Cell Equalization In Battery Stacks Through State Of Charge Estimation Polling

Carmelo Speltino, Anna Stefanopoulou and Giovanni Fiengo

***Abstract*— Battery packs are charged and discharged as a single battery, therefore it is possible that differences between cells (i.e. chemical characteristics, operating temperature or different internal resistance) can cause differences in cell remaining capacity, leading to overcharging or overdischarging of respectively most charged and most discharged cells, decreasing the total storage capacity, shortening the battery lifetime and, eventually, permanently damaging the cell. The system proposed in this paper uses the switching capacitor method for cell equalization during bidirectional operations and it relies on a State Of Charge (SOC) estimator in order to select the target cell for charge distribution. The SOC estimator is based on an Extended Kalman Filter (EKF) that has been validated against experimental data collected from a 10 A - 42 V lithium-ion battery pack, composed by a series connection of 10 SAFT-MP176065 cells, in [14].**

Keywords: Battery Equalization, SOC estimation, Extended Kalman filter, Charge Shuttling.

I. INTRODUCTION

Efficient charging and discharging is one of the major issues in rechargeable battery related research, because it leads to short charging time and extends the life span of the battery pack. Lithium-ion batteries need special protection from overcharge and overdischarge, because if the single cell voltage becomes higher than 4.5 V, the production of carbon dioxide, ethylene and other gases will increase temperature and internal pressure, causing severe battery damage or in the worst case cell explosion, while if the voltage goes under 2.4 V, internal chemical reactions cause the cell to irreversibly lose large part of its capacity [3] [13].

Applications that need high voltage levels, like Hybrid Electrical Vehicles (HEV) usually employ large bank of series-connected cells to provide the power requested. Considering that lithium-ion cells have low rated voltage (i.e. about 3.7 V), generally an HEV battery pack is composed by two or three hundred individual cells. Aging, use and calendar life leads to cell-to-cell variability. It is not, however, possible to substitute a single exhausted cell in a battery pack with a new one. So, it becomes clear that the State Of Health (SOH) of the entire pack is equal to the SOH of the most damaged cell. Simply stopping the discharge when the unit with least capacity is empty (or conversely during a charge when the most charged unit is full) will result in a heavy limitation on using the potential remaining energy.

In order to prolong the battery life cycle and avoid damages to the cells as described above, it is recommended that all the cells in a pack have the same SOC during battery operations. While different type of batter~~y~~ are able to self equalize by extended charging (i.e. trickle charging for lead acid batteries), lithium-ions cannot be overcharged, and so a Battery Management System (BMS) has to be used. Several equalization methods have been proposed in literature [2] and [8]. They can be divided in two big categories, dissipative and non-dissipative. The management systems of the first kind usually try to equalize the cells by extracting energy from the higher charged ones and dissipating it on shunts or resistors [1], or selectively removing imbalanced cells from the battery pack [12]. Even if such systems have high equalization speed, they will consume energy stored into the battery or lower too much the pack voltage causing power failure and so are not suited for HEV, where energy equals mileage.

Non dissipating methods can be divided in discharge equalizing system, like multi-output transformers [5], charge equalizing systems, like distributed Cuk converter [4], [6] and [9], and bidirectional equalizing systems, like switched capacitor or inductor circuit [7]. Each one of those schemes has its advantages and drawbacks, in term of equalization speed, circuit complexity, number of parts needed and rating of the part to be used ~~(i.e. in~~ particular the current rating of the switching components and the voltage rating of the diodes~~)~~, but they all need SOC feedback as control input to perform equalization operation.

Usually, the SOC value used for control in those methods, is often based only on the measured voltage differences between cells. This leads to a limited usefulness of the proposed solution in case of lithium-ion batteries that exhibit an almost flat voltage curve in mid-SOC range, thus cell equalization decisions could be influenced by voltage measurement noise, limiting the performance of chosen solution to the performance of sensor used to measure voltage. Other methods need a short rest of the battery in order to measure the voltage that could be approximately equal to the open circuit voltage, and then estimate the battery SOC from this value. An extensive review of such SOC estimation techniques can be found in [11]. A different solution based on an EKF SOC estimator can be found in [10], where the battery model is mainly based on an equivalent circuit representation including terms that describe the dynamic contribution due to open-circuit voltage or temperature effects, while the closed-loop feedback regulation provides root-mean-squared error lower than the quantization error expected on the sensor

