Publishable Summary for 23IND04 MetSuperCap
Metrology for static and dynamic characterisation of supercapacitors

Overview

Supercapacitors (SCs), an environmentally friendly technology, are being used as energy-storage devices across an increasing number of fields, including as a replacement for batteries in higher-power density applications. This electrochemical energy storage device has an operating principle and charge storage mechanism which is more closely associated with those of rechargeable batteries than electrostatic capacitors. However, as the behaviour of SCs differs from both, and in order to support the growing use of SCs, accurate characterisation is required for SCs and SCs banks, both in the laboratory and under operating conditions. In addition to this, validated software is needed to identify the equivalent electrical model of SCs for dynamic applications. Quick, traceable, and effective measurement techniques are also required to evaluate the State of Charge (SoC) and State of Health (SoH) of SCs and to promote the uptake of SCs in industrial and energy applications.

Need

The EU's Battery regulation 2023/1542 aims at improving the protection, preservation, and quality of the environment by, for example, imposing maximum quantities for certain types of metals and chemicals contained in batteries. SCs, an environmentally friendly technology, strongly reduce the presence of certain chemicals and metals, which is unavoidable in many types of batteries. In addition, the life cycle of SCs is very long (a hundred times longer than batteries), their charging and discharging limits are not critical, unlike for batteries, and they pose zero thermal runaway risk over a wide temperature range. These devices can be used, amongst others, in industrial and energy applications but their uptake and future commercialisation is currently hampered due to technical problems and a lack of established electrical parameter models, consistency in testing, and industrial standards.

SCs metrics are only partially defined by manufacturer guidelines and standards and these furthermore lack the appropriate accuracy analysis. Therefore, guidelines on the methods for accurate characterisation of SCs and banks are needed. To implement SCs and SC banks into applications, reliable tools for the accurate determination of a multiparametric equivalent circuit model (ECM) are needed. A clear measurement and identification tool is not within the knowhow of many companies. A reliable and recognised tool would allow designers and manufacturers to easily implement SCs into a wide range of applications. Applications require frequent monitoring of the SoH and SoC of the supercapacitive components to provide correct feedback to the users and to ensure a sufficient maintenance schedule is in place. Therefore, developing rapid and reliable methods of measurement and diagnosis is of great interest for many applications. In specific applications, for example, the coexistence of batteries and SCs may lead to complex charging management systems. New models and methods developed for SCs have to be verified in the presence of distorted waveforms (low power quality) and the limits of their validity 'in operation' must be defined. Finally, it should be noted that to date almost all the studies, standards and guidelines mainly concern Electric Double Layer Capacitors (EDLCs) while new guidelines for the characterisation of SCs also need to take into account hybrid SCs and pseudo-SCs.

Objectives

The overall objective of the project is to establish a traceable, consistent and sound measurement and characterisation framework for both SCs and SC banks. This includes the development of rapid techniques for

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or EURAMET. Neither the European Union nor the granting authority can be held responsible for them.

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

the determination of SoC/SoH of SCs, for the determination and assessment of ECM parameters, the verification of the proposed techniques in real conditions and the processing of inputs for standards developing organisations.

The specific objectives of the project are:

1. To develop metrologically traceable methods, including the assessment of uncertainty, for characterising the capacitance, resistance, specific power and energy for SCs of different sizes (from 1 farad to 3000 farads, for discharge currents up to 500 A and voltages up to 60 V) and at least two different types and brands. The developed methods should be suitable for the characterisation of SCs banks with maximum instantaneous discharge power up to 25 kW (e.g., 420 A at 60 V).
2. To develop software/models for identifying relevant parameters for the static and dynamic characterisation of SC and SC bank models. The target error of the developed software/models will be lower than 5 % (for voltages greater than 200 mV). In addition, to define optimised voltage/current waveforms, based on representative SC charging and discharging cycles, for characterising SCs and for validating models by measurement.
3. To develop rapid techniques, including the assessment of uncertainty, for accurately measuring the SoC and SoH of SCs. Additionally, to test and verify the developed techniques on at least two different types of SCs.
4. To design and produce two test benches fitted with a measurement system and a measurement procedure to evaluate the actual behaviour of SCs under operating conditions, including battery/emulator-SCs hybrid systems. The test benches will also be used for the validation of the outputs of Objectives 1 3 and for the evaluation of at least two applications of SCs in energy systems, (e.g., photovoltaics (PV), uninterrupted power supplies (UPS), electric vehicles (EVs)).
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain, standards developing organisations (those associated with the EU's Batteries regulation (Directive 2006/66/EC), and end users (e.g., EMN for Smart Electricity Grids, the aerospace, automotive and energy sectors).

