Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

A Control System for Battery Charging in Buses

Examensarbete utfört i Fordonssystem
av

Therese Kjelldal

LiTH-ISY-EX--11/4475--SE
Linköping 2011

TEKNISKA HÖGSKOLAN
LINKÖPINGS UNIVERSITET

Department of Electrical Engineering
Linköping University
S-581 83 Linköping, Sweden

Linköpings tekniska högskola
Institutionen för systemteknik
581 83 Linköping

A Control System for Battery Charging in Buses

Examensarbete utfört i Fordonssystem
vid Linköpings tekniska högskola
av

Therese Kjelldal
LiTH-ISY-EX--11/4475--SE

Supervisor: **Michael Skarped**
Scania CV AB
Per Blommegård
Scania CV AB
Christofer Sundström
ISY, Linköpings Universitet

Examiner: **Lars Eriksson**
ISY, Linköpings Universistet

Linköping, June 8, 2011

Presentationsdatum

20110607

Publiceringsdatum (elektronisk version)

Institution och avdelning
Institutionen för systemteknik

Department of Electrical Engineering
Fordonssystem

Linköpings universitet

Språk

___ Svenska
_X_ Annat (ange nedan)

Engelska

Antal sidor

Typ av publikation

____Licentiatavhandling
_X_Examensarbete
____C-uppsats
____D-uppsats
____Rapport
____Annat (ange nedan)

ISBN (licentiatavhandling)

ISRN LiTH-ISY-EX--11/4475--SE

Serietitel (licentiatavhandling)

Serienummer/ISSN (licentiatavhandling)

URL för elektronisk version
http://www.ep.liu.se

Publikationens titel

A Control System for Battery Charging in Buses

Författare
Therese Kjelldal

Sammanfattning

A common configuration in buses is that the engine is placed in the rear of the bus and that the batteries are placed in the front of the bus due to optimization of the distribution of the weight. The long wires running between the engine and the batteries together with large power consuming units, such as fans and air condition units, result in voltage drops. The voltage drops contribute to the battery charging voltage level being lower than desired.

The aim with this thesis work is to implement a control system that increases the battery voltage level when the voltage drops occur. Measurements are performed on an articulated bus that is in focus throughout the whole thesis work. A model for the electrical circuit of the bus is created and used when investigating the stability of the control system. The control system is implemented in the bus, where also verification tests are performed.

The verification tests confirm that the control system raises the battery charging voltage to the desired level. The increased voltage level makes the batteries reach a higher state of charge in shorter time since the control system provides the batteries with more charge.

Nyckelord
PID controller, Battery voltage level, Buses.

Abstract

A common configuration in buses is that the engine is placed in the rear of the bus and that the batteries are placed in the front of the bus due to optimization of the distribution of the weight. The long wires running between the engine and the batteries together with large power consuming units, such as fans and air condition units, result in voltage drops. The voltage drops contribute to the battery charging voltage level being lower than desired.

The aim with this thesis work is to implement a control system that increases the battery voltage level when the voltage drops occur. Measurements are performed on an articulated bus that is in focus throughout the whole thesis work. A model for the electrical circuit of the bus is created and used when investigating the stability of the control system. The control system is implemented in the bus, where also verification tests are performed.

The verification tests confirm that the control system raises the battery charging voltage to the desired level. The increased voltage level makes the batteries reach a higher state of charge in shorter time since the control system provides the batteries with more charge.

Acknowledgements

I would like to thank my supervisors at Scania; Michael Skarped for being a great supervisor and supporting with interesting ideas and thoughts during the thesis work and Per Blommegård for great assistance and creative ideas of how to perform measurements on different places in the electrical circuit of the bus. I also would like to thank examiner Lars Eriksson and supervisor Christofer Sundström at the department of Vehicular Systems at Linköpings Universitet, for support and relevant comments when writing the report. Finally I would like to thank my family and friends for their great support.

Södertälje, June 8, 2011

Table of contents

Abbreviations

PWM
Pulse Width Modulated signals is a technique here used for controlling power to electrical devices.

ECU
Electronic Control Unit.

EMS
Engine Management System.

CAN
Control Area Network, a computer network protocol used in vehicles to send information between control units.

CPU
Central Processing Unit.

VCI
Vehicle Communication Interface.

1 Introduction

1.1 Background

In buses a common configuration is that the batteries are placed in the front of the bus and the engine is placed in the back of the bus. This placement is due to optimization of the distribution of the weight in the vehicle. An articulated bus, which will be in focus in this work, measure approximately 18 meters. This results in long wires between the alternator placed at the engine and the batteries placed in the front of the bus. Together with large power consuming units in the bus, such as air condition units and fans this will result in voltage drops in the charging circuit of the bus.

By analyzing data from normal operation it can be found that the battery charging voltage level that is 0.5-1 V below the desired level. In articulated buses the voltage drops are larger than in other buses, see box diagrams in Appendix A.

Today Scania's vehicles have an adaptive battery charging control system. The control system is adaptive in the sense that it adjusts the requested voltage level based on the estimated battery temperature [8]. This system is mostly adjusted for the truck segment, where the batteries are placed close to the engine. The voltage drops that occur in the charging circuit of buses will result in the voltage level at the batteries not being equal to the voltage level generated by the alternator. This leads to that considerations need to be taken to the significant differences between buses and trucks; buses have larger power consuming units and different placement of the batteries.

1.2 Problem

The problem that is studied throughout this report is to keep the charging voltage on a higher and correct level to compensate for the voltage drops that occur on the way from the alternator to the batteries. The problem is visualized in Figure 1, where the measured charging voltage at the batteries is on a desired level until a load of 140 A is applied to the system after approximately 60 seconds. A voltage drop occurs and the voltage does not reach the correct state until the power consuming unit is turned off after 100 seconds. The peaks that appear when the power consuming unit is turned on and off are caused by internal behaviours of the alternator. The controller inside the alternator is not fast enough to compensate for the sudden changes of the load applied to the system. An additional effect, seen in Figure 1 is that the more power that is consumed in the system, the more ripple there will be on the signal from the alternator. This causes the battery voltage in Figure 1 to have more ripple when the load of 140 A is applied to the system.

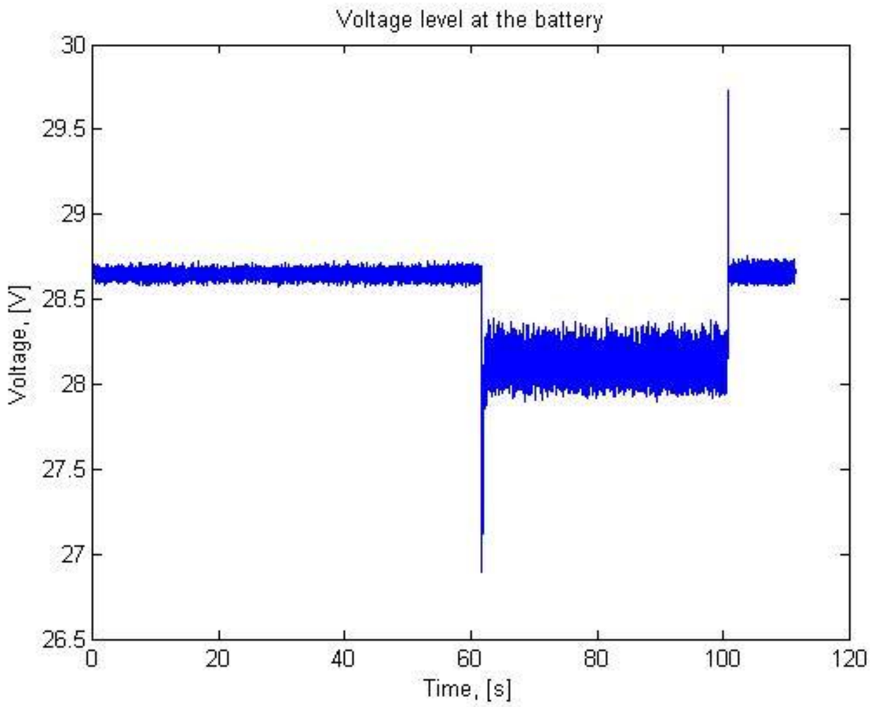


Figure 1: The battery voltage charging level during 2 minutes, with a load of 10 A on the system. A voltage drop occurs after 1 minute when a load of 140 A is applied to the system that is turned off at 100 seconds.

1.3 Purpose

The purpose of this work is to compensate for the voltage drops that occur in the electrical circuit of the bus. The ambition is to keep the batteries' voltage level at the level that has been calculated to be optimal according to the adaptive battery control system.

The aim is to reach a desired voltage level for the batteries by implementing a control system that purely is a software function. It is preferable not to add any extra sensors or to improve the charging circuit resistance with expensive wiring. The aim is also to limit the usage of the Central Processing Unit (CPU).

The thesis' main focus will be on articulated buses, experiments and measurements will be performed on an articulated bus with a large voltage drop.

1.4 Limitations

In this work considerations will not be taken to the capacity of the alternator being too low to deliver as much power as is requested from the electrical components in the system, since that depends on limits in the performance of the alternator.

The system controlling the voltage level of the batteries will be limited by the electrical control units forming error codes when too high voltages are applied to the system. Applying high voltages during long periods of time will also harm the light bulbs on the bus.

1.5 Method and outline

An investigation of the problem is performed in Chapter 2 by studying the electrical circuit of the bus and summarizing articles about lead-acid batteries and influences on their life-length.

A measurement setup is done in the bus, described in Chapter 3, measuring important voltage levels during different circumstances, to capture the dynamics of the system. The signal to be used as a feedback signal is investigated. It is evaluated if the performance of the control system is improved by using a feedback loop and if additional sensors need to be added to make it possible to control the voltage on a correct level. The development of the control system is described in Chapter 5.

The control system is evaluated and it will be investigated if it makes significant improvements to the charging of the batteries in terms of keeping the battery voltage on the desired level. With data from the measurements two black box models are created for the electrical circuit of the bus, Chapter 4. The models are created with different, though static in each case, loads applied to the system. The purpose of the models is to get a simulation environment for the tuning of the control system and to theoretically investigate its stability.

A PID controller is developed for the system and its performance is investigated. The control system is implemented in Simulink and compiled into C-code and written to the memory of an electronic control unit. The implementation of the control system is presented in Chapter 6 and tests of the control system are performed in the lab environment implemented in the bus, described in Chapter 7.

Chapter 8 contains a discussion of the work that has been performed and a discussion about the results. Chapter 9 presents the conclusions from the work and the last chapter describes future work to be performed in the area.

2 Theory

The system to be investigated and controlled in this report is described in this chapter. Some investigations of how the battery voltage affects the life length of the batteries are presented as well.

2.1 System description

The system to be controlled is the electrical circuit of a bus, focus will be on an articulated bus with separate placement of the batteries and the engine. The system has one measurable signal, the battery charging voltage level. There is no sensor that measures the battery voltage directly but a discussion about the battery voltage level measurement can be found in Section 3.4, Data processing. The voltage measurement that will be considered is the internal voltage level measurement that exist in each Electronic Control Unit (ECU). The ECU called the Coordinator is the central ECU that acts as a hub for all ECUs, the designed controller is to be implemented in this ECU and the voltage level measurement in the Coordinator will be considered.

2.1.1 The system

Figure 2 shows a schematic sketch over the information flow in the system. A desired voltage level is calculated in the Coordinator, an ECU, and then recalculated into a value in per cents. The interval is between 10 % and 90 %, where 10 % corresponds to a voltage level of 25.40 V and 90 % corresponds to 30.60 V. In between these two values the relation is linear between voltage and per cents. The value in per cents is sent to the Engine Management System (EMS) where a Pulse Width Modulated (PWM) signal is created based on the received value from the Coordinator. When using PWM signals there are two important measures; duty cycle and frequency. The duty cycle refers to how big part of a period the rectangular pulse wave signal is one. The frequency of the PWM signal decides the length of the duty cycles. The duty cycle is expressed in per cents, 100 % corresponds to that the high signal constantly is used. So if the value is 60 % the PWM signal will be high for 60 % of a period and low for 40 % of the period corresponding to a voltage level of 28.65 V. The signal is sent between the ECUs using the Control Area Network (CAN). The PWM signal is sent to the alternator and the alternator realizes the desired voltage.

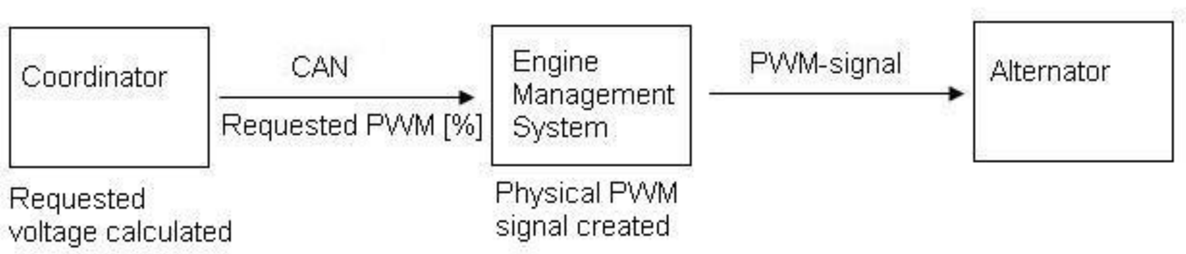


Figure 2: The information flow in the system, the desired voltage level from the alternator is calculated in the Coordinator, the value is recalculated into per cents and sent to the EMS where the pulse width modulated signal is created and sent to the alternator.

2.1.2 The electrical circuit

The schematic of the simplified electrical circuit is described in Figure 3. The resistances R_1, R_2,… R_8 represents the resistances that originate from the wires between the alternator placed in the rear of the bus and the two 12 V batteries placed in the front of the bus. The resistances can be calculated knowing the length of the wires as well as the area and the resistivity. If the currents in the system, represented by $I_1,\dots,I_8$, can be measured, it is possible to calculate the voltage drops that will occur in the circuit, using *Ohm's law,*

$$U = R \cdot I$$

and by using *Kirchhoff's voltage law,*

$\sum_{k=1}^{N} U_k = 0$, where N is the number of voltage drops in the circuit.

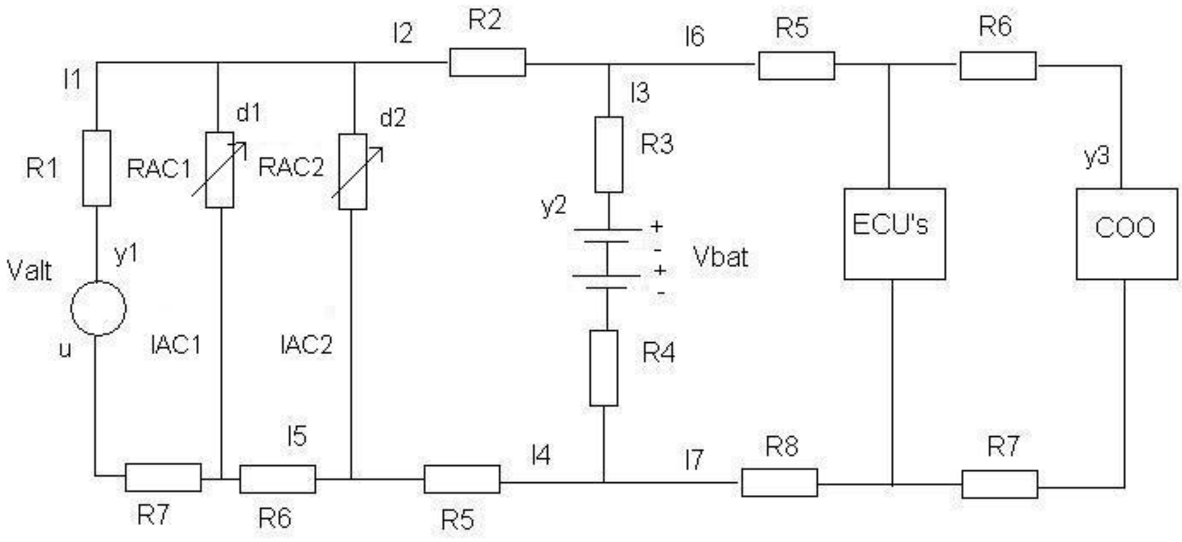


Figure 3: Schematic figure of the system. In this system one air condition unit is connected in front of the articulation, AC1, of the bus and one air condition unit is connected behind the articulation, AC2. The voltage V_{alt} is the output voltage from the alternator.

To make it possible to measure the currents in all wires several sensors need to be added to the system. The currents that mainly affect the system and cause the largest voltage drops are due to the power consuming air condition units. These currents change size when the air condition units are turned on and off and when partly used. When both the air condition units are fully turned on the currents in the air condition units will be rather large, about 180 A. The currents that pass through the air condition units will also pass through the resistances R_6 and R_7. The more power the air condition units consume, the larger currents will pass through the resistances which will cause larger voltage drops. Smaller, though noticeable, voltage drops will occur in the rest of the circuit as well. An articulated bus measure approximately 18 meters and the wires are not drawn straight through the bus and the longer the wire is, the larger voltage drop there is, see Section 2.1.3, Calculating resistance in copper wires for details.

The following equations are obtained from the circuit using Kirchhoff's voltage law and Ohm's law:

$$KVL: \sum_{k} U_k = 0$$

$$V_{alt} - R_1 I_1 - R_2 I_2 - (R_3 + R_4) I_3 - R_5 I_4 - R_6 I_5 - R_7 (I_5 + I_{AC1}) - V_{bat} = 0$$

$\Leftrightarrow$

$$V_{bat} = V_{alt} - R_1 I_1 - R_2 I_2 - (R_3 + R_4) I_3 - R_5 I_4 - R_6 I_5 - R_7 (I_5 + I_{AC1})$$

$\Leftrightarrow$

$$\frac{V_{bat}}{V_{alt}} = 1 - \frac{R_1 I_1}{V_{alt}} - \frac{R_2 I_2}{V_{alt}} - \frac{(R_3 + R_4) I_3}{V_{alt}} - \frac{R_5 I_4}{V_{alt}} - \frac{R_6 I_5}{V_{alt}} - \frac{R_7 (I_5 + I_{AC1})}{V_{alt}}$$

When applying Kirchhoff's current law to the system the following relationship between the currents will be obtained.

$$KCL: \sum_k I_k = 0$$

$$I_1 - I_{AC1} - I_{AC2} - I_2 = 0$$

$$I_2 - I_3 - I_6 = 0$$

$$I_3 + I_7 - I_4 = 0$$

$$I_4 + I_{AC2} - I_5 = 0$$

$$I_6 - I_9 - I_8 = 0$$

$$I_9 - I_7 + I_8 = 0$$

- $\Rightarrow$ $I_6 = I_7$
- $\Rightarrow$ $I_4 = I_2$

With the obtained relationships the following equation from input signal to output signal is obtained

$$\frac{V_{bat}}{V_{alt}} = 1 - \frac{R_1 I_1}{V_{alt}} - \frac{R_2 I_2}{V_{alt}} - \frac{(R_3 + R_4) I_3}{V_{alt}} - \frac{R_5 I_2}{V_{alt}} - \frac{R_6 (I_2 + I_{AC2})}{V_{alt}} - \frac{R_7 (I_2 + I_{AC1} + I_{AC2})}{V_{alt}}$$

Between the battery and the Coordinator there are wires connected in parallel with the ECUs, and current will pass through the wires with resistivity, resulting in voltage drops. On this basis the voltage measurement in the Coordinator cannot be directly used to represent the battery voltage. Investigations have to be done, regarding how much the voltage level at the battery and the voltage level in the Coordinator differ from each other during different loads on the system.

