SUPERCAPACITORS IN PUBLIC TRANSPORTATION

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ABSTRACT

Supercapacitors (SCs) are currently disrupting the energy storage technology sector. They can be used in many applications because of their feature to cope with large current peaks for a short time, without significantly reducing energy performance and without altering their basic characteristics.

Electromobility may need huge peak power, implying a subordinate but not negligible problem: the energy storage. This problem cannot always be solved by electrochemical batteries and an alternative to them is represented by supercapacitors [1].

Nowadays, supercapacitors are used as a support to the electrochemical batteries in the hybrid systems, but they are increasingly used also as a real alternative to them in full electric systems.

In this White Paper, we will illustrate the main features of supercapacitors and their use in the public transportation sector, where the electromobility is spreading and SCs can involve advantages in terms of potential, energy efficiency, reduced consumption and economic savings [2].

SUPERCAPACITORS: AN OVERVIEW

A supercapacitor, called also "supercap" or "ultracapacitor", is a particular capacitor in which the capacitance can be of many orders of magnitude larger than a usual capacitor (from one to thousands of Farads versus μF or mF) thanks to materials with high specific area as electrodes and free ionic charges as counter-electrodes [3].

Within the supercapacitor family, we now look at a specific kind of supercapacitor, the so-called EDCL (Electric Double-Layer Capacitor), where the charging process is completely electrostatic (Fig. 1).

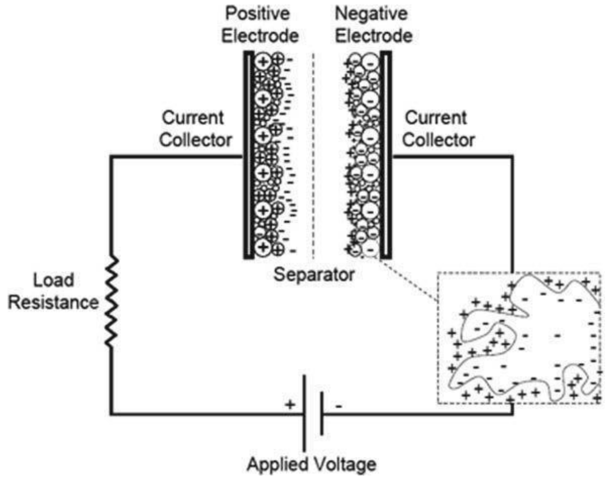

Fig. 1 Scheme of a SC (EDLC) in its simpler configuration in a circuit with only a constant applied voltage and a load resistance [4].

These kinds of SCs are composed of two current collectors on which are glued electrodes made of activated carbon powder. They are spaced by an insulating porous paper sheet and immersed in an electrolytic solution. By applying a voltage, ions of opposite sign accumulate in front of the electrodes, as shown in Figure 1. In short, a single SC cell is like two capacitors in series, physically separated by a porous paper sheet and electrically connected by ions floating in the electrolytic solution.

SCs are useful and mainly used for their outstanding specific power rather than for their specific energy. In other terms, they can be charged and discharged in a very short time (few tens of seconds). Moreover, a SC can withstand a deep discharge (a discharge of all the stored energy) unlike an electrochemical battery, so it has more efficient energy storage [5].

This is the main difference between a battery and a supercapacitor. In fact, a battery stores energy through chemical reactions implying mass transfer and limiting the specific power. Instead, a SC is purely electrostatic, just involving charge displacements that can be very fast, thus ensuring higher specific power. However, depending on the very high surface-to-weight ratio needed for the electrodes, it can store less specific energy than a battery. In conclusion, nowadays SCs cannot be proposed for applications that need large quantities of electric energy for storage, but they are the best possible device for high power applications and/or extremely fast recharge time, on the order of tens of seconds. Because of the same difference in technology, electrostatic vs electrochemical, SC cycle life (one million cycles) and time life (10 to 20 years) are much higher than respective values for batteries.

The researchers are trying to find a device that can be characterized by high specific power and high specific energy for a possible optimal performing device, but quite often the easier and more advantageous solution to a storage problem is using hybrid systems composed of both kinds of devices [6].

As said, the life cycle and time life of a SC are outstanding. Even when working at high power, they do not produce large amounts of waste heat, thus no pressure increase and no mechanical deformation of the device. Thus, their maintenance and replacement are less frequent than battery ones, involving less resource utilization, less pollution, and significant economic savings [7].

