



CURRENT EVENTS

December 2012 Promoting the use of electric vehicles since 1967 Vol. 44 No. 12

Simple Analog BMS For The Tinkerer - Part I

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I honestly don't think there is any rationally thinking fellow out there who believes an EV battery pack composed of modern lithium cells does not need a management system (which is supposed to make sure the pack and individual cells work within allowed limits). No one would dare to just wire cells together and forget it, cycling whole pack as one single cell!

However, to answer the frequently heard question if one needs some kind of a physical BMS installed in the vehicle, the answer is certainly not a simple 'no'. There are two ways to deal with this issue. Battery management can either be carried out by dedicated hardware doing the work for you, or be done by YOU, acting as the battery manager, if you don't mind doing

necessary work yourself! But it must be one or the other! Most people will use some sort of BMS to automate this tedious task, consistently taking care of the battery 24/7/365 without getting tired, distracted, without "calling in" sick or procrastinating until weekend. [Ed: exactly one year ago in Dec. 2011 CE, on page 22 we feature one such story, titled "EV Mania turns to Battery Nightmare from Hell!" It is not a pretty picture painted by that story!] But since the convenience of such a BMS obviously comes at cost, some people decide they'd rather manage their battery manually. Either way works, provided you know precisely what you're doing. (There is a third group of people who steadfastly believe and advocate using no lithium cell or battery supervision at all, as if an EV battery pack is magically "self-curing"! But we're not going to debate that or validate those ideas here. That's what 'natural selection' is for!)

Thinking about how to simplify battery supervision system around 2004, I came up with minimalist cell clumper design. This was simply an amplified classic shunt regulator built around TL-431 adjustable shunt. 96 clumpers were installed in my ACRX – a second reincarnation of Honda CRX conversion with AC drive, done in 1995 (still in service today). It worked very well with good quality cells, but could not cope with inferior (then brand-new) Lithium cells from Thunder-Sky's which were supplied for a 'group purchase' by eleven early (first, actually) adopters. Those who were into EVs 10 years ago when no one was running on lithium yet might remember the story. Anyway, this clumper design for TS cells was predecessor of what became known as MIMIC (MetricMind Infrared-Modulated Intelligent Clumper). This design was contributed to the Tumanako project

continued on page 34



Upgraded LEAF for Japan
... page 12



Capacity Loss Tool
... page 20



Battery Design Innovation
... page 28

Analog BMS

Continued from page 1

initiated by Green Stage Company (New Zealand) and then released to public domain. Those running this project not only listed this design along its sub-projects, but also helped me to write initial software for it to get started.

DIY DESIGN

Today I wanted to share a flavor of MIMIC I re-designed with my fellow EVerS in mind, for whom simplicity, affordability and the ability to build it themselves (from plans) often outweighs the sophistication and completeness of more advanced OEM BMS systems. While as name implies, the original design used infrared light for isolated data transmission (and baby PICs to process data). What is described here is modified in two major ways, which makes it reproducible by anyone with basic skills in assembling electronic circuits:

- No microcontrollers are used, so no software is needed. It's a pure hardware solution.
- Wired bus and standard optocouplers used for data transmission/reception.

With the wide acceptance of lithium batteries (due to capacity and long-term cost strengths) many new BMS designs came out in recent years. While varying in complexity, the majority of them share a common passive balancing concept. In essence such a BMS consists of remote voltage (and usually temperature) measurement system and array of remotely controlled shunt resistors, one across each cell. Normally the BMS also takes care of auxiliary functions such as controlling main contactors and the charger. It works like this: after a cell's voltage, temperature (and sometimes capacity) data is collected and massaged, based on some proprietary algorithm — a decision is made which cells to shunt current away from and when to do so. This is usually done during charging so the overall capacity of the pack is not reduced due to balancing activity. When a cell is shunted, current that used to flow entirely through it, is split in two paths thus reducing that cell's share of total current. This causes the shunted cell to be charged at slower rate, and thus accumulate less Ah over time than the unshunted cells. Since with passive balancing charge can only be removed, only cells with extra charge are shunted. The goal is to keep all cells in balance at all times. While that sounds simple, the first difficulty comes from the ambiguity of definition “cell balance”.

