An Optimal Strategy of Balancing for $LiFePO_4$ Battery in Battery Energy Storage System

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Abstract. Cell imbalance is one of the key factors that limit the capacity and power of battery energy storage systems (BESS), especially the large lithium-ion battery packs. To deal with the unbalancing problem, an effective balancing circuit is required, so is an optimal balancing strategy. In this paper, an optimal strategy for cells balancing has been presented. Contrary to the conventional balancing algorithms which base on instantaneous voltage or state-of-charge (SOC) no matter what the cause of imbalance is, the proposed strategy is targeted to different imbalance situations. Four cases of cell imbalance have been analyzed and the balancing effects of different algorithms are discussed. The simulation results show that the proposed strategy improves the performances of battery packs, including the usable capacity and maximum power.

Introduction

Lithium-ion batteries are widely used in industrial applications, such as cellphone, laptop, electric vehicle (EV), hybrid electric vehicle (HEV) and battery energy storage system (BESS). The potential of a single lithium-ion cell is about 4 V. For a higher voltage, several cells are connected in series. For example, the number of cells contained in an EV, of which the battery pack is almost 400 V, is approximately 100.

Obviously, for the unbalancing effect on the series cells, the cycle life of battery pack is shorter than that of the single cell. In fact, by connecting every cell to a balancing circuit， the battery pack which is “end-of-life” could be effectively resurrected [1-3].

The purpose of cell balancing is to improve the usable capacity of battery packs, not to deal with the failure of cell [4,5]. This improvement tends to optimize the state-of-charge (SOC) relationship of different cells to achieve more possible capacity [2-4,6]. By cell balancing methods, we can prolong the cycle life of cells, improve the rate of utilization and reduce the cost of whole system. In large lithium-ion battery packs, it is more possible to get into cell imbalance for the large number of cells. For the high-cost large capacity lithium battery, it is necessary to introduce cell balancing circuits due to its relatively low cost and its efficiency in prolonging the cycle life.

There have been many studies on battery balancing methods, classified as the active and the passive [7-9]. Usually, the active method is more expensive but more effective than the passive one. For batteries with large capacity, it is important to reduce the capacity loss so that an active balancing method is more acceptable. Based on the active method, a lot of balancing circuits have been proposed, such as switched capacitor, the switched inductor, multiple winding transformer and kinds of converters. Most circuits work well based on voltage and SOC, which means that they are highly effective and take a shorter time to achieve a same voltage or SOC than other cells/take the shortest time to achieve a same voltage of SOC among all cells. However, strategies about balancing process (i.e., when the balancing process is applied and what effect it will have) are seldom discussed.

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Based on the analysis of different imbalance situations in large capacity $LiFePO_4$ battery for BESS, this paper proposed an optimal strategy on balancing process. The comparison with the traditional balancing methods has been made according to balancing simulation.

Imbalance of cells

The cells imbalance is caused by internal and external sources [10]. Internal sources include variations in charge storage volume (cell capacity) and internal impedance, which are generated when produced and affected by the environment. Both of the internal sources are quite stable for the cell capacity and resistor would not change for short term operation. One of external sources is peripheral circuit, such as battery management system (BMS). The peripheral circuits drain charge unequally from different cells. For the circuit power changes with different operation modes, the impact caused by peripheral circuits is changeable. Another external source of imbalance is thermal differential across the pack, resulting in differing rates of self-discharge for the cells. The power for management system and the self-discharge effect can be ignored in terms of the thermal effect to large capacity lithium battery packs. Therefore, the variations in cell capacity and internal resistance are the main imbalance factors. Capacity fade and resistance increase are the performance for cell cycling degradation for $LiFePO_4$ battery [11].

