Improved $LiFePO_4$ cell balancing in battery-backup systems with an Impedance Track™ fuel gauge

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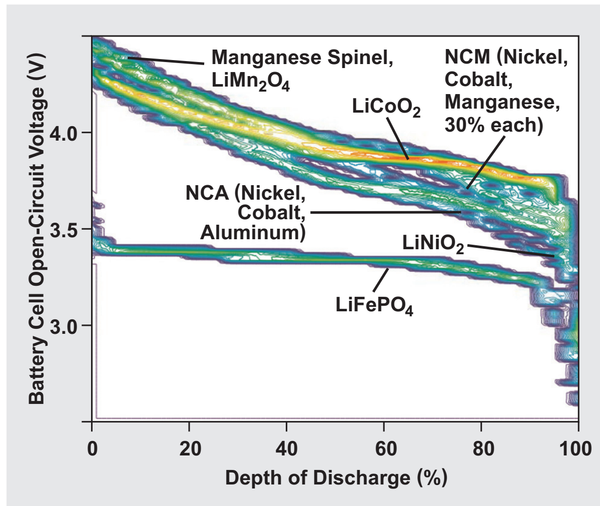
The Impedance Track™ battery-fuel-gauging technology from Texas Instruments (TI) is a proprietary algorithm that learns battery capacity and impedance over time to accurately calculate the state of charge (SOC) and remaining capacity.

There are special conditions that need to be understood when dealing with a battery-backup application where short charge periods occur every couple of days to replenish self-discharge, and a full discharge rarely occurs. When lithium-iron-phosphate ($LiFePO_4$) cells are used, either the gauge's balancing feature must be disabled or an enhanced firmware must be used. This article provides information about TI's specially developed firmware for the bq20z45-R1 gas gauge that allows data-flash parameters to be programmed for proper battery cycling and the best balancing results. Guidelines are also provided for accomplishing off-line cell balancing when balancing has been disabled for normal operation.

Figure 1 shows a voltage-density plot of single-cell, open-circuit voltage (OCV) versus depth of discharge (DOD) for all lithium-based cells that TI has analyzed over a period of approximately ten years. (DOD is simply 1/SOC.) One can see that the voltage profile of the $LiFePO_4$ cells is very flat for a significant portion of the SOC curve. This voltage flatness leads to difficulty in the precise SOC estimation required for cell balancing with the Impedance Track algorithm. The steep voltage increase visible at the end of charge (approximately 0% DOD) can lead to significant cell-to-cell voltage divergence, further complicating SOC estimation and cell balancing.

Figure 1. Map of voltage densities for lithium-based battery cells



Eliminating Q_{max} updates during operation

It is permissible not to have a Q_{max} update during field operation. Although not required, the ideal situation for a highly reliable battery-backup application is for the pack's Q_{max} to be determined with a full discharge during the manufacturing process. After Q_{max} is learned, no further Q_{max} update is required.

Events for determining initial Q_{max}

Table 1 shows typical enhanced data-flash parameters of the bq20z45-R1 with version 7.02 firmware that must be modified via TI's bq Evaluation Software tool to implement a Q_{max} update. These particular parameters are protected (classified as "hidden") but can be unlocked by TI's applications staff. Battery parameters in Table 1 are from the TI database for a 2-series, 2-parallel (2s2p),

Table 1. Protected data-flash parameters that TI's applications staff can unlock based on system characteristics

DATA-FLASH PARAMETER	DEFAULT VALUE	NEW VALUE
Operation Cfg C	0130	05B0
Min % Passed Charge for Q_{max}	37%	No Change
Min % Passed Charge for 1st Q_{max}	90%	No Change
Q Invalid MaxV	3351 mV (chemical ID 404 default)	No Change
Q Invalid MinV	3274 mV (chemical ID 404 default)	No Change
OCV Wait Time	1800 seconds	600 seconds
Max Delta V	40 (10-µV units)	160 (10-µV units)
DOD Capacity Err	2%	No Change
Q_{max} Max Time	18,000 seconds	No Change
Max Capacity Error	1.0%	3.0%
Q_{max} Filter	96	26
Q Invalid MaxT	40.0°C	55.0°C
Q Invalid MinT	10.0°C	No Change
Min Cell Deviation	1750 s/mAh	1909 s/mAh

2500-mAh $LiFePO_4$ battery pack with chemical ID 404. The table also shows the changes that must be made to the data-flash parameters based on these characteristics. The "Operation Cfg C" register change enables the new features provided by the 7.02 firmware. The changes to "OCV Wait Time" and "Max Delta V" allow for the OCV measurements to occur immediately after the charge is complete. The changes to "Max Capacity Error" and "Q_{max} Filter" allow additional time for the Q_{max} update to happen with smaller-capacity batteries (since $LiFePO_4$ cells generally have only 1100-mAh cells in an 18650 size).

Once the default values have been changed, a good Q_{max} update can be achieved with the approach that will now be described.

1. Start of Q_{max} update cycle

A Q_{max} update cycle should start when the battery has rested after a full charge. Ideally the cells should relax as long as possible. However, if the pack has a high self-discharge current because of onboard circuitry, this waiting time could be as short as two hours.