Progress beyond the state of the art and results

SCs and banks of SCs require time-demanding testing, and research laboratories often provide tests which are limited in terms of physical conditions and the SCs sample analysed. This project is going beyond the state of the art, by providing a large database of electrical parameters of SCs and SC banks of various and sizes and brands made available to the public via Open Access (OA).

Measurement of the parameters of SCs and SC banks

The consortium worked in the first part of the project to draft a "Report on the definition of the parameters of SCs and review of existing measurement methods". Based on this report, a substantial document, the "Test plan", was developed and distributed in the consortium, which defined in detail the measurements to be performed, the organisation of the measurements for each SC, assembled into datasets, and the naming of the files and datasets. The test plan contains various types of measurements: electric series resistance (ESR) measurements performed in different modes (charge and self-charging, charge and discharge, CC and CV charge followed by discharge), electrical impedance spectroscopy (EIS) measurements, cyclic voltammetry measurements, DC charge and discharge measurements for determining stored energy, maximum power and efficiency, leakage resistance measurements. Partners performed measurements according to the test plan and to their own capabilities, so the measurements on a certain SC, grouped in a dataset, can be more or less complete.

Currently the datasets are still, in part, under processing, but 38 datasets for a of more than 250 measurement files concerning 13 sizes of SC samples are already uploaded in the Zenodo public repository.

The test plan contains some measurements as suggested by IEC standards (e.g. the standard EN IEC 62391-1:2022), others suggested by scientific literature, and still others developed in the project. In particular, the so-called preconditioning, or training, was included in the measurement protocol, the importance of which was underlined in the paper [2] which reports a first analysis of the interaction of the impact of measurement uncertainty on an ECM identification. In essence, preconditioning brings the SC under test to an acceptable level of measurement repeatability, reducing the uncertainty due to repeatability below the ideal threshold of 1%.

In order to make the datasets public, and therefore the corresponding database, a community, the MetSuperCap community, was created on Zenodo.

The project will go beyond the state of the art by developing a guide that provides a clear relationship between the instrumentation, the measurement method, and the expected uncertainty on the SC parameters.

Equivalent Circuit Models of Super Capacitors

The consortium is pursuing three modelling approaches: the first is based on a three-branch ECM, the second on fractional models, and the third is based on machine learning (ML). While the third requires that most of the database be available to begin the analysis, the second has begun to provide initial results to fit EIS measurements. The first, the three-branch ECM, has been extensively validated using a dozen datasets developed by the project and considering measurement currents from 500 mA to 440 A and capacitances from 1 F (rated 1 mWh, 10 W) up to a large 130 F module (rated 70 Wh, 144 kW) and test power from 1.5 W to 27 kW. The results are under review in the article "Extensive validation of the three-branch model in simulating the static and dynamic behaviour of EDLC supercapacitors," submitted to the journal Energies, MDPI. This project is going beyond the state of the art since it demonstrated that the three-branch ECM model identified based on state equation, and Conventional Trust Region Reflection method, a technique tuned by consortium members in a previous European project Emphasis, provide accuracy better than 3 % in the model identification. The studies also demonstrated the ability of the model in reproducing the cyclic voltammetry behaviour (with the same accuracy) and the time-domain dynamic response to pulse trains having frequency up to 100 Hz (period 10 ms). The dynamic response time profile is rare to be found in the literature because it is difficult to be reproduces and measured. The consortium managed to reproduce it by using a transconductance amplifier as the current source. Interestingly, the three-branch ECM model reproduced the measured terminal voltage values with a relative discrepancy better than 1 % with respect to the SC rated voltage.

