ISSN 0280–5316
ISRN LUTFD2/TFRT--5500--SE

Control of Hybrid Vehicles

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March 1994

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Document name
MASTER THESIS

Date of issue
March 1994

Document Number
ISRN LUTFD2/TFRT--5500--SE

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Sponsoring organisation

Title and subtitle
Control of Hybrid Vehicles. (Reglering av hybridfordon.)

Abstract

As part of general research, AB Volvo Technological development is investigating the prospect for hybrid vehicles. One of the aims is to optimize a hybrid vehicle drivetrain. This is done by

- Minimize the emissions
- Minimize the energy consumption
- Increase battery life
- Improve vehicle performance

This master thesis presents a hybrid vehicle controller, with the above conditions implemented.

The work consists of two parts. First, strategies for the four conditions described above, are developed. Then the controllers are developed with the strategies implemented. The optimal strategies are developed based on information of Internal Combustion Engine (ICE) fuel-consumption, emission data and battery characteristics. To develop the controller, a hybrid vehicle simulation model in Matlab/Simulink has been used. Controller development also include structuring and linearization of the system.

The results from simulated driving of the hybrid vehicle, show that the developed controller reduces fuel-consumption and emission levels. The emission levels are reduced down to California emission limits in two cases of three.

Key words

Classification system and/or index terms (if any)

Supplementary bibliographical information

ISSN and key title
0280–5316

ISBN

Language
English

Number of pages
55

Recipient's notes

Security classification

Acknowledgments

I would like to thank Mr. Anders Romare at AB Volvo Technological Development for giving me the opportunity to work with this project, and for his guidelines on how it should be carried through.

I also like to thank my supervisor at Lund Institute of Technology, Department for Automatic Control, Mr. Karl-Erik Årzén. He has been a valuable help to me at control issues and in examining this report.

Furthermore I would like to thank Mr. Björn Fälth and Lic. Anders Lasson for many fruitful discussions throughout the work. A special thanks to the staff at Volvo TU for making my stay in Göteborg so pleasant.

The financial support from AB Volvo is also gratefully acknowledged.

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Introduction

At the department Technological Development, which is a part of AB Volvo, research about electric and hybrid vehicles is being done. This theses was set out in 1993 and is part of this research.

1.1 Background

Electric vehicles have the advantage of being zero-emission vehicles, but they only have a range of approximately 60 km with lead-acid batteries and about 100 km with Ni-Cd batteries. The short range together with a rather low performance is a serious drawback. The development of high energy batteries is estimated to give results not until somewhere around the year 2000.
Hybrid vehicles are therefore a solution to the problem with short range, as they combine an electric motor with an internal combustion engine (ICE) for propulsion. If the ICE operates only when the electric drive system cannot meet the vehicle's performance and/or range requirement, then the vehicle has the same primary advantage as the electric vehicle. That is, it minimizes the use of liquid fuel, and at the same time meets all the present demands for passenger car owners.

1.2 Aim of the project

The main purpose of the work is to solve four criterion's for the hybrid vehicle:

- Minimize the emissions.
- Minimize the fuel consumption.
- Increase battery life.
- Improve vehicle performance.

This will be used to build up some knowledge of how to optimize a hybrid vehicle drivetrain[1]. This means developing a central controller for the vehicle and implement the four criterion's in the controller. Using a simulation model of a hybrid vehicle [1], I can compare different solutions to the four criterion's and find out which gives the best results.

[1] The parts of the vehicle that creates the tractive force.

1.3 Outline of the report

Chapter 1 is the introduction to this project.
Chapter 2 is a description of the hybrid vehicle simulation model which I have used as a base for this project.
In chapter 3 I describe how to reach the goals of minimizing emissions and energy (e.g. fuel) consumption's for the hybrid vehicle.
In chapter 4 I describe the criterion's 3 and 4, increasing battery life and improving vehicle performance, and solutions for these.
In chapter 5 I explain the controllers, and how to linearize the system.
Chapter 6 shows the simulation results obtained from using 4 different conditions, to solve the 4 criterion's.
Chapter 7 is a summary of my work and the achievements and chapter 8 is the reference list.

2. Hybrid vehicle simulation model

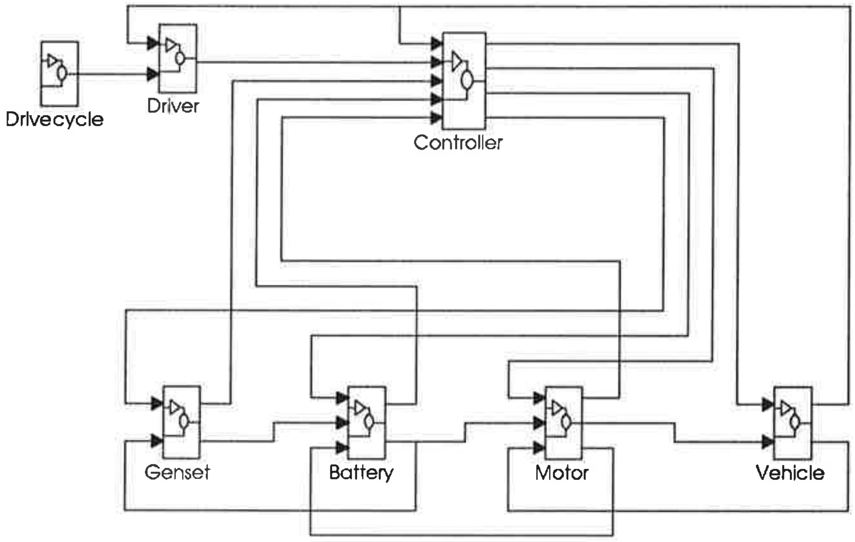

Figure 2.1 *Volvo hybrid vehicle simulation model.*

A simulation model is a powerful tool to work with in any design procedure. The specific model I have been working with [1], is developed at Volvo in a Matlab/Simulink environment.
The advantage of using block diagram simulation over the traditional higher level language programming (as C, Modula2 e.t.c.), lies in the much greater flexibility of model development and subsequent analysis [9]. Substantial modifications of the model or simulation strategy can be accomplished by simply substituting the blocks and/or rearranging the diagram.
The block diagram presented in figure 2.1 represents the major components of a hybrid vehicle schematically. Each block consists of a number of lower level blocks performing particular functions or calculations.
To get an outline of what the different component contains I will give a brief explanation.

Drive cycle

The drive cycle consists of a look-up table containing the required drive cycle. There are two types of drive cycles used, US. FTP 75 as shown in figure 2.2 and US. highway in figure 2.3.

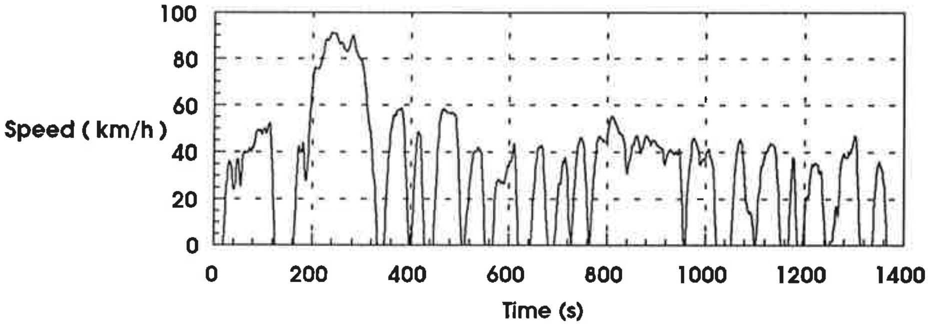

Figure 2.2 *US. FTP 75 drive cycle.*

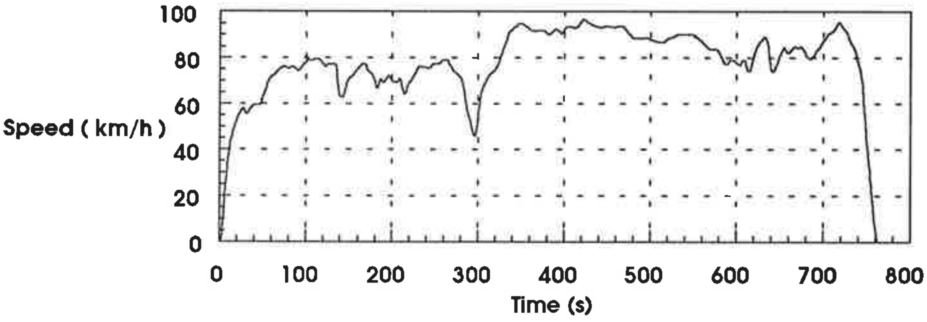

Figure 2.3 *US. highway drive cycle.*

Driver

The driver model compares the actual speed of the vehicle with the required speed from the drive cycle. If there is any difference in speed, the driver will actuate either the accelerator or the brake.

Controller

The controller model receives various signals from the vehicle, driver, genset, battery and the motor. The controllers then calculate the required signals to control the vehicle in an optimized way.

Genset (ICE/generator)

The genset block consists of an internal combustion engine and a generator. The engine runs the generator, modeled as a separately exited DC machine. The genset charges the battery on command from controller.

Battery

The battery is modeled as a lead-acid battery. It is being charged by the genset and discharged by the motor. The controller sets the battery charge current limits as the regeneration currents from the motor may become too high.

Motor

The separately exited DC motor is the same motor as the generator in the genset. The battery is the power supply and the motor can regenerate energy to the battery as the vehicle is braking.

Vehicle

The vehicle model has an automatic gearbox. The driver gets the vehicle speed and the motor gets the required torque.

Figure 2.4 show how the series hybrid vehicle drive train is configured.

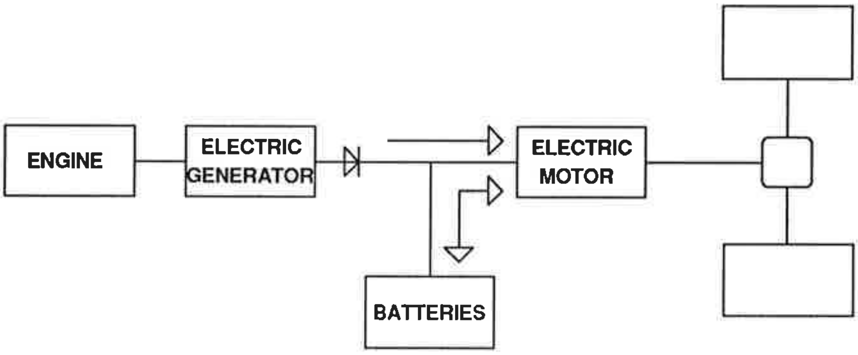

Figure 2.4 *Hybrid vehicle drive train.*

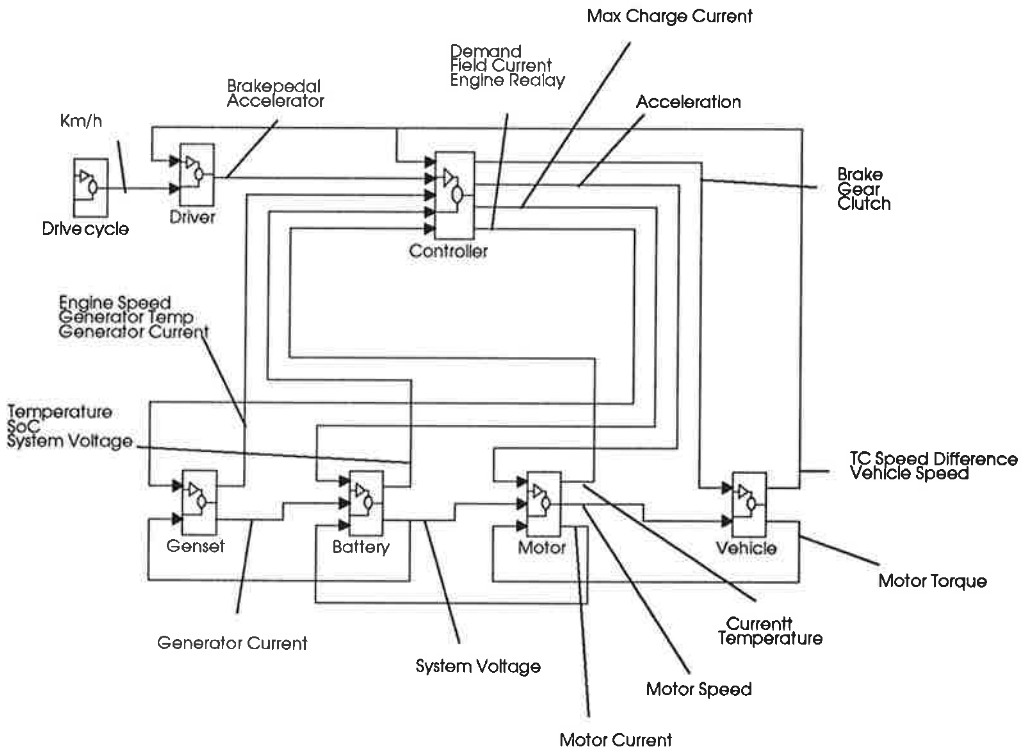

Figure 2.5 *Inputs and outputs in the hybrid vehicle simulation model.*

Figure 2.5 show the outputs and inputs of the controller in the hybrid vehicle simulation model.

