Sodium Nickel Chloride cell model for Stationary Electrical Energy Storage

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Abstract—The purpose of this paper is to present a reliable modelling of sodium-chloride battery in Simulink environment in order to have a powerful tool which is able to foresee the battery behaviour in both discharge and charge operations. The model is based on a wide set of measures (e.g. discharge and charge resistance for different depth of discharge and current rates, etc.). A comparison between the model results and real battery measures, in the same conditions, has been presented.

Keywords—zebra model; sodium-chloride model; Simulink model; stationary storage

I. INTRODUCTION

In the paper, the steady state modelling of a NaNiCl₂ storage cell, also named "zebra" cell, part of Na-beta battery family, is described [1-15]. The basic cell structure consists of an anode part, made by molten sodium (Na), a solid ceramic electrolyte, namely beta-alumina (β''-Al₂O₃) and a cathode part made by nickel chloride (NiCl₂) with the addition of metallic doping substances. One of the main characteristics of this technology, is that its solid electrolyte presents a very low ionic resistivity in the temperature interval between 250°C and 300°C, with an operating temperature equal to 269°C. The main parameters of the modelled cell are reported in tab. 1. It is worth highlight that the described model does not consider transient phenomena during the cell operation, because it is conceived in order to study and simulate the effect of electrochemical stationary energy storage in the electrical network.

Table 1: Nominal NaNiCl₂ cell electric characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial discharge voltage [V]</td>
<td>2.6</td>
</tr>
<tr>
<td>Average discharge voltage [V]</td>
<td>2.33</td>
</tr>
<tr>
<td>Capacity [Ah]</td>
<td>38</td>
</tr>
<tr>
<td>Typical discharge regime</td>
<td>from 3 to 5 hours</td>
</tr>
<tr>
<td>Temperature dependence</td>
<td>(current from C/3 to C/5 A)</td>
</tr>
<tr>
<td>Efficiency [%]</td>
<td>90</td>
</tr>
<tr>
<td>Square section side [mm]</td>
<td>36</td>
</tr>
<tr>
<td>Length [mm]</td>
<td>236</td>
</tr>
<tr>
<td>Weight [kg]</td>
<td>0.680</td>
</tr>
<tr>
<td>Volume [m³]</td>
<td>3x10⁻⁴</td>
</tr>
<tr>
<td>Freeze-thaw</td>
<td>no limitations</td>
</tr>
<tr>
<td>Volumetric energy density [kWh/m³]</td>
<td>280</td>
</tr>
<tr>
<td>Gravimetric energy density [Wh/kg]</td>
<td>140</td>
</tr>
</tbody>
</table>

Nevertheless the model can be considered a "dynamic model" as well. This is due to the fact that all the cell internal influence parameters vary in a non-linear way during the charge/discharge operation, so that the cell behaviour during charge and discharge continuously changes. Therefore, the model has to reproduce "dynamically" these variations. The chosen modelling structure can be adapted to a NaNiCl₂ module (240 cell series connected) [11] or units (64 modules parallel connected) [2,3] very easily. In order to test the model, the simulation responses have been compared with real cell charge/discharge measurements with a very good agreement. The model is wholly based on experimental data which are depth of discharge (DoD), current rate and temperature dependent.

II. SIMULINK NaNiCl₂ CELL MODELLING

The chosen software to implement the NaNiCl₂ cell modelling is Simulink (a comparison with EMTP-RV has been also performed even if EMTP-RV does not allow implementing Matlab functions inside the program). The aim of the paper is to demonstrate that starting from the measured data of:

- cell internal resistance as function of DoD and current rates (see fig. 1)
- open circuit voltage (OCV) as a function of DoD (see fig. 2)
- cell temperature as a function of DoD and current rates

it is possible to represent the behaviour of NaNiCl₂ cells for stationary applications with a very good precision. The first step is to create a controlled real voltage source whose no-load voltage is equal to the NaNiCl₂ OCV. The voltage supply internal resistance is equal to the cell measured one. The considered technology is the second generation of NaNiCl₂ cell [2,3], in which there are two different metal additives in the cathode part. The two peaks in the behaviour of fig. 1, at 75% and 85% of DoD respectively, represent the starting of the metal additive reactions.

A very important issue in NaNiCl₂ cell modelling is that the cell internal resistance varies as a function of DoD and of the discharge current rate, and DoD varies, in turn, as a function...
of current rate and time. Moreover, the cell OCV depends on the temperature variation, which in turn depends on DoD and on the discharge current rate, in accordance with the following equation:

\[ OCV(T) = OCV^* - 216 \cdot 10^{-6} \cdot (T - 269) \]  

Moreover, the cell OCV depends on the temperature variation, which in turn depends on DoD and on the discharge current rate, in accordance with the following equation:

\[ OCV(T) = OCV^* - 216 \cdot 10^{-6} \cdot (T - 269) \]

The same criteria are followed for the cell temperature measurements (see fig. 4).