Table 1 Different sources to cell imbalance

Imbalance source	Internal/External	Stable/changeable	Impact
Cell capacity	Internal	Stable	Increase as aging
Internal resistor	Internal	Stable	Increase as aging
Peripheral circuits	External	Change with operation modes	Little impact for large capacity
Thermal differential	External	Change with currents	Reduced by thermal management

The algorithm controlling the balancing circuit to work, which means when to charge/discharge and which cell needs to charge/discharge, can be based on voltage, final voltage or SOC. The voltage based method is the simplest one, however, the least effective. Because the OCV-SOC curve is quite flat at mid SOC levels, it is hard to detect which cell to charge/discharge. What's more, it is strongly affected by cell internal resistor. The voltage difference caused by different resistances may lead to an unexpected action of balancing circuits. By the final voltage based method, balance proceeds at high or low SOC. According to the curve of OCV-SOC, the voltage changes rapidly with the SOC. And at the high/low SOC, the charging/discharging current is reduced so that the error caused by internal resistance voltage is minimized. But for safe operation, most battery packs are not allowed to be fully charge or discharged to empty. The SOC based method is perfect for operation at all times and little effect on internal resistors. Unfortunately, it is difficult, almost impossible to track the SOC of every cell.

Comparison of algorithm based on cell voltage and cell SOC is in [12], though the cell capacities is quite different with each other, that it is impossible in BESS.

Balancing Strategy

Definition and Assumptions. Before the analysis of the balancing strategy, some key definition and assumptions should be introduced. The SOC of a cell is defined as

$$SOC = \frac{Q}{Q_0} \times 100\% \qquad (1)$$

Where Q is the remaining capacity, which is the capacity that can be discharged from the cell. Q_0 is the whole capacity or the maximum charge/discharge capacity. For example, charge the cell with a constant current C/3 to the voltage of 3.6V, then the voltage stays the same and the current reduces slowly. The charge process would not stop until the current reduces to C/20, where the state is defined as full-charge. Beginning with the full-charge state, discharge the cell with a constant current C/3 till the voltage decreases to 2.8V. Then stop and define the state as empty-discharge. The discharge capacity from the full-charge state to the empty-discharge state is the whole capacity of the cell.

The whole capacities of different cells are different, but the same SOC is to the same OCV, —that is to say, the OCV-SOC curves of different cells are the same. Meanwhile, we assumed that the OCV-SOC curve stay the same, regardless of the decline of capacity due to aging. To estimate every cell SOC accurately is almost impossible, but there are some methods to estimate every cell capacity, such as that in [13].

Another assumption is that the internal resistance (set as r) does not vary with the SOC. It is true when the SOC is neither too high (above 95%) nor too low (below 5%). To simplify the analysis, the hysteresis effect is ignored.

For the OCV-SOC curve is flat at mid SOC levels (about 12 mV difference between SOC=40% and 60%, about 132 mV difference between SOC=10% and 90%), it is hard to detect the SOC difference by voltage measurement and the voltage of the battery pack changes a little when a cell holds a SOC different from others. Many BMS devices measure voltage of the battery packs all the time, but not the voltage of every cell. Some devices take cell monitoring IC to measure the voltage of cells, e.g. the LTC6802 IC. However, for low-power operation, the IC often works as a protector, of which the overvoltage (OV) and undervoltage (UV) are set, only to diagnose the fault state and communicate with the BMS when the cell voltage is up to OV or down to UV.

For safe operation, assume that the optimal pack SOC range is from 10% to 90%, and the safe range of cell SOC is from 5% to 95%. Unlike those two operation mode, if any SOC above 95% or under 5% occurs, the system would alarm and react to this failure state.

Different Imbalance Cases. As mentioned above, the main sources of imbalance are variations of cell capacity and internal resistor. The situations of cell imbalance can be classified as 1) the same of cell capacity and internal resistor, 2) the same of capacity but different with internal resistor, 3) different with capacity but the same with resistor and 4) different with cell capacity and internal resistor respectively.

Assume that there is a battery pack consisting of 16 series $LiFePO_4$ cells. The average capacity is Q_{0A} and the average resistance is r_A. The capacity and resistance of the imbalance cell are Q_u and r_u respectively.

1) $Q_u = Q_{0A}, r_u = r_A$

Battery manufacturers select the cells with the same characteristics (the capacitor and the resistance) to compose battery packs. As we know, the characteristics of $LiFePO_4$ battery are stable. The capacitors of all cells are the same. So are the resistances. When the SOC of a cell is different from that of the pack, the whole capacity of the pack is not Q_{0A} and it means imbalance. Fig.1 shows that the SOC of an unbalanced cell is higher than that of the pack. No matter the cell is charged or discharged, the voltage of the cell is higher than the average cell voltage. The balancing process can operate at any time as long as the voltages are the same at last.