WHAT IS CELL BALANCE REALLY?

The term “balance” applies to cell state of charge (SOC), not cell voltage. A pack is balanced when all its cells are at equal SOC. Some BMS systems declare pack balanced when each cell contains the same amount of Ah at all times, instead of having the same SOC. Many proprietary OEM systems use at least both criteria (and often — have even more, like internal resistance) to determine SOC. However, home-made amateur BMS systems often substitute cell SOC for cell voltage, and declare whole pack balanced simply when cells voltages are equalized. Anybody (well, almost) can

measure cell voltage remotely. This method, however, may or may not present problem depending on whether or not a cell's voltage really represents its SOC for given flavor of lithium chemistry. Voltage based balance works well, for instance, for LiPo cells, but won't work very well for lately popular LiFePO4 cells. Why? The problem is that voltage across each LiFePO4 cell does not change throughout most of its working region (from between ~15-20% SOC and ~80-85% SOC). Meaningful voltage measurements can be done *only outside this region* — exactly where you don't want the cells to be operating. [Ed: Read that statement again!] Moreover, at low temperatures, the terminal voltage of a cell will actually rise while the cell is being discharged! (This happens because falling internal resistance as the cell gets warmer raises the terminal voltage at faster rate than decreasing SOC lowers it). This will certainly confuse voltage based balancing BMS unless smart compensation based on a lot of empirical data or good modeling is deployed. Other parameters such as charge/discharge rate, cycle life, calendar life and even physical cell shape (pouch, cylindrical or prismatic) affects the voltage/SOC relationship in a ways even a manufacturer hasn't characterized.

WHEN IT'S TOO LATE

If voltage balancing starts only when the SOC reaches 80-85% (some people prefer to “bottom balance e.g., while cells are discharged, in this case when the SOC reaches 15-20%) where voltage finally begins more or less, to represent SOC, it's too late — there is no enough time to balance voltages before pack is full (or empty) — that is, unless you use a monstrous force to cool high-current multi-ampere shunts — a sign of a crude BMS, (whose aggressiveness either substitutes for the finesse of more sophisticated predictive balance strategies, or is meant to deal with substandard cells whose parameters are all over the map). This is because the time during which you could gradually remove the necessary amount of Ah out of cells with low current shunt over relatively long course of bulk charging — is lost. Accurate SOC tracking, cell resistance measurement and interpretation, and predictive modeling of cell behavior is far more difficult to implement than just remotely measuring voltages. Therefore for simplicity (read — cheaper, quicker to-market implementations), voltage balancing is being used over and over — it often outweighs the effectiveness of whole system. [Ed: another reason might be that OEM's are hiring inexperience designers who only know to measure the terminal voltage of a cell, and are not familiar with more advanced “smart” techniques.]

Remember, no two cells are identical. Even if they start nearly identical, and come from the same final assembly batch, over time they deviate due to pack location, differences in circuit parameters within the pack, etc. **A BMS is not there to fix bad cells, it simply can't do that.** Add to this the fact that amateurs don't have luxury to cherry pick and match cells for their packs and [unlike for OEM packs] cells might come from different manufacturing batches. [Ed: Most DIY folks don't even purchase spares, as they wince and cringe at the initial expenditure for their pack.] Interaction of all these parameters makes accurate estimation of SOC based on just

continued next page

cell voltage measurement alone impossible, no matter how accurate readout is. These are not your father's PbA EV batteries anymore, where terminal voltage linearly corresponded to SOC!

The subject of this article, however, is not to debate whether equalizing voltages instead of SOC is a good or even a valid idea or to criticize designs of such BMS's. For many one-off battery systems this can be acceptable compromise, and if done right, it will work well enough, especially because in amateur EV projects, where most people loves tinkering with hardware and periodically will intervene with a measurement (and then hurriedly make do with a manual rebalancing, thereby compensating for use of a scheme that lacks "system intelligence." If you happen to be one of those people, this article is for you. It just describes one possible hardware implementation of such BMS method without endorsing it as the only solution.

