Fine-tuning TI's Impedance Track™ battery fuel gauge with $LiFePO_4$ cells in shallow-discharge applications

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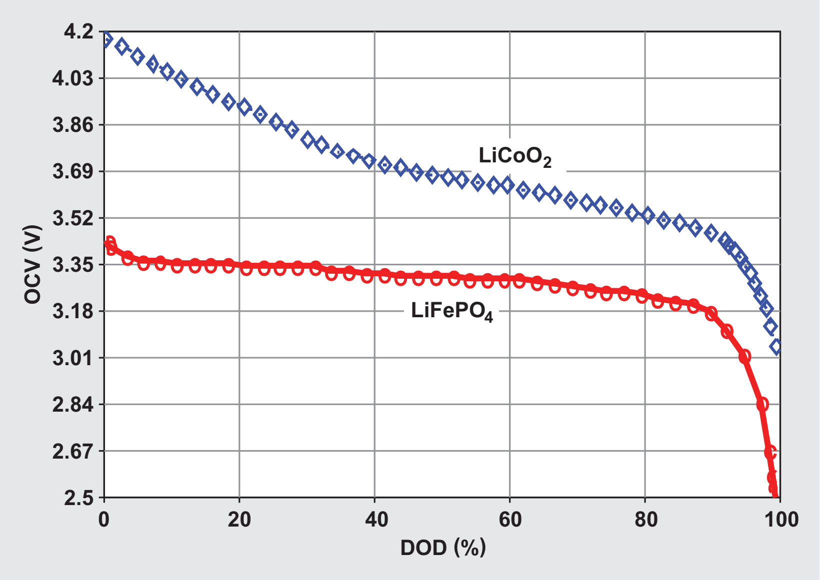
Analog Field Applications

The Impedance Track™ battery-fuel-gauging technology from Texas Instruments (TI) is a powerful adaptive algorithm that learns how a battery's characteristics change over time. Combining this algorithm with knowledge of the battery pack's specific chemistry permits a very accurate determination of the battery's state of charge (SOC) for the life of the pack.

However, certain conditions are required for updating information about the total chemical capacity (Q_{max}) of the cell. This becomes more difficult with the extremely flat voltage profile of lithium-iron-phosphate ($LiFePO_4$) cells (see Figure 1), especially if it is not possible to fully discharge the battery and let it rest for several hours. Figure 1 shows typical open-circuit voltage (OCV) characteristics versus depth of discharge (DOD) for $LiCoO_2$ and $LiFePO_4$ battery chemistries. This article builds on the discussions about Impedance Track technology in References 1 and 2.

Figure 1. Battery OCV measurements based on DOD



TI recommends using the Impedance Track 3 (IT3) algorithm with any $LiFePO_4$ cell. The IT3's improvements to earlier Impedance Track algorithms include:

- Better cold-temperature performance from improved temperature compensation
- Added filtering to prevent capacity jumps in SOC
- Improved accuracy for unfavorable OCV readings with $LiFePO_4$ cells
- Conservative remaining-capacity estimation with additional load-selection configurations

IT3 is included in TI's bq20z4x, bq20z6x, and bq27541-V200 gas gauges (not a comprehensive list).

Typical conditions for Q_{max} update

The Impedance Track algorithm defines Q_{max} as the total chemical capacity of a cell, measured in milliampere-hours (mAh). For a proper Q_{max} update, two conditions must be met:

1. Two OCV measurements must be taken outside of the disqualified voltage range, which is based on the cell's chemical identification (ID) number established by TI. An OCV measurement can be done only on a relaxed cell that has not been charged or discharged for several hours.

