Review on Ultracapacitor- Battery Interface for Energy Management System

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***ABSTRACT* - Electrical energy storage is a central element to any electric-drive train technology, whether hybrid-electric, fuel-cell, or all-electric. A particularly cost-sensitive issue with energy storage is the high replacement cost of depleted battery banks. One possibility to ease the power burden on batteries and fuel cells is to use ultra-capacitors as load-leveling devices. In this overview the technology and difficulties of ultracapacitor-Battery interface for energy management system is analyzed and the related research work is made.**

***Index Terms*: Electrical double layer capacitor, Ultracapacitor, DC-DC converter, Hybrid electric vehicle, Battery, Energy Management.**

I. INTRODUCTION

Electric and hybrid electric vehicles are possible solutions to reduce the air-pollution and fossil fuel dependence of the transportation sector [1]. The fuel cell electric vehicle is currently considered to be the car of the future and consequently the automotive industry devotes great research effort and important resources to develop and integrate these technologies in their future vehicles [19, 22, 23]. Hybrid electric drive trains are an interesting concept to increase the energy efficiency of the road transportation [2, 21]. Peak power units (e.g. super capacitors, flywheels...) can be introduced in the electric drive train to supply the peak power demands of the vehicle [3]. This form of hybridization of the electric drive train allows increasing the life-time of the main energy source in case of a battery-electric vehicle or allows improving or optimizing the dynamic performance of fuel cell vehicles.

One of the most prominent is the ultracapacitor application in hybrid cars. When a hybrid car is decelerating, the electric motor acts as a generator producing a short, but high value energy impulse. This is used to charge the ultracapacitor. Charging the conventional batteries with such a short impulse would be extremely ineffective. Similarly, during start-up of the electric motor a short-time but substantial in value increase of the source power is needed. This is achieved by using the ultracapacitor.

Other area of ultracapacitor application is power electronics converters (mainly inverters) with DC circuit [12].

Ultracapacitors can be found in wind power stations (Abbey, Joos, 2007), where they stabilize the power supplied to the grid. They are charged during the period of strong wind and discharge during calm periods. They can also be applied as energy saving subsystems in underground energy supply system. They are placed along the tracks and they collect the energy during braking and give it back during start-up [32]. Also some back-up systems in electronics use ultra capacitors (e.g. computer memory back-up).

In most of the applications mentioned it is essential to have a fairly detailed model of ultracapacitor. The more accurate model we have, the more advanced control schems can be achieved. Control systems are needed e.g. to stabilize the ultracapacitor voltage which tends to fluctuate significantly [15, 39, 45].

This paper offers a concise review on 1. The technology of ultracapacitor -battery 2. Illustrations of how advanced ultracapacitors can be used in several automotive applications. 3. Ultracapacitors - batteries interface for energy management system.

II. ULTRACAPACITOR WORKING PRINCIPLE

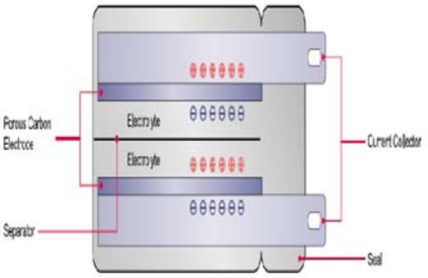

Fig.1 Ultracapacitor Construction

Fig.1 shows the construction of ultracapacitor [5]. It is an electrical energy storage device which offers high power density which was not possible to achieve in traditional capacitors. Ultracapacitor is consisted of two electrodes immersed in an electrolyte and separator prevents the charge from moving between two electrodes having different polarity. Ultracapacitor stores energy relied on electrostatic charges on opposite electrode surface of the electric double layer, which is formed between each of the electrodes and the electrolyte. Randomly distributed ions in electrolyte move toward the electrode surface of opposite polarity under electric field when charged. It is purely physical phenomena rather than through a chemical reaction and highly reversible process, which result in high power, high cycle life, long shelf life, and maintenance-free product [13, 32, 40].

Ultracapacitor is unique energy storage device to offer high power and high energy compared with conventional electrolytic capacitor and battery. The high content of energy stored by Ultracapacitor in comparison to conventional electrolytic capacitor is by activated carbon electrode material having the extremely high surface area and the short distance of charge separation created by the opposite charges in the interface between electrode and electrolyte [37].

