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Smart Battery Management System Using Ultracapacitors

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Abstract: With the advancement of non-conventional energy sources especially solar energy and Electric vehicles, the demand for better energy storage technology is ever increasing. And better batteries require improved Battery Management Systems to improve efficiency and minimize losses. This research paper mainly focuses on developing a Battery Management System (BMS) which uses an active balancing technique. Conventional BMS use passive or dissipate methods to balance the SOC of the cells and active balancing uses charge shuttling methods to reduce loses. A new proposed method is to develop a distributed type BMS which has ultracapacitors on each individual cell board which monitors the cells and stores energy every time a SOC imbalance is generated. This reduces the complex charge shuttling circuitry and also enables the ultracapacitors to discharge when then cell SOC is it's flat profile region i.e., 40-80% SOC or when the system is not actively delivering to the load. It also eliminates the need for balance boosters for faster charge equalization.

Keywords: Battery Management Systems, Passive Balancing, Ultracapacitors, Electric Vehicles, Battery Modeling, Energy management.

1. INTRODUCTION

The need for alternate energy sources is ever increasing with environmental factors kept in mind. A lot of focus is done on how to increase the efficiency of energy conversion and cost reduction of such systems. For example, in Electric Vehicles, most of the research is done on new battery technology with higher energy density and lower cost and for solar energy harvesting system research is more focused on MPPT controllers and inverters and also on new more efficient solar panels like Phillips which launched the most efficient solar panels. But there is very little attention towards actual energy management and efficiency in energy storage.

The existing technology is more focused towards Lithium Polymer, Lithium Ion and other Nano phosphate chemistry for batteries which are highly efficient and have larger energy density which is definitely a breakthrough for modern EVs and other non-conventional energy harnessing equipment. But the fundamental problems with such batteries are cell balancing and thermal management and for which a very efficient battery management system algorithm is required. Two basic methods implemented for cell balancing are passive and active balancing the latter being expensive and complicated is often avoided and OEMs usually stick with passive balancing technique, however, this is a dissipative method where the excess charge is made to flow through a resistor and dissipate in the form of head which leads to losses. In applications such as rooftop solar energy harvesting, the efficiency reduction will be large for the whole system overall. So in order to reduce the losses at the storage level we need to implement active balancing but according several tests performed it was found that For the typical Li-ion application needing only maintenance balancing, all non-dissipative (active) balancers that I analyzed before waste more power overall than plain old dissipative (passive) balancing, because they are on stand-by 24/7, while dissipative draws power only while balancing. Passive components like capacitors are basically used for charge shuttling between the cells and battery modules. But a better alternative to it would be to use a ultracapacitor which has better characteristics and this paper would further analyze the feasibility.