Here follow an explanation of some of the signals in the controller model.

TC speed difference	= Torque Converter speed difference (0-1)
Vehicle speed	= Vehicle speed (km/h)
Engine speed	= Engine speed and Generator speed are the same (0-523 rad/s)
SoC	= State of Charge in the Battery (0-100 %)
System voltage	= Battery voltage (120±20 V)
Demand	= Throttle control in the Internal Combustion Engine (0-3.62)
Field current	= Separately exited DC-generator field current (0-5 A)
Engine relay	= Contactor connection between the armature windings of the DC-generator, and the poles of the battery (0,1)
Max. charge current	= Battery upper charge limit (A)
Accel	= Accelerator

3. Minimizing emissions and energy consumption

Prospects for reducing petroleum use and exhaust emissions presently motivate all work in hybrids [2], but the success of the hybrid concept is very dependent of finding the right control strategy. This, and also a method for finding the appropriate control and measured signals for a controller, will be discussed.

3.1 Strategies

The great advantage for the hybrid vehicle is its variety of operating modes. This creates a possibility to develop an optimized control strategy for fuel consumption and emission reduction [3]. Implementation of the strategy in a controller, for use in the hybrid vehicle, can verify if the chosen strategy is optimal. Figure 3.1 show how the fuel consumption varies with the ICE's speed and torque.

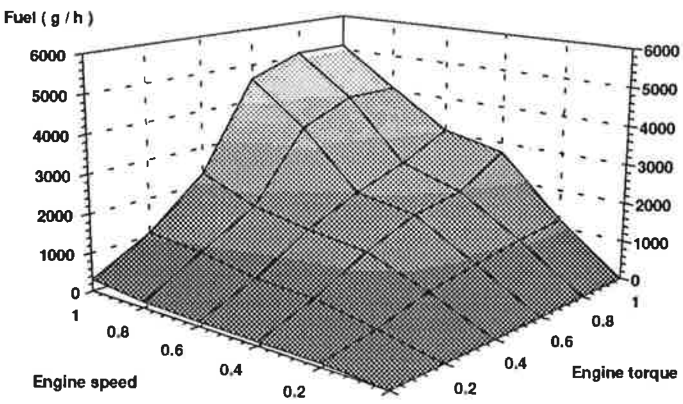

Figure 3.1 *Fuel consumption in an ordinary internal combustion engine (ICE) depending on normalized engine speed and torque.*

Regenerative braking

By reversing the field current at the propulsion motor while braking/retarding the vehicle, we can use the energy to charge the batteries. The regenerated charge current is often quite high (more than 200 A), and a lead acid battery can not handle such charge currents. Therefor the generator is turned off at these moments, and current that exceeds the upper limit for the battery is dumped in a resistor.

The energy saved by regeneration naturally depends on the driving pattern. During simulated conditions described in Chapter 6.2, the regenerated energy was 6% of total used energy.

Genset operation

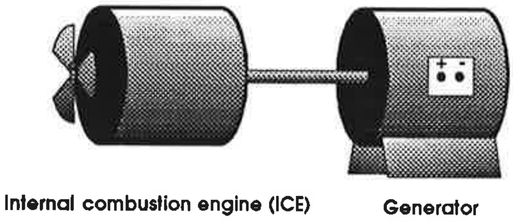

Figure 3.2 Genset construction.

While operating the generator, we need to avoid dumping generator current by turning the generator off during braking [8].

A way to reduce emissions and the fuel consumption at the same time, is to control the engine load (torque) and speed for a certain current. In order to control the engine in an optimized way, we have to make a map of how the current delivered by the generator depend on fuel consumption and emissions from the ICE.

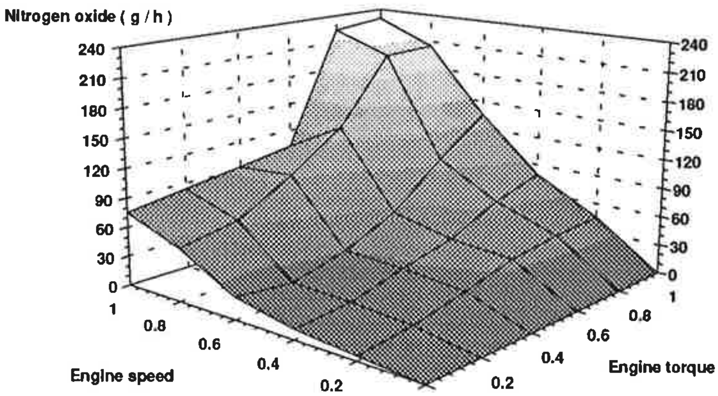

Figure 3.3 NOx in an ICE as function of normalized engine speed and torque.

This engine mapping [3] is done by keeping the current from the generator constant, and vary engine speed and torque. This gives us a range for operating the engine at one specific charge current, and this is the key to control the genset in an optimized way.

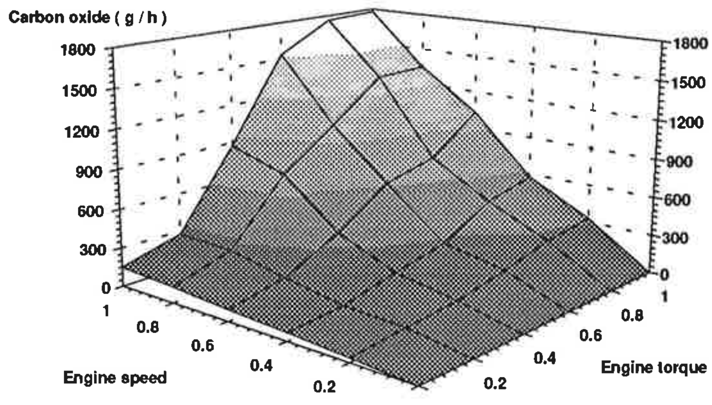

Figure 3.4 CO in an ICE as function of normalized engine speed and torque.

What we have to do now is to interpret the information of fuel consumption, figure 3.1, and exhaust emissions, shown in figure 3.3-3.5, for use in the controller. This is done by finding the operating point (speed-torque) with the lowest fuel consumption and least emissions, for a specific current.

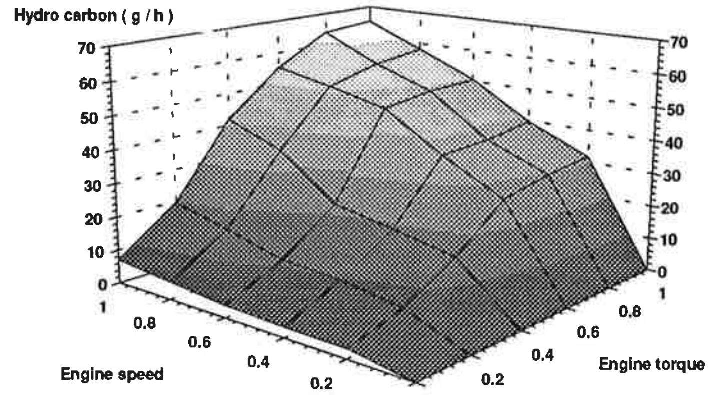

Figure 3.5 HC in an ICE as function of normalized speed and torque.

To consider fuel consumption, NOx, HC and CO at the same time in an optimized way is not possible. A way through this is to weight the four factors equally, and use this as information for the controller. This is shown in figure 3.6.

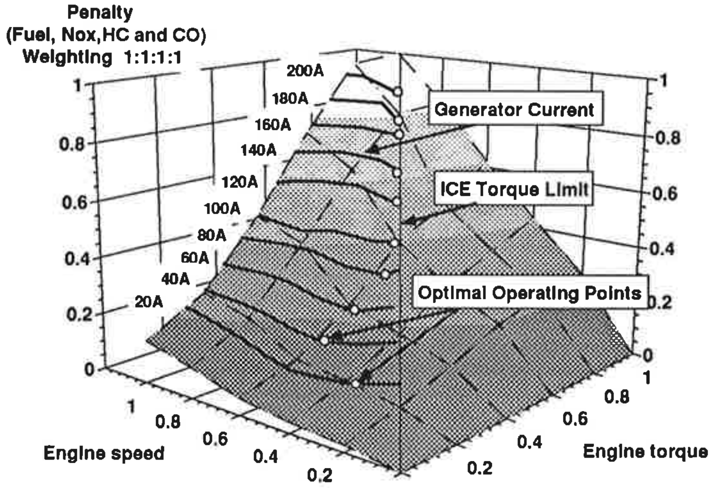

Figure 3.6 Weighted fuel consumption and emissions from an ICE, as function of normalized engine speed and torque. Corresponding generator currents with their optimal operating points regarding fuel consumption and emissions.

In figure 3.6 we can also see how the charge currents have their lowest points at the mark in the diagram. This is therefore the optimal operating points for the charge currents.
By finding optimal operating points for different charge currents through the entire register of the engine, we can make trajectories for engine torque and speed.

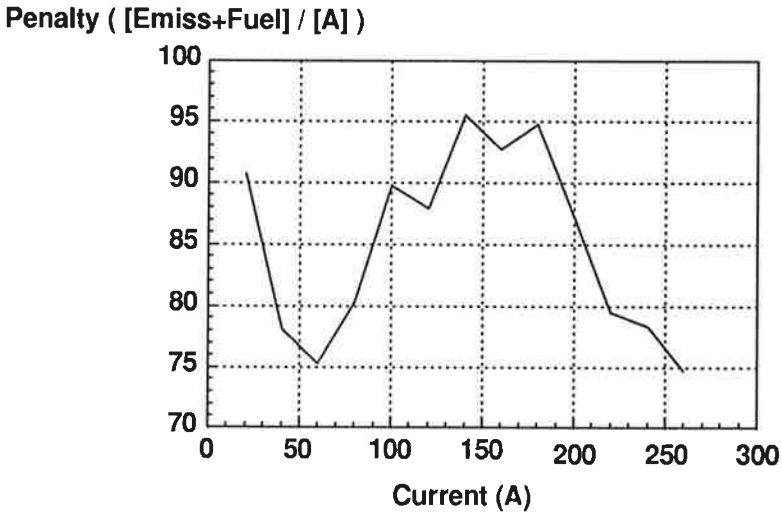

Figure 3.7 Overall optimal charge current diagram.