III. MODELING OF ULTRACAPACITOR BANK

The parameters used in the mathematical modeling of the ultracapacitor (UC) bank are as follows [20]:

C	capacitance [F]
$C_{\text{UC-total}}$	the total UC system capacitance [F]
EPR	equivalent parallel resistance [Ω]
ESR, R	equivalent series internal resistance[Ω]
E_{UC}	the amount of energy released or captured by the UC bank [W s]
n_s	the number of capacitors connected in series
n_p	the number of series strings in parallel
$R_{\text{UC-total}}$	the total UC system resistance [Ω]
V_i	the initial voltage before discharging starts [V]
V_f	the final voltage after discharging ends [V]

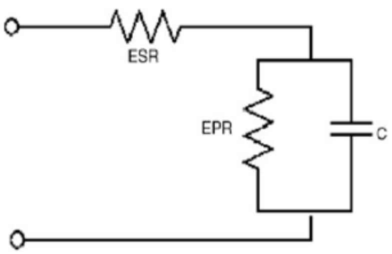

Fig. 2 Electrical Equivalent Circuit

Fig.2 shows the classical equivalent circuit of the ultracapacitor UC unit. The model consists of a capacitance (C), an equivalent series resistance (ESR, R) representing the charging and discharging resistance, and an equivalent parallel resistance (EPR) representing the self-discharging losses [4]. The EPR models leakage effects and affects only the long -term energy storage performance of the UC. The amount of energy drawn from the UC bank is directly proportional to the capacitance and the change in the terminal voltage, given by equation 1.

$$E_{\text{UC}} = \frac{1}{2}C(V_i^2 - V_f^2) \qquad \text{———— } 1$$

When the ultra-capacitor bank is subject to supply a prescribed amount of energy, the UC terminal voltage decreases. The terminal voltage equation represents the voltage variation versus energy released or captured by the ultra-capacitor bank. If the UC bank releases energy to the load side, EUC is positive. If energy is captured by the UC bank, EUC is negative. The effective specific energy for a prescribed load can be supplied by various UC bank configurations. In practical applications, the required amount of terminal voltage and energy or the capacitance of UC storage system can be built using multiple UCs in series and parallel [20]. The terminal voltage determines the number of capacitors which must be connected in series to form a bank and the total capacitance determines the number of capacitors which must be connected in parallel in the bank. The total resistance and the total capacitance of the UC bank may be

$$R_{\text{UC-total}} = n_s \frac{\text{ESR}}{n_p} \qquad \text{———— } 2$$

$$C_{\text{UC-total}} = n_p \frac{C}{n_s} \qquad \text{———— } 3$$

IV. ADVANTAGES OF ULTRACAPACITORS

A. Higher Power Density

Ultracapacitors, also known as electrochemical double layer capacitors (EDLC) or supercapacitors, are new energy storage devices that have advantages over other energy storage devices. In terms of energy density, existing commercial ultracapacitors range from 1 to 10 Wh/kg. Power density for ultracapacitors may typically range from 1000 to 5000 W/kg [4], and some newer ultracapacitors have higher power density [29, 31, 42].

In contrast, the energy density for the bipolar lead-acid battery is typically from 24 to 27 Wh/kg and the power density is around 450 W/kg, the energy density for modern lithium-ion batteries is from 150 to 200 Wh/kg and the power density is from 300 to 1500 W/kg, and for automobile applications gasoline has an energy density around 12,000 Wh/kg. Fig.3 shows the power – energy relationship for various electrical energy storage devices. A high power density, high energy density device does not exist, but one can emulated by carefully controlled power distribution between electrolytic ultracapacitors and lead acid batteries[43].

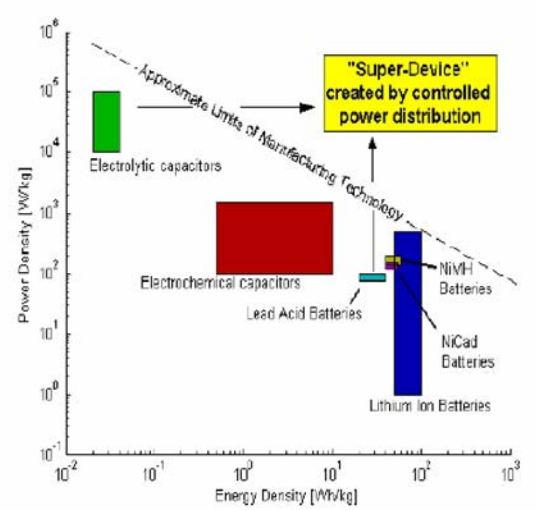

Fig.3 Power Energy relationship for various energy storage devices

Although existing ultracapacitors have energy densities that are only 1/10 those of some batteries, their power densities are generally ten to one hundred times greater than those of batteries. This special feature makes ultracapacitors a unique fit for applications that require pulse power, such as burst-mode communication for wireless systems, writing to disk and LCD operation for digital cameras, and starting vehicles. As a result, ultracapacitors are becoming more widely used as energy storage devices[16,50].

