Lithium Ion Capacitor – Review of Applications and Advantages

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Abstract **- In the last few years, lithium-ion capacitors received special attention due to their favorable performance characteristics in terms of power, safety and cycle life compared to the lithium-ion battery technology and higher energy density compared to the electrical double-layer capacitor technology. In particular the combination of higher energy and power densities make this technology very attractive for most of the traction applications where high peak powers are required. The main advantage of lithium-ion capacitors is the higher energy density and the higher nominal voltage compared to electrical double-layer capacitors. This makes that less cells will be needed in series and less stacks in parallel in order to achieve the needed capacity and voltage of the energy storage system, allowing to reduce the mass and the volume of the system. However, the implementation of this technology until now was quite limited compared to electrical double-layer capacitors. In this paper, the operating principles and specific characteristics of lithium-ion capacitors are highlighted and an overview is provided of the applications in which this technology is already implemented.**

I. INTRODUCTION

Lithium-ion Capacitors (LICs) are an innovative type of energy storage components that belongs to the class of hybrid electrochemical capacitors. LICs combine the high power capability and long lifetime of Electrical Double-Layer Capacitors (EDLCs) with the high energy density of Lithium-ion Batteries (LIBs). These characteristics make them a very attractive for traction applications that need a high peak power, such as hybrid buses, trams, trains, etc. [1], [2]

Today, this market is mainly dominated by LIBs due to their high energy density densities (in between 70 and 230Wh/kg depending on the chemistry). However, LIBs face limitations in terms of power density (300-2000W/kg) and lifetime [3]–[6]. EDLCs, also known as supercapacitors, on the other hand can reach very high power density (10kW/kg) and lifetime (over one million cycles), but have a limited energy density (5Wh/kg) [7]–[11]. LIC cells have characteristics in between those of LIBs and those of EDLCs - capacitance up to 3300F, operating voltage: 2,2V-3,8V, energy density: 8-14 Wh/kg, power density: 10kW/kg and cycle life of more than 1 million cycles [12]–[14]. The higher operating voltage allows decreasing the amount of cells needed for obtaining the required voltage of the application, while the higher energy density compared to EDLCs allows reducing the amount of parallel stacks required for obtaining the desired energy content. These characteristics make them thus an interesting candidate for applications in which the gap between LIBs and EDLCs needs to be bridged.

In section 2, the electrochemical configuration of LICs is explained in order to understand the working mechanisms of the cells. In section 3, the characteristics of LICs are highlighted and compared with those of LIBs and EDLCs. In section 4, the applications that are known to be powered by LICs are highlighted.

II. LITHIUM-ION CAPACITOR OPERATING PRINCIPLES

This difference in characteristics between both types of components can be explained by the electrochemical mechanism occurring within the cells: LIBs store their charge according to the insertion or intercalation process, meaning that lithium ions are inserted in / extracted from the crystal lattice of the electrodes without changing their host structure [15], [16]. This process can thus be referred to as a Faradaic reaction as the charge is transferred from the electrolyte to the electrode. The operating principle of EDLC however are non-Faradaic: EDLCs store their charge electrostatically, by charge separation, at the interface between the electrode and electrolyte [17]. An illustration of the working mechanisms of both types of energy storage components is presented in Fig. 1.

The research towards increasing the energy density of EDLCs has, among other technical evolutions, lead to the development of pseudo-capacitors and hybrid capacitors. Pseudo-capacitors use redox-active materials in their electrodes, such as Ruthenium oxides and Manganese oxide, while hybrid capacitors combine an activated carbon electrode (EDLC-like) with an insertion compound (LIB-like). In the last year, several companies started commercialization of hybrid capacitors. JM Energy Corporation introduced their Ultimo LIC on the market in 2007. This technology uses a pre-lithiated graphite negative electrode in combination with an activated carbon (AC) positive electrode, according to the original patent of Fuji Heavy Industry [18]. The lithium ions can then be (de)inserted at/from the surface of the pre-lithiated (lithium pre-doped) graphite electrode, while the Li-ions are desorbed/adsorbed at the surface of the activated carbon electrode [19]. An overview of the elementary structure of this LIC cell is presented in Fig. 1. This cell will be the basis of this research due to the amount of application-based information obtained from JSR Micro N.V., the exclusive partner of JM Energy Corporation in Europe [20]. Lithium-ion Capacitors however also are commercialized by Shin-Kobe [21], Asahi Kasei FDK Energy Device (AFEC) [22] and Yunasko [23].

