

BATTERY CELL BALANCING, A NOVEL PARADIGM: ETA-LEVELING

Reclaim lost capacity and extend pack life

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PEM
MOTION



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INTRODUCTION

Battery packs in modern energy storage systems and electric vehicles (EVs) are composed of hundreds of cells connected in parallel to increase capacity, and in series to raise the overall voltage of the pack. Due to manufacturing tolerances and varying operating conditions, even if the cells are produced in the same batch and sorted, no two cells will be identical. Each cell will exhibit variations in the state of charge (SOC), self-discharge rate, capacity, impedance, and thermal properties. These small differences, although minor at first, accumulate over time. When the imbalances become significant, the entire battery pack's performance is affected, reducing usable capacity, accelerating degradation, and increasing the potential for safety issues.

In this context, PEM Motion and Benning CMS Technology GmbH (BCT) have established a strategic partnership designed to meet these challenges head-on. By integrating BCT's patented technology into PEM Motion's portfolio, the collaboration addresses one of the most pressing needs in modern battery applications: balancing cells to extend battery life and ensure reliable, cost-effective operation. This synergy offers clients a powerful combination of expertise in engineering and system integration, backed by a proven cutting-edge balancing solution.

The objective of this white paper is to demonstrate how **ETA-Leveling**, a firmware-based leveling strategy, removes the long-standing trade-offs between cheap but wasteful passive balancing and efficient yet costly active hardware.



We will review the main challenges of balancing technologies, core imbalance mechanisms, a high-level look at the algorithm, and clear implementation options.

Whether you are designing a new BMS, extending the life of batteries already in the field, or repurposing retired packs for grid storage, the pages that follow will illustrate how a straightforward software upgrade can unlock the hidden kilowatt-hours you have already paid for.

BENNING
CMS Technology



1. CHALLENGES OF BATTERY CELL BALANCING

Even with advanced balancing strategies in place, maintaining uniform cell conditions across large battery packs remains complex. Below are some of the most relevant challenges resulting from cell imbalance and the balancing methods themselves:

1.1. REDUCED CAPACITY UTILIZATION

The BMS protects the battery pack by enforcing cell voltage limits. In practice, charging stops as soon as any cell exceeds its safe voltage threshold, even if the rest of the pack isn't fully charged. Similarly, discharging is halted the moment a single cell drops below its undervoltage limit, even if other cells still have energy left.

Because of this early termination in charge or discharge, the overall capacity of the pack is reduced.

Voltage-triggered balancing, the industry's preferred solution, tackles the symptom, not the cause. It overlooks **capacity and impedance mismatch**: lower capacity cells fill and empty sooner, while high impedance cells show larger voltage swings.

Without effective management, in each cycle, the cells drift further apart, forcing earlier cut-off and amplifying capacity loss.