B. High Efficiency

Coulombic efficiency is defined as the ratio of the number of electrons discharged to the number of electrons that need to be recharged in order to bring an energy storage device back to its original state of charge (SOC). Coulombic efficiency of ultracapacitors is as high as 99%. In addition, ultracapacitors have high round trip efficiency. The round trip efficiency is defined as the ratio of the electrical energy produced after charging and discharging the storage system to the electrical energy required from the charging source. At a five-second rate (discharging to half rated voltage in five seconds, and recharging at the same rate until the ultracapacitor is fully charged), the round trip efficiency is greater than 70% and at a ten-second rate, it is greater than 80% ; this round-trip efficiency is just as high as that of batteries. In contrast, the round trip efficiency of a regenerative fuel cell is about 50%. The ultracapacitor's high round trip efficiency implies that an ultracapacitor-based energy storage system needs less cooling capacity than most other alternative technologies, since ultracapacitors dissipate much less energy in heat. Figure 4 shows the illustrative efficiency versus power level for various energy storage components [8,17].

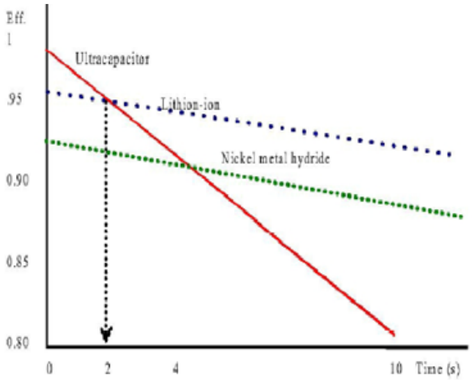

Fig.4 Efficiency versus power level for various energy storage components.

C. High Current

The equivalent series resistance (ESR) in ultracapacitors is extremely low, so the ultracapacitor can be charged with a very high current, this is not possible in energy storage devices like batteries that have higher ESR, because in those devices current must be limited to avoid overheating. In addition, no chemical reactions are involved in the storage and release of energy from ultracapacitors. This means that charging and discharging can be done with the same high rated current. This feature makes the ultracapacitor a good fit for regenerative braking applications, to successfully absorb energy from braking requires a very high charging current profile. In contrast, battery-based energy systems are not able to successfully absorb as much of the braking energy because their charging current must be limited to avoid damage to the batteries [6,35].

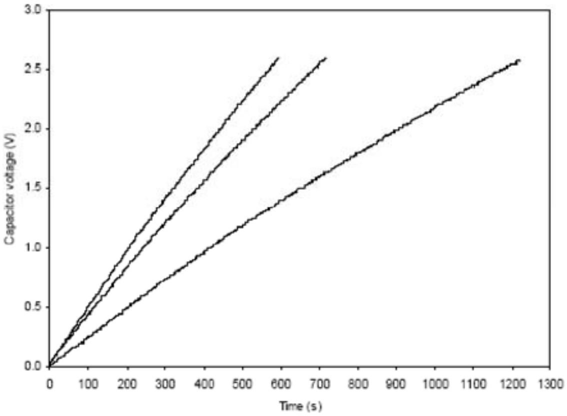

Fig. 5 Charging profile with various charging currents

An ultracapacitor can accept a wide of charging current so that precise current control is not necessary. The criterion for terminating charging is the maximum rated voltage of an ultracapacitor. Figure.5 shows the charging profiles of a 680F ultracapacitor with various charging currents. The result reveals that the characteristic of the ultracapacitor is closed to that of an ideal capacitor. The specimen is subjected to constant current charging with charging currents of 1.5A, 2.5A and 3A respectively. The ampere-hour capacity or energy storage capacity of a battery depends on the charging current. For an ultracapacitor, experimental results reveal that the energy storage capacity is nearly constant under different rates of charging [47].

D. High Operating Temperature

Generally, ultracapacitors can operate over a wide range of temperatures. The range of operating temperatures for ultracapacitors is determined by the electrolyte. If the temperature is low, the mobility of the ions in the electrolyte will be low near the freezing point of the electrolyte the mobility of the ions will be affected dramatically. In modern ultracapacitors, an organic solution that has a very low freezing point is employed as the electrolyte. As a result a typical ultracapacitor can be operated at temperatures as low as -45^{O}C. They can be operated at temperature as high as 60^{O}C [6].