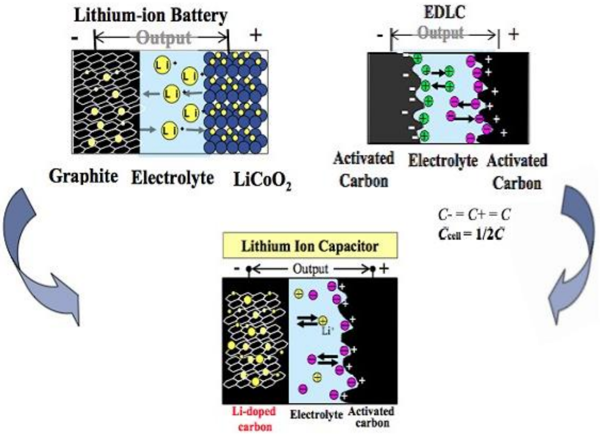

Fig. 1: Operating principle of lithium-ion capacitor [1]

III. LITHIUM-ION CAPACITOR CHARACTERISTICS

The specific electrochemical configuration explained above thus results in a component with characteristics in between those of LIBs and those of EDLCs. The LIC cells can operate in a voltage range from 2,2V to 3,8V, which is similar to the voltage range of LIBS and higher than that of EDLCs (typically up to around 2,7V). This high voltage, and the capacity of the pre-lithiated anode, leads to the high energy density of the LIC cell compared to EDLCs, as can be observed from (1).

$$W = \frac{1}{2} C \,.\, \Delta V^2 \tag{1}$$

Where W resembles the usable energy content of the cell (Wh), C the capacitance of the cell (F) and ΔV the difference of the maximum and minimum voltage levels of the cell (V). The higher energy density of the LIC technology compared to EDLCs can also be retrieved in the Ragone plot presented in Fig. 2. The AC cathode is key to the high power density and long cycle life compared to LIBs. Regarding the lifetime of the cells, it was shown in [20] that the Ultimo LIC cells of JSR Micro N.V. can sustain more than 2 million cycles at 200A, 100% Depth of Discharge (DoD) and without rest time.

The operating temperature of these LIC cells can vary from -30˚C to 70˚C. This operating window is similar to EDLCs, while the temperature range of LIBs is typically limited from 0˚C to 45˚C (other limits are possible depending on the technology). Furthermore, the use of AC as cathode also prevents the occurrence of a thermal runaway. The oxide materials used in the cathode of LIBs can release oxygen at high temperatures, which is an exothermic process that thus causes the risk of a thermal runaway.

Additionally, from safety point of view, the electrolyte of the LIC cell is a lithium salt in contrast to acetonitrile used in the EDLC technology. Acetonitrile however is a flammable and toxic chemical which is already banned in several countries, e.g. in Japan.

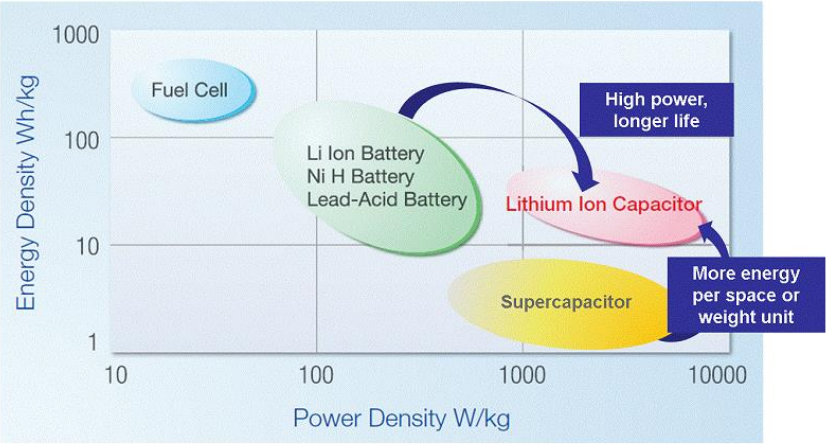

Fig. 2: Ragone plot of different energy storage components [14]

IV. APPLICATIONS

As presented in the Ragone plot (see Fig. 2), the LIC cell has unique characteristics in between those of LIBs and EDLCs. LICs thus have a large potential for applications that require both a high energy content and the high power capabilities, such as heavy traction applications like metros, trams, hybrid buses, hybrid trucks etc. The rechargeable energy storage systems used in these kinds of applications are today overdimensioned – for EDLCs in terms of energy and for LIBs in terms of power. The energy storage system for these applications can then be optimized by using LICs, which could lead to reduction of the mass and the volume of the final system. Additionally, from the point of view of integration in the application, the LIC technology also benefit from their prismatic shape, low mass and low volume. Aside from traction applications, the specific characteristics of LICs make them also an interesting component for energy storage in stationary applications, such as uninterruptible power supply (UPS) or load levelling. They can again make the bridge between the high energy content of LIBs and the high power content of EDLCs and in Table 1 the typical requirements of some of these applications are shown.