2) $Q_u < Q_{0A}, r_u = r_A$

The capacity of the unbalanced cell is lower than that of the pack but the resistances are the same. The voltage difference of them keeps the same at the same SOC point no matter what the charging/discharging current is. It seems that balancing point at low SOC, mid SOC or high SOC makes no difference for the pack capacity, which is decided by the unbalance cell. However, it does affect the operation schedule, especially in the low and high SOC levels.

For less capacity of unbalanced cell, the unbalanced cell may get into the unsafe state even if the system is in optimal operation. For example, the capacity of unbalanced cell is 8/9 of the normal one. If the system gets balanced at SOC=10% and the pack continues charging as usual, the average SOC of the whole pack might increase to 90% while the low-capacity cell would charging to SOC=100%. According to assumptions above, the system alarms before SOC=90%. Charging must stop when one cell is full, although others are not [14]—that is to say , balancing the cells at low SOC is not suggested because it is incompatible with the safe operation range, and vice versa, when balancing at high-level SOC. Instead, if the balancing is done at mid-level SOC such as 50%, the low-capacity cell ranges from 5% to 95% as the average SOC of the pack changes from 10% to 90%. Therefore, the system operates more safely and the benefits more from the balancing, although the low-capacity cell is not in the optimal operation range.

3) $Q_u = Q_{0A}, r_u > r_A$

The resistance of the unbalanced cell is higher than that of the pack but the capacities are the same. The voltage difference at the same SOC is related to the current because of different internal resistances. If the battery is charging, the voltage of the unbalance cell is higher than the average cell voltage. If the battery is discharging, the voltage of the unbalance cell is lower than the average cell voltage. The higher current, both charge and discharge, makes the greater voltage difference between the unbalance cell and the normal ones.

The most commonly used criterion to start or stop balancing circuits is voltage difference. Based on the voltage, the unbalanced cell should discharge by bypass balancing circuit when the battery pack is charging and charge when the battery pack is discharging. The method can increase the capacity for some applications. However, it is not an effective means, and may even deteriorate the balance of cells. For example, the unbalanced cell keeps the same voltage as others when it charges. That means the OCV/SOC of the unbalanced cell is lower than that of others. When it turns to discharge, the voltage difference is greater than that without balancing circuit.

In this case, balancing algorithms should be based on SOC or OCV, not the voltage, especially the voltage when charging or discharging is ongoing. Accordingly, the balancing point could be selected at any SOC level if applying the balancing algorithm based on SOC.

4) $Q_u < Q_{0A}, r_u > r_A$

The capacity and the resistance of the unbalanced cell are different with the average values respectively. The imbalance is the combination of the second and the third cases. The imbalance source of capacities or resistances has little effect on each other. Therefore, the balancing algorithm consists of that in the second and the third cases.

The optimal strategy on balancing is to select the mid SOC as the balancing point and base the balancing algorithm on SOC. The maximum capacity and power can be achieved by this strategy.

Table 2 Different imbalance cases and optimal balancing strategies respectively

Imbalance case	Optimal balancing strategy
$Q_u = Q_{0A}, r_u = r_A$	At any SOC level, based on voltage/SOC
$Q_u < Q_{0A}, r_u = r_A$	At mid SOC, based on voltage/SOC
$Q_u = Q_{0A}, r_u > r_A$	At any SOC level, based on SOC
$Q_u < Q_{0A}, r_u > r_A$	At mid SOC, based on SOC

Simulation Results

Cell Model. To simplify the simulation, the cell model is showed as Fig.1. The hysteresis and relaxation effects are ignored. The OCV-SOC relationship obtained by experiments based on a 180 Ah $LiFePO_4$ cell. So did the internal resistance, as showed in Fig.2.

