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Hybrid supercapacitors contributions to intra-urban transport ecosystem based on RES for seasonal tourism

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Abstract. Renewable Energy Sources (RES) use at local scale reduces the environmental impact, maximizing the effect as production and consumption are carried out in the same place. Therefore, this limits the losses associated with distribution networks, and minimizes the impact on the landscape in areas of special interest, including touristic beaches and other natural sites, where there are high-value natural environments, and where the citizens' comfort must be considered.

Implementation of an intra-urban transport ecosystem, based on fleets of light electric vehicles charged from RES, is proposed for these natural touristic areas.

In this context, Urban Touristic Transport at Sustainable Environments (TTUES) project aims to promote the implementation of a transport ecosystem, using specifically designed and tested light and small-sized electric vehicles (EVs), and suitable charging stations based solely on RES.

This paper presents a development of an Energy Storage System (ESS) based on Hybrid Supercapacitors (HSC) for their application in light EVs recharging points.

It details the main equipment and capabilities of the testing facilities, and the tests performed by INTA, the Spanish National Institute for Aerospace Technology, in the framework of the project TTUES, as well as the experimental results validating the HSC system for its application.

Key words. Hybrid supercapacitors, electro-mobility, intra-urban transport, tourism applications, electric vehicles.

1. Introduction

Increasing energy demand, growing concern regarding global warming and climate change have accelerated the path of transport sector electrification.

In recent years, a great deal of progress in the use of electric vehicles has been observed. It is estimated that by 2040 the market share of Light Battery Powered Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV) will increase to 55% [1]. The large-scale implementation of electric vehicles significantly affects the socio-economic and environmental aspects of the city functioning [2].

However, a large-scale adoption of electric vehicles needs availability of sustainable and easily accessible charging infrastructure.

Multiple variables, such as stochastic nature of the renewable energy source, unsteadiness on citizen's demand, different storage commercial systems, a wide range batteries storage capacity and charge/discharge rate, and diverse penetrating patterns of electric vehicles, have significantly raised the load elasticity on the power grid. Smart-grid environment promises to assist the addition of EVs into national grids by enabling both EV-charging and discharging (G2V and V2G) load. Different infrastructures can be done through which EVs are charged. These infrastructures are studied and compared on the basis of some parameters. It has been found that distributed infrastructure shows best results for the charging of electric vehicles [3].

Thus, the implementation of an intra-urban transport ecosystem, based on fleets of light electric vehicles charged from RES, could be a great solution for seasonal tourism in areas of special interest, such as tourist beaches and other natural sites. Competitiveness for hotels that are not close to the leisure destination of tourists, such as the coast itself, depends on the use of vehicles to transport its guests. This implies greater acoustics and air pollution, degradation of high-value natural environments and decrease in the citizens' comfort.

RES use at local scale reduces the environmental impact, maximizing the effect as production and consumption are carried out in the same place, limiting the losses associated with distribution networks, and minimizing the impact on the landscape, compared to the fumes and noise of traditional energy generation, for these touristic areas [4].

In this context, Urban Touristic Transport at Sustainable Environments (TTUES) project aims to promote the implementation of a transport ecosystem that mitigates mentioned problems, using specifically designed and tested light and small-sized electric vehicles, and suitable charging stations based solely on RES, to provide the tourist areas of Huelva (SW of Spain) and Algarve (S of Portugal).

In this paper, main objectives, approached by the Spanish National Institute for Aerospace Technology (INTA), are the definition, evaluation, characterization and validation of innovative energy storage systems for the intermediate "buffer" between the RES of charging points and the vehicles, as well as the adequate integration of the intermediate energy storage system with the batteries on board the vehicles. Therefore, this paper objective is to develop a hybrid supercapacitor system characterization to fulfil TTUES goals. Relevant literature about the use of HSC in electric vehicles reflects very few references, mostly mathematical models [5],[6]. However, there are no remarkable references on its use for light EV, so this article proposes a novel application and experimental characterization applicable to light EV.

These objectives are carried out at the Energy Laboratory that INTA owns at Huelva, SW of Spain, which includes adequate experimental testing facilities for these goals, such as a microgrid (integrates RES generation, electrical energy storage systems and several loads) that allows the testing and evaluation of components and technologies, at pilot plant scale, in real operating conditions, and batteries and super-capacitors test benches that allow the testing of energy storage equipment in controlled conditions.