2. Full charge and valid OCV learning

When the charge terminates, the IT enable command (0x0021) must be sent to prevent OCV learning from occurring before the cell voltages have stabilized. The cells then should be allowed to relax as long as possible. $LiFePO_4$ packs have a tendency for one cell's voltage to run away at the end of charge during taper conditions. This runaway can be prevented by charging to a lower voltage (3.5 V per cell) or disabling the charger after one cell's voltage skews beyond 20 mV higher or lower than any other cell.

For chemical ID 404, if the lowest cell voltage in the battery stack is 3353 mV or more after the cells rest, the discharge procedure that follows can be started. If any cell voltage drops below 3353 mV while resting, another charge cycle is required to top off the battery, and the process must be started again. Different voltages apply to different chemical IDs. See Reference 1 and "Related Web sites" at the end of this article for more information.

The IT enable command is again sent to begin the Q_{max} update process. After this command is sent, there should be a five-minute wait before discharge begins, for two reasons: (1) to clear out the coulomb counter's digital filter, which is integrated over five minutes; and (2) to allow the fuel gauge some time for calculations after the enable command is sent.

3. Discharge and rest

The battery should be discharged to empty or to sufficiently below its minimum disqualification voltage. As the cells relax, their voltages increase. All cell voltages must remain under the minimum disqualification voltage during the entire rest time specified by the "Q_{max} Max Time" setting, plus an additional five-minute buffer.

4. Completion of Q_{max} update

The updated Q_{max} values can be read from data-flash "state" offset 82/Q_{max} cell offset 0–8. If Q_{max} is not learned or updated, then the update cycle should be restarted so that the battery is again charged to full capacity, the appropriate commands are issued, and the battery is allowed to rest.

The golden cycle

To create the golden-image data for any battery pack, several charge and discharge cycles should be run to obtain reliable Q_{max} and resistance-table (Ra-table) values. With $LiFePO_4$ cells, it is preferable for Q_{max} to be learned on a discharge cycle following the process outlined previously.

It is important to create a log file (.LOG) with the bq Evaluation Software tool during both the charge and the discharge cycles of the golden cycle. This allows the values for Q_{max} and the Ra table to be verified by a Mathcad® calculation tool provided by TI's applications staff.

When the golden gas gauge (.GG) file is created, conservative numbers based on cycling data should be assigned to the Q_{max} values. The assigned set of Ra-table values should be the same for each cell, and the Q_{max} values should be the same for parallel cells. Using nonsymmetrical Q_{max} and Ra-table starting values with continuous cycling could cause an SOC error and balancing issues. Table 2 shows an example of adjusted golden .GG values that can improve cell balancing in a 2s2p pack configuration.

Table 2. Example of learned data-flash parameters compared to those used in golden .GG file

Example Learned .GG Parameters for 2s2p Configuration with 2500-mAh Capacity (not comprehensive)	Values Used in a Golden .GG File
[Cell Balancing Cfg (Charge Control)]	[Cell Balancing Cfg (Charge Control)]
FC-MTO = 32400	FC-MTO = 0
[State(Gas Gauging)]	[State(Gas Gauging)]
Qmax Cell 0 = 2583	Qmax Cell 0 = 2510
Qmax Cell 1 = 2510	Qmax Cell 1 = 2510
Qmax Cell 2 = 2500 (not used)	Qmax Cell 2 = 2500 (not used)
Qmax Cell 3 = 2500 (not used)	Qmax Cell 3 = 2500 (not used)
Qmax Pack = 2583	Qmax Pack = 2510
Update Status = 06	Update Status = 02
[R_a0(Ra Table)]	[R_a0(Ra Table)]
Cell0 R_a flag = 0000	Cell0 R_a flag = 0055
Cell0 R_a 0 = 34	Cell0 R_a 0 = 34
Cell0 R_a 1 = 37	Cell0 R_a 1 = 37
Cell0 R_a 2 = 49	Cell0 R_a 2 = 49
Cell0 R_a 3 = 59	Cell0 R_a 3 = 59
Cell0 R_a 4 = 54	Cell0 R_a 4 = 54
Cell0 R_a 5 = 60	Cell0 R_a 5 = 60
Cell0 R_a 6 = 73	Cell0 R_a 6 = 73
Cell0 R_a 7 = 67	Cell0 R_a 7 = 67
Cell0 R_a 8 = 73	Cell0 R_a 8 = 73
Cell0 R_a 9 = 81	Cell0 R_a 9 = 81

(Continued on next page)

When the golden-image data is being created and during normal operation, the gas gauge's charge time-out feature, FC-MTO, should be disabled (set to 0) so that the battery can continuously be topped off without requiring a discharge to clear this timer. FC-MTO is hidden in TI's bq20z4x/7x products, but fortunately it is already set to zero by default. The feature is called "FC-MTO" for TI's bq20z80 and "CMTO" for TI's bq20z6x/9x.

