Model order reduction for efficient battery electro-thermal simulation

Lucas Kostetzer[1] and Evgeny Rudnyi[1]

CADFEM (Suisse) AG, Wittenwilerstrasse 25, CH 8355 Aadorf, Switzerland lkostetzer@cadfem.de, erudnyi@cadfem.de

Summary. Battery finite element thermal model is reduced using moment matching method and coupled with electrical cell models at the system level in order to have accurate and fast simulation for designing management systems. A switching method between reduced order models is presented to evaluate different cooling conditions of the battery pack.

1 Introduction

Battery performance is direct related to operating temperature [1] due to influences in the electrochemical behavior, specially for Lithium ion types. High temperature can initiate exothermic side reactions that cause self heating, and a potential damage. At low temperatures slow diffusion of Lithium ions can cause saturations at the electrodes that results in higher internal electrical resistances [2], in other words power is influenced. Battery life is also affected by temperature. For calendar life (only storage), internal resistances can increase 30% more if temperatures are raised from 30°C to 55°C [3]. Hence an efficient and accurate thermal management is necessary.

For an electro-thermal battery model first we need a temperature dependent electrical battery model which is also capable to describe heat losses. Heat losses from a battery enter into the thermal subsystem where temperature distribution is evaluated. Temperature influences electrical properties of the battery as well as its power dissipation. The joint simulation of an electrical and a thermal subsystem can therefore be referred as electro-thermal simulation, Fig. 1 . A practical problem is related to the fact that finite elements are usually employed to develop a thermal model of the battery pack. Such models are high dimensional and incompatible with system simulation as its transient simulation takes too much time. The development of a compact thermal model based on a finite element model is therefore necessary as an intermediate step.

2 Model Order Reduction

After the discretization of a finite element transient thermal model one get a system of ordinary diferential equations in the following form:

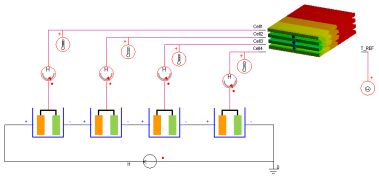

Fig. 1. Electro-thermal coupling at the system level applied to a battery pack

$$E\dot{\mathbf{x}} + K\mathbf{x} = \mathbf{f} \tag{1}$$

Where E is the heat capacity matrix, K is the heat conductivity matrix, and the state vector $\mathbf{x}$ contains the degrees of freedom, DOF, which for thermal problems are the node temperatures. For model order reduction, MOR, the concept of input/output is introduced. The load vector $\mathbf{f}(t)$ is divided in constant vectors $\mathbf{b}_i$ and in time functions $u(t)$. Constant vectors transfer the time functions to specific degrees of freedom.

$$\mathbf{f}(t) = \sum \mathbf{b}_i u(t) \tag{2}$$

At the system level there is no need of the complete state vector $\mathbf{x}$ but just a part of that, named $\mathbf{y}$. The relation between them is defined by the output matrix C:

$$\mathbf{y} = C\mathbf{x} \tag{3}$$

The idea of model order reduction is to reduce the dimension of the state vector and preserve the dynamical behavior of the input/output relations [4]. Mathematicians and engineers developed [5] different techniques for model reduction and some of them use the projection idea

$$\mathbf{x} = V\mathbf{z} + \varepsilon \tag{4}$$

The projection matrix V approximates the state vector $\mathbf{x}$ with a few of degrees of freedom $\mathbf{z}$. Neglecting the approximation error ε the original state vector is described in the sub-space defined by matrix V. The reduced order model is found by projecting the eq. 1 into the lower sub-space:

$$V^T EV\dot{\mathbf{z}} + V^T KV\mathbf{z} = V^T BVu \tag{5}$$

$$\mathbf{y} = CV\mathbf{z} \tag{6}$$

Among existing methods, the present work focus in the moment matching via Krylov subspace. The moment matching means after transforming the dynamic

system into Laplace domain, in such that lower-order system have the same first derivatives in the Taylor expansion around expansion points. A particular Krylov subspace finds the projection and the reduced order model matches the first moments automatically.

