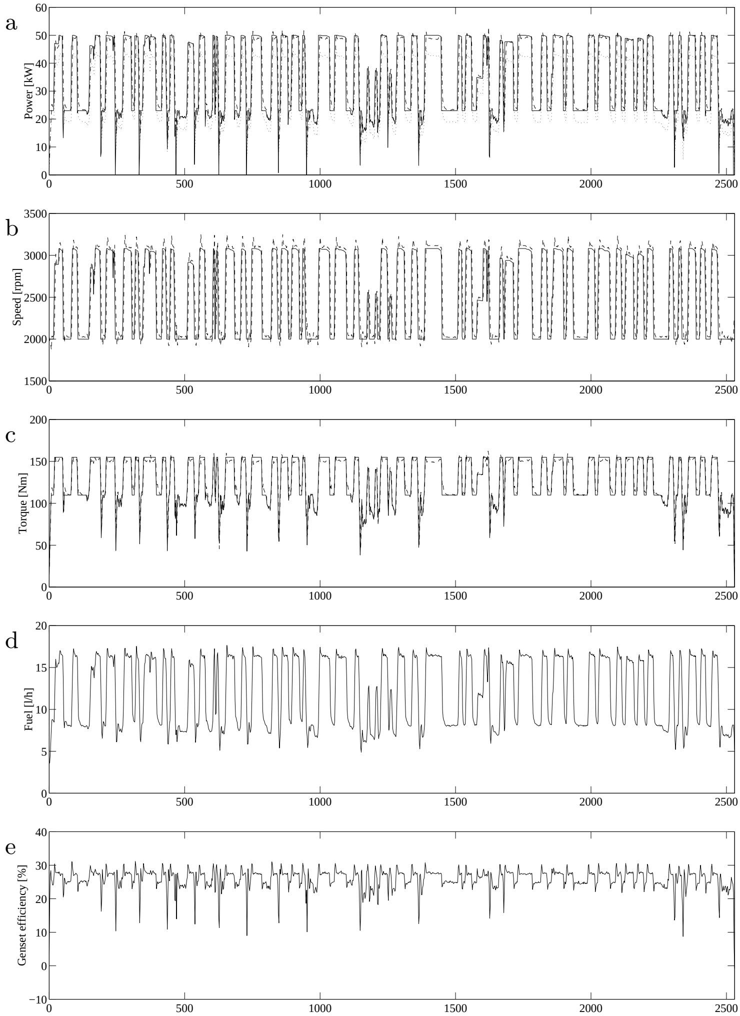

Figure A.2 (a) ICE power reference (solid), ICE power (dashed) and generator power (dotted). (b) speed reference (solid) and speed (dashed). (c) torque reference (solid) and torque (dashed). (d) fuel consumption in l/h. (e) genset efficiency.

