Active Cell Balancing Control Method for Series-Connected Lithium-Ion Battery

Ohirul Qays, Yonis Buswig, Martin Anyi

Abstract: Power conveyance potentiality for series and parallel allied battery-packages are constrained by the wickedest cell of the string. Every cell contains marginally dissimilar capability and terminal voltage because of industrialized acceptances and functional situations. During charging or discharging progression, the charge status of the cell strings become imbalanced and incline to loss equalization. Therefore, the enthusiasm of this paper is to design an active charge balancing system for Lithium-ion battery pack with the help of online state of charge (SOC) estimation technique. A Battery Management System (BMS) is modeled by means of controlling the SOC of the cells to upscale the efficacity of rechargeable batteries. The capacity of each cell is calculated by dint of SOC function estimated as a result of Backpropagation Neural Network (BPNN) algorithm through four switched DC/DC Buck-Boost converter. The simulation results confirm that the designed BMS can synchronize the cell equalization via curtailing the SOC estimation error (RMSE 1.20%) productively.

Index Terms: Active Cell balancing, Battery Management System, Battery modeling, SOC estimation.

I. INTRODUCTION

Smart grids and Electric vehicles (EVs) are turning out to be widely held owing to the increment of atmospheric apprehensions and deficiency of fossil fuels. As a perilous condition of the energy involving machineries, battery energy storage system (BESS) performs an indispensable role to provide power source and enhance the stowage strength [1]. Nevertheless, the BESS struggles with the variation of cell-to-cell parameter inconsistencies as well as these factors affect the battery cells life-time undesirability. To fix this delinquencies, BMS is entitled as the intellect of a battery system to observe the charge equilibrium scheme. The remainder of this paper is structured as follows: The previous related work is presented in section 2. In section 3, the proposed methodology is explained descriptively. Numerical simulation and a brief discussion for the proposed method is demonstrated in section 4. In the last section 5, the conclusion of this paper is drawn.
II. RELATED WORK

The series cell sequences decrease the capability of entire battery pack due to any weaken battery cell of the strings. To improve the efficiency of the storage system, [2] proposed an improved BMS for LIB pack to regulate the temperature, SOC and SOH of the cells by the dual active bridge DC/DC converter. Extended Kalman Filter (EKF) and active cell balancing technique was implemented to improve the accuracy of the SOC estimation and charge equalization respectively where the SOC variation was obtained only 3%. In the long run, the fragile cell was recommended to avoid from the string if the cell eminence can’t be improved finally. A significant parameter named Residual Available Energy (RAE) can be utilized to measure the departure of energy from the battery pack. Depending on this statement, [3] experimented active cell balancing equalization technique on eight capacitive battery cells which were preferred from 95 aged batteries commencing a company’s EV. The internal resistance and capacity of every single cell were applied to compute the status of RAE for entire battery pack where the energy employment improved nearly 10.97%. Though the error between the experimental and simulation was obtained less than 1%, only, the load was assumed as static for the projected system. Finally, a compensation between the improved RAE and energy forfeiture was suggested for further research to boost the adeptness of the stratagem. After the increment of 70% SOC of the Li-S battery, self-discharging occurrence can be noticed extremely due to the polysulfide shuttle appliance. To get rid of from this energy tempest of the Li-S battery, [6] investigated electrochemistry based cell balancing technology on the series-connected Li-S cells by dint of varying temperature, charging time and wasting period in elevation SOC. At last, the author concluded that electronic circuit can be simplified or excluded to reduce the cost of the system by means of this proposed method. Nevertheless, the cells aging effect was endured questionaries about the charge effectivity at a number of self-balancing environments. Reference [4] proposed switched-capacitor cell balancing topology under zero-current switching where a pair of complementary square wave was essential to regulate the balancing circuit.

III. PROPOSED METHODOLOGY

A. Battery modeling

Battery model is exercised to conduct the affiliation between internal and external performance of a battery. Usually two types of battery models are classified namely electrochemical model and equivalent circuit model [12]. Electrochemical model entirely depends on internal chemical reaction of a battery. For this reason, electrochemical model contains analytical complexity and calculation delinquencies to achieve parameter accurateness. On the other hand, equivalent circuit model relies on external dynamic appearances that can sidestep the comprehensive deviousness of internal electrochemical progressions. Therefore, Equivalent circuit model is frequently enrolled to replicate the cells’ peripheral characteristics and enhance the truthfulness of BMS [13],[14]. This paper contains the first-order Thevenin Equivalent circuit model which is shown in Fig. 2; V<sub>0</sub> and V<sub>OCV</sub> are the terminal voltage and open circuit voltage (OCV) respectively as well as the relation between them can be stated from (1) to (3). Here, V<sub>R</sub> and V<sub>P</sub> are termed as the ohmic voltage and polarization voltage respectively.

![First-order Equivalent Circuit Model](image)

\[ V_0 = V_{OCV} - (V_R + V_P) \]  
\[ V_R = iR_S \]  
\[ C_P \frac{dP}{dt} = i - \frac{V_P}{R_P} \]

Here, R<sub>S</sub> is ohmic resistance that is the function of temperature, operating current and SOC. The solution of charge and discharge resistance are labeled as well.

