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Life Balancing – A Better Way to Balance Large Batteries

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Abstract

A new cell balancing technology was developed under a Department of Energy contract which merges the DC/DC converter function into cell balancing. Instead of conventional passive cell balancing technology which bypasses current through a resistor, or active cell balancing which moves current from one cell to another, with significant cost and additional inefficiencies, this concept takes variable amount of current from each cell or small group of cells and converts it to current for the low voltage system.

Introduction

A traction (high voltage) battery pack for modern plug-in hybrid and battery electric vehicles consists of a large number of cells (typically 80 to 100 lithium ion) in series. As each cell is an individual unit, the cells may change over life relative to each other due to a variety of factors, including self-discharge differences due to temperature differences in the pack, piece-to-piece manufacturing differences, and even differences in loads from the cell voltage monitoring chips. Therefore, to maximize the usable energy and power of the pack, cell balancing hardware is used. Two main types of cell balancing systems are in use, known as passive balancing and active balancing. Passive balancing consists of a resistor in parallel to each cell, controlled by the cell voltage monitoring chip. The intent is simple – discharge the cells at higher SOCs (or higher remaining charge) to match the rest of the cells. Passive balancing is the dominant method in use today. Active cell balancing is a technique where charge is moved from cells which have “extra charge” to those who need the charge. Active cell balancing hardware often has an intermediate storage location; the cells that need the charge are rarely next to the donor cells and it is infeasible to connect all the cells to each other – that would require (n-1)! connections, where n is the number of cells in the battery. The cost for active cell balancing hardware is typically higher than passive cell balancing, and its adoption has been low in automotive traction batteries.

Life balancing is different. Instead of discharging through a resistor, the charge is converted to power the low voltage bus, in place of traditional DC-DC converters (or alternators in conventional vehicles). Life balancing was first proposed [1] as a bidirectional system to allow a low voltage (12V) battery to be able to charge a high voltage battery, enough so it can start the engine, similar to jump starting a conventional vehicle, although it was not commercialized. Independently, the authors (led by Prof. Zane) developed the concept, and proposed it for the AMPED program, as a collaborative effort with experts in a variety of fields.

Hardware

For the prototype system, one DC-DC converter was designed for one cell. Each converter cam convert up to 30W of power to a low voltage (nominal 12V) load, at efficiencies of up to 93%. A value of

30W was chosen to allow full power draw slightly higher than present production DC-DC converters, meaning the converters could supply full power and still balance the pack. Figure 1 shows a converter as mounted over a cell from a Ford PHEV battery. The standoffs are there to for the first prototypes to minimize heat transfer from the converters to the cells, these prototype converters were air cooled. Later versions have increased efficiency, so the standoffs can be removed. The converter can also measure the cell voltage; this would replace the existing voltage measurement chips in the BECM. Life balancing converters may be either bidirectional (current flowing in either direction) or unidirectional (current flowing in one direction). For this project unidirectional operation (through software) was chosen in large part to avoid the possibility of a converter overcharging a cell. We thought this was especially important for a first concept program where the software did not go through the rigors of production validation.

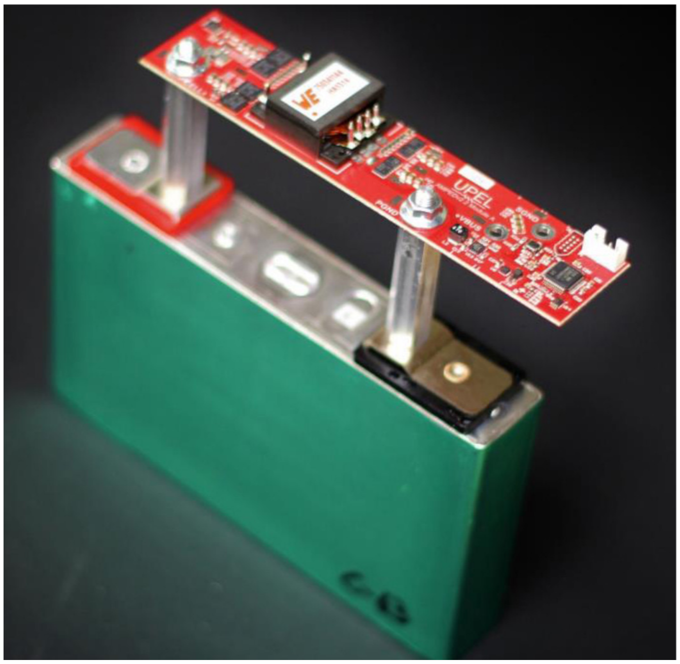

Figure 1. DC/DC converter as mounted on a cell from Ford C-Max PHEV.