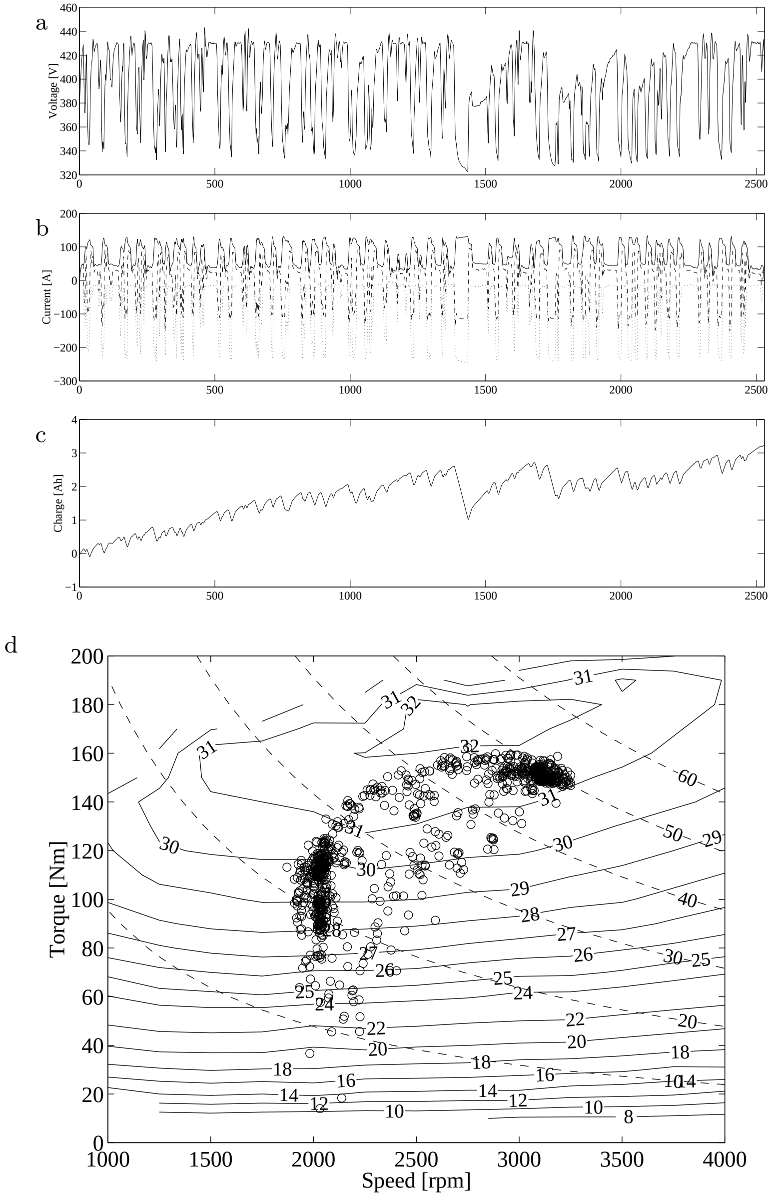

Figure A.3 (a) battery voltage. (b) generator current (solid), battery current (dashed) and bus current (dotted). (c) battery charge. (d) torque vs speed.

A.2 Experiment 9

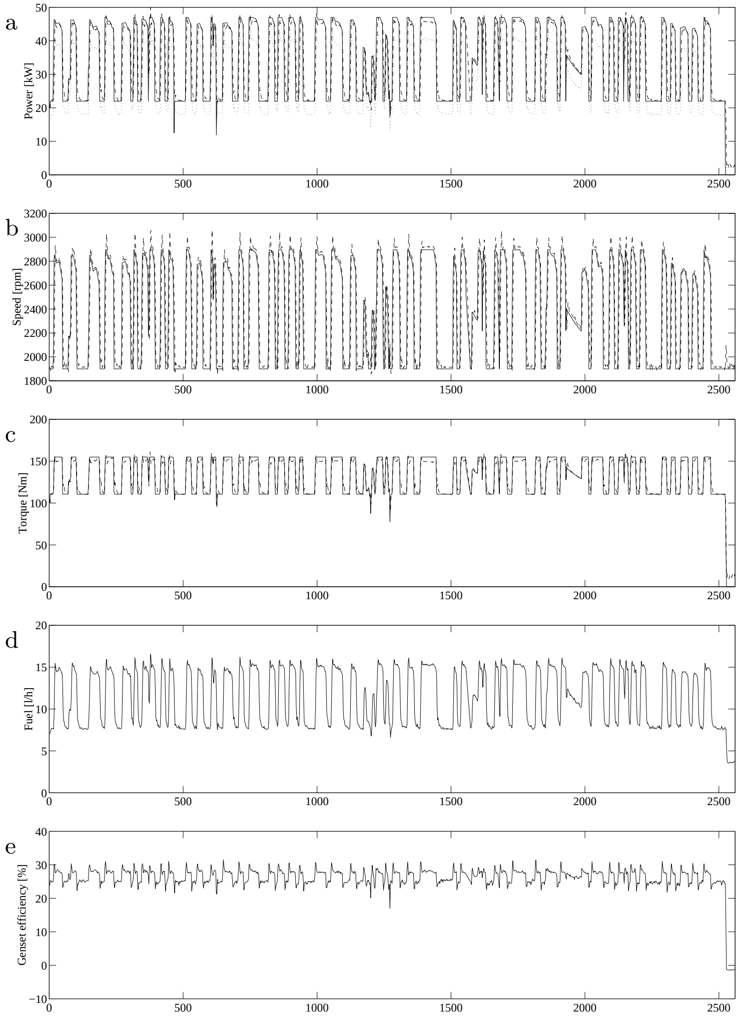

Figure A.4 (a) ICE power reference (solid), ICE power (dashed) and generator power (dotted). (b) speed reference (solid) and speed (dashed). (c) torque reference (solid) and torque (dashed). (d) fuel consumption in l/h. (e) genset efficiency.