In this work first we show how a thermal battery pack finite element model is reduced to system level and coupled with electrical battery cell model. Second we explore a model order reduction switching between two reduced models applied to the battery pack model.

3 Electro-thermal coupling at the system level

The battery pack thermal model contains four battery cells that are cooled by air flow. The model is 3D and build in ANSYS. Fluid channels are modeled with 1D elements (FLUID116) and coupled with the thermal elements by a convection boundary condition. For the reduced order model, ROM, inputs are defined as the heat generation per battery cell and outputs are the temperature at cell center. Fluid operation conditions are constant.

The model reduction is done with the tool MOR for ANSYS with 10 DOF's per input resulting a dimension of 40 in the reduced model. The coupling is done with electrical cell model in a system level environment, ANSYS Simplorer [6], according to fig. 1. The electro-thermal coupled model is then used to evaluate the battery thermal management in a more accurate way since more realistic temperatures are predicted by using the ROM. In the other side better heat generation loads can be calculated at the system level.

4 Switching reduced order models

One limitation of the battery pack reduced model in section 3 is a fixed fluid cooling velocity. In an active cooling a control system is necessary, and for that the ROM should have fluid velocity as input. One can solve this in two ways, by using parametric model reduction or by switching different reduced order models. We studied the second methodology.

The fluid velocity has two contributions in the model: convection transport of heat by the fluid (mass flow) and the heat transfer coefficient (convection BC). Both quantities after discretization are in the K matrix from eq. (1). In this context we generate one reduced model for each desired velocity (we assume all channels have the same velocity) and switch between the ROM's at the system level.

At every switch event the reduced state variables $\mathbf{z}$ must be initialized and this is done based on the last value of the previous reduced model assuming the equality of the full state vector $\mathbf{x}$ from eq. (4) as the following:

$$V_I \mathbf{z}_I + \varepsilon_I = V_{II} \mathbf{z}_{II} + \varepsilon_{II} \tag{7}$$

$$\mathbf{z}_{II} = V_{II}^T V_I \mathbf{z}_I \tag{8}$$

Results show that switch from a non-zero fluid velocity to a case with zero velocity is not successful since state variables from the two ROM's at switching event have differences in the order of 30%. Behavior that may be explained by a too different K matrix, what makes the projection from eq. (8) not accurate enough.

When the change of fluid velocity is not to zero, but a value up 1000 times, the switching transition is successfully smooth with differences in the states vectors in the order of 0.05%. Absolute values are also good by comparing with the full solution obtained from ANSYS, see fig.2. Differences are smaller than line thickness.

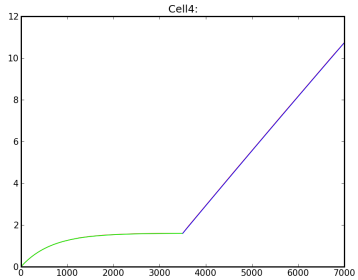

Fig. 2. Temperature rise values from a heat generation step response with a ROM switch at instant 3600s, fluid velocity is reduced by a factor of 1000.

References

1. A. Pesaran. Battery thermal management in evs and hevs: Issues and solutions, 2001.
2. K. Smith, T. Markel, G.H. Kim, and A. Pesaran. Design of electric drive vehicle batteries for long life and low cost, 2010.
3. E.V. Thomas, I. Bloom, J.P. Christophersen, and V.S. Battaglia. Statistical methodology for predicting the life of lithium-ion cells via accelerated degradation testing. *Journal of Power Sources*, 184(1):312 – 317, 2008.
4. T. Bechtold and E.B. Rudnyi. Introduction into model order reduction. *CADFEM Journal - Infoplaner*, N1:53–55, 2012.
5. T. Bechtold, J.G. Korvink, and E.B. Rudnyi. *Fast simulation of electro-thermal MEMS: efficient dynamic compact models*. Microtechnology and MEMS. Springer, 2007.
6. L. Kostetzer. Battery pack electro-thermal simulation. Master's thesis, University of Applied Sciences of Landshut and University of Applied Sciences of Ingolstadt, 2012.