B. Buck-Boost Converter

Non-inverting DC/DC Buck-Boost converter can convert the supply-voltage lower or higher according to its’ requirements. Fig.3 shows the circuit diagram of a synchronous Buck-Boost converter [16][17]. Four high speedy MOSFET switches (Q1-Q4) are engaged to regulate the energy conduction of cell strings. Following to the energy requirement of the system, the converter can be applied for Buck, Boost or Buck-Boost converter. When the cell voltage is higher or lower comparing to the desired voltage, the converter is set to buck and boost mode operation respectively. From Fig.3, in case of Buck mode operation, Q3 is off and Q4 is on at all times as well as Q1 and Q2 are exploited to control the procedure. When MOSFET Q1 is closed and Q2 is open, inductor is charged by the supply power. During inductor charging period, capacitor provides output current and the inductor current rises in straight. Additionally, Q2 is closed and Q1 is open at inductor discharging period as well as inductor delivers stocked-energy to the capacitor to charge the load. Average terminal voltage V<sub>out</sub> (equals dV<sub>SC</sub>) can be obtained by controlling duty cycle d<1 along with the supply voltage V<sub>SC</sub>. Furthermore, MOSFET M1 is on and M2 is off permanently for boost mode operation. M3 is closed and M4 is open at inductor charging period as well as M3 and M4 operations are reversed at discharging cycle. The average output voltage V<sub>out</sub> equals I/(1-d)V<sub>SC</sub>. The converter is fixed to Buck-Boost maneuver when the cell voltage is adjacent to the desired voltage. In this mode MOSFET M1 and M3 are kept closing as well as M2 and M4 are kept opening for inductor charging. Again the MOSFETs are operated in reverse position to discharge the inductor. The output load voltage V<sub>out</sub> equals to d/I-d)V<sub>SC</sub>.
C. **SOC Estimation**

State of charge (SOC) is a precarious valuation for battery enduring capacity. The significance of SOC estimation accuracy is prodigious for lithium-ion battery to certify its safety operation and avoid from over-charging and deep-discharging factors. Nevertheless, SOC estimation for the battery is a challenging issue owing to the nonlinear electrochemical reactions [18][19]. In this study, BPNN based SOC estimation algorithm is employed for which the structural design of the procedure is shown in Fig. 4. BPNN is the most far and widely utilized onlooker technique for nonlinear systems as a result of its self-learning and feedback characteristic [20]. The proposed model estimates SOC for every single cell individually as indicated in Fig. 5. Three parameters: voltage, current and temperature are collected from each cell in addition to estimate SOC bestowing the equations from (4) to (7). Weights are attuned according to the Root Mean Square Error (RMSE) of the SOC estimation so as to construe the assessed-outcomes more accurately. The total input of a hidden layer neuron can be deliberated from (4)

$$net_{i,n} = \sum_{i=1}^{3} x_i w_{i,m} + b_n$$

(4)

Where, $net_{i,n}$ is total input of the hidden layer neuron $n$, $x_i$ is the value of input neuron to hidden layer neuron $n$, $w_{i,m}$ is weight between input layer neuron $i$ and hidden layer neuron $n$, $b_n$ is the bias of the hidden layer neuron $n$.

Furthermore, in the hidden layer neuron, the applied activation function is the tangent function (5). In addition, the evaluation of output layer neuron can be obtained from (6)

$$h_{n} = f\left( net_{i,n} \right) = \frac{1 - \exp(-2net_{i,n})}{1 + \exp(-2net_{i,n})}$$

(5)

$$neto = \sum_{i=1}^{n} h_i g_i + p$$

(6)

Here, $neto$ is total outcome of the output layer neuron $n$, $h_i$ is the value of hidden layer neuron to output layer neuron $i$, $g_i$ is the weight between hidden layer neuron $i$ and output layer neuron $\phi$, $p$ is the bias of the output layer neuron $\phi$.

D. **Cell Equalization**

In the battery pack, operational voltage/current is attained by concerning numerous cells in series/parallel connection. Higher terminal voltage is obtained by connecting the cells in series connection. In contrast, parallel connection attains high capacity of a battery pack by the addition of over-all ampere-hour [21][22][23]. To avoid the cells damaging and lengthen the battery life-time, charging/discharging of the entire battery pack is stopped instantaneously if any cell reaches to the particular charging or discharging cut-off voltage respectively neglecting others. With the purpose of progressing the adeptness of battery pack along with possessing the standardization of SOC in the cell string, active charge equalization technique is implemented through the Buck-boost DC/DC converter. BMS commands the converters to decrease SOC variance among the cells. In order to balance the charge equalization of the cell string, average SOC is compared with all cell’s SOC as well as higher SOC containing cells transfer energy to lower charged cells. If the dissimilarity between average SOC and a cell SOC occurs more than a presumed threshold value, BMS facilitates the corresponding DC/DC Buck-boost converter to charge or discharge the cell as stated by the requirement. Fig. 6 designates the cell balancing operational appliance for the proposed model. The mathematical explanation of the active charge equilibrium scheme is stated in (8)

$$SOC_i - \overline{SOC} > SOC_{th} \quad Discharging$$

$$SOC_i - \overline{SOC} < SOC_{th} \quad Charging$$

$$ Others \quad Islanding$$

(8)