Throughout the range of operating temperatures, ESR and capacitance do not vary much, as shown in Figure.6. In contrast, lead-acid and lithium-ion batteries, which of all the battery types are the most tolerant of temperature changes, can be operated only from -20^{O}C to 45^{O}C. Further, for some kinds of batteries such as lithium-ion cells, performance drastically decreases at temperatures below 0^{O}C [31].

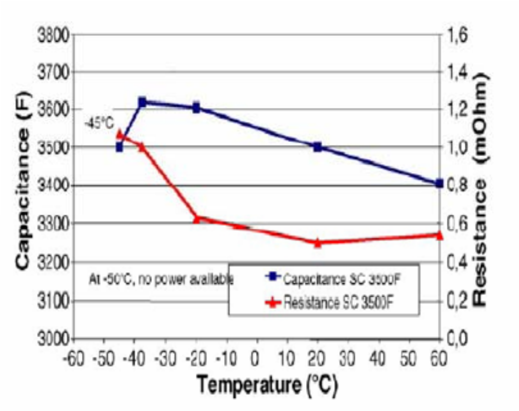

Fig.6 Temperature dependence of ultracapacitor parameters

E. Long Life

Industry standards specify that an ultracapacitor’s useful life ends when its capacitance decreases by 20% or its ESR increases by 200%. As an ultracapacitor is used, its performance continually degrades, and its end of life is when its performance will no longer satisfy the application requirements. The ultracapacitor will have unlimited shelf life if it is stored in a discharged state [9]. The ultracapacitor is good for several hundred thousand charge/discharge cycles, this is many more than can be achieved with batteries, some of which are good for only several hundred cycles. In addition, because ultracapacitor operation involves no chemical reaction, its operation produces no environmental pollution. Thus using ultracapacitors in hybrid electric vehicles can improve the fuel economy and decrease vehicle emissions throughout the vehicle life [36,37,38].

V.COMPARISON OF ULTRACAPACITOR WITH BATTERIES

The comparison of batteries and ultracapacitors is tabulated in Table 1. Ultracapacitors and batteries possess the advantages of high power density and high energy density, respectively. An ultracapacitor-battery combination system puts the advantages together [6, 27, 28].

Table.1

Attribute	Ultracapacitr	Batteries
Power Density	> 1000 W/kg	< 500 W/kg
Energy Density	< 5 Wh/kg	10-100 Wh/kg
Cold Temperatue	< -40 ^{o}C	-20 ^{o}C
Hot Temperatue	+65 ^{o}C	+40 ^{o}C
Efficiency	98%	95%
Charging time	Fraction of a second to several minutes	Several hours
Charging/discharging efficiency	88% - 98%	70% - 85%
Self discharging	Hours to days	Weeks to several months
Cycle life	$10^{6} – 10^{8}$	200 - 1000
Lifetime	8-14 years	1-5 years
Toxicity	Non-toxic	Lead, Strong Acid
Monitoring	Not required, simple voltage, current measurement	Sophisticated
Handling	Human handling	Requires equipment

VI. ULTRACAPACITOR-BATTERY INTERFACE FOR POWER ELECTRONIC APPLICATIONS

The electrical load in electric vehicles consists mainly of an inverter-fed induction motor for motive power. During regenerative breaking, the motor is turned into a generator by reducing the frequency of its terminal voltage, thus reversing power flow and producing braking torque[14,34]. As far as the power source in concerned, power demand is sufficient for analysis. Since the DC bus voltage is not allowed to vary significantly from its nominal value, current demand gives a good approximation of power demand. Thus the load can be modeled simply by a time-varying current source that reverses direction as the vehicle switches from coasting or acceleration to regenerative braking [26, 30].

1. The role of the ultracapacitor is to maintain the battery current as constant as possible with slow transition from low to high current during transients to limit battery stress. On the other hand, the ultracapacitor ought to charge as fast as possible without exceeding maximum current from regenerative breaking, and to discharge most of its stored energy during acceleration. Energy flow in and out of the ultracapacitor can be controlled with a pulse-with-modulated (PWM) DC/DC converter.

Adding a ultracapacitor bank to a battery- or fuel cell driven vehicle makes sense and advantages by far outweigh the disadvantages. A direct parallel connection will reduce battery stress by assisting with transient currents during acceleration and deceleration. The parallel combination of the battery system and UC bank also exhibits good performance for the stand-alone residential applications during the steady-state, load-switching, and peak power demand. Without the UC bank, the battery/fuel cell system must supply this extra power, thereby increasing the size and cost of the battery/fuel cell system [7].

2. The ultracapacitor addition removes 20% of the mass of the battery pack of the electric vehicle. Another method for reducing the size of the capacitor bank would use some battery power during each shot. If the application were to permit this, the ultracapacitor stack would still supply most of the power while the load was at its peak, but the battery would supply a lower, consistent level over the full ten-second duration. Such a hybrid approach can significantly reduce the size of the ultracapacitor stack [9, 24].