State of Health and State of Charge determination

The determination of SoC and SoH allows systems to increase reliability, predictive maintenance and real time condition monitoring. Rapid methods are not common but are of great applicative interest and the determination of the SoC/SoH requires the use of complex techniques or the use of complex algorithms combined with the device's ECM. This project will progress the state of the art by exploring the possibility of using rapid (e.g. impulsive) measurement techniques and other approaches linked to ECM parameters, in order to obtain a reliable SoC/SoH assessment. The project in its early stages produced the report "Review of the state of the art of SC equivalent circuit models" and then a second report "State of the art of rapid techniques" which have been circulated among partners. Many techniques are being considered for rapid SoC estimation like, open circuit voltage method coupled with an ECM, coulomb counting method, Kalman filter method, Artificial Neural Networks, Observer based techniques, and for the determination of the SoH, such as EIS, Pulse current testing, Leakage current measurement, model-based methods for SoH (such as the already mentioned Kalman Filter), Data based methods for SoH. The results will be developed in the second part of the project on the basis of a specific database on a SC subset that has been started to develop based on the accelerated aging of SCs.

Real applications with hybrid “SC plus battery" systems

The use of SCs in conjunction with batteries provides undoubted advantages in terms of absorption and return of power peaks, which, when actively managed by SCs, improve efficiency and extend the life of the batteries. Applications for such hybrid storage devices, e.g., Electric Vehicles (EV) and Photovoltaic (PV) systems, require hybrid charge control strategies, detailed models of SCs, and dedicated validation platforms that go beyond state-of-the-art. To address this gap, the consortium is developing two dedicated test benches to characterise SCs under representative, real operating conditions and to validate advanced hybrid control approaches. The consortium has defined the requirements for two complementary setups, one dedicated to a hybrid PV test bench and the second to a hybrid EV test bench, specifying configuration options, operational conditions, and performance targets to enable reproducible benchmarking beyond current laboratory practice. The design and development of the test benches are progressing from specification to implementation. In particular, the consortium has conceived the architecture and initiated the assembly of the hybrid PV battery–SC test bench, enabling controlled power-peak profiles and hybrid charge/discharge management in a single experimental platform. Key components consist of IGBT half-bridge power modules and a rapid control prototyping (RCP) system. The complete system has been modelled and fully simulated with state-of-the-art circuit simulation software to develop, de-risk, and pre-validate the control logic prior to hardware deployment. Initial experimental testing is underway to tune charge and discharge behaviour and to assess dynamic response under peak-power operation. In parallel, the consortium is performing component-level testing of the hybrid EV setup, integrating an SC module as a first step toward a scalable platform that will later support full powertrain emulation and system-level validation of hybrid energy management.

Outcomes and impact

Key dissemination and communication activities:

The consortium created a website which provides key information regarding the project's structure, objectives, outcomes, and news. A LinkedIn and a Instagram channels were also created. In the first part of the project, 19 news items were spread through the three channels (website, LinkedIn, and Instagram), and two newsletters were published and advertised. At the launch of the project on June 12, 2024, in Torino, Italy, a joint workshop was hosted in collaboration with the European Emphasis project. The event focused on the full spectrum of supercapacitor technology, from development and testing to diverse applications ranging from electric mobility to textiles. Attended by over 60 in-person participants—including industry experts and academics—the workshop featured fourteen pitch talks and fostered a dynamic environment for networking and professional interaction.
The consortium has held several presentations at national and international conferences including CPEM 2024, XXIV IMEKO World Congress, CIM 2025, I2MTC 2025, ECCE Europe 2025 and many others. Overall, the consortium held 17 presentations. Two papers have been published open access in international peer-reviewed journals, and two more have been submitted. Currently, the project yielded one master thesis and contributed to a PhD dissertation and other doctoral theses have been started at the partners. Two short online workshops were held with stakeholders and collaborators, with whom constant interaction is maintained. The dozens of datasets produced by the MetSuperCap consortium are going to be adequately publicized on the project's channels.

Outcomes for industrial and other user communities

The consortium established a Stakeholder Committee with 11 members from 7 countries, including 8 profit organisations, which provided valuable input into the project's activities. One of the most significant was focusing on the 25 F, 60 F, and 300 F or 400 F sizes, which are among the most attractive on the market. These sizes were therefore included in the test plan, and the plan was deemed interesting by industrial stakeholders. The temperatures for the "hot" and "cold" tests were also discussed with stakeholders, and thus the consortium received feedback that the experimental investigation approach was of interest.