Seeing the system in Figure 3 as a black box, it has one input signal; the requested voltage level from the alternator, u. The system will have three output signals; the output voltage level from the alternator, y_1, the voltage level at the battery, y_2, and the voltage level in the Coordinator, y_3, according to Figure 3. With the two air condition units connected to the circuit there will be two disturbance signals, as can be seen in Figure 4.

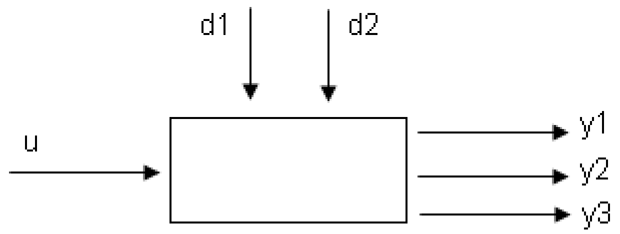


Figure 4: The system described as a black box with input signal, output signal and disturbance signals.

2.1.3 Calculating resistance in copper wires

The wires in the electrical circuit of the bus are made of copper. The resistances, R_1, R_2,… R_9 in Figure 3 represents the resistances that will occur in the wires due to the resistivity of copper. The resistances are calculated in the following way:

$$R = \rho \cdot L/A$$

$$where$$

$$R = Resistance$$

$$\rho = Resistivity, 1.72 \cdot 10^{-8}\ \Omega m\ for\ copper$$

$$L = Length$$

$$A = Area$$

2.2 Life length of lead-acid batteries

When the battery charging voltage level is low, the battery charging current will be lowered as well. A high state of charge of the batteries will be achieved faster when a larger charging current is applied. A low state of charge makes the battery less capable of incepting the charge applied to it. Included in the battery life measurements is the *cycle life* of a lead-acid battery, that is a measure of how many charge and discharge cycles a battery can handle before its lead-plates are expected to collapse. The more discharged the battery gets in each cycle the less cycles it manages to stay alive [5].

There are two 12 V lead-acid batteries connected in series in Scania's buses. A lead-acid battery uses a reversible chemical reaction to store energy, lead plates are used together with electrolyte consisting of diluted sulfuric acid. The interaction results in converting electrical energy into chemical energy and then the reaction is recursed [6].

Experiments have been performed and confirm that all sulfate crystals cannot be reconverted back into active mass and the battery's capacity therefore gets significantly reduced during and after being charged with a low voltage level, this causes the phenomenon sulfation. Sulfation describes the crystallization of a battery plate, where lead-crystals are formed, leading to that the lead sulfate is no longer electroactive and does not participate in the charge-discharge process [6]. Since the lead sulfate is a completely or partly irreversible process, loss of electrochemically active form will occur resulting in a loss of capacity and power in the battery [10]. If partly irreversible the sulfation process has only prolonged for a limited period of time and the crystals can be reconverted back into charged active mass during full charge of the battery [4].

3 Measurements

This chapter describes the measurement setup on the bus and how the data was collected and processed.

3.1 Measurement setup

To initialize the work with creating a control system with the purpose of controlling the voltage level at the battery a measurement setup is done. The measurements are made on an articulated bus that is used throughout the investigation. The motive of the measurements is to record the voltage level at the battery, the output voltage level from the alternator and the voltage level in the Coordinator, i.e. the control unit where the control system will be implemented, see Chapter 6, Implementation. The physical placement of the measurements on the bus can be viewed in Figure 5.

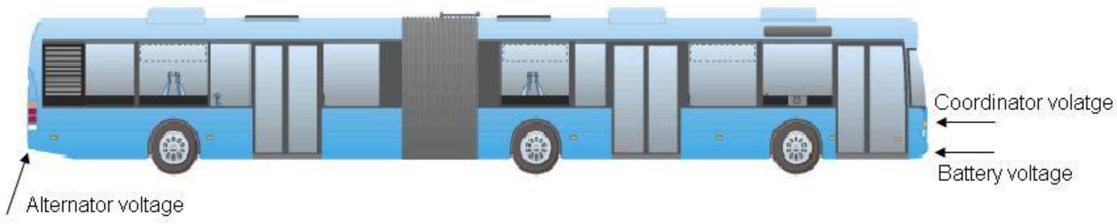


Figure 5: Measurement setup on the articulated bus. Three voltages are measured, the battery voltage level and the Coordinator voltage level in the front and the alternator voltage level in the rear of the bus.

The purpose of the measurements is to collect data to make it possible to make a model of the system, see Chapter 4, Modeling, and to enable for comparisons between the voltage level at the battery and the voltage level at the Coordinator. Another intention of the measurements is to get a basis for the identification of the characteristics of the signals to make it possible to analyze how the voltage measurement, that will be used in the control system, should be processed to get a reliable signal, see Section 3.4, Data processing.

The voltage measurement at the batteries is made with a measurement module, sending the voltage level on CAN. The module is connected to two wires, measuring the voltage difference between the poles of the batteries and the module is configured to send this level on the CAN-bus. The CAN-bus is connected to the program CANalyzer and the voltage level of the batteries is recorded. The measurement at the Coordinator is made in the same way and the sensor is connected to the same measurement module. To measure the voltage level at the alternator a second measurement module is installed close to the engine in the test vehicle.

The Coordinator has an internal sensor, measuring the voltage level, that is recorded in CANalyzer as well. To make that possible, the CAN bus from the Coordinator is connected to another channel of CANalyzer than the other voltage measurements. A signal is created in the implementation environment and sent on CAN. The signal is created since the voltage measurement in the Coordinator is an internal signal that is not normally being sent on the CAN-bus. For details about the implementation see Chapter 6, Implementation.

3.2 Simulating an Air condition unit

To observe the system with varying loads, it is desirable to simulate large currents in the electrical system of the bus. With the possibility to stimulate the system with large loads it is also possible to observe extreme cases; the impacts on the system when more power is consumed in the system than the alternator is able to deliver and how variations of the load will affect the system. The air condition unit is a big power consumer and will cause the largest voltage drops in the circuit.

With this background an air condition unit is simulated and connected to the electrical circuit of the bus. To make it authentic one air condition unit is connected in front of the articulation and one air condition unit is connected behind the articulation in the electrical circuit of the bus according to Figure 3. The air condition units are simulated by using power resistances. The power resistances placed on three plates and are connected in parallel. The air condition units consist each of 15 power resistances, representing the load of an air conditioner. The simulated air condition units can be seen in Figure 6.

Figure 6: The simulated air condition units, consisting of plates with power resistances and a fan, cooling the plates.

With the simulated air condition units are turned on each of the units applies a load of 70 A to the system, which sums up to a total of 140 amperes. These two air condition units can be viewed as connected in parallel to each other in the electrical circuit, as can be seen in Figure 3. The basis of simulating two air condition units that uses 70 A each is that during normal operation each air condition unit in the bus in focus uses about 70 A. Though the range can be in between 50 A and 90 A for each air condition unit.

The voltage level at the battery is presented in Figure 1 where the two simulated air condition units are turned on after approximately 60 seconds. It can be seen that this causes a voltage drop of about 0.5 V. The noisy appearance of the signal when much load is applied to the system and the peaks that appear when the air condition units are turned on and off are caused by internal behaviours of the alternator and are not possible to eliminate with the control system that is created in this thesis work. However the peaks appear under short periods of time and they will not cause any error codes in the control units, since they can handle high voltages in the system if the high voltage appears as peaks.

3.3 Collecting data

Different input signals are applied to the system when collecting data to capture the dynamics of the system, more details can be found in Chapter 4, Modeling. The recording of data is mainly made with the batteries normally charged, that is about 70 per cents of fully charged.

During the test drive the engine speed, the gear, the vehicle speed and the acceleration varies. To stimulate the system power consuming units on the bus are turned on and off; lamps inside the bus, beam lights, indicators, the simulated air condition unit and extra fans. The CAN signals for these are recorded during the test drive to make it possible to analyze the data afterwards, the data is collected at a frequency of 100 Hz. Figure 7 shows a collection of data of the voltage level at the battery, at the alternator and at the Coordinator, under a period of 110 seconds. In Figure 7 the noisy appearance of the output signal from the alternator is visible. Figure 8 is the input signals applied to the system to receive the output signals in Figure 7.

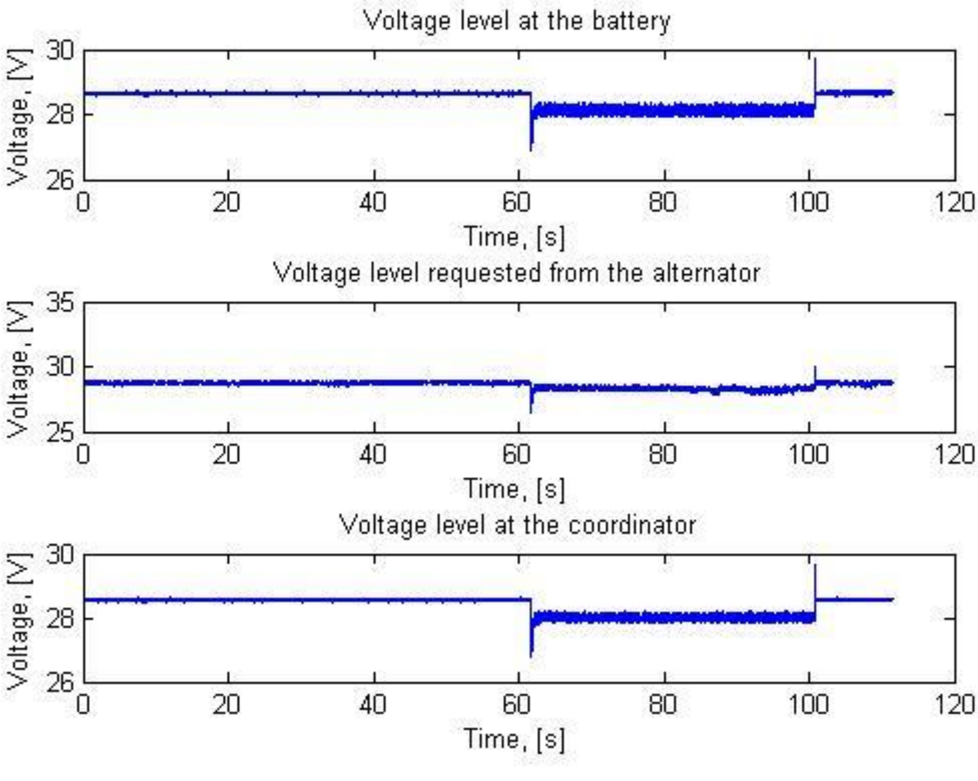


Figure 7: Data of the measured voltages, with a voltage drop after approximately 60 seconds when the air condition units are turned on and turned off again at about 100 seconds. The top graph is the voltage level at the battery, the graph in the middle is the output voltage from the alternator and the graph at the bottom is the voltage level measured at the Coordinator.

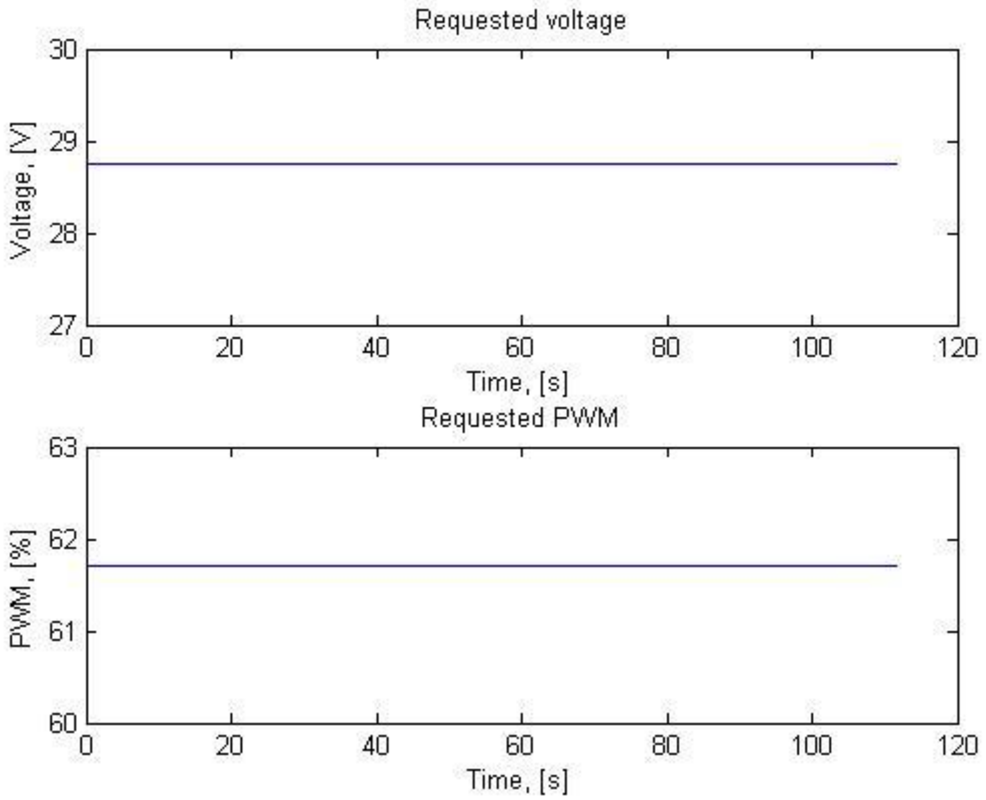


Figure 8: During the sequence in Figure 7 the demanded PWM signal from the alternator is 61.7%, which corresponds to a demanded voltage of 28.76 V.

3.4 Data processing

It is investigated if it is possible to use the internal voltage measurement in the Coordinator as a feedback signal to the control system, serving as the battery voltage. Two important aspects are taken into consideration.

- If the quality, in terms of noise, of the measurement of the voltage inside the Coordinator is good enough to be used as a feedback signal
- If the measure of the voltage inside the Coordinator is close enough to the battery voltage

3.4.1 Filter selection

The evaluation about if the quality of the internal voltage measurement inside the Coordinator is good enough is done after some processing of the signal. To reduce noise from the voltage measurement a frequency selective filter is applied to the signal. The frequency selective filter is of low pass character since unwanted high frequency noise is desired to be removed. The signal also has to be sampled to be used in the implementation of the control system. Frequencies higher than the Nyquist frequency must be removed to avoid for aliasing effects, according to the sampling theorem. The sampling theorem says:

A signal that does not contain any frequency contributions higher than a certain frequency ω_0 can be exactly reconstructed from the sampled values [2].

The Nyquist frequency, ω_0, is defined as half the bandwidth of the system. If the signal contains frequencies higher than the Nyquist frequency they will appear as slow frequencies in the interesting frequency interval [2]. Therefore it is of great importance to apply a low pass filter to the signal before the sampling. These kinds of filters are often referred to as anti-aliasing filters since they are used for avoidance of aliasing. The signal will be resampled to 2 Hz and therefore the cut-off frequency of the low pass filter needs to be less than 1 Hz. A Butterworth filter of first degree with cut-off frequency chosen to 1/4 Hz is applied to the signal before it is decimated. The frequency response of the filter can be viewed in Figure 9 and the zoomed in important part of the impulse response of the filter can be seen in Figure 10. The impulse response is zero for $t<0$, which implies a causal filter. It is necessary to have a causal filter for real time systems, since there is no knowledge about the signal in the future. The filter will be used in the real-time application, see Chapter 6.

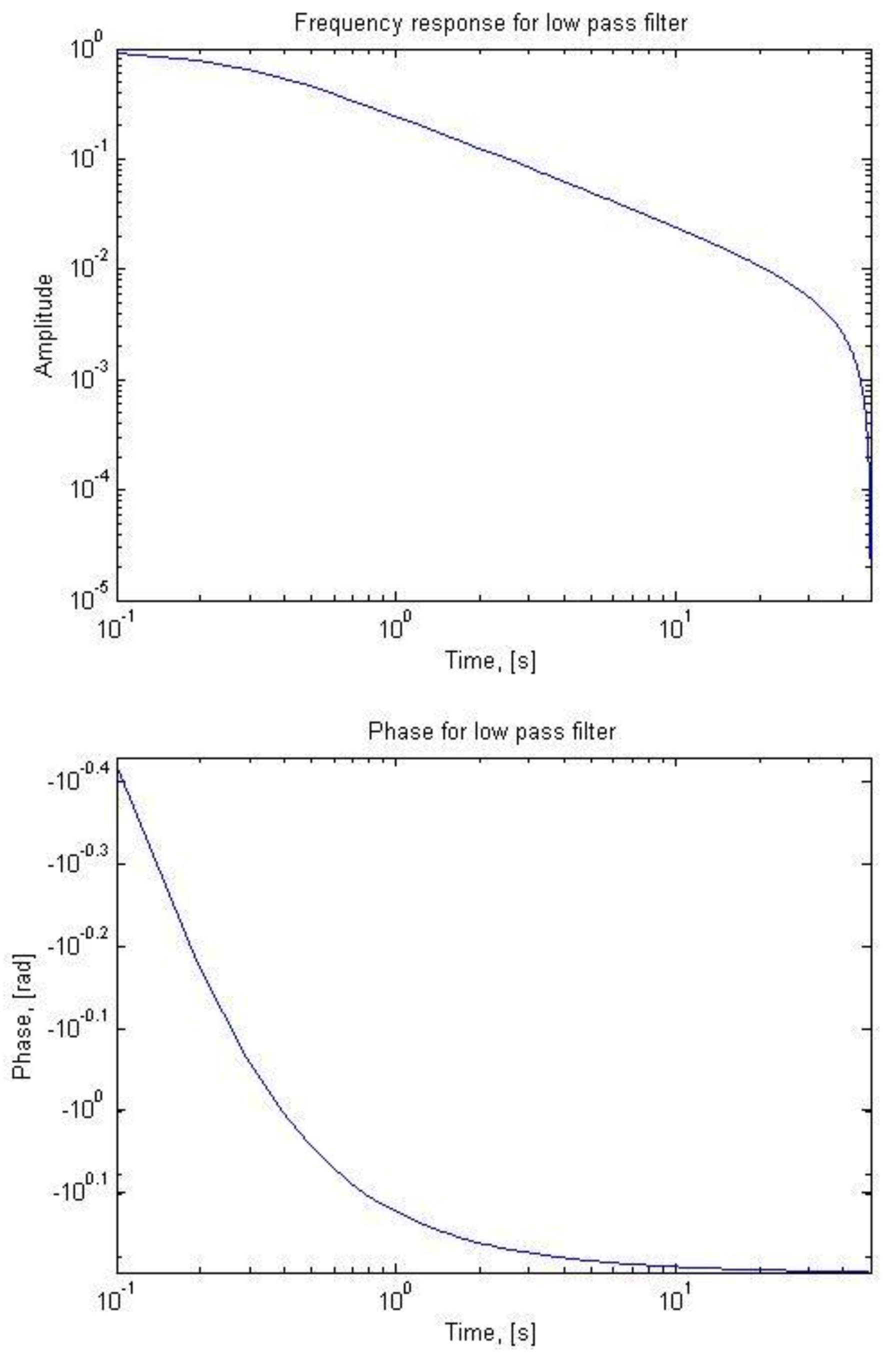


Figure 9: Frequency response, amplitude in top graph and phase in bottom graph for the low pass filter applied to the signal before being decimated and used in the control system.

