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An overview of ultracapacitors applicability in high power applications

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Abstract. Ultracapacitors are entering into applications dominated by batteries. The complementary features of ultracapacitors and batteries may allow in certain applications to combine them enhancing the performance of the overall energy storage system. In other applications, the advantages of ultracapacitors may allow to completely displaced batteries avoiding some of its drawbacks. Determined key issues and weaknesses of ultracapacitors are being intensively researched, leading to a greater applicability of ultracapacitors.

Key words

Ultracapacitor, supercapacitor, battery, energy storage, high power applications

1. Introduction

Ultracapacitors (also known as supercapacitors) have taken off in recent years in high power applications [1],[2]. The evolution of the technology of ultracapacitors has placed them in good position in the field of energy storage technologies [3].

In applications in which batteries used to dominate the market, developments combining ultracapacitors or even based only on ultracapacitors are being implemented due to their advantages [4].

This article aims to give an overview of the applicability of ultracapacitors in high power applications and the research which may improve it. In section 2, intern structure of ultracapacitors is described. In section 3, a comparison of features of ultracapacitors and batteries is presented. In section 4, high power applications representing a clear relevant nest for ultracapacitors are presented. In section 5, the research needed to increase ultracapacitors application opportunities is presented. Finally, conclusions are presented in section 6.

2. EDLC and AEDLC

Ultracapacitors are divided into two different types: symmetric (EDLC) and asymmetric (AEDLC). The first and most common type consist of two porous activated carbon electrodes on current collectors and separated by an insulating dielectric separator. The electrodes are immersed in an electrolyte composed of ions (positive and negative) dissolved in a solvent (Fig. 1). A difference of potential between the current collectors attracts the opposite-charged ions to the carbon electrodes, achieving energy storage by an electric field, in contrast to the batteries in which a chemical reaction is generated. A high capacitance results from the very large area of the electrodes and its extreme closeness.

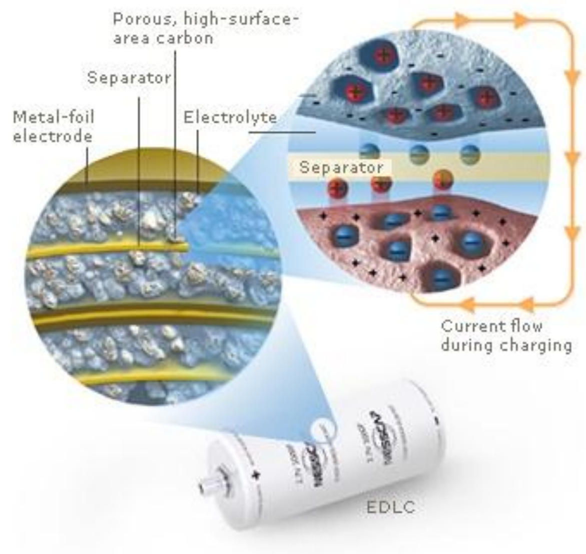

Fig. 1. Internal structure of an ultracapacitor [5]

In an asymmetric ultracapacitors one of the electrodes has been replaced by, for example, a battery type electrode. This change provides a mixture of features of ultracapacitors and batteries, increasing energy density compared to a symmetric ultracapacitor and narrowing the voltage variation. However, it also increases charge/discharge times and shortens cycle life. Asymmetric ultracapacitors would be suitable for applications without heavy-duty cycling, such as UPS or power backup.

3. Ultracapacitors vs. batteries

Points of comparison between batteries and ultracapacitors are shown in table I.

Table I. – Features of ultracapacitors and batteries comparison

Ultracapacitor	Battery
Low energy density	High energy density
Very high power	Medium power
Very long cycle life	Short cycle life
Voltage depends on the state of charge	Voltage relatively constant
Sized to fit power profile	Sized to fit energy profile
High efficiency	Medium efficiency
Performance decreases smoothly	Performance decreases sharply
Quick charges/discharges	Slow charges/medium discharges
Good performance at very low temperatures	Bad performance at very low temperatures

The capacitance of an ultracapacitor changes with temperature variation, during charge/discharge and during the cycle life [6]. This affects directly to its energy density and consequently to its voltage, hindering partly its control. The energy density of a battery also changes with some parameters, but its chemical behavior keeps relatively constant its voltage.

