MODULAR CONSTRUCTION OF BATTERY SYSTEMS[1]

The battery industry may be on the verge of a significant growth cycle in large format Li-Ion battery systems due to expected demand for electric vehicles. Important to this growth is what was once thought of as a detriment of the Li-Ion chemistry – that it requires monitoring and control electronics for safety and for reliability. Engineers are turning this detriment into an advantage by using intelligent electronics to make battery systems that have capabilities that would not be practical, or even possible, without these electronic tools. This article will show how this new battery system technology can be incorporated into products that are not in the high production mainstream but that have the same or even more stringent performance requirements. This new battery system development methodology utilizes ***battery modules*** to construct complex battery systems.

BATTERY MODULARITY CONCEPT

Battery modularity design methodology is the construction of a complex rechargeable battery system using series and parallel combinations of identical, independent battery modules. Each battery module is a self contained rechargeable battery of a convenient size for on-site construction of multiple battery system applications and for meeting DOT requirements for safety in transport.

The battery modularity design methodology relies on the battery module having a means of internal charge control that allows it to be charged from multiple energy sources such as power supplies, solar panels, fuel cells, or combinations of these. A battery system constructed from these modules has the capability of using these charging energy sources to charge the whole battery system while deployed.

Figure 1 is an example of the potential power of constructing a large 47.5 KWh battery system from 40 rechargeable battery modules. The system shown could be charged at 32 KW and discharged at 86 KW. Full recharge time in this instance is as fast as 2 – 4 hours.

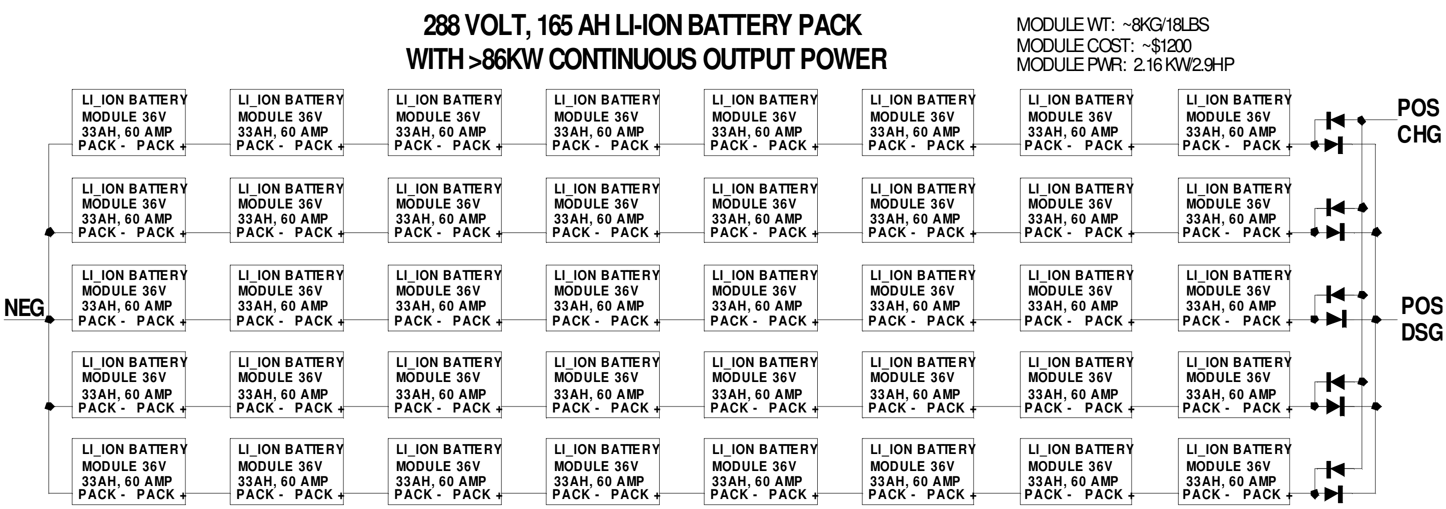

Figure 1. High Power & High Energy Battery System Constructed From Battery Modules

