# Optimal Cell Removal to Enhance Operation of Aged Grid-Tied Battery Storage Systems

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***Abstract*—The proper operation of *aged batteries* is essential to improve the reliability and performance of grid-connected battery energy storage systems (BESS). In this paper, we investigate on the phenomenon that removing certain battery cells within an aged battery pack, may lead to increasing the *effective capacity* of the BESS, because those cells with reduced capacity become the limiting factor for the overall BESS operation, while the remaining capacity of some other cells is not used. We optimize the process of identifying which battery cells from a grid-tied BESS should be removed in order to improve the overall BESS performance for smart grid applications. The experimental hardware-in-the-loop (HIL) testing of a grid-integrated BESS with aged cells is used to validate the developed models and show the increase in the effective capacity once the identified cells are removed. We also perform case studies to assess the impact of cell removal on the operation of an aged BESS in a peak demand shaving smart grid application.**

***Keywords*: Aged battery pack, grid-tied storage system, cell removal, peak demand shaving, hardware-in-the-loop testing.**

## NOMENCLATURE

| | |
|---|---|
| $n, m$ | Index variables for cell number |
| $t$ | Index variable for a timeslot |
| $s$ | Index variable for string number |
| $\mathcal{T}$ | Set of all timeslots |
| $\mathcal{A}$ | Set of all battery cells in series |
| $\tau$ | Duration of a timeslot |
| $\overline{n}$ | Number of battery cells in series |
| $r$ | Internal resistance of a battery cell |
| $P_o$ | Output power of a battery cell |
| $V_o$ | Terminal voltage of a battery cell |
| $I$ | Current into a battery cell |
| $C$ | Energy level of a battery cell in a timeslot |
| $\overline{v}, \overline{c}$ | Maximum cell voltage and capacity limits |
| $\underline{v}, \underline{c}$ | Minimum cell voltage and capacity limits |

## I. INTRODUCTION

The costly process of installing grid-tied BESS, calls for practical methods to increase the lifetime of these installations while maintaining the maximum effective capacity and therefore usefulness of the BESS. Battery cells degrade over the nominal lifetime of the BESS. To maintain economic viability though, the grid-tied BESS may still operate after the expiration of the warranty term, where the maintenance falls into the hands of the system operator. Operators currently augment the BESS system original capacity with new additional capacity in order to prevent performance losses from the shortfall in aged battery pack capacity. In addition, operators may delay and accumulate the maintenance needs until the reduced performance justifies the cost of sending crews [1].

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Although modeling and operation of grid-connected BESS has gained substantial attention in the literature, e.g. in [2], [3], there are still limited studies focusing on operating BESS with *aged batteries*. For example, there are studies on degradation modeling and capacity estimation of battery cells, e.g in [4]–[7]. There are also limited studies, e.g. in [8], [9], to support the use of second life batteries in grid applications. Aged batteries and their characteristics are also considered in designing customized converters [10], battery monitoring systems [11], and transportation electrification [12]. However, the existing literature on grid-tied BESS often overlooks a simple yet practical solution, and that is the idea of removing certain cells that are holding back the performance of the grid-tied BESS as a whole. Removing such cells can be done manually if the cells are large enough to be accessed directly, c.f. [13], or it can be automated by the manufacturer for the small cells that collectively operate within a battery module.

In this paper, we seek to address the above open problem by answering the following two questions: *"how does the performance variation of aged battery cells and the battery cells' arrangement in the pack impact the overall capacity and performance of a grid-tied BESS?"* Accordingly, *"how can we systematically remove one or more battery cells to improve the overall capacity and collective operation of the remaining cells in the BESS?"* We develop a method to identify under what conditions a battery cell should be removed from the battery pack to enhance its operation in grid-tied applications.