Considering energy and power density, batteries and ultracapacitors are complementary (Fig. 2).

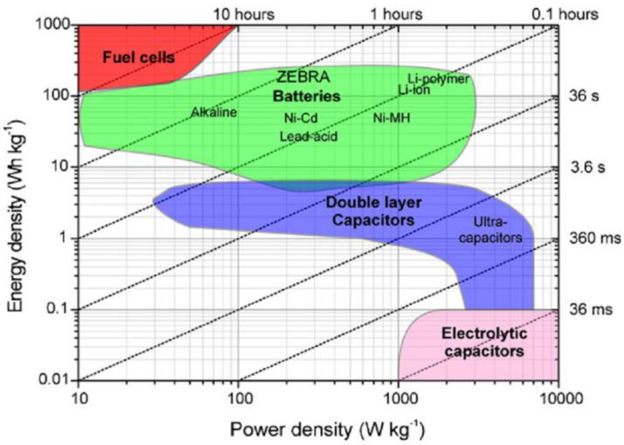

Fig. 2. Ragone diagram [7]

4. High power applications

However, in many applications, ultracapacitors are in direct competition with batteries. Those in which the energy density needed is relatively low, ultracapacitors (EDLC and AEDLC) compete with lead-acid and nickel-metal hydride batteries, due to the medium energy density of these technologies. Those in which the energy density represents the main goal lithium-ion batteries are the best solution. But in those applications in which a high power (or other ultracapacitors remarkable features such as long cycle life) is critical, ultracapacitors has no competitors [8].

Applications requiring relatively large capacitances and representing a clear relevant nest for ultracapacitors are listed below.

1) *Hybrid & pure electric on-road vehicles.* Batteries could be completely replaced in electric buses (where a quick charge could be made in every stop), or can be combine with ultracapacitors avoiding oversizing the batteries [9],[10]. In addition, ultracapacitors facilitate energy harvesting during braking [11].
2) *Railways.* As in electric buses, in light trains ultracapacitors could be combined with batteries [12],[13] or replace them and could be charged in the stations. A 27 second charge may allow reaching a 2 km distance [14].
3) *Wind turbines.* Replace big batteries banks by ultracapacitors acting in drops of electrical grid [15]. Ultracapacitors react quicker and more reliably [16].
4) *Grid storage and grid power factor correction and frequency control.* As in wind turbines, the quick reaction and instantaneous power of an ultracapacitors bank could give the necessary energy to control diversions of the main parameters of electrical grid [17],[18].
5) *UPS.* Short start up times is required to compensate the main source fall. Ultracapacitors are suitable since can bridge power developing a high current very quickly [19],[20].
6) *Heavy pulse power.* Ultracapacitors can work in parallel with batteries smoothing the peak currents and extending the battery life [21],[22].

In order for ultracapacitors to provide the benefits shown above, a restriction must be addressed. In high power applications, DC link of power electronics converters is the common point for the connection of ultracapacitors [23]. DC links usually operate at high voltages. Considering that, voltage ratio of ultracapacitors cells represents a clear restriction due to two basic reasons. On the one hand, their rated voltage is extremely low, ranging from 1 V to 2,8 V depending on the electrolyte technology [24]. And on the other hand, their voltage depends on the state of charge, usually ranging from 50% to 100% of the rated voltage [23]. Thereby, a series connection of ultracapacitors is necessary to reach workable voltages. However, this connection brings the problem of the non-uniformity of some parameters of ultracapacitors, mainly the capacitance. A different state of charge, derived from a different capacitance, will end in a drop in performance and lifespan.

Table II. – Ultracapacitor modules parameters

Capacitance (F)	Rated voltage (V)	Max. current (A)	Leakage current (mA)	ESR DC (mΩ)	Max. power (W/kg)	Energy density (Wh/kg)	Mass (kg)	Temp. (ºC)	Voltage balance type	Manufacturer
500	16	2000	5,2 170	2,1	5500	3,2	5,51	-40 to +65	Active Passive	Maxwell [25]
165	48	1900	5,2	6,3	6800	3,9	13,5	-40 to +65	Active	
130	56	1800	120	8,1	5400	3,1	18	-40 to +65	Passive	
94	75	1600	50	13	4300	2,9	25	-40 to +65	Passive	
63	125	1800	10	18	3600	2,3	60,5	-40 to +65	Active	
500	16	2020	5,2	1,9	5614	3,03	6	-40 to +65	Active	Nesscap [5]
166	48	2030	5,2	5,6	6857	3,63	15	-40 to +65	Active	
125	64	2030	5,2	7,5	7186	3,83	19	-40 to +65	Active	
93	86	2030	5,2	7,5	9482	3,7	26	-40 to +65	Active	
62	125	1850	5,2	15	4569	2,36	57	-40 to +65	Active	

