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Advanced Electric Storage System Modeling in Modelica

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1 Abstract

This paper will discuss two important components in the future electrical system of an automobile: the battery and supercapacitor. Models of these components have been developed in the Modelica language. The power of the Modelica language is shown by simulating a so-called dual storage system, consisting of a supercapacitor and battery. This paper also shows the comparison between the simulation and measurement results.

2 Introduction

Due to the increased amount of electric content in a vehicle, the electric powernet will have a significant influence on the fuel economy of a vehicle. In addition, new power supply/starting systems such as Integrated Starter Generators (ISG) will enable new features that improve fuel economy and emission attributes of a vehicle. It is therefore necessary to develop models that capture the detailed behavior of the electric powernet.

This paper will discuss models of two important components of the future powernet: the battery and supercapacitor. A description of the models will be given after which a simulation is performed with a so-called dual voltage storage system (also known as 14+x). This is an electric storage system consisting of a supercapacitor and battery in parallel, which allows a Belt-driven Integrated Starter Generator (B-ISG) to operate on two voltage levels. Such a system has been published by Sebille in **[1]**. Finally, simulation results will be compared with measurement results.

3 Battery

At the Ford Forschungszentrum Aachen (FFA), a battery model has been developed in Modelica, which is based on work of the Aachen University RWTH. This section describes both the model background as well as the implementation in Modelica.

3.1 Model Background

The battery behavior is characterized using impedance spectroscopy. As part of this process, the battery is excited with currents at different frequencies. Different operating points are also taken into account: temperature and State of Charge (SOC). A schematic of an impedance spectroscopy measurement of a battery is displayed in Fig. 1.

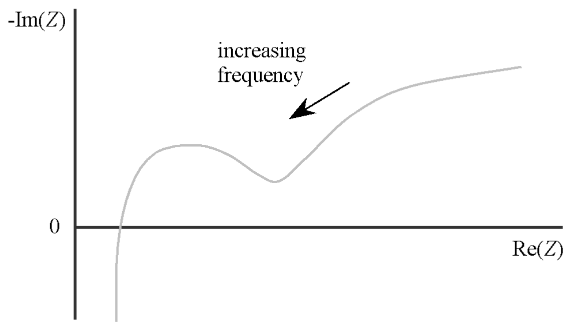
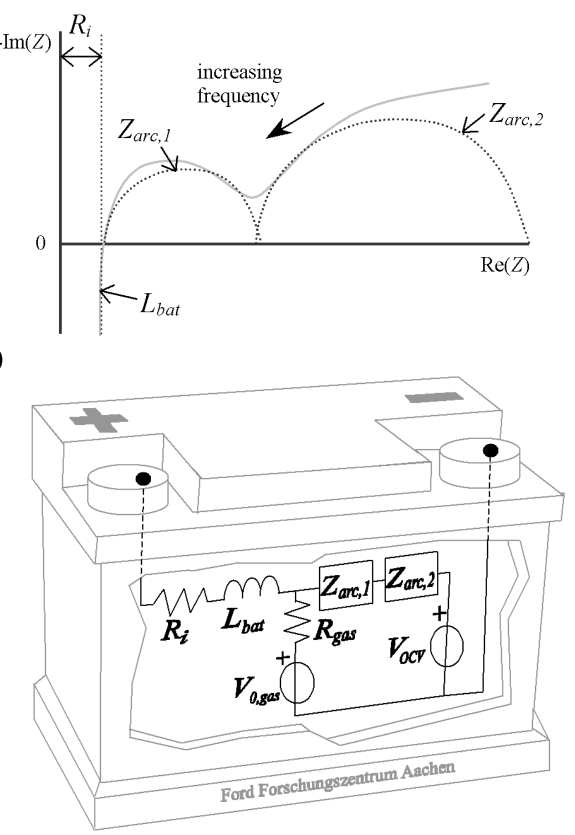


Fig. 1 Schematic plot of an impedance measurement of an automotive battery

A method has been developed by Buller *et. al.* **[2]**, **[3]** to represent the impedance measurement into an electric equivalent circuit. This procedure is schematically displayed in Fig. 2a. The electric equivalent circuit for this representation is displayed in Fig. 2b.



