Journal of Power Sources 399 (2018) 372–382

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Electrical storage systems based on Sodium/Nickel chloride batteries: A mathematical model for the cell electrical parameter evaluation validated on a real smart microgrid application

Stefano Bracco[a,*], Federico Delfino[a], Angela Trucco[a], Stefano Zin[b]

[a] University of Genoa, Savona Campus, Via Magliotto 2, 17100, Savona, Italy
[b] FIAMM S.p.A, V.le Europa 75, 36075, Montecchio Maggiore (VI), Italy

HIGHLIGHTS

- Evaluation of the cell performance within an electrical storage system.
- Model developed to study Sodium/Nickel chloride batteries.
- Cell terminal potential determined as a function of discharge current and state of charge.

ARTICLE INFO

Keywords:
Electrical storage systems
Sodium/Nickel chloride batteries
Electrochemical cell model
Smart microgrid
Experimental validation

ABSTRACT

In the smart grid field, renewable power plants coupled with electrical storage systems are becoming a promising challenge to optimize the exploitation of renewable sources in order to maximize self-consumption, thus minimizing the exchange with the grid. Sodium/Nickel chloride batteries are considered optimal storage systems, due to their limited environmental impact, high reliability and specific energy, and reduced maintenance. The present paper describes a mathematical model elaborated to calculate the electrical parameters, during the discharge phase, of a Sodium/Nickel chloride galvanic cell contained within an electrical storage system designed for smart grid applications. Some results of the model have been compared with values achieved in experimental tests carried out on the FZSoNick electrical storage batteries of the Genoa University Smart Polygeneration Microgrid.

1. Introduction

As reported in Refs. [1,2], in the past decade the Renewable Energy Source (RES) exploitation has strongly increased worldwide and the massive diffusion of RES power plants has been often associated with the installation of smart microgrids within distributed generation architectures [3,4]. Within the aforementioned context, storage technologies are acquiring more and more importance to compensate the fluctuation of the RES production and to supply ancillary services to the electrical grid [5]. Electrical Storage Systems (ESSs) can be used to: smooth the load peaks on the grid, contribute to regulate voltage and frequency, act as a spinning reserve provider within the electric power exchange, provide power to limit the negative consequences of congestions on the grid, and defer investments on the grid consequent to the increase in loads.

There are a lot of electrical storage technologies (capacitors, batteries, flywheels, superconducting magnetic storage, compressed air, pumped storage hydro, etc.), each one suitable for a certain purpose, and so characterized by different values of storage capacity and charge/discharge time. In Ref. [6] the authors focus the attention on hydrogen, batteries and flywheel storage, whereas in Ref. [7] lead-acid batteries and ultra-capacitors are analyzed. It is important to highlight that batteries are mainly used to supply energy for long periods, while ultra-capacitors are characterized by a very fast response which can be exploited in the RES sector to mitigate the intermittency of the solar source. Obi et al. in Ref. [8] assess that, due to the spread of RES plants, the costs of small-size storage systems are decreasing, and when they are installed, the management of the RESs become more accurate and the effects of RES production forecasting errors diminish [9]; moreover, as reported by Azcarate et al. in Ref. [9], the use of storage systems permits to increase the RES penetration index: storage systems are charged when RES production overcomes the demand, whereas they

* Corresponding author.
E-mail address: stefano.bracco@unige.it (S. Bracco).

https://doi.org/10.1016/j.jpowsour.2018.07.115
Received 17 January 2018; Received in revised form 16 June 2018; Accepted 29 July 2018

are discharged when RES production is lower than the demand.

About Battery Energy Storage Systems (BESSs), on which the present paper is focused, different technologies are available on the market: Li-ions, Na/S, Na/$NiCl_2$, lead acid, Ni/Cd, Pb/Sb liquid metal, etc [5,10–18]. It also important to mention Redox flow batteries (RFBs) which are more and more employed, also in the energy sector, due to their capacity to efficiently store big amounts of energy at reasonable costs [5]. In the literature, many scientific papers are relative to BESSs: some studies are focused on electrochemical aspects [11–14,19–24], whereas other analyses deal with electrical issues [7,9,25–30]. Among them, several papers are relative to specific and very detailed electrochemical and material topics [31–41] while other studies are mainly focused on the storage battery application in different sectors (transportation, ICT, energy) [7,16,25–30,42–48].

In Ref. [30] the use of BESSs in microgrids is analyzed, whereas in Ref. [27] operation and control strategies for the integration of photovoltaic plants and BESSs in a DC micro-grid are proposed, with a particular attention to islanded operation modes. The compensation of photovoltaic power production fluctuation adopting BESSs is described in Ref. [26], while in Ref. [28] the control strategies of a Li-ion battery group with a photovoltaic array within a microgrid are investigated. Control strategies to manage a photovoltaic field coupled with a storage system are proposed in Ref. [29], whereas in Ref. [49] the authors deal with the modelling of both thermal and electrochemical aspects of battery cells and they propose some models useful to predict the behavior of batteries for vehicle applications. Indeed, as also highlighted by O'Sullivan et al. in Ref. [43], storage batteries are acquiring more and more importance in the electric vehicle sector, where they are used to reduce emissions and noise that characterize internal combustion engine vehicles.