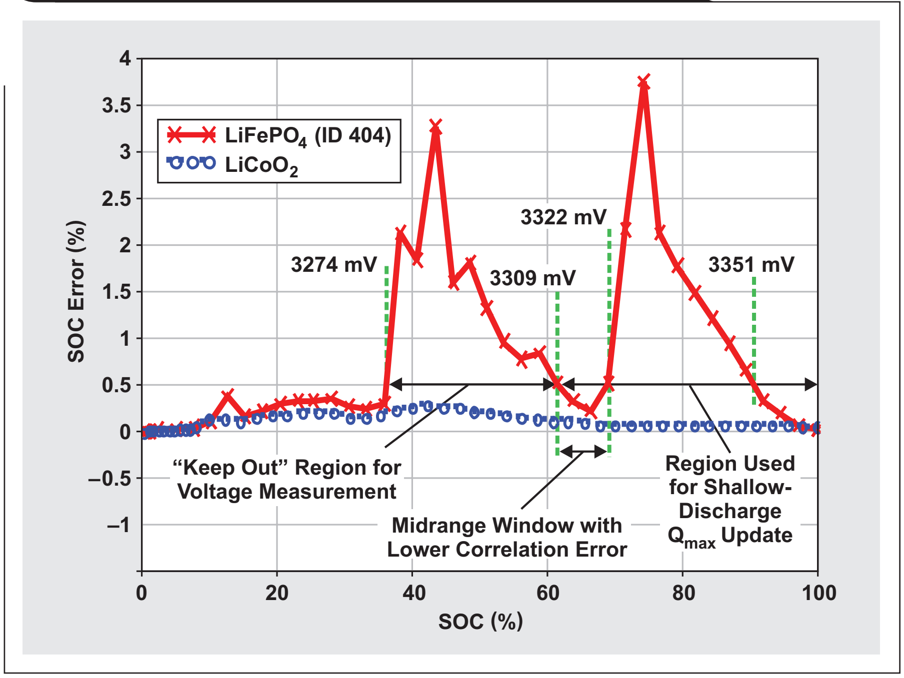
Reference 3 lists a subset of the disqualified voltage ranges, some of which are shown in Table 1. It can be seen that, for chemical ID 100, no OCV measurements are allowed if any cell voltages are above 3737 mV or below 3800 mV. This is essentially a "keep out" range for OCV measurements for best accuracy. Even though an SOC percentage is given in this article, the gauge determines disqualification based only on voltage.

2. A minimum amount of passed charge must be integrated by the fuel gauge. By default, it is set at 37% of the total cell capacity. This percentage of passed charge can be decreased to as low as 10% for a shallow-discharge Q_{max} update. This decrease will be at the expense of SOC accuracy but will be tolerable in a system that would not otherwise be able to update Q_{max}.

Table 1. Excerpt from Reference 3 showing disqualified voltage ranges based on chemistry for Q_{max} update

Description	Chemical ID	Vqdis_min (mV)	Vqdis_max (mV)	SOC_min, %	SOC_max, %
LiCoO2/graphitized carbon (default)	100	3737	3800	26	54
Mixed Co/Ni/Mn cathode	101	3749	3796	28	51
Mixed Co/Mn cathode	102	3672	3696	6	14
LiCoO2/carbon 2	103	3737	3800	26	54
Mixed Co/Mn cathode 2	104	4031	4062	77	88
LiFePO4/carbon	**404**	**3274**	**3351**	**34**	**93**
LiFePO4/carbon	409	3193	3329	12	92

Figure 2. SOC correlation error for 1-mV voltage error



Now that we have an understanding of what is required for a shallow-discharge Q_{max} update, let's look at an example of data-flash parameters that need to be changed in a configuration with a lower-capacity pack. The default Impedance Track algorithm is based on typical laptop battery packs having 2 parallel strings of 3 cells in series (3s2p). Each string has a 2200-mAh capacity, giving a total capacity of 4400 mAh. $LiFePO_4$ cells have approximately half of that capacity, so if they are used in a 3s1p configuration, the total pack capacity will be 1100 mAh. With smaller-capacity packs like this, specific data-flash parameters need to be fine-tuned in TI's gas-gauge evaluation software for optimal performance. The remainder of this article describes this process.

Example calculations

Consider a 3s1p-configuration battery pack using A123 Systems™ 1100-mAh 18650 $LiFePO_4$/carbon cells. TI's chemical ID number for this cell type is 404. This battery will be used in a storage system with normal temperatures of around 50°C. The discharge rate is 1C, and a 5-mΩ sense resistor is used with the gauge for coulomb counting.

