Printed Super-Capatteries for Smart Energy Storage Systems

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***Abstract*—Advances in roll-to-roll printing and in functional inks have made it possible to integrate printed super-capacitors and printed Li-ion batteries in one substrate, at a low cost, and high manufacturing throughput. Combined with smart power management circuitry, this new super-capattery device can offer the advantages of both underlying energy storage systems: high power-density and high energy-density. The power management circuitry has to maximize the super-capattery performance regarding charging speed, versatility, life time, and security. To cover a wide range of applications we propose different combinations of super-capacitor cells, Li-ion battery cells, and power management. As a result we can cover application profiles that fit active long-term low-power devices like active RFID-tags, NFC-tags, autonomous sensor nodes, other battery powered mobile devices like localization devices, but also high-power short-term profiles like remote controlled vehicles and robotics.**

***Index Terms*—energy storage, printed super capacitor, printed lithium-ion battery, super capattery**

I. Introduction

Electric energy storage system should securely store as much energy as possible at a low cost, small volume, long lifetime, and light weight. Simultaneously, they should usually be able to deliver a constant output voltage and high power, independent of their load conditions. On top of that, a convenient voltage level that is compatible with the used consumer is much preferred over the need to have voltage conversion in a device. However, the range of consumers is very wide and the voltage requirements can be very different. Further, quick recharge times are also important. In summary, the requirements posed to energy storage systems are manifold and their individual realizations are contradictory in nature.

Important parameters to describe the characteristics of an energy storage are its specific energy (energy-to-weight ration, EWR) or energy density, usually given in Wh/kg or Wh/l, respectively. Equally important are the parameters specific power (power-to-weight ratio, PWR) or power density, which describe how much power a storage can absorb and deliver, usually given in Wh/kg or Wh/l, respectively. The ratio of of specific energy to specific power is what is known as the characteristic time t_{C} of an energy storage.

$$t_{\mathrm{C}} = {}^{\mathrm{EWR}}/_{\mathrm{PWR}} \tag{1}$$

It roughly determines how long it takes to fully charge an energy storage (lower is better) and how long it can deliver its maximum power before being depleted. In reality, depending on the power profile, either the charging or discharging process will be faster than the other. The three described parameters are shown in Fig. 1 in the so-call Ragone plot for the most relevant electric energy storages.

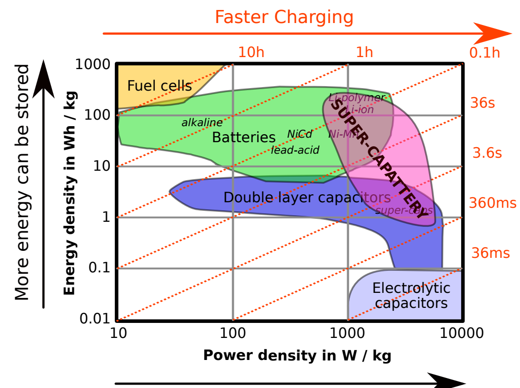


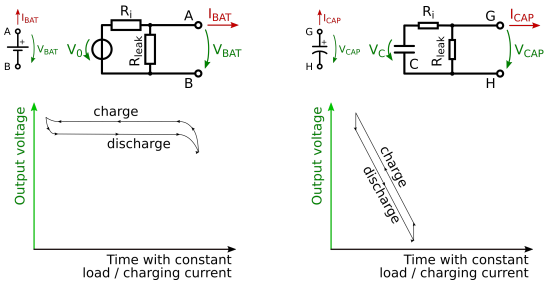
Fig. 1. Ragone plot classifying and comparing super-capatteries to the most relevant electric energy storage technologies. The diagonal lines mark the characteristic time of the technologies (based on data from [1]).

In this work, we focus on super-capatteries, a new combination of super-capacitors and Li-ion batteries that can cover an area in the Ragone plot, where no monolithic energy-storage type can currently operate. Only by combining the benefits of the two individual technologies super-capacitors and Li-ion batteries in a heterogeneous systems can this area be covered. Figure 2 and Tab. I show and compare the main characteristics of both super-capacitors and Li-ion batteries. Their cost-efficient and compact integration has recently become possible by the advances of roll-to-roll printing, active inks for Li-ion batteries, as well as active inks for super-capacitors [2]–[6]. Since it is a degree of freedom in what ratio to combine the two underlying technologies, there is a large spectrum of power density and energy density combination that can be covered, which is illustrated by the large size of the pink super-capattery area in Fig. 1. This freedom allows us to address a wide range of requirements and cover the needs of a wide variety of consumers.