A SC can work in a wide temperature range (−40 to +60 °C) without any downturn in quality and lifetime. This range can be largely extended for specialty applications. As regards environmental aspects, the SC electrode materials, aluminum and carbon, they are abundant and safe and do not raise any disposal issues like battery materials do. Moreover, SC substitution is a rare event due to its long lifecycle, so we should consider reusing it after the application end-of-life, rather than recycling its materials. Unfortunately, the most common solvent used for the electrolyte, namely acetonitrile, is toxic and flammable [8]. For this reason, a large part of our research activity is focused on the design and synthesis of innovative polar aprotic and other sustainable solvents that aim to overcome safety and toxicity issues.

SUPERCAPACITORS IN PUBLIC TRANSPORTATION

Battery-powered electric vehicles have limitations such as low power density. Thus, charging and discharge cycles are limited (especially fast charges that reduce battery life), strongly depending on temperature and charging times are very long, compared to the service needs. Supercapacitors are immune to these limitations, because of their nature and technology. They can ensure many advantages if applied in public transportation, especially in terms of potential, energy efficiency, reduced consumption, and economic savings [9].

RAILWAY/TRAMWAY SYSTEM

In railway systems, supercapacitors may be a viable solution to improve commercial speed, reducing the grid stress, saving energy through regeneration, and providing emergency backup power when off-grid.

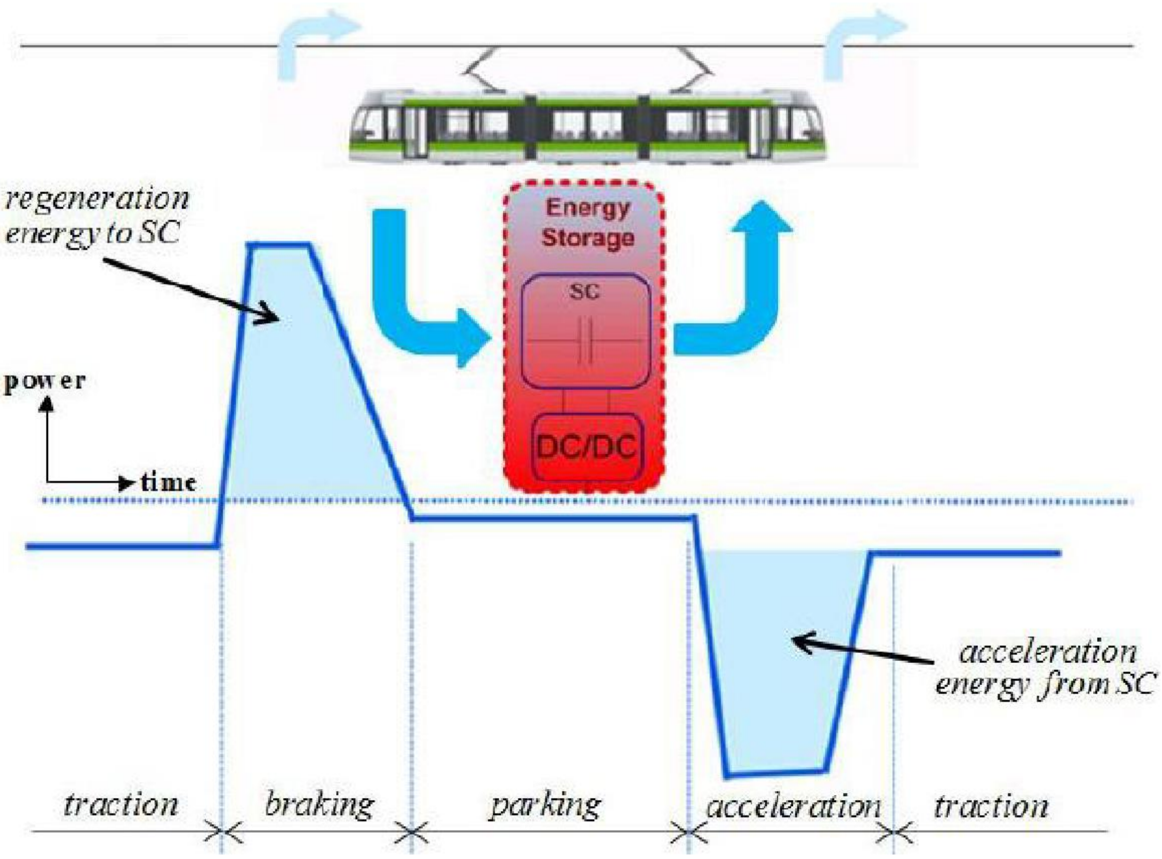

Fig. 2 Supercapacitor regenerative system [10]

When several trains are accelerated at the same time, the mains voltage is drastically reduced, worsening their performance; use of supercapacitors ensures that the voltage is sustained during the operation of starting the means, creating a stabilization phenomenon of the mains voltage.

