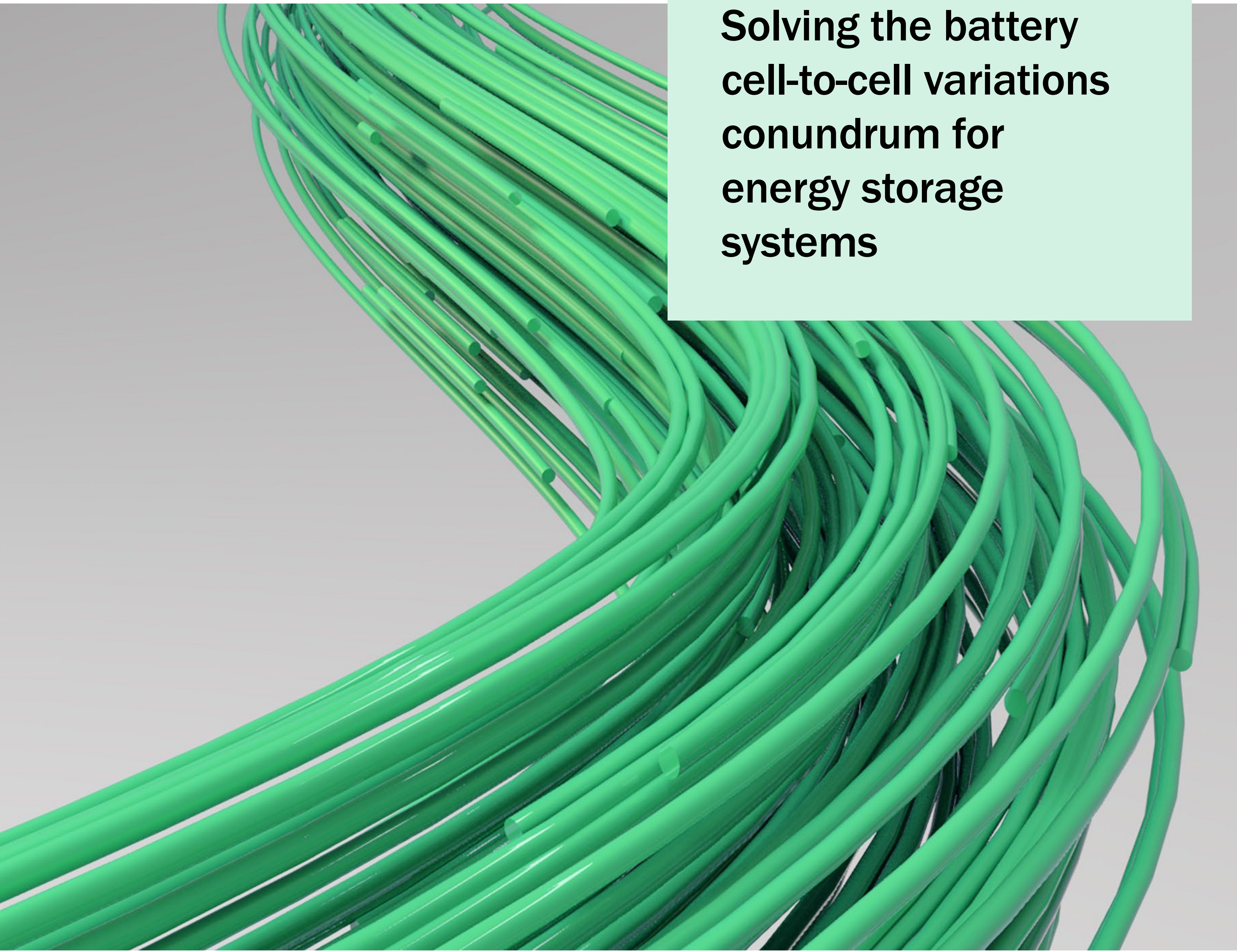
Brill Power



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Solving the battery cell-to-cell variations conundrum for energy storage systems

File Information

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Introduction

Many people are aware that there are many different types of lithium-ion cells, and that different chemistries, shapes or manufacturers will greatly affect the performance of a cell. A lesser-known fact is that even “identical” cells exhibit differences. These differences may not be apparent or measurable in new cells, but they will affect the performance, lifetime and even the safety of aged battery systems.