Among the targeted consumers are active RFID- and NFC-tags as well as battery powered small mobile sensor nodes. These can benefit for example from a ultra-fast charging time combined with very long energy retention, because the high-power density of the super-capacitors is combined with the very high energy density and low leakage of rechargeable Li-ion batteries. Another scenario that can be covered is energy harvesting in mobile devices [7]. The presented solution can provide low leakage during the harvesting and storage phase, but can also, on-demand, provide high power, for example during short bursts of activity of a mobile wireless sensor node.

The durability of Lithium-ion (Li-ion) batteries is very sensitive to under voltage, over voltage, as well as too high

 The DOI of the final version is 10.34712/142.51 .



(a) (b)

Fig. 2. Comparison of the charging and discharing curve of (a) Li-ion batteries and (b) super-capacitors. At the top the respective basic equivalent circuit is shown.

TABLE I
COMPARISON LI-ION BATTERY AND SUPER-CAPACITOR CHARACTERISTICS.

Characteristic	Li-ion Batteries	Super-Capacitors
Voltage	typically 3.7 V, stable during discharge	V_{break} ~ 4.0 V, drops during discharge
Output impedance, R_i	higher	lower → can drive larger output current → can deliver larger output power
Specific power	lower (1.8 kW/kg)	higher (1-10 kW/kg)
Specific energy	higher (100 Wh/kg)	lower (1-10 Wh/kg)
Charging efficiency*	85 %	95 %
	*ratio of energy consumed by charging process and stored energy	
Leakage, I_{leak} = V / R_{leak}	lower loses 5 % of charge per month	higher loses 50 % of charge per month
Lifetime	2'000 cycles sensitive to deep discharge, overcharge, reverse polarity, and over temperature	100'000 cycles sensitive to over voltage, reverse polarity, and over temperature
Polarity	has polarity	has polarity

and too low temperatures. Exceeding permissible limits, for example by deep discharge, over charge, or a heavy continuous power drain, significantly reduces cell lifetime. Therefore it is necessary to have current limiters, temperature control, and voltage balancers directly integrated into the battery package, which we also investigate in this work.

II. APPLICATION PROFILES

As already indicated above, the requirements for an energy storage system depend heavily on the application and its profile. The core specifications of such an application profile are usually: 1) cost requirements 2) trade-off between energy density and power density 3) peak power and internal resistance 4) charging time 5) electric capacity 6) volume and/or weight.

Consider a wireless environmental sensor node with integrated localization. Such a battery powered device will be dormant most of the time. As a measurement of, for example, air quality commences, the node has to wake up and conduct several operations including: determine the air measurement and store the measurement datum. After a certain number of cycles the node also has to determine its position and establish a wireless link to a base station, via which it will transmit previously accumulated measurement data. The wireless transmission as well as the operation of the micro-controller require bursts of energy, while the rest of the time, almost no energy is consumed from the battery. Representative active currents for wireless front-ends operating at 3.3 V are 4.5 mA / 9.3 mA / 2.9 mA for Bluetooth Low Energy (BLE) / ZigBee / ANT, while the sleep currents are as low as 0.78 µA / 4.18 µA / 3.1 µA [8]. Depending on the duty cycle of the sensor node, the average currents can be well down in the tens of µA-range. A low-power micro-controller at 3 V consumes around 1 mA when active and drops to around 1 µA during sleep. The active currents of sensors can have a very wide range. For example, temperature and humidity sensing do not require much energy per measurement; localization usually consumes a relatively large amount of energy, because an active RF-front-end is required.

We also consider other applications profiles. On example are battery powered agile vehicles, which require the maximization of energy-density and power-density.

III. SUPER-CAPATTERY DESIGN & POWER MANAGEMENT

A. High power-density focused

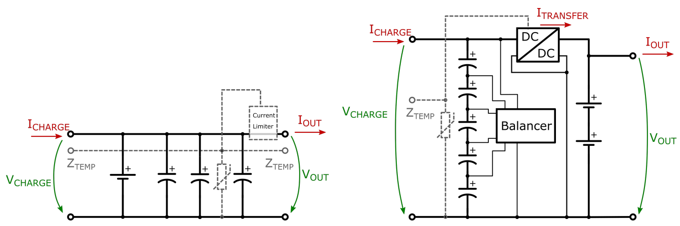
Application examples that requires a high momentary power are for example photoflash lamps, flashing warning lights, robotics, and many other applications that involve mechanical actuators that are only rarely activated. Figure 3a shows the super-capattery design that will be optimized for this application profile. It contains a relatively large amount of super-caps and as little integrated electronics as possible. It is the cheapest and simplest proposed super-capattery, does however lack over- and under-volt protection.