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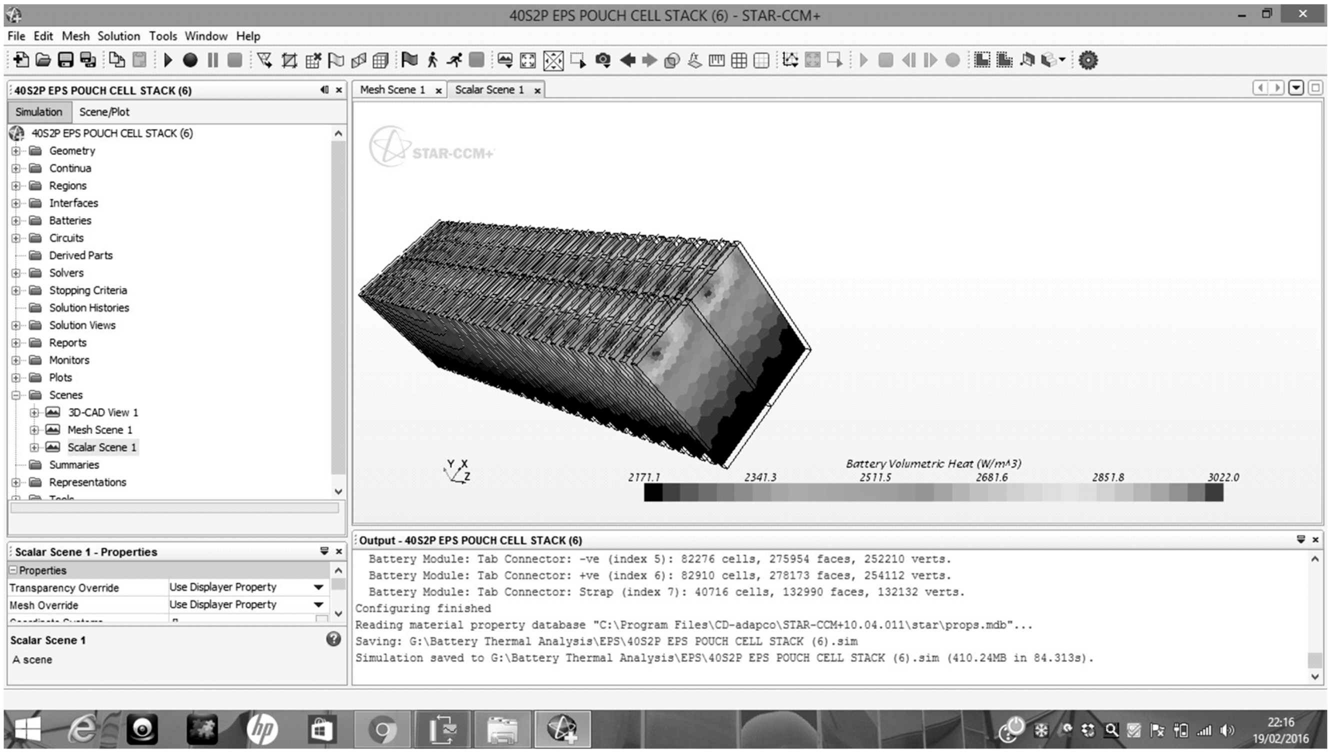
2. LITHIUM CHEMISTRY BATTERY ANALYSIS

Battery analysis for lithium chemistry based cells is essential as the SOC(State of Charge) deviation is due to multiple factors. Experimentally it may seem that SOC may only depend on cell voltage but to estimate accurate SOC we must have information about the cell temperature and internal impedance

$$\mathrm{SOC} = f(\mathrm{V}, \mathrm{T}, \mathrm{Z})$$

Voltage remains pretty much constant throughout the battery pack but the temperature varies throughout the battery pack and there is a gradient from the center to the outside of the battery pack. And most of the imbalance is generated due to lack of proper thermal management however; there is a limit to which we can control these issues. So an effective study and proper analysis of batteries were performed on CD-Adapco's STAR CCM$^+$ and BDS (Battery Design Studio). Numbers of iterations were performed at different C ratings and the graphs were analyzed to actually find the effect of heating and passive balancing on the SOC vs Volatge profile. And it was found that the performance was improved by almost 10-15% if the losses due to passive balancing were avoided which is way more than the efficiency increase due to improvements in the MPPT controllers and inverters done recently.