Table III. – Battery modules parameters

Capacity (Ah)	Voltage (V)	Max. discharge current (A)	Internal resist. (mΩ)	Energy density (Wh/kg)	Mass (kg)	Temp. (ºC)	Technology	Lifetime at 100% DOD (cycles)	Manufacturer
45	48	50	-	115	19	-20 to +60	Li-Ion	8000	Saft [26]
45	38,4	90	25	91	19,6	0 to +45	LiFeMgPO4	2800	Valence [27]

Some voltage balancing strategies have been proposed in the literature to overcome this problem [28]-[29]. More common solutions are voltage balancing circuits, going from a resistance in parallel with each cell (passive balancing) to those including semiconductors (active balancing) [30]-[31], that is, going from circuits with high losses to those offering the possibility of individual control of each cell of the ultracapacitors stack. Leakage current values shown in table II represent a good evidence of the losses of passive balancing.

Many are the manufacturers offering a wide range of ultracapacitors for relatively low power applications, such as Panasonic and Nichicon. By contrast, few are the ones able to offer a well-tested range of modules of ultracapacitors. Nesscap and Maxwell are two of those manufacturers, and the parameters of a sample of their modules are shown in table II. The parameters of two battery modules are presented for comparison in table III.

5. Improves being research

In order to increase ultracapacitors application opportunities some features must be improved. Some of them are described below.

1) *Increase of energy density (per weight unit)* [19] *and decrease of prices* [20]. This is the most important research being carried out. Batteries are far ahead with energy densities 10 times higher, a partial improvement may allow ultracapacitors to replace more batteries in applications in which ultracapacitors are now used only for protecting batteries from power peaks. Less batteries means avoiding their disadvantages, e.g. system reliability and performance would be increased [32].
2) *Longer life guarantees.* Ultracapacitors have a lifetime of more than a million of cycles, namely, far greater than that of batteries. However during its lifetime, changes in their parameters occur. That is the reason why, although ultracapacitors might reach 20 years of lifetime [33], commercial guarantees rarely reach ten years. Methods to increase ultracapacitors lifetime are being develop [34], such that guarantees may extend leaning on them.
3) *Increase operation frequency.* Internal charge redistribution takes place inside an ultracapacitor. That phenomenon, along the inductive effect appearing at high frequencies, represents a constraint on ultracapacitors performance in pulse power applications. As that constraint is intrinsic to its manufacturing, research has focused on modelling [23].
4) *Non-toxic, inflammable, environmentally friendly materials.* Some electrolytes used in ultracapacitors are toxic and flammable, such as acetonitrile. Moreover, in high volume on-board applications, non-toxic non-flammable materials are desired for improving safety. Although there are non-toxic alternatives [35], there is still a wide field to research so that they catch up the whole performance of the toxic ones.
5) *Reduce leakage.* Although it is already low, it would improve applicability in medium time energy storage. Active balancing substantially avoids increasing it, but it can’t compete in long time energy storage with the 5% of discharge per month of a battery.

6) *Reduce capacitance drop.* Capacitance in ultracapacitors is reduced during discharge and during cycle life [6]. Improving this fact would ease the application of ultracapacitors where it's difficult to replace them, such as in ultracapacitors banks near wind turbines.

Increasing energy density (desirable to compete in volume/weight), reducing prices (desirable to compete economically) and increasing life cycle (desirable to compete in durability and reduce of maintenance) are the three key issues more interesting to be reached.

6. Conclusion

Although ultracapacitors aren't extended as a standard in many applications (usually because of their price), their use should be justified because of the energy savings achieve and also due to the longer cycle and the mistreatment resistance that characterize the ultracapacitors in comparison with batteries.

Taking into account the research being carried out to overcome ultracapacitors weaknesses, the nest of application in which they can be applied and can replace other technologies such as batteries will increase considerably.

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