As can be seen in Table 1, the disqualified voltage range for OCV measurements for chemical ID 404 is 3274 mV minimum (~34% SOC) and 3351 mV maximum (~93% SOC). Most $LiFePO_4$ cells have a very wide disqualified voltage range (see chemical ID 409 as a comparison). However, depending on the cell characteristics, it may be possible to identify a higher minimum disqualified voltage for a shallow-discharge Q_{max} update. For chemical ID 404 it is possible to raise this value to 3322 mV, allowing for a shallow Q_{max}-update window from 3309 to 3322 mV (see Figure 2). The designer can use this midrange low-error window with data-flash modifications. Since only a high and low disqualified voltage range can be programmed, the host system must guarantee that the lower OCV measurement will not happen below 3309 mV. (As the correlation error increases, OCV-measurement error increases dramatically between 3274 and 3309 mV.) Even though there is only a 13-mV window to work with for the lower OCV measurement (3322 – 3309 mV = 13 mV), it corresponds to an SOC range of 70% to 64%.

$LiFePO_4$ cells have a very long relaxation time, so let's increase the data-flash parameter "OCV Wait Time" to 18,000 seconds (5 hours). Since the battery's normal operating temperature is elevated, the parameter "Q Invalid Max Temperature" should be changed to 55°C. Additionally, "Q_{max} Max Time" should be changed to 21,600 seconds (6 hours).

To decrease the Q_{max} passed charge from 37% to 10%, the "DOD Max Capacity Error," "Max Capacity Error," and "Q_{max} Filter" need to be modified, as they all play a part in the disqualification time between the OCV1 and OCV2 measurements. "Q_{max} Filter" is a compensation factor that varies Q_{max} relative to passed charge.

The goal of these parameters is to have less than 1% "Max Capacity Error" based on measured passed charge and including ADC maximum offset error ("CC Deadband"). However, these values need to be changed to allow for the shallow-discharge Q_{max} update.

Example 1: Time-out period for Q_{max} update

To have less than 1% of accumulated error across a 10-mΩ sense resistor with a 1000-mAh cell and "CC Deadband" set by the hardware to a fixed value of 10 µV, the time-out period for the Q_{max} update can be determined as follows:

10 µV/10 mΩ = 1-mA offset current.

1000-mAh capacity × 1% allowed error
= 10-mAh capacity error.

10-mAh capacity error/1-mA offset current
= 10 hours.

Therefore, from start to finish, including rest periods, only 10 hours are available to complete a Q_{max} update. After the 10-hour time-out, once the gauge takes its next proper OCV reading, this timer will restart.

Example 2: Modifying data-flash parameters

In the design scenario using 1100-mAh cells with a 5-mΩ sense resistor, the time-out period for the Q_{max} update is determined in the same way:

10 µV/5 mΩ = 2-mA offset current.

1100 mAh × 1% = 11 mAh.

11 mAh/2-mA offset current = 5.5 hours.

In this case, the percentage of capacity error needs to be relaxed to increase the Q_{max} time-out. Changing the "Max Capacity Error" to 3% (from the default of 1%) gives

1.1 Ah × 3% = 33 mAh,

which will increase the Q_{max} disqualification time to

33 mAh/2-mA capacity error = 16.5 hours.

The "DOD Capacity Error" needs to be set to twice the "Max Capacity Error," so let's change it to 6% (from the default of 2%).

The default value of 96 for "Q_{max} Filter" needs to be decreased proportionally, based on the percentage of passed charge:

"Q_{max} Filter" = 96/(37%/10%) = 96/3.7 = 26

Table 2 shows typical data-flash parameters in gas-gauge evaluation software that must be modified to implement a shallow-discharge Q_{max} update. These particular parameters are protected (classified as "hidden") but can be unlocked by TI's applications staff. The example battery pack used for this table is the one mentioned earlier,

Table 2. Protected data-flash parameters that can be changed by TI applications staff based on system usage

