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ULTRACAPACITOR – FUTURE OF REGENERATIVE STORAGE IN ELECTRIC VEHICLE

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ABSTRACT

No Energy Storage System has the ideal characteristics required for the grid integration as well as for the electric vehicle. In relation to Battery Storage System, the regenerative becomes most impossible due to its slow charging and rapid power available. Ultracapacitor (UC) s have the characteristics of fast charging and discharging. In this paper, the attempt is made to show that the UC has suitable characteristics to meet with the regeneration of Electric Vehicle braking and also decrease the weight of it.

KEYWORD: Ultra Capacitor, Modeling, State of Charge (SOC), Regenerative Breaking, Electric Vehicle

INTRODUCTION

Although the theory behind the Electrolytic Capacitor has been known for over 100 years, in the 1990s the technology scaled up and commercialized targeting pulse power applications, engine starting applications, and specialty energy storage applications. The Capacitor has been replaced by Ultra capacitors (UCs) in the specific needs now-a-days. UCs has an excellent power density, sometimes up to 100 times with respect to batteries. Load characteristics are also very good with an efficiency of almost 100% compared with batteries that only have 50-60%. The fact that they have pretty low energy density, up to 300 times with respect to the batteries, limits their use in HEVs to instant power assist. UCs are excellent as life time is concerned, its lifetime can be up to almost 80 years. It is also possible to deep cycle it more than 5, 00,000 times. UC has unlimited life cycle, low impedance, rapid charging and simple charging methods. Though UC has also some limitations - linear discharge voltage prevents use of the full energy spectrum, low energy density, but UC cell has low voltages and high self-discharge. [1]

Hybrid electric vehicles, HEVs, encompass a wide range of different designs with a combustion engine either in parallel, in series or a combination of them both, with an electric drive. One is called plug-in HEV or PHEV and is intended to be a commuting car that is able to drive 50-100 km on pure electrical propulsion. The PHEV utilize a large battery pack, which have a large energy density but not so high power density, which can be charged from the power grid when depleted. An option, or complement, to this strategy is to change storage system into HEV if the battery runs down during driving. In that case the electric drive is used as power assist for acceleration and to put the combustion engine to a better level of efficiency. This will eventually charge the battery due to its ability to store energy at regenerative braking. The idea behind this vehicle is that the average person only uses the car for commuting between their home and their place of work. Normally this distance is 45 km per person per day. This investigation says that the average person drives 13150 km per year. With these numbers it would be much likely to develop a car that would have zero emissions at commuting distances. Of course this would be very attractive on the market due to the fact that electric energy is more cost-effective than petrol, diesel. The electric motor reaches much higher efficiency than the combustion engine and it is environment friendly too. To grab the opportunity for the regenerative power usage, the fast charging and discharging of UC is excellently utilized in EV.

In HEV applications, a UC unit will have a voltage of 200-400 V, this results in many cells in series and parallel. Therefore it is important that there are not too big variations between the cells. Otherwise the maximum voltage of the unit must be significantly reduced to prevent over voltage of individual cells due to their lower capacitance or higher resistance. This results in energy losses due to equation:

$$E = \frac{1}{2}CV^2 \tag{1}$$

Here, E = Energy Stored in Capacitor, J

C = Capacitance, F

V= Voltage, Volt

Therefore quality control in the making of UC module is very crucial and important [2]. It's possible to solve this problem if an active balancing circuit [3] may be used with heavy capacitive pack.

WORKING OF UC

A UC, sometimes referred as an electrochemical capacitor, is an electrical energy storage device that is constructed much like a battery. They utilize two electrodes immersed in an electrolyte with a separator between the electrodes. The electrodes are fabricated from high surface area, porous material having pores of diameter in the nanometer (nm) range. The surface area of the electrode materials used in UCs, 500–2000 m^2/g, is much greater than that used in battery electrodes being below 50 m^2/g. Charge is stored in the micro pores at or near the interface between the solid electrode material and the electrolyte. Calculation of the UCs capacitance is much more difficult as it depends on complex phenomena occurring in the micro pores of the electrode. There are many types of UC technologies; some examples are carbon double-layer capacitors, utilizing pseudo-capacitance capacitors, metal oxide capacitors, conducting polymer capacitors and hybrid capacitors. The breakdown characteristics of the dielectric material determine the maximum voltage of the capacitor.

