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A computationally efficient Li-ion electrochemical battery model for long-term analysis of stand-alone renewable energy systems

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ABSTRACT

In this paper we introduce a Simplified Single Particle Model (SSPM), which is obtained from the general mathematical formulation of Li-ion batteries. The model is validated by using different commercial graphite/$LiFePO_4$ cells, and results show agreement with more complicated models and experimental data for low operating currents of less than 1C. A maximum relative error of less than 2% can be observed to estimate cell voltage in the plateau region of the charge/discharge curves. Therefore, the proposed model is suitable in the case of stand-alone renewable energy systems, where battery current is typically lower than C/10. By increasing the current, the SSPM deviates from more accurate models and experimental data. However, it is sufficiently precise and computationally efficient to be used in the simulation and optimization framework of off-grid renewable energy systems. Finally, the proposed model will be applied to two different case studies; one for an installed PV-battery and the other for a Wind-battery system which are located near Zaragoza, Spain, in order to predict battery state over time.

1. Introduction

About 17% of the world's population does not have any access to electricity, and around 80% of those without electricity live in rural regions in which grid expansion may be significantly expensive [1]. Renewable energy systems can produce energy for these far-from-the-grid regions and at the same time provide energy independence for users [2].

In stand-alone renewable energy systems, energy storage is the most important component to ensure system reliability [3,4]. In spite of the many recent advances in battery technology, nearly 100% of the batteries used to store electrical energy in this type of system are lead-acid [3,5]. This is because of the affordable price and maturity of lead-acid batteries [6,7].

Lithium-ion batteries have been used in portable devices and EV applications recently because of their high energy density and specific energy [6,8,9]. Although longer lifetime of this kind of batteries in comparison with lead-acid types is a remarkable advantage, previous research and application of lithium-ion batteries for stand-alone renewable energy systems have been extremely limited. This fact is due to the high system cost that needs a long-term simulation and optimization framework, which is a time-consuming task, to investigate system technical and economic performance during its lifetime.

Lithium-ion battery models can be classified into different groups, from equivalent circuit models [10–12] to complicated accurate full order electrochemical models that are based on battery kinetics and transport phenomena [13]. Using electrochemical models, which are accurate enough and also take full advantage of advancements in battery engineering design would be helpful for manufacturers to create innovative battery cells for a particular application. However, model simplification for using this type of model in real-time online estimation of battery parameters and offline optimization frameworks is evident. This model reduction order is highly depended on the battery application and consequently its operating condition.

The development of phenomenological approaches to predict lithium-ion battery behavior based on electrochemical models has been started since 1990, with the work of Newman's group [13,14]. They estimated battery performances using Butler-Volmer equations and porous electrodes theory [15]. This type of model has been applied in some investigations using significant computational resources to predict battery behavior over time [16,17].

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Santhanagopalan et al. [18] reviewed the major electrochemical battery models by comparing the P2D, PP and SP models in terms of computational efficiency. In the reduced-order single particle model, Li concentration in the electrolyte is supposed to be uniform along the cell. To perform lithium-ion battery analysis faster and at the same time preserving model precision, Prada et al. [19] developed a simplified 1D electrochemical model from the original P2D structure. In order to design this simplified electrochemical model, the AM developed by Di Domenico et al. [20] was expanded. For this aim to be achieved, the mass conservation equations in both electrodes and electrolyte were solved to enable the variation of Li concentration in the solid and liquid phases at any time. In this research, authors mentioned that neglecting Li-ion concentration distribution along the cell in SP model assumptions can limit the model usefulness for high-load applications. Tang et al. [21] have taken the advantage of 1D electrochemical-thermal modeling approach to predict capacity fade of graphite/$LiFePO_4$ cells under high discharge rates of 1C–5C. Shimomura et al. [6] used the 1D electrochemical model that was developed by Prada et al. [19] in numerical analysis of Li-ion batteries for an off-grid residential PV system without any mathematical model reduction. Weibhar et al. [22] have recently used a multi-scale physically-based modeling approach of LFP cells, which was developed formerly by Kupper et al. [23] for charge/discharge currents of 0.1C–10C, in the performance analysis of a stationary photovoltaic battery system.

In optimization environments, many different combinations of components and control strategies of the stand-alone renewable system must be simulated and evaluated for their performance and cost, therefore solving some complicated or coupled partial differential equations (which need too much computation time) are inadmissible. Consequently, using the above-mentioned kinds of battery modeling approaches, that still requires some intricate equations to be solved simultaneously, in long-term simulation and optimization framework of stand-alone renewable energy systems seems not to be computationally efficient.