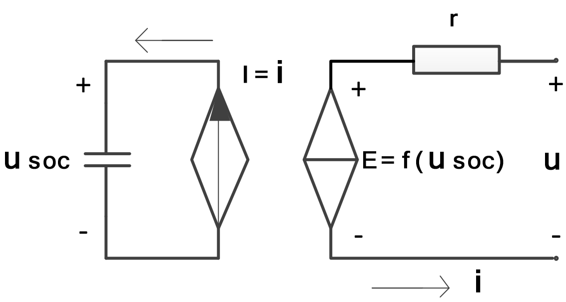


Fig. 1 Cell model for balancing simulation

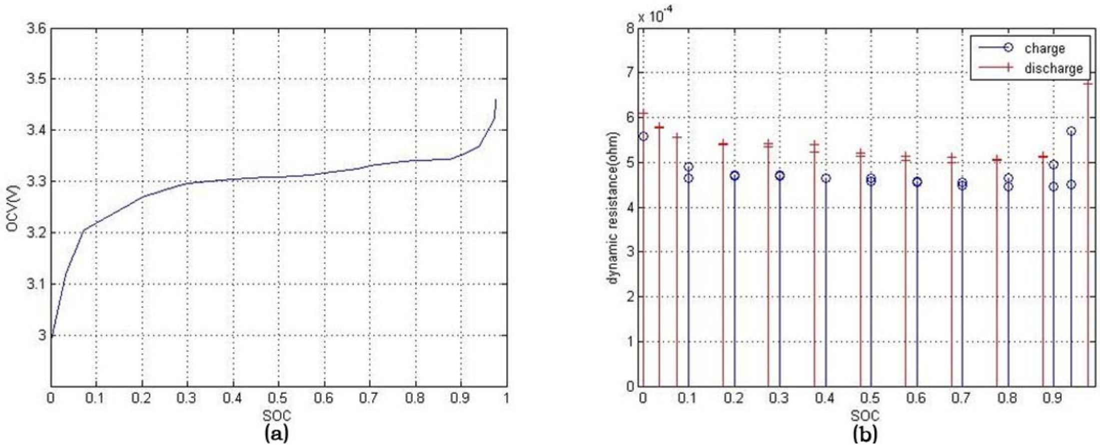


Fig. 2 The OCV-SOC relationship (a) and the internal resistance (b) of 180Ah $LiFePO_4$ cell

Simulation and Analysis. Based on the battery model in Fig.3 and model parameters in Fig.4 (r=0.5mΩ), run the balancing process on MATLAB. The results are showed as follow.