Advantages of constructing large battery systems using battery modules include:

1. Extreme flexibility of battery system design
2. Fast development
3. Cost reduced DOT testing
4. Increased safety in handling and shipping
5. Lower assembly costs
6. Lower repair & replacement costs
7. Lower inventory costs
8. Improved time-to-repair, and system availability

NOTE 1. *The methods disclosed in this article are protected by US patent 7,199,556 B1 and other US and International patents already granted or pending.*

BATTERY MODULE REQUIREMENTS

Construction of dissimilar battery systems using a multiplicity of same battery modules requires considerable foresight into the battery module design. Following is a list of typical requirements:

1. Fast and easy maintenance
2. Battery module replacement
3. Internal charge control
4. Configurable for distinctly different applications
5. High battery module reliability
6. Programmable architecture
7. Support individual or centralized status, state of health monitoring, and remote control
8. Support display of state of health, capacity, charge status, etc.
9. Chemistry agnostic
10. The Key Requirement – A means to balance all cells and all battery modules in the battery system

WHY BALANCING IS THE KEY REQUIREMENT

Modern Li-Ion cell chemistries are remarkably robust in their ability to maintain balance. Never-the-less, field return data on high series count batteries support the need for a robust balancing capability for complex battery systems. For high cell count battery systems battery pack unbalance is the number one reason for pack failure. To understand why consider the following:

1. The likelihood of an imbalance increases with the number of series connected cells
2. A larger battery pack has a greater likelihood of portions of the pack being at different temperatures
3. Pack imbalance can be caused by differential leakage currents external to the cell such as:
   - Differential leakage currents within the pack-protect circuit itself
   - Differences in the insulation resistance between cells
   - Humidity & condensation on the pack-protect circuit board and on the cell insulators
4. Pack imbalance can be caused by inter-module or intra-module capacity differences due to:
   - Different lots of same cell
   - Differences in module age
   - Cell electrolyte leakage, contamination, or other damage
5. Replacement of battery modules typically requires a system re-balance due to:
   - The replacement module's state of charge being different from other modules
   - The replacement module's capacity being different from other modules

The resultant requirement is that a robust balancing capability must be designed into the whole battery system. In the instance where the module design concept is utilized, this means intra-module and inter-module balancing.

EXAMPLE IMPLEMENTATION OF INTRA-MODULE AND INTER-MODULE BALANCING

Electronic cell balancing is not new. Two common methods are discharge balancing and charge transfer balancing.

Discharge balancing is balancing by discharging higher capacity cells until they match the capacity of the lowest capacity cells.

Charge transfer balancing is balancing cells by transferring charge from the higher capacity cells into the lowest capacity cells until the cell capacities are equalized.

Both methods can theoretically be done at any time and in any battery operating mode. Neither method will reduce the usable capacity of a battery pack from what it was prior to being balanced.

These balancing methods are commonly only described for balancing across a complete, inflexible, battery system using centralized control. There is an unmet need for a balancing method for highly configurable battery systems constructed from independent rechargeable battery modules. The following two methods, developed by Southwest Electronic Energy Group, meet this need:

Zener Diode Module Balancing (See Figure 2)

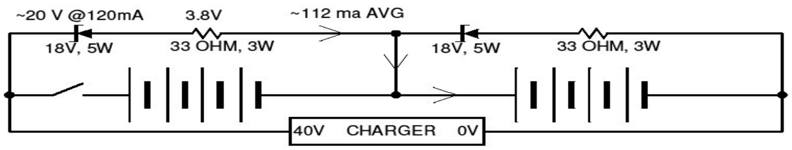

Figure 2 - Zener Diode Module Balancing Circuit

A simplified schematic of two, 4 series, Li-Ion battery modules that utilize Zener diode module balancing is shown in Figure 2. Assumed, but not shown, are the pack-protect circuits associated with each of the modules. The two modules in the figure are unbalanced and are in the process of being charged. The first module has attained full charge status and its charge FET (shown as a simple switch) has opened. The other module is at a lower relative state of charge and has not yet attained full charge status. Charge current is bypassing the fully charged module via the Zener diode and current limiting resistor and is charging the module at the lower state of charge. The charge current will continue until both modules are balanced at which time the 2nd module's pack-protect circuit will open its charge FETs.