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  Battery Module: Tab Connector: -ve (index 5): 82276 cells, 275954 faces, 252210 verts.
  Battery Module: Tab Connector: +ve (index 6): 82910 cells, 278173 faces, 254112 verts.
  Battery Module: Tab Connector: Strap (index 7): 40716 cells, 132990 faces, 132132 verts.
Configuring finished
Reading material property database "C:\Program Files\CD-adapco\STAR-CCM+10.04.011\star\props.mdb"...
Saving: G:\Battery Thermal Analysis\EPS\40S2P EPS POUCH CELL STACK (6).sim
Simulation saved to G:\Battery Thermal Analysis\EPS\40S2P EPS POUCH CELL STACK (6).sim (410.24MB in 84.313s).
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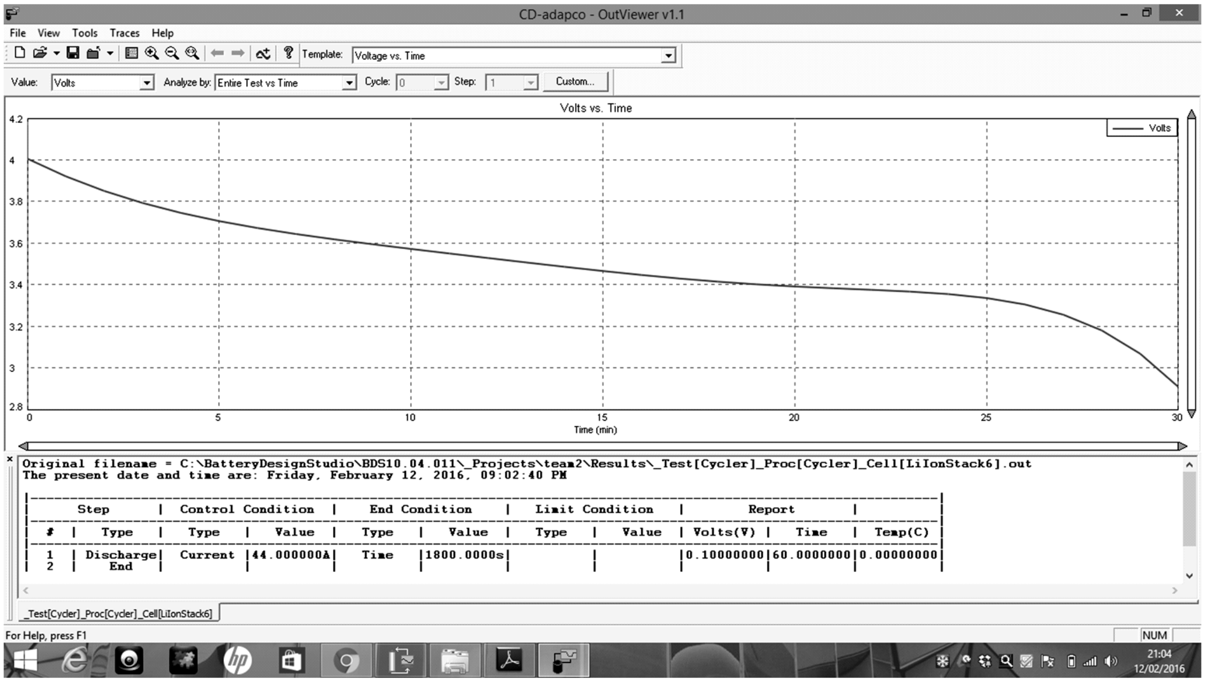
Figure 1: Thermal analysis of pouch cells

Further iterations were performed for finding the perfect discharge rate for minimal SOC imbalance and to keep the battery pack thermally stable. A Voltage v/s time profile was generated for an optimized pack.

3. BATTERY MANAGEMENT SYSTEM

The BMS (battery management system) is an important component which constantly monitors all the system parameters of the battery pack and protects from over-charge and over-discharge and overcurrent also short circuit faults and thermal runaways. The primary objective of a BMS is to balance charge or voltage of the cells and monitor the SOC. There are some classifications of BMS which are distributed and centralized and for the type of balancing there is active and passive balancing. This research paper will mainly focus on distributed type active balancing method. There are several algorithms used by the BMS for calculating SOC the most common being Single Particle Model(SPM).



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|       Step      |  Control Condition  |    End Condition    |   Limit Condition   |       Report        |         |
|---------------------------------------------------------------------------------------------------------|
|  #  |   Type    |  Type   |   Value   |  Type   |   Value   |  Type   |   Value   | Volts(V) |   Time   |  Temp(C) |
|---------------------------------------------------------------------------------------------------------|
|  1  | Discharge|  Current |44.000000A|  Time   |1800.0000s|         |           |0.10000000|60.0000000|0.00000000|
|  2  |    End    |         |           |         |           |         |           |          |          |          |
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Figure 2: Voltage v/s Time profile for discharge

The SPM concept was first applied to lithium battery systems in [1] where the key assumption is that the solid phase of each electrode can be idealized as a single spherical particle. In addition, the electrolyte concentration diffusion and migration dynamics are neglected and thermal effects are ignored. Mathematically, the model consists of two diffusion PDEs governing each electrode's concentration dynamics, where input current enters as a Neumann boundary condition. Output voltage is given by a nonlinear function of the state values at the boundary and the input current. Below are the set of governing equations for the Single Particle model to be realized.