Cell-to-cell variation

Due to small variations in materials and production processes, even high-quality cells from the same production batch will be slightly different. Because the size of lithium-ion cells is limited to a few hundred Watt-hours (Wh), large batteries are made up of hundreds, sometimes thousands of cells that are electrically connected in parallel to increase the current the battery can deliver, and in series to increase the voltage of the battery. A residential battery will typically consist of a few hundred cells, while utility-scale batteries may contain tens of thousands of cells.

Commercial high-quality pristine cells will only exhibit small differences in capacity and resistance, not least because they are tested and sorted into quality groups by the manufacturer. Therefore, cell-to-cell differences are often ignored in new high-quality batteries. However, the rate at which each of these cells degrades is also different, such that over time these small differences can greatly increase, even if the battery pack can tightly control the temperatures and state of charges of all cells. In reality, operating conditions are never perfectly uniform for all cells in a system, which further enhances cell-to-cell variations over time.

Figure 1 below shows three public datasets investigating this effect. In each study, the researchers bought many identical cells and cycled them under identical conditions. When cell-to-cell differences are small, all cells exhibit the same energy storage capacity. The graphs of figure 1 below show the measured capacity of each cell. At the start, all dots practically overlap as expected, showing that the cell-to-cell differences are small for these new cells. However, as the cells are cycled and slowly degrade, the differences get bigger and bigger, and the measured capacities start diverging. Towards the end of the tests, which represent the end-of-life of a battery, the capacities vary significantly.

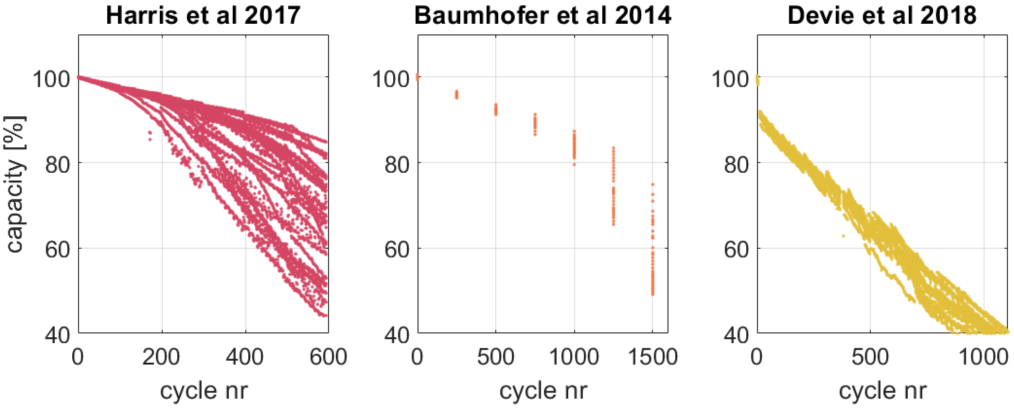

Figure 1: battery degradation data set showing cell-to-cell variation increasing over the lifetime of a battery.

Battery layout and BMS systems

When cells are connected in parallel, they share the same voltage. This means that cell-to-cell variations are compensated because all cells will reach the lower or upper voltage limit at the same time, such that all energy can be extracted from all cells. In other words, parallel-connected cells behave like the 'average' of all cells. However, a side-effect is that the current is not shared equally. Especially differences in resistance can cause inhomogeneous current distributions, with some cells receiving significantly larger currents than others. This can lead to increased degradation on those cells, which in turn will increase the cell-to-cell variation.

When cells are connected in series, the same current must pass through them. Because lithium-ion cells should never be over-charged or under-discharged, this means that charging must be stopped as soon as the first cell reaches its maximum voltage, and vice-versa. Discharging must be halted as soon as the first cell reaches its minimum voltage. In other words, the series-string is limited by the cell with the lowest capacity, similarly to how a chain is limited by the weakest link.