TABLE 1: TYPICAL REQUIREMENTS FOR APPLICATIONS FOR LICS [1]

Application	Voltage (V)	Power (W)	Cycle life	Duration
Bus	700-800	150k	1.000.000 cycles	10s
Metros	800-900	1-2M	200.000-400.000 cycles (1 year)	10-20s
Trams	700	300k-400k	?	10-20s
Load leveling	400	200k-1G	2500 (10 year)	50-300min
Back-up power	400	1k-1M	100 (10 year)	15 min
Cranes	800	350k	1.000.000 cycles	10s

A. *Transportation*

In Fig. 3, a picture is shown of an LIC system implemented on a hybrid bus. The hybrid bus consisted of a diesel engine and an LIC system. The LIC system is based on the 2300F Ultimo LIC cells of JSR Micro N.V. and contains one string of 180 cells in series, resulting in a DC-bus voltage of 675V. The final LIC system had an energy content of 0,55kWh and a power capability of 135kW [24].

Within a series hybrid bus, both the diesel engine and the LIC system provide simultaneously power to the electric motor, which propels the wheels. A theoretical study performed in [25] for EDLCs suggest that implementation of the moving average control strategy could lead to a reduction of the fuel consumption of the bus with 35%. The moving average control strategy ensures optimal usage of both types of energy storage systems in the hybrid bus: the diesel engine will provide the moving average power and will thus almost continuously operate at a constant working point, which can then be optimized in terms of efficiency. The LIC system on the other hand provides the peak power for acceleration of the bus and recuperates the regenerative braking energy. The moving average control strategy can be implemented by using a low pass filter, which blocks the high frequency component of the required power and thus result in the moving average power of the demand. The moving average power can then be calculated according to (2).

$$P_{ma} = \frac{1}{\tau . s + 1} . P_d \tag{2}$$

where

P_{ma} = moving average power, provided by the diesel engine (kW);

τ = time constant of the filter (s);

P_d = power demand (kW).

The power peaks provided by the LIC system are then

$$P_{LIC} = P_d - P_{ma} \tag{3}$$

where

P_{LIC} = power provided by the LIC system (kW);

In Fig. 4, an illustration is presented of the division of the required power to propel the hybrid bus (in blue) into power provided by the LIC system (in green) and power provided by the internal combustion engine (ICE) (in red). It can be clearly observed that the diesel engine only is practically working at a constant operating point, thus providing the moving average power. The LIC system then provides the peak power for the bus and captures part of the braking energy of the bus.

In Table 2, a comparison is made between the mass and volume of the LIC system and of those of a typical EDLC system for the same application. The clear benefit of the LIC system over the EDLC system can be observed: as the LIC technology has a higher operating voltage and higher energy density, the amount of cells needed to reach the DC-bus voltage of 675V can be reduced. Additionally, the prismatic shape also reduced the required space for the LIC system and the low weight of the cells resulted in a final system which was less than half of the EDLC system.

TABLE 2: COMPARISON OF VOLUME AND MASS OF LIC AND EDLC SYSTEMS ON HYBRID BUS [24]

	LIC system	EDLC system
Mass (kg)	135	340
Volume (dm^3)	317	470

Fig. 3: LIC system on hybrid bus [24]

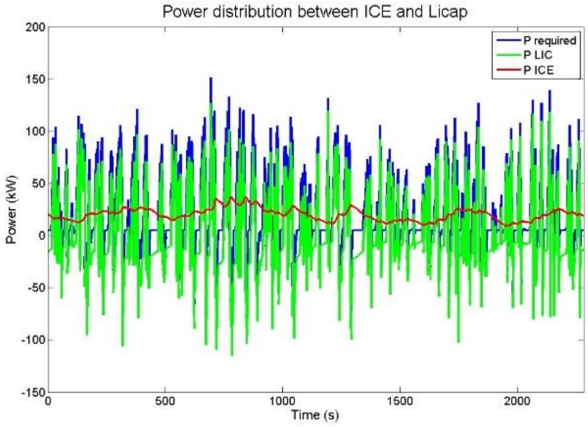

Fig. 4: Division of required power between LIC system and ICE [24]

The advantages regarding compactness and weight can also be expected in (light) rail applications. In these applications, further energy savings can be obtained by implementing braking energy recovery technologies. The main approaches for recovery of the braking energy are on-board energy storage system, wayside energy storage system and reversible substations. The combination of the high energy content with the power capability and long cycle life of LICs make the LICs a suited energy storage technology for these applications. Furthermore, it was retrieved in [14] that LIC modules were certified towards the EN45545 (Railway Smoke and Fire) standard.