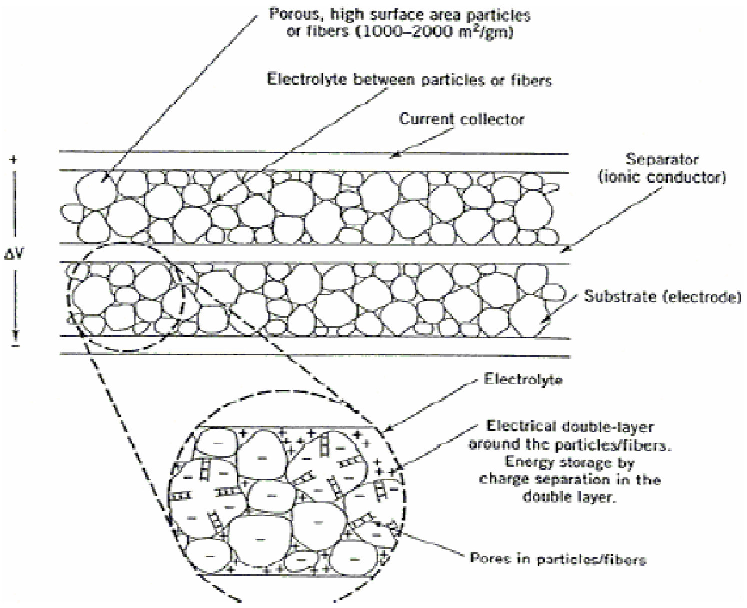

Figure 1: Schematic of a Double Layer UC

CV gives the charge Q (coulombs) stored in the capacitor. The capacitance of the dielectric capacitor depends on the dielectric constant (*K)* and the thickness (th) of the dielectric material and its geometric area (*A).*

$$C = K\,A/th \tag{2}$$

Here, C = Capacitance, F

K = Dielectric Constant, F/m

A = Area, m^2

CHARGING AND DISCHARGING IN SC

During charging the electrolyte anions and cations are driven to electrodes of opposite polarity (see Fig. 2) where they accumulate into layers inside the activated carbon pores with a distribution governed by pore size. While charging, the electrolyte is depleted with ions.

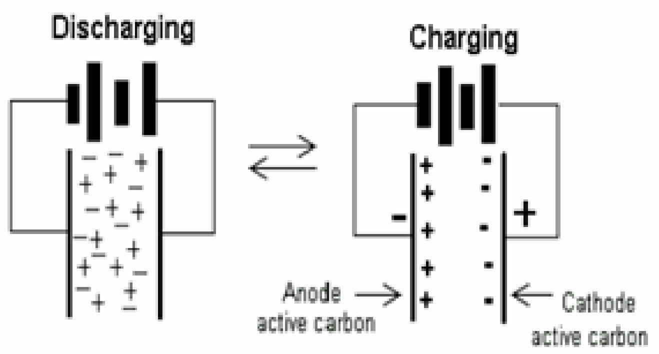

Figure 2: Distribution of Cations and Anions in the Capacitor

ELECTRODES AND ELECTROLYTE

Various materials are proposed as electrodes and electrolytes. To increase the surface area of the electrodes and thus the energy density of the capacitor, the electrodes are made from materials such as activated carbon. In the sulphuric acid electrolyte system, activated carbon is used for the electrode material. In the organic electrolyte system, activated carbon or activated carbon fiber is used for the electrode material. Organic electrolyte systems are favourable because of their high decomposition voltage.

UCs with organic electrolytes have voltage ratings of <3.0 V per cell whereas with aqueous electrolytes the voltage rating <1.23 V per cell, typically 0.9 V. In all UCs the terminal capacitance consists of the series combination of an anode UC and the cathode UC, so the net rated voltage is twice the value of the electrolyte decomposition voltage. Organic electrolyte UCs have higher decomposition voltages and higher specific energy but higher resistance than aqueous types. The low conductivity of the organic electrolyte UC results in higher Equivalent Series Resistance (ESR) [16].

OVERCHARGING AND OVERDISCHARGING

The UC cannot be over discharge by reason of that it can operate linearly in its entire voltage range, but when it comes to overcharging it must be protected. If it is charged with a voltage level above its maximum rated voltage it is damaged and its lifetime shortens dramatically. Besides that the lifetime is reduced and gas can be generated by the electrochemical reactions inside the capacitor and this may cause it to leak or rupture.