Figure 1 shows the test bench for characterization and evaluation of electrochemical systems and technologies of energy storage systems (batteries and supercapacitors).

Fig. 1. INTA test bench for energy storage systems.

This paper presents the application of Hybrid Supercapacitors (HSC) as intermediate storage systems (buffer) for use in EV recharging points, based on RES. Following the framework of the project objectives, main tests are performed to be validated for tourist coastal environments transport.

2. Development and characterization of ESS

Local RES grids, commonly referred as renewable microgrid [7]–[10], are based on ESS to maintain the energy storage and act as a buffer between the RES and the load. In this specific case it would be the EV recharging point, including photovoltaics as RES, the EVs as load and the HSC operating as ESS.

Among the possible ESS, there are differentiating characteristics which must be considered to find the best solution for each application. Most common ESS are compared, including HSC, in Table I [11]. Batteries provided high specific energy (Wh/kg), with limited specific power (W/kg). Supercapacitors provide high specific power with reduced specific energy, providing faster refueling but with limited quantity of EV that can be refueled since energy capacity limitation.

Table I. - Energy storage systems analysis

ENERGY STORAGE TECHNOLOGY	SPECIFIC ENERGY (Wh/kg)	SPECIFIC POWER (W/kg)
Lead Acid Batteries	20-50	25-300
Lithium Ion Batteries	75-200	100-360
Supercapacitors	0,2-15	100-5000
Hybrid supercapacitors	20-30	3000-14000

Supercapacitors are capable to compensate the power variations of renewable energy sources due to the stochastic nature of the primary resources. These applications can be used in numerous domains, such as electrical transport, power supply to electronic devices and in combination with renewable energy sources for autonomous power supply in remote areas [12]. However, the low specific energy of supercapacitors does not make them a suitable application for EV power supply.

On the other hand, HSC systems have great advantages for charging points. The typical HSC is formed by a positive electrode of activated carbon along with a Faradaic electrode, in an organic electrolyte [11]. This allows HSC to combine a balance between power and specific energy, reducing the contaminating material of lithium batteries and increasing the useful life of batteries with which they are configured in hybridization. They also provide extended cycle life, compared to batteries [13].

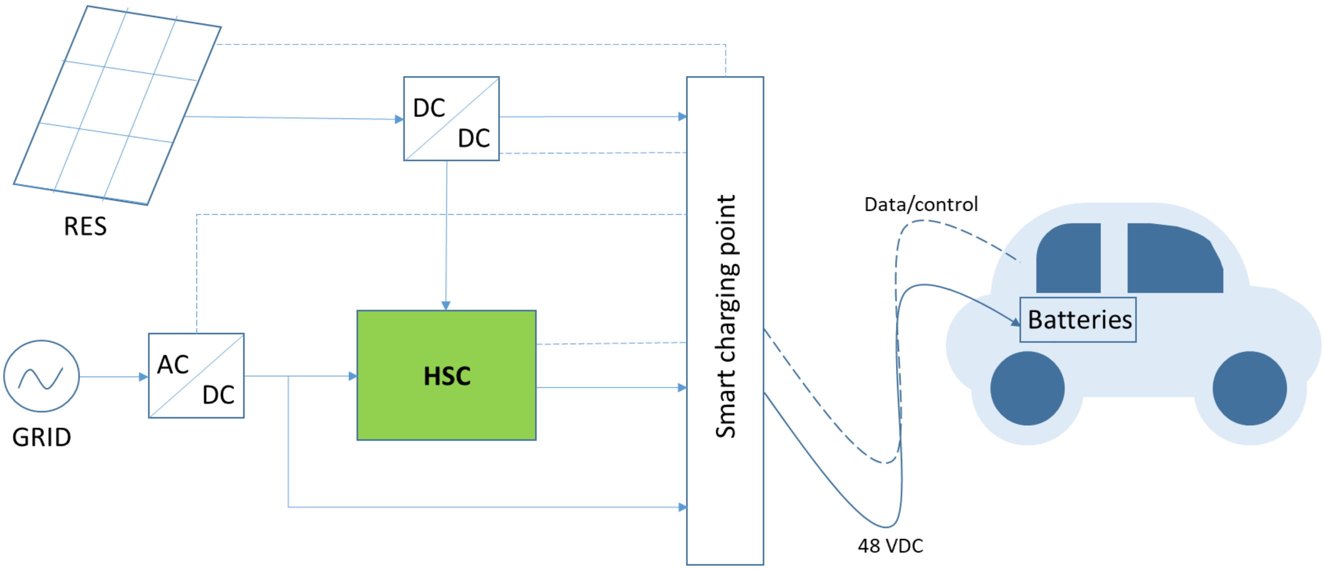

Fig. 2. Smart charging point with HSC - TTUES.