It should be noted that the the proposed cell removal method in this paper can be beneficial under two different use-cases; (i) for aged BESS systems where warranty is lapsed and the system operator has direct access to modify the cell/module arrangement, and (ii) for BESS with automated cell configuration management, where the manufacturer can leverage the process to extend the lifetime and capacity guarantees. In the former case, however, the operator should consider the cost and planning for operation interruption of the BESS.

## II. BATTERY PACK CAPACITY ESTIMATION WITH AND WITHOUT A PARTICULAR CELL

A battery pack comprises several battery cells that are connected in series to make strings, and strings of cells connected in parallel to make the entire pack. Different battery

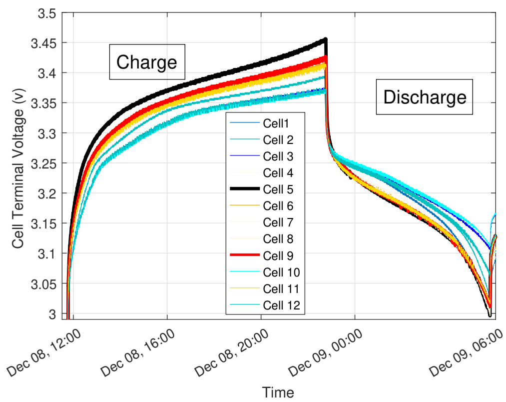


Fig. 1. The voltage profiles of all 12 cells in an aged battery pack.

cells within the pack do *not* have the same characteristics when they are manufactured. Over time, they *age in a different rate* as well; thus, diverging further in their conditions. As a result, the voltage trajectory during charge/discharge will vary for different cells. For instance, consider the voltage profiles of a 12-cell BESS, in Fig. 1, during one charge cycle and one discharge cycle. While all 12 cells in this single battery pack are discharged and charged with the same current, the voltage of some cells decline and rise faster than others. Therefore, during discharge, some cells reach to the minimum allowed voltage sooner than the other series cells in the string. At this point, the battery management system (BMS) stops the discharge operation for safety concerns. Accordingly, certain cells become the limiting factor for the overall battery pack operation, while the remaining capacity of some other cells is not used. This is essentially a *lost capacity* due to the different aging conditions of different cells within the pack.

### A. Initial Capacity

Consider a battery pack with one string, and $\overline{n}$ as the number of cells in series. We discretize the operation horizon into time slots of duration $\tau$. Suppose $C[t,n]$ denotes the energy level of cell $n$ at time slot $t$. Also let $\overline{c}_n$ denote the energy capacity limit of cell $n$. Naturally, when the battery module is discharged/charged, the power drawn/stored in the battery module at any time slot $t \in \mathcal{T}$, denoted by $P_{out}[t]$, is the sum of the power (at the cell terminals) drawn/stored in each cell $n$, denoted by $P_o[t,n]$. $P_o[t,n]$ can take both positive and negative values, where negative values indicate discharging.

If we assume a simple model with an internal resistance $r[n]$ for each cell, the stored energy in the cell is equal to:

$$C[t,n] = C[t-1,n] + \tau(P_o[t,n] - r[n]I^2[t]). \tag{1}$$

In practice, a cell cannot be charged beyond a voltage limit $\overline{v}$ or discharged below a voltage limit $\underline{v}$. If a cell reaches these voltage limits, the battery operation must cease. Thus, cell $n$ is considered at its maximum energy level, in time instance $t_{\overline{v}}$, when its terminal voltage $V_o[t,n] = \overline{v}$. We denote this energy level $C[t_{\overline{v}},n] = \overline{c}[n]$ as the "capacity limit" of cell $n$. Similarly, a cell is considered at its minimum capacity, $\underline{c}[n]$, at time instance $t_{\underline{v}}$, when $V_o[t,n] = \underline{v}$. Since these two time instances are the primary metrics for measuring cell energy during a cycle, the energy capacity of cell $n$ is estimated as:

**Algorithm 1** Cell Removal

```
for s = 1, 2, ..., s̄ do
    Obtain string initial capacity from (2) and (3)
    for x = 1, 2, ..., n̄ do
        Obtain string capacity from (4) after removing
        the x lowest capacity cells.
        if (5) holds then
            Remove x lowest capacity cells from all strings
        end if
    end for
end for
```

$$\overline{c}[n] = \sum_{t=t_{\underline{v}[n]}}^{t_{\overline{v}[n]}} \tau(P_o[t,n] - r[n]I^2[t]), \tag{2}$$

Since we cannot overcharge a single cell, every cell is limited to the capacity of the smallest capacity cell; even if the cells were balanced, i.e. even if we discharged them individually, so that they start from a balanced state of charge. Due to this we can find the maximum usable energy storage capability for a pack of cells, denoted by $\overline{C}$, to be:

$$\overline{C} = \overline{n} \min_{n \in \mathcal{A}} \overline{c}[n], \tag{3}$$

where $\mathcal{A}$ is the set of all cells in the pack and $\overline{n}$ is the number of cells, i.e, the cardinality of set $\mathcal{A}$.

### B. Capacity After Cell Removal

Next, we investigate if removing a cell could increase the capacity of the BESS. Normally, if a cell is out of balance then it is *not* removed; instead, the battery pack is balanced, c.f. [14]. Therefore, for our analysis, we assume that the pack is already balanced and the minimum SoC of each cell is zero Wh. Let $\mathcal{A}_{-x}$ denote the set of all cells *except for* the $x$ lowest capacity cells, i.e., $\mathcal{A}_{-x} = \mathcal{A}/x$. The cardinality of set $\mathcal{A}_{-x}$ is $n - x$ cells. The new capacity would be:

$$(\overline{n} - x) \min_{m \in \mathcal{A}_{-x}} \overline{c}[m]. \tag{4}$$

The number of cells is reduced by $x$, but now the minimum capacity cell(s) have been removed; therefore the $\min(\cdot)$ term in (4) is now greater than the $\min(\cdot)$ term in (3). The question becomes: *for which number of cells this new capacity gain will be greater than the capacity loss from the removed cells?*

Mathematically, this question can be answered by checking whether the following inequality holds for a given $x$:

$$\overline{n} \min_{n \in \mathcal{A}} \overline{c}[n] < (\overline{n} - x) \min_{m \in \mathcal{A}_{-x}} \overline{c}[m]. \tag{5}$$

If it does hold, then removing the $x$ lowest capacity cells would improve the total usable energy in the pack.

### C. Algorithm and Implementation

The above process is summarized in Algorithm 1. The outcome of Algorithm 1 is to remove $x$ cells, where $x$ itself is decided by the algorithm. If no cell is removed then $x = 0$.

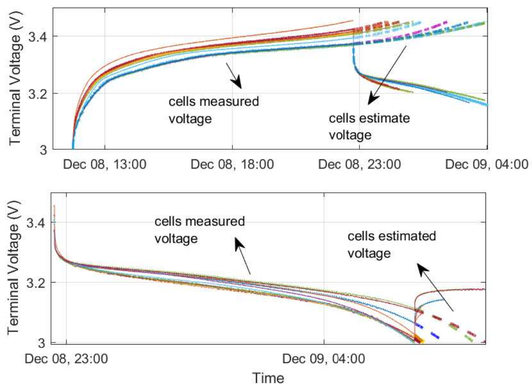


Fig. 2. Measured and estimated model output of battery cells during (a) continued charge and (b) continued discharge.

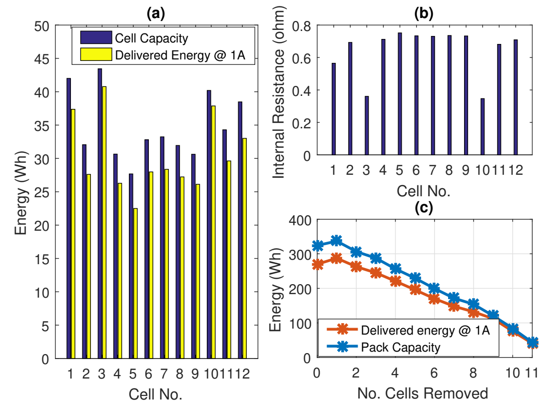


Fig. 3. The results of parameter estimation for all cells: (a) energy capacity, (b) internal resistance, (c) pack energy capacity with $x$ weakest cells removed.