System Architecture

The overall system architecture is shown in Figure 2. Note that the architecture is such that a single balancing converter can cover one or more cells. The prototype pack built used one converter per cell. The main reason why a single converter would cover multiple cells is cost - the goal is to improve performance while at the same time reducing the cost of the battery. When a converter covers multiple cells, the converter could also contain passive cell balancing circuitry. The net result is the merging of the functions of today's cell voltage monitoring chips and vehicle DCDC converter. Inputs on the converters for cell temperatures are optional. Communications to and from the BECM are by a standard communications protocol such as CAN. It is expected the output voltage set point would be received from the controller in the vehicle which has that function at present.

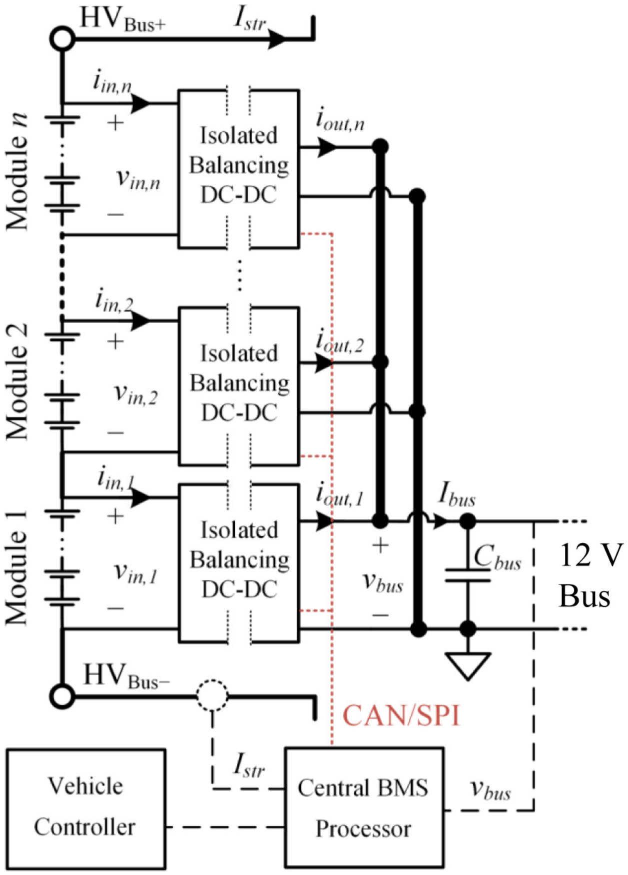

Figure 2. System Architecture.

Controls

The determination of output current for each DC-DC converter wound up being two distinct problems. First, the determination of how much total current was required to maintain the 12V system to the desired voltage, and secondly the distribution of the current among the various converters to balance the cells.

DC-DC Input Current Determination

Conventional vehicle alternators and DC-DC converters work by regulating the output voltage to a target set point. The voltage set point is typically a function of low voltage (lead-acid) battery temperature. The target voltage is set to maximize the life of the 12V battery. During the development of this project, it was realized that the old method would not work: with multiple converters we needed to know how much current to allocate from each cell, and in order to get the proper output voltage we needed the correct total current. We could not allow the output voltage of the converters to "float" in operation, the net result would be the overcharge or undercharge of the low voltage battery.

Algorithms were developed (patent pending) to determine how much total current is required to maintain the 12V battery voltage at the desired level. The balancing algorithms then take that information and distribute the charge among the various cells. The individual cell controllers have authority to make minor adjustments in the output current in based on the measured 12V battery voltage.

Balancing Current Determination

Once the total current is determined, the current must be distributed among the various converters. If all the cells are identical (same state of charge, same capacity, same state of health) then the problem is easy – the current is simply divided equally among the various converters. In older battery packs, that is never the case – batteries decay at different rates. With this hardware different balancing strategies are possible, including the following.

1. Maximum range. During charge, all cells are brought to the desired top of charge. While the vehicle is being driven, the cells with a lower capacity are given proportionally less current. This current is adjusted as the drive progresses to account for inaccuracies in capacity knowledge and variances in SOC.
2. Maximum efficiency. While driving and charging, some converters are turned off during periods of low demand on the DC/DC converters (low 12V loads)
3. Maximize power over the operating range, especially at low states of charge
4. Protect weak cells. In some cases, it may be desirable to keep low capacity/high resistance cells away from either the low or high SOC, to ensure the life of the battery is maximized. A small amount of range may be given up in trade, but only a fraction of a percent.
5. Combinations of the above.