If we go one step further and plot the optimal operating point penalty values, devided with the normalized corresponding current we get the overall optimal charge current diagram, showed in figure 3.7. As we see the currents 60 A and 260 A gives low penalty values. 260 A is not realistic though. The battery will soon get overheated when charged with this high current for a longer time. 60 A is better but might not be sufficient if the vehicle is driven on a highway for a longer time.

3.2 Principles of structuring

Controlling a hybrid vehicle is a large-scale and non-linear control problem, and ordinary control theory can only handle small well-defined problems. The controller showed in figure 3.8 deals with several inputs and outputs, furthermore none of the transfer functions being controlled are linear. At first sight this seems like a major difficulty, but there is a solution to this problem, called structuring [4]. Structuring describes the gap between the real problems and the problems that control theory can handle.

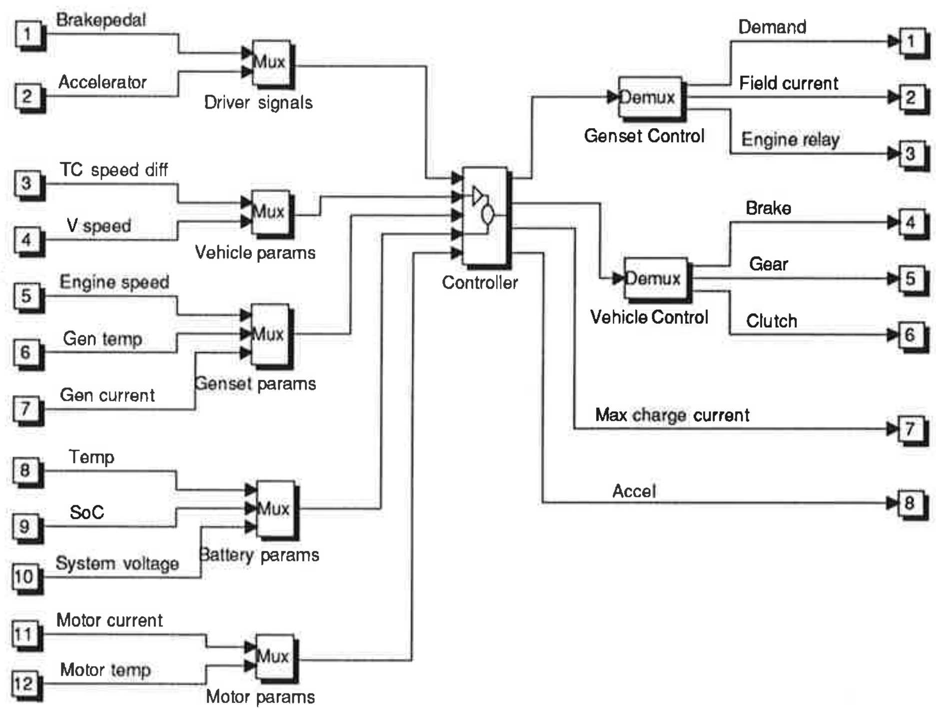

Figure 3.8 Inputs and outputs of the hybrid vehicle controller

Top-down approach

There are two major approaches, called top-down and bottom-up.
The *top-down* approach starts with the problem definition. You then divide the problem into successively smaller pieces, adding more and more details. The procedure stops when all pieces correspond to well-known problems.

I have chosen to work with the top-down approach. This involves the selection of *control principles*, choice of *control variables* and *measured variables*, and *pairing* of these variables.

Control principles

A control principle gives a broad indication of how the process should be controlled. The control principle thus tells how a process should respond to disturbances and command signals. The establishing of a control principle is the starting point for a top-down design.
The choice of a control principle is an important issue. A good control principle can often simplify the control problem.

Choice of control variables

After the control principle has been chosen, the next logical step is to choose the control variables.
The natural choice is the control variables that have a close relation to the variables given by the control principle.

Choice of measured variables

The control principle gives the primary choice of the measured variables. If you can not measure the variables used to express the control principle, it is natural to choose measured variables that are closely related to these control variables.

Pairing of inputs and outputs

A large system will typically have a large number of inputs and outputs. Even if a control principle, which involves only a few variables, is found initially, many variables typically must be considered once the variables that can be manipulated and measured are introduced. With a top-down approach, a system should be broken down into small subsystems. It is then desirable to group different inputs and outputs together, so that a collection of smaller subsystems is obtained.

***Table 3.1** Structuring, using top-down approach, in order to get a manageable controller for the system.*

Problem definition	Control principles	Control variables	Measured variables
Minimize the emissions and energy consumption.	A certain charge current from the *genset* to the battery can be obtained at different operating points (speed-torque) for the engine. Find the operating point that gives the lowest emissions and least fuel consumption for the given charge current.	Demand Field current	Engine speed Engine torque
	Transients in engine speed when generator load varies fast should be avoided. Control the generator field current and engine demand synchronized.	Demand Field current	Motor current Battery voltage

3.3 Structuring the system

Using the *top-down* approach we start with the *problem definition* and continues as described in chapter 3.2.
Table 3.1 show the choices of control principles, control variables and measured variables. Below follows some explanations of the choices.

Problem definition

This definition is given in the thesis specification as an aim for the control strategy.

Control principles

Realization of these two control principles will have a major impact on the goal of reducing fuel consumption and emissions.

Control variables

I. The control variable demand, operates the throttle in the engine to obtain the acquired torque.
   Field current operates on the generator. It has a major influence on the *genset* speed, and I use this for speed control.

II. In the second control principle these two variables are controlled synchronized.

Measured variables

I. Engine speed is measured for speed control of the *genset*.
   Engine torque is measured for torque control.

II. To know when the regenerative braking operates, the motor current is measured. It turns negative when the vehicle is retarding, and I use this to turn the charge current from the generator off.
   Measuring battery voltage is necessary to control the field current in an efficient way.

Paired inputs and outputs

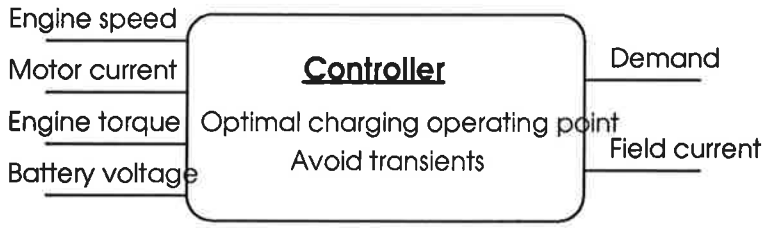

***Figure 3.9** Inputs and outputs in the controller for minimizing fuel consumption and emissions.*

In this case the pairing of inputs and outputs, figure 3.9, comes natural as they all belong to the same problem definition.

4. Increasing battery life and improving vehicle performance

The lifetime of a battery is partly an environmental question (if not recycled), but today mostly an economic question. The cost of batteries in a hybrid vehicle, and especially in an all-electric vehicle, is a great part of the total price. The vehicle performance is a security matter as the acceleration of the vehicle is important at overtaking.

4.1 Strategies

The first way to reach the goal of long battery life is by limiting the working temperature for the battery. Both heat and cold have bad influence on the battery. The second way is to control the depth of discharge, and the charge level. Fully charged or discharged the battery will suffer. Keeping SoC between the right limits will preserve the battery at health.

Battery temperature

For a Ni-Cd battery the temperature limits should be around 10-30 °C, and for a lead-acid battery around 10-50 °C.
To prevent the battery from overheat, we can either increase the cooling or, minimize the energy outlet from the battery. Considering the last alternative, we can have the motor current as reference for the generator. The generator will now generate the energy for propulsion of the vehicle. In this way we can control the temperature of the battery.

Figure 4.1 show the power flows in the hybrid vehicle during different operating modes.

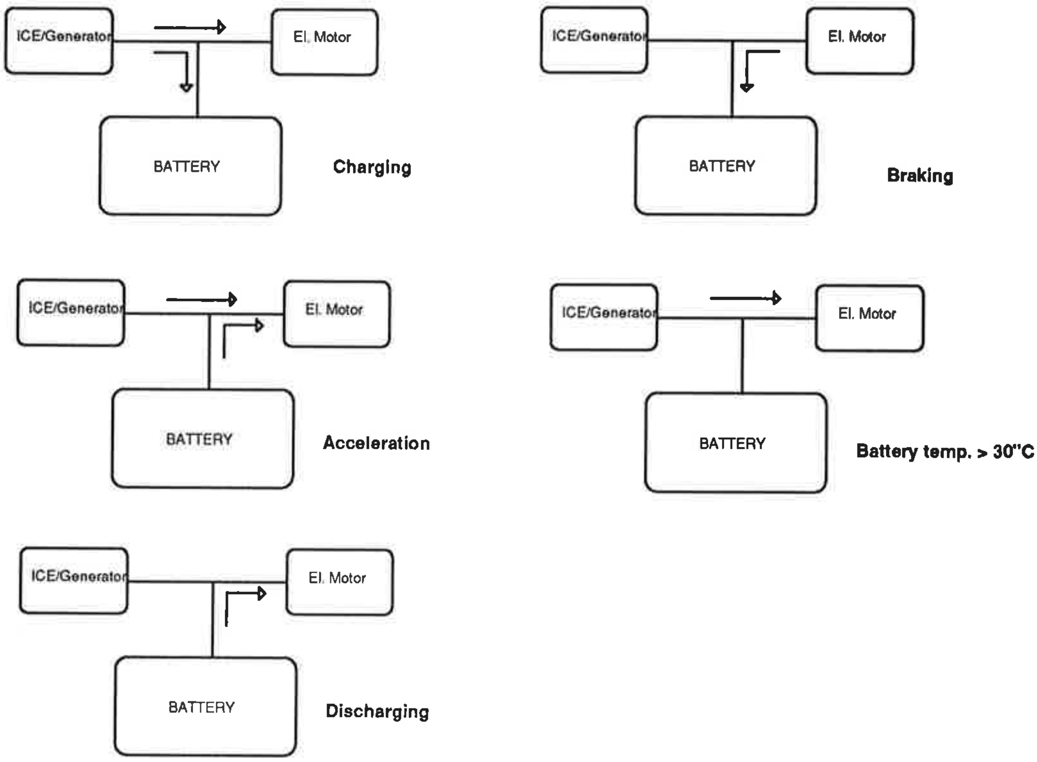

Figure 4.1 *Power flows in the hybrid vehicle drivetrain, during different operating modes.*

Battery charge limits

Overcharged, a battery will produce explosive gas, and the charge energy will turn to heat. At the other end, when SoC is close to zero, other unfavorable things can happen . Continuing to discharge, one or more cells in the battery may reverse, and this will soon put an end to the life of the battery.
Therefor, the battery should be kept between 90-20% SoC.

Table 4.1 *Structuring, using top-down approach, in order to get a manageable controller for the problem.*

Problem definition	Control principles	Control variables	Measured variables
Increase battery life and improve vehicle performance.	Battery SoC should be kept between 20-90%. Turn the generator on at SoC<20% and off at SoC>=90%.	Demand Field current Armature voltage	State of Charge
	Current demand from the motor can be greater than battery current capacity. Short time extra current supply from the *genset*.	Demand	Motor current
	Charge current from motor or generator is greater than battery charge-current limit. Dump excessive current in resistor.	Max. charge current	Motor charge current Genset charge current
	Battery temperature is too high. Relieve battery by letting the generator take over battery load.	Demand Field current	Motor current Genset current Battery temperature

4.2 Structuring the system

I use the *top-down* approach as described in chapter 3.2.
Table 4.1 show the choices of control principles, control variables and measured variables. Below follows some explanations of the choices.