The LIC technology is also already commercially used in hybrid excavators for energy recovery in the swing structure with the benefit of the compact size of the LIC system and a reduced cooling system [14].

Furthermore, the performance of the LIC technology has also been demonstrated for several traction applications. The Forze VI Racingteam of the University of Delft has used LICs in a hybrid energy storage system combined with fuel cells. The LIC cells in this configuration acted as energy buffer and for capturing of the braking energy [26].

The usage of LICs for inductive charging of an electric car in motion was demonstrated in [27], [28]. Wireless charging of a vehicle in motion presents challenges in terms of power smoothing at both grid side and in the vehicle. The implementation of an LIC system at the grid side during an inductive charging cycle resulted in a reduction of the peak power drawn from the grid with 81%, as can be observed in Fig. 5. The battery current without LIC system had a peak of 16A, while the LIC resulted in a smoothening of the battery current such that its peak current only was 2,6A.

B. Stationary applications

The long lifetime and compact prismatic geometry also make LICs attractive for usage in stationary applications, such as load levelling, voltage sag compensation and short term Uninterruptible Power Supply (UPS). The specific characteristics of LICs would result in UPS systems that can handle power interruptions with a range from seconds to minutes. In [14], a 600kW LIC based UPS system was shown which was designed to provide back-up power for 11s and recently, JSR Micro N.V. announced the launch of an LIC based UPS at their own facility in cooperation with Socomec [25].

Additionally, LICs are also used in medical equipment due to their safe usage, low mass and compactness. Additionally, as the lifetime of the cells exceeds that of the product, there is no need for replacement of the energy storage component. The same features offer an attractive solution to other applications, such as automation, telemetry, aerospace, forklifts, harbor cranes and others [14].

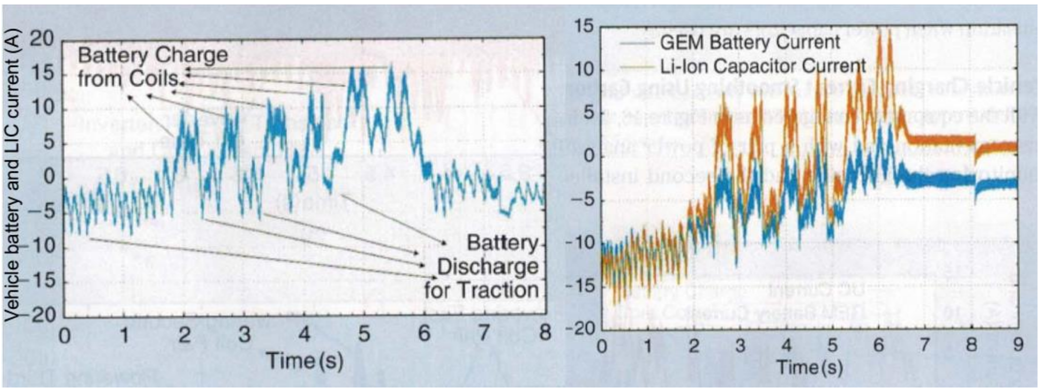

Fig. 5: Influence of LIC system on battery current during inductive charging [28]

V. CONCLUSIONS

Lithium-ion capacitors show a high potential for those applications that require energy storage systems with both a high energy content and a high power capability. Additionally, the LIC technology has a lifetime of over 1 million cycles and is a light and compact technology. These characteristics resulted in several commercially successful cases and several demonstration projects, mainly in the transport sector and for stationary applications. A fleet of hybrid buses that contains a diesel engine and a LIC system is currently driving around in Europe, where the LIC provides the peak powers and recuperates the regenerative braking energy. The LIC solution has also proved to be commercial in hybrid excavators and its performance was demonstrated for stabilization of the grid during inductive charging of the electric vehicle and as buffer in an electric race car combined with fuel cells. Additionally, several LIC based Uninterruptible Power Supply systems are operating for enhancing the power quality of sensible machinery in the range from several seconds to minutes and the LIC technology is also known to be used in medical equipment.

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