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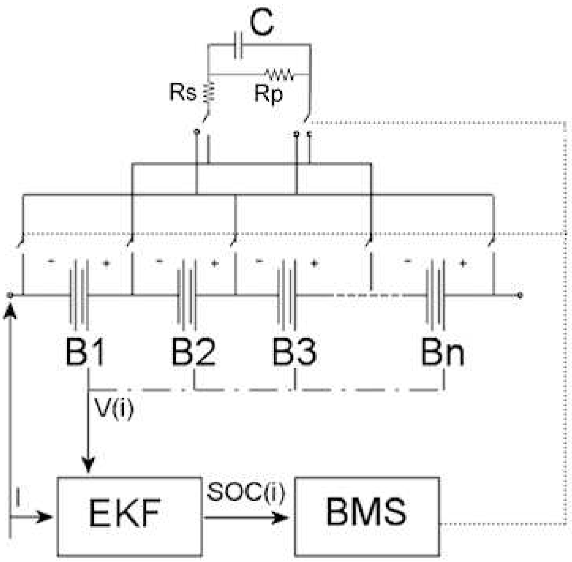

Fig. 1. Schematic connections of the BMS components.

measurements. The solution proposed in this paper also uses an EKF SOC estimator previously developed and illustrated in [14] in order to estimate remaining charge in the single cells and use the estimated value to control the operation of a simple bidirectional method based on charge shuttling. A capacitor will absorb energy from the whole battery, charging very fast and selectively discharging on the weakest cell in the pack.

II. BMS OVERVIEW

The BMS system is composed of a SOC estimation block (the EKF), the logic management block (the BMS) and the charge shuttling unit, that can be a capacitor or an ultra-capacitor. The capacitor used has 20 F capacity at 15 V rate. A resistance $R_p = 50\ m\Omega$ has been added in parallel with the capacitor is used to model the self discharge rate of the capacitor, while a resistance $R_s = 2\ \Omega$ has been placed in series with the capacitor in order to model the capacitor equivalent series resistance and provide a limitation on the current flowing into the capacitor itself. Figure 1 shows the connection between the various component of the system. The EKF uses the battery pack current and the single cell voltage to estimate the SOC of the *i-th* cell. SOC values are then used by the logic management to control the opening and closing of the switch, allowing the capacitor to charge itself and after to discharge on the selected cell. When the BMS detects a difference in SOC between the cells higher than 10% the following procedure starts:

1) Identify the lowest charged cell while charging the capacitor up to a fixed threshold HV.
2) Discharge the capacitor over the selected cell until its voltage goes under a fixed threshold LV.
3) Check SOC difference for all the cell.
4) Repeat step 1, 2 and 3 until maximum difference in SOC become lower than 2%.

The procedure is very similar to all the other proposed methods to equalize different charged cells. The main difference is in the SOC estimation technique used. The solution proposed is able to track the SOC of the cell continuously, without need ~~of~~ resting the battery during operations. The estimation of SOC status of single cells can be updated constantly, incorporating part of step 3 during operation of step 1 and 2. Instead of having a dedicated EKF for each cell of the battery pack, we propose a solution with a single estimator that polls cyclically the cells, using current and voltage measurements of the cell being polled to estimate its SOC. Because the estimator does not need to be initialized with a starting value, those two measurements are sufficient to the EKF to converge to the SOC value very quickly.

The Kalman filter gain has been tuned in order to ensure the convergence of estimation in less than 5 s. Figure 2 shows the cyclic polling among the cells and the convergence of SOC estimation on a series of 3 cells during a constant current charge. Every 10 s, the EKF polls a new cell, estimating the SOC of the new target with the feedback measurements of its current and voltage. The model used to simulate the cell is the reduced order battery model presented in [15]. Model parameters have been identified versus data collected from a SAFT-MP176065 3.7 V - 6.8 Ah cell. The cell model has the current supplied to the battery as input, while its outputs are the cell voltage and the cell SOC, computed on the base of the average concentration of lithium inside the electrodes. The current is positive when the battery is discharging. The polling time is fixed to 10 s, while the charging current is limited to 6 A. Figure 2 shows the fast convergence of the filter estimation during the cell switching. To simulate real sensor measurement, uniform random noise has been added to the inputs of the EKF in order to take into account both sensor noise and quantization error. The current input has a superimposed uniform random error of ± 0.05 A, while the voltage error is ± 0.02 V. The amplitudes of the error signals have been chosen in order to reflect realistic sensor measurements. The SOC of the cells that are not polled by the EKF are tracked by simple integrator models, based on the cells current inputs and its nominal capacity:

$$SOC(i) = \frac{1}{C}\int I dt + SOC(i)_0, \tag{1}$$

where C is the cell nominal capacity, I is the input current and $SOC(i)_0$ is the last estimated SOC for the *i-th* cell. In this way it is possible to keep track of single cells SOC even during normal battery operation, updating the $SOC(i)_0$ value in (1) each time the cell is selected for EKF polling at the end of its 10 s period. During step 2, the $SOC(i)_0$ value of the cell selected for charging is not updated because the EKF SOC signal has a peak during the charge injection that may lead to error when comparing it the other cell SOC values as provided by the BMS model. The reason is that the integrator model is unable to catch the fast dynamics of the cell Even if the bank of integrator does not provide a precise SOC calculation, it retains the differences in SOC among the cells when subject to the same current input. For

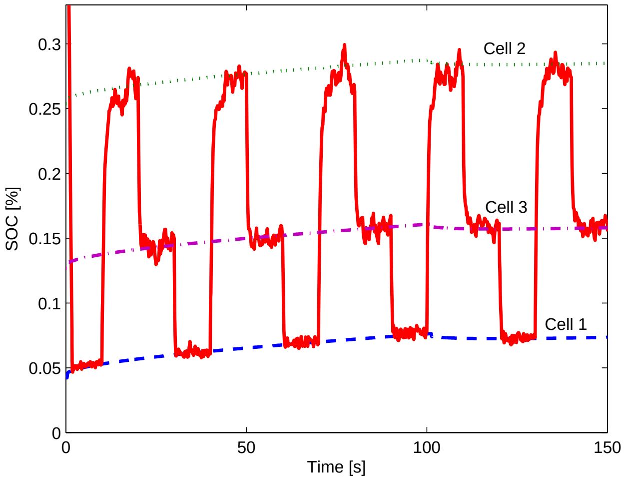

Fig. 2. Kalman filter SOC estimation in daisy chain polling. Red solid line is the EKF SOC, while the blue dash, green dot and purple dash-dot are respectively cell 1, cell 2 and cell 3 SOC as calculated from cell model.

the purpose of equalizing the cells, the differences in their SOC values are more important than the absolute SOC, that is fixed to the correct value each time the cells are polled by the EKF.

Charging and discharging a capacitor using a DC voltage source is not an efficient way to transfer charge between the component of the system. The performance of the BMS can be increased by placing an inductor in series with the capacitor, or controlling the switching rate during the charge and discharge of the capacitor as in [16]. It is important to note that the principal aim of this paper is not to provide a new battery management design but instead to apply the previously derived EKF SOC estimator as fundamental component for the BMS design. The efficiency and speed of the equalization process depend on the circuit design and characteristics, but the correct estimation of cell SOC is the critical control input for any BMS design, in particular for lithium-ion batteries, because of their flat voltage/SOC relationship. The charge shuttling method used in this paper is not the most sofi~~sticated~~ solution that can be found in literature, but is able to equalize the battery during both charge and discharge and it is very simple to model in order to test the performance of the proposed solution in simulation. The algorithm proposed in step 1 to 4, is valid for any equalization method, because it provides the logic behind the cell selection to balance the SOC of the cells.

III. BMS OPERATION AND RESULTS

In this section two different operating cases of the BMS will be presented. The first case shows the performance of the system during a constant current charge, with the SOC of the cell slowly varying due to the almost steady current input. The constant current allows a clear distinction between the external battery input current due to the power generator and the individual cell loads due to the BMS. The second case shows the performance of the system during a periodically repeating step current demand, that charges and discharges the battery alternating positive and negative current requests. The mean value of the second case input is positive so the overall effect during time is a slow discharge of the battery pack. The objective of the second case is showing the performance of the system during a bi-directional use of the battery. An advantage of the proposed method is that the equalization method chosen does not require a particular load condition and the EKF is able to continuously track the SOC during battery operations. For clarity the battery pack will be composed by three cell in series (i.e. like a typical notebook battery), but the system is scalable in order to manage more cells.