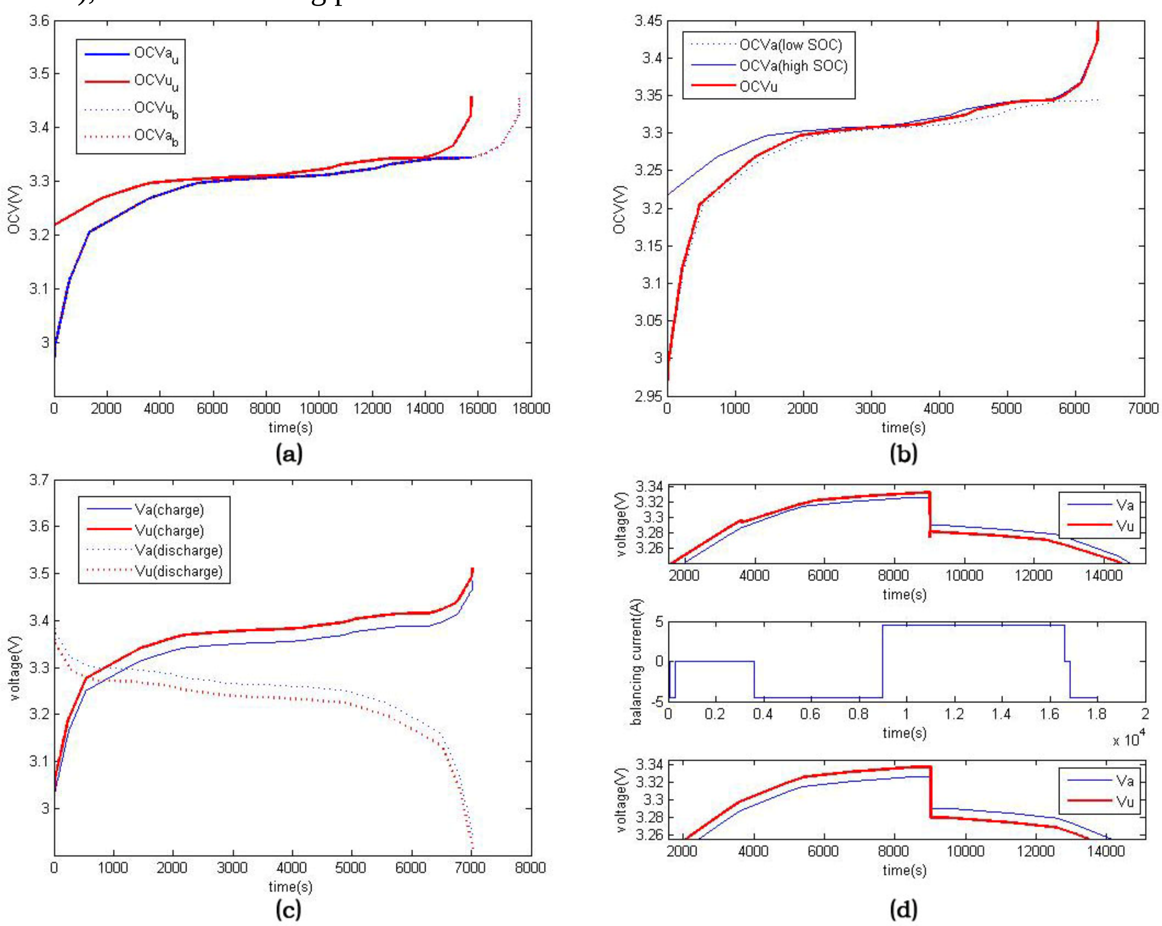
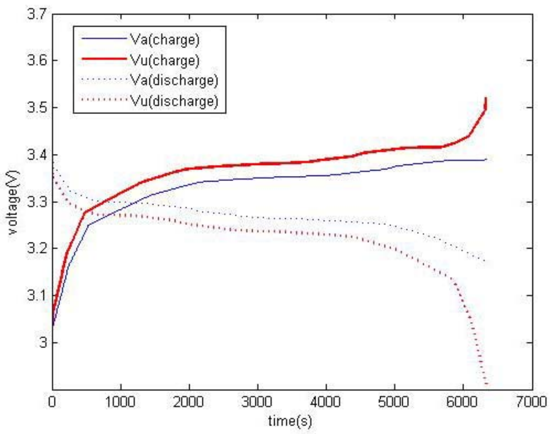


Fig. 3 Simulation result, (a) $Q_u = Q_{0A}, r_u = r_A$, (b) $Q_u < Q_{0A}, r_u = r_A$, (c) $Q_u = Q_{0A}, r_u > r_A$, (d) comparision of different balancing strategies when $Q_u = Q_{0A}, r_u > r_A$

Fig.3 (a) shows the charging curves without balancing processes. The unbalanced cell holds the same capacity and resistance as that of others, while the SOC of the unbalanced cell is 10% greater than the average SOC. Therefore, without balancing process, the battery pack can only increase to SOC=80% when the unbalanced cell charge up to SOC=90%. Undoubtedly, those curves would coincide if any balancing process is adopted, regardless of where the balancing point is. It shows that the balancing strategy could be based on SOC or voltage, and setting different balancing points could achieve the same result.

Fig.3 (b) shows that if the SOC of the unbalanced cell is lower than the average one, the unbalanced cell goes to the charge voltage limit (CVL) and discharge voltage limit (DVL) first. The pack SOC is limited by the unbalanced cell. The SOC voltages keep the same at the balancing point. The farther the SOC is from the balancing point, the greater the voltage difference is. To get a smaller maximum voltage difference and insure the pack voltage not going to CVL or DVL, the balancing point should be set at mid SOC.