Therefore, hybrid supercapacitors are a promising ESS with higher specific energy than supercapacitors, maintaining a balanced specific power [11].

System design considered in this work is presented below with a multi-configuration for energy supply. This system can present different charging point operating modes.

The complete supply and recharge system for EV is shown in Figure 2. The HSC system is contemplated for recharging from RES, as well as charging and discharging from the grid. Though the smart charging point, operational data is monitored and the different connections of the elements, that define the modes of operation, are controlled.

Functionalities or working modes are:

1) Slow recharging system for the batteries of a light electric vehicle through the different power conversion elements. In this case, the contribution of the different energy sources must be managed, either photovoltaic solar or from the 230 V_{AC} power grid, according to different operating criteria, maximizing the corresponding cost function. When the energy availability is greater than that necessary for recharging, it is stored in the HSC (priority to always keep it full). Oversizing equipment should be avoided to save investment costs.

2) Fast vehicle battery recharging system through the HSC. For public parking areas it is essential to be able to recharge 80% of the battery capacity in the shortest possible time. In these cases, the energy stored in the HSC would be used (situations of high power demand). If necessary, the grid could contribute energy to the HSCs, if the appropriate technical-economic conditions are met.

The fast charging mode is the main case study in this work, where the HSC acquires a relevant character. The experimental results aim to validate the HSC system for its application and experimentally demonstrate the capabilities of an HSC system while analysing a real case of an HSC system implementation. The system consists in an HSC 7500F/48V module with external overcurrent protection for safe characterization.

Figure 3 shows the physical implementation of the HSC system for its experimental validation carried out at INTA. The photo on the left shows the HSC module (below), the protection system (on the table in front) and the experimental characterization system (in the background). The photos to the right show a close-up view of the HSC module (top) and the protection system (bottom) that includes relays, switches, and fuses, up to 40 A operation.

Figure 3. HSC experimental system.

A series of tests are performed to characterize the HSC system proposed. Test 1 performs a complete discharge of the HSC system, checking the energy provided and the voltage and current parameters. Test 2 carries out a process of charging and discharging the HSC at different progressive current steps, checking capacity, voltage and current. Finally, Test 3 analyses the stability before a specific EV supply profile, scaled to shorter test times.

After first test, Figures 4 and 5 show the behaviour when a controlled 30 A discharged is applied to the fully charged HSC. Although the HSC system can withstand much higher currents, up to 750 A, the value of 30 A is taken for the experimental characterization applied to the battery recharging function. Most conventional commercial light EV batteries work around that lower current range. This test is carried out over the entire voltage range of the HSC module, thus verifying its energy capacity. The use of parallel modules would increase the capacity of the system.

HSC energy during discharge is measured with a maximum of 2691 Wh supplied during test (Figure 4), achieving almost rated energy (2.8 kWh). Then experimental specific energy (at 30 A) is around 25 Wh/kg, while rated is 26 Wh/kg.

Voltage goes from 51.77 V (almost maximum 52 V) to 35.9 V (cut-off voltage) during the 30 A discharge (Figure 5). Therefore, power directly supplied goes from 1.5 kW to 1 kW.

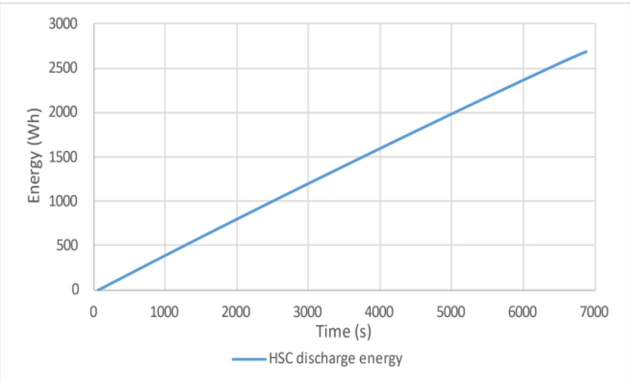

Figure 4. HSC energy during Test 1.