A. Case 1 - Constant current charge

Figures 3-5 show the performance of the BMS during a constant current charge. The initial SOC for the cells of the battery have been set equal to $[5\%, 25\%, 12\%]$ and the maximum charging current has been set to 5 A. A simple model of a power generator has been used in order to simulate a realistic charge with a Constant Current part followed by a Constant Voltage (CC/CV) end of charge. The generator model is based on the following relationship:

$$I = \frac{V_B - V_G}{R_B}, \tag{2}$$

where I is the current supplied to the battery pack from the generator, V_B is the voltage of the battery pack, V_G is the voltage set point of the generator (in this case $4.2 \times 3 = 12.6$ V) and R_B is the equivalent battery resistance. The current output is saturated in order to provide a maximum charging current equal to -5 A and is passed through a low pass filter to stabilize the current supply to the battery. The CC/CV is the commonly used pattern used for lithium-ion battery chargers.

Figure 3 top plot shows the output voltage of the battery pack, subject to charge and equalization process. Voltage fluctuations are due to current absorbed by the capacitor during step 1, and after released during step 2. Bottom plot shows the single cell SOC. It is possible to see how the equalization process decreases the imbalance during the charge, stopping itself when the final maximum SOC difference is under the fixed threshold of 2%. The vertical line in the plot shows the end of equalization process. Figure 4 shows the current inputs of the single cells during the equalization phase. During step 1, all the cell receive the same current, equal to the charging current from the power generator minus the current absorbed from the capacitor. During step 2 instead, only the selected cell receives the current surplus coming from the discharge of the capacitor. Because cell 3 is the weakest of the whole pack, it is the first to be selected, until it becomes more charged than cell 1 at about 2200 s. From this point (highlighted by the two vertical lines in Figure 4) the two cell will be selected alternatively (as it is possible to appreciate in the middle zoom of cell SOC in Figure 3 - bottom plot), until their SOC will differ from cell 2 SOC by less than 2%. At this point the

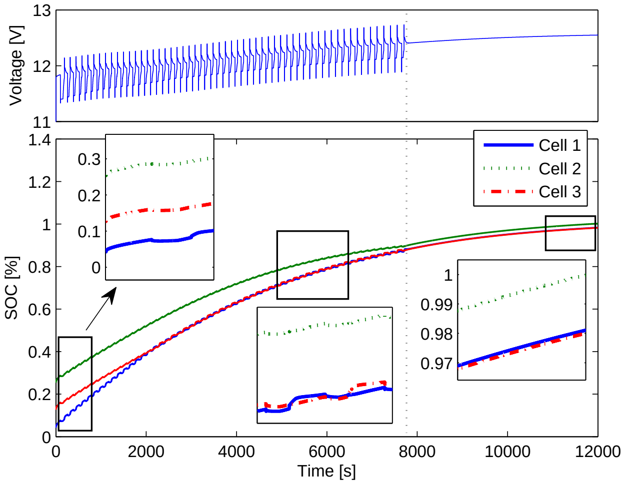

Fig. 3. Top plot, battery pack voltage during charge and equalization. Bottom plot, SOC of the single cells. A 20% SOC imbalance is recovered in about 2 hours.

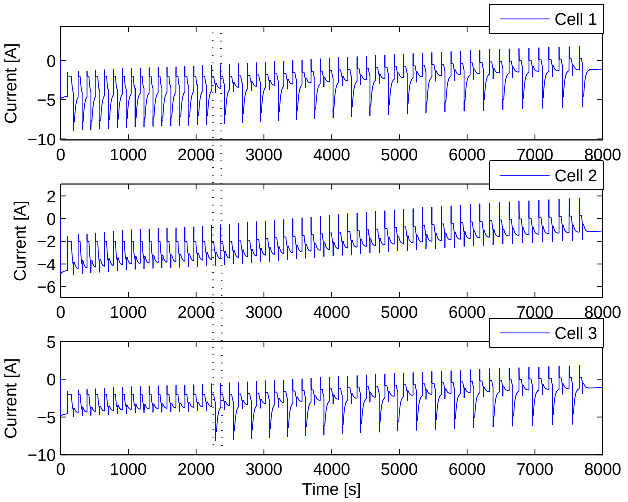

Fig. 4. Single cell current inputs during charge and equalization. The selected cell receives more current than the other cells during the capacitor discharge. The dot vertical lines indicate the first cell selection switch.