Figure 3 illustrates how Zener diode balancing works. Each module in the example has internal charge control. Module 2 is at a higher state of charge than Module 1. At the beginning of the data set, Module 2 is near its end-of-charge cycle and has begun pulse charging – allowing charge current to flow into both modules in a pulsed fashion. When Module 2 is at full charge, it stops pulsing and opens its charge FET. Module 1 completes its charge using the bypass Zener diode current. When Module 1 has reached full charge status it also opens its charge FET. Both modules are now balanced and charge current stops going through the modules. Some small amount of quiescent current will bypass both modules as long as the charging power source is attached.

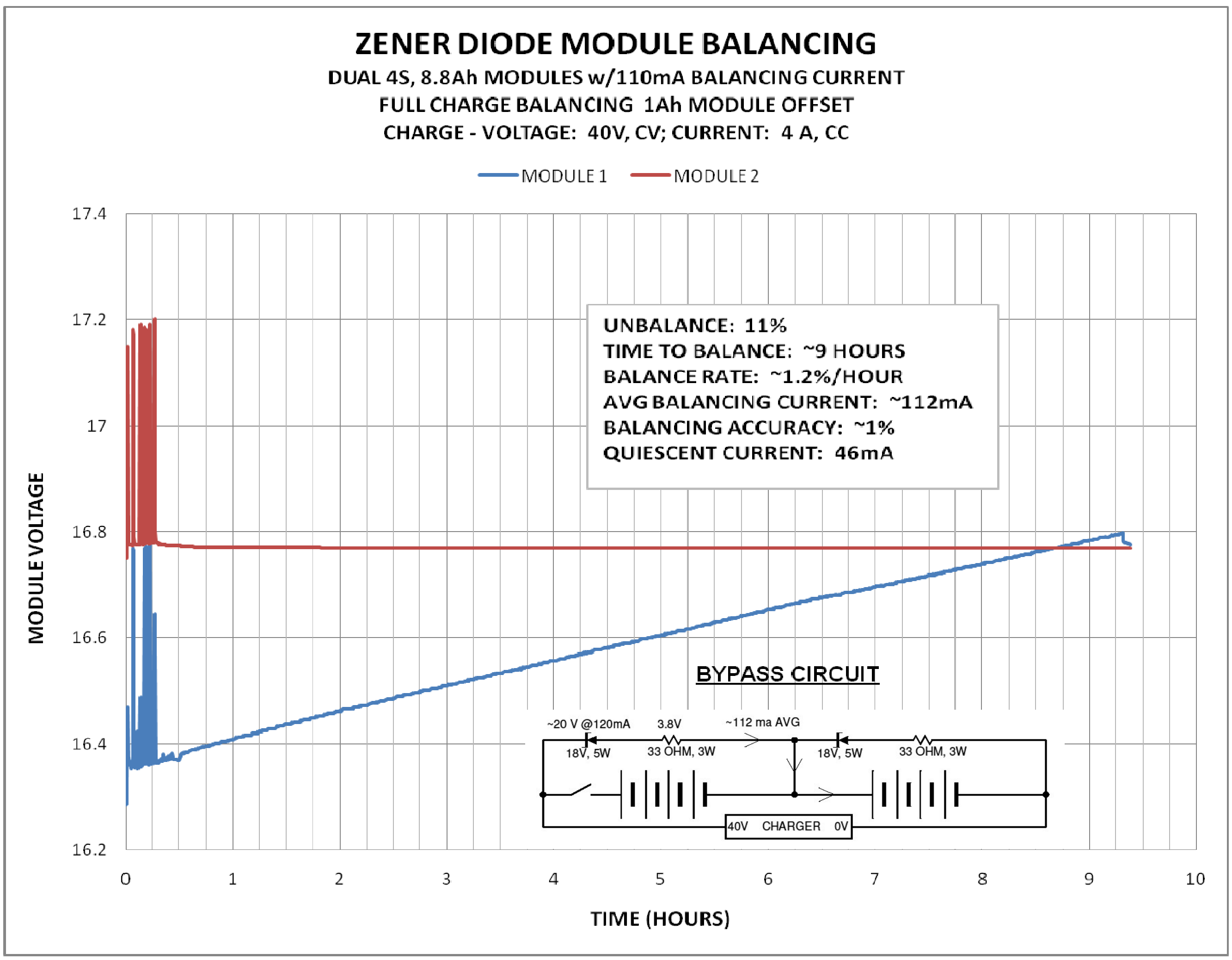

Figure 3 - Zener Diode Module Balancing Example

Discharge Module Balancing (See Figure 4)