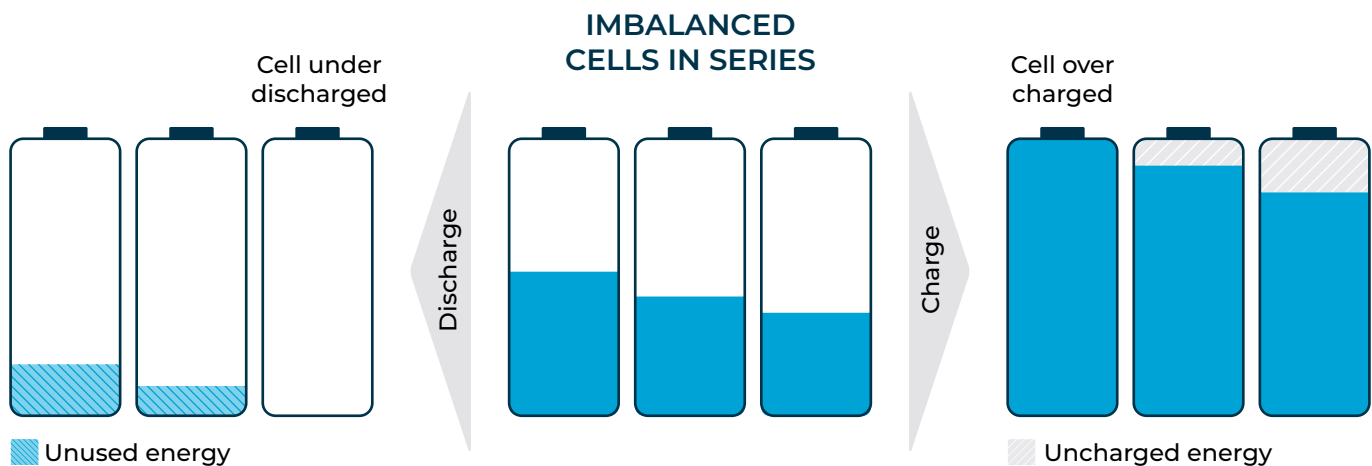


Figure 1 Effect of Battery Imbalance

1.2. ACCELERATED CELL AGING AND DEGRADATION

Theoretically, balancing should mitigate degradation caused by imbalance, but if it is overused or misapplied, it can become a hidden contributor to cell aging. Over time, this unintended aging can outweigh the benefits of balancing itself. Some key causes of this phenomenon are:

1. Overvoltage Exposure:

Cells with lower-capacity charge faster and tend to experience higher stress voltage than the rest. If balancing doesn't compensate properly, these cells can be repeatedly pushed into overvoltage, accelerating capacity loss and increasing internal resistance.

2. Balancing Frequency and Duration:

Whether using active balancing (redistributing energy) or passive balancing (dissipating energy), performing balancing too frequently or for too long can backfire. When balancing attempts to correct every small mismatch,

it may end up imposing additional thermal and electrical stress. If not carefully limited, this can lead to a self-reinforcing cycle where balancing contributes to the very degradation it's trying to prevent.

3. Cells Impedance and thermal effects:

Cells with higher internal resistance generate more heat during operation and balancing. Applying high balancing currents amplifies this effect. As they degrade further, their impedance increases, which worsens the mismatch and further stresses the pack.

As the pack ages, maintaining balance becomes more difficult and necessary. Without a carefully designed strategy, balancing efforts can lead to a vicious cycle where weaker cells degrade faster, forcing the BMS to intervene more frequently, accelerating aging, and ultimately reducing pack lifespan.

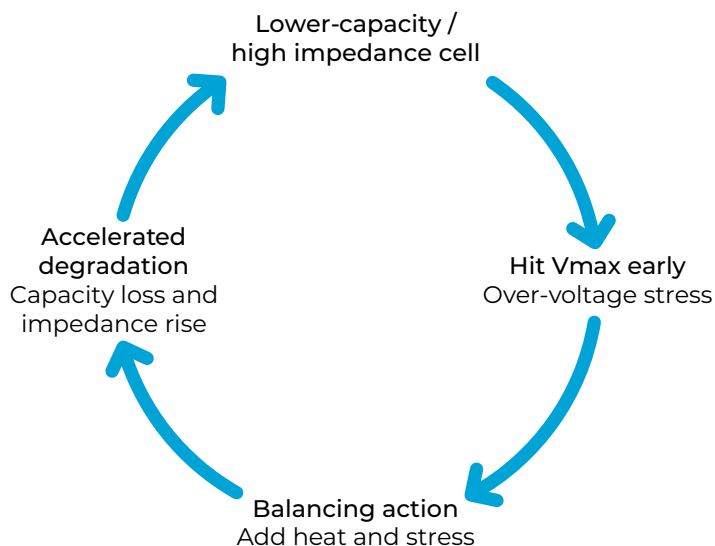


Figure 2 Balancing vicious cycle

1.3. COST VS. PERFORMANCE TRADE-OFF

Battery designers face a classic dilemma: save money now or save energy later.

When comparing traditional passive and active balancing systems, the trade-offs are clear. Passive balancing is cheap, simple, and almost bullet-proof, but every coulomb it “balances” is lost energy, and the bigger the battery, the longer that hot trickle lasts. Active systems, by contrast, move energy efficiently and quickly, so it suits larger packs. Yet, it demands higher upfront costs, extra circuitry, and advanced controllers.

So, what to choose? low cost and wasted energy, or high cost and added complexity? Until now, those were the only options. In the next section we introduce a third path that captures efficiency with simplicity.