B. High energy-density focused and safely stackable

Application examples that require a high energy density and high power density are different kinds of autonomous agile vehicles and robotics. The stackability provides the voltages required for motors. A light weight and high energy density enables a large range of the vehicles. Figure 4 shows a versatile stackable super-capattery that achieves a high energy density. An active or passive balancer is needed (at least during charging) to prevent reverse polarities across the super-capacitor and battery cells. Figure 4 shows two designs for different charging methods. In Fig. 4a all cells can be charged in series, which requires a balancer circuit that is integrated in the cells to prevent reversed polarities across cells. As shown in Fig. 4b the cells can alternatively be charged individually. The benefit of charging individually is that the balancer does not need to be integrated in the cell, but can be part of the external charger, which would benefit the energy density of the super-capattery.

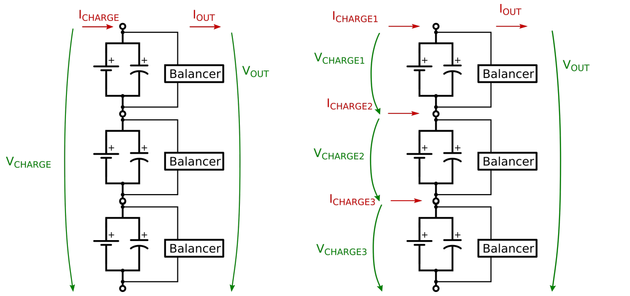
C. Ultra-fast chargeability

To achieve ultra-fast charging a super-capattery with a large amount of super-capacitors as shown in Fig. 3b can be used.



(a) (b)

Fig. 3. Schematic of (a) high-power focused and (b) ultra-fast chargeable super-capattery.



(a) (b)

Fig. 4. Schematic of high-energy focused super-capattery. (a) Charging cells in series. (b) Charging cells individually.

The ultra-fast charging super-capattery operates in four modes. Ultra-fast charging is done by quickly charging the series of super-capacitor to a large voltage. The charging voltage can also be applied for a long period, which will give the batteries sufficient time to charge via the current $I_{TRANSFER}$. The charge is subsequently transferred to the batteries via a highly efficient, inductor less DC-DC-converter. As a result, in the long term, the energy is stored in the lower leakage battery cells. As soon as the voltage across the super-capacitors drops to the level of the battery, the DC-DC-converter is disabled. Power is now primarily supplied to a consumer from the energy stored in the battery cells. If the consumer temporarily requires high power the series of super-capacitors can directly buffer this demand. In this configuration, a passive or active balancer is necessary to ensure the lifetime of the super-capattery. Otherwise asymmetries of the super-capacitor capacities may lead to a reversing of the polarities across individual cells, which affects their lifetimes. Depending on the integration density, temperature sensor may also be necessary for the lifetime of the super-capattery, because of the high current flows during the very fast charging process. The required DC-DC-converters have an efficiency of around 90 % and a footprint of only 3 mm × 4 mm. This configuration effectively trades off super-capattery energy density and power density for a ultra-fast charging speed.

IV. Conclusion

Advanced printing technology and functional inks have enabled the direct integration of printed super-capacitors and printed Li-ion batteries on the same substrate. In this project SuperBat, first samples of super-caps have successfully been printed with a capacity of 100 mF at a dimension of 40 mm × 45 mm × 0.5 mm and a weight of only 1.44 g. They have the advantage of being much lighter and smaller compared to a current commercial super-cap that weighs in at 5.0 g and roughly has a diameter of 16 mm and a height of 11 mm. The printed super-cap has an ESR as low as around 5 Ω, i.e. this sample, when shorted delivers up to 200 mA after having been charged to 1 V. In this project also first Li-ion battery samples of similar dimensions and a capacity of around 100 mAh and 3 V have been printed. As a next step, both devices will be integrated on a flexible substrate in a high-volume low-cost roll-to-roll printing process, which will allow cheaper manufacturing compared to current super-caps and Li-ion batteries. Having both devices tightly integrated in one package together with smart power management, the new device becomes a super-capattery that can provide the advantages of both underlying energy storage systems. We showed how the super-capattery can be tailored to the needs of different application profiles including localization applications and can provide at the same time an higher power-density, higher energy-density, and lower cost compared to other electric energy storages.

Acknowledgment

This work was supported in part by AiF/IGF project SuperBat (331EBR/2). We would like to thank the Institute for Print and Media Technology at the University of Technology Chemnitz, Germany as well as the Institute of Metallurgical and Materials Engineering at Sakarya University, Turky for the discussions about printing technologies and functional ink technologies. We want to thank the BMBF (Federal Ministry of Education and Research of Germany) program 6G-life and the DFG cluster of excellence CeTI for discussions regarding the potentials of advanced DC supplies for information and communication technologies. We would like to thank Metirionic GmbH, Dresden, Germany for the collaboration on use cases and application profiles in this work.

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