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Sodium nickel chloride battery steady-state regime model for stationary electrical energy storage

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ABSTRACT

The purpose of this paper is presenting a reliable modelling of sodium-nickel chloride battery in order to have a powerful tool which is able to foresee the steady state battery behaviour in both discharge and charge operations. The proposed modelling approach allows representing both constant current operations and variable charge or variable discharge current ones, but it does not allow passing instantaneously from one battery mode to another one. This method is based on experimental measures. All the main modelling steps are described and a comparison between the model results and real battery measures, with the same conditions, is presented. The very good agreement between measures and model confirms the robustness of the approach for steady state applications. The paper proposes to adopt a set of standard battery measures from which it is possible to infer a simple but very precise modelling structure.

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1. Introduction

In the paper, the steady state modelling of a $NaNiCl_2$ storage cell, part of Na-beta battery family, is described. This is one of the most promising technologies, in the short term, for load levelling, voltage regulation, time shifting and power fluctuation mitigation of the renewable energy sources in High Voltage networks [1]. Some installations of $NaNiCl_2$ battery for large-scale stationary storage purpose in the high voltage network are described in Refs. [2,3].

The most common battery modelling approaches available in literature [4–8] do not consider neither the cell resistance dependence on the current rate and DoD, nor the cell voltage dependence on DoD and temperature contemporaneously, which are typical $NaNiCl_2$ battery behaviours. The existing Sodium Nickel Chloride battery models [9,10] are very complicated because they use several parameters, such as different resistances and capacitances, whose exact values have to be obtained. This is due to the fact that these approaches are conceived for electrical vehicle applications [11,12]. The chief characteristic of this model is its seeming simplicity, since the $NaNiCl_2$ cell is represented by a voltage source with a non-linearly variable resistance in series, which depends upon Depth of Discharge (DoD) and current rates. The aim of this paper is demonstrating that only one variable resistance is sufficient to represent with very good precision the stationary working of $NaNiCl_2$ batteries, by starting from the cell measures of the:

- complete charge/discharge Open Circuit Voltage (OCV) as a function of Depth of Discharge (DoD);
- internal resistance for different current rates as a function DoD (the resistance dependence on the temperature has been experimentally demonstrated to be negligible. This is due to the fact that the cell temperature is maintained in the optimum temperature range of 260 °C–300 °C by means of some heaters. This guarantees an optimal and almost constant ionic conductivity);
- temperature for different current rates and DoD.

Therefore, the described model does not consider transient phenomena during the cell operation, but it is a steady-state model. This choice is suitable for studying and simulating the effect of electrochemical storage in the electrical network with the purpose of stationary applications, but it is not suitable to represent the behaviour of a battery installed on a vehicle. Paper [9] provides a very good approach to represent vehicular applications of $NaNiCl_2$ batteries. Nevertheless, the model can be considered a “dynamic model” as well. This is due to the fact

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Table 1
Nominal $NaNiCl_2$ cell electric characteristics [2,3].

Average open circuit discharge voltage	2.6
End-of-discharge voltage	2.33 V
Capacity [Ah]	38
Typical discharge regime	from 3 to 5 h (current from C/3 to C/5 A)
Electrochemical Efficiency [%]	90
Square section side [mm]	36
Length [mm]	236
Weight [kg]	0.680
Volume [m^3]	3×10^{-4}
Freeze-thaw	no limitations
Volumetric energy density [kWh/m^3] or [Wh/l]	280
Gravimetric energy density [Wh/kg]	140
Operating temperature [°C]	260

that the cell internal resistance varies 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 allows adapting beyond to one cell also to a $NaNiCl_2$ module (240 cell series connected) or units (64 modules parallel connected) [13] 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 DoD, current rate and temperature dependent.

1.1. Cell characteristics

The basic cell structure consists of an anode part, made by molten sodium (Na), a solid ceramic electrolyte, namely beta-alumina (β''-Al_2O_3) [14,15] and a cathode part made by nickel chloride ($NiCl_2$) with the addition of metallic doping substances [16]. One of the main peculiarities 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 260 °C [17,18].

The main parameters of the cell are reported in Table 1.

2. Theory and calculation

2.1. Basic $NaNiCl_2$ cell discharge electrochemistry

By measuring voltage and current during the discharge operation of one $NaNiCl_2$ cell, it is possible to infer an equivalent electrical circuit which is able to simulate the cell behaviour.

In particular, if the cell is supplying a load (see Fig. 1), a difference between the OCV of the cell and the On-Load one (OLV) at different DoD can be observed. The cell OCV in discharge mode is bigger than the OLV. Consequently, this voltage drop can be modelled as an electrical non-linear resistance. In order to understand the cell internal resistance and OCV variations during the discharge process, the basic $NaNiCl_2$ cell electrochemistry has to be analysed. By considering the scheme in Fig. 1, once the switch *s* is closed, the sodium anode releases electrons and, as a consequence, sodium positive ions are formed in the anode zone.

Consequently, an electric current flows through the circuit and the sodium ions pass through the beta-alumina to the cathode zone of the cell. In the latter zone, the positive ions and the

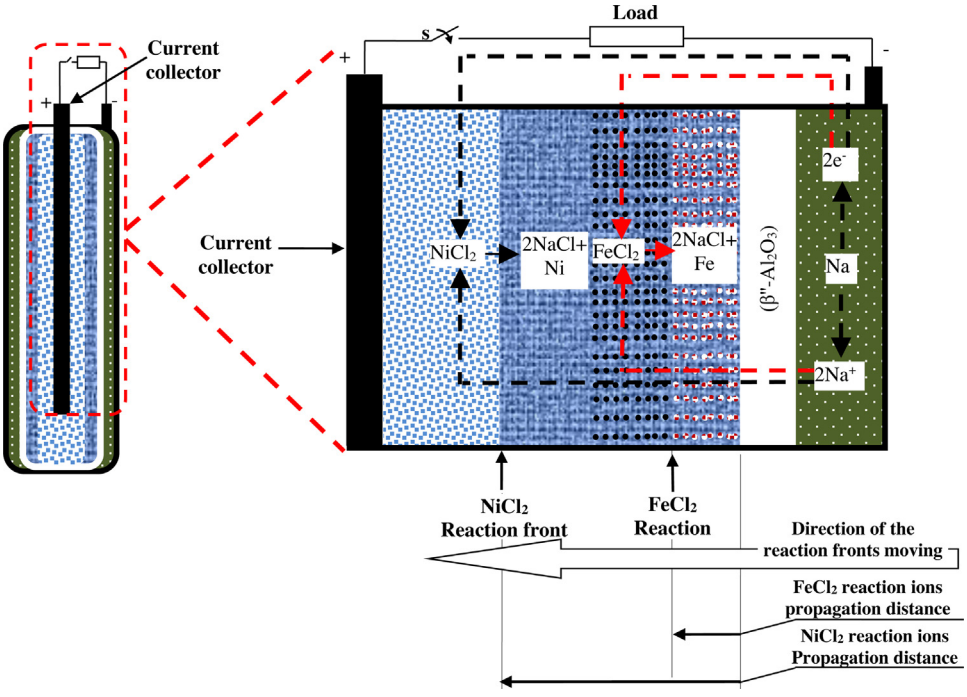

Fig. 1. Discharge reaction scheme of $NaNiCl_2$ storage cell doped with iron.

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