	PASSIVE	ACTIVE
Hardware	Bleed Resistor and FET per cell	Inductors / Capacitors bidirectional converters
Efficiency	Low (energy dissipated)	High (80 - 90%)
Speed	Slow	Fast
Heat generated	High	Low
Cost	\$1-2 per cell	5-10 x higher
Complexity	Very low	High

Table 1 Comparison of balancing methods

1.4. COMPLEXITY OF CONTROL ALGORITHMS AND DATA REQUIREMENTS

Balancing control algorithms span a wide spectrum. At one end, **simple voltage triggers** work with nothing more than cell voltage data, fast and lightweight, yet prone to error when impedance drifts. A step up are **SOC-based methods**, which rely on cell models. They track capacity more accurately but demand cell characterization, calibration, and extra processor cycles.

The most advanced approaches involve **predictive or AI-driven algorithms** that use large data sets to anticipate imbalance before it happens.

Each step in sophistication requires more processing resources, tighter real-time constraints, deeper cell characterization, and a heavier verification burden.

These requirements inflate development and maintenance budgets and bind the algorithm to specific cell chemistries. For applications where cost, flexibility, or long-term serviceability are critical, this added complexity can become a limiting factor.

In summary, maintaining balanced cells across a battery pack is essential for unlocking its full performance. Yet, traditional balancing methods, whether passive or active, face significant trade-offs in terms of speed, efficiency, cost, and system complexity. As packs get larger and operate under increasingly demanding conditions, the limitations of these approaches become more pronounced. What's needed is a new paradigm that boosts efficiency without adding significant hardware, cost, or risk. The following section introduces a novel approach designed to meet this need: **A solution that fills that gap by controlling energy in a smarter way based on the hardware already present in a standard BMS.**

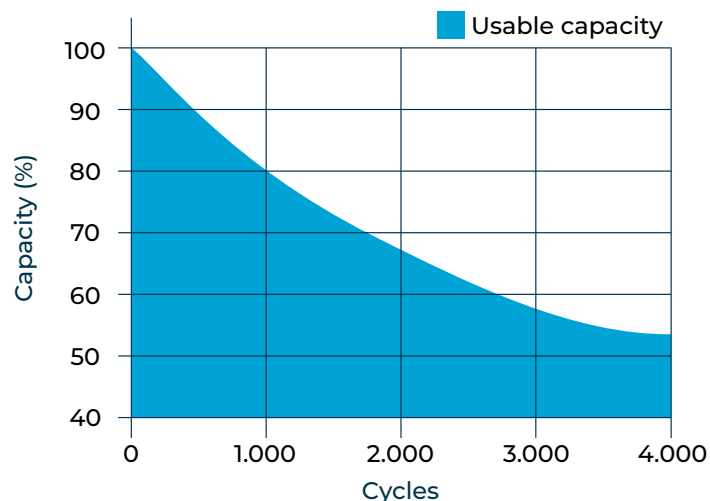
2. INTRODUCING A NOVEL APPROACH: ETA-LEVELING

Traditional passive or active balancers react after an imbalance appears as a voltage or SOC spread. ETA-Leveling (also referred to by the Greek letter η , for “efficiency”), proposes a new paradigm. It steers the charge current profile, so the **voltage spread never grows large in the first place**, keeping the hardware simplicity of passive balancing but reaching unique efficiency and battery lifetime.

ETA-Leveling blends charging control and balancing logic in one loop:

1. **Continuous cell monitoring from the existing BMS sensors**, without additional hardware requirements.
2. **Real-time efficiency correction:** Lightweight math infers each cell usable capacity and impedance on-the-fly.
3. **Dynamic current shaping:** If any cell gets closer toward its upper limit (typical of a low-capacity or high-impedance cell), the algorithm drives the current, so all cells converge on the cut-off voltage simultaneously.
4. **End-of-charge leveling using already existing hardware**, with minimized passive balancing heat and stress.