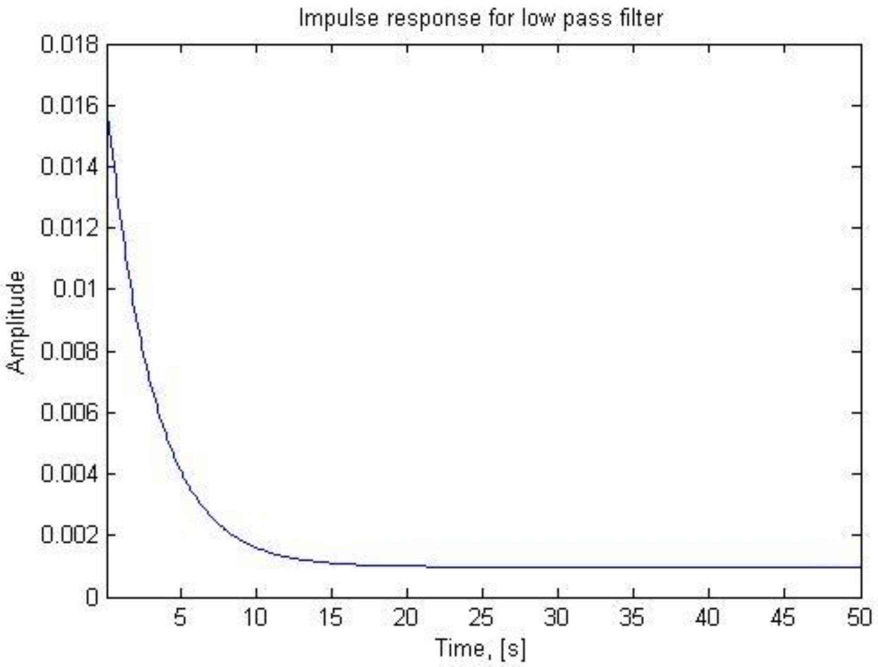


Figure 10: Impulse response for the low pass filter, the impulse response is zero when t<0 implying that the filter is causal.

The down sampling of the input signal is done before it is used in the control system. Since the signal is low pass filtered before it is decimated the risk of aliasing when down sampling is eliminated. The voltage signal is sampled in 100 Hz and is decimated to consider only every 50 sample which results in a sampling time of 0.5 s for the control system. The dynamics of the system is not as fast as 0.01 seconds and therefore the voltage measurement is down sampled after being filtered. When the voltage measurement is low pass filtered and decimated, the Coordinator voltage seen in Figure 11 would look like the signal in Figure 12. The filtered signal in Figure 12 is smooth and appropriate to use as feedback signal to the control system.

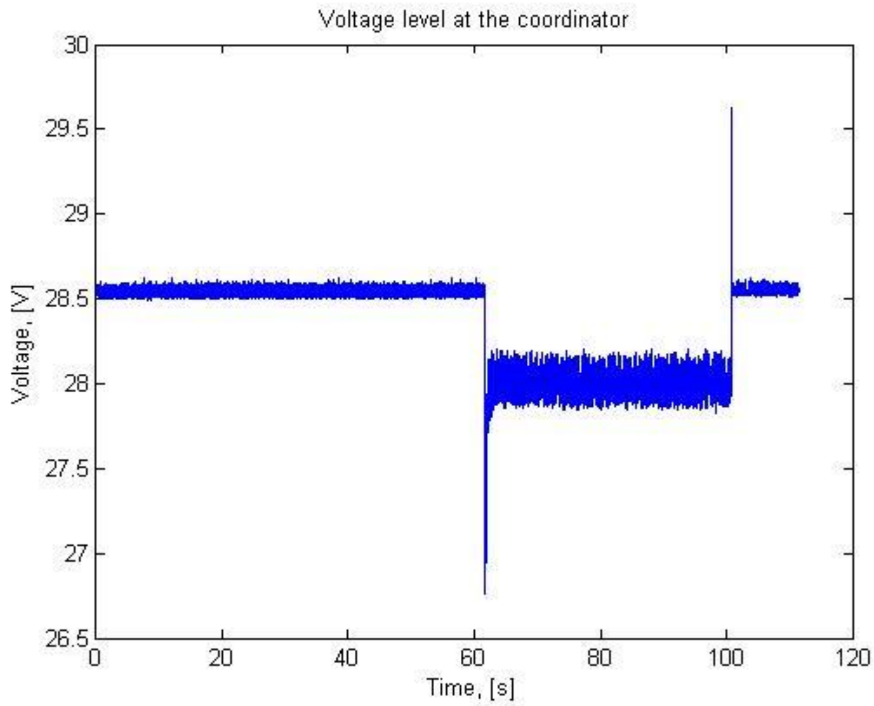


Figure 11: Voltage level measured in the Coordinator without filtering and decimation when a load is put on the system at 60 seconds and the load is put off at 100 seconds.

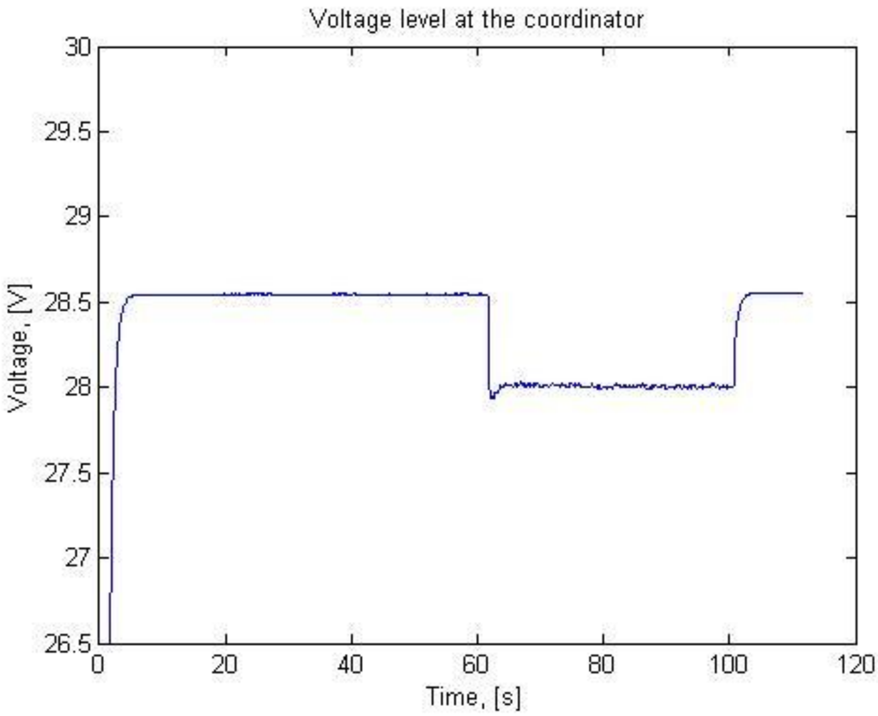


Figure 12: The voltage level in the Coordinator from Figure 11, after applying Butterworth filter and decimating the signal.

3.4.2 Comparison between the battery voltage level and the voltage measurement inside the Coordinator

Both the Coordinator voltage measurement and the battery voltage level are recorded under different circumstances as mentioned in Section 3.3, Collecting data. Important results from the experiments are that the Coordinator voltage behaves like the battery voltage signal, the signals look alike except from a constant bias. The internal measurement inside the Coordinator is lower than the voltage level at the battery. This is due to a voltage drop caused by the resistance in the wire between the Coordinator and the battery as can be seen in Figure 3. The behaviour of the voltage level at the battery and the voltage level at the Coordinator can be viewed in Figure 13 and Figure 14 with different loads applied to the system affecting the voltage drop between the battery and the Coordinator. This information is used to estimate a mean for this difference. The signals are filtered and decimated as described in Section 3.4.1 before they are compared to each other.

Investigations of the difference between the two signals are made instantaneous over time as well as statistically over time, and on different data sets. Figure 13 shows measurements of the battery voltage level and Figure 14 shows measurements of the Coordinator voltage level with different loads on the system. In the beginning of the first graph in Figure 13 and Figure 14, no loads are added to the system, after 60 seconds 140 A is applied and after about 100 seconds the power consumer is turned off and there is no extra load on the system. In the second graph in Figure 13 and Figure 14 the curves are quite straight, no extra loads are applied to the system. In the third graph in Figure 13 and Figure 14 a load of 70 A is applied to the system after 315 seconds, turned off, turned on and turned off between 320 and 325 seconds and then at 327 seconds a load of 140 A is applied to the system, that power consumer is switched off at 332 seconds. In Figure 15 the difference between the battery voltage level and the voltage level measured inside the Coordinator can be seen in every time instance, the Coordinator voltage level subtracted from the battery voltage level. Figure 15 indicates that the difference between the two signals has a mean at about 0.1 Volts. Figure 16 shows histograms with the statistical difference between the two measured signals. It shows in how many samples the difference is 0.1 V and 0.11 V etc. The horizontal axis represents the difference in volts and the vertical axis shows in how many samples the difference appears. The histograms indicate that the difference between the voltage levels has a mean at 0.1 Volts. Graph 1, 2 and 3 in Figure 13 and Figure 14 corresponds to graph 1, 2 and 3 in Figure 15 as well as in Figure 16.

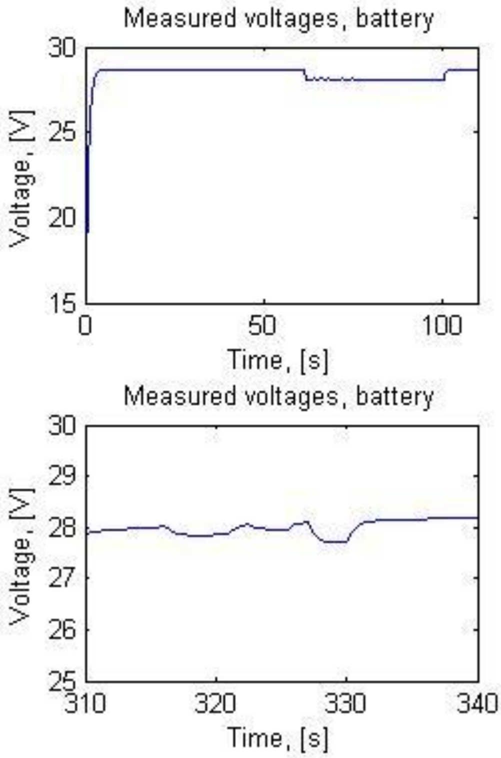


Figure 13: Three different voltage measurements at the battery, with different loads on the system during different periods of time

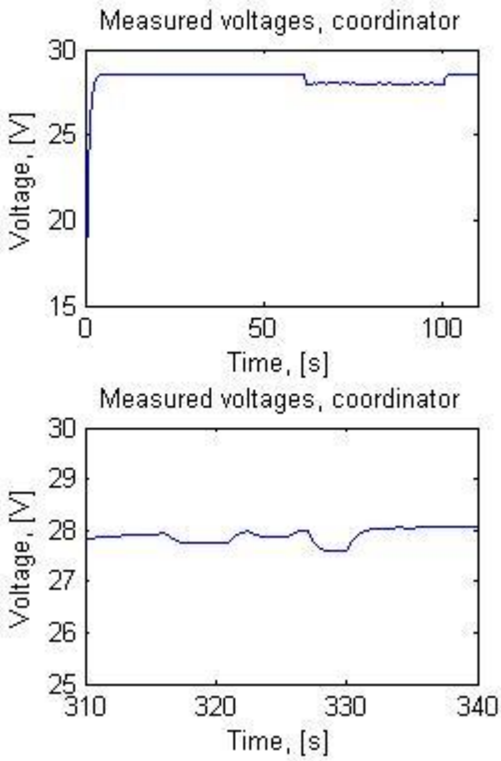


Figure 14: Three different voltage measurements at the Coordinator, the same as in Figure 13, but in this case the measurement is from the Coordinator.

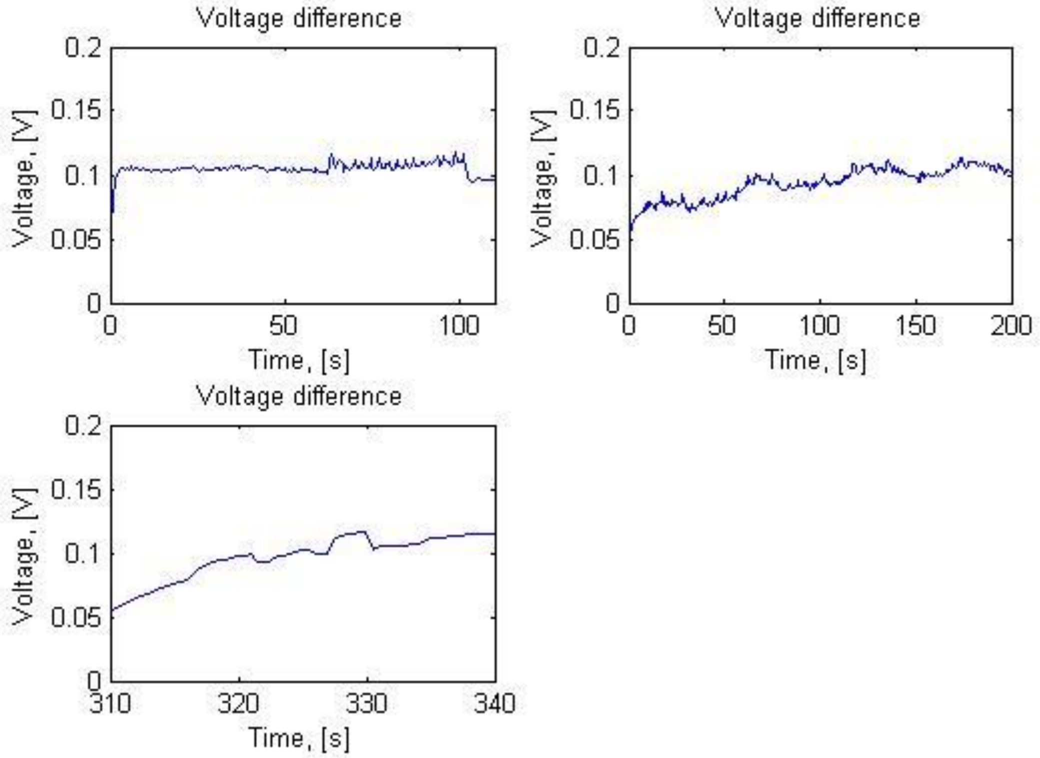


Figure 15: Voltage difference between the battery voltage level and the Coordinator voltage level, from Figure 13 and 14.

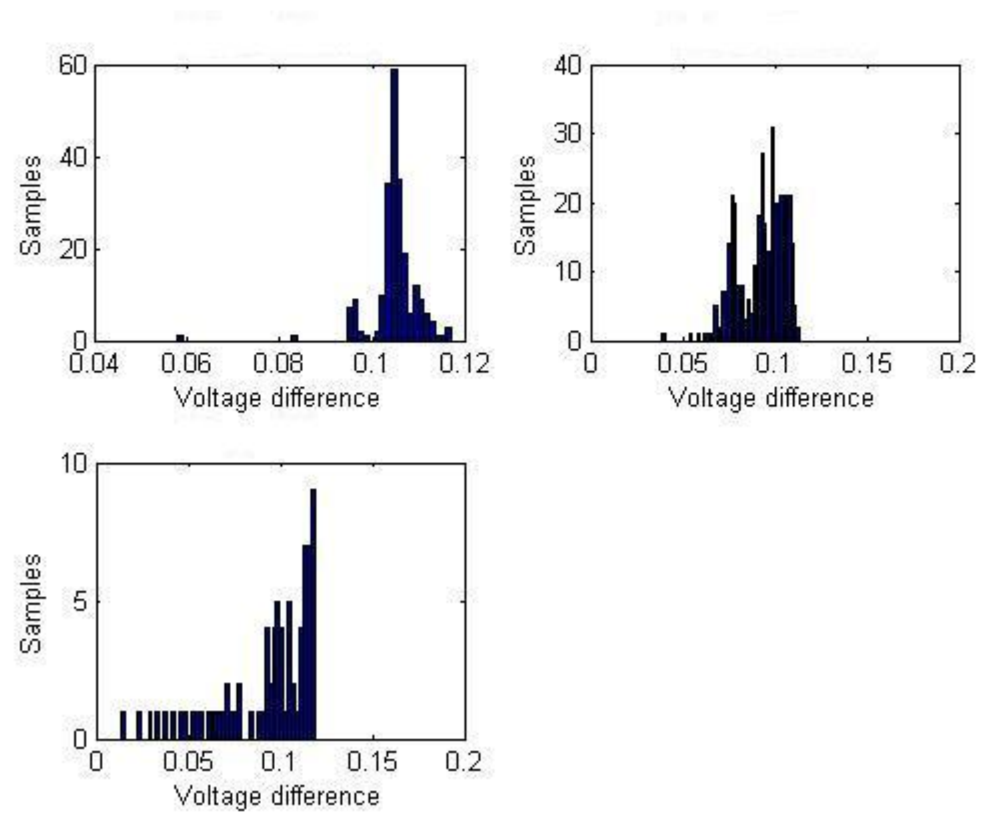


Figure 16: Histogram of the statistic difference between the battery voltage level and the Coordinator voltage level from Figure 13 and 14.

The results from this investigation shows that the mean of the difference between the measured voltage level at the battery and the measured voltage level inside the Coordinator can be estimated to 0.1 V. This bias will be added to the internal measurement of the Coordinator, the input signal to the control system. The difference between the voltage level in the Coordinator and the voltage level at the battery will differ when currents of different sizes pass through the wires between the Coordinator and the batteries. Measurements of the difference are performed on buses of different configurations and show that the difference is within an interval of 0.023 V to 0.14 V. This implies that by adding the constant of 0.1 V to the Coordinator voltage, the error can be at the most 0.077 V.

4 Modeling

This chapter is about the two black box models that are created with the purpose of creating a simulation environment where a control strategy can be formed and appropriate parameters for the control system can be found the purpose is also to make it possible to theoretically investigate the stability of the closed loop system when the controller is implemented. The chapter also includes a validation of the models deciding that they are good enough for their purpose. A scheme of the black box model to be constructed can be seen in Figure 17.

Figure 17: Schematic sketch of the black box model, the desired battery voltage is the input signal and the battery voltage is the output signal.

4.1 Black box modeling

When data from the measurements in the Chapter 3 is collected it is possible to create a simulation environment for the development of the control system using black box modeling. Black box modeling is the chosen strategy since the input (the requested battery voltage) and the output signal (the battery voltage) to the system are possible to record during different circumstances. It is possible to manipulate the input signal to the system and in that way capture the dynamics of the system. To be able to get all the parameters for the physical model described in Section 2.1.2 it would be necessary to measure currents in the circuit, by adding extra sensors. Since the ECU's and the Coordinator are not modeled, the voltage measurements that are performed will not provide enough information to get all parameters. Adding extra sensors to the system adds complexity and is expensive. Therefore creating a black box model is the simplest and most straight forward strategy for the modeling. The models are created using the System Identification Toolbox in Matlab under the assumption that the battery is normally charged.

A varied input signal is applied to the system and to stimulate its behaviours the input signal, the requested alternator voltage, is chosen to vary between two selected values during different periods of time, to get a large frequency span for the input signal, and by that excite the system. A binary input signal is a good choice of input signal when identifying a linear system [3]. This system is assumed to be linear, since no nonlinear behaviour is captured and since the electrical circuit of the bus does not contain any non-linear parts. Relevant sequences of data are selected for the modeling.