The SC power modules produced by CapTop recover the energy otherwise wasted during train deceleration and provide high power during train start and acceleration, reducing electricity (or fuel) consumption, improving grid interaction and performance, and mainly reducing travelling time from one stop to the next. Thanks to its superior power density SCs can manage very high currents without taking damage when compared to electrochemical batteries.

It is possible to quote several examples of this application.

One of the greatest, in economic terms, is a $318 million tender, won by Meidensha/Sojitz, to provide 2 MW of SCs to the South Island Metro Line of Hong Kong. This installation should reduce by 10% the consumption along the 7.1 km, five-station route [11]. In Paris, tens of thousands of SCs were installed on Bluecars (electric cars) as an aid to traditional batteries [12].

In 2014, China started the initial testing of trams and electric trains, in which a hybrid system of traction, equipped with SCs, will allow the employment of the vehicle even in an emergency and to furthermore eliminate, for aesthetic reasons, the aerial power lines in sites of particular value or at intersections. Bombardier, a well-known manufacturer of buses with low environmental impact, seems to be considering the use of SCs for energy recovery during braking, and Riversimple intends to use them in assisting the fuel cells that power its vehicles [13].

It should be emphasized how the transition from hybrid systems without SCs to other mixed battery/SCs systems, and then to systems with only SCs, has taken place at an amazing speed. The following is yet another proof of the unexpected technological opportunities that this type of batteries can offer. MAN and CSR Zhuzhou Electric Locomotive [14] supply examples of "fully electric" vehicles using only SCs. The latter is testing the prototype of a light metro— therefore on rails—in which a "plug", located under the floor of the train, can connect SCs, fitted on the roof, to a "grip" on the ground. The refills take place during the stops, require only 30 s each and provide 2 km of autonomy, thanks to the recovery of braking energy [15].

The system proposed by CapTop interfaces the grid line (typically 600V DC for tramways) and manages to charge and discharge the supercapacitors in order to avoid fluctuations on the grid when the tramway starts/stops. It removes the acceleration limit, used to prevent voltage fall over the grid, and allows traveling faster to the next stop. Also, the system provides backup when the trolley is down, or the grid is not available.

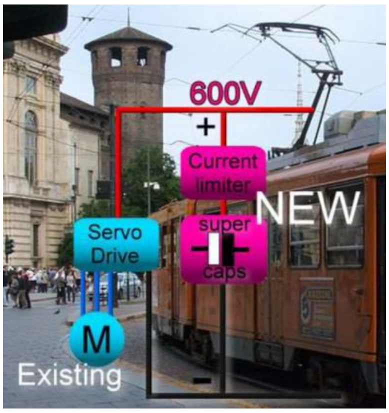

Fig. 3 CapTop - Scheme of Supercapacitor power backup and regenerative system – tramways

The system can work in a similar way for railways, according to the specific grid and train features.

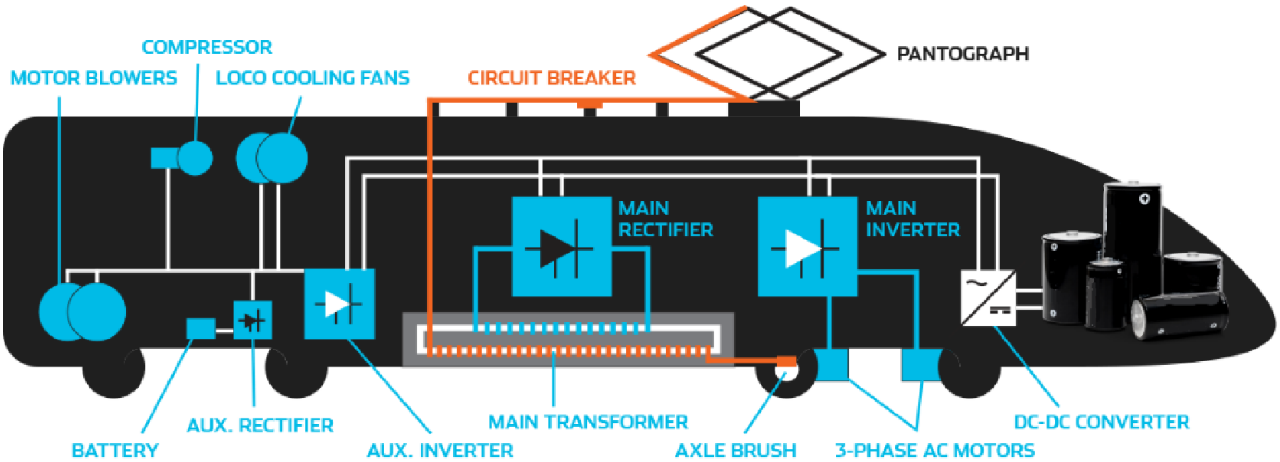

Fig. 4 Scheme of Supercapacitor auxiliary power and regenerative system – railways [16]