CONVENTIONAL BMS
(Regulation via voltage measurement)



BMS WITH η -LEVELING
(Leveling dependent on the given cell conversion efficiency)

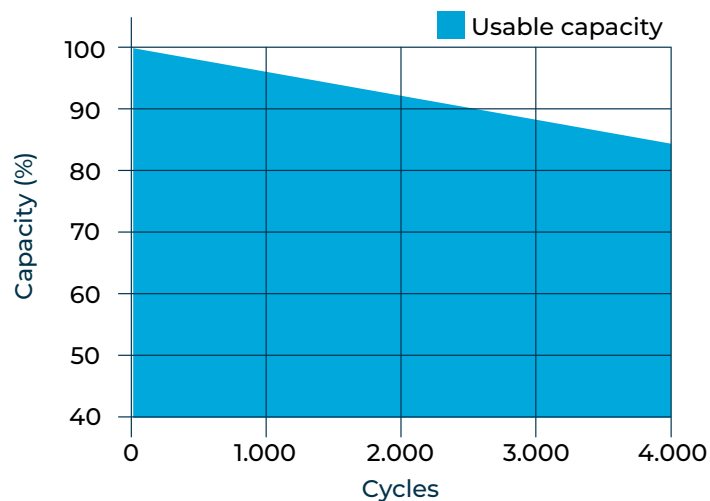


Figure 3 Comparison of loss of capacity in a single cell

Key result: up to 2 times less capacity loss in comparison with traditional voltage-based balancing.

2.1. HOW ETA-LEVELING HANDLES THE THREE ROOT CAUSES OF IMBALANCES

Every series string shows cell-to-cell variation, and the mismatch that limits pack performance can almost always be traced to three main causes:

- 1. **Capacity differences:** cells leave the factory (or age) a few percent apart in total Ah, so the low-capacity cell fills and empties first.
- 2. **Impedance mismatch:** Cells DC resistance can vary by $\approx 15\%$ within one production batch and rises with aging; the resulting I-R drop pushes the on-load voltage up and hides the true SOC.
- 3. **Self-discharge or SOC drift** – tiny leakage differences accumulate between cycles and pull the cells SOC apart.

Conventional voltage-based balancing struggles because all three might look the same to a voltmeter. A high voltage could mean an over-full cell (*capacity differences*), an I-R spike (*impedance mismatch*), or simply a cell that has leaked less charge. Reacting to raw voltage alone often bleeds the wrong cell, wastes energy, or even widens the spread.

ETA-Leveling breaks the ambiguity. It lets the “weakest” cell set the pace while keeping it below stress limits, neutralizing all three imbalance drivers before any bleed resistor needs to switch on ideally.

IMBALANCE	CONVENTIONAL OUTCOME	ETA-LEVELING RESPONSE
Capacity Differences	Low capacity cell hits Vmax first. BMS terminates charge and pack ends under-charged.	Charge / leveling loop is tuned based on every cell voltage, allowing them to reach 100% SOC. The pack finishes fully charged without tripping BMS protections.
Impedance mismatch	I-R drop makes the high-R cell look over-full, so a passive balancer bleeds the wrong cell.	Efficiency is considered to eliminate the I-R error. The current taper is applied so that cell voltages converge without unnecessary bleed and heat.
Self-discharge or SOC drift	SOC drifts during operation and storage; it is balanced in each cycle.	At the end of each cycle a short bleed re-aligns small SOC differences.

Opportunity: Long-term testing has shown that after a few-hundred cycles: 48% of lost energy is irreversible chemistry fading (SOH). **The other 52 % is perfectly healthy energy that stays trapped** because conventional balancing leaves cells out of sync. **ETA-Leveling releases the lost capacity back into useful runtime.**

3. RAPID EVALUATION AND IMPLEMENTATION PATH

To shorten the validation time from months to hours, PEM Motion offers an **evaluation toolkit**. A Simulink Simulation Module that can replace the balancing algorithm in any BMS model. Customers can run their own load profiles, duty cycles, use their cell models, introduce capacity or impedance skew, and instantly see the impact on usable energy, charge time, and projected lifetime. Because the model contains all ETA logic, the same can flow straight into firmware once the results are proven.

Implementation paths PEM Motion can guide you:

- 1. Desktop validation:** Plug the Simulink ETA-Module into your existing BMS and battery model to quantify ETA-Leveling benefit against your current balancing method.
- 2. Model-based BMS integration:** Import the ETA-model, generate C code, and drop it into your BMS for rapid implementation and experimental validation.
- 3. Firmware patch for existing BMS:** Import the C ETA-library into your existing codebase, add some commands to the charger, and leave all safety features and hardware unchanged.
- 4. Use a turnkey PEM Motion BMS:** Adopt a complete hardware-and-software customized solution that already contains ETA-Leveling, with functional-safety documentation and fully personalized features.