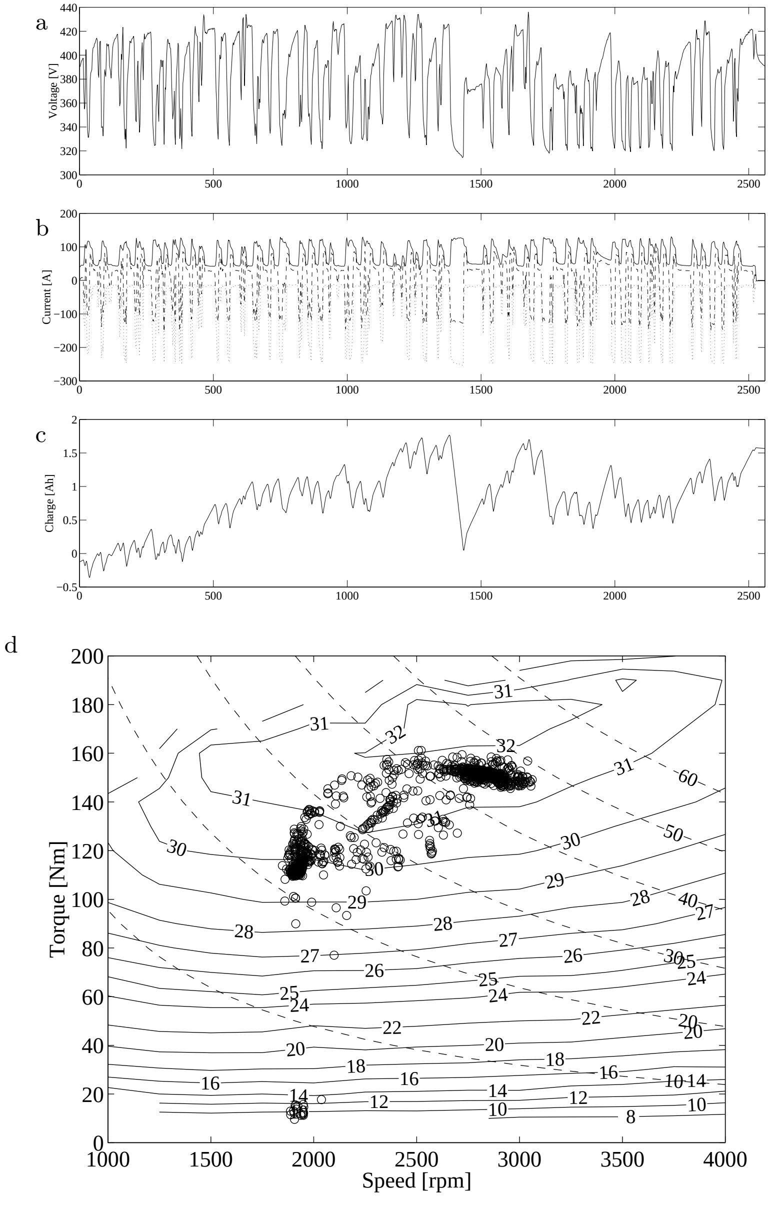

Figure A.5 (a) battery voltage. (b) generator current (solid), battery current (dashed) and bus current (dotted). (c) battery charge. (d) torque vs speed.