Problem definition

This definition is given in the thesis specification as an aim for the control strategy.

Control principles

These four control principles will help us to solve the problem of optimizing battery life and vehicle performance.

Control variables

I. The three variables demand, field current and armature voltage are synchronously controlled by a relay which turns the *genset* on and off at the two break points .

II. Controlling demand (the throttle) for maximum torque, gives extra power at current peaks from the propulsion motor.

III. Depending on what battery you use the maximum charge current varies. Lead-acid batteries also depend on SoC.

IV. Here I use the field current to keep the *genset* at constantly 500 rad/s, and demand controls the *genset* current with propulsion motor current as reference.

Measured variables

I. SoC is input to a charge relay which decides when to charge the battery.

II. When motor current exceed 100 A, the generator delivers extra power.

III. Measurement of motor and generator charge currents for decision of dumped currents.

IV. Measuring battery temperature tells us when it passes high limits. Motor current is reference value, and generator current is feedback value.

5. Controllers

There are two common design methods to develop a linear controller [4]. *Pole Placement* and *Linear Quadratic Control.*
Using pool placement, we can use state feedback or output feedback and place the poles of the closed-loop system for desired behavior.
Linear quadratic controllers can handle gaussian disturbances well and uses a loss function as base for making the controller. The weighting matrixes in the loss function should come from physical arguments. This is not always the fact, which then makes it hard to evaluate the controller.

5.1 Linearization

Seen in control theory terms, the genset is a non-linear second order transfer function. A way to control it is to linearize the system [5], and use a linear controller. This will work well around the linearization point, but if you want to control your system far away from this point, the controller might not work satisfactorily.

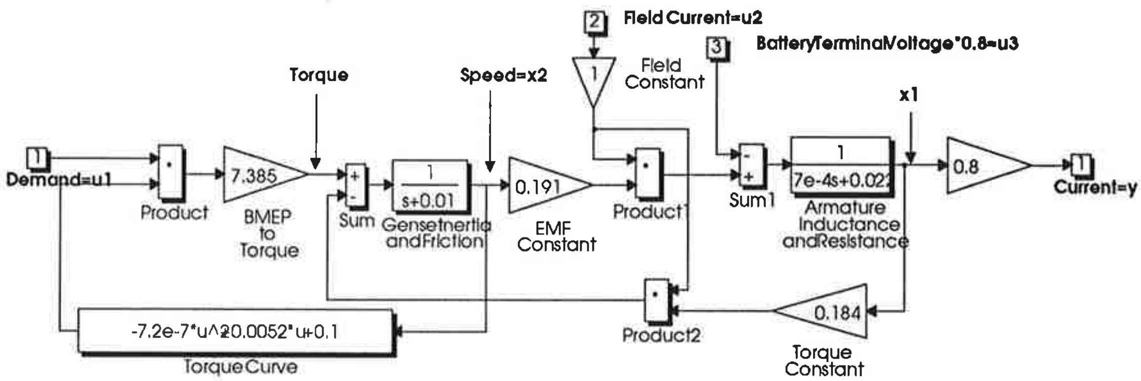

Figure 5.1 *Genset in Simulink block symbols.*

Figure 5.1 shows the genset in block symbols. To make a linear model of genset we define the states and inputs.

$$\begin{cases} \text{Current} \cdot 0.8 = x_1 \\ \text{Speed} = x_2 \\ \text{Demand} = u_1 \\ \text{Field Current} = u_2 \\ \text{Battery Terminal Voltage} \cdot 0.8 = u_3 \end{cases}$$

Variable u_3 can be seen as an input, but will not be used in this sense.

The non-linear state space equations are now derived directly from the system shown in figure 5.1.

$$7\times 10^{-4}\dot{x}_1 = -0.022x_1 + 0.191x_2u_2 - u_3$$
$$\dot{x}_2 = -0.01x_2 + 7.385u_1(-7.2\times 10^{-7}x_2^2 + 0.0052x_2 + 0.1) - 0.184x_1u_2$$

This can be simplified to

$$\begin{aligned}\dot{x}_1 &= -31.4x_1 + 272.8x_2u_2 - 1428.6u_3 \\ \dot{x}_2 &= -0.01x_2 - 5.3\times 10^{-6}x_2^2u_1 + 0.0384x_2u_1 + 0.738u_1 - 0.184x_1u_2\end{aligned} \tag{5.1}$$

I have chosen the linearization point

$$\begin{cases} x_1^0 = 50\ [\mathrm{A}] \\ x_2^0 = 265\ [\mathrm{rad/s}] \\ u_1^0 = 2\ [\max = 3.62] \\ u_2^0 = 2\ [\mathrm{A}] \\ u_3^0 = 100\ [\mathrm{V}] \end{cases} \tag{5.2}$$

We define the deviation from the linearization point (5.2) as

$$\Delta x \equiv x - x^0$$
$$\Delta y \equiv y - y^0$$

and the functional matrix as

$$f'(x) = \begin{bmatrix} \dfrac{\partial \dot{x}_1}{\partial x_1} & \dfrac{\partial \dot{x}_1}{\partial x_2} \\ \dfrac{\partial \dot{x}_2}{\partial x_1} & \dfrac{\partial \dot{x}_2}{\partial x_2} \end{bmatrix} + \begin{bmatrix} \dfrac{\partial \dot{x}_1}{\partial u_1} & \dfrac{\partial \dot{x}_1}{\partial u_2} & \dfrac{\partial \dot{x}_1}{\partial u_3} \\ \dfrac{\partial \dot{x}_2}{\partial u_1} & \dfrac{\partial \dot{x}_2}{\partial u_2} & \dfrac{\partial \dot{x}_2}{\partial u_3} \end{bmatrix}$$

If we insert the linearization point values in the functional matrix we get

$$\Delta \dot{x} = \begin{bmatrix} -31.4 & 545.7 \\ -0.368 & 0.0612 \end{bmatrix} \Delta x + \begin{bmatrix} 0 & 72.2 \cdot 10^3 \\ 10.5 & -9.2 \end{bmatrix} \Delta u \qquad (5.3)$$

$$\Delta y = \begin{bmatrix} 0.8 & 0 \end{bmatrix} \Delta x$$

and with the states and inputs written out we get

$$\begin{bmatrix} \Delta \dot{Current} \\ \Delta \dot{Speed} \end{bmatrix} = \begin{bmatrix} -31.4 & 545.7 \\ -0.368 & 0.0612 \end{bmatrix} \begin{bmatrix} \Delta Current \\ \Delta Speed \end{bmatrix} + \begin{bmatrix} 0 & 72.2 \cdot 10^3 \\ 10.5 & -9.2 \end{bmatrix} \begin{bmatrix} \Delta Demand \\ \Delta Field\ Current \end{bmatrix}$$

$$[\Delta Current] = \begin{bmatrix} 0.8 & 0 \end{bmatrix} \begin{bmatrix} \Delta Current \\ \Delta Speed \end{bmatrix}$$

(5.4)

This is the linearized system in state space form from which we can now get bode diagrams, root-locus plots and other helpful tools to analyze the system. The pool-zero map for this system is showed in figure 5.2.

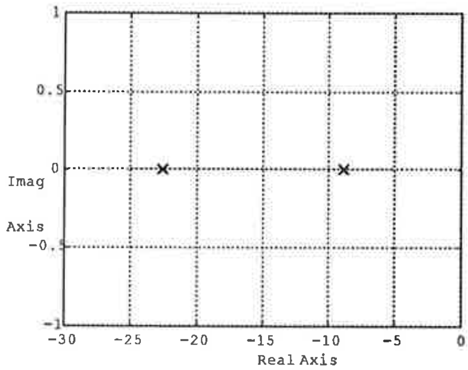

Figure 5.2 *Pool-zero map for system (5.3).*

Alternative linearization point

As the Genset is a quite non-linear system, I have chosen an alternative linearizaton point at

$$\begin{cases} x_1^0 = 125\ [A] \\ x_2^0 = 500\ [rad/s] \\ u_1^0 = 1.62\ [max = 3.62] \\ u_2^0 = 1.1\ [A] \\ u_3^0 = 102.4\ [V] \end{cases} \qquad (5.5)$$

Inserting these values in the functional matrix as described above we get

$$\Delta \dot{x} = \begin{bmatrix} -31.43 & 300.14 \\ -0.202 & 0.0436 \end{bmatrix} \Delta x + \begin{bmatrix} 0 & 136.43 \cdot 10^3 \\ 18.6 & -23 \end{bmatrix} \Delta u$$
$$\Delta y = \begin{bmatrix} 0.8 & 0 \end{bmatrix} \Delta x \tag{5.6}$$

This is the state space representation for the new linearization point.
The corresponding pool-zero map is showed in figure 5.3.

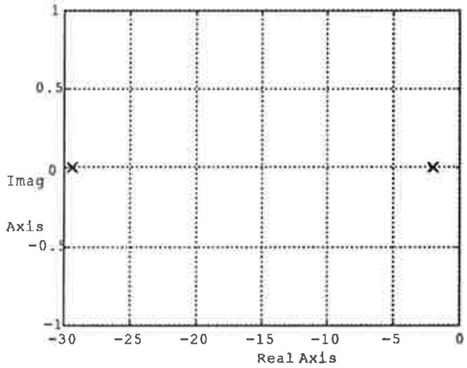

***Figure 5.3** Pool-zero map for system (5.6).*

To get a idea of how the two different linearizations correspond to the real system, we take a look at the step response for the three systems.

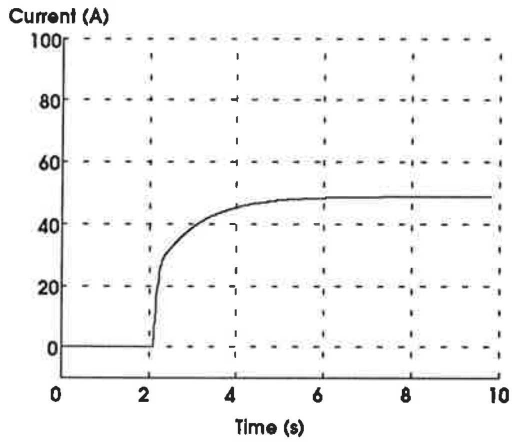

Figure 5.4 *Step response of the real genset system*

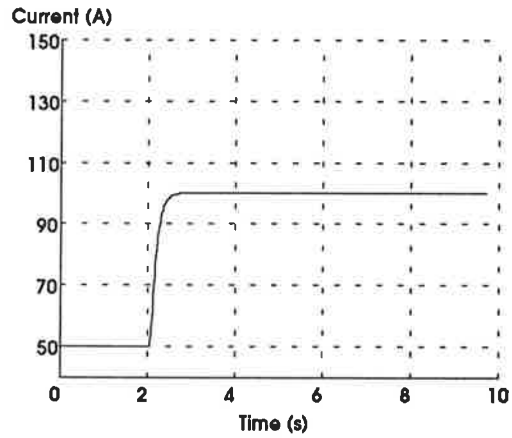

Figure 5.5 *Step response of the linearization point (5.2).*

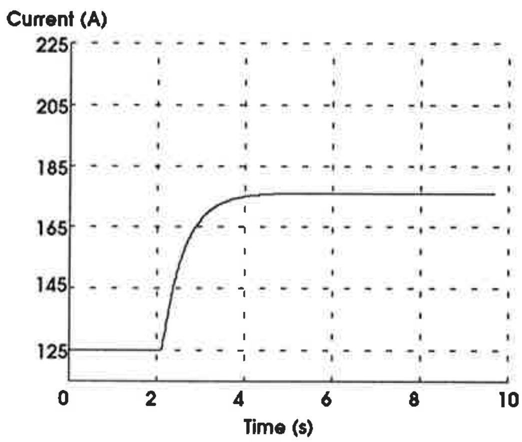

Figure 5.6 *Step response of the linearization point (5.5).*

Comparing the real system step response to linearization point (5.2) show that the linearization point (5.2) only contains the fast mode of the Genset system, while the linearization point showed in 5.6 also contains the slow mode.