The imbalance caused by different internal resistances is showed in Fig.3 (c). The voltage of the unbalanced cell is higher when charging than that of the average. In contrast, the voltage of this “higher cell” changes to lower when discharging. Balancing effect by traditional algorithm based on voltage is showed in the top chart of Fig.3 (d). Admittedly, the voltage difference is limited by bi-directional active balancing circuits, which achieve a balance all the time no matter the cells are charging or discharging. However, the balancing current (5A) reverses when the battery state changes from charging to discharging, showed in the middle chart of Fig.3 (d). The bottom chart of Fig.3 (d) is the reference without balancing. In a BESS, the battery state (charging, discharging or standing) changes at any time, so the balancing process in charging may be disadvantaged to discharge, even to enlarge the imbalance. It is highly suggested that the balancing strategy should be based on SOC in terms of the situation of $Q_u = Q_{0A}, r_u > r_A$, rather than voltage.



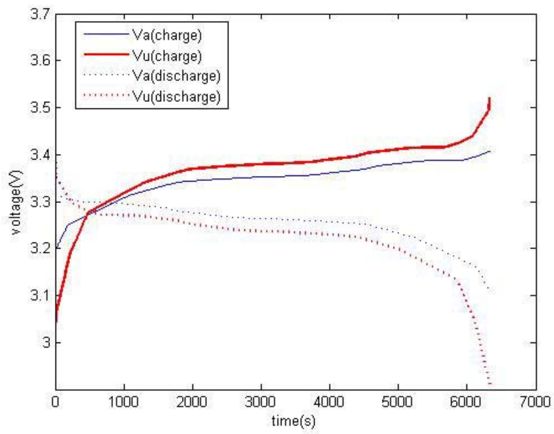


Fig. 4 $Q_u < Q_{0A}, r_u > r_A$ (a) balancing at final SOC, (b) balancingn at mid SOC

The most complex situation, $Q_u < Q_{0A}, r_u > r_A$, is showed in Fig.4. In the left chart, two charge voltage curves are based on the low SOC balance and the other two discharge ones are based on high SOC balance. For fewer capacity, the voltage difference increases as the charging/discharging proceeding. For larger resistance, the voltage of unbalanced cell is higher in charging and lower in discharging, comparing with the average voltage.

Table 3 The voltage difference among different balancing points when $Q_u < Q_{0A}, r_u > r_A$

Balancing point SOC[%]	**Current I[A]**	**Max voltage V_{max}[V]**	**unbalance**	**Min voltage V_{min}[V]**	**unbalance**	**V_{max}-V_{min} △V[V]**
10	45	3.4736		3.1961		0.2775
	60	3.4819		3.1887		0.2932
	90	3.4847		3.1738		0.3109

	120	3.4997	3.1589	0.3408
	180	3.5297	3.1292	0.4005
50	45	3.3851	3.1328	0.2523
	60	3.3926	3.1256	0.2670
	90	3.4076	3.1111	0.2965
	120	3.4226	3.0966	0.3260
	180	3.4526	3.0676	0.3850
90	45	3.367	2.9632	0.4038
	60	3.3745	2.9561	0.4184
	90	3.3895	2.9421	0.4474
	120	3.4045	2.928	0.4765
	180	3.4345	2.8999	0.5346

In the right chart, of which balancing point is at mid SOC, the simulation results are similar to that showed in the left chart. The detail of the difference among different balancing point is showed in Table 3. The higher current results in higher maximum unbalance voltage (V_{max}) and lower minimum unbalance voltage (V_{min}). Meanwhile, the difference ($\triangle V = V_{max}-V_{min}$) of them increases. As the balancing point based on SOC increasing, both the V_{max} and the V_{min} decrease. However, the $\triangle V$ decreases from SOC=10% to SOC=50% while increase from SOC=50% to 90%.

Summary

In this paper, we have presented the balancing simulation results from the different imbalance causes study on large capacity $LiFePO_4$ in BESS. Different imbalance situations are discussed and the results will help to choose an effective balancing algorithm respectively. The optimal balancing strategy for all imbalance cases is that bases on SOC and takes the mid SOC as the balancing point. The optimal strategy could improve capacity of the pack, fulfill the battery’s potential, prolong the battery’s lifetime and avoid capacity retransferring. To some situations, some others algorithms that is easier will make the same effect as the optimal one.

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