Performance Benefits

The performance benefits of life balancing are insignificant for new batteries, but substantial for old batteries.

Maximizing Energy Out of the Battery

The penalty for the capacity fade of a single cell (single cell meaning a single physical cell or a collection of cells in parallel) is significantly less than present art. With conventional cell balancing technology, the range penalty is directly proportional to the capacity of the weakest cell, assuming the resistance change is negligible, or

$$Loss = 1 - \frac{\min(Q_i x_i)}{\min(Q_{i,new} x_{i,new})}$$

Where Q_i is the capacity of each cell and x_i is the fraction of state of charge used for each cell. With our life balancing technology, the normal usable energy in every cell may be used, or

$$Loss = 1 - \frac{\sum Q_i x_i}{\sum Q_{i,new} x_{i,new}}$$

This difference makes the pack extremely robust to capacity fade of a single cell. As an example, a 100 cell pack will be used, where a single cell has lost 10% of its capacity. With passive cell balancing, the usable energy (and thus electric range) would be reduced by 10%. However, with life balancing, the usable energy/range would only be reduced by 0.1%, a value not noticeable to most consumers. If, at the same time, it was decided that the balancing strategy for that same older cell 10% less SOC range, then the range reduction might be on the order of 0.2% - compared to 20% reduction for passive cell balancing. This technology also accommodates for lack of cell balance at top of charge by the exact same methodology, a that same pack with a single cell is 5% lower than the rest would have its range reduced by 0.06%, as compared with closer to 6% for passive cell balancing (depending on the SOC range actually used).

Range losses may be higher in cases where the battery is discharged faster than the DC/DC converters can correct. Typically, these cases would be where the 12V loads are so high that all converters must run near full power in order to maintain the 12V system.

Life Improvement

Simulations were performed to estimate the life improvement of the technology over three types of batteries: a 20 mile PHEV with air cooling, a 75 mile BEV with liquid cooling, and a 225 mile BEV with liquid cooling. Over a variety of climates, the average PHEV battery would show an increased life of about 30%, while BEV batteries could show an increased life of over 40%. The model was tuned based on a battery with an NMC chemistry. The bulk of the life improvement is due to the ability to use all the energy in a battery with a normal capacity distribution.

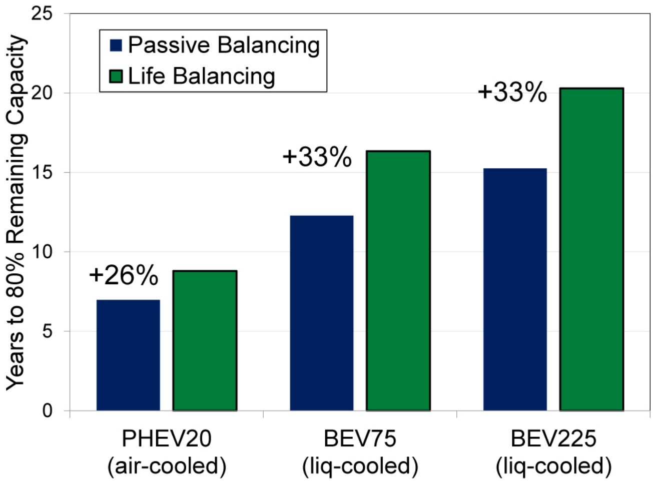

Figure 3. Life improvement simulation results

Flexibility in Sizing & Maintaining Efficiency

Vehicle low voltage loads have increased at a significant rate in recent years; this increase is expected to continue or even accelerate with the advent of autonomous vehicles. During periods of low 12V demand, such as while charging, some of the converters can be turned off, improving the efficiency of the system.

Enablement of Additional Advanced Controls

The cell-level DC-DC converters enable advanced controls. One example [2] would be the use of model predictive control to unlock more of the cell. The hardware could rapidly prevent a single cell from overcharging or overdischarge, and the cell limits may be adjusted.

Cost Benefits

The project team estimates that the production cost for the hardware may be favorable to the existing combination of battery controls and DC/DC converter. This is in addition to extending the life of the battery. This technology may also lead to relaxing requirements on temperature balance across the pack or on cell manufacturing tolerances.

A longer battery life would have additional cost benefits.

1. Warranty costs would also be reduced. It should be noted that PHEV batteries are subject to a ten year, 150,000 mile warranty in California and the states which follow California emissions regulations. Typical warranties for BEV batteries and PHEV batteries in non-California states are eight years, 100,000 miles.
2. Customers desire a life-of-the-vehicle battery, and an improved battery life may lead to a higher resale value for cars, and therefore lower lease prices for customers who choose to lease vehicles. This will be especially true once technology is developed to better predict the remaining battery life for automotive traction batteries.