As mentioned by Dufo-Lopez et al. [5], in stand-alone renewable energy systems the charge and discharge rates are usually much lower than C/2. So, using the original form of single particle models with its assumptions for predicting Li-ion battery behavior in renewable energy applications seems to be adequate at the first insight. Patsios et al. [24] have used the application of single particle models for the analysis and control of grid connected energy storage systems under low (<2C) charge/discharge rates. Owing to the requirement for high days of autonomy for the battery bank in the stand-alone renewable energy systems, the operating C-rates are typically less than C/10. Accordingly, there is no need for a complicated electrochemical Li-ion model or even for conventional SPMs, that at least consider Fick's law in spherical coordinates, and as a result further reduction is possible. It seems that by firstly, taking advantage of the simplified structure of the electrochemical model offered by Prada et al. [19]; secondly, considering the diffusion length concept, which has been developed by Wang et al. [25] and thirdly, assuming the uniformity of lithium concentration in the electrolyte phase will result in a more simplified model that can be applied easily to simulation and optimization framework of stand-alone renewable energy systems. This reduced-order model which is named simplified single particle model (SSPM) would be promising for the application of fast and accurate Li-ion battery electrochemical models in the simulation and optimization of renewable and hybrid renewable energy systems. In Section 2, we investigate the assumptions which are considered to derive the mathematical structure of the proposed model.

2. Model structure

Fig. 1 illustrates a schematic representation of a graphite/LFP Li-ion cell. The cell consists of three main regions including: porous anode with spherical graphite particles, separator and porous cathode with LFP active-material particles. During the discharge process, Li-ions de-insert from the anode side as represented in Eq. (1),

$$Li_xC \overset{discharge}{} C + xLi^+ + xe^- \tag{1}$$

and insert into the positive electrode as shown in Eq. (2).

$$Li_{(1-x)}FePO_4 + xLi^+ + xe^- \overset{discharge}{} LiFePO_4 \tag{2}$$

During the charge process, the above-mentioned reactions proceed in the reverse direction.

Under real working environments lithium intercalation is represented to be a dynamic process which takes place under different stages including randomly lithium intercalation into graphite, forming a uniform distribution in the graphite, forming the Li-riched phase, generation of the lithium concentration gradient and formation of LiC_6 phase [26]. Theoretically in electrochemical modeling approaches, lithium concentration in the solid phase has been calculated using superposition principle or solving rigorous pseudo second dimension modeling approaches [25]. In the P2D models, the solid phase is assumed to contain identical spherical particles with prespecified size and

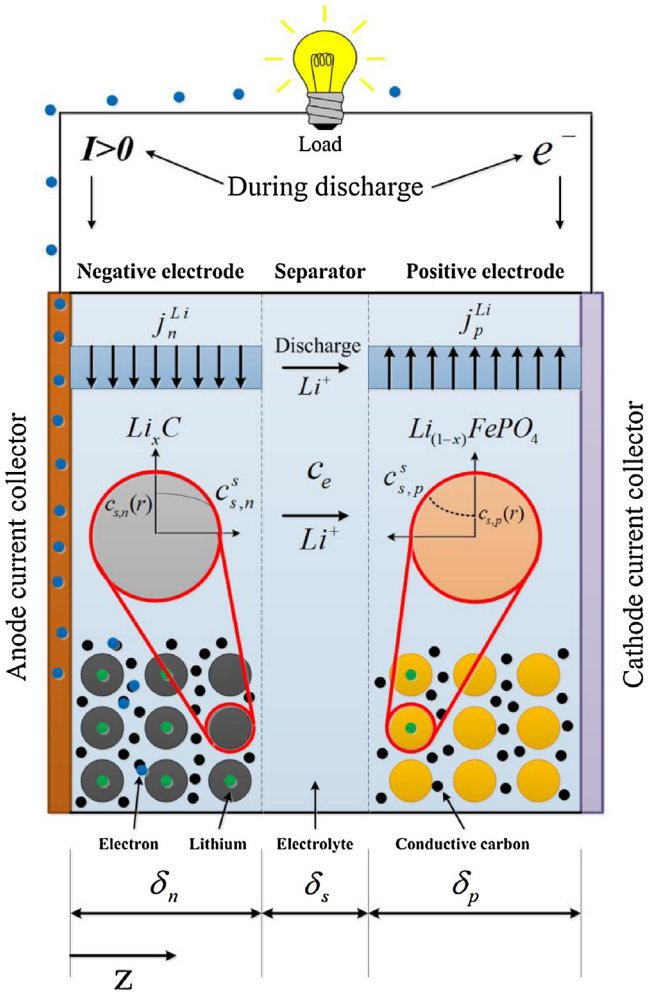

Fig. 1. Schematic representation of a LFP Li-ion cell during SP modeling.