Figure 2 illustrates this *weakest link* phenomenon. From left to right, a string of four series-connected cells is discharged with the second cell from the top having a smaller capacity than others. As this weaker cell discharges faster than other cells, the operation of the entire string must be halted to avoid over-discharging this cell, therefore curtailing the remaining energy in other cells which becomes inaccessible. Exactly the same phenomenon happens during charge. Therefore, each cell in a series connection behaves like the smallest capacity cell in the string and the additional energy stored in bigger capacity cells is inaccessible.

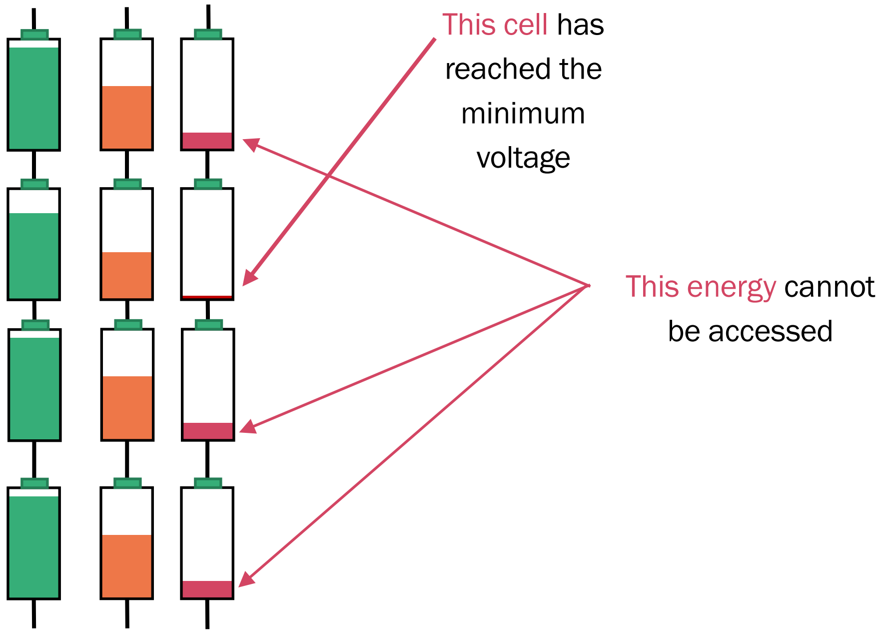

Figure 2: the weakest cell determines when discharging needs to stop

Conventional battery management systems (BMS) cannot compensate for these effects. They have passive or active balancing circuits that will bring all cells to the same state of charge at end of charge. This is shown on figure 3 where a battery pack comprising four initially perfectly balanced series-connected cells is discharged and charged at 1C until the weakest cell reaches its voltage limit, and the balancing system eventually rebalances the cells. The figure depicts a scenario towards the end-of-life of a battery where cell-to-cell variation is large and its effects are clearly visible. The top row shows the states of charge (SoCs) of the cells, while the bottom row shows the cell voltages.

With both passive and active balancing, the cell SoCs and voltages start diverging when the battery is in use, and the discharge needs to be terminated prematurely when the first cell reaches the lower voltage limit. The battery is then charged until the first cell reaches the upper voltage limit. With passive balancing, all cells are slowly discharged over resistances until they reach the voltage or SoC of the lowest cell. With active balancing, the cells exchange energy until they end up at the mean SoC of all cells.

