A Novel Lithium-Sulphur Battery Model for Automotive and Renewable Energy Applications

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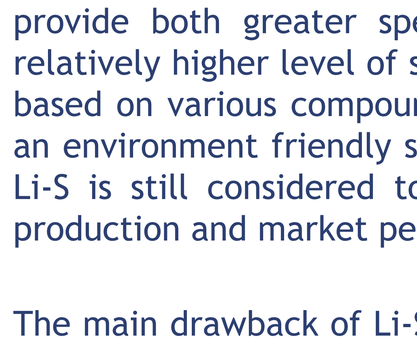
I. WHY LI-S? PROMISES AND CHALLENGES

Although the electric vehicle (EV) adoption has gained momentum thanks to the increasing green energy awareness and motivation of environmental protection, commonly available Lithium-Ion (Li-ion) batteries have some limitations that hinder the wide-spread use of EV technology. Researchers constantly work on newer designs and electrode materials in order to improve the crucial aspects of currently marketed batteries, such as safety issues, limited driving range and cycle life. One of the most promising candidates is Lithium-Sulphur (Li-S) chemistry for the next generation of energy storage systems. The main advantage of Li-S batteries is that they provide both greater specific capacity (1.675 mAh/g, theoretical) and relatively higher level of safety in comparison with the Li-ion cells that are based on various compounds of transition metals [1]. Moreover, Sulphur is an environment friendly substance and it is abundant worldwide. Although Li-S is still considered to be mostly in experimental phase, large scale production and market penetration can be expected in the next few years.

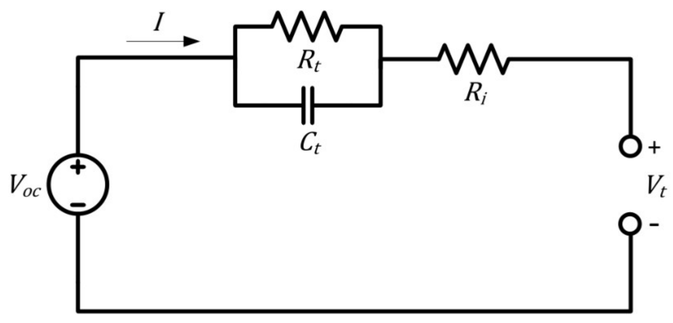
The main drawback of Li-S cells is the high internal resistance which limits their C-rate capability. The other problems can be summarized as poor cycle life, higher self-discharge rate, and lower coulombic efficiency when compared to the state of the art Li-ion technology. All of these disadvantages are associated with the polysulphide shuttle effect which takes place during charging and discharging reactions [2-4].

II. THE REACTION MECHANISM



Unlike the intercalation in Li-ion cells, the Li-S cells have progressive chemical reactions that start from the elemental Sulphur (cathode) and then transform into polysulphides of different combinations with Lithium. These polysulphides travel between the electrodes, hence creating the shuttling effect [4]. The highly nonlinear characteristic curve with two distinct plateaus creates a great challenge for modeling.