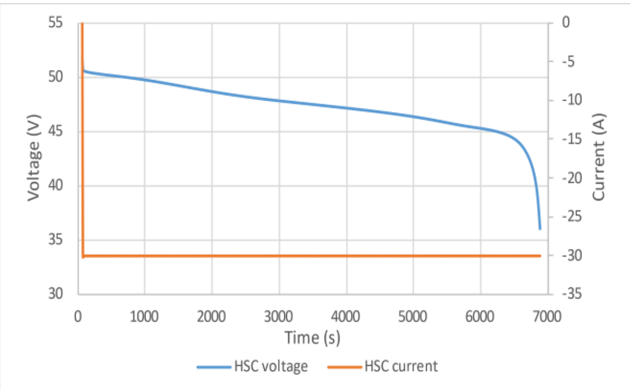

Figure 5. HSC voltage and current (at 30 A) during Test 1.

At tested power, with fast charging mode (around 2 hours), a total of 6 parallel HSC modules would be needed to fit a fully recharge of commercial EV vehicles (Peugeot iOn: 16 kWh; German E-Cars CETOS: 17.1 kWh) [14], [15]. Meanwhile, for light EV models, just 2 parallel HSC modules would be necessary for fast-charging (Renault Twizy: 6.1 kWh) [16].

Next, Test 2 is approached to obtain further characteristic analysis of the HSC system including both charging and discharging. First, the HSC is fully charged. Then a series of current steps, up to 35 A, are applied during discharging until the lower voltage limit is reached. Next, similar current steps are applied for HSC charging until a fully charge is achieved again. Figure 6 shows the voltage and current during Test 2, while Figure 7 shows the capacity.

Note that slow charging is tested here, as lower currents are applied to characterize the signal evolution between them.

From Figure 6, it is verified the quick stability of the HSC against the current steps changes, showing a smooth voltage curve without critical peaks.

Results of Figure 7 shows summative capacity, so discharging capacity is verified to be around 57 Ah, while charging capacity correspond to 69 Ah. However, as an initial charging was applied, the maximum capacity during a complete charging process equals to 57 Ah, as occurs during a complete discharging.

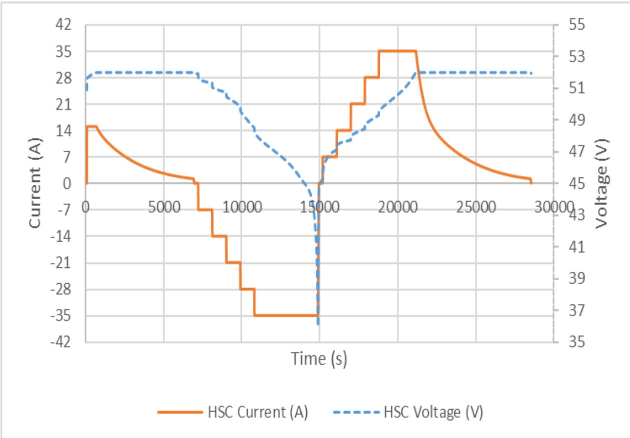

Figure 6. HSC voltage and current during Test 2.

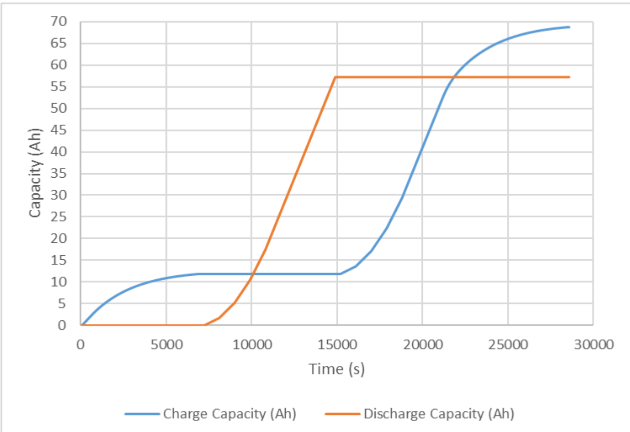

Figure 7. HSC capacity during Test 2.