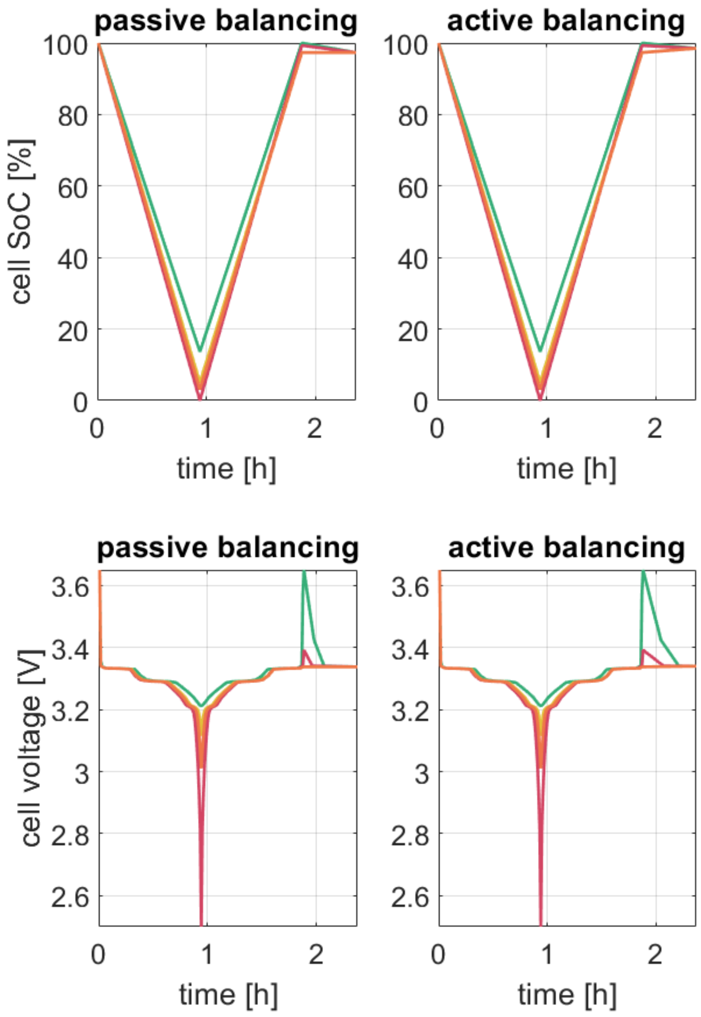

Figure 3: passive and active balancing cannot avoid the weakest-link problem

This problem can be solved by using BrillCore, a new type of battery architecture developed by Brill Power, which applies a novel concept called *active loading* to control and balance battery systems. BrillCore works by having a power-electronic converter next to every cell or module, such that the system can control how the total power is distributed. In other words, we control the share of power each cell or module delivers or receives (during charging), to achieve a predetermined objective. This is shown on figure 4 where the cells at lower state of charge deliver a smaller fraction of the discharge power compared to the fully-charged cells. As a consequence, their SoC decreases slower and all cells can reach the minimum voltage at the same time.