For the validation of the models a different data set is used. The difficult part with the modeling in this case is that the load on the system can be varied but it cannot be used as an input signal to the system, since it is not measured. Therefore one model is created under the assumption that the load on the system is constant, no extra load is put on the system for the data set used both for modeling and for validation. Another model of the system is created when a large load is applied to the system, also in this case the load is constant.

4.1.1 Black Box model with no extra load applied to the system

The first model is created under the assumption that no extra load is put on the system. Different linear models with different degrees are applied to make attempts to capture the dynamics of the system. The model that is chosen for the system is a linear ARX-model. Before the model is created the output signal is low pass filtered, since the ARX model is adjusted with much weight on the behaviors of the model and the system corresponding to each other at high frequencies. The ARX model is using linear regression to estimate the parameters for the model [3].

The black box model that is chosen for the system when no extra load is applied is the following ARX model:

$$m1 = \frac{0.001617\ (\pm 8.309 \cdot 10^{-5}) z^{-18}}{1 - 2.029(\pm 0.004899) z^{-1} + 2.074(\pm 0.009475) z^{-2} - 1.925(\pm 0.009405)\ + 0.8822(\pm 0.004725) z^{-4}}$$

The numbers inside the parenthesis' are the confidence interval for the estimated parameters of the model. Since they all are significantly smaller than the parameters all parameters are of relevance and the model is not of a too high order. The term z^{-18} is used to capture the time delays of the system.

4.1.1.1 Model validation

Before this black box model can be used for representing the system under the condition that no extra load is applied the system, the model is validated.

The first validation that is performed on the model is cross validation, i.e. another data set is applied to the model than the one used when creating the model. The input to the model is then the input signal from the validation data set, and the output of the model is compared to the output of the validation data set. The result of the cross validation can be seen in Figure 18. The dashed line in the figure is the output signal from the model and the solid line is the real battery voltage, filtered through a low pass filter to reduce the noise. The input signal for this validating data sequence can be seen in Figure 19.

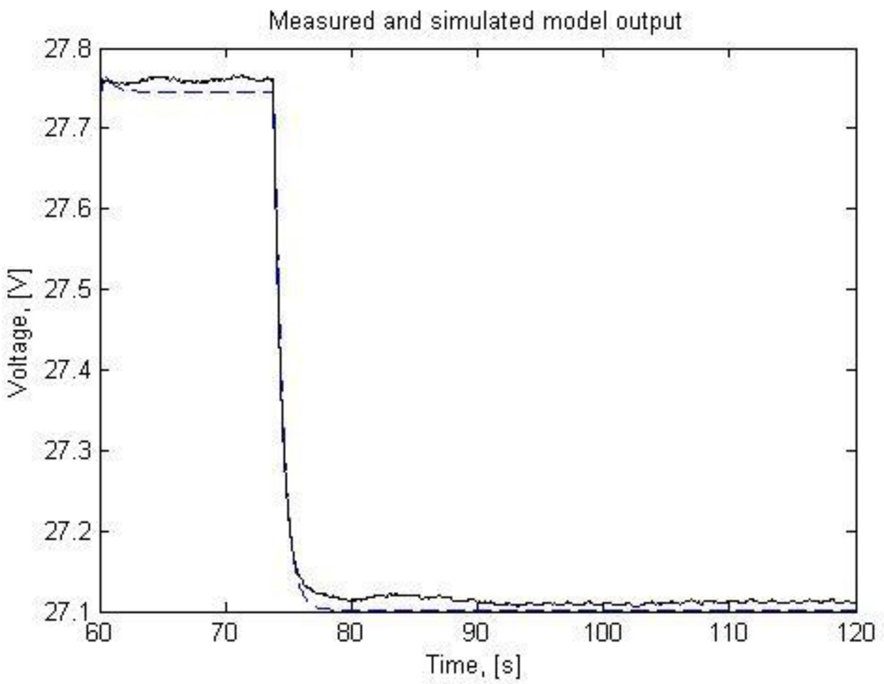


Figure 18: Cross validation for the black box model, the dashed line is the output from the model and the solid line is the filtered value of the battery voltage.

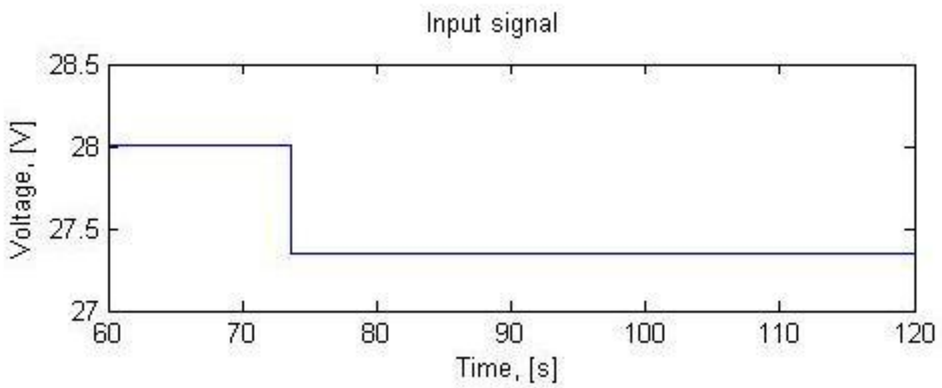


Figure 19: Input signal for the validating data sequence.

To get an indication of how close the model is to the real system, the prediction errors are studied. The prediction errors, the residuals, are the difference between the measured and filtered output signal and the output signal from the model, when applying another data set than the one used when creating the model.

The prediction errors are defined as:

$$\varepsilon(t) = \varepsilon(t, \hat{\theta}_N) = y(t) - \hat{y}(t|\hat{\theta}_N),$$

where $\ddot{\theta}(t)$ is a vector of the estimated parameters and $y(t)$ is the real output signal and $\hat{y}(t|\hat{\theta}_N)$ is the estimated output signal. It is desired to minimize the prediction errors and if there is no difference between $y(t)$ and $\hat{y}(t|\hat{\theta}_N)$ the model would describe the system perfectly.

An important measure on if the model is a good description of the real system is the root mean square error (RMSE), the square root of the variance of the residuals. This measure is an absolute measure, that indicates how close the estimated parameters are to the observed data points. The RMSE can be interpreted as the standard deviation of the variance that is not explained. The lower the value of RMSE the better fit of the model there is.

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N} \varepsilon^2 (t, \hat{\theta}_N)}$$

If the loss function is zero the model would be a perfect match to the system. The loss function is connected to the cost of using the model to represent the system. In this case the loss function is $1.02 \cdot 10^{-4}$. This is a number close to zero and the model can be assumed to be a close enough fit to the system.

4.1.2 Black Box model with large load applied to the system

A second black box model is made for the system under the circumstance that the simulated air condition units are fully turned on. This model is made to make it possible to investigate the stability of the closed loop system when the controller is implemented. A total load of 200 A is what can be applied to the system, the largest voltage drops will occur when the air condition unit is turned on, since it is the largest power consumer. The model can be used when investigating the stability for an extreme case, during largest possible voltage drop on this bus. The largest resistances will be affected by the current through the air condition units and thereby cause the largest voltage drops. The model that is obtained is an ARX model as well. The input signal used to stimulate the system is a binary signal, with the difference that the simulated air condition unit and fans are turned on in this case.

The following ARX model is obtained when much load is applied to the system:

$$m2 = \frac{0.0007801 \ (\pm 4.497 \cdot 10^{-5}) z^{-18}}{1 - 1.863(\pm 0.004461) z^{-1} + 1.705(\pm 0.008609) z^{-2} - 1.737(\pm 0.008586) \ + 0.8957(\pm 0.004392) z^{-4}}$$

Also in this case all parameters are of relevance since they are significantly larger than their uncertainties which implies that the model is not of a too high order. The term z^{-18} is used to capture the time delays of the system.

4.1.2.1 Model validation

The cross validation of the second model when the load is put on the system can be seen in Figure 20. A new data set is applied when validating and the validation implies a good fit between the model and the real system. The input signal for this validating data sequence can be seen in Figure 21.

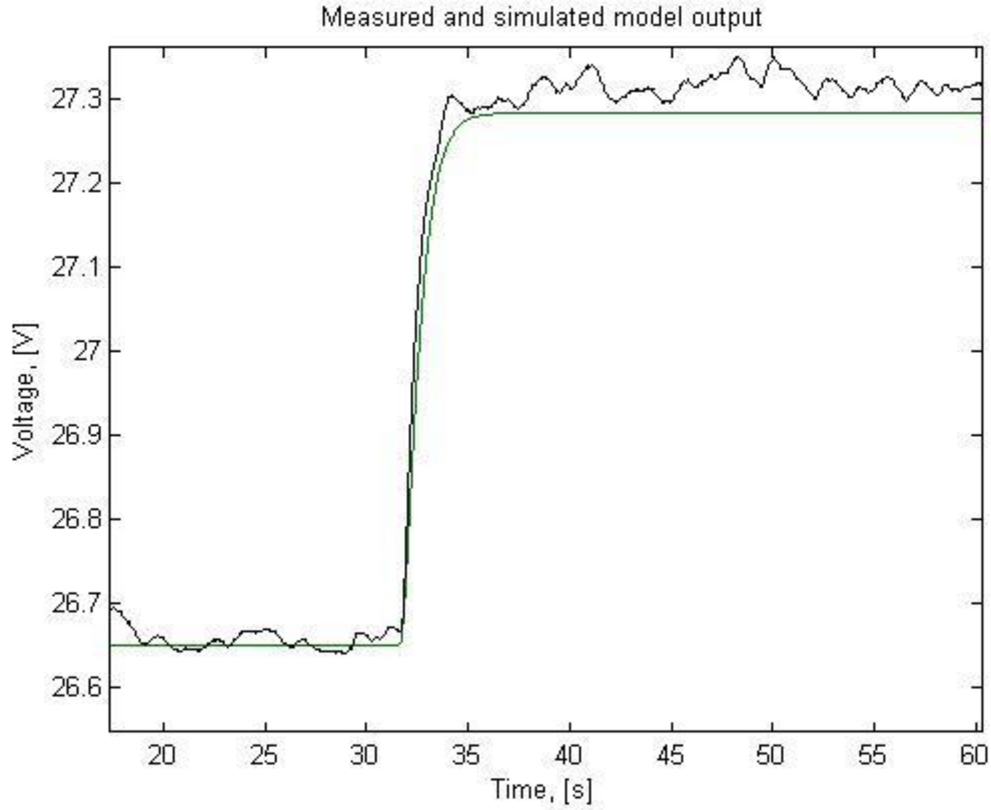


Figure 20: Cross validation for the second black box model, the solid line is the output from the model and the uneven line is the real value of the battery voltage, sent through the low pass filter as explained in Section 3.4, Data processing.

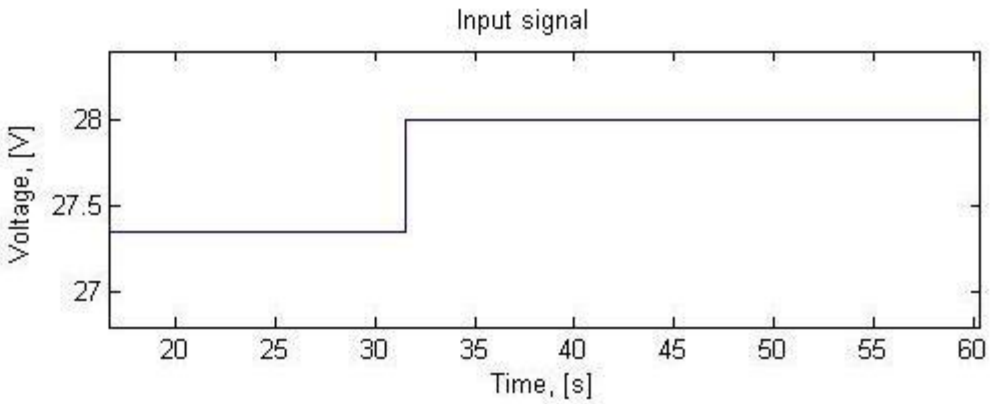


Figure 21: Input signal for the validating data sequence.

The RMSE, described in Section 4.1.1.1, for this model is RMSE=$1.4 \cdot 10^{-4}$, also in this case a small number indicating a good fit for the model.

5 The control system

This chapter is about the PID controller that was created for the system, the basis of the selection of the parameters of the controller and an investigation of the performance of the controller.

5.1 Control strategy

The main strategy of the control system is to use a feedback signal for the closed loop system and to make the controller as basic as possible but still achieving a good and reliable result. When using a feedback signal there has not to be an exact knowledge of the behaviour of the system. This is an important factor when treating this problem, since no extra sensors are added it is not possible to know the exact behaviour of the system. Figure 22 shows a system description of the control strategy to be used. The desired voltage level at the batteries is the input signal to the control system and the feedback signal is the measured voltage level at the batteries, measured in the Coordinator as described in Section 3.4, Data processing.

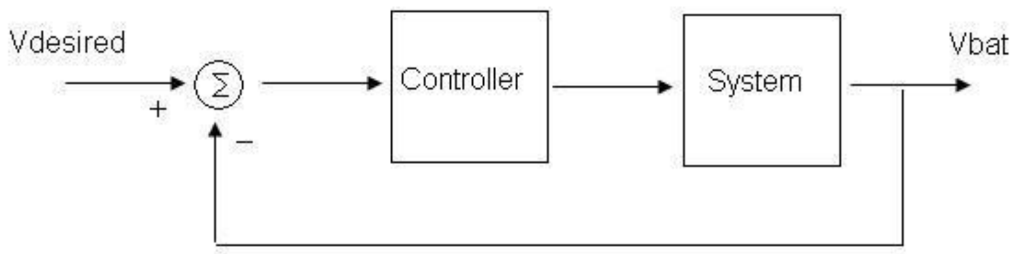


Figure 22: The control strategy, a feedback loop, with the desired voltage level as input and the battery voltage level, calculated from the Coordinator voltage measurement as output and feedback signal.

5.2 PID controller

PID-controllers are the most common control strategy in industrial applications. The PID controller consists of three parameters, the proportional part, the integral part and the derivative part [2]. If a PID controller is able to control the system in a satisfying way, there is no need to attempt to create another type of controller. In this case it is of relevance not to use more CPU than necessary, since there are many functions that shall fit into the electronic control units. The PID controller seems in this case to be the best selection of controller since the dynamics of the system is not known during operation. To get a PID controller with satisfying characteristics it is important to find the correct balance between the three parts of the controller. There are different systematic ways to iteratively tune the parameters to get a desired behaviour of the control system.

5.3 Selecting parameters for the PID controller

The parameters for the PID controller are chosen by studying a step response of the system, Figure 24. The Internal Model Control (IMC)- method is used to tune the parameters of the control system. The PID-controller can be implemented either in series or in parallel. The parallel form is chosen for this subject, since the P-part, the I-part and the D-part can be implemented one by one and then summed up together. This approach makes it easier to try different values on the different parameters without affecting other parameters in the controller than the one in focus. The controller can be described by the following formula in continuous form:

$$F(s) = K(1 + \frac{1}{T_i s} + \frac{T_d s}{\mu T_d s + 1})$$

To get a basis for the tuning of the PID controller a step response for the system is studied. From a step response a three parameter model can be constructed to describe the system. The typical characteristics of the step response will be captured by the simplified three parameter model, and on that ground the parameters for the PID controller can be tuned by a systematic approach. The three parameter model has the following form: $G(s) = \frac{K_p}{1+sT} e^{-sL}$ and the values of the parameters can be read from the step response of the open loop system in Figure 24. Input signal to the system when receiving the step response in Figure 24 can be studied in Figure 23.

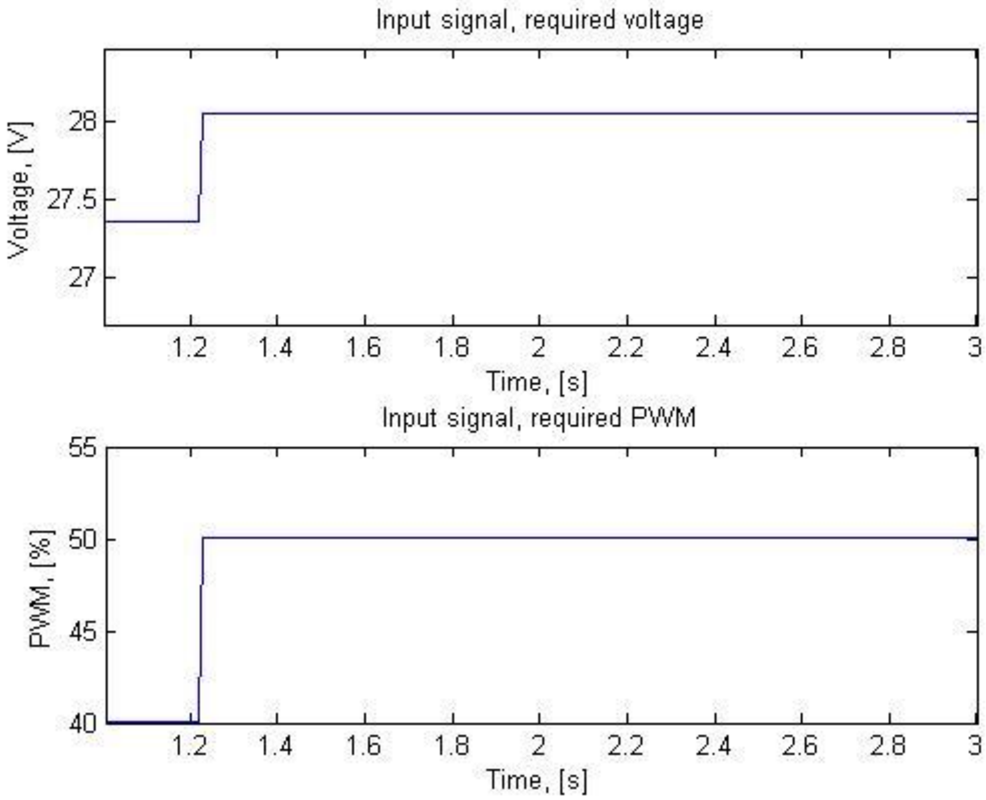


Figure 23: Input signal to the system when obtaining the step response in Figure 24, The top graph is the requested voltage and the lower graph is the requested voltage recalculated into per cents.

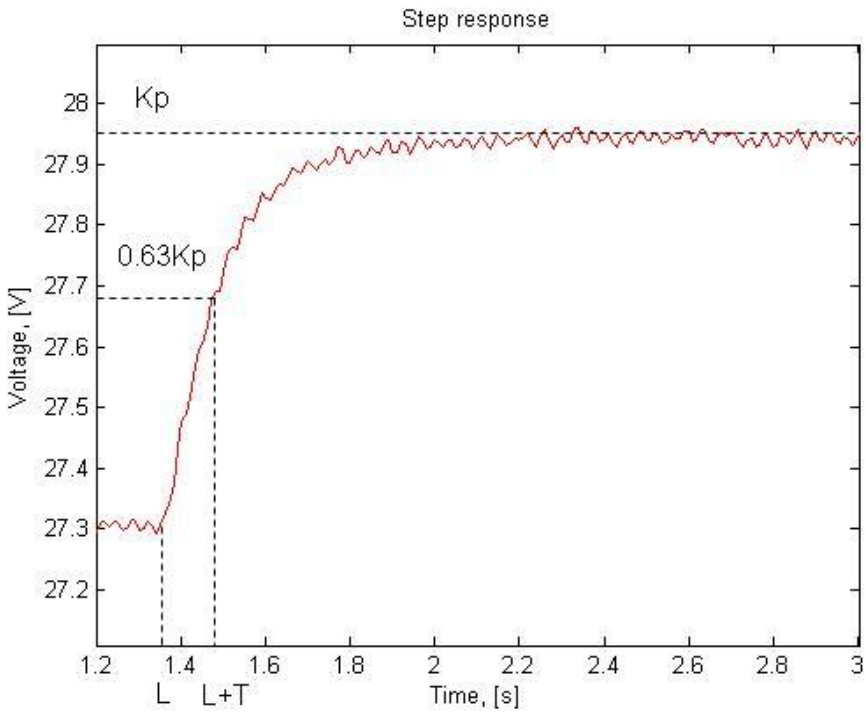


Figure 24: A step response of the open loop system, used for calculating the parameters for the PID controller.