CLAMPERS IN ACTION

For a fixed clamper circuit in its simplest form, it would be enough to have something like a powerful Zener diode or its equivalent across each cell. [Ed. A Zener will conduct heavily or breakdown at a fixed voltage, unlike a regular diode.] It will start bypassing fraction of charging current after that certain voltage threshold is reached. The main problems with this approach are:

- Selection of breakdown voltages is limited to a few fixed, discrete values;
- that breakdown voltage has wide tolerance, and is not adjustable.
- the breakdown voltage is very heavily temperature dependent.
- the diode's dissipated power losses are unacceptably large for decent charging rate.

Substituting single Zener diode by few forward biased new silicon carbide (SiC) Schottky diodes greatly diminishes temp. dependence and power dissipation per device, and is absolutely simplest and cheapest practical clamp circuit one can come up with. You can also make a "Zener equivalent" (a transistor amplifier with or without the help of an OpAmp, so it becomes adjustable), or use window comparators (as was done in my 'Smooth Talk' hardware-based BMS), but the main issue with any such clamper remains the same: a static breakdown voltage cannot track cell voltage changes nor can it get adjusted remotely. Therefore a fixed clamper can only protect cell from overcharge when its voltage hits certain threshold. Below that threshold, clampers are useless – if cells are cycled in the middle of charge/discharge curve, such clampers simply never get chance to clamp. That happens when the EV is opportunity charged, anywhere around the middle of its SOC.

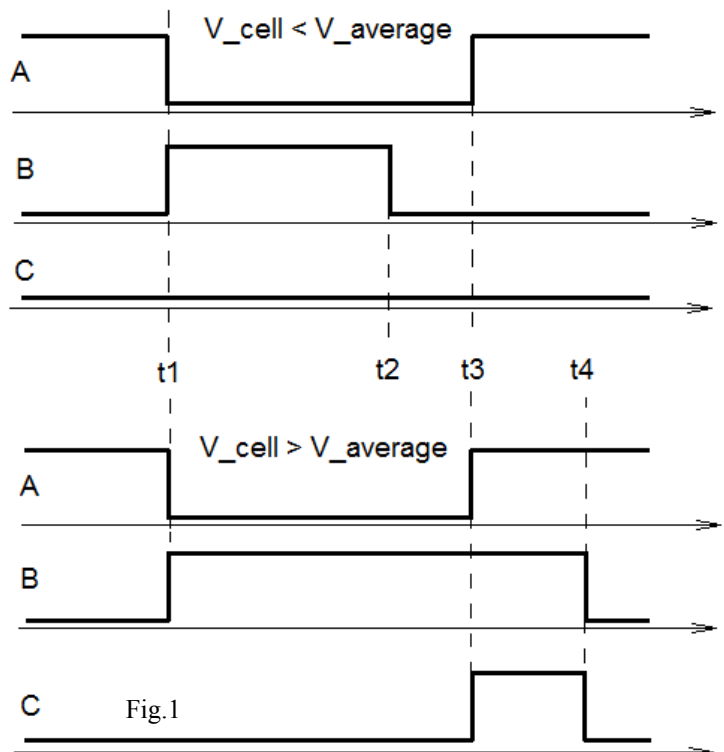
MIMIC addresses these issues as following:

- It does not use Zener diodes as the reference;
- An average ("ideal cell") voltage is being continuously tracked and transmitted to each MIMIC module – a function which makes the clamper remotely adjustable and is able to bring cell voltage to the ideal cell voltage anywhere within charge/discharge curve;
- MIMIC compares this average ("ideal cell") voltage to monitored cell voltage and turns on the shunt for a time duration proportional

to the difference between these voltages (if the target cell voltage is higher than average, we bleed current). Comparison is done by an analog circuit so there is essentially infinite resolution;

- Shunting takes place anywhere on the cell discharge curve, not after certain fixed threshold is reached, at the extreme ends only.
- Any temperature dependency of cell voltage measurement is compensated for by the same circuit on transmitting side, so errors caused by temperature variations cancel out.

