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State-Of-Charge Evaluation Of Supercapacitors

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ABSTRACT

In the last years, energy storage systems are increasingly involved in applications in which they are required to deliver or adsorb significant charging or discharging currents in short intervals of time, typically a few seconds. Thanks to their high specific power, supercapacitors may represent one of the most promising technologies for this kind of applications. However, one of the main concerns regarding their operation is the accurate estimation of their state of charge; the most common technique, based on ampere-hour counting, typically requires some correction mechanisms, since it implies a significant loss of accuracy over time, due to the accumulation of measuring errors.

In the present paper, a novel algorithm to assess the state of charge of supercapacitors is described and implemented. The algorithm is based on the evaluation of the parameters of an equivalent electric circuit of the supercapacitor, and on the consequent use of a Luenberger-style technique for the runtime evaluation of its state of charge, based on the measure of current and voltage at supercapacitor's terminals. The algorithm estimates the cell open circuit voltage while the current is highly variable, as typical in power-oriented applications, hence the corresponding state of charge.

1. Introduction

Energy storage systems are increasingly required to deliver or adsorb very high currents in short intervals of time, typically few seconds or tens of seconds. This kind of performance is commonly described saying that the considered storage device is “power oriented”. Several case studies may be cited. As an example, hybrid vehicles are moved by at least two energy sources, one of them fuel-powered, the other composed by a storage system. Typically, as described in [1–3], the first meets the average load, while the storage system delivers or absorbs the ripple around the average value of requested power, thus providing energy during acceleration, while recovering energy during braking. Usually, acceleration and braking phases last seconds or, at most, tens of seconds, thus requiring high currents.

Another case study of interest is oriented to railway applications, in which there is the need to recover braking energy of trams or trains. Several studies have investigated tramway systems [4–6]. Depending on the considered case study, the energy storage system provides current peaks for about 10-20 s.

One of the most promising technology for this kind of applications is constituted by supercapacitors (SCs), typically characterised by high power and low energy density. Furthermore, due to the absence of electrochemical reactions during charging and discharging processes, supercapacitors are also suitable for workloads characterised by hundreds of thousands charging and discharging cycles, without significant aging phenomena, and very fast dynamic, up to some Hz. However it's worth noticing that in some applications modern high power lithium batteries could be just as competitive and effective, as demonstrated in [7–9].

One of the most pressing concerns of designers and users of supercapacitors is how accurately assess the state of charge (SOC) of the energy storage system. The easiest technique is to evaluate SOC based on ampere-hour counting, i.e. integrating the current at the supercapacitor's terminals. Nevertheless, if specific correction mechanisms are not adopted, the accuracy of this technique is jeopardized by the accumulation over time of unavoidable measuring errors.

The most common technique to correct this drift is the so-called OCV-SOC correlation, which requires the supercapacitor's current to be kept at zero for a while; at the end of this phase, the voltage measured at capacitor's terminals corresponds to the open circuit voltage (OCV) of the supercapacitor. The need for a time interval in which the current is null is however a clear disadvantage of this technique, especially in power oriented applications, in which the current typically varies continuously over time.

This paper is aimed to show and discuss a novel algorithm for the evaluation of the state of charge (SOC) of a supercapacitor, even

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during transients with highly variable currents. The existing scientific literature significantly lacks about this topic. In fact, most of the literature about supercapacitors is focused on the evaluation of their performance, investigates aging phenomena [10,11] or analyzes technical improvements like the use of new materials for electrolytes [12] or electrodes [13]. Contrary to the case of batteries, very few studies are focused on supercapacitors' SOC evaluation; a technique based on a Kalman filter is for instance proposed in [14].

The possibility of adapting to supercapacitors some SOC evaluation algorithms widely tested and used for batteries is far from obvious; in fact, in the case of supercapacitors, currents are significantly higher, so the errors due to current integration are a major concern. In particular, the Luenberger-style algorithm described in [15] for the SOC estimation of batteries was never adapted to be implemented and tested on SCs.

In order to assess if a SOC estimation algorithm originally deployed for batteries may be used also for SCs and how effectively it works, it's worth remembering that these techniques require the formulation of proper mathematical models. The accurate identification of the model's numerical parameters on real case studies, the right setup of the SOC estimation algorithm, and the experimental validation of the quality of both the model and SOC estimation algorithm are described in the following. Since the model's numerical parameters may depend on SOC itself, a discussion about the definition of SOC is also reported in the section that describes the model formulation. Assuming a realistic case study, the SOC estimation problem is firstly approached with an Ampere-hour counting technique, with the simple addition of a voltage-based compensation; subsequently, the Luenberger-style technique is implemented, compared and experimentally validated.