The parameters of the three parameter model are read from the step response in Figure 24 according to the dashed lines in the figure.

- $L = 0.15\ s$, the delay from a step in the input signal until a reaction in the output signal.
- $K_p = 27.95\ V$, the final value to reach for the step response.
- $T = 0.22\ s$, The time constant of the system, it is calculated as the time from L until the time when the system has reached 63 % of the final value.

The parameters from the step response will result in the following three parameter model:

$$G(s) = \frac{27.95}{1 + 0.22s} e^{-0.15s}$$

The concept of the Internal Model Control is to only use the new information in the measured signal for the feedback signal [1]. The IMC-method allows trade-offs between the performance of the system and the robustness of the system [7]. The IMC method is able to achieve good tracking performance for the system [9], which is desired in this case. In the Internal Model Control approach, the parameters are chosen as described below, where T_c is the only design parameter and the other coefficients originates from the three parameter model. T_c is the desired time constant for the closed loop system and T is the desired time constant for the open loop system. $\frac{L}{L+T}$ is the relative time delay for the system.

$$K = \frac{L}{K_p(T_c+L)} \cdot (\frac{1}{\frac{L}{L+T}} - \frac{1}{2}) = \frac{0.15}{27.95(0.22+0.15)} \left(\frac{1}{\frac{0.15}{0.15+0.22}} - \frac{1}{2}\right) = 0.0352$$

$$T_i = L(\frac{1}{\frac{L}{L+T}} - \frac{1}{2}) = 0.15 \left(\frac{1}{\frac{0.15}{0.15+0.22}} - \frac{1}{2}\right) = 0.2950$$

$$T_d = L \frac{1-\frac{L}{L+T}}{2-\frac{L}{L+T}} = 0.15 \cdot \frac{1-\frac{0.15}{0.15+0.22}}{2-\frac{0.15}{0.15+0.22}} = 0.0559$$

With the calculated values of the parameters for the PID-controller on parallel form the following controller is obtained:

$$F(s) = 0.0352 \cdot (1 + \frac{1}{0.2950s} + \frac{0.0559s}{\mu \cdot 0.0559s + 1})$$

When the controller is implemented some adjustments need to be done, the value of μ in the equation above is chosen to 0.2 and is an adjustable parameter. A perfect derivative cannot be implemented and therefore the term $T_d s$ is replaced by $\frac{T_d s}{\mu T_d s+1}$.

To implement the controller it is necessary to use the discretized version of the controller. The sampling is done in Matlab with zero order hold transformation, assuming the signal is piecewise constant over the sampling period, the sampling period is chosen to 0.5 seconds. The zero-order-hold method gives an exact discretizing of the controller.

$$F(z) = \frac{0.2111z^2 - 0.3274z + 0.1759}{z^2 - z + 3.876 \cdot 10^{-20}}$$

The controller on parallel form can be separated to

$$F(z) = F_K(z) + F_I(z) + F_D(z) \quad where$$

$$F_K(z) = 0.0352$$

$$F_I(z) = \frac{0.05963}{z-1}$$

$$F_D(z) = \frac{0.1759z - 0.1759}{z - 3.876 \cdot 10^{-20}}$$

The poles of the discrete controller are $z = 1,\ z = 3.876 \cdot 10^{-20}$

The pole in $z = 3.876 \cdot 10^{-20}$ is approximated to $z = 0$ in the implementation. The tuning of PID-parameters is not an exact knowledge and adjustments are done to make the controller appropriate for the process that is being controlled. With some modifications after the controller being evaluated in the lab environment the parameters described below are chosen for the system to get a satisfying behaviour. The behaviour of the system is satisfying in the sense that it is stable, see Section 5.4.3, Stability of the system, it is fast enough with the selected sampling time and it does not show any signs of oscillative behaviour, related to the stability of the system.

$$F_K(z) = 0.0268$$

$$F_I(z) = \frac{0.04065}{z-1}$$

$$F_D(z) = \frac{0.1342z - 0.1342}{z}$$

The implementation and attenuation of the control signal makes the controller a bit slower than ideally. This is caused by the properties of the signal sent on CAN from the Coordinator to the EMS, which steers the alternator. The signal sent from the Coordinator to the EMS is called Requested Generator PWM and is a value in per cents, that is transformed to a PWM signal inside the EMS. A difficulty with this signal, sent from the Coordinator to the EMS, is that it only has a size of 6 bits and each discrete step is 1.66667 % which equals to 0.11 Volts. For the PWM signal to take one discrete step, the voltage, that is an internal signal in the Coordinator and of 32 bits needs to change 0.11 Volt. As can be seen in Figure 25, in the top graph, the requested voltage signal, changes much faster than the middle one, the Requested PWM signal.

5.4 Characteristics of the control system

Figure 25 shows the performance of the control system. When the positive peaks appear in the battery voltage level, a large load is applied to the system and when the negative peaks appear in the system, a large load is turned off. The control system compensates for the voltage drops by demanding a higher voltage from the alternator, which results in the battery voltage level rising to the reference value.

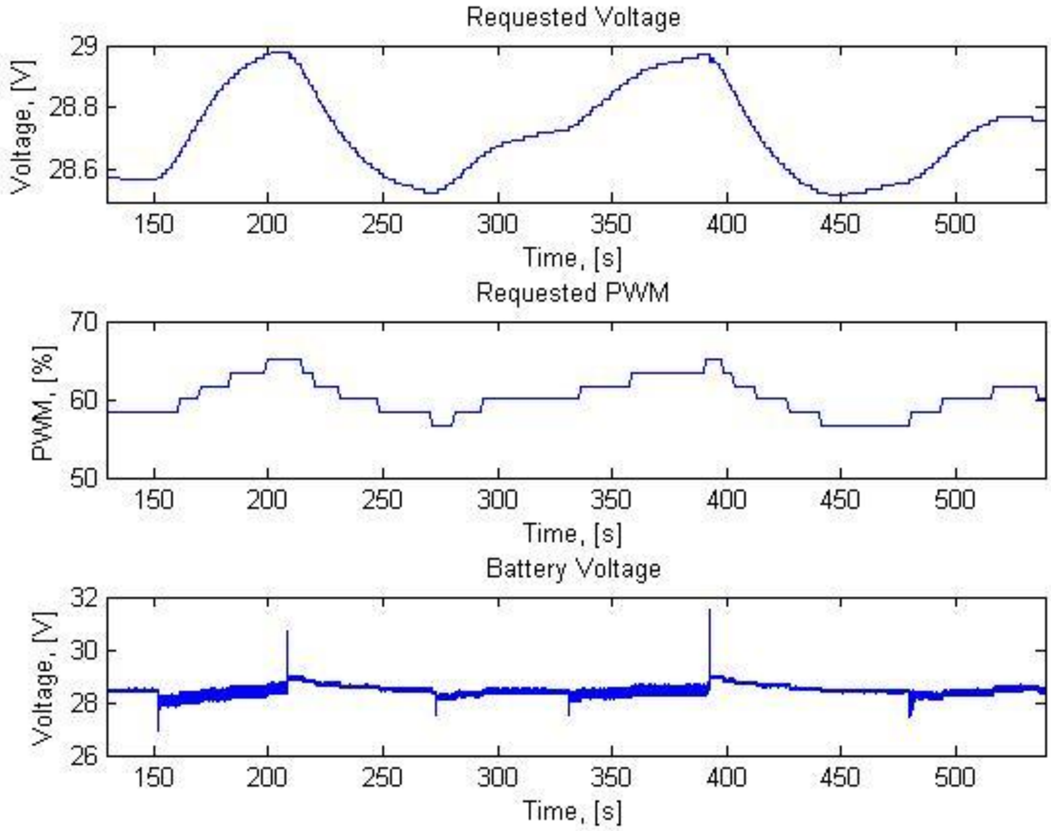


Figure 25: The top graph is the control signal in voltage, the second curve is the control signal in per cents, i.e. the requested PWM signal, and the third curve is the battery voltage.

To analyze the characteristics of the closed loop system, some different aspects will be taken into consideration. For this a step response of the system is studied. The step response in Figure 26 occurs when a large load is put on the system and the controller compensates for the voltage drop – a step from a lower level to the desired battery voltage level.

5.4.1 Settling time

The settling time is defined as the time it takes for the system to reach its new steady state [2]. In Figure 26 it can be seen that the load is applied to the system after approximately 880 seconds and the signal has reached the desired level after about 912 seconds.
$912 - 882 = 30\ s$ is the settling time of the closed loop system. A normal air condition cycle has periods of 3 minutes until it changes level, 30 seconds is within this period which means that the control system adjusts the voltage to the correct level before it switches again. This means that the control system is fast enough in the sense of adjusting the voltage to the correct level well within the limits before the system is changing to another level. What is left to investigate with a test is if the control system is fast enough when loads are turned off. When one air condition unit is turned off for instance, this will have the effect that the voltage level will rise and the controller will compensate for that. This will be done with the same dynamics as when a voltage drop occurs since the controller is symmetric. If over voltage is applied to the system, this may harm the lamps and it could cause error codes to be formed in the control units. To decide if over voltage is applied to the system, the period of time that

the system has a too high voltage has to be investigated. To test this an air condition cycle adjusted for hot climate will be the test scenario, see Chapter 6, Verification tests.

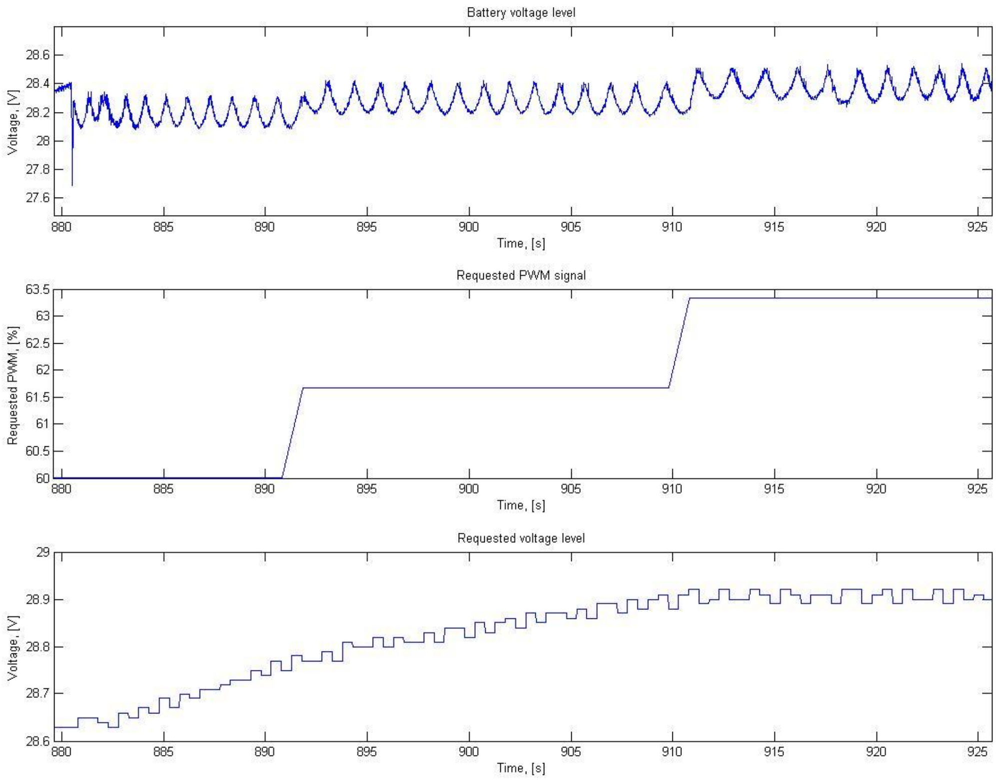


Figure 26: Step response of the system, the third curve is the control signal expressed as voltage, the second curve is the control signal, expressed in per cents for the PWM-signal and the top curve is the voltage level at the battery. The peak that appears in the beginning of the battery voltage level curve is caused by that a load is put on the system, that lower the voltage level, and the control system rise the voltage to the correct level.

The appearance of the battery voltage signal in Figure 26 is caused by perturbations affected by the internal behaviour of the alternator. The different behaviour of the battery voltage in Figure 27 is caused by the bus standing still in this case. Less perturbations will then be able to affect the battery voltage.

5.4.2 Static error

The difference between the output signal and the desired signal in steady state is the static error of the closed loop system. The static error is not possible to determine from recorded data when the control system is implemented. The error will depend on if the voltage demanded from the alternator is close to a discrete level of the PWM signal or not. If the voltage level demanded from the alternator is a value in the middle of two discrete levels of the PWM signal the control signal will vary between these two levels. On that basis the error will not be static, since it will vary over time and depend on which level of voltage that is demanded from the alternator.

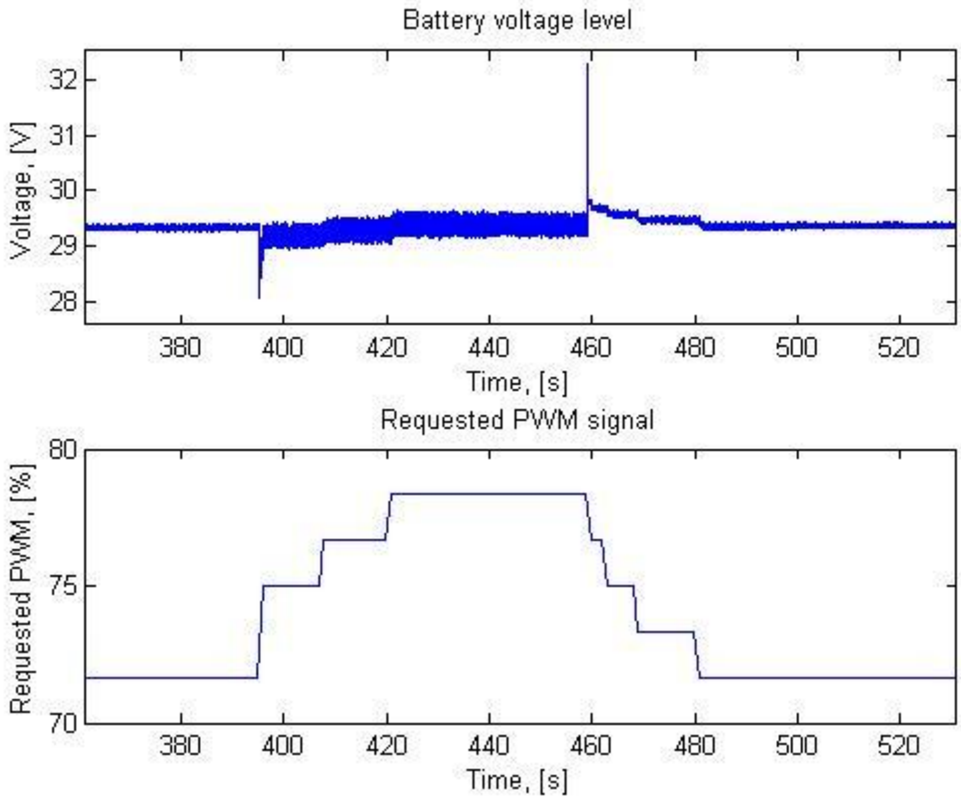


Figure 27: The desired voltage is 29.3 Volts, after 395 seconds 140 ampere is applied to the system and after 460 seconds the load is turned off.

In Figure 27, the desired voltage level is 29.3 Volts, this is the highest value for the required voltage to be sent from the existing temperature model. With this desired voltage, the highest voltage levels to be reached for the system will be recorded. When the ACs are turned off at 460 seconds a peak appears in the system. The peak, as described before, depends on inner characteristics of the alternator and cannot be compensated for with the software function. The top value of the peak is 32.3 Volts when 140 amperes are taken off the system instantaneously. According to Scania document TB1901 the system shall not form error codes if peaks appear due to load taken off the system, if they are less than 65 V and if there are less than 5000 pulses. Each pulse shall be shorter than or equal to 200 ms.

The voltage will step down from a higher level when the ACs are switched off and this will cause a higher voltage level than the one requested during approximately 20 seconds. The higher voltage level is between 30 Volts and 29.3 Volts in Figure 27. According to the Scania document TB1901 the system shall not form error codes if the over voltage is less than 36 Volts over a period of one hour. In this case the over voltage is less than the limit of 36 Volts and the time period is shorter than the restricted time of one hour.

5.4.3 Stability of the system

The stability of the closed loop system needs to be investigated for the control system to be reliable. In this case the system is not exactly known, since the behaviour of the system depends on how much load that is applied to the system. The load varies but is an internal signal in the system. It is unknown when the load is changing but when it does the system behaves differently and it will be noticed on the output signal. A higher voltage drop will occur if more load is applied to the system. One way to get an indication of the stability is to study a step response of the system. The linear system is stable if a bounded input gives a bounded output signal. This can be seen in Figure 26 and Figure 27, PWM-signals in the interval 60-78 % are requested from the alternator, and the output from these signals is bounded.

It is desirable to observe the placement of the poles of the closed loop system to theoretically confirm that the system is stable. With this follows some difficulties in this case since an absolute mathematical model that describes the system is not known. Though it is possible is to use the ARX models from Chapter 4 for the system, that represents the system in one state each, when a static load is applied to the system. The system is linear, the voltage drops depend on resistances in the wires and currents that pass through the wires.

For the first case, when no extra load is applied to the system, the model from Section 4.1.1 is used the poles for the discrete closed loop system will wind up in what can be seen in Figure 28 and all poles are within the stability margin. The left half plane in continuous time represents the inner part of the unit circle in discrete time, this is due to the fact that when discretizing, the transformation have the following appearance: $z = e^{sT}$.