A.3 Constant Power

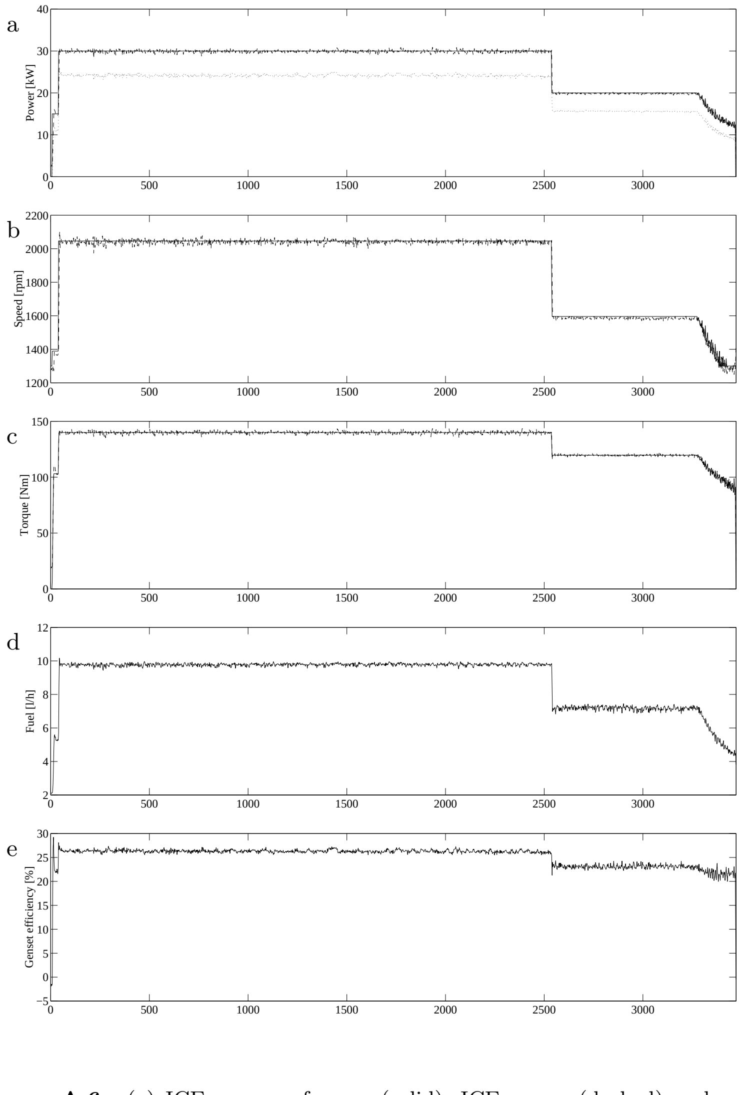

Figure A.6 (a) ICE power reference (solid), ICE power (dashed) and generator power (dotted). (b) speed reference (solid) and speed (dashed). (c) torque reference (solid) and torque (dashed). (d) fuel consumption in l/h. (e) genset efficiency.

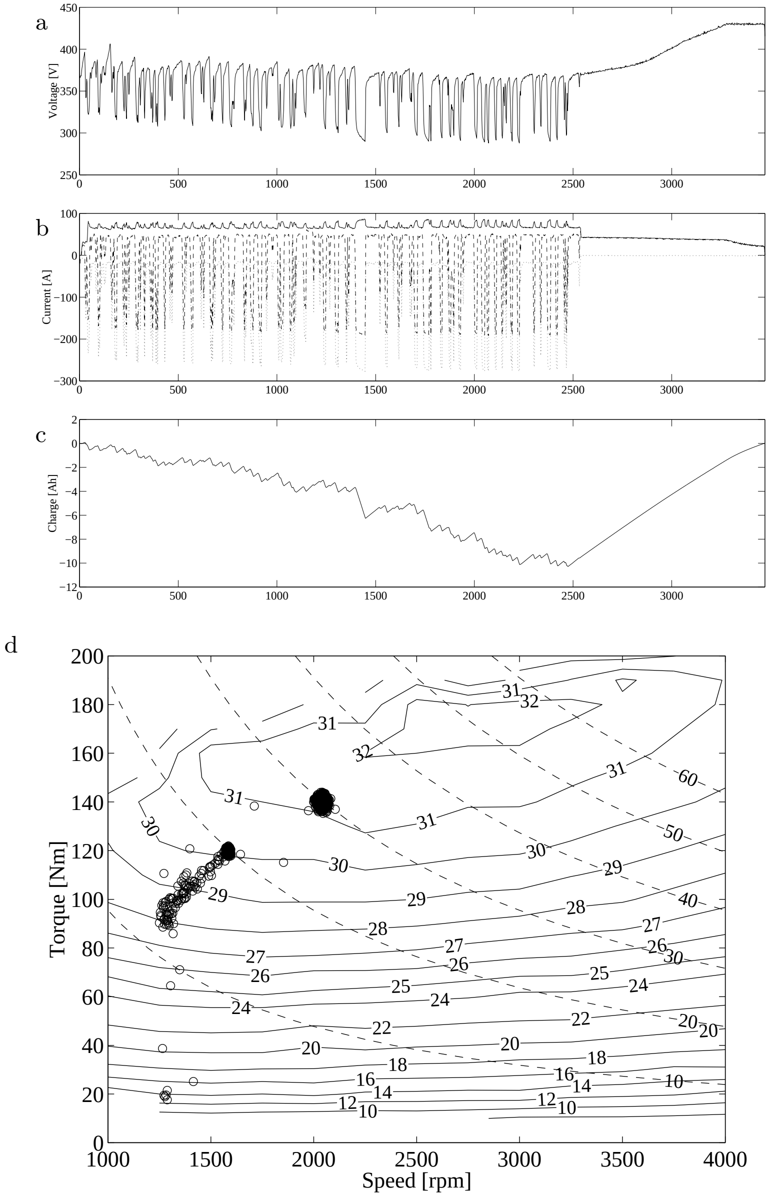

Figure A.7 (a) battery voltage. (b) generator current (solid), battery current (dashed) and bus current (dotted). (c) battery charge. (d) torque vs speed.