The self-discharge rate of a UC, as shown in Figure 3, is quite high compared to electrochemical batteries. UCs with an organic electrolyte is affected the most. In 30 to 40 days, the capacity decreases to 50 percent. The data in Figure 3 is for a

UC with symmetric carbon electrodes and an organic electrolyte rated at 3600F. The reason why UCs has a higher self discharge rate than batteries is because of the fact that the UCs larger (Brunauer–Emmett–Teller) BET surface area favours [15] oxidation of the electrolyte. This means that there is a larger leakage current in the UC than in batteries [4]

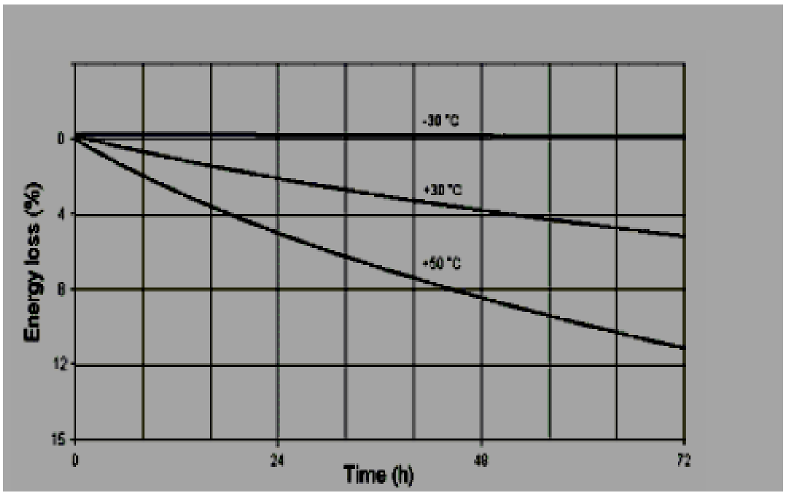

Figure 3: The Self Discharge Rate of UCs at Different Temperatures

MODELLING OF UC

The equivalent circuit used for conventional capacitors can also be applied to UCs. The original form of the equivalent circuit, in the Simulink model, is a first order model (Figure 4). It is comprised of four ideal circuit elements, the internal capacitance C, and a series resistor R_s (ESR), the parallel resistance R_p and L. ESR contributes to energy loss during capacitor charging and discharging. R_p simulates the energy loss due to capacitor self discharge. The last component, a small inductor L results primarily from the physical construction of the UC.

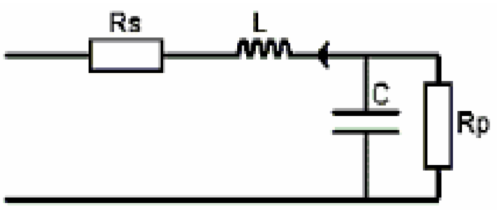

Figure 4: A First Order Model for Capacitors

It is possible to neglect the resistor R_p because the simulation time is quite small compared to self discharge time. The car utilization is only dc from the UC, thus currents charging and discharging the UC are only dc, which makes it possible to neglect the inductor L. This results in the equivalent circuit as shown in Figure 5 [5].

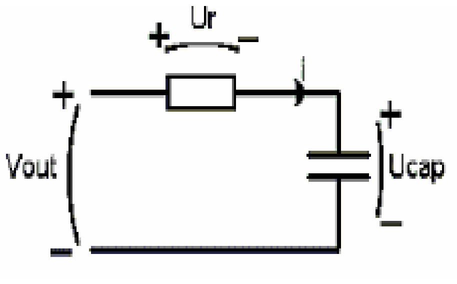

Figure 5: Simplified Model of Capacitor

To implement the UC model, in Simulink a state space equation used. Using Kirchhoff's voltage law for the equivalent circuit yields:

$$V_{out} - U_r - U_{cap} = 0 \Leftrightarrow V_{out} - R*I - 1/C \int I\,dt = 0 \qquad (3)$$

$$dU_{cap}/dt = 1/C * I \qquad (4)$$

From this, it is rather easy to derive the state space equation for the voltage across the capacitor U_{cap}. In equation 4 the only state of the state space is calculated. The actual UC internal resistance (R) and capacity (C) vary with quantities as current, voltage and temperature. So if the UC model should fit to the real UC the variables C and R should vary in the state space equation. This is done with value from the manufactures data sheet and implemented in the Simulink model as Look-Up Tables. The variations for Maxwell's $_{PC}$*2500* capacitor are seen in Figure 6.