A further application may concern the leveling of loads in hybrid vehicles.

Hybrid drive systems are an intermediate stage in vehicle propulsion design between conventional petroleum-based fuels and pure electric drive.

Storage systems allow the combustion engine to work in optimal conditions in terms of efficiency. Moreover, they allow energy recovery during braking, and reduction of the power developed by the Diesel locomotive during the acceleration phases (we therefore speak of advantages in terms of both energy efficiency and braking with energy recovery). Please note that such systems may provide cold start auxiliary power for the locomotive engine. It turns out that, for regional trains, increasing the acceleration by 0.3 m/s^2, e.g from 0.8-1.1 to 1.1-1.4 m/s^2, the travel time between terminal stations will be significantly reduced, especially when there are several intermediate stations. Installing a SC section in hybrid trains, with electric/diesel engines, has proved to be the most viable and economic solution to reach such acceleration increment.

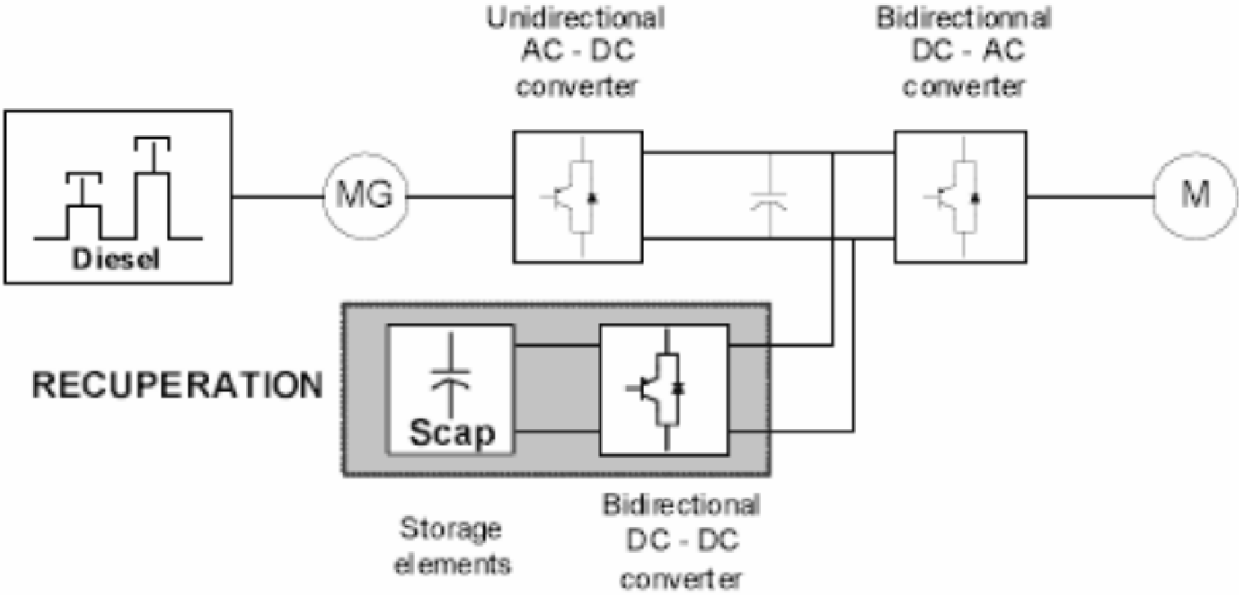

Fig. 5 Scheme of Supercapacitor auxiliary power and regenerative system – diesel locomotive [17]

HYDROGEN FUEL-CELL POWERED VEHICLES

Green urban mobility projects are looking at fuel-cell powered vehicles to achieve zero emissions. Fuel cells cannot recover energy during braking and have a steady power output, unsuitable for sustaining frequent change of power regime required in mobility applications and, therefore, require buffer storage to manage start and stop. Supercapacitors are the ideal buffer storage as they can provide frequent and deep power discharge without taking damage during accelerations and recover more than 70% energy when the vehicle stops. Electrochemical buffer storage has a shorter life due to deep discharge degradation and lesser energy recovery rate.