After previous characterization, during Test 3 the HSC system is connected to a supply profile from an EV charging point (Figure 8). Note that the timeline corresponds to the hourly profiles and not to the shortest test time, consequently when the demand decreases, the voltage recovers a higher value quickly, since the energy consumption is small during this test. This is approached to analyses HSC voltage stability against different high demands over time. HSCs quickly adapt to changes in demand at the charging point setpoint, with instabilities during transients of less than 2 %. This experimentally demonstrate the smoothness and stability in the HSC supply.

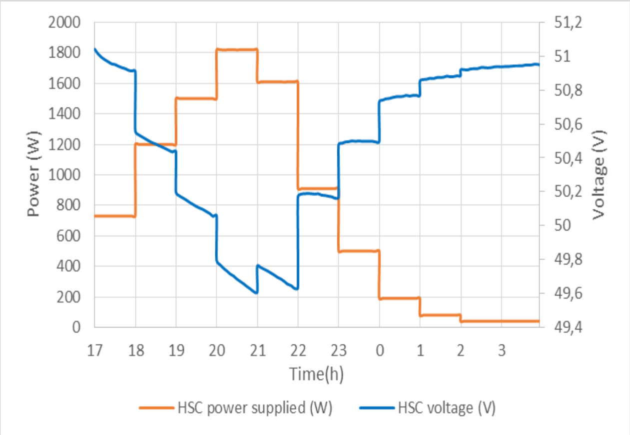

Figure 8. HSC Power-Voltage.

Once the characterization of the EV recharging application, based on HSC, has been carried out, the implementation of the system indicated in Figure 9 is proposed.

The EV battery is charged directly from the HSC system. Considering the previous HSC characterization and taking into account the duration and consumption of the usual routes in the area, this HSC would be suitable for recharging light electric vehicles with 48 V batteries.

Battery specifications, based on typical commercial models available from eNerlit SolarGreen, in the range of 40 Ah would have a maximum charge/discharge current of 40 A. Therefore, the HSC system is capable of charging one EV battery each time, having more than 55 Ah of capacity. Additionally, a current regulator ensure that the current provided by the HSCs never exceeds the maximum allowed by the batteries during recharging. For HSC supply, both photovoltaic generation and main grid are considered as sources. In this way, all possible operations are taken into account within the proposed work mode.

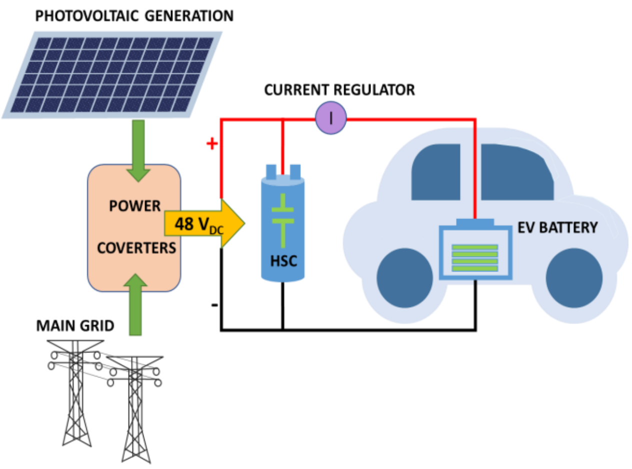

Figure 9. EV charging point with HSC system

To summarize, both HSC and battery characteristics are showed in Table II.

Table II. – System specifications

Parameter	HSC	EV Battery
Voltage (V)	48	48
Power (kW)	36	4
Current $_{MAX}$ (A)	750	40
Energy (kWh)	2.7	2
Capacity (Ah)	56.1	40

3. Conclusions

In this work an HSC system for fast EV recharging is presented. The designed system has been validated for its application according to the needs of commercial light electric vehicle recharging. Furthermore, the system provides a scalable design.

The following future works framed in this project will deal with its integration with the charging point based on the designed system, as well as the experimental validation of the scalable possibilities. Likewise, the energy management of the different sources that can contribute to the system, with its corresponding automatic control systems, will be analyzed.

Although hybrid supercapacitors are a promising ESS with higher specific energy than supercapacitors, maintaining a balanced specific power, providing faster refuelling of EV, currently the main disadvantage of hybrid supercapacitors is their high price along with the lack of experimental applied literature, to which this work contributes with the analysis of the technology, the design of a real application with great contributions to sustainability, as well as the validation and experimental characterization.

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