Several outcomes are emerging from the analyses underway in this first phase of the project. One aspect concerns instrumentation, as much of the equipment comes from manufacturers who, already building battery testing equipment, also resell it for SC testing. The first limitations we encountered concern sampling time, which sometimes prevents adequate measurement of ESR in SC, while is compliant with accurate measurements for batteries. The definition of ESR can be ambiguous and depends on both the measurement method and the type of test being conducted. As one might expect, there are also significant effects due to fixtures, both for DC and for EIS-type measurements. Capacitance estimation also appears to be method dependent.

The measurements must also be addressed taking into account the limits of the object being measured, which needs to be preconditioned, and which suffers variations in its parameters both due to natural aging and normal use, although the latter is very limited compared to batteries.

All the experiences along the way converge in the drafting the good practice guide for evaluating the uncertainty of electrical parameters in SC testing and characterisation, covering a wide range of SC sizes (1 F – 3000 F) developed within the project will enable SCs users, designers and SC manufacturers to simplify the characterisation of SCs and SC banks. A widely recognised standard procedure associated with a metrological infrastructure providing the traceability for such assessment will provide higher trust to both the customer and the manufacturer.

The methodologies and procedures for the accurate determination of the characteristics of the SCs will improve the reliability and accuracy of these parameters which are crucial for designers and users, especially for more demanding applications, such as space, e-mobility and energy applications. The validation of the methodologies for the use of SCs in real conditions, verified for different types and sizes of SCs, will allow manufacturers of systems using SCs (e.g., for renewables, automotive applications, e-mobility in general) to design more robust technical solutions and better predictive maintenance plans.

The three-branch model has recently been validated for a wide range of SC capacitances and has been found to be accurate for both static and dynamic tests, potentially providing the basis for creating a digital twin. Such a tool, also suitable for real-time applications, could provide a reference for SC manufacturers and provide an additional design parameter.

The rapid techniques that will be developed in the second part of the project, for determining the SoC/SoH of SCs, can be used by manufacturers of electronic systems that use SCs as power supply units, increasing the reliability of the systems and allowing the successful implementation of predictive maintenance techniques. These techniques are also important for manufacturers of aerospace and e-mobility storage systems.

The availability of two large databases, one regarding the characterisation and characteristics of SCs and a second developed regarding the SoC/SoH of SCs could constitute a benchmarking for manufacturers for the development of new products.

Outcomes for the metrology and scientific communities

The database currently under completion and the one that will be completed in the second part of the project (SoC/SoH) will certainly be useful to the scientific community as a database for the development of models and benchmarking for the measurement, as well as providing various measured data on SCs. The dataset files were designed to be 'findable', and in fact they are in a public database and each dataset has a DOI, 'accessible' as the download is free, 'Interoperable' as basic formats such as the .txt format and summary files in easy-to-read .pdf format are used, complete for reuse in the scientific community, and in fact the data are 'reusable' since the datasets are provided under the BB-CY license.

The project will provide the scientific community with traceable measurements for the characterisation of SCs and banks of SCs, and for the definition of the SoC. In this sense, in addition to the ongoing measurement uncertainty assessment, some specific calibration methods are also being studied, especially for EIS measurements. In this regard, it is worth mentioning some presentations made by the consortium, such as “Propagation of uncertainty through generalised correction schemes for impedance metrology” (Mathmet 2025), “Calibration of mutual inductance standards with a fully-digital impedance bridge” (I2MTC 2025), “EIS-Based State of Charge Characterisation of Electric Double-Layer Capacitors” (ECCE 2025) and others.

NMIs will deliver a report containing the CMCs concerning the characterisation of SCs, compliant with those published in the KCDB website, which will be ready for use in NMIs depending on market demand in the various countries. These CMCs will be of high relevance to the metrology community, as at the moment no NMIs deal with high capacitance measurements, especially in the 10 F – 3000 F range, which is the one that is receiving great interest in SC applications.