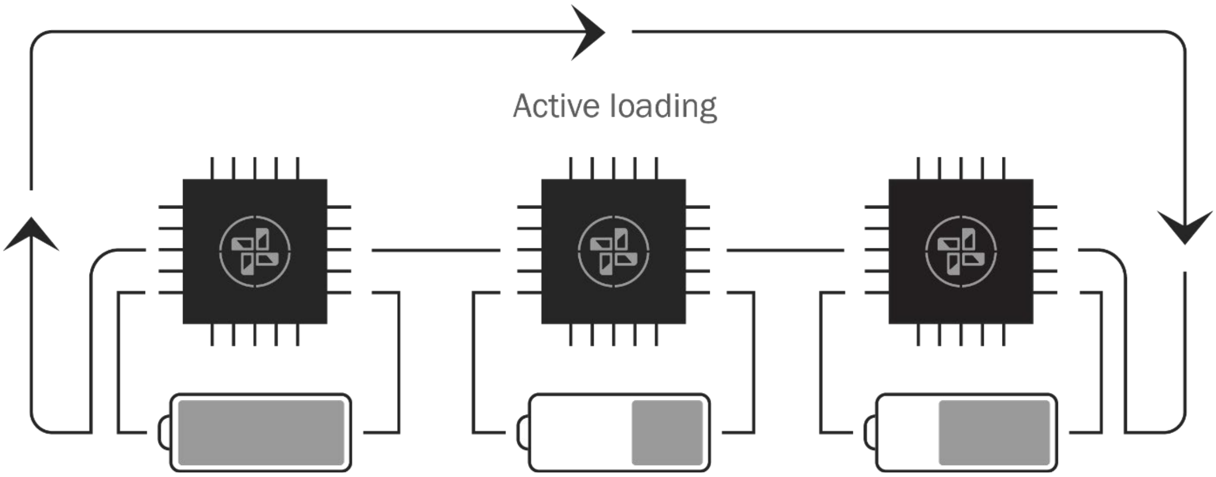

Figure 4: BrillCore technology to avoid the weakest-link problem

Figure 5 below shows what happens when the objective is to equalise the cell SoC and voltages. The control scheme will constantly adapt the currents to each cell to ensure that all voltages remain the same. This means that all cells will reach the lower voltage together, or in other words that we can extract all the energy from each cell or module. The same happens during the charge, and all cells reach the upper voltage limit together. No active or passive balancing is required because the cells are already at the same SoC. Note that other objectives are possible, which will be explored in a future white paper. The accessible capacity of active loading is bigger than that of the previous approaches, as shown in the bar graph.

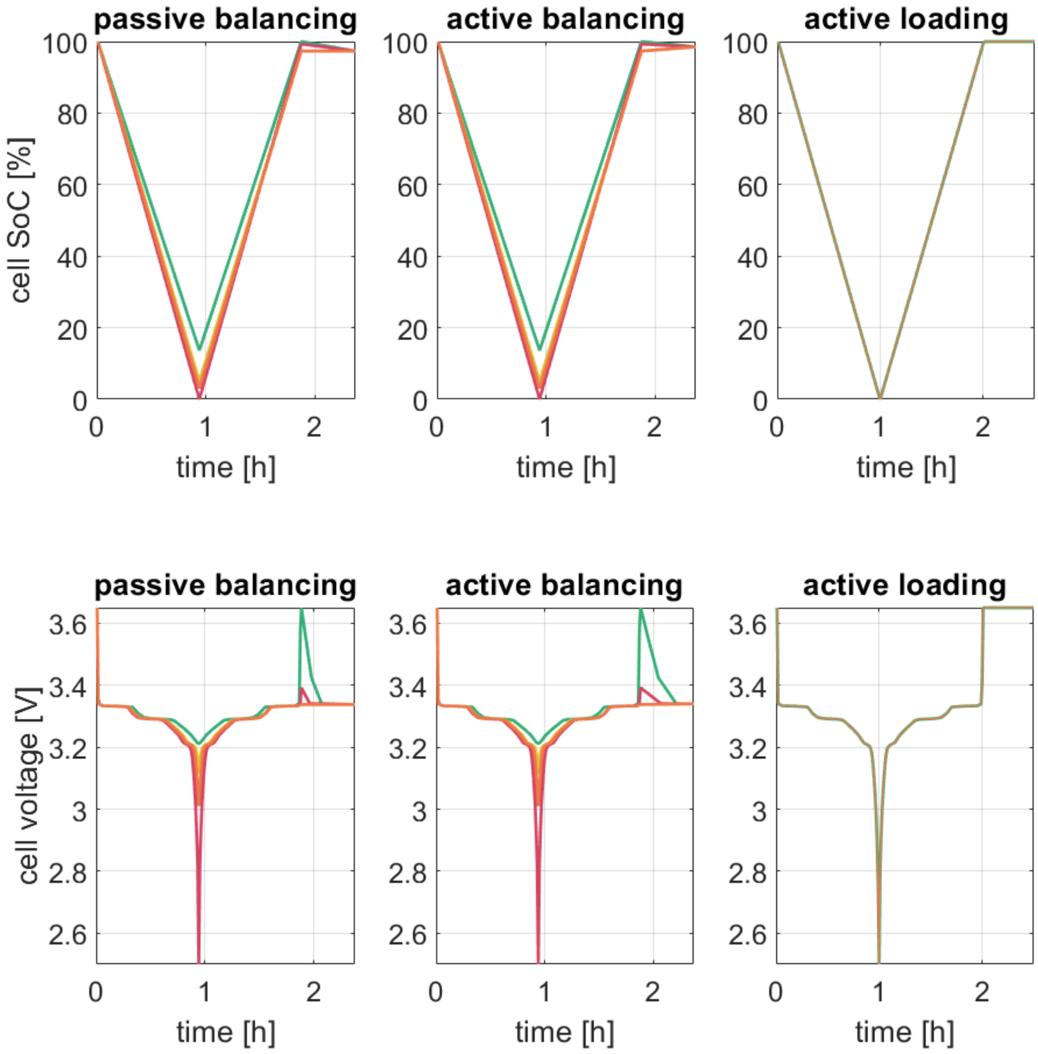

Figure 5: Comparing active loading with passive and active balancing

Cell-to-cell variations have a significant impact on the lifetime of the total asset. Figure 6 shows on top the simulated evolution of cell capacities in a 2-hour 50 kWh battery system used for frequency response and wholesale arbitrage. The top figure shows how the cell capacities evolve over time, starting with a tight distribution and showing the increasing cell-to-cell variation observed over a battery's lifetime.