(a)

(b)

Fig. 2 (a) Approximation of a measured impedance spectroscopy line by electrical elements, (b) electric circuit representation for a battery

The measured impedance of the battery is approximated by an internal resistance R_i, an inductance L_{bat} and two depressed semi-circles in the complex impedance domain: $Z_{arc,1}$ and $Z_{arc,2}$. Inaccuracy arises at low frequencies where the modeled impedance does not approximate the measured impedance. Fig. 2b also includes the open circuit voltage V_{OCV} and the gassing reaction (R_{gas} and $V_{0,gas}$). The gassing reaction is mainly important for overcharging situations, where the charging efficiency of the battery decreases. This is the result of current that is lost in the gassing reaction. In the case of a valve-regulated lead-acid battery, *e.g.* in Absorbent Glass Mat (AGM) technology, other parasitic reactions have to be added in the gassing branch (especially oxygen recombination), but the topology remains valid.

The two depressed semi-circles ($Z_{arc,1}$ and $Z_{arc,2}$) are represented using specialized RC-circuits. The number of RC-circuits that are used in series to represent the depressed semi-circle is described by N_1 and N_2 (Fig. 3). This number of RC-circuits is critical for both simulation speed and model accuracy.

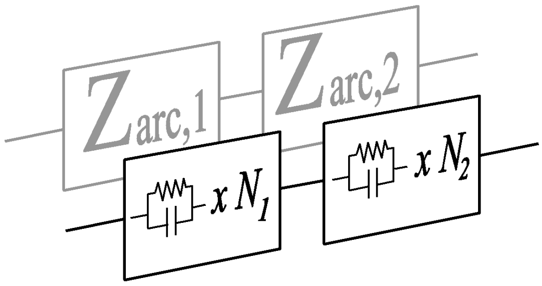


Fig. 3 Representation of the two semi-circles in the complex impedance domain ($Z_{arc,1}$ and $Z_{arc,2}$) by RC-circuit elements

3.2 Model Implementation

The model as displayed in Fig. 2b is constructed in Modelica. The result is displayed in Fig. 4.

The structure of the model is basically the same as the structure displayed in Fig. 2b. On the left you can see the internal resistance of the battery, after which the main branch is divided into two sub-branches. The upper branch shows the gassing reaction. The lower branch shows an element that calculates the SOC, the two depressed semi-circle elements ($Z_{arc,1}$ and $Z_{arc,2}$) and the Open Circuit Voltage (OCV) element. The battery inductance is not taken into account since the inductance of cabling and connectors to the battery are much more significant.

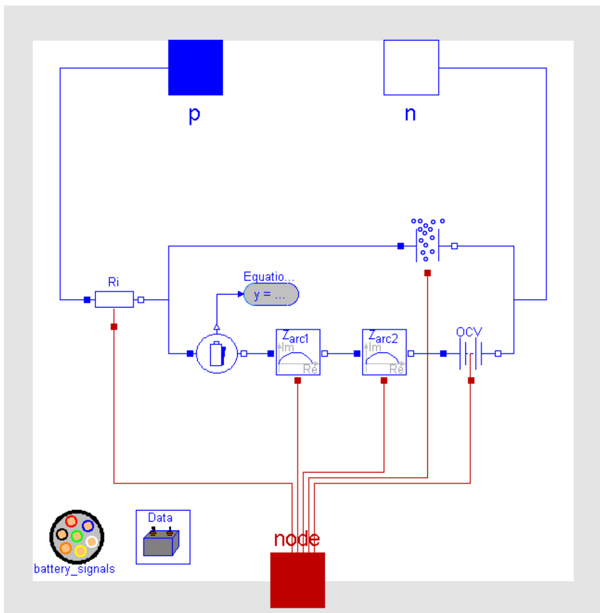


Fig. 4 Implementation of the battery model

The SOC element (circle in Fig. 4) has been added to monitor the energy content of the battery. Since gassing current is not stored in the battery, this SOC element is positioned in the lower branch.

Also added to the components of the battery model are thermal connectors (going to the 'outside' thermal connector `node`). Not only the behavior of the battery is dependent on temperature, but the battery also generates a heat flow. If the heat capacity of the battery is known, the self-heating effect of the battery can be simulated. This self-heating effect is of minor effect (on the timescale of for instance a NEDC drivecycle) for a regular flooded battery. When however a more advanced lead-acid battery of the AGM-type is used, the self-heating effect can become significant. More detailed information of thermal battery modeling can be found in Berndt **[4].**

Since each battery type needs its own impedance spectroscopy measurement and parameterization, the battery model has been programmed in a way that allows to change the battery type (and its corresponding parameter set) in the parameter window (Fig. 5).