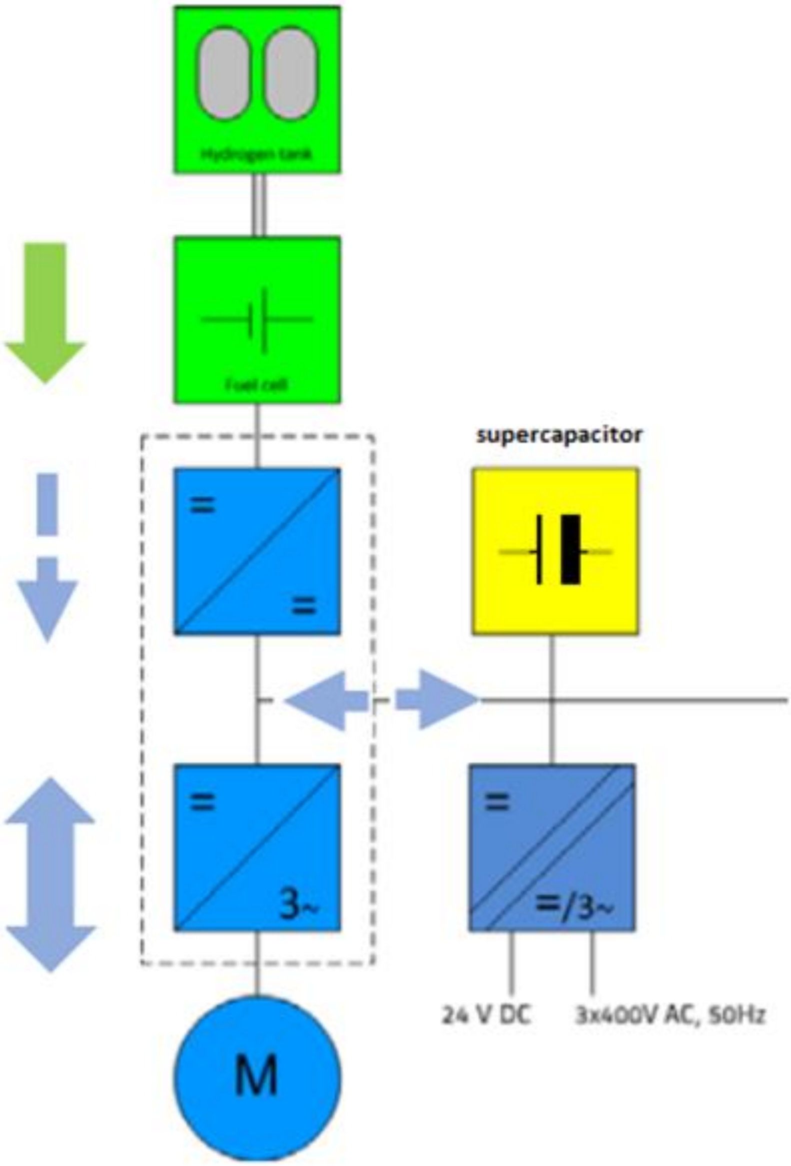

Fig. 6 CapTop design of Supercapacitor auxiliary power and regenerative system supporting fuel cell

FAST RECHARGING PURELY CAPACITIVE VEHICLES

Even more radical solutions, in which energy is accumulated only by SCs, can be used on city buses, because of their charging speed.

Actually, there are many situations in which vehicles do repetitive tasks, like city bus trips, airport shuttle, school bus, waste management truck and forklift in a port or in a factory. In all these cases, vehicles run for a short route and repetitively stop at the same places, where there is the opportunity to perform a fast recharge during such stops, provided the vehicle has a SC storage on board. The storage may be small and cheap because the task is short-lasting, as said. Although SCs can manage a greater power compared to batteries, still an issue similar to BEVs remains: not always there is enough grid power availability at the point of charge. This issue can be resolved by placing at each stop a stationary SC storage, responsible for the fast energy transfer to the vehicle, and then recharging it more slowly with the available grid power (and/or solar panels) [18].

CapTop is developing an ultra-fast recharge for purely capacitive vehicles (electric vehicles without batteries) that exploits the International Patent WO2008020463A2 of which the Italian inventor M. Ippolito is the proponent.