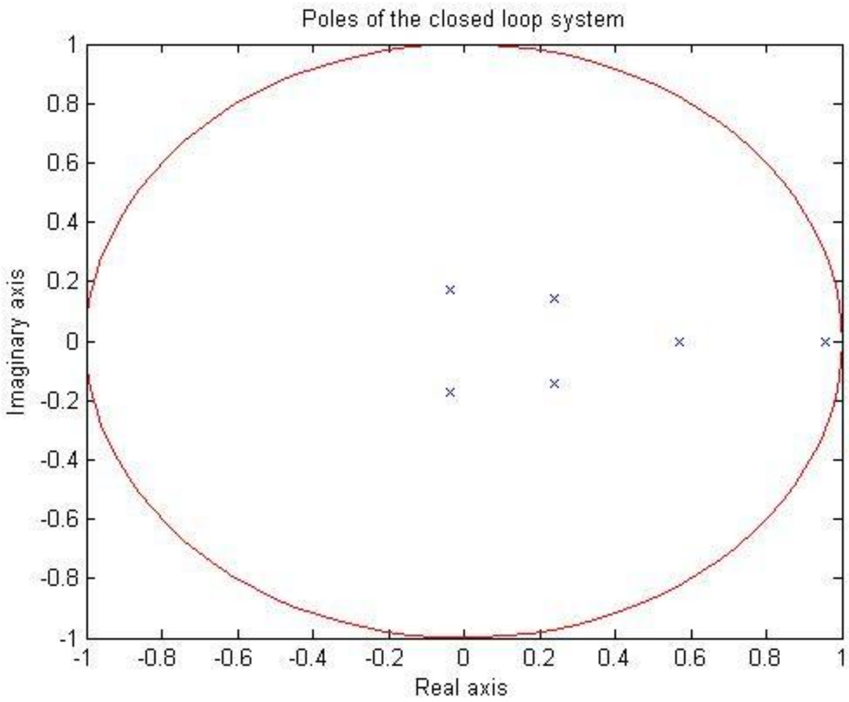


Figure 28: Pole placement for the discrete closed loop system with no extra load applied to the system. The circle shows the stability limit and the crosses represent the poles.

The closed loop system, when using the ARX model, implies stability according to the placement of the poles. The black box model is created on the basis that no extra currents are added to the system. That is larger currents can be applied to the system, causing voltage drops and the model will not be valid for the system. This implies that the stability investigation of the system has to be extended to cover the case when larger currents are applied to the system. This implies that the system is stable when no extra load is put on the system.

To make the stability investigation for the system when a large load is applied to the system, the model from Section 4.1.2 is used. This model is developed when the simulated air condition units are fully turned on and the current will be approximately 140 A, plus regular power consumers, resulting in a total power consumption close to the maximal one, without hitting the limit of the capacity of the alternator. The poles of the closed loop system with this model can be viewed in Figure 29 where all poles are within the unit circle, which implies stability of the closed loop system.

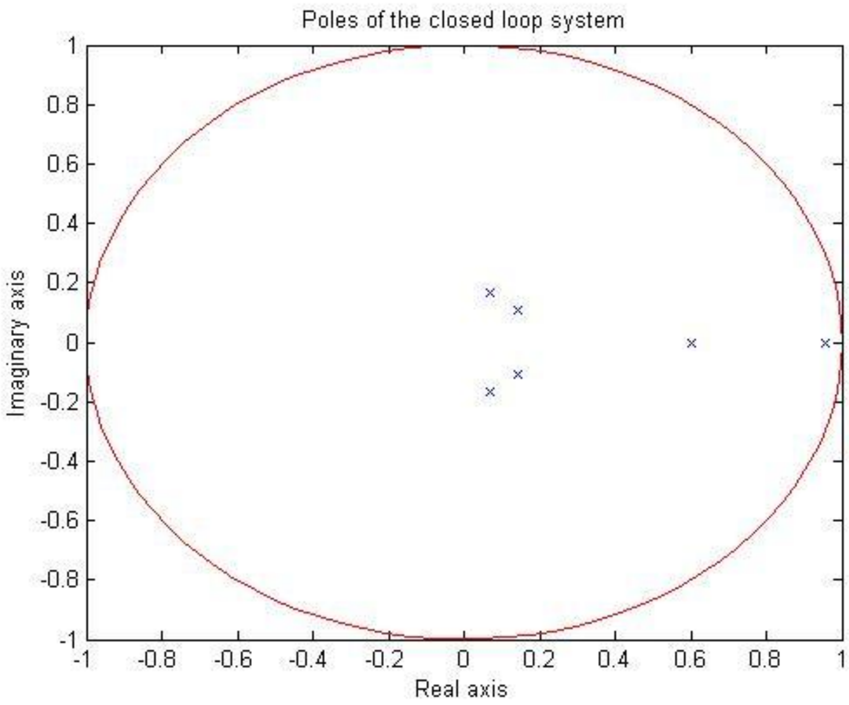


Figure 29: Poles of the closed loop system with the model with full load on the system.

The conclusion of the investigation of the stability is that the closed loop system is stable when no extra load is put on the system as well as when a large load is put on the system.

5.4.4 Windup

Modifications of the PID controller have to be done when it is implemented. An important case to handle is the consequences of the control signal getting saturated when hitting a limit. Since the control signal is saturated it will take a long time for the output signal to reach the level of the reference signal. During this time, the integrator part of the PID controller will keep on integrating the error which will make the integrator part of the controller very large. This effect on the system will be that it will take a long period of time after the error has switched signs until the integrator part is integrated down to a normal value. This behaviour will keep the control signal on a maximum value for a longer time than desired.

There are different approaches on how to avoid windup. The one chosen in this case is conditional integration. In this approach the system turns off the integrator part when the control signal gets saturated. It stops the updating of the integrator part and does not start to update it until the control signal is within its limits [1].

The following algorithm avoids for windup

$$if \quad u_{min} < v_n < u_{max}$$

$$I_n = I_{n-1} + K\frac{T_S}{T_i(z-1)}e_n$$

$$u_n = \begin{cases} u_{max,} & if \quad v_n > u_{max} \\ v_{n,} & if \quad u_{min} \leq v_n \leq u_{max} \\ u_{min,} & if \quad v_n < u_{\min} \end{cases}$$

$$else$$

$$I_n = I_{n-1}$$

$$u_n = \begin{cases} u_{max,} & if \quad v_n > u_{max} \\ v_{n,} & if \quad u_{min} \leq v_n \leq u_{max} \\ u_{min,} & if \quad v_n < u_{\min} \end{cases}$$

Where v_n is the control signal calculated without consideration taken to saturation.

6 Implementation

This chapter is about how the control system is implemented in Simulink and compiled and written to the memory of an electrical control unit.

6.1 Implementation of the control system

Several options for how to do the implementation of the control system are considered. The two main ideas are to:

1. Implement the control system with LabView in a computer by National Instruments
2. Implement the control system in an electrical control unit, the Coordinator with Matlab/Simulink

The selected path is after some consideration the second alternative, to implement the control system in Simulink and then to compile it into C-code and to write the code to the Coordinator. This Coordinator only contains this model and not the regular software of a Coordinator. Therefore this extra Coordinator is connected in parallel with the original one, a bypass with supply voltage is connected from the regular Coordinator to the new one and the wire for this is created to fit both Coordinators. To the new Coordinator three CAN buses are connected, one CAN bus is used to take in CAN signals from the regular red CAN on the bus, one CAN bus is used to send the requested PWM signal to the EMS, and one CAN bus is used to flash the Coordinator, so also CAN wires are created. To the last CAN a socket is created to make it possible to write the code to the Coordinator via a Vehicle Communication Interface (VCI).

It is desirable when setting up the implementation/lab environment to capture as much as possible of the time delays of the system. To achieve this an extra EMS is connected to the system as well. To make the lab environment authentic, the new Coordinator is connected via CAN to the added EMS. This EMS has a special software which makes it possible to just supply it with voltage and to send a requested PWM signal from the new Coordinator via CAN. The new EMS then creates a physical PWM signal from the requested per cents. The contacts to the alternator coming from the EMS are connected to a bypass, so that the new EMS is the one sending PWM signals to the alternator. The old EMS is still getting the output signals from the alternator, to get the necessary information, such that the alternator is charging. In this way the dynamics of the lab system is alike the dynamics of the real system since the whole information flow for the signal is kept in the lab environment. The required voltage is still being calculated and recalculated into a per cents in the Coordinator, sent to the EMS and turned into a physical PWM signal and sent to the alternator, that generates the requested voltage. This results in the same information flow for the lab environment as for the real system, see Figure 2. Figure 30 shows the placement of the different parts of the implementation in the bus. This is the lab environment in the work that is used for testing and verification of the control system that is developed.

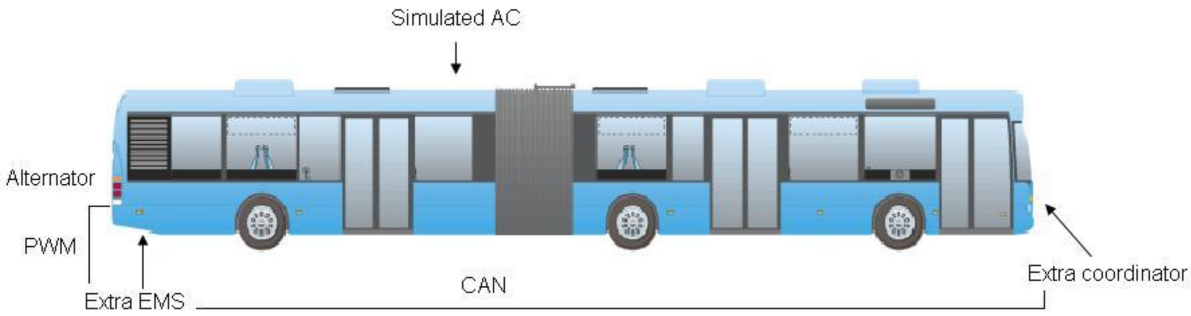


Figure 30: The information flow for the implemented function in the bus, the extra Coordinator is placed in the front of the bus and the extra EMS is placed in the back of the bus, by the engine.

The model is implemented in Simulink, in a special interface that is used for development and is developed at Scania. The control system is implemented using the blocks from Scania's standard library, supporting the building and compiling of the code. To make it possible to use this interface three .m-files are necessary. Of great importance when using this interface to Simulink is to define the data types and to stick to the types.

Constants
In this .m-file the constants used in the calculations are defined. It is also defined which data types they are of.

DataDef
In this .m-file data definitions are made. The CAN input and output signals, the parameters and RTDB signals (inner signals) are defined. In this file the attributes of the signals are defined, address, size, type, scaling factor, offset, period and which CAN bus to be used. If a signal is converted into a signal with fewer bits, a less accurate signal will be created, in this case the scaling factor of the signal has to be considered as well.

rpsApplication
In this .m file it is selected which Simulink model to be used in the compiling and building process.

Parameters in the model that are desired to be changed during a development process are being defined as input CAN signals. In this way it is possible to manipulate the signals during testing in the lab environment to reach desired values for instance the PID-parameters. The desired voltage level, i.e. the input to the control system, is sent on CAN as well during the development process, to simulate the changes that occur when the desired voltage level changes due to changes in the battery temperature when the Adaptive Battery Charge (ABC) system is used. The ABC- system selects a higher reference value for the voltage when it's cold outside since the batteries are not as good receivers of charge during cold conditions and the model selects a lower requested voltage level when its warm outside to not over heat the batteries since that can happen when charging with a high voltage when it is warm outside [8].

To use this interface to Simulink three different subsystems need to be implemented as can be seen in Figure 31. The figure illustrates a scheme of the complete system, containing one block for the input signals, one block for the output signals and one block for the main algorithm. The subsystems and the signals in the system will be described in Section 6.1.1 – 6.1.7. In these sections the structure of the implementation of the system is presented. In the main system there are several subsystems, which are explained in Section 6.1.1-6.1.7.

6.1.1 The input signals

The input signals originates from three different blocks, the first block takes in the input CAN signals, the second block consists of parameters and the third block consist of RTDB signals.

- genCharging – this signal is 1 if the alternator is charging and 0 if the alternator is not charging, CAN signal
- UBat – this signal is the internal voltage measurement of the Coordinator, RTDB, inner signal.
- OldPWM – The requested PWM signal from the latest sample, RTDB, inner signal.
- I_Old – The Integrator part from the latest sample, RTDB, inner signal.

6.1.2 The output signals

There are two different kinds of output signals from the system, CAN signals and the RTDB signals.

- ReqVolt – The requested voltage level, RTDB, inner signal.
- PWM – The requested PWM signal sent to the alternator, CAN signal.
- OldPWM – The requested PWM signal saved to be input to the next sample of the controller, RTDB, inner signal.
- IOldIn – The integrator part saved to be input to the next sample, RTDB, inner signal.

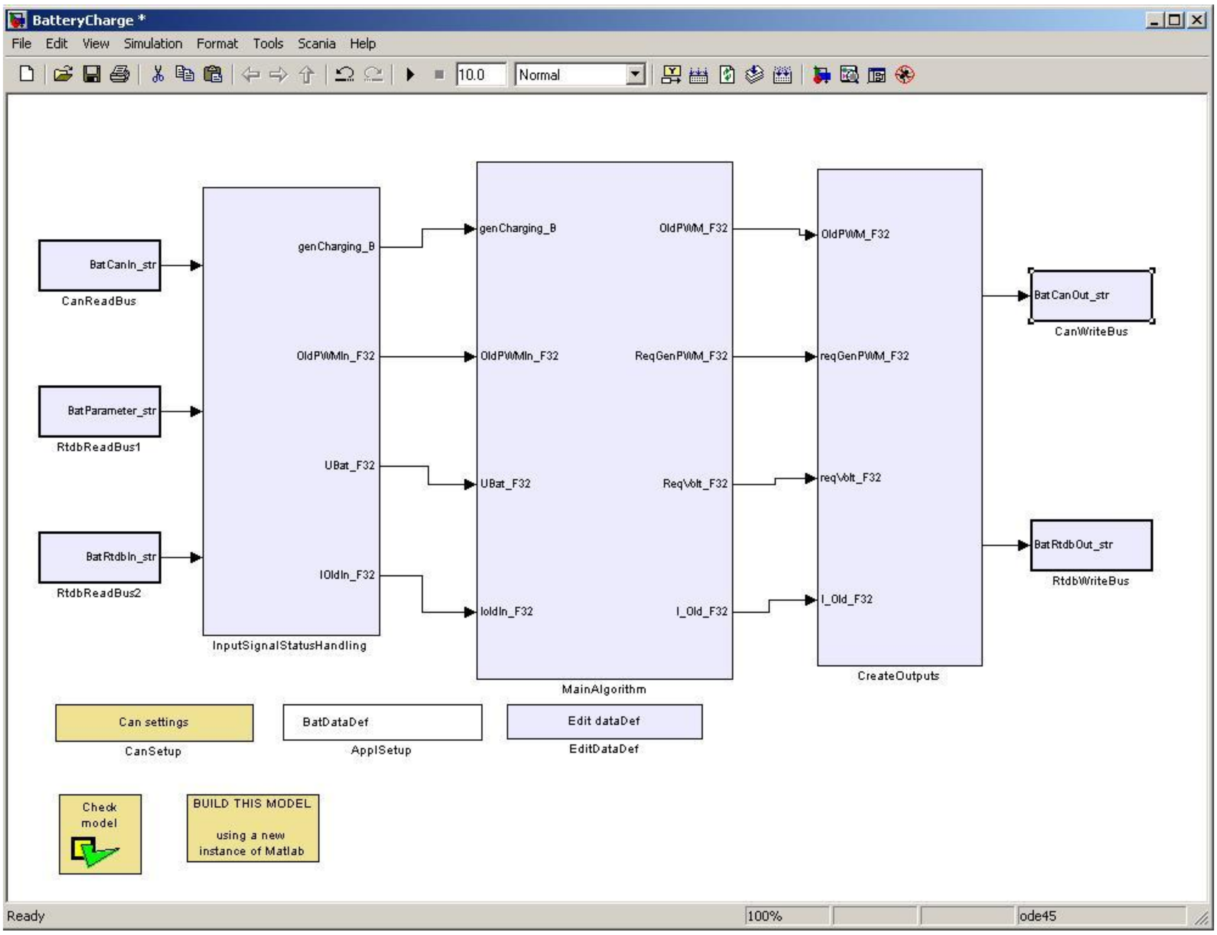


Figure 31: Simulink blocks of the control system, inputs and outputs.

6.1.3 genCharging_B

This signal is a Boolean signal that is true if the alternator is charging and false if the alternator is not charging. If the signal is true, the control system is used and if the alternator is not charging the requested PWM sent is a default value of 55 %. This is a default value corresponding to 28.3 V, the desired voltage level when the temperature is 0-20 Celsius.

6.1.4 UBat

UBat is an internal RTDB signal, that is not sent on CAN and the signal is sampled every 0.01 seconds. Before the UBat is used in the control system, the signal is filtered using a low pass filter with cut off frequency ¼ Hz, as described in Section 3.4.1.

A constant value is added to the filtered signal, to compensate for the difference in voltage level between the Coordinator and the battery. The signal is then decimated to take in only every 50 sample. Since the low pass filter is applied before decimating the signal no alias effects will appear.

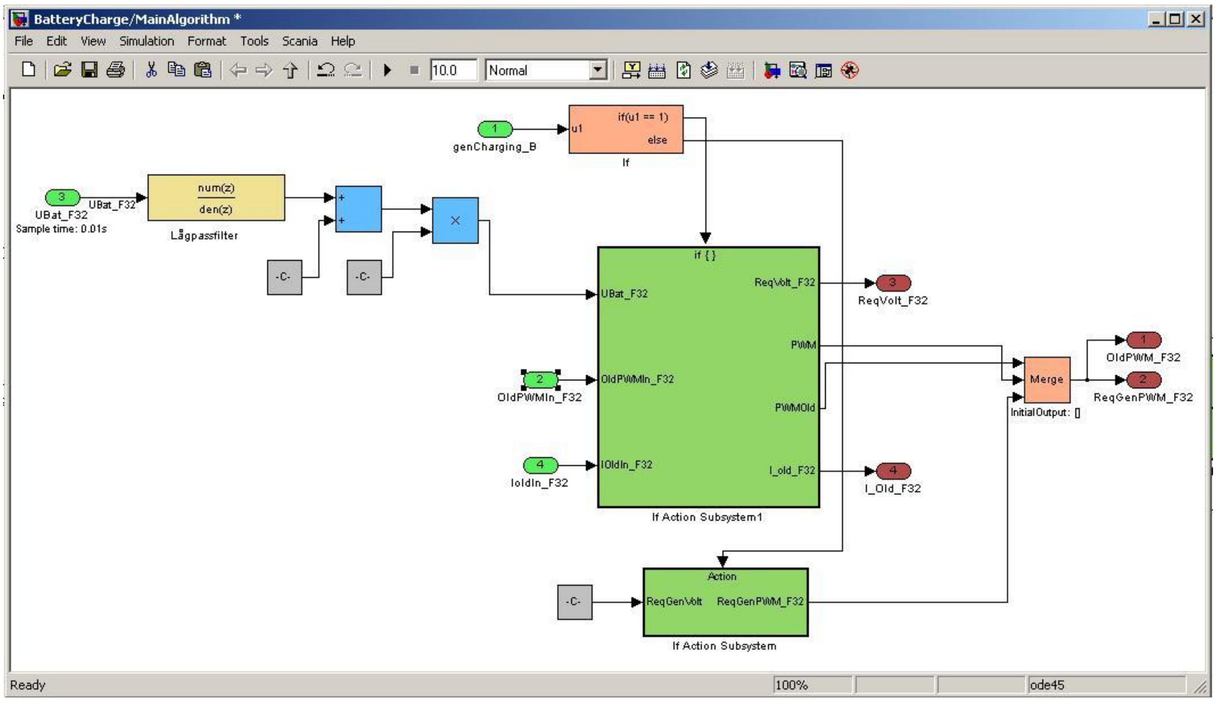


Figure 32: Simulink blocks for the main algorithm of the control system.

The requested generator PWM signal is the output from the main algorithm. This signal is also saved as the last requested PWM signal. The two different signals, the output signal from the controller and the constant requested PWM are merged together.