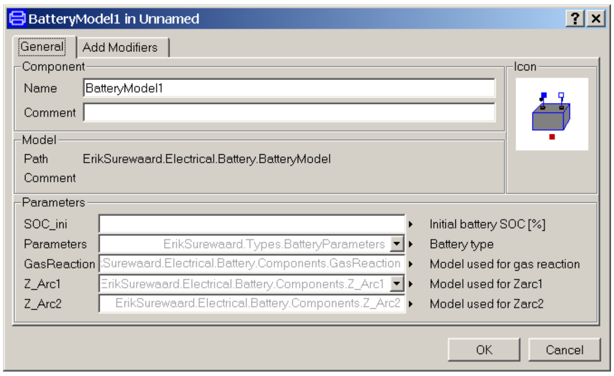


Fig. 5 Parameter window for the battery model

In this parameter window it is possible to change the battery initial charge (SOC_ini), its parameter set (Parameters), the models that are used for the gas reaction (GasReaction) and the description of the first and second depressed semi-circle (Z_Arc1, Z_Arc2). Currently, there are three types of parameter sets available:

- Ford Motorcraft SLI flooded battery, 12V, 70Ah
- Hoppecke AGM, 36V, 27.5Ah
- JCI Optima Red Top, AGM, 12V, 44Ah

It is also possible to 'design' new batteries by changing the voltage and capacity in the parameter set. This should however be done very carefully, since differences in technology and construction over different type of batteries exist.

The model enables replacing the model of the first and second depressed semi-circle ($Z_{arc,1}$ and $Z_{arc,2}$). This makes it possible to (i) change the number of RC circuits (Fig. 3) and (ii) remove the capacitance of the $Z_{arc,1}$ element. When larger simulation time-steps are taken (in the order of 0.01s), the capacitance of the first $Z_{arc,1}$ element can be neglected since their time constants are typically smaller than 0.01s. Removing this capacitance will increase simulation speed.

4 Supercapacitor

As was the case with the battery model, the Modelica supercapacitor model is based on work of the Aachen University RWTH. Both model background and the Modelica implementation are discussed in this section.

4.1 Model Background

As with the battery model, use has been made of impedance spectroscopy measurements to characterize the supercapacitor behavior. For this purpose, the supercapacitor is excited with AC currents in different operating points: temperature and voltage. Fig. 6 shows a typical impedance curve for a supercapacitor.

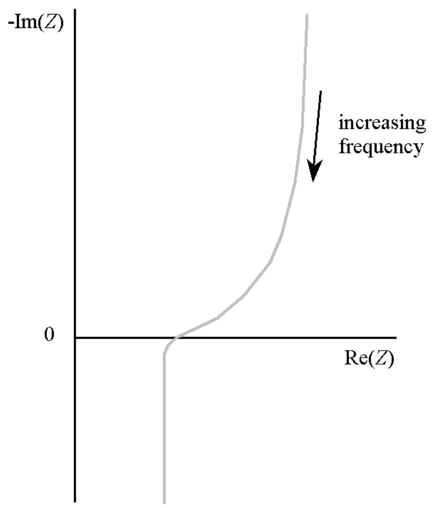


Fig. 6 Schematic plot of an impedance measurement of an automotive supercapacitor

To represent an impedance measurement of a supercapacitor with an electric circuit, Buller suggests in **[5]** to use the equivalent circuit shown in Fig. 7. For the pore impedance Z_{pore} there are two implementation forms possible: (i) with an RC-series networks and (ii) an RC-ladder network.

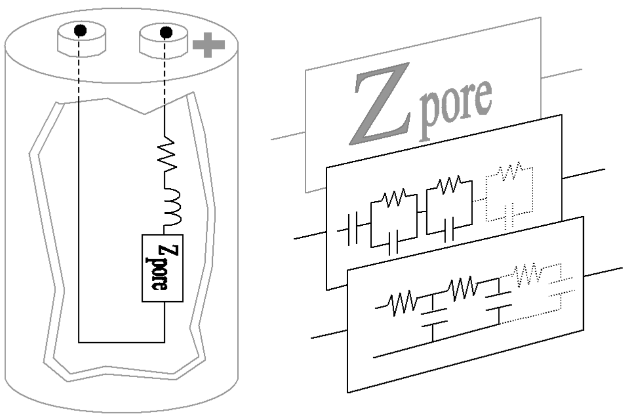


Fig. 7 Equivalent electric circuit for a supercapacitor cell and the two implementation forms for the pore impedance Z_{pore} (RC-series and RC-ladder circuits)