The patented technology was exploited by the Italian company Sequoia Automation in the frame of the EU project K-VEC [19]. A fast-charging conductive system recharges the on-vehicle SCs from a ground station SC storage in less than a minute during the vehicle stops, practically unaffecting the regular operativity. The modality of passenger transport and of loading/unloading times remains almost unchanged. The system comprising the ground storage and the vehicle is called K-Bus [20].

The bus is equipped with a SC storage of proper size, depending on the largest distance between two charging points, it may have an auxiliary battery of small capacity and limited power as a range extender for emergency cases (such as charging point off-service, route change) or simply return to depot. The powertrain is a plain bidirectional servo driving the bus AC motors. During the bus trip, SCs provide power to the motor when accelerating and performing power regeneration when braking. A power switch manages the high power during the fast recharge phase at bus stops.

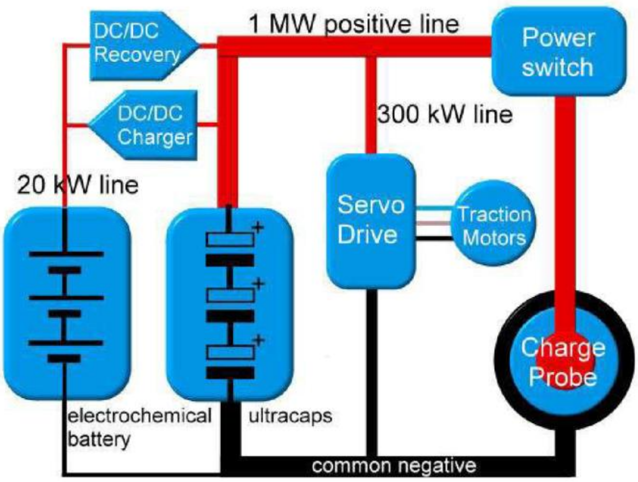

Fig. 7 K-Bus onboard bus diagram [21]

The key point of the system is the set of SCs to the ground, an "energy reservoir" that can supply, within dozens of seconds, energy at a power rate unmanageable for the normal electrical network. Then, the latter recharges the ground based SCs at a lower power, during the much longer time that elapses between the passage of one bus and the next. This technology avoids the need for expensive and complex cabling [22].

The Ground Station is built by:

- A ground cabinet containing Supercapacitors, a control system, an optional auxiliary generator.
- A conductive device for transferring energy to a similar device present on the vehicle.

Several implementations of such conductive connection may be designed: trolley, manual/automated plug-in of power cable or conductive carpet, trolleys are well known and proven but may add undesired loads on the bus top, automated plug-in may raise safety issues, therefore we describe here a patented solution of conductive carpet based solution.

The conductive mat allows contact of the vehicle for charging through a retractable plate positioned under the vehicle. As soon as the vehicle stops and the plate descends contacting the carpet, the control unit must scan the hexagons of the carpet to establish the positioning of the plate and consequently which hexagons are involved in the charging process (fig.8).

Subsequently, from these hexagons, activated by means of an appropriate power switch, the electric charge passes to start the recharging process, if necessary. Another circuit (inverter based current generator) works as a "power limiter" and allows the gradual recharging of the supercapacitors (step up).

Ground supercapacitors are recharged by the grid through a power converter. Optionally, an auxiliary generator such as an uninterruptible power supply or a solar panel with a DC/DC converter is provided so that the recharging of the storage can be performed through the connection to the grid and / or from a photovoltaic system.

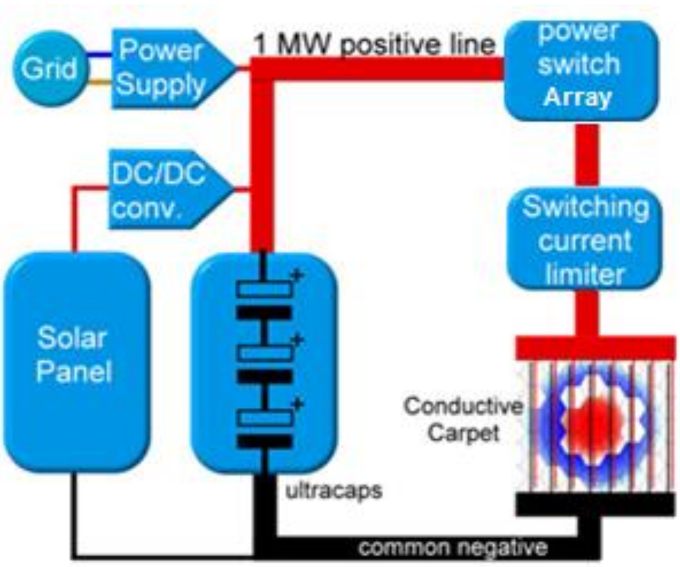

Fig. 8 K-Bus ground station diagram [23]