A. Equations

$$\frac{\partial c}{\partial t}(r,t) = \varepsilon \frac{\partial^2 c}{\partial r^2}(r,t) \tag{1}$$

$$c(0,t) = 0 \tag{2}$$

$$\frac{\partial c}{\partial r}(1,t) - c(1,t) = -q\rho \mathrm{I}(t) \tag{3}$$

where $\rho = \frac{\mathrm{R}_s^-}{(\mathrm{D}_s^- \mathrm{F}\alpha^- \mathrm{AL}^-)}$.

$$\mathrm{V}(t) = \frac{\mathrm{RT}}{\alpha^+\mathrm{F}} \sinh^{-1}\left(\frac{\mathrm{I}(t)}{2a^+\mathrm{AL}^+ i_0^+(c_{ss}^+(t))}\right) - \frac{\mathrm{RT}}{\alpha^-\mathrm{F}} \sinh^{-1}\left(\frac{\mathrm{I}(t)}{2a^-\mathrm{AL}^- i_0^-(c_{ss}^-(t))}\right)$$

$$+ \mathrm{U}^+(c_{ss}^-(t)) - \mathrm{U}^-(c_{ss}^-(t)) - \mathrm{R}_f \mathrm{I}(t) \tag{4}$$

where

$$i_0^j(c_{ss}^j) = k^j \sqrt{c_e^0 c_{ss}^j(t)(c_{s,\max}^j - c_{ss}^j(t))},\ j \in \{+,-\} \tag{5}$$

Charge Shuttles

One simple approach for redistributing the energy among cells is to connect a capacitor first to the higher voltage cell, then to the lower voltage cell, as shown in Figure 4.9(a). More complicated implementations allow us to connect not only two nearby cells, but also several series cells, as shown in Figure 4.9(b), Figure 4.9(a) Simple capacitor-based shuttle cell balancing circuit. (b) Charge shuttle circuit with several series cells. Cell-Balancing Suppose there are n cells in series and that Cell 1, cell 2, ..., cell *n* share flying capacitors with their two neighboring cells, so the charge can travel from one end of the cell string to the other. This approach would take a large amount of time to transfer charge from the high cells to the low cells if they are on the opposite ends of the pack because the charge would have to travel through every cell with time and efficiency penalties. This would not be an efficient solution. Energy loss during capacitor charging is 50%, so heating in the FETs used as switches have to be considered if high-current balancing is supported. However, because there is no charge loss with this process, the energy available on the pack terminals decreases only due to the decrease of cell voltages. Another problem is that high voltage differences between the imbalanced cells exist only in highly the discharged state. Because this method transfer rate is proportional to voltage differences, it only becomes efficient near the end of discharge or the end of charge so the total amount of imbalance, that can be removed during one cycle, is low. The figure below is a representation of a BMS modified with a ultracapacitor bank with the cells.