5.2 PID

I have chosen pole placement design, implemented in a PID-Controller. PID-Controllers are common in electric motor applications, easy to work with and satisfy the needs to control a second order system as the genset.

Figure 5.7 shows how the controller is built up. What we want to control is the charge current I, but I is kept in open loop. The reason for this is that we need to control the two engine states, speed and torque, in order to obtain optimal emissions and consumption. A solution with cascade-control is not possible due to too long time constants, so the charge-current I has to be controlled indirectly with the trajectories.

We chose Iref by concerning both the overall optimal charge-current (fig 3.7), and the battery tolerance to heat and charging.
The reference current Iref is then transformed to the ideal torque and speed, in the two trajectories. This information is obtained from the engine mapping described in chapter 3.1. The PID-controllers with state feedback are used to control the two engine states, torque and speed.

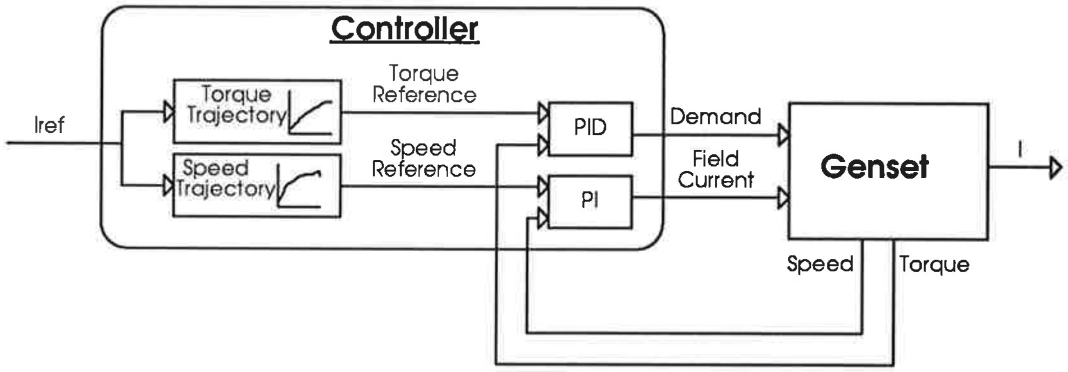

Figure 5.7 *Principle of State feedback control for genset current.*

The two PID-controllers use integration anti-windup and bumpless transfer to generate the control signals demand and field current.

To prevent the battery from overheating (discussed in chapter 4.1) we can make a change in the control mode. From controlling the genset current with a constant current Iref as reference , shown in figure 5.7, we can use the motor current as reference current, figure 5.8. With this change in the references for the controller we can now minimize the energy outlet from the battery — the car is now driven with the current from the genset — and in this way prevent the battery from overheating.

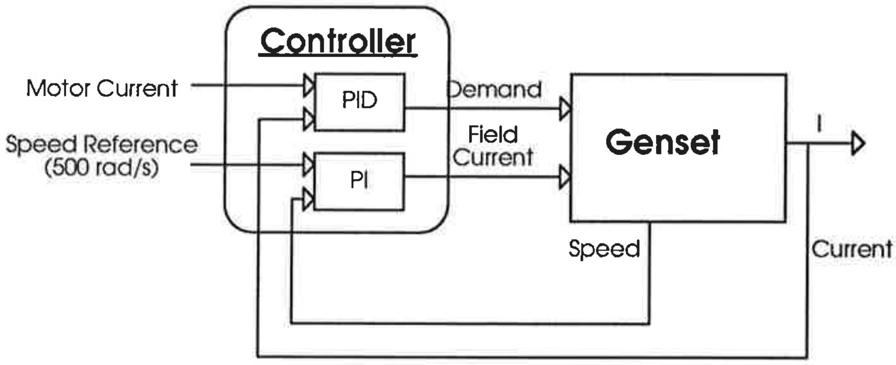

Figure 5.8 *Control mode for limiting battery temperature.*

5.3 Tuning

A PID controller can be described as

$$U(s) = K_c\left[\beta u_C(s) - Y(s) + \frac{1}{sT_i}(U_c(s) - Y(s)) + \frac{sT_d}{1 + sT_d / N}(\gamma U_c(s) - Y(s))\right] \quad (5.7)$$

To make the system with PID controllers work well we have to determine suitable values of the controller parameters. The parameters are $K_c, T_i, T_d, N, T_t, \beta, \gamma, u_{\min}, u_{\max}$. The primary parameters are

- Controller gain K_c
- Integral time T_i
- Derivative time T_d

Maximum derivative gain can be given a fixed default value e.g. $N = 10$. The tracking time constant can be chosen in the range $T_d \le T_t \ge Ti$. Parameters $u_{\min}, u_{\max}$ should be chosen inside the saturation limits. Parameters β and γ can position the zeros of the transfer function arbitrarily and are then chosen between 0 and 1. When no positioning of zeros is used, they are chosen $\beta = 1$ and $\gamma = 0$.

Model based tuning

When we have a mathematical model of the system, the parameters can then be computed using pool placement [6].

Starting with the PID controller which controls the demand, shown in figure 5.8.
Figure 5.9 show the bode plot for this system, and we can tell that the phase-margin for the system is about 30 degrees.

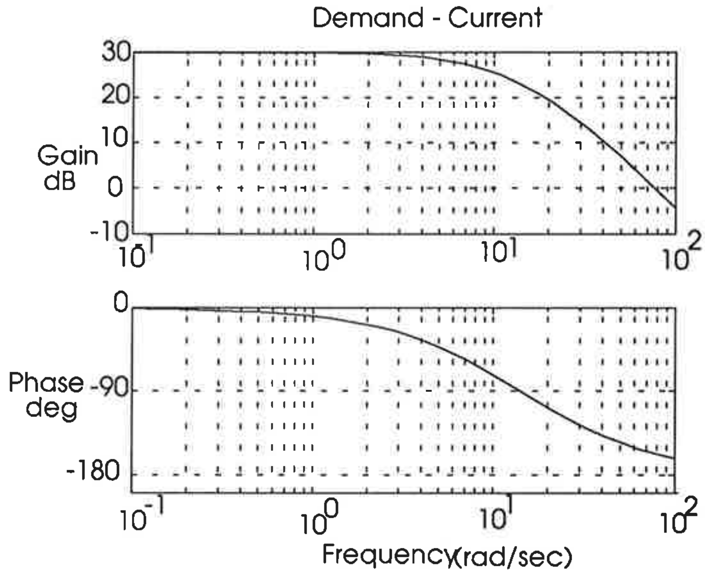

Figure 5.9 *Bode plot for transfer function from demand to current, described in (5.8).*

The transfer function for the system, demand to current, can be described as

$$Y(s) = \frac{4540}{s^2 + 31.4s + 199} U(s) \tag{5.8}$$

at linearization point (5.2).

In algebraic terms we can write this equation as

$$Y(s) = G_p(s) U(s) \tag{5.9}$$

were G_p is the transfer function

$$G_p = \frac{b}{s^2 + a_1 s + a_2}$$

Using the controller (5.7) in a simplified form, and eliminating $U(s)$ between (5.7) and (5.9) gives

$$Y(s) = G_p(s) K_c (\beta + \frac{1}{sT_i} + \gamma s T_d) U_c(s) - G_p(s) G_c(s) Y(s)$$

where

$$G_c(s) = K_c \frac{1 + sT_i + s^2 T_i T_d}{sT_i} \tag{5.10}$$

is the controller transfer function hence

$$(1+G_p(s)G_c(s))Y(s) = G_p(s)K_c(\beta + \frac{1}{sT_i} + \gamma sT_d)U_c(s)$$

The characteristic equation for the closed loop system is

$$1+G_p(s)G_c(s) = 1+\frac{bK_c(1+sT_i+s^2T_iT_d)}{sT_i(s^2+a_1s+a_2)} \tag{5.11}$$

which can be simplified to

$$s^3+(a_1+bK_cT_d)s^2+(a_2bK_c)s+\frac{bK_c}{T_i}=0 \tag{5.12}$$

The closed loop system is thus of third order. An arbitrary characteristic polynomial can be obtained by choosing the controller parameters. Specifying the closed loop characteristic equation as

$$(s^2+2\zeta\omega s+\omega^2)(s+\alpha\omega) = s^3+(2\zeta+\alpha)\omega s^2+(1+2\zeta\alpha)\omega^2 s+\omega^3\alpha = 0 \tag{5.13}$$

Equating coefficients of equal powers of s in (5.12) and (5.13) gives the equations

$$a_1+bK_cT_d = (2\zeta+\alpha)\omega$$
$$a_2+bK_c = (1+2\zeta\alpha)\omega^2$$
$$\frac{bK_c}{T_i} = \alpha\omega^3$$

Solving these linear equations we get

$$\begin{cases} K_c = \dfrac{(1+2\alpha\zeta)\omega^2-a_2}{b} \\ T_i = \dfrac{(1+2\alpha\zeta)\omega^2-a_2}{\alpha\omega^3} \\ T_d = \dfrac{(\alpha+2\zeta)\omega-a_1}{(1+2\alpha\zeta)\omega^2-a_2} \end{cases} \tag{5.14}$$

We now have the equations to tune the PID. What we need now, is a way to place the pools of the closed loop system, described in (5.13).

One way of placing the pools is to arrange them as a Bessel-polynomial of third order [7]. This might give us a nice step-response for the output current. Using the Bessel-polynomial and the root-locus plot for pool placement we get

$$\begin{cases} \zeta = 0.72 \\ \omega = 21.8 \\ \alpha = 0.91 \end{cases}$$

If we insert these values in (5.14) we get

$$\begin{cases} K_c = 0.146 \\ T_i = 95 \times 10^{-3} \\ T_d = 22 \times 10^{-3} \end{cases} \tag{5.15}$$

This will give us the step-response shown in figure 5.10.

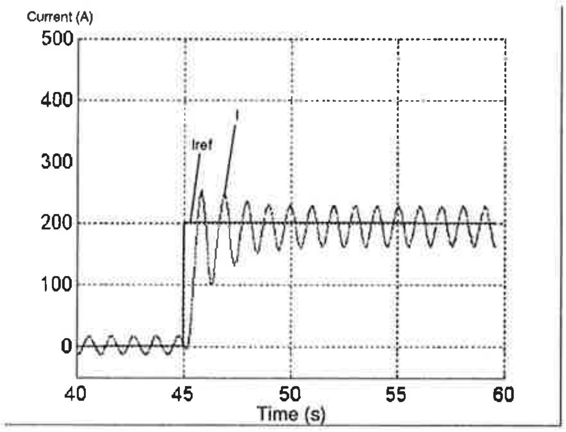

Figure 5.10 *Step-response of genset current, when the controller is tuned with Bessel coefficients.*

The step response received from the Bessel polynomial is unstable. If we take a look at the closed-loop pools, figure 5.11, we find that they are well damped ($\zeta = 0.72$). But changing the slowest pole in the system from $(s+8.8)$ to $\omega = 21.8$ is to much, and the system becomes unstable.