About the modelling of storage systems, it is interesting to cite [50] where the authors propose a survey of models used to test the operation of storage batteries under different operating conditions. In Ref. [51] several advanced rechargeable batteries (lithium-ion, sodium nickel chloride) are investigated, whereas in Ref. [5] some chemical aspects concerning batteries are analyzed in detail, as well as in Ref. [52] where important advantages of all-solid-state batteries are highlighted.

Several papers in literature discuss Sodium/Nickel chloride batteries [11,13,15,16,42,44–46,53,54], derived from ZEBRA batteries [12,14,17,24,31,43,55–57]. This kind of batteries is more and more used in the energy sector but, as assessed by Redey et al. in Ref. [54], O'Sullivan et al. in Ref. [43] and by Dustmann in Ref. [56], these batteries are also suitable for electric vehicles since they are characterized by very high energy density values and not require so many maintenance interventions; moreover, their operation is safe and environmentally friendly. In Ref. [31] the microstructure of the ZEBRA cells is examined at different cycle lifetimes, whereas in Ref. [43] an equivalent electrical circuit is used to represent the behavior of ZEBRA cells. Finally, in Ref. [55] the degradation of a ZEBRA battery is examined referring to different operating conditions and chemical structures.

In this paper a mathematical model of a Sodium/Nickel chloride galvanic cell during electrical discharging is presented. On physical bases, the Na-$NiCl_2$ cell has been simulated in a large range of electric currents and considering different initial State Of Charge (SOC) values. The cathodic zone is a porous sponge plunged into a liquid electrolyte. The electrochemical process is simplified and only heterogeneous reactions are considered, not taking into account the solubility of $NiCl_2$ into the sodium chloroaluminate ($NaAlCl_4$) molten salt. The proposed model is steady-state, isobaric, isothermal, one-dimensional and the cell geometry is assumed of cylindrical form with inner positive pole. The model predicts, along the radius and in function of both the current and SOC values, the profiles of the more important parameters of the process: the current of the ionic species in migration into the liquid secondary electrolyte, the current of electrons collected by the positive electrode distributed in the cathodic volume, the voltage, the efficiency and so on. The results, relative to the terminal potential of the cell during the discharge process in function of different values of current and different SOC values, have been compared with experimental results obtained during some test campaigns on the FZSoNick battery storage system installed within the Smart Polygeneration Microgrid of the University of Genoa [48,59,60]. The paper is structured as here reported: in Section II Sodium/Nickel chloride batteries are described referring to the literature, whereas in Section III the mathematical model of the Sodium/Nickel chloride galvanic cell during electrical discharging is reported; Section IV is focused on the experimental tests carried out at the Savona Campus whereas in Section V conclusive remarks are reported.

2. Sodium/Nickel chloride batteries

The description of the electrochemical process occurring inside sodium/nickel chloride ($NaNiCl_2$) batteries is here reported, together with a brief analysis of the main literature studies related to their modelling. Moreover, the main technical data of the $NaNiCl_2$ batteries used as testbed in the present study are highlighted.

2.1. Operating principle and literature analysis

As reported by Li et al. in Ref. [57], $NaNiCl_2$ batteries have been investigated for many years as a promising device for RES and microgrids. The abundance of sodium, which is one of the elements that constitute the $NaNiCl_2$ battery cell, also facilitates the diffusion of the aforesaid technology [41]. Also called "salt batteries", these batteries are known on the market mainly as ZEBRA and SoNick trademarks. ZEBRA (Zero Emission Battery Research Activities) batteries were developed in South Africa where the first patent was applied in 1978 [17]; their development was handled by different companies (BETA Research and Development Ltd, AEG Anglo Batteries GmbH, MES-DEA) in the past and, now, by the company FZSoNick, belonging to the Italian FIAMM Group, that supplies energy storage solutions for the RES and other sectors (e-mobility, uninterruptible power supply, etc.) [58].

As highlighted by Restello et al. in Refs. [44,45] and by Gaillac et al. in Ref. [46], the aforesaid technology is also promising to provide backup power in the telecommunication sector. Furthermore, Shukla et al. [18] point the attention on the advantages consequent to the operation of ZEBRA batteries at high temperature (almost 300 °C) and on their optimal use in places characterized by hot ambient temperatures; analogous conclusions are drawn up in Ref. [61], where the authors underline the challenges of current high temperature sodium batteries.

The Sodium/Nickel chloride batteries, initially developed for applications in electric and hybrid vehicles, being characterized by high gravimetric power and voltage, and zero-self-discharge, are today successfully employed for their capacity of energy storage in stationary applications and to level the electric load in grids partially fed by renewable energy.

For the single rechargeable cell of a Sodium/Nickel chloride battery, two main reactions may be written:

- at the positive electrode:

$$NiCl_2 + 2Na^+ + 2e^- \leftrightarrow Ni + 2NaCl \quad (1)$$

- at the negative electrode:

$$2Na \leftrightarrow 2Na^+ + 2e^- \quad (2)$$