Once the resistance and temperature matrixes are created, it is necessary to implement a function which can calculate the instantaneous cell DoD during the discharge simulation and the actual current rate. Therefore, the current \( i(t) \) supplied by the controlled voltage source of the Simulink library has to be integrated by means of a Simulink limited integral block, the limit of which is the maximum cell charge capacity \( M_{cc} \). By taking into account that \( \text{DoD} = (1 - \text{SoC}) \), where SoC is the cell State of Charge, it is immediate to infer the normalized DoD variation as a function of time:

\[ \text{DoD}(t) = 1 - \frac{M_{cc} - \int i(t) dt}{M_{cc}} \]

The broken thick line box in fig. 5 shows the Simulink block chain, indicated with block chain 1 in the following, to calculate the percentage DoD variation \( \text{DoD}(t) \) as a function of the cell discharge simulation time. By implementing in Simulink environment the \( r \) and \( T \) matrixes it is possible to interpolate them with (2) and \( i(t) \), by means of two Simulink Matlab functions (Interpol 1 and Interpol 2 in fig. 5), so that the correct resistance and temperature cell values as a function of DoD and current rate can be obtained. By considering that the \( \text{DoD}_{\text{disc}_r} \) and the \( \text{DoD}_{\text{disc}_T} \) intervals in the \( r \) and \( T \)
matrixes are different from the DoD(t) ones derived from the block chain 1, these two intervals have to be interpolated with the functions Interpol 1 and Interpol 2 by means of two Simulink dynamic look up tables, DLUT 1 and DLUT 2 in fig. 5, whose outputs are the cell resistance \( r(i(t), DoD(t)) \) and temperature \( T(i(t), DoD(t)) \) respectively. These values are used to control the Simulink voltage source, by taking into account (1) (represented by the function "(I) implementation" in fig. 5) and by using the following equation:

\[
V_c = OCV(T,t) - r \left( \int_0^t i(t) \, dt \right)
\]

(3)

were:

- \( OCV(T,t) \) is the OCV as a function of temperature and time, which can be obtained by interpolating the function of fig. 2, \( OCV_{dod\_disc\_r} \) in fig. 5, and the output of the block chain 1 by means the DLUT 3 dynamic look up table (see fig. 5);

- \( V_c \) is the output voltage of the Simulink voltage source.

It is worth noting that it is not possible to use in (3) the current \( i(t) \) as it is measured by the Simulink current sensor. In fact this current is never zeroed during the simulation, so that it is not possible to represents the end of the cell discharge.

Consequently the current \( i(t) \) has to be calculated as the derivative of the voltage source integrated current. Moreover, for a constant current discharge, before of integrating \( i(t) \), it has to be limited at the desired current value by means of a Simulink saturation block. In this way it is not necessary to create a constant current load in Simulink. Once the voltage source has been controlled by means of the \( V_c \) value, it is possible to connect a load to the source in order to simulate the cell discharge.

This modelling approach can be used to simulate both the cell discharge and charge operations, but it is worth noting that the cell parameter variations in discharge mode are different from the variations in the charge one.

Therefore it is necessary to create two separated models, and to implement a logic function in order to pass from one model to the other on the basis of the current flow direction. In this way it is possible to join the two models in an unique bidirectional cell model (see fig. 6).

This modelling structure allows to represent easily a NaNiCl₂ module, but it is worth considering that each zebra module is equipped with a Battery Management System (BMS). This device controls the module in order to ensure a safety operation by regulating the battery current and temperature. Therefore, the module modelling has to comprise a BMS model to correctly simulate the battery behaviour (see fig. 6).

The model results have been compared with real measurements of both NaNiCl₂ cells and modules.
In order to validate the above presented cell model, a comparison between the model results and a series of battery measures is presented.

It is worth underlining that the following comparisons are referred to a NaNiCl₂ module [11], (Fiamm SoNick ST523 module), i.e. a battery made by 240 cells in series, with incorporated battery management system (BMS).

In fig. 7 two comparisons between the model battery voltage results and the measured ones for a complete discharge, with a constant current of 2.38 A (see fig. 7a)) and 38 A (see fig. 7b)) are shown.

The maximum voltage difference between the two curves in fig. 7a) is 1.05% and the discharge time error is zero. The maximum voltage difference between the two curves of fig. 7b) is 2.04% and the discharge time error is zero.

In fig. 8a) and 8b) a comparison between the model battery voltage and current results and the measured ones for a charge from 0% to 95% of the SoC, with a constant current of 5 A, is shown. In particular in fig. 8a) it is possible to see the BMS effect, which cut the current in order to limit the battery voltage increase. The maximum voltage difference between the two curves of fig. 8a) is 4.6% and the maximum error between the two current curves of fig. 8b) is 5.2%. 

III COMPARISON BETWEEN BATTERY CHARGE/DISCHARGE MEASURES AND MODEL RESPONSES

Discharge and charge models +BMS

Fig. 6 Combination of discharge model, charge model and BMS
Fig. 7 a) Comparison between the model battery voltage results and the measured one for a 2.38 A complete discharge current, b) Comparison between the model battery voltage results and the measured one for a 38 A complete discharge current

Fig. 8 a) Comparison between the model battery voltage results and the measured one for a 5 A charge current from 0% to 95% of the SoC, b) Comparison between the model battery current results and the measured one for a 5 A charge current from 0% to 95% of the SoC

IV CONCLUSIONS

In this paper an experimental data-based model has been developed with a very good agreement with real discharge-charge measures. The differences between the measures and the model results are basically due to the fact that the discharge/charge current is not perfectly constant during the whole battery charge/discharge operation, as it has been assumed in the model.

The present NaNiCl$_2$ model structure allows simulating with a very good precision the discharge operation and the charge one of a sodium-chloride cell or module, as the comparison with real measures clearly demonstrates. Therefore it appears as a useful tool in order to foresee the effect of the energy storage installation in the electrical network, by adding to the battery model a power conversion system model [13] and an electrical network model [20, 21]. Moreover, this modelling approach could be used to understand if some parasitic elements are present in the battery during switching operations. In fact, by comparing the steady state modelling voltage results and a series of battery switching voltage measures in the same conditions, the difference in the voltage behaviour, such as voltage peaks, can be ascribed only to parasitic elements which can
be inferred by comparing the model results and the measured ones. Moreover the used modelling approach can be easily accounted for other Na-beta family batteries, e.g. sodium-sulphur batteries or Na-S [16,17].

REFERENCES