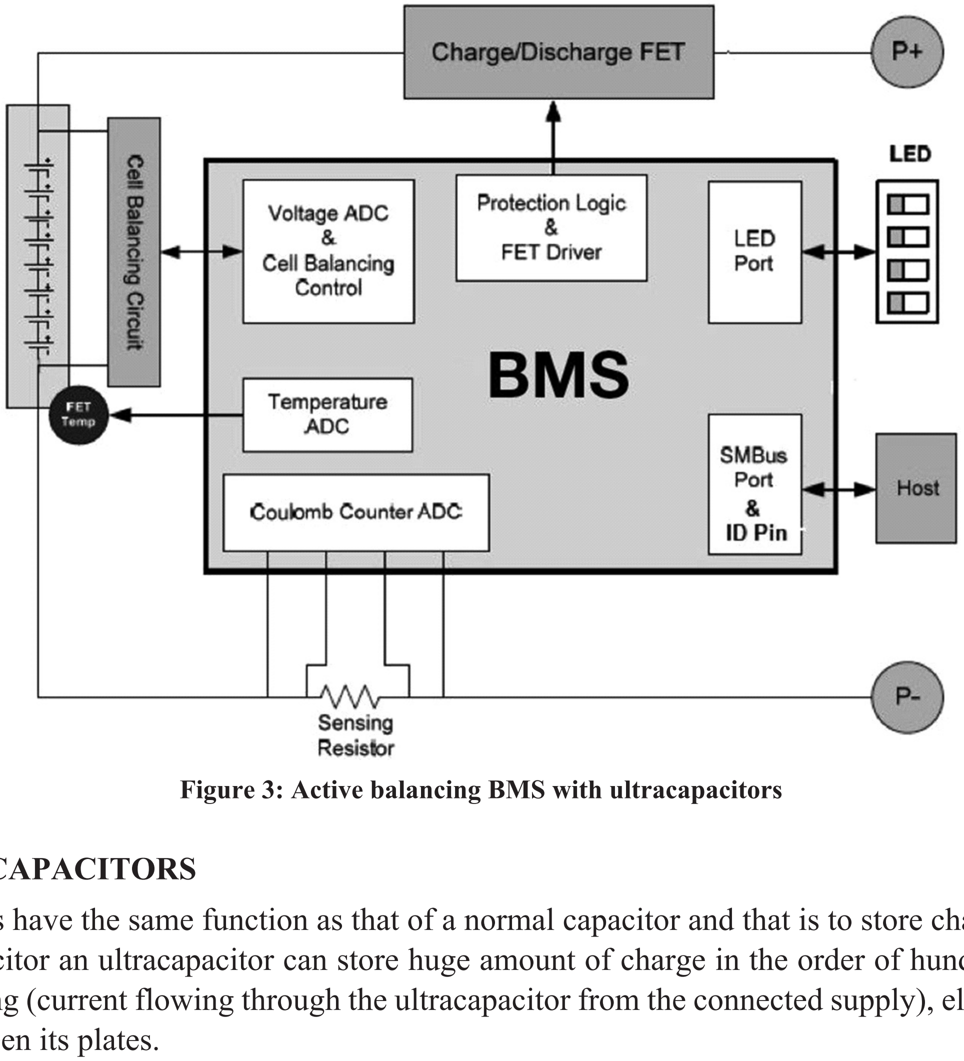


Figure 3: Active balancing BMS with ultracapacitors

4. ULTRACAPACITORS

Ultracapacitors have the same function as that of a normal capacitor and that is to store charge but unlike a normal capacitor an ultracapacitor can store huge amount of charge in the order of hundreds of Farad. During charging (current flowing through the ultracapacitor from the connected supply), electrical energy is stored between its plates.

Once the ultracapacitor is fully charged, current stops flowing from the supply and the ultracapacitors terminal voltage is equal to the voltage of the supply. As a result, a charged ultracapacitor will store this electrical energy even when removed from the voltage supply until it is needed acting as an energy storage device. But the maximum voltage is only about 2.7 V, series or parallel connections are required to achieve desired power.

While discharging (current flowing out), the ultracapacitor changes this stored energy into electrical energy to supply the connected load. Then an ultracapacitor does not consume any energy itself but instead will store and release electrical energy. As required with the amount of energy stored in the ultracapacitor being in proportion to the capacitance value of the capacitor.

5. ULTRACAPACITORS AS CIRCUIT ELEMENTS

The governing equations and equivalent circuits are similar for both a simple electrolytic capacitor and an ultracapacitor . The circuit schematic in Fig. 2 represents the first-order model for an ultracapacitor. It has been modeled using passive elements similar to that of RC models for batteries and has a capacitance C, a series in resistor Rs, a resistor in parallel Rp, and a series inductor L. Rs is called the equivalent series resistance (ESR), it is the cumulative resistance offered by the electrolyte, contact resistances, the carbon(graphene) and this is what causes losses during charging and discharging. Rp simulates energy loss due to capacitor self-discharge, and is often referred to as the leakage current resistance. Inductor L results primarily from the physical construction of the capacitor and is usually small. However, in many applications, it can't be neglected—particularly those operating at high frequencies or subjected to hard switching. Resistor Rp is always much higher than Rs in practical capacitors.

$$\mathrm{Z} = \mathrm{R} + i\,(2pf\,\mathrm{L}^{-1/2}\,pf\,\mathrm{C}),$$

Where L is the inductance in [Henrys]. The impedance is purely resistive when

$$2pf\,\mathrm{L}^{-1/2}\,pf\,\mathrm{C} = 0$$

or,

$$f = 1/2\,p(\mathrm{LC})1/2$$

The ESR(Equivalent Series Resistance) of an ultracapacitor is much lesser than a normal electrolytic capacitor. Which leads to minimal losses due to self-discharge.