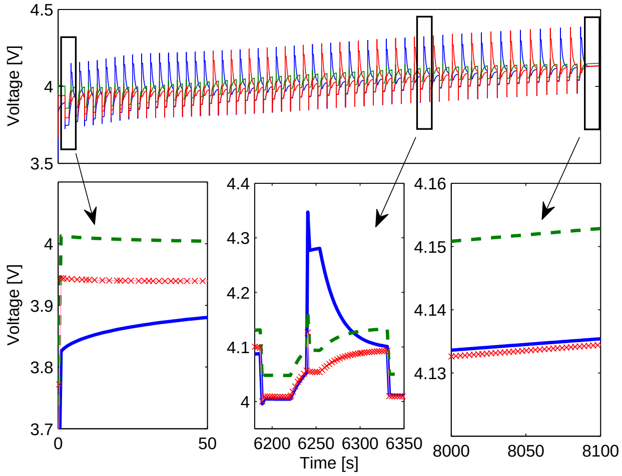

Fig. 5. Single cell voltage output during charge and equalization. It is possible to notice the different starting voltage of the cells, due to SOC imbalance. Solid blue line is cell 1, green dash line is cell 2 and red line with (x) marks is cell 3.

BMS disables the switching control, allowing normal battery charging. During the equalization phase, the current supply to the cells can even become positive (e.g. the battery is discharging), because the current absorbed by the capacitor is greater than the current provided by the power generator. In this case the BMS is simply shuttling charge between the whole pack and the capacitor, reversing the process during step 2, but on a single selected cell. Figure 5 shows the single cell voltage outputs. Comparing the zoom of the first 50 s with Figure 3 top plot, it is possible to see how the battery voltage is simply the sum of cell voltages and how this does not reflect the inequalities in single cell remaining charge. Estimating the battery SOC from the pack voltage leads to an initial value of 14% causing the overcharge of cell 2 and a not full charge of cell 1 at the end of a normal charging without cell equalization. The middle zoom in bottom plot of Figure 5 shows the voltages of the cells nearly at the end of the equalization process, during the charge of the capacitor (from 6190 s to 6240 s) and the following capacitor discharge on cell 1 (from 6240 s to 6330 s). The voltage difference between cells is smaller than at the beginning due to the equalization process. The left zoom of Figure 5 shows the voltage of the cells after the equalization process has met the fixed threshold in SOC difference among the cells. Finally, Figure 6 shows the SOC signals of cell 1, as provided by the cell model, by the EKF and from the BMS open loop charge estimation as defined in (1). The top plot of Figure 6 shows the comparison between the SOC as calculated from the cell model and the SOC estimated by the EKF during the cells polling. It is possible to notice as the EKF cycles between the various cells, focusing on cell 1 every 30 s and quickly recovering the correct SOC value. The bottom plot of Figure 6 shows the comparison between the BMS tracked SOC and the value provided by the model. Because the cell 1 is selected by the BMS for charging, the starting value $SOC(1)_0$ of the BMS tracked SOC is not updated until the capacitor discharge is finished. At 970 s, 1060 s and 1090 s, the cell 1 is not selected for charging and so the $SOC(1)_0$ value is updated with the value provided by the EKF SOC estimation.

B. Case 2 - Periodic step current discharge

Figures 8-10 show the performance of the BMS during a 120 s periodic step current input as shown in Figure 7. The initial SOC for the battery cells have been set equal to $[52\%, 63\%, 70\%]$. Figure 8 shows the voltage of the battery pack in the top plot and the SOC of the battery cells in bottom plot. As in the previous case the initial imbalance among the cells is recovered by the BMS that stops itself as the SOC difference becomes smaller than the

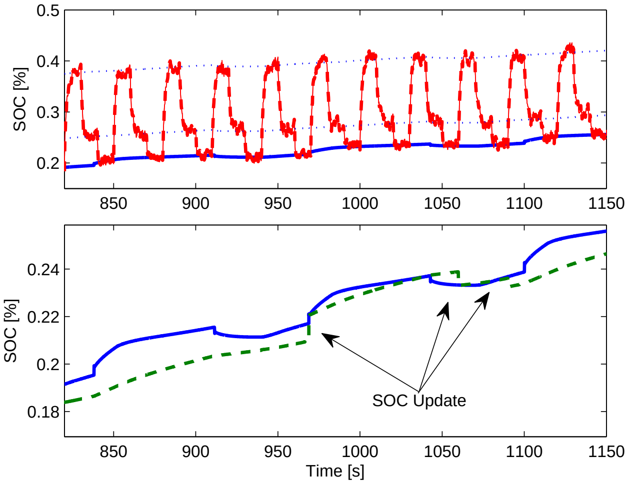

Fig. 6. Cell 1 SOC signals as provided by the model, the EKF and the BMS. Top plot, solid blue line is the cell model SOC, red dash line is the EKF and dot lines are the other cells SOC. Bottom plot, solid blue line is the cell model SOC and green dash line is the BMS SOC.