For illustration, we simulated three NMC cells in series, each exaggerated to highlight a different mismatch, see table. The string was cycled 100 times under a 1 C charge / 1 C discharge profile, first with a conventional voltage-triggered bleed balancer and then with ETA-Leveling.

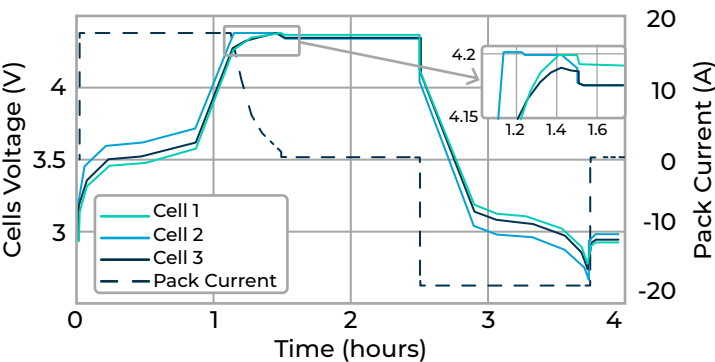


Figure 4 Simulation example

	CELL 1	CELL 2	CELL 3
Capacity [Ah]	20	20.2 (+1%)	19.8 (-1%)
Impedance [mΩ]	8.5	12.75 (+50%)	6.8 (-20%)
Self-Discharge [mA]	0.6	0.5 (-16%)	0.6

Simulation Results: Even in this deliberately skewed stack, ETA-Leveling reclaimed roughly **3% more capacity per cycle**, and reduced routine bleed losses from **18Wh to 11Wh**, demonstrating how ETA-Leveling corrects capacity, impedance, and drift errors before they turn into heat or degradation.

4. SPECIFIC USE CASE BENEFITS OF ETA-LEVELING

From prototype to megawatt-scale storage farms, operators share the same goal: extracting every safe watt-hour at the lowest possible cost. **Below are three high-impact scenarios where customers see the payoff immediately.**

1. Cut procurement cost with unsorted cells: Premium-grade, tightly sorted cells increase BOM cost. ETA-Leveling prevents out-of-tolerance cells from becoming bottlenecks, so packs built with capacity spread still reach excellent energy utilization. Manufacturers can buy lower-cost, unsorted lots yet meet the same performance.

2. Revive ageing packs already in the field: After several hundred cycles, cell voltages drift farther apart, stealing valuable runtime.

A single firmware update realigns cells, recovering up to 52% of the apparent capacity loss, extending service life without costly pack swaps.

3. Unlock profitable second-life modules: Retired EV packs enter ESS duty with mixed capacities and impedances. ETA-Leveling is perfect for keeping those differences controlled without bulky and expensive DC/DC converters. Second-life projects enjoy smoother discharge curves, fewer hot modules, and a shorter path to ROI.

In short, whether you're buying new cells, managing mid-life fleets, or repurpose batteries for a second life, ETA-Leveling turns hidden kilowatt-hours into usable revenue through smarter current control alone.

CONCLUSION

Balanced cells are essential to unlock the full capacity of any battery pack, but traditional balancing methods fall into a dilemma. Passive strategies are simple but waste energy as heat and still leave cells out of sync, while active hardware shuttles charge efficiently but adds expense, complexity, and reliability risk. As capacity, impedance, and self-discharge differences widen over time, voltage-triggered balancers often bleed the wrong cell, accelerate ageing, and strand roughly half of the “lost” energy that operators assume is gone for good. ETA-Leveling resolves this, using only the cell voltages and pack current which are already present in BMS, yielding to tangible advantages:

Higher usable capacity: By preventing early cut-offs, the full capacity of the pack becomes available on each cycle.

Faster, safer charging: Cells reach full SOC simultaneously, so charging finishes sooner without over-stressing any cell.

Extended cell life: More uniform cycling and effective depth-of-charge resulting in slow degradation.

Cost-effective design: As a simple software strategy, ETA-Leveling avoids the component and design cost of complex hardware and algorithms.

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