As with any passive balance BMS's, the power is dissipated in a bypass power resistor. And as with any crude voltage measurement based BMS, it starts working only when cell voltages deviate from average far enough, e.g. for LiFePO4 chemistry — near the end of charge. It works much better with LiPo cells or any chemistry where voltage more-less represents SOC. The relationship doesn't have to be linear as with lead acid batteries, it just has to be never varying. The core of MIMIC module is unambiguous 555 timer and the highest cost component is power resistor. This makes MIMIC very inexpensive – about just \$5-\$7 worth of electronic components per cell, and entire system for high voltage pack can probably be built for well under \$500.



Please note that MIMIC is not a substitute for a real BMS. It has no memory, no stored algorithms or battery models. It does not control charger or main contactors. It is pure analog hardware solution for what the name implies – an intelligent clamper. It does not know what the voltage of each cell is. All it knows at any time if a cell voltage exceeds average, and if so, acts upon it. MIMIC shunts higher than average cells with a variable rate proportional to the degree of discrepancy. MIMIC will ignore cells with voltages lower than running average. However, there are means to visually check

continued page 36

Continued from page 35

for any low cells in the pack. Finally, there are no fancy displays for each cell, as I don't think this is necessary. (Think of the Nissan LEAF – thousands of their drivers not only have no 'per cell display', but even have no idea how many cells their battery has! Yet, they drive every day just fine, as long as they are confident the battery is taken care of).

My background is hardware design (mostly – analog), but I'm no programmer. So I designed MIMIC to have what I believe is one important attribute – anyone who has sufficient basic knowledge of assembling electronic circuits can build it. The system might require troubleshooting, but never debugging. It is like old fashion transistor radio – if assembled from known good components with no mistakes, it is pretty much guaranteed to work.

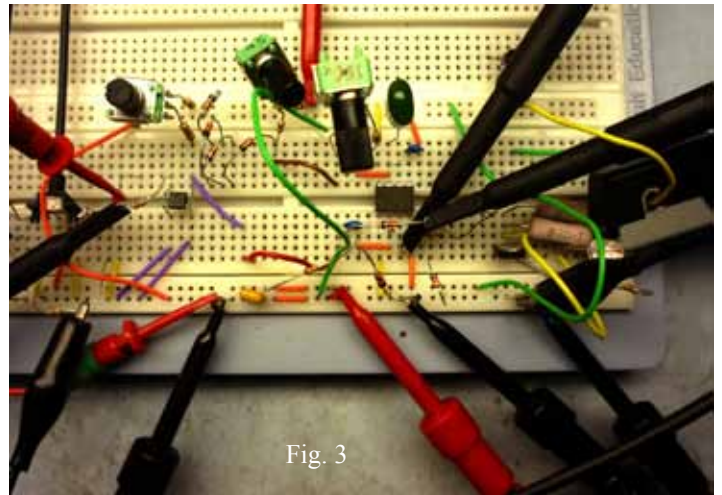
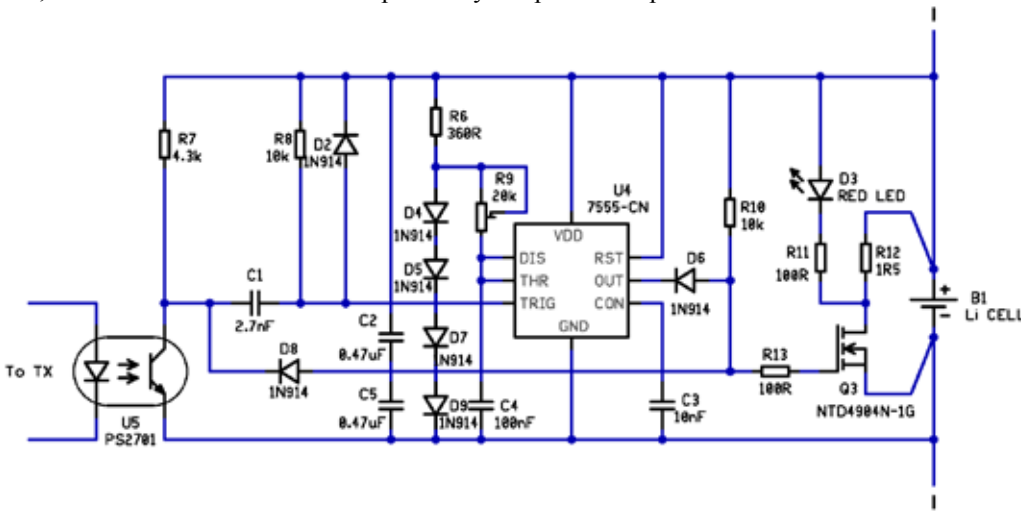