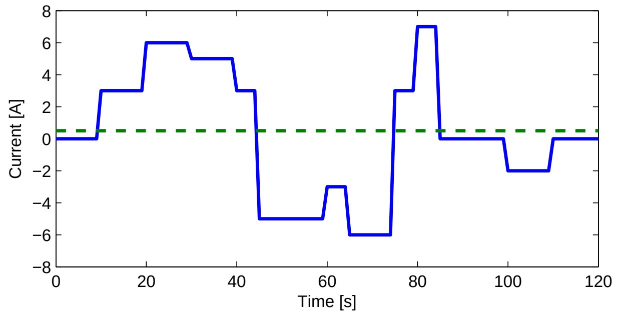

Fig. 7. Second case step current input, single 120 s period. Solid line is the current input, dash line is the mean value.

fixed threshold. In this case the voltage fluctuations are due both to the equalization process and to the step current input. The voltage drop at the end of the discharge is due to the reached depletion state of the battery cells, when the SOC is close to 0% as correctly estimated by the EKF.

Figure 9 shows a section of the cell currents to the first change in cell selection by the BMS due to cell 2 being more charged than cell 1, as is possible to see in Figure 8 - bottom plot. The withe areas indicate the cell selected for charge injection by the BMS. It is possible to see how cell 3, being the most charged cell of the pack, is never selected by the BMS. From this point on (about 2400 s), the BMS selection will switch between cell 1 and cell 2, until their SOC value will differ from the highest charged cell (i.e. cell 3) less than the fixed threshold. When two or more cells have been equalized, a small error in the BMS SOC estimation can lead to consecutive selections of the same cell (as is possible to see in Figure 9 - top plot, where at 2900s cell 1 is selected instead of cell 2). This error is compensated by multiple selections of the other cells during the equalization process, leading to the same final equalization result. Figure

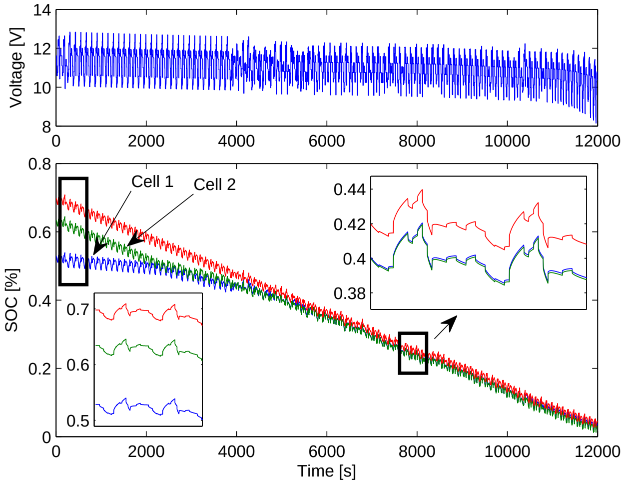

Fig. 8. Top plot, battery pack voltage during periodic step current demand and equalization. Bottom plot, SOC of the single cells. A 18% SOC unbalance is recovered in about 1.5 hours.

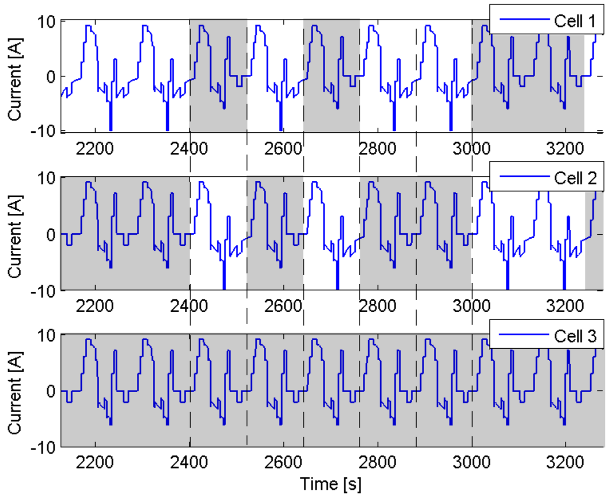

Fig. 9. Single cell current input during periodic step current demand and equalization. The selected cell receives more current than the other cells during the capacitor discharge. White areas indicate cell selected by the BMS.