In practice, when some cells are removed, the overall voltage of the string may drop. The BESS inverter is typically capable to operate on a varying DC voltage. However, in order to deliver the same power output, the current draw from the remaining cells will increase in each cycle. Still, this increase will not be significant if one or few cells are removed from the string, since the typical voltage of a grid-tied BESS on the DC side is in the 600 V to 1000 V range, whereas a typical cell voltage is around 3.5 V. In addition, as the battery cells are operating in the $\approx 0.5$ C rating to provide about 2 hours of energy, we presume that a mild increase in the cell's discharge current will not be a major concern in affecting the battery life.

A grid-tied BESS may include multiple strings of battery cells paralleled in a pack. In that case, we can replace condition (5) with the following condition in line 5 in Algorithm 1:

$$\sum_s \overline{n} \min_{n\in\mathcal{A}^s} \overline{c}[n,s] < \sum_s (\overline{n}-x) \min_{m\in\mathcal{A}^s_{-x}} \overline{c}[m,s] \quad \forall x, \qquad (6)$$

where $s$ denotes the battery cells in each string. Note that, in the presence of multiple parallel strings, the impact of cells with poor health leads to at least two additional operational challenges. First, in order to preserve the voltage balance across the parallel strings, removing a cell from one string, would require removing cells from all other parallel strings. This may lead to removing more capacity than it is desired. Second, even if the cell(s) with poor health are not removed from the pack, the voltage drop on one/few poor cells may cause an imbalance across voltage levels of parallel strings. Here, we addressed the impact of the first challenge by using (6) instead of (5); but we leave the second challenge out of the scope of this paper. In order to account for the second challenge, one requires a detailed modeling of the parallel battery cells/strings with varying state of health.

## III. Experimental Results, Model Validations, and Operation Impact Assessment

### A. Initial Capacity Testing

The Power Hardware in Loop (PHIL) test-bed presented in [15] was used to perform experimental testing on BESS operation. The battery pack consists of twelve 40Ah GBS Lithium Iron Phosphate cells. The cells are in the *used condition*, and several of them have *degraded over time*.

Before the test, all cells were balanced and discharged to a voltage of 3.00 V. The test included operating the BESS over a full cycle, by charging/discharging at a constant 1 A current. The voltage at the terminals of each cell was recorded. The results are shown in Fig. 1 in Section II.A. The battery pack delivered 274 Wh of energy during discharge. Based on the BESS operation test, the values of $t_{\overline{v}}$ and $t_{\underline{v}}$ for individual cells were estimated using a quadratic regressive model fitted to the measured data. Having these values, the internal resistance and energy capacity for all cells were estimated, see Figures 2(a), 2(b), 3(a), and 3(b).

We can see that several cells have severely reduced capacity, e.g., below 50% of their nominal capacity. In particular, cell No. 5, has the weakest capacity of 22.48 Wh. Next, we verify if removing the weakest cell can increase the pack capacity.

### B. Optimal Cell Removal Analysis

Based on the analysis in Section II-A, the following assessments were made: (i) the available energy of the pack can be estimated from that of cell No. 5 at $12 \times 22.48 = 269.7$ Wh. (ii) The next cell that would limit the battery operation is cell. No. 9. (iii) Thus removing cell No. 5, the delivered energy of the battery pack will increase to $11 \times 26.2 = 288$ Wh, where 26.2 Wh is the capacity of cell No. 9. (iv) Additional cell removal will results in decrease of the overall pack capacity. The energy capacity of the battery pack from removing the $x$ weakest cells is shown in Fig. 3(c).