Here, $SOC_i$ is the SOC of a particular cell, $\overline{SOC}$ is average SOC of the cell string and $SOC_{th}$ is the threshold SOC of the system that is predefined before simulation.
IV. SIMULATION RESULT & DISCUSSION

With the aim of validating the usefulness of the anticipated BMS, the proposed model is simulated in the Matlab/Simulink environment. The battery model including the active cell-balancing methodology are assembled in the Simulink background. Generally non-uniform characteristics are occurred among the series-connected cells. Consequently, Three serially-allied A123 Li-iron-phosphate ANR26650M1 cells (Nominal voltage 3.3V and capacity 2.3Ah) are employed in this project for which the relationship between OCV and SOC of the predictable LiFePO₄ cell is shown in Fig. 7(a). Root Mean Square Error (RMSE) of the estimated SOC as well as Table 1 permits the authentication of the proposed methodology because of the innovative BPNN algorithm. Some authors studied on SOC estimation policy accompanied by Proportional Integral (PI) Observer, Extended Kalman Filter (EKF), Dual EKF (DEKF), H-infinity EKF (HEKF) etc. Nevertheless, the error produced by BPNN algorithm is reduced comparing to other standing methods as a result of weight regulation scheme. Though the cells contain same initial capacity (78% SOC) for the real world application in case of without cell balancing methodology, SOC differs at charging/discharging condition after some moment. However in BMS, the SOC inequality of the cells is diminished by dint of active charge equalization strategy. Fig.8 illustrates the estimated SOC charging/discharging profile of 3 cells for before and after cell balancing stratagem. Although the divergence of SOC is occurred at charging condition for the scarcity of SOC balancing technique, the dissimilarity is deducted with the help of novel charge balancing process. Similarly, Fig.9 to Fig.10 clarifies the advantages of the proposed BMS in lieu of cells terminal voltage and current profile by comparing the before and after active cell balancing strategy. In addition, the entire flowchart of the planned methodology is shown in Fig.11.

Table I. Reviews of SOC estimation approaches.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Year</th>
<th>Battery Model</th>
<th>Algorithm</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[24]</td>
<td>2016</td>
<td>1st order</td>
<td>PI Observer</td>
<td>3</td>
</tr>
<tr>
<td>[25]</td>
<td>2017</td>
<td>1st order</td>
<td>Dual EKF</td>
<td>&lt;5</td>
</tr>
<tr>
<td>[26]</td>
<td>2017</td>
<td>1st order</td>
<td>EKF</td>
<td>3</td>
</tr>
<tr>
<td>[27]</td>
<td>2018</td>
<td>2nd order</td>
<td>HEKF</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Proposed</td>
<td>2019</td>
<td>1st order</td>
<td>BPNN</td>
<td>&lt;1.2</td>
</tr>
</tbody>
</table>

Fig. 7 (a) OCV vs SOC Relationship for LiFePO4 cell (b) RMSE for the estimated SOC

Fig. 8 SOC charging/discharging profile of 3 cells (a) Before (b) After cell balancing
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Fig. 9 Voltage profile of 3 cells (a) Before and (b) After cell balancing

Fig. 10 Current profile of 3 cells (a) Before (b) After cell balancing

Fig. 11 Flowchart for active cell balancing strategy.
V. CONCLUSION
With the intention of progressing the overall productivity of a battery pack, an active energy equalization scheme is proposed for LiFePO$_4$ battery combining with online SOC estimation technique. BMS commands the activation signal through Buck-boost converter to supervise the battery pack with the help of SOC estimation levels. Each cell is instructed to charge or discharge properly following the guidance of BMS. Moreover, the weakest cell is recommended for repairing or even replacing from the battery pack if the charge level of this cell is not calibrated with active charge equalization technique in an attempt to escape from the stress on the strongest cells. In the long run, comparing to the existing methods, the proposed BMS contains succeeding advantages:

- The deliberated BMS can accurately orchestrate the SOCs of the series-connected cells accompanied by minimalizing the estimation error.
- In the battery pack, there is no discomfiture of energy on account of active charge balancing strategy through bidirectional Buck-boost DC/DC converter that decreases energy dissonance from one cell to another.
- The proposed methodology can be effortlessly prosecuted to several kinds of battery packs caused by its uncomplicatedness.

Conflicts of Interest
The authors declare no conflict of interest.

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Ohrul Qays was born in Chaudanga, Bangladesh, in 1995. He received his B.Eng. degree from Khulna University of Engineering & Technology, Bangladesh, in 2017. He worked for a research assistantship grant in 2018 for power electronics section entitled by “A Novel Multi input DC-DC Power Converter for Integrated Solar PV-Micro Hydro Renewable Energy System”. Currently he is continuing the M.Sc. degree in Electrical and electronics engineering at Universiti Malaysia Sarawak. He is a member of International Association of Engineers (IAENG) as well as Institute of Electrical & Electronics Engineers (IEEE).
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