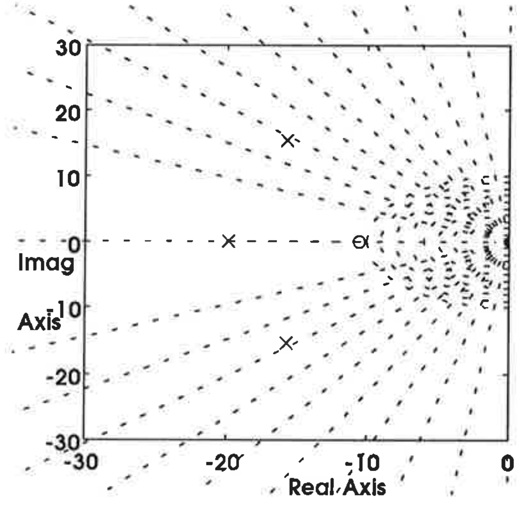

Figure 5.11 *Closed-loop pools for the system (5.8) controlled with parameters (5.15) obtained from Bessel polynomial.*

Taking a look at equation (5.12) will show that it is possible to make a Bessel-tuned controller as slow as $\omega = 12.9$ rad/s, e.g. 50% faster than the original system. Trying out the corresponding parameters obtained from Bessel polynomial still gives an unstable system. The reason for this is that the linearized system (5.3), is a poor representation of the real genset system. The alternative linearization point (5.5), lies closer to the real system working point (speed = 500 rad/s). It also gives a better estimation of the real system behaviour (slower pools). The transfer function for the system, demand to current, at the alternative linearization point (5.5) is

$$G(s) = \frac{4466}{s^2 + 31.4s + 59.3} \tag{5.16}$$

I have tried several different ways to place the closed loop pools. For a nice step response we can chose $\zeta = 0.9$. This gives us a well damped system, $\omega = 4$ will make the closed loop system twice as fast as if no feedback were used, and finally choosing $\alpha = 6.85$ lets the fast pool remain fast.

These parameters seem to work well.

$$\begin{cases} \zeta = 0.9 \\ \omega = 4 \\ \alpha = 6.85 \end{cases} \tag{5.17}$$

If we insert these values in equation (5.14) we get

$$\begin{cases} K_c = 34.5 \cdot 10^{-3} \\ T_i = 0.351 \\ T_d = 20.8 \cdot 10^{-3} \end{cases} \tag{5.18}$$

We now have a closed loop system with the transfer function

$$G(s) = \frac{\alpha\omega^3(1+\beta s T_i + \gamma s^2 T_i T_d)}{(s^2 + 2\zeta\omega s + \omega^2)(s + \alpha\omega)}$$

As we see the zeros of the transfer function can be placed arbitrarily by choosing the parameters β andγ . If we chose $\gamma = 0$ we can cancel the pole at $s = -\alpha\omega$ by choosing

$$\beta = \frac{1}{\alpha\omega T_i} = 0.104 \tag{5.19}$$

The response to the command signal is thus a pure second order response. This is showed in figure 5.12.

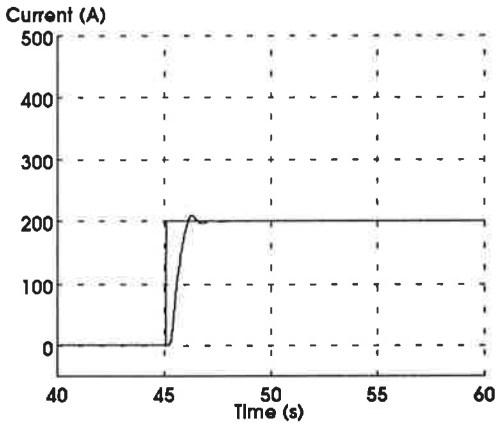

Figure 5.12 *Step-response of the genset current with controller parameters (5.18)*

Taking a look at the closed looped pools for parameters (5.18). Figure 5.13 show the well damped complex poles, and the pool-zero cancellation.

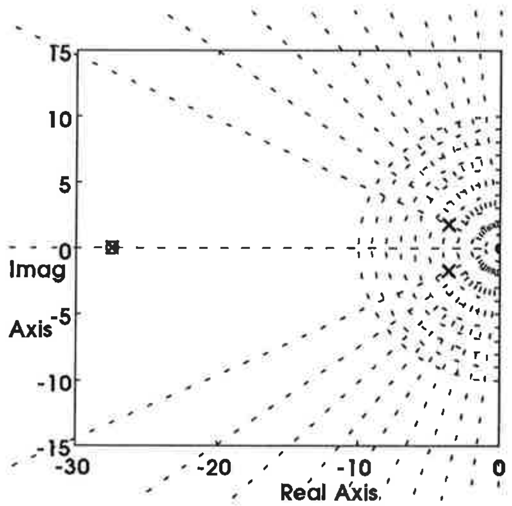

Figure 5.13 *Closed-loop pools for the system (5.6) controlled with parameters (5.18).*

I have chosen the parameters (5.18) and (5.19) for the linearized system (5.6). This is implemented in the current-controller in figure 5.8.
In the torque-controller, figure 5.7, I have implemented the same parameters but with a scaling factor of 300 on the input signals torque reference and torque.

Manual tuning

For the second PID-controller, controlling field current, we have the bode plot field current-speed, according to the state space representation (5.6). This is shown in figure 5.14. The phase here starts at 180 degrees (or -180 degrees) and this implies that we must have a positive feedback in order to control the system.

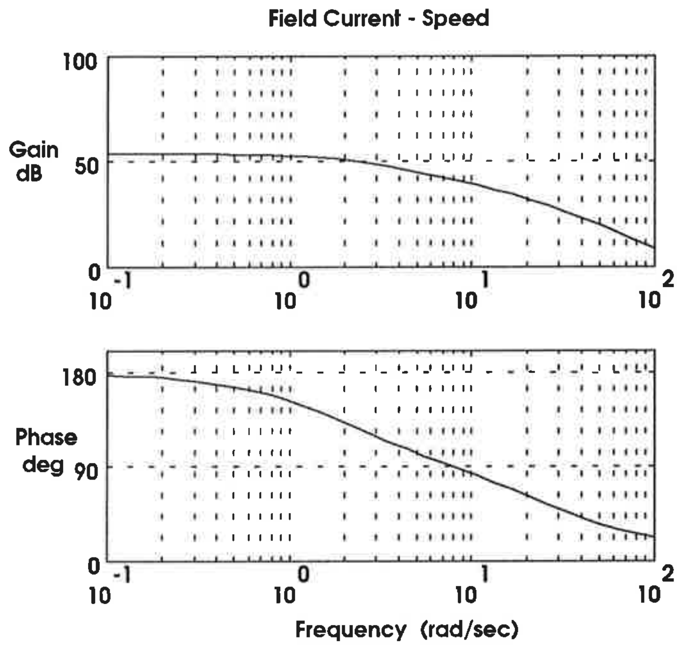

Figure 5.14 *Bode plot for transfer function from field current to speed, described in (5.20).*

The transfer function for the system, field current to speed, can be described as

$$Y(s) = -23\frac{s+1.23\times10^3}{s^2+31.4s+59.3}U(s) \tag{5.20}$$

If we take a look at how the field current influences the genset current (se equation (5.4)) we find that a small change in the field current has a major impact on the dynamics of genset current. To avoid huge transients in output current I have limited the reference signal slew-rate to 30 rad/s.
The transfer function for this system, field current to genset current, can be described as

$$Y(s) = -109.1\times10^3\frac{s-0.09}{s^2+31.4s+59.3}U(s) \tag{5.21}$$

Another complication is detected when we look at the numerator of (5.21). The system has a zero on the right hand side of the s-plane (s-0.09), and this show that it is a non minimum phase system.

I have chosen to place the pools as shown in figure 5.15.

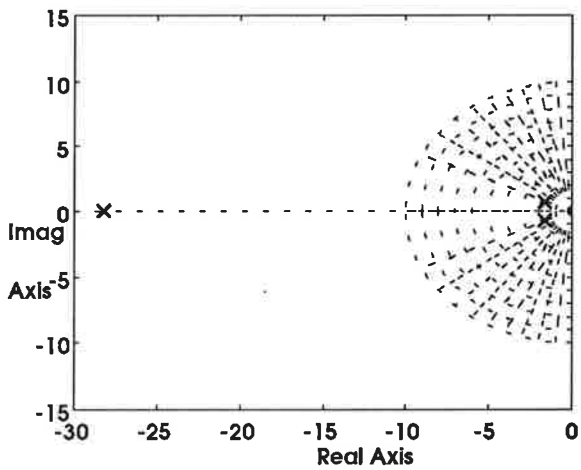

Figure 5.15 *Closed loop pools for the system (5.20) controlled with parameters (5.22).*

The poles close to zero give the system a slow behaviour. This is desirable in order to avoid the large transients that otherwise would appear in the output current.

The corresponding parameters are

$$\begin{cases} K_c = 1/800 \\ T_i = 0.4 \\ T_d = 0 \end{cases} \qquad (5.22)$$

5.4 Stability robustness

The simulation model of the system genset, is a simplification of a real ICE/generator. The uncertainty of how the system behaves, especially at high frequencies, can be large. This is caused by unknown behavior of, for example actuators. Because of this it is important that the control system has built in robustness. This means that the system should remain stable, even though reality differs some from the model.

Robustness criteria

A way to find out how large the model uncertainty is allowed to be, can be stated by the following criteria [5].The complementary sensitivity function is given by

$$Q(s) = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)}$$

were $G_c(s)$ is the transfer function of the controller, and $G_p(s)$ is the transfer function for the linearized process. The real system (or process), can be written as

$$G_p^0(s) = G_p(s)(1+\Delta G_p(s))$$

What we have here is a relative model uncertainty at$\Delta G_p(s)$. The question is how large the model uncertainty $\Delta G_p(s)$ can be before the closed-loop system becomes unstable. The answer is given by (5.24)

$$|Q(i\omega)| < \frac{1}{|\Delta G_p(i\omega)|} \forall\omega \tag{5.24}$$

If (5.24) is valid, the closed-loop system obtained by $G_p^0(s)$ and $G_c(s)$ will be stable.

Test of stability

First we have to estimate the relative model uncertainty$\Delta G_p(s)$.
I made the assumption that the real system is twice as slow as the one I have as model, but with same static gain. This gives us

$$G_p^0(s) = \frac{1107}{s^2+15.7s+14.7} \tag{5.25}$$

With this assumption applied on the system , with PID-controller controlling genset current in figure 5.8, we get

$$\Delta G_p(s) = \frac{\dfrac{1107}{s^2+15.7s+14.7} - \dfrac{4466}{s^2+31.4s+59.3}}{\dfrac{4466}{s^2+31.4s+59.3}} = \frac{-0.75s^2-7.9s}{s^2+15.7s+14.7}$$

The PID-controller can be described as

$$G_c(s) = K_c\left(\frac{1+sT_i+s^2T_iT_d}{sT_i}\right)$$

With controller parameters , and system , the complementary sensitivity function becomes

$$Q(s) = \frac{3.2s^2+154.1s+439}{s^3+34.6s^2+213.4s+439}$$

The answer to the question if the system is stable, can now be viewed as a plot, figure 5.16, of condition (5.24), were the two curves are not to be crossed.