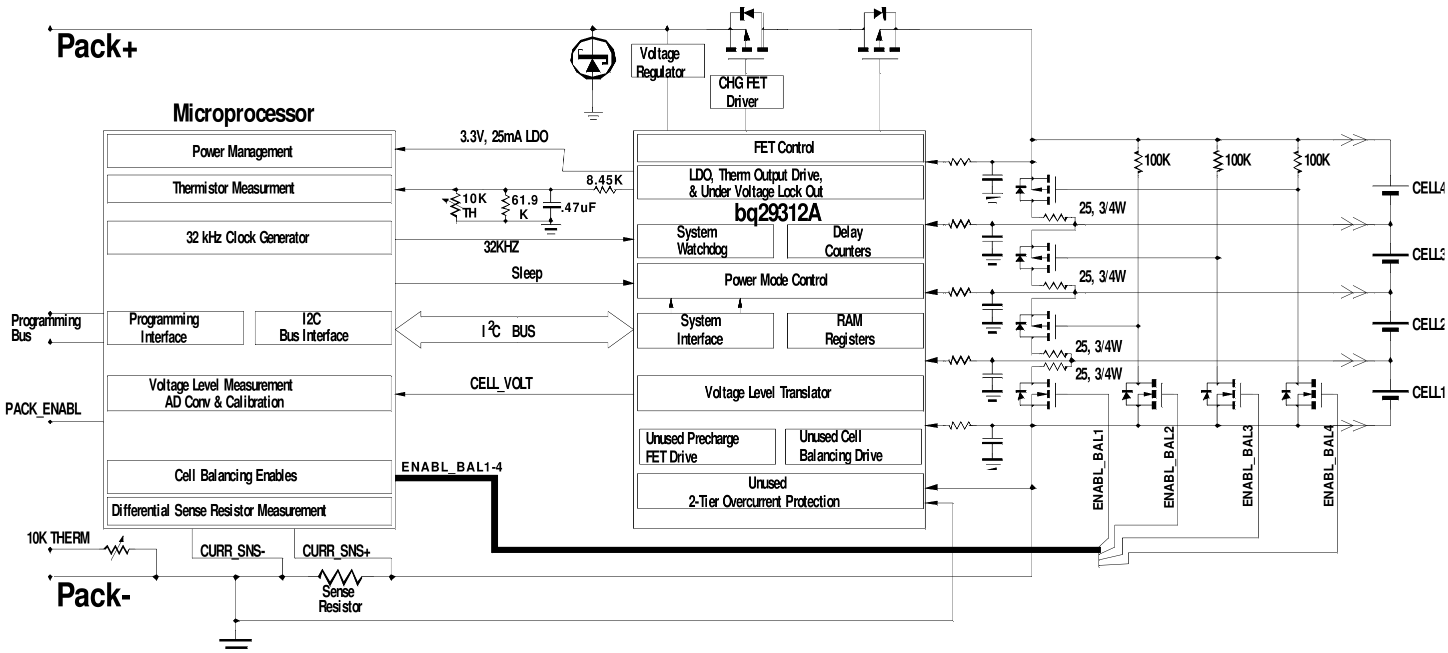

Figure 4 Discharge Module Balancing Circuit

A simplified schematic of a 4 series battery module that includes the Li-Ion cells and the protect circuit is shown in Figure 4. The circuit in the figure is capable of intra-module and inter-module discharge balancing. The circuit is constructed using off-the-shelf parts including a microprocessor, an AD converter, an Analog Front End circuit, external balancing switches, and external discharge balancing resistors. An 8 amp implementation of the pack-protect circuit in Figure 4 will fit onto a 2.5” X .75” PCA.

As in the previous example, consider a battery system made from two, Figure 4 modules connected in series. Each Figure 4 module is able to balance the cells it is connected to using the external FET switches and the 25 ohm, 3/4W discharge resistors. This is conventional intra-module balancing. What may not be obvious is that each Figure 4 module, under appropriate internal software control, is also capable of inter-module balancing with the other module connected in series with it without there being any control communication between the modules.

Figure 5 illustrates how Discharge Module Balancing using two, Figure 4 modules connected in series is accomplished. The two modules are programmed for intra-module charge control to 80% capacity as might be required in a battery back-up application. There are no control signals connecting these modules; the battery modules’ external connections were only PACK+ and PACK-. A description of the action taking place in Figure 5 follows:

> Prior to being balanced, Module 2 is at a higher state of charge than Module 1 – they are unbalanced. A 34 Volt current limited power supply is connected across the two modules as a charge source. Module 1 has its charge FETs constantly on but Module 2 is close to being fully charged so it pulses its charge FETs to reduce average charge current. The pulsed charge current from Module 2 charges both Module 2 and Module 1 until Module 2 reaches 83% capacity, opens its charge FET, and stops pulse charging. Between charge pulses, Module 2 discharges itself down to 80% capacity by enabling all 4 of its balancing resistors. Module 1 does not discharge itself during this time because it has not reached 83% capacity. When Module 2 discharges down to 80% capacity it begins pulse charging once again until it again reaches 83% capacity and opens its charge FET. Thus, Module 2 charges and discharges itself between 80% and 83% capacity while Module 1 only charges without discharging. This continues until Module 1 attains the same 83% capacity at which time the two modules become balanced. Once balance is attained, both modules continue to perform 3% capacity charge – discharge mini-cycles. Pulse charge current range is approximately 2.2 to 3 Amps due to 0.44 ohm resistor in series with the 34 Volt charge source. Charging and discharging 3% at about 80% capacity is not stressful on the cells. Cycle rate is about 0.8 cycles per hour, 19.2 cycles a day, 7008 cycles a year. An obvious question is how many of these mini-cycles are required to reduce cell full charge capacity to 80% of their initial value? Some NASA studies indicate this number may be in the 10s to 100s of thousands. Thus, it is feasible that continuous mini pulses such as this do not appreciably affect battery module life. Never-the-less, if mini-cycles are objectionable, it is possible to lengthen them or cause them to stop altogether once balance is attained.