4.2 Model Implementation

The model, as described in the previous section, is constructed in Modelica. The number of RC-circuit in either the RC-series or RC-ladder network can be chosen. A for-loop has been used to connect these RC-circuits. A code fragment of the supercapacitor where the RC-circuits are connected is:

```
connect(p, R.p);
connect(R.n, Rpore[1].p);
for i in 1:numberRC loop
  connect(Rpore[i].n, Cpore[i].p);
  connect(Cpore[i].n, n);
  if (i < numberRC) then
    connect(Rpore[i].n,Rpore[i+1].p);
  end if;
end for;
```

First the positive connector on the supercapacitor is connected to the resistor (R). After that the pore impedance is represented by the RC-ladder method. The number of RC-ladders is determined by the parameter `numberRC`. The inductance of the supercapacitor is not taken into account in the model, since it is assumed that it can be neglected compared with the inductance of the connection and the cabling to the supercapacitor.

As with the battery, a parameter window is made available in which the parameter set (for the specific supercapacitor) can be chosen. This window is displayed in Fig. 8. The number of cells, initial cell voltage, number of RC-circuit for the approximation of the pore impedance Z_{pore} and the parameter set (type of supercapacitor) can be chosen. Currently, the following parameter sets are available:

- Montena 1400F
- Montena 2600F
- NESS 5000F

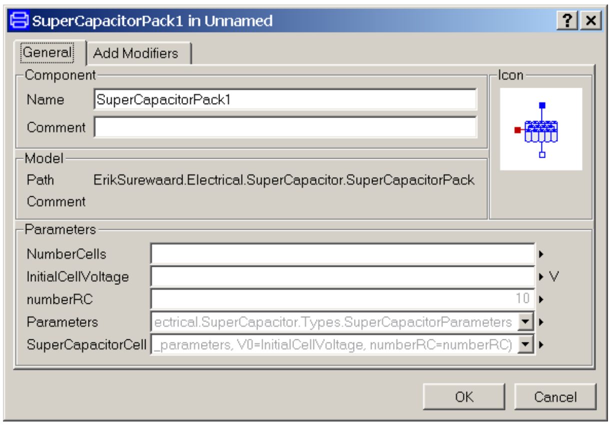


Fig. 8 Parameter window for the supercapacitor model

5 Simulation results

The battery and supercapacitor model will be simulated in a model of the so-called dual storage system. This section will first describe the dual storage system after which the Modelica implementation and the simulation results are displayed.

5.1 Dual Storage System

The dual storage system, also known as the 14+x system, is displayed schematically in Fig. 9. More information on the idea behind the dual storage system can be found in **[1]**.

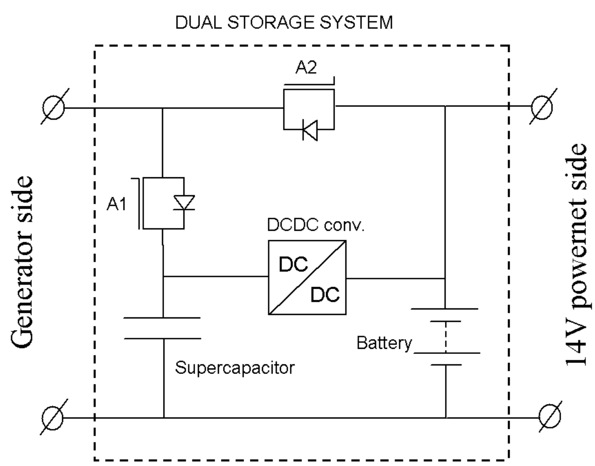


Fig. 9 Electric circuit representation for the dual storage system (14+x)

The dual storage system is particularly interesting for use with a B-ISG. The B-ISG is actually an advanced alternator, which has a higher efficiency and facilitates both generating and motoring mode. In this way the B-ISG can be used to crank the engine (*i.e.* the starter motor can be omitted). To deliver a high torque up to a high engine speed during engine cranking, it is beneficial to have the B-ISG operate on a higher voltage during cranking than is the case during generating. A storage system that can supply the B-ISG with two voltage levels for cranking and generating mode is the dual storage system:

- During motoring of the B-ISG, switch A1 is closed and A2 open. In this case the B-ISG is connected to the voltage of the supercapacitor. Since the supercapacitor voltage is not connected to the powernet, this voltage is therefore allowed to fluctuate significantly. The lower voltage-level of the supercapacitor is determined by the minimum required for cranking. The upper voltage level is determined based on the nominal supercapacitor voltage (lifecycle).