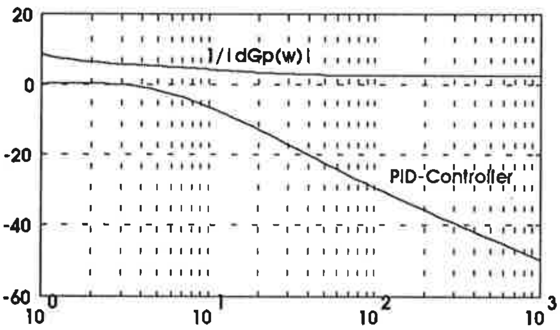

Figure 5.16 *Test of stability robustness for PID-controller, during model error (5.25).*

As we se there is no risk of instability for the PID-controller during the model error (5.25).

Making the same assumptions for the PI-controller in figure 5.7, that the real system is twice as slow as the one modeled, but with same static gain, we get

$$G_p^0(s) = \frac{-23s-7011}{s^2+15.7s+14.7} \qquad (5.26)$$

and applied on system , the relative model uncertainty becomes

$$\Delta G_p(s) = \frac{20.1 \cdot 10^3 s^2 + 222.9 \cdot 10^3 s - 6.9}{23s^3 + 28.6 \cdot 10^3 s^2 + 444.4 \cdot 10^3 + 415.7 \cdot 10^3}$$

The PI-controller can be described as

$$G_c(s) = K_c \left(\frac{1 + sT_i}{sT_i} \right)$$

With controller parameters , and system , the complementary sensitivity function becomes

$$Q(s) = \frac{29 \cdot 10^{-3} s^2 + 35.4s + 88.4}{s^3 + 31.4s^2 + 94.7s + 88.4}$$

We can now check stability of the closed-loop by plotting the condition (5.24).

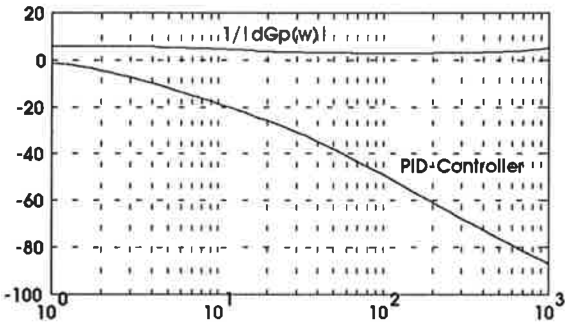

Figure 5.17 *Test of stability robustness for PI-controller, during model error (5.26).*

Figure 5.17 show that the PI-controller handles model errors with up to 100% slower pools in a real system, without losing stability.

6. Results

A comparison between the optimized and a basic controller has been performed. The basic controller work in the same way as the optimized, but does not have any of the control strategies implemented. The comparison show that there are gains to make in fuel consumption and emission reduction, using the developed optimized controller.

Simulations of four charge cases have been performed. The results are presented in terms of fuel consumption and emissions. Conclusions from the results show the optimal operation of the genset.

6.1 Comparison between a basic and optimized controller

To get a view of how the optimized controller works, I have made a comparison between a basic and optimized controller.
The basic controller does not have an optimized strategy, but simply charge the battery with a constant charge current through the full drive cycle.

Figure 6.1 show the comparison between the basic and optimized controller, regarding to emissions and fuel consumption. The test is performed with drive cycle FTP75, and the battery SoC reach the same final value in both cases, e.i. the same energy amount is put into the battery.

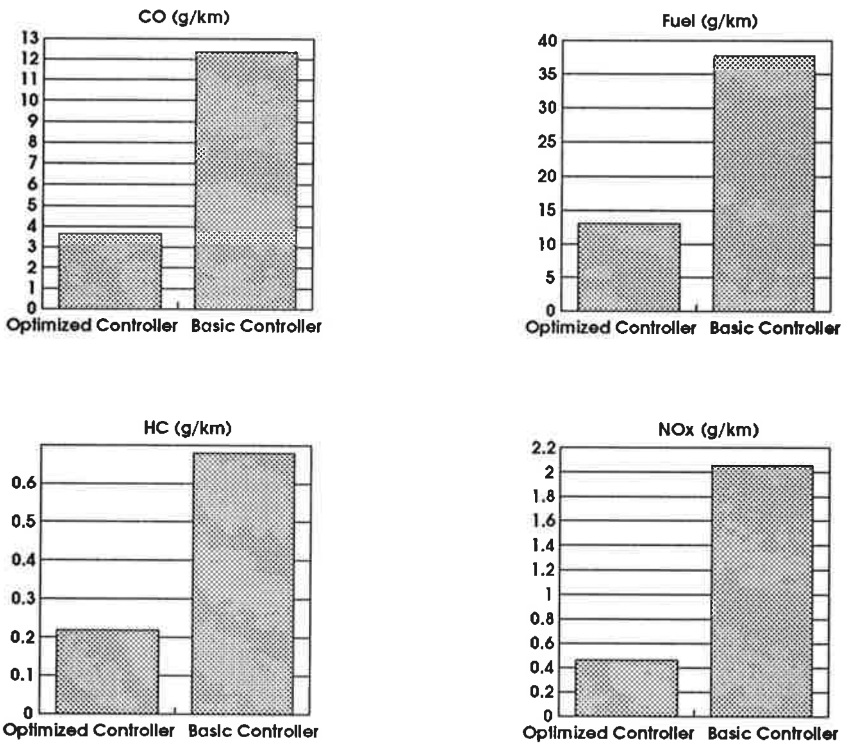

Figure 6.1 *Fuel and exhaust emission comparison of optimized control and basic control for genset. Vehicle is driven on FTP 75 drive cycle and charge current is 63 A.*

6.2 Simulation and evaluation of four different charge conditions

In order to find out how different charge conditions influence the fuel-consumption and emissions, four cases are simulated. In all cases the drive cycle is a mix of FTP75 and US: highway.
The different conditions in the four cases are as follows

1. Genset charge when SoC < 20%, but is turned off when SoC >= 90% and remain off during the discharge cycle. Charge current is 116 A. When battery temperature reach 55°C, the controller switches to battery overheat control mode. The controller switch back to normal at battery temperature 50 °C. Figure 6.2.

2. Genset charge when SoC < 20%, charge current is 116 A, and keep running after SoC has reached 90%.
   The genset is now able to support the battery when battery current > 100 A, e.i. the car accelerate. When battery current < 100 A, the genset current is at idle. When battery temperature reach 55°C, the controller switches to battery overheat control mode. The controller switch back to normal at battery temperature 50°C. Figure 6.3.

3. The battery state of charge is kept constant at 50%. Genset is running through the entire drive cycle. Charge current is self adjusted to the average motor current[1]. Genset supports the battery at battery current > 100 A. When battery temperature reach 55°C, the controller switches to battery overheat control mode. The controller switch back to normal at battery temperature 50 °C. Figure 6.4.

4. This is the same as case 2, but here we assume that we have a Ni-Cd battery instead of a lead-acid. When battery temperature reach 30°C, the controller switches to battery overheat control mode. The controller switch back to normal at battery temperature 28°C. Figure 6.5.

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[1] The motor current is filtered through a low-pass filter. This is the reference to a PI-controller which output is the reference charge current Iref.

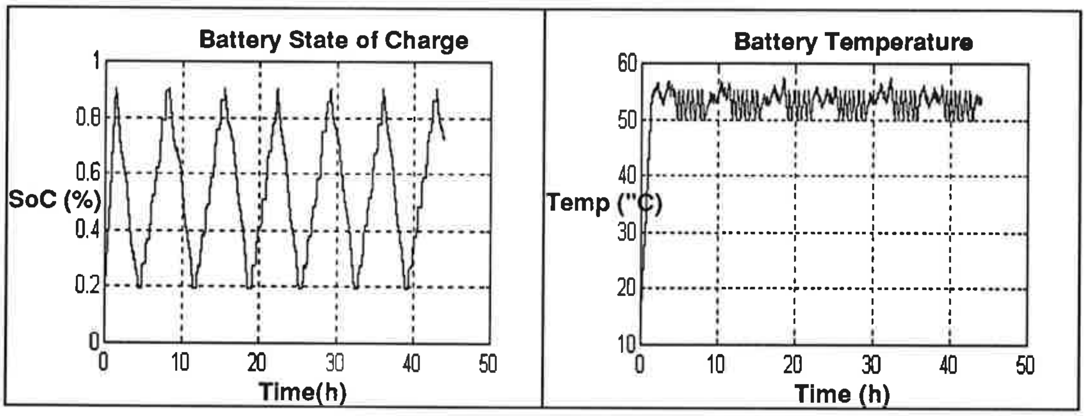

Figure 6.2 *Simulation of case 1, battery is charged to 90 % and then discharged down to 20 %. This is repeated through the entire drivcycle. The temperature reach the limit at 55 ° C and battery overheat mode is turned on, but release at 50 ° C.*

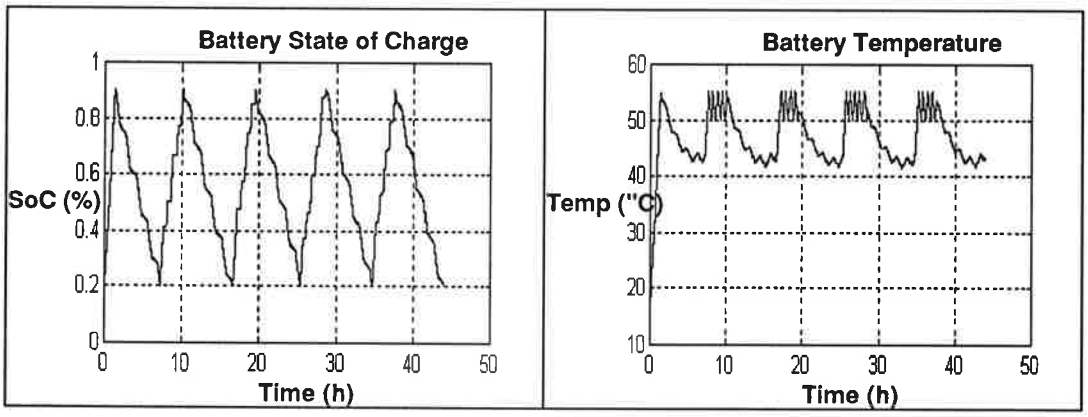

Figure 6.3 *Simulation of case 2, battery is charged to 90 % and then discharged down to 20 % but with assistance from generator at acceleration. The temperature reach the limit at 55 ° C and battery overheat mode is turned on, but release at 50 ° C.*

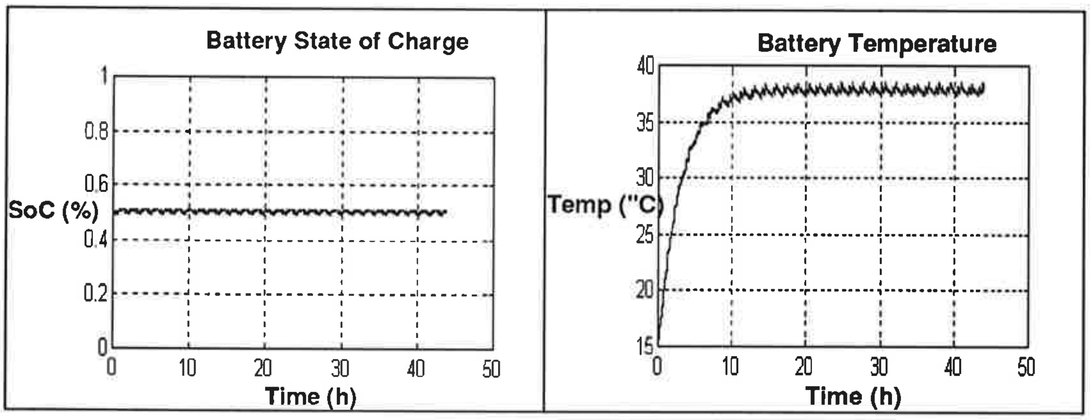

Figure 6.4 *Simulation of case 3, battery SoC is kept constant and the temperature never reach the upper temperature limit at 55 ° C.*