As said, during the recharging phase, contact between the ground SCs and those on-board the vehicle is assured by two cooperating systems:

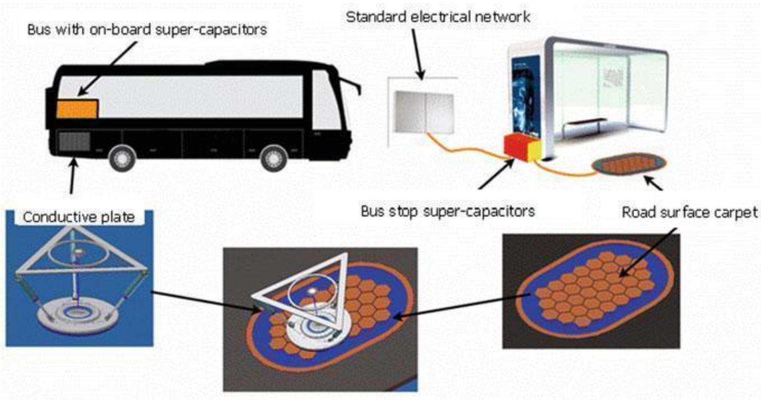

Fig. 9 K-Bus fast-charging system operating diagram [24]

- under the chassis of the vehicle, through an electromechanical arm that holds a conductive plate, equipped with a thick cluster of metal pins;
- on the road surface, through a "carpet" of metallic hexagons, each one electrically isolated from the others, but each one connected to the electrical and electronic charging system and made from a material that ensures long-lasting resistance to deterioration, which do not pose limits, or constitute danger, to the mobility of vehicles or pedestrians. The arm can drop or rise in a few seconds and can adapt to any change in the vehicle balance, letting the plate to optimally descend and settle on the "carpet" and maintain stable electrical contact during the entire charging phase [25] (Fig. 8).

Plate and carpet ensure the electrical connection between the SCs installed on the vehicle and those on the ground station, allowing to recharge the former in a very short time. The power flow is very high indeed—hence a recharge time similar to that required for normal passenger loading and unloading—but is risk free for people or things thanks to the architecture planned for the coupling of plate and carpet and to the electronic assistance. The dimensions of the carpet, in addition, facilitate the placement of the charging device, since they allow margins of error of tens of centimeters, which is much greater than those required, for example, by inductive charging systems [26].

Key safety feature during the charging phase complies with the following procedure:

- A Wi-fi signal allows the vehicle's electronic system to perceive the approach to a charging point and starts the descent of the supply arm.
- The plate, which is also equipped with a brush to clean the carpet from any possible debris, is pressed against the carpet to ensure an optimal electrical contact.
- The pins on the plate are distributed on concentric circumferences: the inner ones are the positive pole, while the outer ones, "protective", are the ground.
- Contact between each pin and the hexagonal metal of the carpet is checked by an electronic device capable of identifying the socket and bus code number, the exact position of the vehicle with respect to the carpet, the number of

pins in touch with every single hexagon and the absence of "bridges" or conductive contact interruptions due to external causes.

- Only after verifying that there are no obstacles to a safe energy transfer, the electronic system supplies power only to the hexagons in contact with the positive pole pins, and the charging phase takes place [27] (Fig. 9).

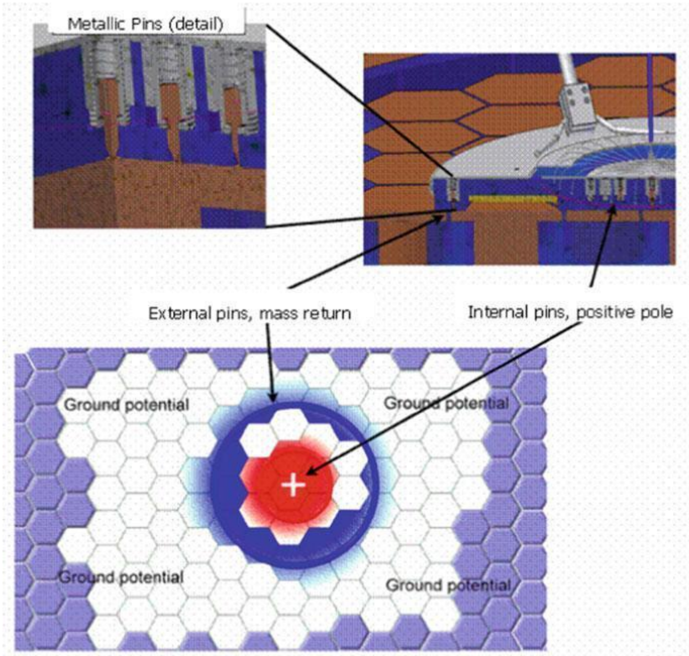

Fig. 10 Construction details of the conductive plate in the vehicle and its power supply [28].