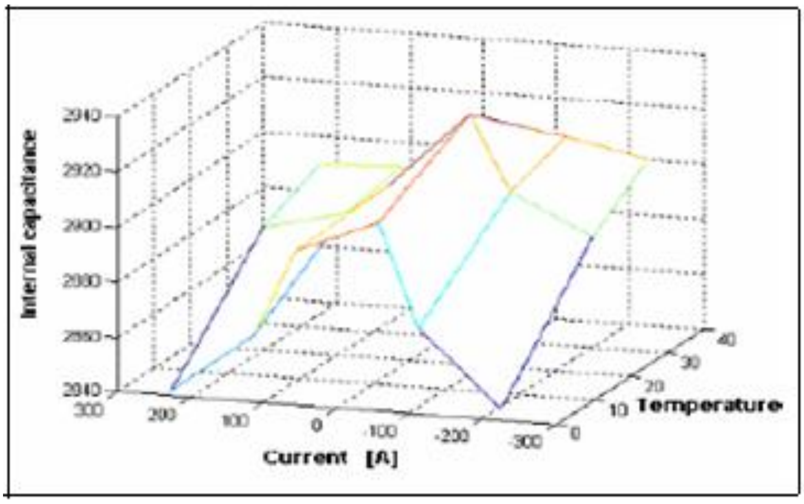

Figure 6(A): Internal Capacitance Vs Current Vs Temperature

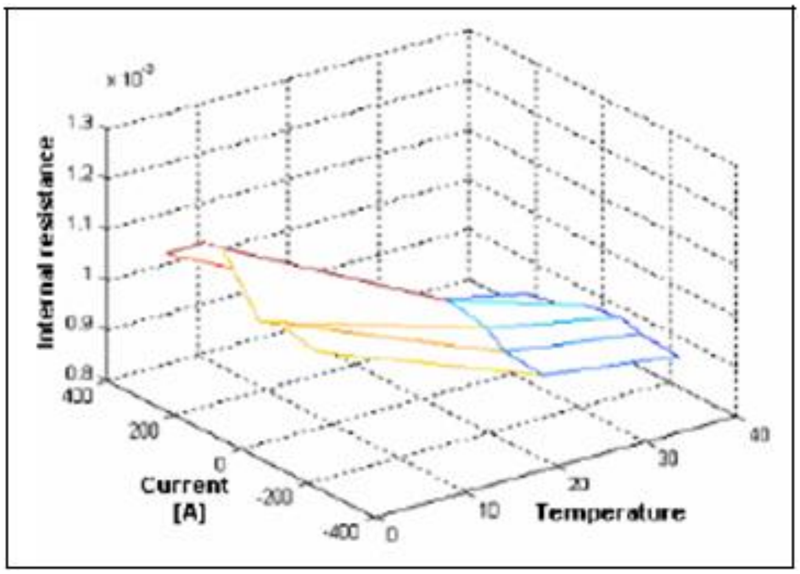

Figure 6(B): Internal Resistance Vs Current Vs Temperature

The definition of the SOC in the UC model is the energy in the UC divided with the total energy when it is fully charged.

$$\begin{aligned} SOC &= E_{cap}/E_{max} \\ &= \{U^2_{cap} * C/2\}/\{U^2_{cap,max} * C/2\} \\ &= U^2_{cap}/U^2_{cap,max} \end{aligned} \tag{5}$$

Because of the variation in the capacitance the total energy vary with current too. Ucap is found as a state in the state space function and Ucap, max is the max voltage that the capacitor can deal with. This voltage is obtained from the datasheet of the UC. The temperature model of the UC is modeled in the same way as for the batteries. The only thing to be changed is the specific heat capacitance and the weight [6]