Fig. 3

So, how does it work? The concept is very simple and depicted



on fig. 1.

HOW IT WORKS

The concept is very simple and depicted on fig. 1. This is a timing diagram is read from left (where time = 0) to the right, with multiple things happening on different horizontal lines, all in sequence.

Incoming inverted pulse A (delivered to each MIMIC module) whose length t_3-t_1 is proportional to average ("ideal") cell voltage is logically AND'ed with locally generated pulse B, whose length is proportional to the voltage of cell being monitored. The output of AND gate (pulse C) directly drives FET switch connecting shunting resistor across the cell. So voltage differences become translated into proportional time differences which turn on the switch. As the voltages converge, the time spent 'on' goes to zero. That's really all there is to it.

There are two distinct conditions – 1: when a cell voltage is less then (or equal to) average, and 2: when it is greater. First condition depicted on top of fig 1. $B=t_2-t_1$ is shorter than $A=t_3-t_1$. Therefore there are no positive overlaps of both pulses, so $A*B=C$ remains zero and no shunting occurs.

Another condition is when measured voltage exceeds average reference as shown at the bottom of fig. 2. In this case $B=t_4-t_1$ becomes longer than $A=t_3-t_1$. Logic AND of both pulses yields overlapping pulse $C=t_4-t_3$ whose length is the difference