If an unforeseen event should hinder the recharge of the K-Bus at a certain station, each vehicle is equipped with a limited sized electrochemical battery. This auxiliary battery will provide enough autonomy to allow the vehicle to safely cover at least twice the maximum distance between two stations. This zero-emission solution therefore allows to have a limited battery weight on board the vehicle, without limiting the range of action, thus decreasing the operating costs (see Fig. 6). Furthermore, it makes the vehicle perfectly functional in urban traffic, without having the restrictions other public means of transport have, such as trolleybus or tramways, and with the same use flexibility offered by road vehicles. The charging stations would also have limited initial investment and management costs, when compared, for example, to a system of overhead power lines, which also involves a remarkably unpleasing aesthetic impact. In addition, to limit the overall energy usage, the recovery of kinetic energy is fully exploited during braking and while proceeding downhill on routes with marked differences in altitude. A cost analysis and economical evaluation of the K-Bus technology was made through a comparison of real data, obtained by the GTT Star 1 urban electric bus line circulating in Turin (Italy), with the simulated ones of a hypothetical similar line, equipped with K-Bus vehicles. The real Star 1 line is served by electric battery powered buses, which cover a distance of nearly 12 km and that undergo partial recharges at the terminal stations and a total recharge during night [29].

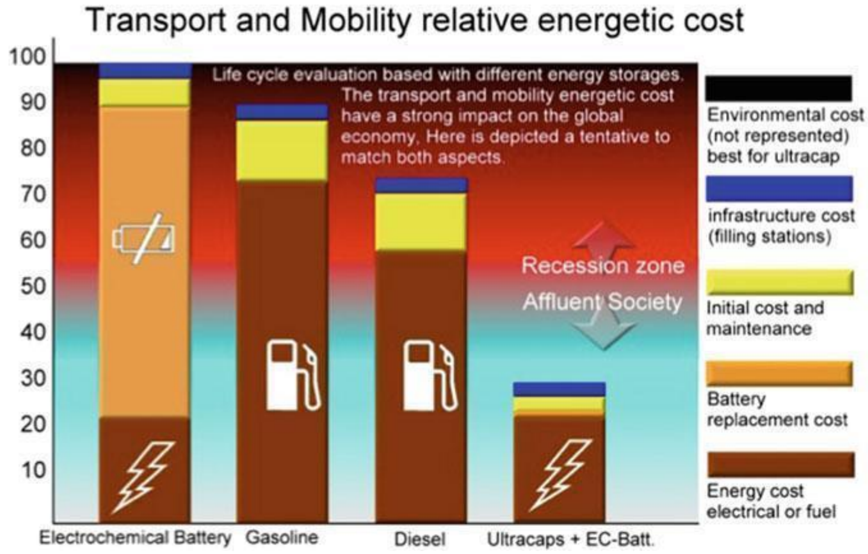

Fig. 11 Comparison of operating costs between various alternative power systems for urban buses [30]

The resulting data showed that if the present system were replaced with the innovative K-Bus, the initial investment costs would be almost halved. Moreover, the overall operating costs after 12 years (including maintenance and material substitution costs) would amount to less than half of the costs required by the present system, where a major cost comes from the need for frequent battery replacement. In a similar way, in the context of urban public transport, an electric K-Bus vehicle, even with an operational autonomy limited to a few kilometers, could replace an internal combustion engine vehicle thanks to the patented fast charge technology. This system, in fact, does not limit in any way the vehicle operation or the public comfort and safety, but rather would provide a big advantage in terms of environmental care and, in the medium term, even in economic terms. The fast charge K-Bus technology could be extended to other areas of the same type, i.e. services for which a number of vehicles perform fixed routes with stop points at short distances, such as garbage collection, mail delivery, industrial or airport logistics. Nor can one rule out, at least in principle, the possibility that multiple services, independent of each other, recharge their SC-based electric vehicles through a single network of appropriately distributed K-Bus-type "carpets" [31].

NOTES

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