- During generating of the B-ISG, switch A1 is open and A2 closed. In this case the B-ISG is connected to the battery and the powernet, which are at a relatively constant voltage of 14V compared to the supercapacitor voltage, which is allowed to fluctuate.

A bi-directional DC-DC converter is used to enable a current flowing between the battery and supercapacitor and vice versa.

5.2 Modelica Implementation

A model of the dual storage system, as displayed in Fig. 9, is constructed in Modelica. The DC-DC converter is modeled with a table lookup model. The MOSFET switch has been modeled as the parallel connection of an ideal switch and an ideal diode with treshhold voltage `Vd`. The code for this MOSFET switch is:

```
model IdealMosfetSwitch
  import Modelica.Electrical.Analog;
  import Modelica.Blocks.Interfaces;
  extends Analog.Interfaces.OnePort;
  parameter Real Ron(final min=0) = 1E-5;
  parameter Real Goff = 1E-5;
  parameter Real Vd;
protected
  Real s;
  Boolean on;
  Boolean u;
public
  Interfaces.BooleanInPort BooleanInPort1;
equation
  u = BooleanInPort1.signal[1];
  on = not (u) or not (s < Vd);
  if not (on) then
    v = s;
    i = s*Goff;
  else
    if u then
      v = Vd + (s - Vd)*Ron;
      i = s - Vd;
    else
      v = (s - Vd)*Ron;
      i = s - Vd;
    end if;
  end if;
end IdealMosfetSwitch;
```

The resulting model is displayed in Fig. 10. Since this model will be used in fuel economy studies in Simulink[1], input and output connectors have been used for the switching and sensoring signals.

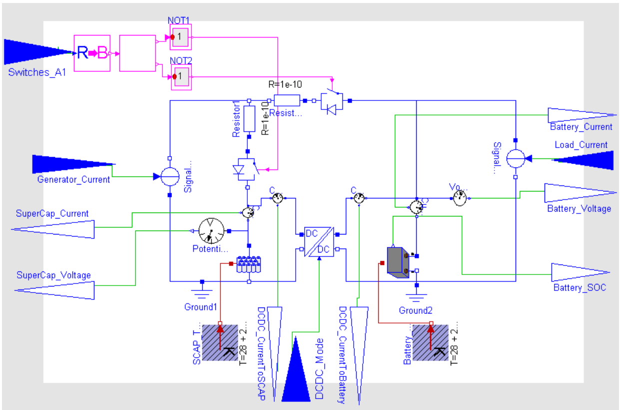


Fig. 10 Modelica model for the dual storage system

The model displayed in Fig. 10 is compiled to a Simulink native S-function block (Fig. 11):

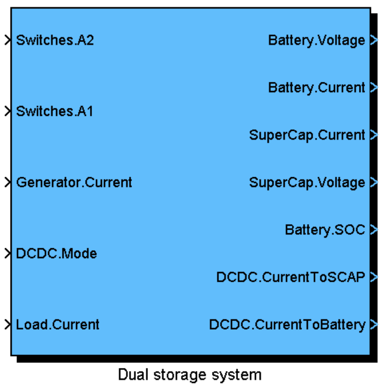


Fig. 11 Simulink block, compiled from the Modelica model, which represents the dual storage system

[1] Simulink is a registered trademark of The MathWorks, Inc.

The reason for making a Simulink S-function of the dual storage system, is that presently Simulink is the standard for control systems development within the Energy Management Group of FFA. That constructing the physical plant model in Modelica has advantages compared with plant modeling in Simulink is shown in **[6]**.

5.3 Simulation Results

Simulation has been performed in Simulink using the block in Fig. 11. Model inputs are taken from a measurement that is performed with hardware of the dual storage system. The results for the battery are displayed in Appendix A. It should be mentioned that the results for the battery voltage do not completely agree due to the fact that the overcharging behavior of the battery has not yet been completely modeled. This will be improved in future versions of the battery model. In **[6]** it is already shown that the battery model shows excellent results in discharging operation.

6 Conclusions

This paper shows complex models for a battery and supercapacitor. These models are based on impedance spectroscopy and have been modeled in Modelica. Using these models, a dual storage system is constructed and simulated. The simulation results have been compared with measurement results.