The two large open access databases that group together a significant amount of relevant data on different types of SCs, will enable academic communities (both metrological and non-metrological with limited or no capabilities to perform measurements and characterisations on SCs) to undertake further research activities including analysis of data and information about SCs’ variability versus charging conditions, versus charging patterns, versus SoC/SoH and related aging.

The development of rapid techniques for the definition of SoC/SoH also requires the development of both analysis and measurement techniques. These developments will benefit both the metrology and scientific community since they can improve and speed up the assessment of these parameters.

Outcomes for relevant standards

The project will support the EU’s Batteries Directive 2006/66/EC which aims at improving the protection, preservation, and quality of the environment by, for example, imposing maximum quantities for certain types of metals and chemicals contained in batteries. The project, by promoting the use of SCs combined with batteries, allows, for the same power supplied, to reduce the part borne by the battery and also significantly reduces the amount of energy borne by the battery. This indirectly leads to a reduction in the metal-pollutants embedded in the battery, reducing the related risk associated with disposal.

MetSuperCap

EURAMET

The consortium is collaborating closely with an industrial partner, a SC manufacturer, that is also a member of IEC TC40 on the topic of SCs. To date, there have been extensive discussions regarding some critical parameters such as ESR and leakage current, as well as dynamic and EIS measurements. Potential outcomes of the project may be considered by the technical committees, but beyond the scientific value of these outcomes, proposals for implementation in the standard must take into account the need for easy implementation for the industrial world.

The consortium is also connected with IEC TC 113 "Nanotechnology for electrotechnical products and systems" and has the presidency of the Italian national mirror committee. Consortium members are participating in the project team of a new IEC standardisation project on electrochemical impedance spectroscopy for energy storage devices (including novel nano-enabled chemistries for supercapacitors and batteries) and discussion about the implementation of reliable measurement protocols and uncertainty estimation is regularly taking place within the TC.

Longer-term economic, social and environmental impacts

The contribution to SoC/SoH assessment provided by the project has a significant impact on predictive maintenance techniques, which is a key factor boosting the growth of this technology, whose market is already expected to double in the next 5 years. Promoting the diffusion of SCs in electrical systems by design, and their adoption, also means meeting the needs of the European Strategic Energy Technology (SET) Plan, which provides a roadmap to enable the transition towards a climate neutral energy system through the development of low-carbon technologies. SCs, differently from the batteries, do not require the use of rare or polluting materials and, on the contrary, can also implement organic materials, constituting an environmentally friendly component. To promote the diffusion of SCs also responds to the social demand for high-capacity portable power supply that is becoming more and more crucial.

List of publications

[1] M. Zucca, N. Al-Zubaidi-R-Smith, L. Bartova, H. van den Brom, L. Callegaro, A. Cultrera, L. Fast, A. Girimonte, M. Hassanzadeh, A. Mariscotti, A. Masouras, J. Medved, S. Musumeci, G. Nicol, M. Ouameur, G. Rietveld, “MetSuperCap: Metrology for static and dynamic characterisation of supercapacitors”, Measurement: Sensors, 38, Supplement, 101434, 2025, doi: 10.1016/j.measen.2024.101434. LINK

[2] M. Zucca, M. Hassanzadeh, D. Signorino and U. Pogliano, “Uncertainty Evaluation of a Supercapacitor Equivalent Circuit Parameters,” in IEEE Transactions on Instrumentation and Measurement, 74, pp. 1-9, 2025, art n. 1502509, doi: 10.1109/TIM.2025.3544362. LINK

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2024, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Mauro Zucca, INRIM Tel: +3901139191827 E-mail: m.zucca@inrim.it
Project website: https://www.metsupercap.eu/</td></tr>
<tr><td>Internal Beneficiaries:
1. INRIM, Italy
2. CMI, Czechia
3. LNE, France
4. RISE, Sweden
5. VSL, Netherlands</td><td>External Beneficiaries:
6. CRF, Italy
7. Keysight AT, Austria
8. Novac, Italy
9. Pleione, Germany
10. POLITO, Italy
11. UNIGE, Italy
12. UTwente, Netherlands</td><td>Unfunded Beneficiaries:
n/a</td></tr>
</table>