REGENERATION USING ULTRACAPACITOR

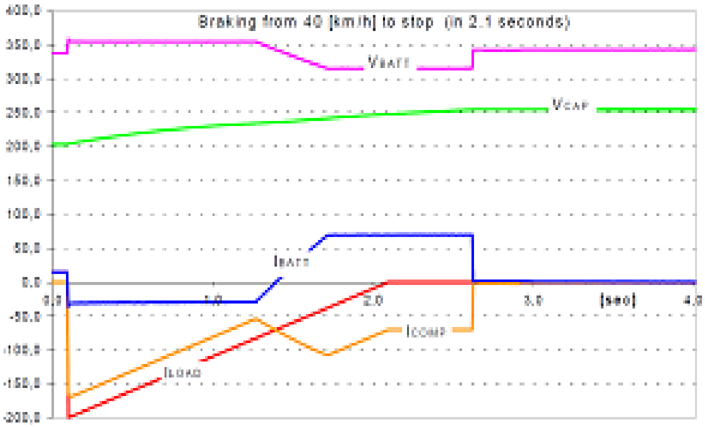

Figure 7: Capacitor Voltage, Braking and Battery Voltage

The level of Energy is calculated through the Electric Vehicle Speed and the battery state of charge. The simulation done in paper [11] shows deceleration from 40 km/h to stop. This action takes 2.1 seconds. The regenerative current goes from 200 Adc to zero in the time said. Here both Battery and Capacitor will receive the current as shown in Figure 7. The battery receives a current smaller than the limit of 70 Adc. This happens because the maximum voltage allowable by the battery is reached 360 Vdc in the said experiment of paper [11]. For this reason, most of the current is taken by the UC. Once the vehicle stops, the battery continues charging the UC until it reaches the final charge.

The below Figure 8 represents the required amount of charge. In this case, UC corresponds to a voltage of around 260Vdc.

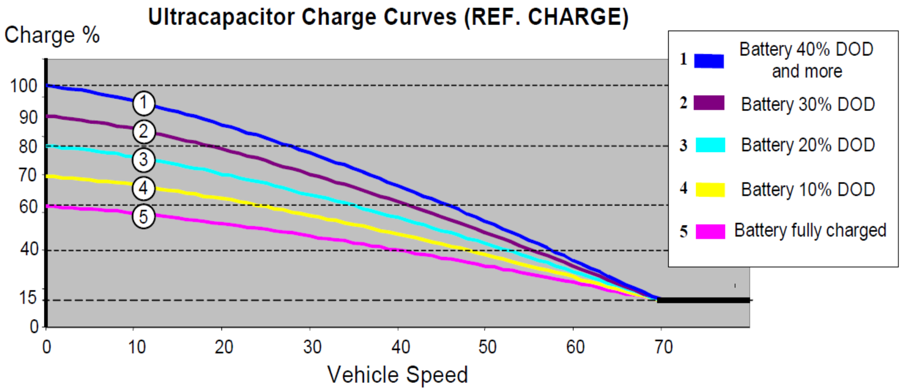

Figure 8: Vehicle Speed Vs % of Charge of UC

COMMENTS

UC– FUTURE OF EV

UCs is created by using thin film polymers for the dielectric layer and carbon nano-tube electrodes. They use polarized liquid layers between conducting ionic electrolyte and a conducting electrode to increase the capacitance. They can be connected in series or in parallel. Ultra Capacitor Energy Storage (UCES) systems usually have energy densities of 20 MJ/m^3 to 70 MJ/m^3, with an efficiency of 95% [7]. The main attraction of UCES is its fast charge and discharge, combined with its extremely long life of approximately 1 x 10^6 cycles. This makes it a very attractive replacement for a number of small-scale (<250 kW) power quality applications. In comparison to batteries, UCs have a longer life, do not suffer from memory effect, show minimal degradation due to deep discharge, do not heat up, and produce no hazardous substances [8]. As a result, although the energy density is smaller, UCES is a very attractive option for some applications such as hybrid cars, cellular phones, and load leveling tasks. UCES is primarily used where pulsed power is needed in the millisecond to second time range, with discharge times up to one minute. [9]

PRACTICAL PROBLEMS

The capacitor may not be charged with voltages above its rated maximum voltage, normally 2.5V. However it can't be either over discharged or overcharged due to the fact that it may operate in its entire range of voltage without being damaged. Normally it isn't applicable to operate it below half the maximum voltage. This is because of that the energy of the capacitor is then reduced to a fourth of its capacity, and the voltage of the system might be to low for the electric parts in the drive system of the PHEV to operate properly. As for the batteries one need a cooling system in order not to exceed the temperature limit, which normally is about the same as for batteries. Due to the fact that the UC has quite low energy density and very high power density it is only considered in the PHEV. As said before the state of charge can be practically operated between 25% and 100% SOC. The fact that UCs almost has 100% efficiency yields a normally used reference value at 60% SOC. The Regeneration power available is respectively low and needs a further study in comparison of cost effectiveness of both – UC and availability of power.

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