Pack Integration & Preparation

To test the hardware, a battery for a 2014 Ford C-Max PHEV was used. This battery consists of 84 lithium ion cells, where each cell has a capacity of 25 ampere-hour. The battery is constructed with four arrays of 21 cells each. Each array was prepared/configured differently.

Two arrays were removed from the battery and artificially aged by cycling them at a US06[1] type of profile for four weeks in a temperature chamber set to 35°C. This had the effect of reducing the capacity by 6%, with a negligible change in resistance. These will be referred to as aged arrays.

Two arrays (one fresh, one aged) were placed in the bottom of the battery pack, and used passive balancing under existing Ford strategy. The other two arrays (again, one fresh and one aged) were fitted with project cell balancing hardware and placed in the top of the battery pack. The passive cell balancing hardware was present, but disabled by software. From an electrical perspective, the two arrays with the converters were the "middle" two arrays in the pack.

Because of the increased height of the pack to accommodate the converters, a new lid was designed. The lid was designed to allow cooling air to flow over the converters, and a transparent top portion of the lid was fabricated. Half the converters were on green printed circuit board, and the other half were on red circuit board. This was done because the cells alternate orientation in the pack, therefore two different versions were required for this prototype. The two colors allowed for easier assembly and verification of the assembly. Figure 4 shows the assembled prototype battery.

Figure 4. Ford C-Max PHEV battery pack with prototype DC/DC converters

The controls architecture for the prototype system was slightly different than a production system. To simplify implementation, the DCDC converters were connected to a secondary controller located in a PC external to the battery pack, via an RS-482 interface. Contactor control, safety, etc. were under the responsibility of the Ford BECM. The only damage possible by the external circuits would be to continuing to discharge the cells after the BECM opened the contactors. All data acquisition performed by the BECM was transmitted via CAN to the external PC. Additional temperature sensors were also put on the battery and converters, and used by the project algorithms. In a production application, the additional controls would be, of course, consolidated in the BECM.

The battery controls were stripped of most of the interface signals received from a vehicle, and in addition the remaining signals were modified such that the battery would not work in a production vehicle.

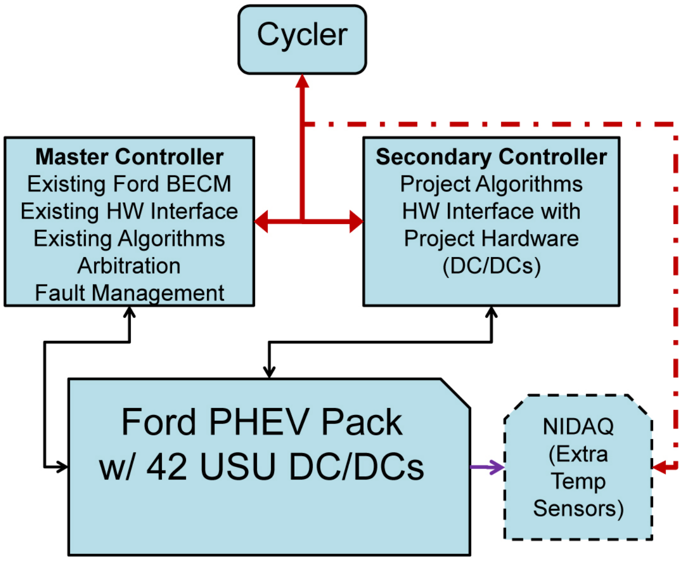

Figure 5. Test architecture

Test Methodology

Three cyclers were required to test the pack. One cycler managed the standard drive cycles. A second cycler took care of the 12V loads for the converters, while a third cycler took additional power from the half pack which did not have the converters on them, to avoid the situation where the cells with converters were discharged faster than the cells without converters. The 12V loads were maintained at a constant level of 750W for each half pack, representing a typical average load while driving. Subsequent tests will test the algorithms against the varying 12V loads found in vehicles; the constant loads were felt to be adequate for a proof-of-concept.

Testing

Validation testing was performed at the National Renewable Energy Laboratory in Golden, Colorado. The test cycles are a series of US06 drive cycles followed by constant power charging, simulating the 3.3 kW charger in the Ford C-Max PHEV. It should be noted that a US06 drive cycle is a very aggressive profile, one intended to push the limits of a vehicle. This cycle was chosen so the Ford battery

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[1] The US06 drive cycle is a speed-time profile, a generic power-time profile was used for charge depletion operation.

controller published charge and discharge power limits, the cycler was programmed to never exceed the published power limits regardless of the desired power from the cycle.