6.1.5 Subsystem – The control system

The subsystem, including the control system, can be seen in Figure 33 and contains the PID controller and some modifications to the controller, to correct for unwanted consequences of the implementation of the controller. If the most recent calculated voltage level does not differ more than 0.05 V from the last calculated voltage level, the requested PWM signal will not be updated. This feature is implemented to avoid for the control signal to switch too much between two values caused by noisy behaviours of the alternator voltage that are left despite of the low pass filter.

The relationship between the value of the voltage and the PWM value is linear. The transformation is made by a subtraction followed by a division;

$$PWM = (ReqVolt - 26.40)/0.065.$$

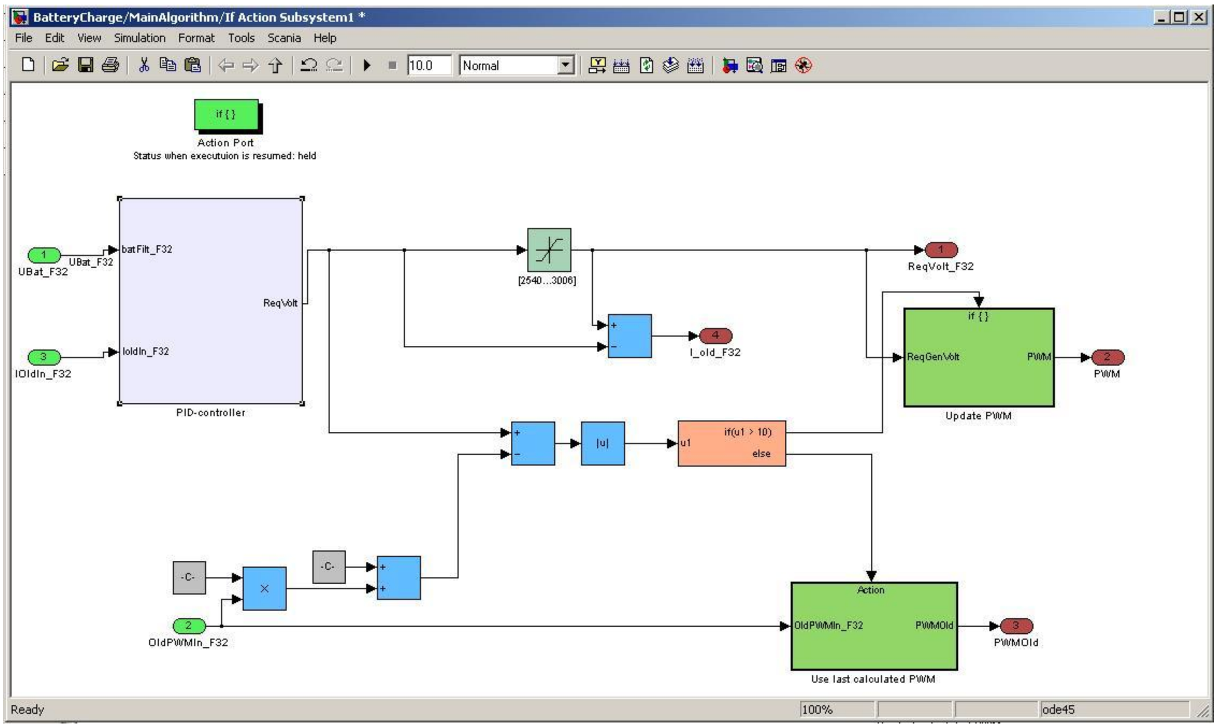


Figure 33: Simulink blocks of the control system

6.1.6 The PID-controller

The implementation of the PID controller can be seen in Figure 34. The reference signal of the PID-controller is the desired value for the system to aim at. In this case it is chosen to 28.33 Volts since that is the optimal value for the battery charging voltage level under ideal conditions [11]. This signal minus the feedback signal (the filtered voltage measurement) is the input signal to the PID controller. The PID controller is implemented on parallel form, the proportional, the integral and the derivative parts are summed together. The reference signal is added to the output of the PID-controller to get a better fit.

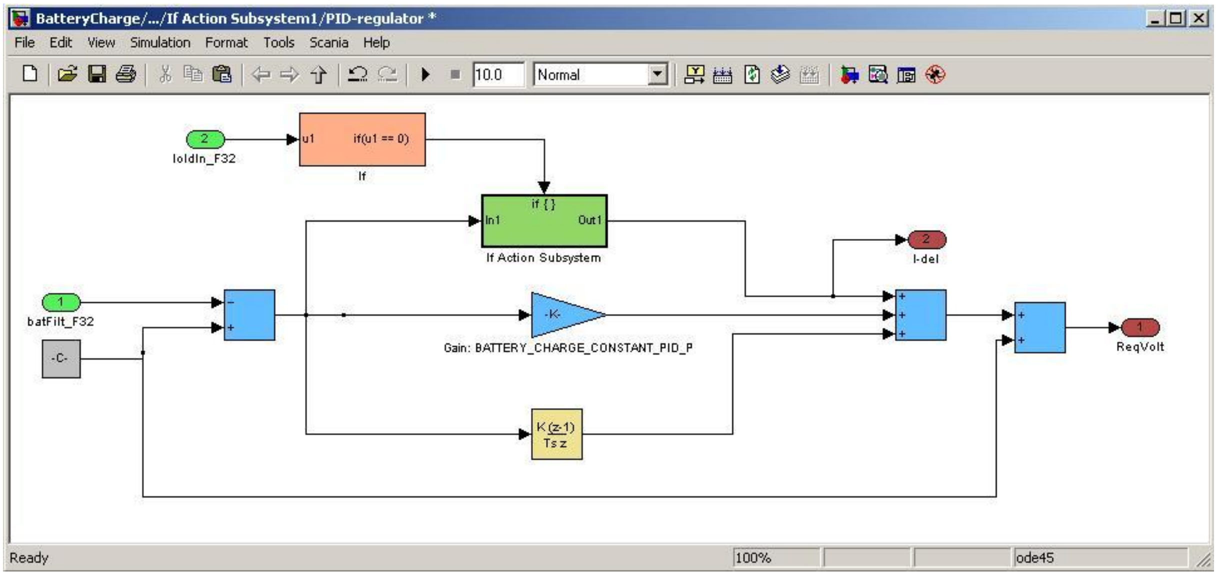


Figure 34: Simulink blocks of the PID controller, implemented on parallel form

6.1.7 Windup

The output signal from the PID controller is sent through a saturation block, to limit the control signal to be in the interval 25.40 to 30.50 Volts. The difference between the input and the output from the saturation block is saved in every iteration. If this difference is separated from zero, the control signal is saturated. The integration part of the controller will then not be updated until the control signal is not saturated any longer. This is done to prevent the integrator part of the PID controller from becoming indefinitely large when the control signal is saturated, as described in Section 5.4.4.

7 Verification tests

This chapter is about the verification tests that are performed when the control system is implemented in the bus. Two tests are performed to verify the performance of the function and the improvements the function possibly can make to the charging of the batteries.

7.1 Test 1, Distribution of voltage

The first verification test is done to evaluate the performance of the control system that has been implemented. The test is done to resemble a drive in warm climate and the air condition unit will be used. The test is performed first with the control system and then without the control system. The aim with the test is to show that the distribution of the voltage level will increase when using the control system. This is to show that the control system will have the effect on the system that the batteries will be charged with a higher voltage level than without the control system. The expected result from the test is to get a normal distribution of the voltage level around the desired voltage level with the control system. Another purpose of the test is to investigate during how long time the batteries will be charged with a too high voltage and if that too high voltage is within the limits of tolerance.

The test is performed on the test track at Scania with the articulated bus that has been used throughout the thesis work. The test is performed with the aim to assemble a normal route in a city with a warm climate. After stops that exist quite often when driving city buses, the ACs are turned on with full power and after 4 minutes the AC connected in the rear of the bus is switched off for a minute and then turned on again. The following test procedure is done, first with the control system used and then without the control system, to make it possible to compare the tests to each other.

1. Drive with the AC’s with full power for 4 minutes
2. Drive with the AC’s with half power for 1 minute
3. Drive with the AC’s with full power 4 minutes
4. Drive with the AC’s with half power for 1 minute
5. Stand still with the AC’s with full power 4 minutes
6. Stand still with the AC’s with full power for 1 minute
7. Drive with the AC’s with full power 4 minutes
8. Drive with the AC’s with half power for 1 minute

The total time for the test is 40 minutes, separated into two parts, 20 minutes with the control system and 20 minutes without the control system. The result from the test is summarized in the histograms in Figure 35 and Figure 36. Figure 35 and Figure 36 describes the difference between the desired voltage level and the actual voltage level, measured at the battery. In Figure 35 it is visible that the measured voltage level at the battery is lower than the desired voltage level most of the time, about 0.5 V too low. In Figure 36 when the control system is used, the difference between the desired voltage level and the battery voltage level is distributed around zero. Another result from the test can be studied in Figure 36, which shows that a too high voltage level is applied to the system when using the control system, this too high voltage level is maximum 1 V when a desired voltage of 28.33 V is applied to the system. The high voltage is only applied to the system during short periods of time are well within the limits stated in Scania document TB1901.

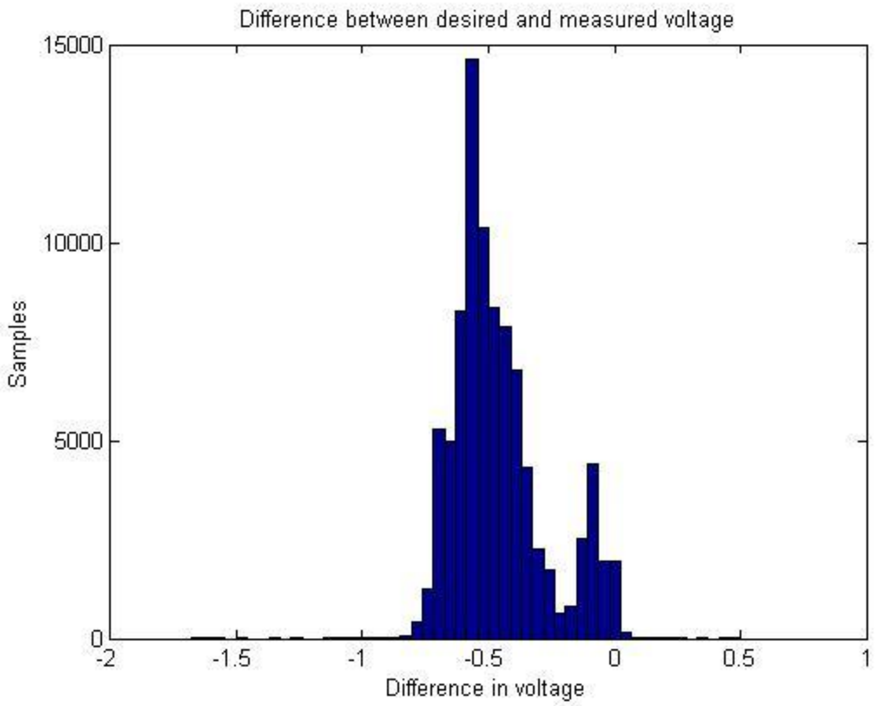


Figure 35: Histogram of distribution of the difference between the desired voltage level and the battery voltage level when the control system is not used for the test drive in verification test 1.

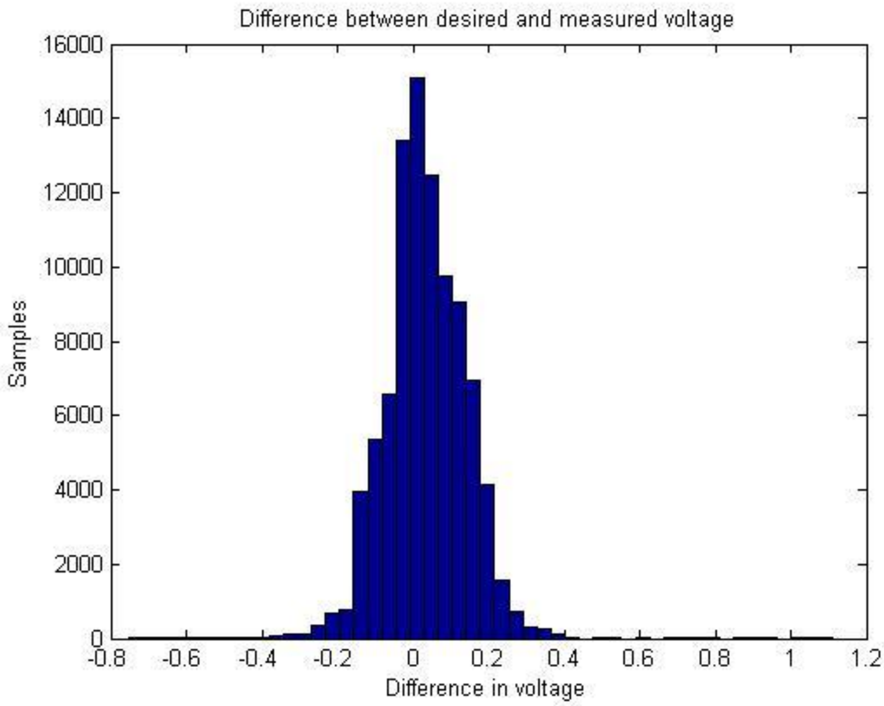


Figure 36: Histogram of distribution of the difference between the desired voltage level and the battery voltage level when the control system is used for the test drive in verification test 1.

The appearance of the distributions of the voltage levels, in Figure 35 and 38 depend on the power consuming unit being turned on and off during the drive. A turning off sequence, when the controller is used, can be seen in Figure 37. The turning on and off sequences contributes to a variation of voltage levels at the batteries, the width of the distribution. As seen in Figure 37 when the voltage is stepping down to the correct level. The height of the distributions depend on the number of times the power consumer is turned on and off. If the power consumption would be constant, i.e. the distribution would be very thin, at the center of the distribution. The appearance of the distribution looks different when the control system is not used, since there is no stepping up and down of the voltage level, the discrete steps caused by voltage drops are larger.

The distribution of the voltage level when the control system is used, Figure 36, shows that the voltage level is a bit over weight to the positive part. This means that the voltage is more often too high than it is too low when the control system is used.

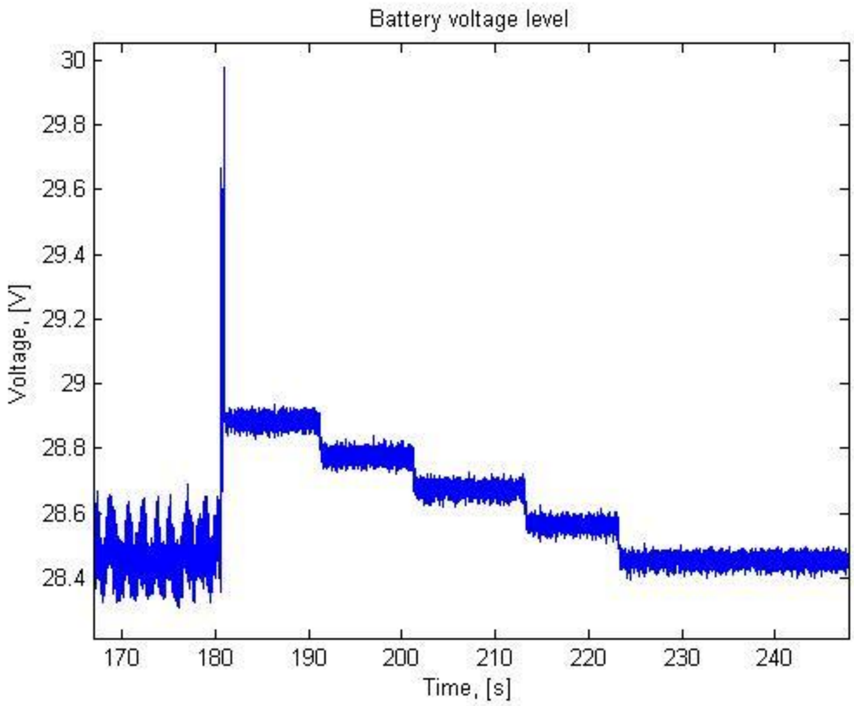


Figure 37: A large power consumer is turned off after 180 s, the voltage is stepped down to the desired level.

7.2 Test 2, Charging of the batteries

The second verification test is done to evaluate the usage of the function that raises the battery voltage level. The aim is for the batteries to reach a higher state of charge in shorter time with the control system.

The same test is performed with the control system and without the control system and the results are compared to each other. To get equal prerequisites for the test a new set of batteries are installed in the bus. When the batteries are new they have not yet been sulfated and it is more likely that they reach a high state of charge. The bus is placed indoors, so the effect of the temperature on the test result is minimized. In this test the definition of fully charged batteries is when the charging current is 1 A.

The test is performed in the following way:

1. The batteries are charged until the current into the batteries is 1 A
2. The batteries are discharged by 24 A during 35 minutes

3. The batteries are charged with the alternator when idling while the load on the system is approximately 150 A.
4. The test is performed until the current into the battery is 1 A again.

The test is performed in the following test cycle:

1. Perform the test with the controller
2. Perform the test without the controller
3. Perform the test with the controller
4. Perform the test without the controller

The result from the test can be seen in Figure 38. The curves show how much current that goes into the battery. The solid curve is the battery current obtained when charging the battery using the control system, i.e. applying a higher charging voltage to the battery. This results in more ampere hours into the battery, which implies the battery reaching a higher state of charge in shorter time with increased charging voltage level.

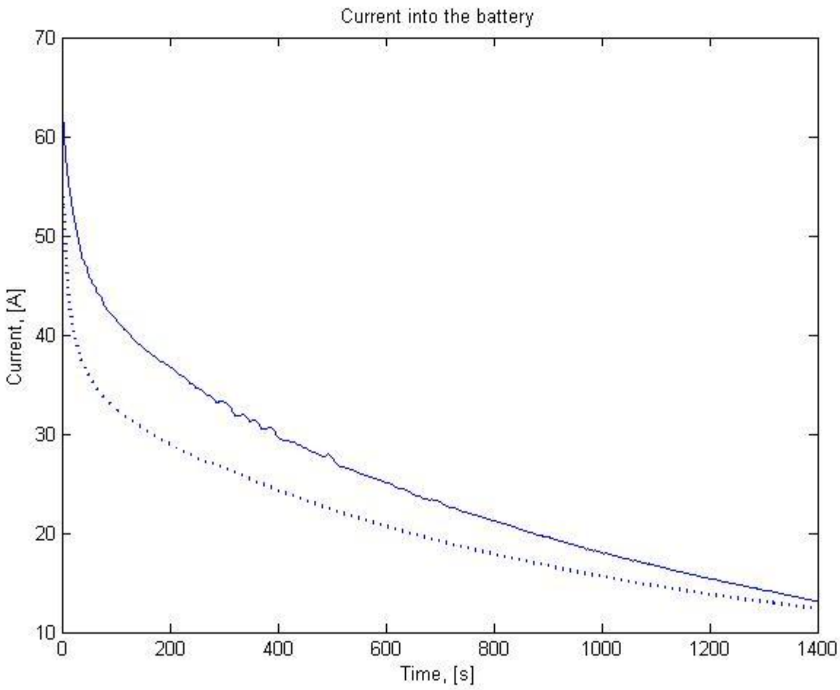


Figure 38: Current into the battery. The dotted curve is the current into the battery during charging when the control system is not used, while the solid curve is when the control system is being used and a higher charging voltage level is applied.