### C. Modified Battery Pack Capacity Testing

Next, we actually modified the battery pack in the PHIL system and did the second BESS operation test, to verify the assessments. We removed the weakest cell, i.e. cell No. 5. We balanced the pack and then operated the BESS with 11 cells for a full cycle, similar to the test in Section III-A. Fig. 4 shows the voltage characteristics of the pack with the remaining 11 cells during a full cycle. The curve for the weakest cell from the previous experiment is also shown as reference.

We see that both charge and discharge times of the BESS have significantly increased. Discharge time increases more than charge time due to higher resistance of the removed cell. The pack discharge time increases by 2.5 hours. *As predicted,*

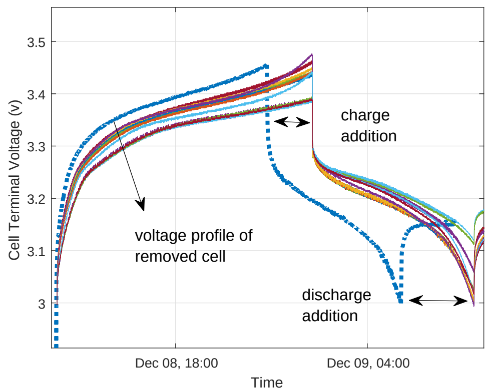


Fig. 4. The voltage characteristics of the remaining 11 cells.

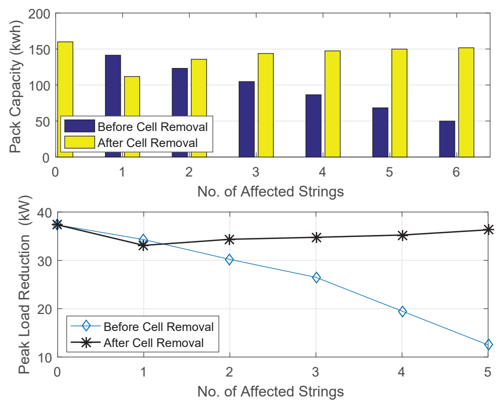


Fig. 5. (a) BESS capacity *before* and *after* cell removal; (b) weak cell and cell removal impact on BESS performance in peak shaving application.

*the delivered energy of the modified pack increases to 300 Wh*. The limiting cell in the modified pack is now cell No. 9, which again we had predicted. Finally, we see that the pack delivered energy also closely matches that of our prediction.

## IV. Impact on Smart Grid Applications

To examine the impact of the cell removal analysis on the performance of a grid-tied BESS, we consider a 100 kW/ 200 kWh BESS operated for commercial demand peak shaving [13]. The battery pack includes 6 parallel strings, each with 260 cells in series. The cells have the same model, as described in Section III-A. The BESS is in the used condition and the cells have $\sim 80\%$ of nominal capacity. We assume there are 5% weak cells with the characteristics similar to cell No. 5.

We operate the BESS in six test cases, where the same number of weak cells affect one or more of the battery strings. The BESS is also operated without any weak cells. Again, each string of the series cells, is constrained based on the performance of the weak cells. However, the BESS is operated in each case *without the knowledge on any such weak cells*. The BESS was operated for one week in each case *before* and *after* applying the proposed cell removal procedure.

Fig. 5(a) shows the BESS overall energy capacity in each test case before and after cell removal. We see that when we have the same number of weak cells, their impact on BESS capacity is more severe, i.e. the BESS capacity reduces more, when they are speared among more strings.Thus, cell removal in such cases leads to a significant increase of BESS overall energy capacity. In contrast, when the weak cells are all affecting one string, the cell removal is not useful. Recall that, removing weak cells also requires removing cells from other strings; thus, when the the weak cells are in few strings, the cell removal operation is less effective.

Fig. 5(b), shows the impact of the weak cells on BESS operation performance. When two or more strings are affected by the weak cells, the performance loss becomes significant. In such cases, the operation controller is also mislead on available capacity; hence, the impact is more than the loss of capacity.