10 shows the voltage output of the battery cells under the periodic step current demand and equalization. In this case it is possible to notice how the initial cell voltage difference (top bottom plot of Figure 10) is lower than the final cell voltage difference (bottom plot of Figure 10), e.g. at the end of the discharge process), even though the SOC unbalance is initially 18% and only 2% at the end of the simulation. This is due to the flat characteristics of lithium-ion battery voltage in mid-SOC range, while it decreased much more rapidly as the cell is close to its depleted state. In this case, a SOC estimation method based on the voltage difference will fail to correctly catch the initial high SOC imbalance or conversely will flag a difference in cell status when there is only a little variation among them. Figure 8 show also the inefficiency

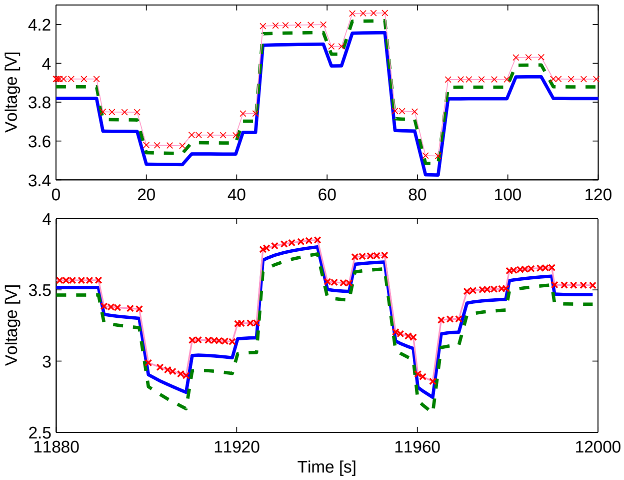

Fig. 10. Single cell voltage output during periodic step current demand and equalization at the beginning (top plot) and at the end of discharge (bottom plot). Solid blue line is cell 1, green dash line is cell 2 and red line with (x) marks is cell 3.

of the equalization method chosen. Infact it is possible to notice how the current input leads to a complete discharge of the battery pack in about 3.3 hours, while without the BMS operation the estimated discharge should be more than 4 hours. This is due to the energy loss during the charge and the discharge of the capacitor and can be avoided choosing a different equalization circuitry.

IV. CONCLUSIONS

Maintaining the equalization of all the cell in a pack is fundamental for prolonging the life and the performance of the battery. To this aim, a BMS based on an EKF SOC estimator for lithium-ion battery has been presented and its results shown in simulation during a constant current charge and a periodic step current discharge. The proposed system is able to equalize the single cell SOC during bidirectional operations, continuously tracking individual cell SOC. Thanks to its fast recovering performances, the EKF polls cyclically each cell while a simple integrator model tracks the SOC of the cell not being polled, in order to supply to the lack of measurement during battery operation. The BMS shows a good performance both in speed and accuracy of the equalization process, starting from highly imbalanced cells and bringing the SOC difference among the cells under the fixed threshold during a single charge or discharge cycle. The drawbacks of the proposed system are the maximum number of cells that can be controlled by a single EKF with the polling cycle and the performance of the BMS equalization method due to the energy loss during the charge and discharge of the capacitor. With 10 s per cell, polling a battery composed by 60 cells will need more than 10 minutes to update the measurement of the i-th cell. In this case a good compromise will be to divide the battery pack in subset of 10 or 20 cells and manage each pack separately with a dedicated BMS system per pack. In order to obtain better performance in terms of energy efficiency, it is necessary to change the equalization method, using one of the design indicated in the literature. Because each of this methods is based on the SOC estimation, it is not necessary to apply changes into the BMS algorithm, that retains its validity for any design presented. In order to ensure the best performances it is recommended to choose a non-dissipative/bi-directional design, able to equalize the battery pack continuously during any kind of operations.

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