Cell balancing

For 3s or 4s cells, only internal cell balancing should be used in a battery-backup application. This is because adjacent cells cannot be balanced properly with external cell balancing. However, it is permissible to use external cell balancing in a 2s pack. Since a backup battery spends most of its time at rest and much less time in charging, adjacent cells need to be balanced correctly.[2]

As discussed earlier, the enhanced bq20z45-R1 firmware's data-flash parameters must be modified for a battery-backup application and for the designer's particular pack characteristics (chemical ID 404 in this article). The enhanced firmware offers a weighted measurement of OCV values throughout the rest period and locks the cell-balancing calculation immediately after the first OCV measurement is taken after the charge is complete. It also disables cell balancing in the disqualified range after power-up or a reset condition.

Periodic discharges to learn Ra-table values is recommended. Updates of these values happen with approximately every 11% change in SOC during discharge (89%, 78%, 67%, etc.).

Additionally, loss in cell capacity over time can be estimated and compensated for by using the reserve-capacity feature of the gas gauge. Another option to compensate for capacity loss is to have the host system calculate it. If the system is to be operated with no Q_{max} update, then the host controller must make sure that a Q_{max} update does not occur by issuing the IT enable command (0x0021) after a charge is complete.

Off-line cell balancing without enhanced firmware

TI's bq20z6x/7x/8x/9x devices do not offer the enhanced firmware for $LiFePO_4$ cells. If these devices are used in a standby application, the balancing must be disabled during normal operation. This is accomplished by setting the minimum cell deviation to zero. If the host system determines that cells are misbalanced over time, the following steps should be taken:

1. Cell balancing should be enabled by setting the minimum cell deviation to 1909 (or whatever the appropriate value is as calculated in Reference 2).

Steps 2 through 6 should be used in conjunction with the events and conditions given earlier to ensure a valid Q_{max} update.

Table 2 (Continued from previous page)

Example Learned .GG Parameters for 2s2p Configuration with 2500-mAh Capacity (not comprehensive)	Values Used in a Golden .GG File
Cell0 R_a 10 = 85	Cell0 R_a 10 = 85
Cell0 R_a 11 = 94	Cell0 R_a 11 = 94
Cell0 R_a 12 = 93	Cell0 R_a 12 = 93
Cell0 R_a 13 = 204	Cell0 R_a 13 = 204
Cell0 R_a 14 = 304	Cell0 R_a 14 = 304
[R_a1(Ra Table)]	[R_a1(Ra Table)]
Cell1 R_a flag = 0055	Cell1 R_a flag = 0055
Cell1 R_a 0 = 137	Cell1 R_a 0 = 34
Cell1 R_a 1 = 144	Cell1 R_a 1 = 37
Cell1 R_a 2 = 165	Cell1 R_a 2 = 49
Cell1 R_a 3 = 178	Cell1 R_a 3 = 59
Cell1 R_a 4 = 168	Cell1 R_a 4 = 54
Cell1 R_a 5 = 180	Cell1 R_a 5 = 60
Cell1 R_a 6 = 211	Cell1 R_a 6 = 73
Cell1 R_a 7 = 210	Cell1 R_a 7 = 67
Cell1 R_a 8 = 223	Cell1 R_a 8 = 73
Cell1 R_a 9 = 241	Cell1 R_a 9 = 81
Cell1 R_a 10 = 257	Cell1 R_a 10 = 85
Cell1 R_a 11 = 287	Cell1 R_a 11 = 94
Cell1 R_a 12 = 322	Cell1 R_a 12 = 93
Cell1 R_a 13 = 650	Cell1 R_a 13 = 204
Cell1 R_a 14 = 962	Cell1 R_a 14 = 304

2. The battery should be discharged to empty and the cells allowed to relax for five hours and five minutes (or five minutes past the setting for "Q_{max} Max Time"). Once this relaxation occurs at empty, a good SOC estimation can be made from the voltage measurement of each cell.
3. The battery should be charged to full to allow cell balancing to occur throughout the entire charge cycle.
4. After charging is complete, the host system should send an IT enable command, read the cell voltages, and determine whether another deep-discharge balancing cycle and rest are required.
5. If an additional balancing cycle is required, the discharge to empty can be begun right away. Another rest period of five hours and five minutes is required at empty as before.
6. After the cells have been determined to be properly balanced, the minimum cell deviation should be set back to zero to disable cell balancing.

Conclusion

TI's Impedance Track battery-fuel-gauging technology is an adaptive gauging algorithm that can provide considerable

SOC accuracy over the life of a battery. However, in battery-backup applications, there are several things to consider and change for the best possible operation. This article has discussed using TI's enhanced bq20z45-R1 firmware with $LiFePO_4$ cells to achieve proper cell balancing and to obtain reliable Q_{max} updates for the best possible accuracy.

References

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2. Simon Wen, "Fast cell balancing using external MOSFET," Application Report. Available: www.ti.com/slua420-aaj
3. "Theory and implementation of Impedance Track™ battery fuel-gauging algorithm in bq20zxx product family," Application Report. Available: www.ti.com/slua364-aaj
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Related Web sites

Power Management:
www.ti.com/power-aaj

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