The figure.8 shows how allowing battery power during the shot cycle reduces the size of the bank, the top trace corresponds to a constant-current charger, and the bottom trace represents the operation of a constant-power charger. The figure 8 show that a 17% size reduction is possible if 2 kW were available during the shot and a further 20% reduction in size is possible if a constant power algorithm were allowed.

3. Time domain and frequency domain measurements both confirmed that ultracapacitors are very efficient for low frequency use. Both also show that the capacitance drops (with corresponding decrease in efficiency) for frequencies greater than 0.1 Hz is measured by various frequency response of ultracapacitors as shown in figure.9. The time domain measurements show that capacitor loss becomes very significant (70% for some tests) for fast discharge times [6]. As Ultra-capacitors are always used for energy storage or energy buffer applications, their poor high frequency response makes them completely unsuitable for high frequency applications and

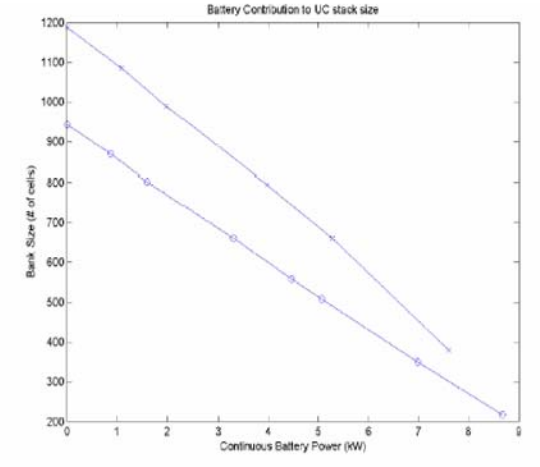

Fig.8 UC bank size reduction with battery contribution

are therefore more suitable for dc circuits. Thus it is proposed that the Ultracapacitors should be connected to any high frequency charging converter with a small inductance of about 20 μH in series to the converter. The measured frequency response of various ultracapacitors is shown in figure 9.

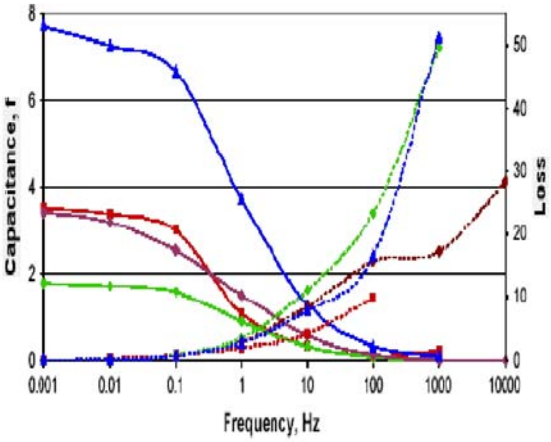

Fig.9 Measured frequency response of various ultracapacitors

4. The main problem with the application of ultracapacitors is that maximum voltage of each cell in the stack (2 ,5 V) should not be exceeded. It is probably reasonable to limit the number of cells in series in batteries, and to match voltages of interconnected DC links using a converter containing an AC medium frequency link with transformer.

5. Ultra-capacitors are used as an energy storage buffer by simultaneously charging and discharging them by paralleling them to an energy source like a battery, fuel cell, DC-DC converter [11], etc and a load. The voltage and current ripple caused by the charging converter can often cause over charging or temperature rise of the capacitor [48, 49]. The increasing filter inductance or increasing the switching frequency of the buck derived DC-DC converter that is usually used for charging will be one solution, they will significantly either increase both size and cost or increase losses in the converter. Moreover, increasing inductance requires higher turns and this increases both the radiated fields from the inductor and the inter-winding capacitance of the inductor. These radiated fields and the feed through noise through the inter-winding capacitance from the inductor mainly couple to surrounding circuits and increase EMI [18]. Thus a better solution would be to use additional filter circuits that attenuate both voltage ripple and ripple current during charging. Such design strategies that significantly improve the energy storage performance and lifetime of these capacitors without being overstressed by the voltage and current ripple [10].

VII. CONCLUSION

There is an essential need for an efficient energy storage system that is_affordable and has a drive cycle life for future hybrid vehicles. This paper has focused on the overview of modeling, advantages, disadvantages and various characteristic of ultracapacitor in the energy management strategy. This paper also emphasizes some limitations, problems and a solution of ultracapacitor for power electronics applications is reviewed.

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