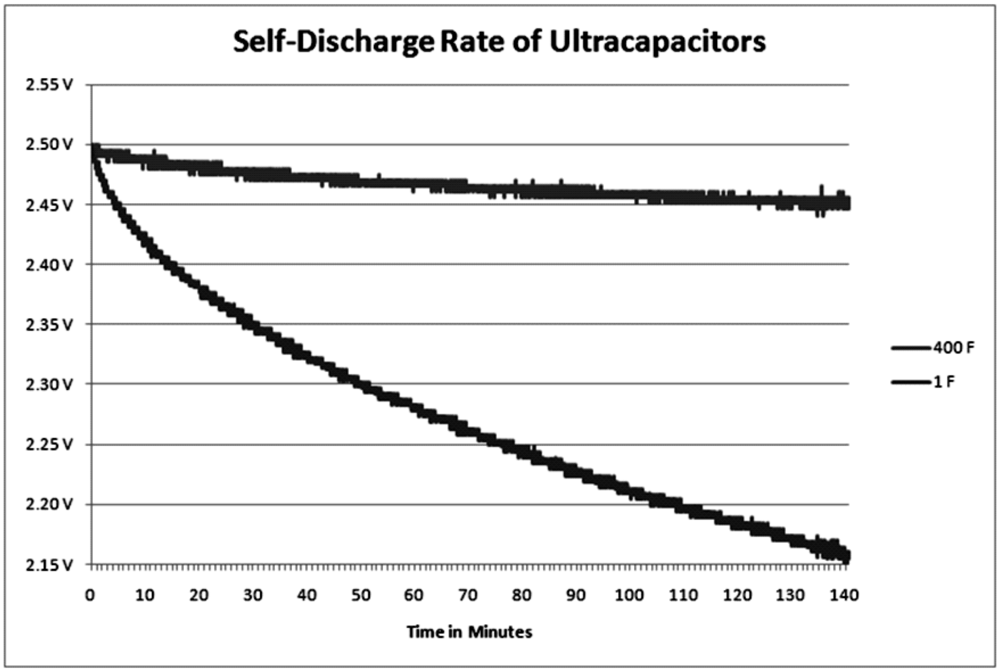
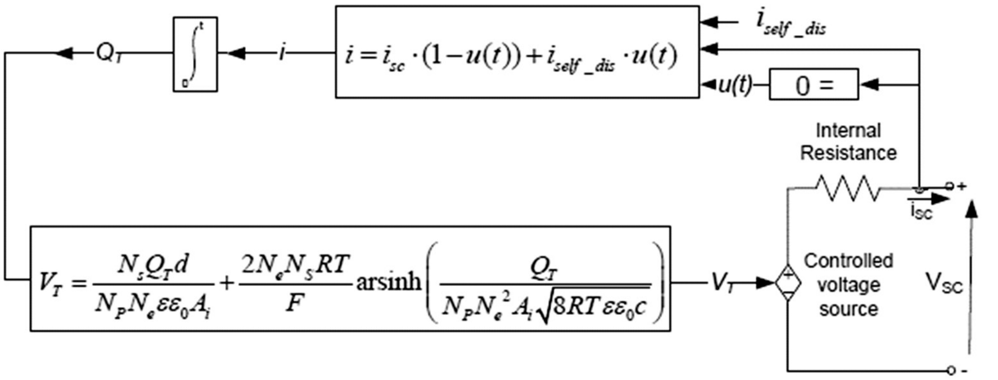


Figure 4: Ultracapacitor discharge over time

Due to it's inherent characteristic of very low ESR and high self-discharge period it is very useful for storing charges which are developed due to SOC imbalance in cells. And these can be connected on the individual cell boards of each cell switched via a bi-directional MOSFET which can charge during cell balancing and also discharge in the opposite direction when the battery pack is not actively used or when the tractive system of an EV is shut down the excess charge can be redistributed in the battery pack.