III. THE ELECTRICAL CIRCUIT EQUIVALENT MODEL



$$R_i = \frac{V_0 - V_1}{I}$$

$$R_t = \frac{V_{OC} - V_t'}{I}$$

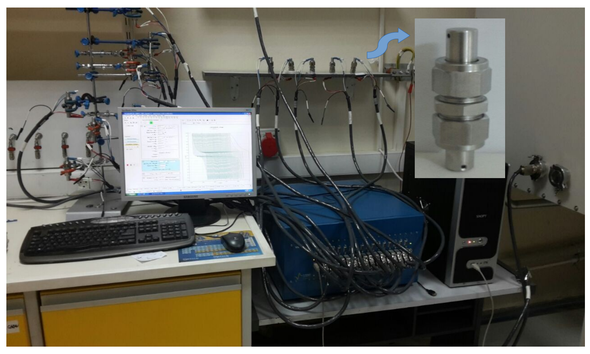
$$\tau = R_t C_t$$

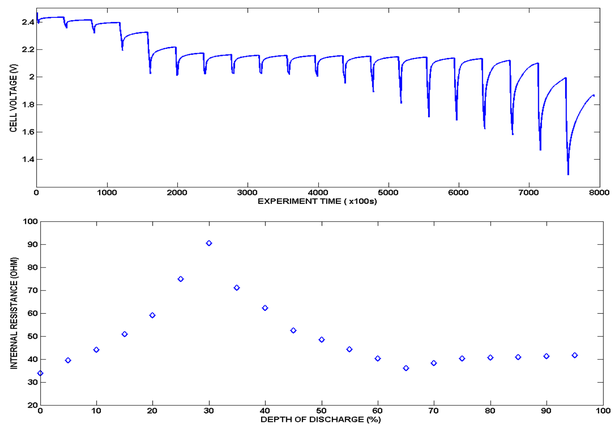
Battery models are indispensible for accurate and reliable simulation of renewable energy storage systems. Even though electrochemical/kinetic models for Li-S chemistry exist in literature [3], they consist of a large number of differential equations that explain the chemical reactions in detail and need long computational time, along with special simulation packages. However, electrochemical models cannot be used in a power electronics simulation effectively, thus an electrical equivalent circuit model is necessary. For instance, the DC/DC converter performance with respect to the highly nonlinear behaviour of Li-S cells should be considered in a power electronics system that depends on renewable energy storage.

In this interdisciplinary work, a novel Li-S electrical equivalent battery model is presented. After carrying out characterization experiments on a Li-S cell that was manufactured in-house, a modified Thévenin model with one parallel R, C network was developed . Equivalent circuit parameters were identified in accordance with the nonlinear nature of terminal voltage-current relationship based on experimental data [5].

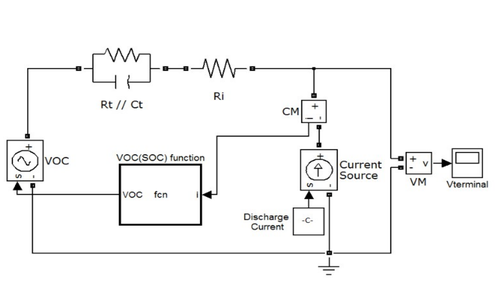
IV. EXPERIMENTAL SETUP AND PARAMETER EXTRACTION

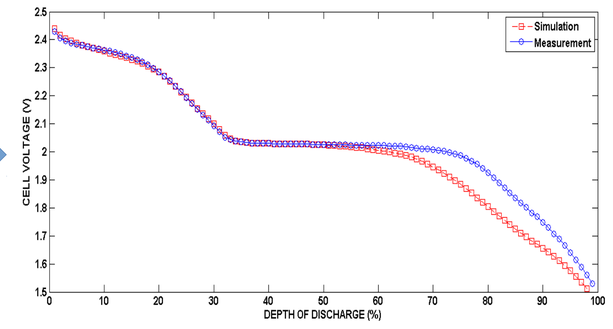
The experiments involved a small sized Li-S cell that was manufactured in-house, with a capacity of 2.36 mAh. The time-domain based current interruption technique was employed instead of electrochemical impedance spectroscopy (EIS) measurements [5, 6]. A sequential series of 0.1 C discharge pulses were applied at equally placed State-of-Charge (SoC) points, starting from %100 with 5% decrements, and 10 hours of waiting time between them in order to reach an equilibrium potential in open circuit condition after the recovery effect. The SoC dependent parameters were identified for each corresponding level.





V. RESULTS AND OUTLOOK





In order to validate the proposed model, a Simulink model was constructed and a constant current discharge of 0.1 C was applied. The simulation result demonstrates its ability to reproduce the characteristic double-plataeu terminal voltage of the actual Li-S cell to a certain degree of accuracy. In this form, the proposed model is suitable to be used in a power electronics context. It can serve as the energy storage component in an electric drive system and coexist with other subsystems for automotive powertrain simulations, or any other power system simulation for renewable energy applications.

It was shown that the current interruption technique can be employed to develop an equivalent circuit Li-S battery model. Even though the preliminary model fails to reconstruct the exact cell behaviour around the depletion zone, where it is always problematic to model with other chemistries as well, the concept was proven. It can be concluded that a longer relaxation time should have been spent between the measurements, especially for the second plateau, because the equilibrium voltage had not yet been reached and the identified internal resistance values have some discrepancy. Currently we are working on an improved model with more precise measurements and better dynamic response, we expect to present new results of the ongoing work soon.

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