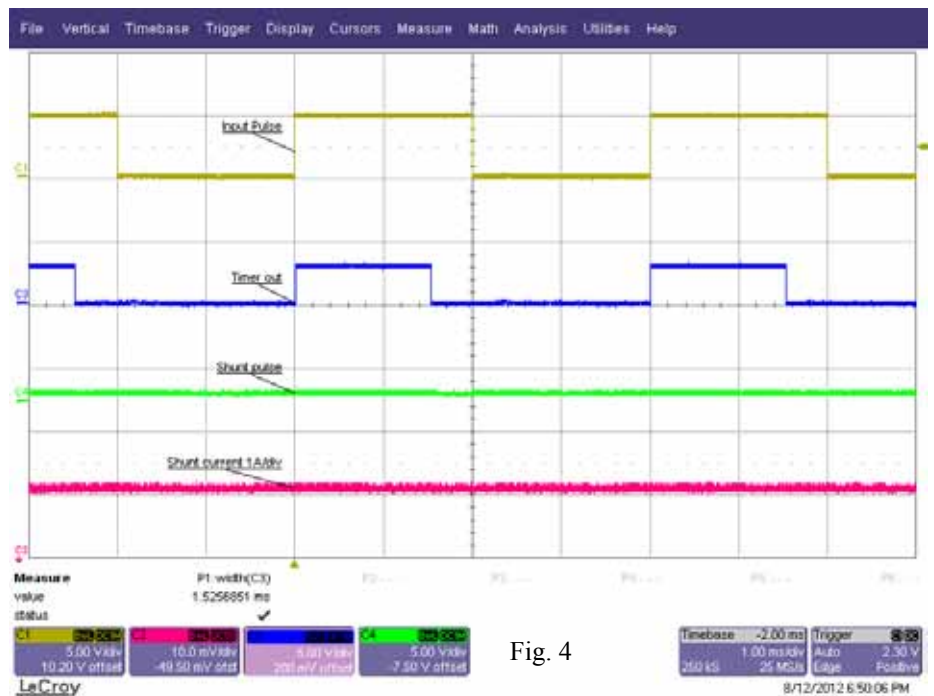


Fig. 4

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between B and A, and that is proportional to the voltage difference between monitored cell and ideal average cell. The more the difference – the longer pulse C is, thus longer shunting time. So, more Ah is taken out of the cell one pulse at the time, until cell's voltage becomes equal to the average.

Because transmitted average cell voltage (e.g. pulse A length) changes as whole pack is charged or discharged, it is precisely being tracked by every MIMIC – each cell gets compared to ideal average one. Think of all MIMICs as means to make sure total pack voltage is divided among all cells exactly equally, and if it isn't – they will correct for it. An electrical schematic of a single MIMIC module installed on each cell is presented on fig. 2.

THE DETAILS

The heart of the circuit is voltage to time period converter built around U1 timer chip. I arranged the circuit in a slightly unconventional manner to turn it into a 'Vdd supply voltage to time period converter' working on a monostable (one-shot) multivibrator principle. Opto U2 inverts a positive incoming TX pulse. The resulting falling front edge of reference pulse shaped by differentiating RC network C1R3 [re]triggers V/T converter. As a nice side effect, cap C1 also increases the circuit's fault tolerance by creating a fail-safe feature — it DC isolates the timer TRIG input from the optocoupler thereby preventing the output of timer from going high if the opto were to get stuck (either high or low). In that condition, there would be no falling edge on the TRIB input and resistor R8 will keep the TRIG high at all times, fortunately keeping the power FET off, enabling the desired clamping action!

Logic AND gate is formed by D5, D7 and R5. The low gate threshold FET switch Q1 connects shunt resistor R7 across cell B1. D1 prevents TRIG input of U1 raise above Vdd rail, D3, D4, D6 and D8 form reference voltage for V->T converter. U1 bypass capacitor is split in two C2 and C3 in series, for reliability reasons. If only one capacitor were to be used, and should it fail as a short circuit, it would short out cell B1. With two caps remaining one will take up the slack as if nothing happened. The probability of both caps failing as shorts is near zero, at least far lower than, say for Q1 FET. An extra half-cent cap is very cheap insurance to avoid potentially catastrophic problem.

Unlike the original design where average cell information is delivered to each MIMIC by modulated IR light, to simplify and reduce cost this design uses regular optocouplers and wired "bus". the Optocoupler's speed is not critical since pulse periods are chosen large enough for opto's propagation delays to be irrelevant. The circuit is so simple that it took me less than an hour to mock it up on a proto board (see figure 3) and just one evening to fine tune it. With so few components it is hard to even see them all behind the various probes.

The operation of the circuit is confirmed in figure 4, depicting the condition when cell voltage is less than average, and in figure 5 – when it is more than average. You may notice the gate voltage rise time is slowed down by gate capacitance charged through resistor R8. However due to low threshold of Q1 it turns on pretty sharply and the shape of shunting current (lower trace) monitored by a DC current probe is actually pretty rectangular. The ideal average cell

voltage generator and transmitter are separate circuits. The pack voltage is isolated and scaled down to the single cell voltage. This voltage then feeds identical MIMIC circuits as described above, except the output drives a string of LEDs in optocouplers. This is done intentionally so any pulse-width drift due to temperature changes will affect the reference pulse to the same degree as a locally generated pulse; in other words temperature related errors are largely cancelled out.

TO BE CONTINUED!

Due to limited space, part II of this article (transmitting circuit description) will be published in an upcoming issue of Current Events.