The figure below shows the effectiveness of this technology in maximizing range given capacity imbalance. For this particular test, the lower capacity cells (in blue) started at a lower state of charge than the higher capacity cells (in black). This was the “protect weak cells” usage case described above, where the lower capacity cells (intentionally one half of the cells with converters) were charged to a lower SOC. However, because of the technology we were able to discharge all the cells to the same SOC – and charge them back up such that the lower capacity cells are at a lower SOC. Note that with traditional technology, such a distribution would have caused a range reduction on the order of 20%, which is the conventional end-of-life capacity fade criteria used by the United States Advanced Battery Consortium, and the end of life criteria used in the life improvement modeling in this study.

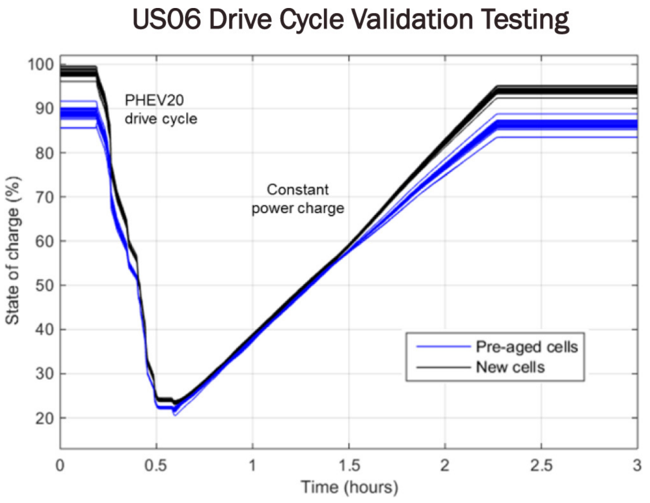

Figure 6. Drive cycle test summary

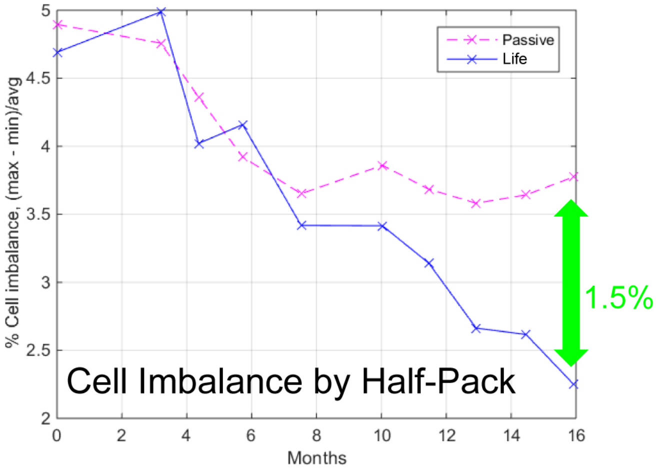

Figure 7. Cell imbalance

The half-pack with the life balancing hardware also shows a reduced capacity imbalance during the life testing. As was stated earlier, two quarter packs were aged before the tests started, giving a capacity imbalance of about 5% when the test started. After sixteen months of testing, the capacity imbalance of the pack with passive balancing has decreased to about 3.8% (see Figure 7), and appears to be stable. However, the capacity imbalance of the cells with life balancing is now about 2.3%, and has been decreasing at a more-or-less continuous rate. This decrease in capacity imbalance was predicted – the life balancing methodology allows the reduction of stress on the weaker cells, which slows the capacity decay and reduces capacity variation.

Summary/Conclusions

Life balancing provides a method to operate a PHEV or BEV battery with robustness to the weakening of a single cell, allowing more energy from the battery over a longer period of time. Capacity degradation is reduced, and cell capacities are more uniform. A battery with this technology will provide more usable energy to a vehicle for a longer period of time, potentially at a lower cost than traditional in-vehicle HEV architectures.

The architecture also leads itself as a platform to implement further advanced cell-level battery controls. The authors believe further development of this technology is warranted.

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Definitions/Abbreviations

AMPED - Advanced Management and Protection of Energy Storage Devices (U.S. Department of Energy program)

BEV - Battery Electric Vehicle

BECM - Battery Energy Control Module. The SAE name for the central controller of the battery management system

PHEV - Plug-in Hybrid Electric Vehicle

BMS - Battery Management System.

SAE - Society of Automotive Engineers

SOC - State of Charge. The fraction of charge in a battery available for use. Equivalent to a fuel gauge.

CAN - Controller Area Network. The most commonly used communications protocol in automobiles

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The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

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