2. Model Formulation

2.1. Equivalent circuit representation

The models of SCs described in the literature are usually based on an equivalent electric circuit able to represent the voltage/current profile when a current/voltage profile is imposed to its terminals. Two general approaches are commonly followed: the first one is based on a time-domain analysis [16–19], validated by experimental laboratory tests [20] or in real existing applications [21]. The second one is performed in the frequency domain [22–24].

Both approaches show a general uniformity of models, basically based on the equivalent circuit depicted in Figure 1 [22]. This general model is able to fully represent the dynamic behavior of the device. Furthermore, it is described by a small number of independent parameters, easy to be determined.

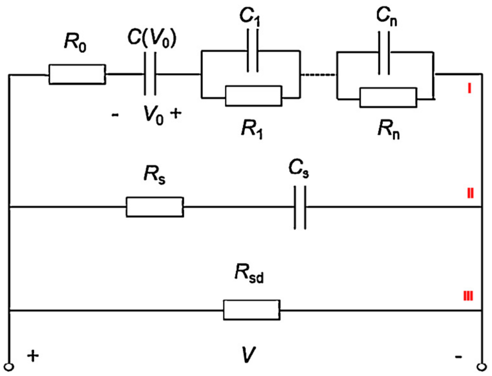

Figure 1. General model of a SC.

The model shown in the previous figure is composed by three branches:

- The first branch consists of the series connection of the resistance R_0, of the main non-linear capacitance $C(V_0)$, and of n parallel R-C blocks; this branch accounts for the frequency response of the device in the frequencies ranging from 10^{-2} to 10^3 Hz.
- The second branch consists of the series connection of the resistance R_s and the capacitance C_s; it represents the dynamics of the device for frequencies between 10^{-3} and 10^{-6} Hz, corresponding to the redistribution of the electric charges on the electrolytic solution.
- The R_{sd} branch takes into account the self-discharge of the device, whose effect becomes evident for frequencies below 10^{-6} Hz.

If the slow dynamics of the device is not under investigation, the second and the third branches of the model can be neglected [22]. This latter configuration, characterised by the presence of a single branch with a generic number of R-C blocks, is reported in Figure 2. It must be observed that, as specified before, this approach is normally considered also for batteries [25,26]. According to this model, the voltage across the main capacitance is V_{OC}, also commonly named OCV (Open Circuit Voltage), which corresponds to the voltage that appears at the supercapacitor's terminals after transients settle down.

The number n of R-C blocks has to be chosen as a compromise between the ease to use (lower values) and the desired accuracy (higher values). In order to avoid excessive complexity of the model and of the procedure required to evaluate the numerical values of model's parameters, it is normally assumed $n = 1$ or $n = 2$.

Since the transients simulated by the R-C blocks have time constants around one or tens of seconds, whenever only the very first part of the capacitor's dynamic response is of interest, $n = 0$ can be assumed. In this case, the first branch is simply composed by the capacitance $C(V_{OC})$ with the resistor R_0. Naturally, the correspondent precision is expected to be low, but also the procedure to obtain the parameters from experimental tests is simplified. Finally, although some papers show that the dependence of C on V_{OC} is not negligible [27], often a constant value of C is typically assumed.

2.2. SOC definition

The State-Of-Charge (SOC) is very commonly used in electrochemical batteries as an indicator of the level of charge stored into the device: it is assumed to be 1 and 0, respectively when the battery is fully charged and totally discharged. This indicator is also

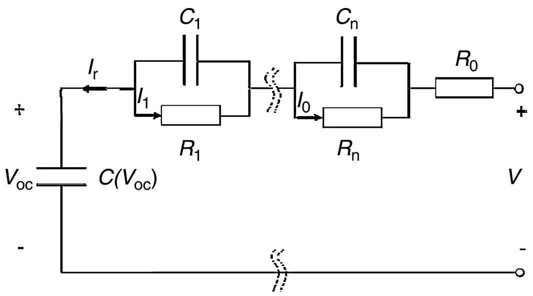

Figure 2. Selected model for SC.