Doctoral Program in Metrology (XXXVII cycle)

SINTESI / ABSTRACT

Accurate Characterization and Modeling of Electric Double-Layer Supercapacitors

By

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Declaration

I hereby declare that the contents and organization of my dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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* This is the abstract of my dissertation which is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Doctoral School of Politecnico di Torino (ScuDo).

Abstract

The thesis “Accurate Characterization and Modeling of Electric Double-Layer Supercapacitors” concerns the characterization of supercapacitors (SCs), with particular reference to Electric Double-Layer Capacitors (EDLCs). These components have gained significant attention as high-power energy storage devices due to their quick charge-discharge cycles, long cycle life, and high efficiency. These characteristics make them interesting for applications such as power electronics, renewable energy systems, hybrid and electric vehicles.

SCs have a reputation for being unstable components, difficult to be characterized, where the few parameters provided by manufacturers are affected by very large uncertainties. On the other hand, when SCs can work in synergy with batteries, for instance smoothing out peaks in power demand like in braking and acceleration in e-mobility, a rather accurate model of the SC parameters is required by the charge control, to work efficiently and safely with batteries.

This thesis aimed to contribute to some aspects of SC characterization and model identification, and the work provides the following investigations.

- Discusses the SC as a component, including definitions of main quantities, such as capacitance, series resistance, specific power, and so on. Then are described both, a brief history of the technology and the general characteristics and the three main families of SCs. We then move to an analysis of SCs essential components such as current collectors, electrodes, electrolytes and separators, by providing an idea of the extensive research in progress, especially on electrode materials, which largely determine the characteristics of the device.
- Provides a review of existing measurement techniques and international standards governing SCs characterization, highlighting their limitations in providing accurate and repeatable parameter estimation. The analysis focuses on time-domain measurement methods, because these methods are considered by international standards and offer direct insights into the static and dynamic behavior of EDLCs in the laboratory and under real

operating conditions. This thesis work has contributed to introduce an original technique for the measurement of leakage resistance, which allows to determine the behavior of the SC over a long-time span, even days.

- Analyses the measurement repeatability and training. No measurement has meaning if it is not repeatable, and this depends both on the method, on the measurement instrumentation and on the device under test. In this case the SC is not a repeatable device, but it becomes so if adequate preliminary training is carried out. Repeatability is maintained even after days, and training must be repeated when the SC is left in long phases (weeks) of standby.
- Discusses the modeling of the time behavior of a SC. A simple RC circuit is not so accurate for simulating the behavior of the SCs in an electronic system but a multi branch model is needed. In this thesis the three-branch model has been chosen as a compromise between simplicity and accuracy, also introducing the original non-linear leakage resistance identified in Chapter 2. This thesis also contributed to a new method for the accurate identification of the circuit parameters from the measurements, based on state equations and on optimization, which improves the matching between measurements and model over long periods.
- Finally, provides a new general method for the uncertainty assessment of SC equivalent circuit parameters, and here it is applied to a three-branch equivalent circuit.

In summary, this thesis work shows how SC measurements can have good repeatability and limited measurement uncertainties. Moreover, this work highlights how the proposed modified three branch equivalent circuit model, together with the proposed identification procedure, results to be a very good tool for the SC simulation and control. Finally, a new method for the measurement of the non-linear leakage resistance and another new method providing the estimate of the equivalent circuit parameters uncertainty is also proposed and applied in this thesis.