By integrating the current into the battery with respect to time, the amount of ampere hours into the battery will be obtained. The curves for the integrals of the currents can be seen in Figure 39. The total difference during the first 23 minutes of the charging results in a difference of 17.63 Ah. The total capacity of the batteries is 225 Ah, so 17.63 Ah corresponds to 7.8 % of the capacity. The higher state of charge will then improve the susceptibility of charge into the battery. After 23 minutes the charging current decreases as the battery reaches a higher state of charge.

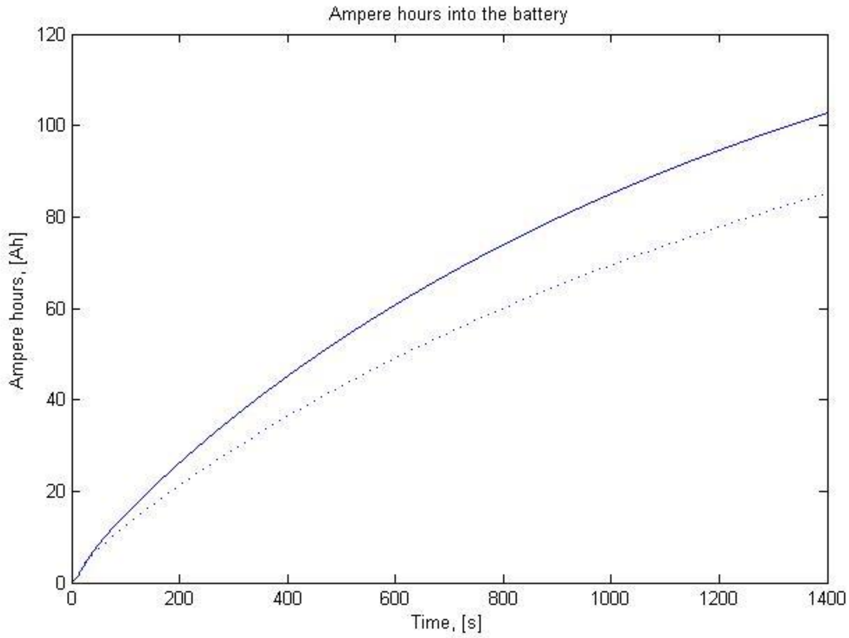


Figure 39: Ampere hours into the battery during verification test 2, the dotted line is when the control system is not being used and the solid line is when the control system is used.

The batteries have a capacity of 225 Ah and a comparison is made, regarding the time it takes to charge the batteries with 10 % of the capacity (22.5 Ah) with and without the control system. The solid line is the charge into the battery when the control system is used and the dashed line is the charge into the battery when the control system is not used.

It takes 167 seconds to reach a charge of 22.5 Ah into the battery with the control system in use, i.e. when an increased battery charging voltage is applied to the system. When the control system is not used, the time needed to get the same amount of charge into the batteries is 216 seconds. This results in a difference of 50 seconds to charge the batteries with 10 % of their capacity. A higher state of charge will be reached in shorter time for the batteries when the control system is used. This according to Figure 42.

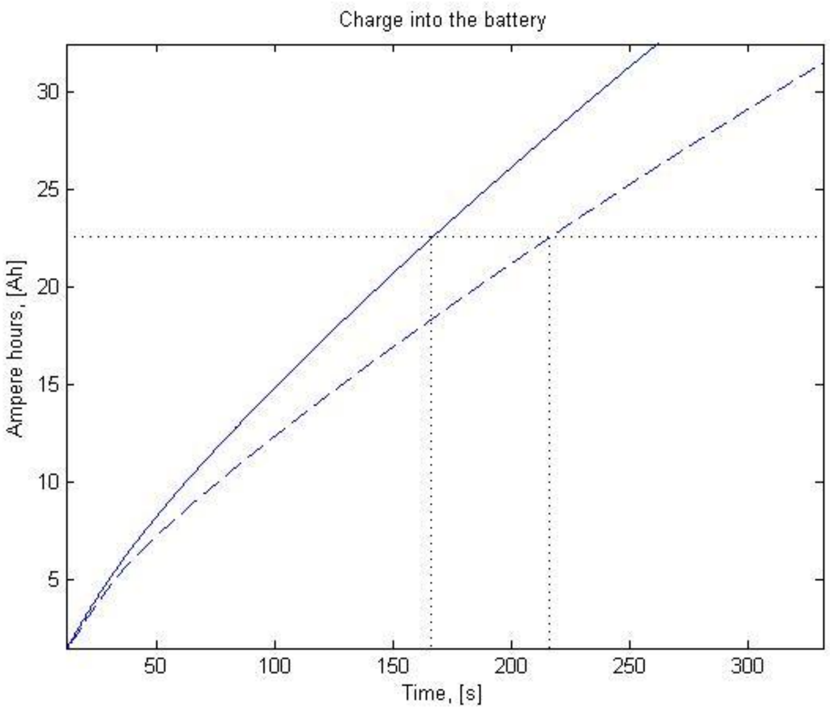


Figure 40: The time for charging the batteries with 22.5 Ah with the control system, solid line and without the control system, dashed line.

8 Discussion

One of the largest concerns when starting this work was if it was possible to use the Coordinator voltage measurement as a feedback signal. The concern was regarding if this signal was of good enough quality and if it was close enough to the battery voltage. The investigation showed that the signal was noisy, caused by the alternator delivering a noisy signal. By applying a low pass filter to the signal and then decimating it, the signal was considered to be good enough to be used as feedback signal for the control system. The investigation about if the measured voltage level in the Coordinator was close enough to the battery voltage level showed that the signals have the same appearance, except from the Coordinator voltage level being constantly a bit lower than the voltage level at the batteries. The investigation of the size of the difference and whether or not the difference was constant implied that the difference could be approximated to 0.1 V. The analysis of the interval for the difference of the measured voltage level at the battery and the measured voltage level in the Coordinator showed that there can be an error of -0.077 V or +0.04 V from 0.1 V for the voltage measurement used in the calculations. Adding 0.077 V to the voltage level when a power consumer is turned off would still keep the level of the battery voltage on a level within allowed limits. Charging the batteries with a voltage level 0.04 V below the desired level would still improve the charging of the batteries since, according to Appendix A, a big part of the buses have a voltage level at the batteries 0.5-1 V lower than the desired level.

Implementing the control system and evaluating it in the lab environment in the bus showed that since the requested PWM signal only has the size of 6 bits the discrete steps are quite large, the smallest discrete steps between two values of the control signal corresponds to 0.11 V. This has the effect that if the reference value for the voltage is in between two of those values the control signal will vary between these two levels when the aim is to be as close to the desired voltage as possible in every time instance. Otherwise it is possible to add a hysteresis to the system, always keeping the battery voltage on the low or the high voltage if the calculated PWM is in between two values. A higher resolution of the PWM signal would keep the battery voltage even more alike the desired voltage level.

The selected implementation turned out to be a good choice, since the whole information flow could be captured. The lab environment that was used for testing and verification of the control system was connected to the electrical circuit of the bus in parallel to the regular control units in the bus. The calculations of the control system were performed in the Coordinator, where the adaptive battery charge control is implemented. The Requested PWM signal is sent on a CAN bus to the EMS, where the physical PWM signal is created and sent to the alternator as the flow of information is implemented in the vehicles today. This implementation of the lab environment made it possible to test the system having the correct time delays for calculations and information flow.

It was possible to create reliable black box models for the system to be used for the investigation of the stability of the closed loop system as well as for tuning of the PID parameters. The models were possible to create for different sizes of currents in the system, though static, since the currents were not measured. The dynamics of the system could be captured by stimulating the system with different input signals. The feedback strategy chosen for the control system turned out to be a good choice of strategy. The voltage maintains at a higher level and most preferably the desired level. The PID controller is a basic controller but turned out to be good enough for the system. Since the PID controller does not contain a big amount of calculations, it will not take much CPU which makes it attractive to implement.

During the development process it was considered whether or not to make the control system faster, i.e. to sample the voltage measurement in the Coordinator more often. Though some balancing had to be made between having an accurate or a fast system. By down sampling the risk of the signal getting adapted to noise is reduced. Taken into account when making the decision of the speed was also that a faster control system was not necessary since the too high voltage levels were within allowed limits.

The verification tests showed that the control system raises the battery charging voltage to be distributed with center approximately on the desired voltage. The distribution of the voltage level when the control system is used is a bit over weight to the positive side, i.e. the voltage level is more often too high than it is too low. This implies that it takes longer time for the voltage level to decrease from a higher to a lower level than to increase from the lower to the higher level. Though the most likely reason is that the constant value added to the measured voltage level inside the Coordinator is a bit too low.

The second verification test showed that the control system contributes to the batteries getting charged faster. This verifies that a higher charging voltage level at the batteries will provide the batteries with more charge. The batteries will receive more charge in shorter time, making the batteries reaching a higher state of charge faster. The difference of 17 Ah between the control system being used and not being used is significant, since it corresponds to about 8 % of the capacity of a battery of 225 Ah.

9 Conclusions

The conclusions to be drawn from this thesis work are that it is possible to control the voltage level of the batteries with a software function. No extra sensors were added to the system, neither more wiring. The usage of CPU was low by keeping the calculations of the controller as simple as possible.

On this specific bus the center of distribution of the voltage level increased from being 0.5 V below the desired level to have a centre approximately at the desired level. When the control system is used the distribution of the voltage also is more narrow around the desired value than when it is not used. The voltage level of the batteries is more close to the desired level, which makes it possible to demand a higher voltage without risking the electrical control units to form error codes or harming the light bulbs. This results in the batteries reaching a higher state of charge in a shorter period of time.

The control system was implemented in the lab environment identical to the real system. This verifies that the whole information flow was captured as well as the time constants and the delays of the system when tests and verifications of the function were performed.

10 Future work

To improve the function several features can be added. To remove parts of the limitations a solution would be to raise the idling when the alternator is not able to deliver as much power as is demanded when the engine idles.

To verify that this function is good enough for its purpose and that it will do significant improvements to the charging of the batteries, several verification tests need to be done. The function also needs to be tested over a long period of time during different circumstances, to make it possible to draw any further conclusions about the functionality and the effects of adding the function.

A more thorough investigation of the difference between the voltage measurement in the Coordinator and the battery voltage level need to be performed. Since this difference is varying on busses of different configurations a sensor should be added measuring the difference during a longer period of time and on different configurations of buses.

By adding sensors to the system and measure the currents in the electrical circuit of the bus it would be possible to get a physical model of the system. By doing this it would also be possible to add a model based filter instead of the frequency selective filter.

11 References

11.1 Books

1. Industriell Reglerteknik, kurskompendium. Linköping University. 2008

2. Torkel Glad and Lennart Ljung. Reglerteknik, Grundläggande teori. Linköping University. Edition 4:3, Studentlitteratur 2006.

3. Torkel Glad and Lennart Ljung. Modellbygge och Simulering. Linköping University. Second edition. Studentlitteratur 2004.

11.2 Articles

4. Paul Ruetschi. Aging mechanisms and service life of lead-acid batteries. Journal of Power Sourced, Vol. 127 March 2004, pages 33-44

5. http://batteryuniversity.com

6. Dirk Uwe Sauer, Eckhard Karden, Birger Fricke, Holger Blanke, Marc Thele, Oliver Bohlen, Julia Schiffer, Jochen Bernhard Gerschler and Rudi Kaiser. Charging performance of automotive batteries—An underestimated factor influencing lifetime and reliable battery operation. Journal of Power Sources Volume168 Issue 1 (2007)

7. M. G. Lin, S. Lakshminarayanan, and G. P. Rangaiah. A Comparative Study of Recent/Popular PID Tuning Rules for Stable, First-Order Plus Dead Time, Single-Input Single-Output Processes. Ind. Eng. Chem. Res., 2008, 47 (2), pages 344–368

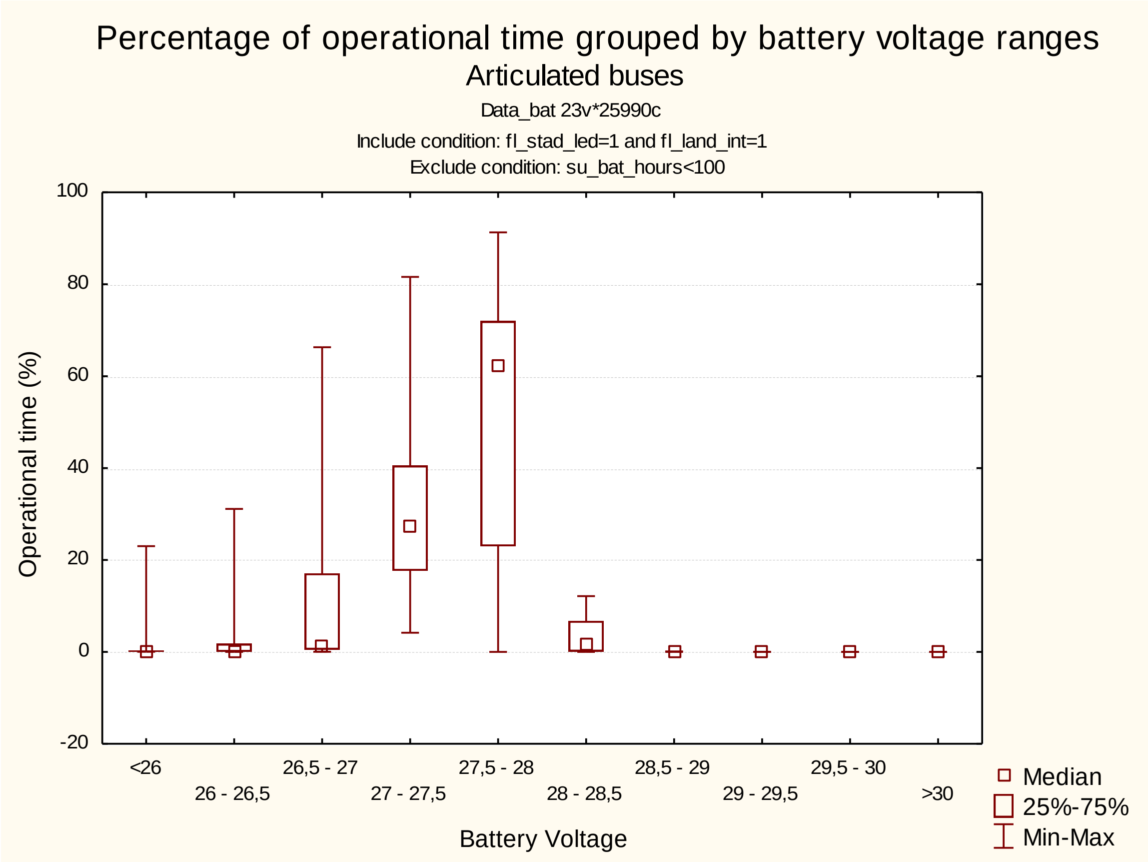
8. Sara Hallgren. Battery Temperature Model. XR-EE-RT_2006:002 Royal Institute of Technology, February 2006

9. Wen Tan. Unified Tuning of PID Load Frequency Controller for Power Systems via IMC. IEEE Transactions on power systems, Vol. 25, Issue 1, February 2010.

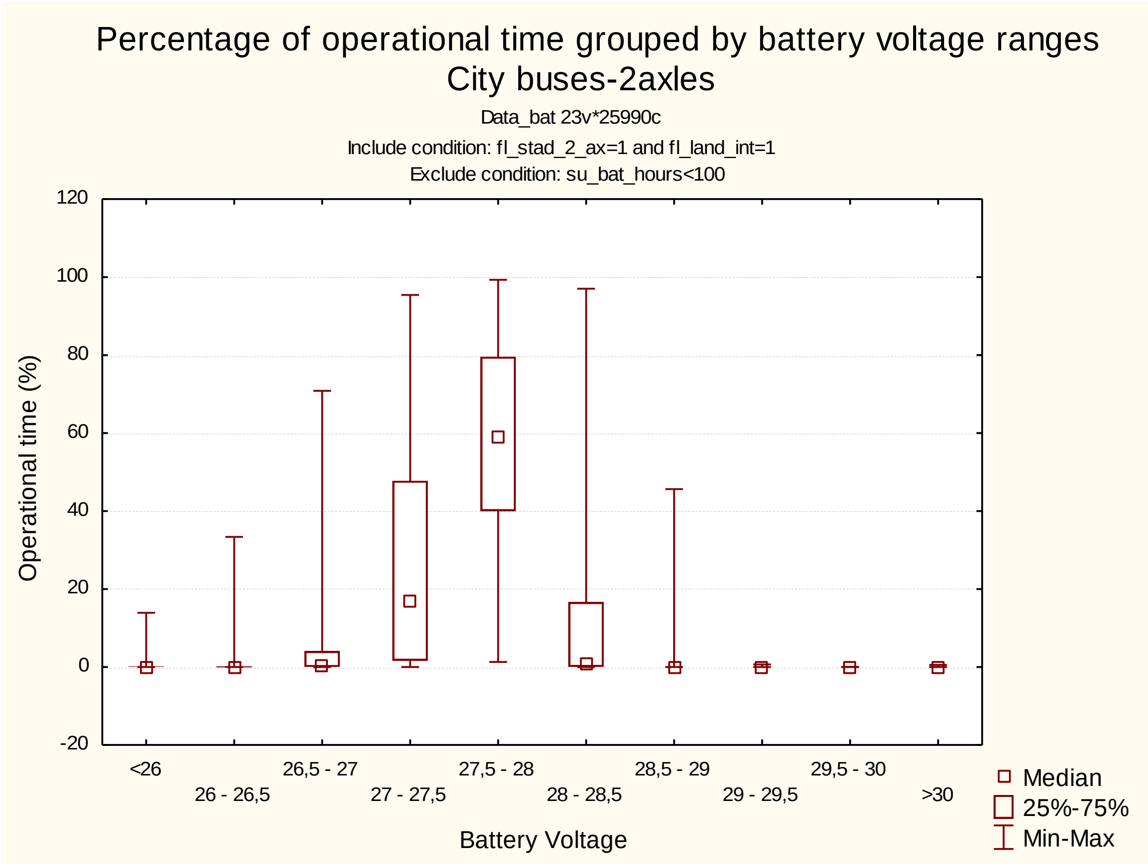
10. Henry A. Catherino, Fred F Feres, Francisco Trinidad. Sulfation in lead-acid batteries. Journal of Power Sources 129 (2004) pages 113-120

11. Scania CV AB. User Function Specification UF448 Adaptive Battery Charging. Södertälje 2006.

Appendix A



Percentage of operational time grouped by battery voltage ranges
Articulated buses
Data_bat 23v*25990c
Include condition: fl_stad_led=1 and fl_land_int=1
Exclude condition: su_bat_hours<100
Operational time (%)
100
80
60
40
20
0
-20
<26
26 - 26,5
26,5 - 27
27 - 27,5
27,5 - 28
28 - 28,5
28,5 - 29
29 - 29,5
29,5 - 30
>30
Battery Voltage
Median
25%-75%
Min-Max


Percentage of operational time grouped by battery voltage ranges
City buses-2axles
Data_bat 23v*25990c
Include condition: fl_stad_2_ax=1 and fl_land_int=1
Exclude condition: su_bat_hours<100
Operational time (%)
120
100
80
60
40
20
0
-20
<26
26 - 26,5
26,5 - 27
27 - 27,5
27,5 - 28
28 - 28,5
28,5 - 29
29 - 29,5
29,5 - 30
>30
Battery Voltage
Median
25%-75%
Min-Max