6. MATLAB SIMULATION FOR ULTRACAPACITOR

A Simulink model has been generated to test the authenticity of the system where the ultrcapacitors are storing charge on the cell board, moreover the self-discharge rate of the ultracapacitor is also analyzed.



The ultracapacitor output voltage is given by Stern equation:

$$V_{SC} = \frac{N_S Q_T d}{N_p N_e \varepsilon\varepsilon_0 A_i} + \frac{2N_e N_s RT}{F}\sinh^{-1}\left(\frac{Q_T}{N_p N_e^2 A_i\sqrt{8RT\varepsilon\varepsilon_0 c}}\right) - R_{SC}\cdot i_{SC}$$

With

$$Q_t = \int i_{SC}\cdot dt$$

Due to self-discharging of the ultracapacitor the equation for charge stored is modified as:

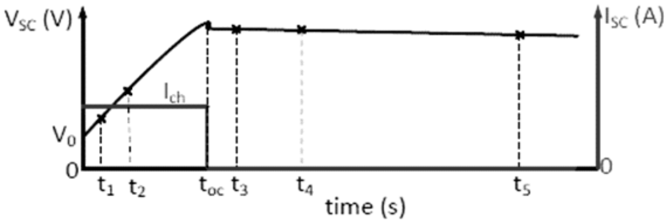
(for, $i_{SC} = 0$):

$$Q_t = \int i_{\text{self\_dis}}\cdot dt$$

Where,

$$i_{\text{self\_dis}} = \begin{cases} \frac{C_T\alpha_1}{1+sR_{SC}C_T} \text{ if } t - t_{OC} \le t_3 \\ \frac{C_T\alpha_2}{1+sR_{SC}C_T} \text{ if } t_3 < t - t_{OC} \le t_4 \\ \frac{C_T\alpha_3}{1+sR_{SC}C_T} \text{ if } t - t_{OC} > t_4 \end{cases}$$

The graph shows change in ultracapacitor voltage during time intervals (t_{OC}, t_3), (t_3, t_4) and (t_4, t_5) respectively.



The percentage of charge present in the ultracapacitor is quantified using a parameter similar to that used in batteries which is called SOC(State Of Charge)

$$\mathrm{SOC} = \frac{\mathrm{Qinit} - \int_0^t i(\tau)\, d\tau}{\mathrm{Q_T}} \times 100$$

However there are a couple of assumptions made for this particular model:

1. The Internal resistance offered by the electrolyte and the carbon is assumed to be constant for charging and discharging cycles
2. It does not consider thermal effects on the electrolyte(since there is very negligible variation).
3. Aging effect of ultracapacitors is not taken into account.
4. The block does not model charge or SOC balancing.
5. Current through the ultracapacitor is assumed to be continuous.
6. The redistribution of charge is assumed to be constant for different voltages.

7. CONCLUSION

This research paper essentially provides us an insight over ultracapacitors and it's potential application for using it for a BMS with active balancing to minimize losses. The superior properties of ultracapacitors like very low ESR and self-discharge rate make it perfect for EV applications as well where the power consumed by the low voltage (LV) system in the sleep state is completely saved. The MATLAB simulations exhibit the ability of the ultracapacitors to hold the charge for long durations of time enables to balance and even out the charges over the battery pack even after a long period of continuous run. However, there is still scope for research in terms of having a more efficient charging of ultracapacitors but the cell boards on most of the commercially available BMS have inherent current limiters and controlled discharge circuitry which can satisfactorily solve the charging and discharging issues. This paper also gives brief information about how the battery analysis was performed and the corresponding iterations enabled us to understand the passive dissipation losses if avoided can drastically improve the voltage-time profile. So a distributed type active BMS with ultracapacitors are probably the best energy efficient method for battery management for EVs and Solar Panels.

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