DATA-FLASH PARAMETER	DEFAULT VALUE	NEW VALUE
Min % Passed Charge for Q_{max}	37%	10%
Min % Passed Charge for 1st Q_{max}	90%	Keep default at 90%[1]
Q Invalid MaxV	3351 mV (chemical ID 404 default)	Keep chemical ID 404 default at 3351 mV
Q Invalid MinV	3274 mV (chemical ID 404 default)	3322 mV
OCV Wait Time	1800 seconds	18,000 seconds
DOD Capacity Err	2%	6%
Q_{max} Max Time	18,000 seconds	21,600 seconds
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	Keep default at 10.0°C[2]

[1] This parameter is important during the golden-image process. If a standard 4.2-V Li-ion cell is being used and charged only to 4.1 V in-system, it is still necessary for the first Q_{max} update to occur after the cell is charged to 4.2 V to meet the requirement for a 90% change in capacity. The capacity change is checked against both the specified cell capacity, or "Design Capacity," and the estimated DOD for the start and end points based on the chemical ID number programmed in the gauge.

[2] A wide-ranging temperature change can cause errors when Q_{max} is calculated. In a system with normal operation at high or low temperatures, it is necessary to modify this parameter.

a 3s1p pack using A123 1100-mAh 18650 $LiFePO_4$/carbon cells with chemical ID 404.

Events of Q_{max} update

The following events describe a practical approach to achieving a Q_{max} update after the data-flash parameters described in Examples 1 and 2 have been changed.

1. A Q_{max} update should start when the battery voltages are within the low-correlation-error window as shown in Figure 2. The designer's own algorithm can be used to discharge/charge the cells into this range.*
2. In this example, to be in the valid measurement range (for chemical ID 404), all cell voltages must be greater than or equal to 3309 mV and less than or equal to 3322 mV. If cell voltages happen to relax outside the valid range during the discharge routine, another discharge or charge cycle must be started prior to the programmed "OCV Wait Time" of 18,000 seconds. If all cell voltages are within 3309 to 3322 mV after 6 hours and 10 minutes, a proper OCV measurement has been taken.
3. The next step is to fully charge the battery. Once the battery is full, or at 100% SOC, it should rest for another 6 hours and 10 minutes before the second OCV measurement is taken. The Q_{max} value will then be updated. If charging takes approximately 2 hours, then a minimum of 8 hours will be needed for the time-out period. From the calculation of the 16.5-hour time-out period in Example 2, we know there is more than enough time with an additional cushion of 8.5 hours.
4. The OCV timer can always be reset by issuing the gas gauge a ResetCommand (0x41) while the gauge is in unsealed mode.

Table 3 shows the results from cycling the battery as just described when the example pack configuration is used.

Conclusion

TI's Impedance Track technology is a very accurate algorithm for determining battery SOC over the life of the cell. In $LiFePO_4$ applications where a full discharge of the battery with a rest period is not possible, it is necessary to explore a shallow-discharge option for the Q_{max} update. This article has described the considerations and data-flash programming configurations for implementing a shallow-discharge Q_{max} update. Changes to these parameters must be approved by TI applications staff based on system configuration and requirements.

Table 3. Results from full-cycle and shallow-charge Q_{max} updates

	NORMAL CHARGE CYCLE[1]	SHALLOW CHARGE CYCLE	
	UPDATED Q_{max} (mAh)	UPDATED Q_{max} (mAh)	RESTING VOLTAGE BEFORE CHARGING (mV)
Cell 0	1062	1062	3312
Cell 1	1066	1038	3310
Cell 2	1064	1063	3311
Pack	1062 (cell minimum)	1038 (cell minimum)	9933 (total)

[1] Charging from empty after rest to full charge with rest.

References

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Related Web sites

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Replace *partnumber* with BQ20Z40-R1 or BQ27541-V200

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*Because of the long voltage hysteresis of $LiFePO_4$ cells after charge or discharge, it is preferable to discharge the battery only into the shallow-discharge range. It is okay to charge the battery during the hone-in algorithm as long as the voltage does not rise above the specified "Q Invalid Max Voltage" at any time. It is also permissible to have multiple discharges to get the cells into the range of 3309 to 3322 mV after the OCV wait time.

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