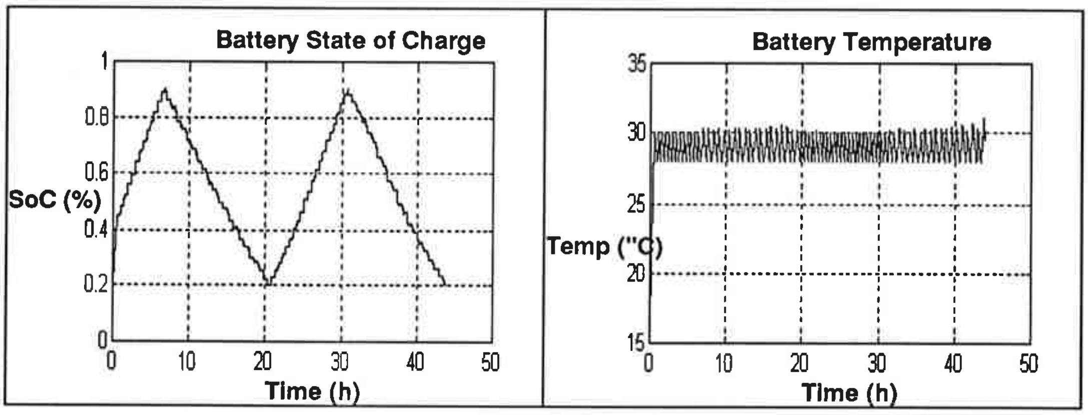

Figure 6.5 Simulation of case 4, battery is charged to 90 % and then discharged down to 20 % but with assistance from generator at acceleration. The temperature reach the limit at 30 ° C and battery overheat mode is turned on, but release at 28 ° C.

The simulation results from above are presented in table 6.1, in terms of fuel-consumption and emissions.

***Table 6.1** Fuel-consumption and emission results from simulations of case 1-4.*

g/km	Case 1	Case 2	Case 3	Case 4
NOx	0.95	1.56	0.52	1.28
HC	0.32	0.37	0.32	0.35
CO	5.39	6.94	4.14	6.50
Fuel	17.8	21.0	15.1	20.0

As we see from table 6.1, case number 3 is the overall winner in this test. The reason for this is that it manages to keep the battery temperature within the limits, without switching to the uneconomic battery overheat mode in the controller. In this mode the optimal trajectories can not be followed, and therefore the fuel and emission values get high.

If we compare case 1 and case 2 we notice something interesting. The difference between the two was that in case 1, the genset was turned off during the discharge cycle, but in case 2 it was kept running to complement the battery at vehicle acceleration. From table 1 we see that the gain in better acceleration cost quite a lot in fuel-consumption and emissions.

Case 4 sets the battery temperature limit to 30°C which suites the Ni-Cd battery. As we see the fuel and emission values are not in parity with case 3. This is due to that battery temperature limit is reached very often, and controller overheat mode is switched in.

It is interesting to compare the results from simulations to California emission limits [10], table 6.2. The following classifications exists

- Transitional Low Emission Vehicles (TLEV)
- Low Emission Vehicles (LEV)
- Ultra Low Emission Vehicles (ULEV)
- Zero Emission Vehicles (ZEV)

***Table 6.2** California Legislation new emission limits.*

g/km	**TLEV**	**LEV**	**ULEV**	**ZEV**
NOx	0.64	0.32	0.32	0
HC	0.24	0.24	0.12	0
CO	5.45	5.45	2.72	0

Comparing case 3 to (TLEV) show that the Hydro Carbon values are to high. This can easily be compensated for, by adjusting the weighting for Hydro Carbon in the weighting matrix. The values for Carbon Oxides ,Nitrogen Oxide and fuel-consumption may then become a little higher, but by iteration the weighting can be fitted to the emission limits.
We can also change components in the vehicle model and/or define new strategies in the controller to adjust the emission values.

7. Summary

7.1 Conclusions

For optimal fuel-consumption and emissions, we chose the genset charge current in figure 3.7 that gives the lowest fuel and emission values.
As the optimal charge currents tend to be found at high values, we must chose a battery not sensitive to high temperature and/or that have a high heat capacity. If we don't have access to such a battery, the charge method used in case 3 will give the best results.
Using the information above the hybrid vehicle should be equipped with a temperature resistant battery, charged with the overall optimal charge current, and controlled with the optimal strategies described in chapter 3 and 4.

7.2 Suggestions for future development

The hybrid vehicle simulation model can be further improved by changing some general parameters to more specific, for example in the battery.
The models of the motor and the generator can also be improved. This means implementation of the full dynamics for a separately magnetized DC-motor. Also the IC-engine model can be improved regarding to the torque-curve characteristics.

The genset mapping, described in appendix A, can be made automatically. This means writing a Matlab program that operates the engine through its entire register, and collects the corresponding charge currents. The program can then also calculate the torque and speed-trajectories for minimal emissions and fuel consumption.

8. References

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Appendix

A. Genset mapping

The genset mapping is done by running the IC-engine through its entire torque and speed-register collecting the corresponding charge currents.
The weighted values of emission, fuel consumption can be seen as a penalty function, and then the different speed and torque's have corresponding penalty values.
Comparing the charge current and penalty values gives an optimal speed-torque for every charge current.

Below follows a listing of collected data used for making the speed and torque-trajectories.

***Table A.1** Corresponding values for genset current=20 A*

Speed	Torque	Penalty
rad/s	Nm	%
523	9.8	22.0
500	9.8	21.3
450	9.8	19.3
400	10.0	16.7
350	10.4	12.9
300	11.1	10.0
250	12.1	9.4
200	14.0	9.1
150	17.6	9.5

***Table A.2** Corresponding values for genset current=40A*

Speed	Torque	Penalty
rad/s	Nm	%
523	14.5	26.3
500	14.7	25.6
450	15.3	24.4
400	16.1	22.4
350	17.4	18.5
300	19.2	15.6
250	21.9	16.0
200	26.3	16.9

Table A.3 Corresponding values for genset current=60 A

Speed	Torque	Penalty
rad/s	Nm	%
523	19.2	34.0
500	19.6	33.7
450	20.8	33.0
400	22.3	31.1
350	24.4	26.2
300	27.4	22.6
250	31.8	24.1

Table A.4 Corresponding values for genset current=80A

Speed	Torque	Penalty
rad/s	Nm	%
523	24.0	42.0
500	24.6	41.8
450	26.3	41.6
400	28.6	39.9
350	31.6	35.1
300	35.7	32.1

Table A.5 Corresponding values for genset current=100 A

Speed	Torque	Penalty
rad/s	Nm	%
523	28.8	50.0
500	29.7	50.3
450	31.9	50.9
400	34.9	49.6
350	38.8	44.9
315	42.0	42.2

Table A.6 Corresponding values for genset current=120A

Speed	Torque	Penalty
rad/s	Nm	%
523	33.7	59.1
500	34.8	59.8
450	37.6	60.5
400	41.2	59.4
350	46.1	52.7

***Table A.7** Corresponding values for genset current=140 A*

Speed	Torque	Penalty
rad/s	Nm	%
523	38.7	69.1
500	39.9	69.3
450	43.3	69.7
400	47.7	66.9
375	50.4	63.0

***Table A.8** Corresponding values for genset current=160 A*

Speed	Torque	Penalty
rad/s	Nm	%
523	43.6	78.3
500	45.1	78.0
450	49.1	77.5
400	53.2	74.2

***Table A.9** Corresponding values for genset current=180 A*

Speed	Torque	Penalty
rad/s	Nm	%
523	48.7	86.4
500	50.4	86.2
450	55.0	85.4
415	56.7	81.2

***Table A.10** Corresponding values for genset current=200 A*

Speed	Torque	Penalty
rad/s	Nm	%
523	53.7	94.8
500	55.7	94.4
450	60.3	87.2

B. Components used in simulation

In the Volvo hybrid vehicle simulation model the following components with corresponding data are used.

Battery

***Table B.1** Battery characteristics.*

Battery type	Max. capacity	Fully charged voltage	Max. discharge current	Thermal resistance	Heat capacity	Capacity temperature coefficient	Open circuit voltage	Fully charged battery internal resistans
ALCO 2200	Ah	V	A	°C/W	J/K	1/°C	V	mW
lead-Acid	150	120	400	0.2	40000	0.0001	126.7	24.7

Controller

***Table B.2** Controller, battery parameters.*

Upper temp limit	Lower temp limit	State of charge upper limit	State of charge lower limit	Max. charge current	Charge current
°C	°C	%	%	A	A
30	27	90	20	140	116

***Table B.3** Controller, field controller parameters.*

Gain Kc	Integration time Ti	Derivative time Td	Beta	Derivative divisor	Low limit saturation	High limit saturation
	t	t				
1/800	0.4	0	1	10	0	5

***Table B.4** Controller, demand controller parameters.*

Gain Kc	**Integration time Ti**	**Derivative time Td**	**Beta**	**Derivative divisor**	**Low limit saturation**	**High limit saturation**
	t	t				
0.0345	0.351	0.0208	0.104	10	0	3.63

Genset

***Table B.5** Genset characteristics.*

Inertia	**Friction**	**Max. speed**
kgm^2	Nm•s/rad	rad/s
1	0.01	523

***Table B.6** Internal Combustion Engine (ICE) characteristics.*

Max. Torque	**Bore**	**Stroke**	**Number of cylinders**
Nm	mm	mm	
70	81.0	90.0	2

***Table B.7** Generator characteristics.*

Torque constant	**EMF constant**	**Field constant**	**Internal resistance**	**Inductance**	**Thermal resistance**	**Heat capacity**
Nm/A	V/rps	Wb/A	Ω	H	°C/W	J/K
0.184	0.191	1.0	0.022	$7 \cdot 10^{-6}$	0.12	1350

Motor

Table B.8 DC-motor characteristics.

Motor	EMF constant	Torque constant	Field constant	Armature resistance	Armature inductance	Thermal resistance	Motor heat capacity
Unique	Vs/rad	Nm/A	Wb/A	Ω	H	°C/W	J/K
DR156	0.191	0.184	1	0.022	$7 \cdot 10^{-6}$	0.12	1350

Vehicle

Table B.9 Vehicle A parameters.

Vehicle mass	Max. brake force	Rolling resistance	Drag coefficient	Air density	Tire rolling radius	Road gradient
Kg	N	N/Kg	C_D	Kg/m^2	m	%
1134	500	0.005	0.38	1.2	0.2	0

Table B.10 Vehicle A gearbox.

	1st	2nd	3rd	Final drive
Gear ratio	2.7	1.5	1	3.8
Gear efficiency	0.96	0.97	0.98	0.95

Table B.11 Vehicle B parameters.

Vehicle mass	**Max. brake force**	**Rolling resistance**	**Drag coefficient**	**Air density**	**Tire rolling radius**	**Road gradient**
Kg	N	N/Kg	C_D	Kg / m^2	m	%
1588	500	0.005	0.5	1.2	0.2	0

Table B.12 Vehicle B gearbox.

	1st	**2nd**	**3rd**	**Final drive**
Gear ratio	2.7	1.5	1	3.8
Gear efficiency	0.96	0.97	0.98	0.95