## V. Conclusions

We showed how the characteristics of the weakest cells impact the operation of a grid-tied BESS with aged battery cells. We developed models to determine the conditions where removing weak cells could lead to increasing the battery pack effective capacity. The analysis was done for both single-string and multi-string scenarios. Experimental results in a PHIL testing platform confirmed that the proposed methodology can result in increasing the BESS effective capacity. In particular, we showed the advantages of the proposed cell-removing approach to operate grid-tied BESS, to improve the BESS performance for peak-load shaving applications.

## References


[1] H. Walker, "Best practices for operation and maintenance of photovoltaic and energy storage systems," National Renewable Energy Lab.(NREL), Golden, CO (United States), Tech. Rep., 2018.

[2] G. Henri and N. Lu, "A supervised machine learning approach to control energy storage devices," *IEEE Trans. on Smart Grid*, pp. 1–1, 2019.

[3] J. E. Contreras-Ocaña, M. A. Ortega-Vazquez, and B. Zhang, "Participation of an energy storage aggregator in electricity markets," *IEEE Trans. on Smart Grid*, vol. 10, no. 2, pp. 1171–1183, March 2019.

[4] B. Xu, A. Oudalov, A. Ulbig, G. Andersson, and D. S. Kirschen, "Modeling of lithium-ion battery degradation for cell life assessment," *IEEE Trans. on Smart Grid*, vol. 9, no. 2, pp. 1131–1140, March 2018.

[5] M. A. Roscher, J. Assfalg, and O. S. Bohlen, "Detection of utilizable capacity deterioration in battery systems," *IEEE Trans. on vehicular technology*, vol. 60, no. 1, pp. 98–103, 2011.

[6] K. Abdulla, et. al., "Optimal operation of energy storage systems considering forecasts and battery degradation," *IEEE Trans. on Smart Grid*, vol. 9, no. 3, pp. 2086–2096, May 2018.

[7] B. Xu, Y. Shi, D. S. Kirschen, and B. Zhang, "Optimal battery participation in frequency regulation markets," *IEEE Trans. on Power Systems*, vol. 33, no. 6, pp. 6715–6725, Nov 2018.

[8] D. Strickland, et. al., "Estimation of transportation battery second life for use in electricity grid systems," *IEEE Trans. on Sustainable Energy*, vol. 5, no. 3, pp. 795–803, July 2014.

[9] A. Saez-de-Ibarra, et. al., "Second life battery energy storage system for residential demand response service," in *Proc. of IEEE International Conference on Industrial Technology*, 2015, pp. 2941–2948.

[10] N. Mukherjee and D. Strickland, "Control of second-life hybrid battery energy storage system based on modular boost-multilevel buck converter," *IEEE Trans. on Industrial Electronics*, vol. 62, no. 2, pp. 1034–1046, Feb 2015.

[11] S. Tong, et. al., "Demonstration of reusing electric vehicle battery for solar energy storage and demand side management," *Journal of Energy Storage*, vol. 11, pp. 200–210, 2017.

[12] Q. Liao, et. al., "Performance assessment and classification of retired lithium ion battery from electric vehicles for energy storage," *International Journal of Hydrogen Energy*, vol. 42, no. 30, 2017.

[13] Z. Taylor, et. al. , "Customer-side scada-assisted large battery operation optimization for distribution feeder peak load shaving," *IEEE Trans. on Smart Grid*, vol. 10, no. 1, pp. 992–1004, Jan 2019.

[14] Y. Barsukov, "Battery cell balancing: What to balance and how," *Texas Instruments*, pp. 2–1, 2009.

[15] Z. Taylor, H. Hejazi, and H. Mohsenian-Rad, "Power hardware-in-loop simulation of grid-connected battery systems with reactive power control capability," in *Proc. of IEEE PES NAPS*, Morgantown, WV, Sep. 2017.