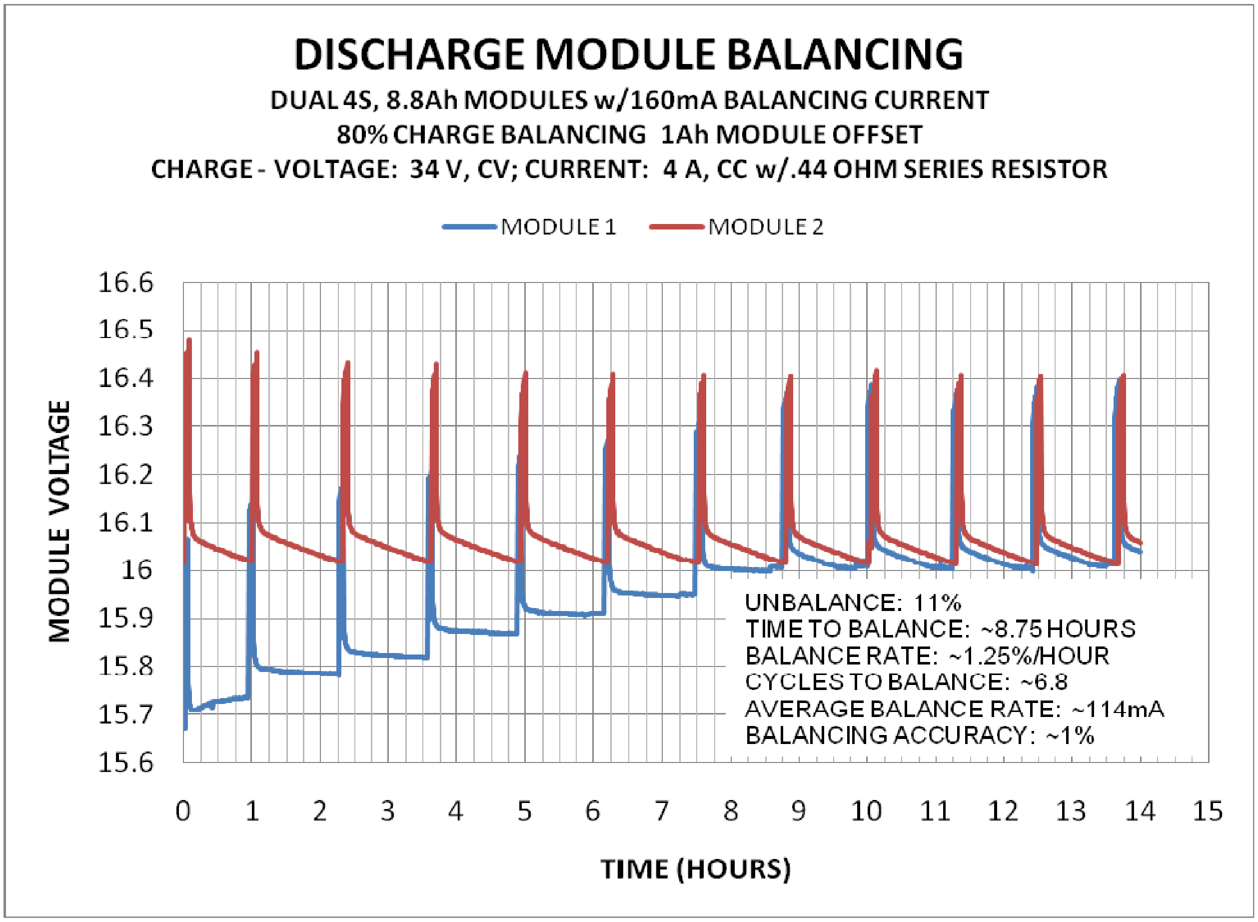

Figure 5 – Discharge Module Balancing Example

CONCLUSIONS

Electronic balancing is a requirement for Li-Ion battery systems because the chemistry does not provide for overcharge balancing as do previous rechargeable chemistries. Engineers having to live with this restriction are discovering that the ability to automatically electronically balance all parts of a complex battery system leads to new paradigms in battery system design, use, and maintenance that are only recently becoming evident. Among these are:

1. Applying electronic balancing to other, non Li-Ion, rechargeable chemistries
2. Increased number of series connections in a battery
3. Increased flexibility in modularity & replaceable unit concepts
4. Smarter battery systems
5. More flexible charge control
6. Multiple charger energy sources
7. Potential for multi-energy source hybridization