The bottom graph shows the simulated capacity of the battery as a whole. We compare two 800V systems: one with BrillCore technology and one with conventional BMS technology. Since BrillCore's active loading technology is not limited by the weakest cell, it can access approximately 36% more energy storage capacity at a lifetime of 12 years, and extend the useful battery life more than three years[1] for this particular use case.

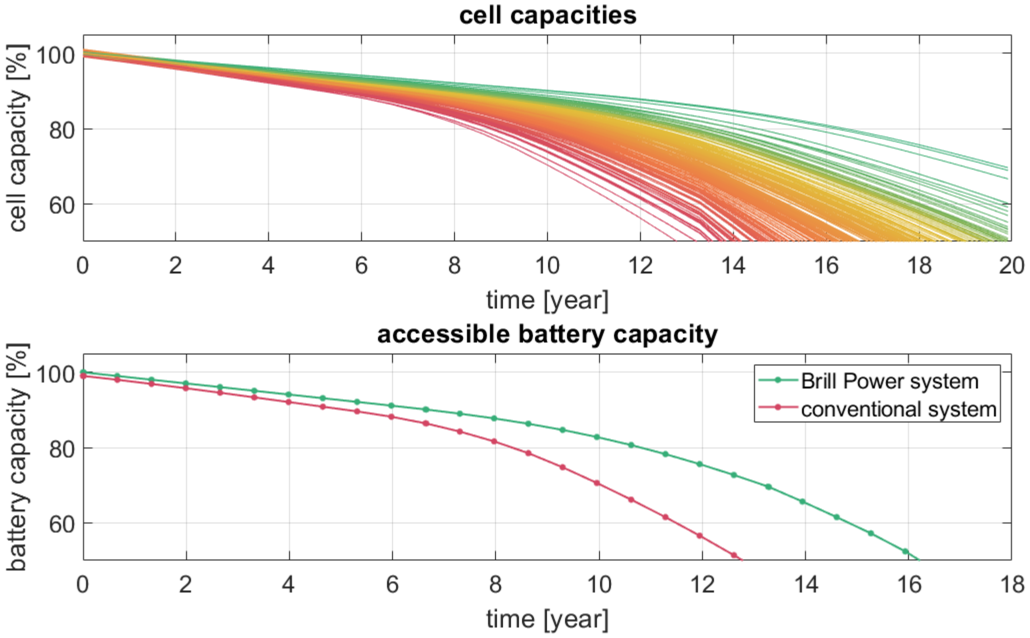

Figure 6: battery capacity over time for different configurations and battery management systems.

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[1] End of life is defined as the point in time when the battery reaches 70% of its original energy storage capacity.

Conclusion

The thousands of cells making up large batteries are all different. In a new battery, these differences are small but it has been shown that they increase over time. Because not a single cell can be over-charged or over-discharged, conventional batteries are limited by the weakest element in a series-link and they cannot access all energy in every cell. Over time, this has an increasingly detrimental effect on the lifetime and performance of a battery system.

Using Brill Power's advanced battery control technology (BrillCore) solves this problem by integrating power conversion into the battery and loading each cell or module relative to its capabilities. This increases the energy capacity and lifetime of battery systems, compared to battery systems using passive or active balancing BMS technology. It also increases the project lifetime, reduces overengineering, and allows the use of lower-quality cells.

Brill Power's technology can increase the lifespan of battery systems by up to 60% and, in the case of second-life battery systems, it overcomes safety and performance issues that result from receiving cells in differing State of Health (SOH).

Get in touch

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