Acknowledgement

The authors gratefully acknowledge the collaboration with Aachen University of Technology, Institute of Power Electronics and Electrical Drives (RWTH-ISEA), especially Stephan Buller, Marc Thele and Dirk Linzen who developed the theory behind the physical representation of the battery/supercapacitor model used in this paper, and the method of its parameterization.

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Contact

Erik Surewaard is a member of the Energy Management Group of FFA. He graduated his studies of mechanical engineering at Eindhoven University of Technology in February 2002 on a model, which he developed for describing what occurs during cold cranking of an internal combustion engine. He continued working for the Energy Management Group and now develops models, using Simulink and Dymola, to describe (i) the electric powernet and (ii) the engine cranking process. He can be reached by mail on:

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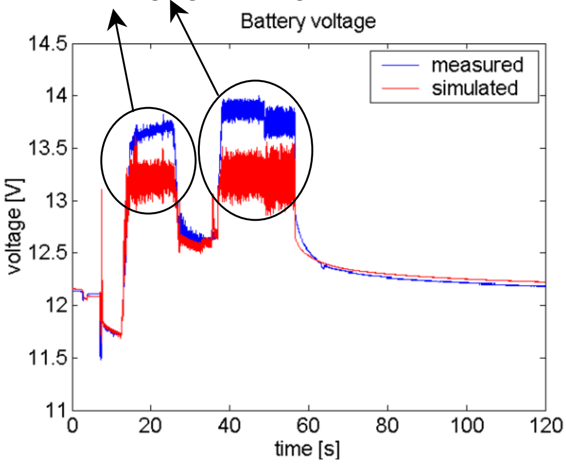
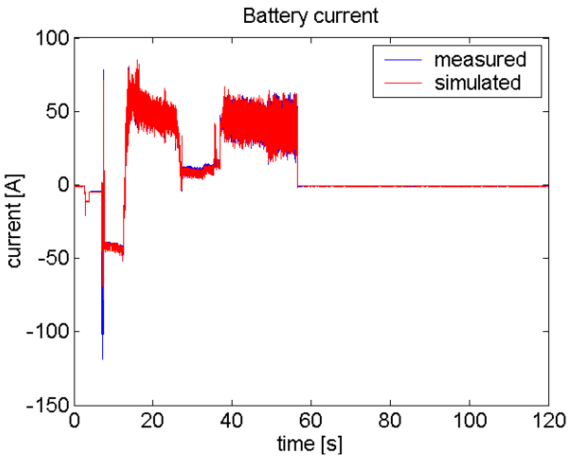
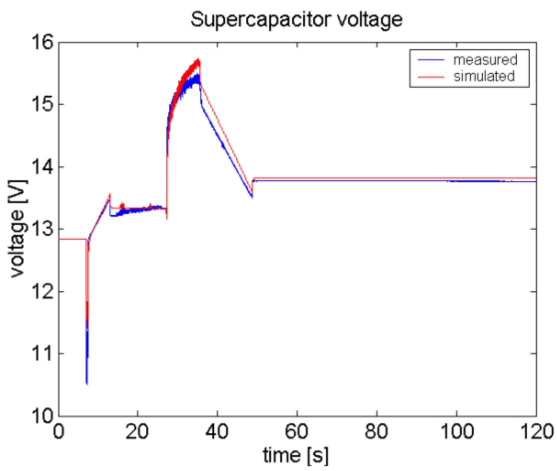
Appendix: Simulation Results

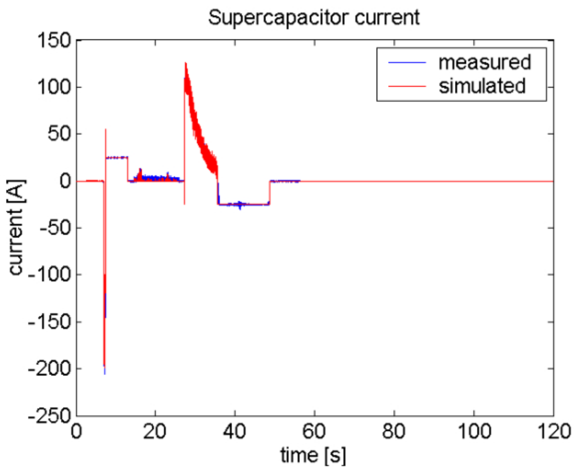
Battery





Supercapacitor





DC-DC converter