![Texas Instruments logo]

How to Complete a Successful Learning Cycle for the bq40z80

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ABSTRACT

This paper discusses the steps necessary to complete the initial optimization cycle (also known as learning cycle) in order to ensure the accuracy and excellent performance of the gauge. A learning cycle is typically performed on a single representative battery pack during the development stage. The resulting values are then programmed into every pack during mass production as there should be minimal pack-to-pack variation for a well-controlled manufacturing process. The flash image extracted from a so-called "golden pack" during development is called the "golden file" and is used in mass production once it's performance is verified by testing and validation.

Contents

Trademarks

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1   Introduction

Impedance track is a proprietary algorithm developed by Texas Instruments where the battery gauge dynamically learns the resistance and the total chemical capacity of the battery during field operation in order to maintain accurate predictions even as the battery cells age. In order to go into production using the bq40z80, a golden file has to be created which is programmed on multiple devices. The learning cycle is a part of the golden file creation process which requires the user to carry out a few cycles on the pack to make sure that possible variation in cell manufacturer processes is accounted for in the learned resistance as well as to account for the board contact and trace resistances which could impact the gauges state of charge reporting and accuracy.

Once the learning cycle is complete, the IT parameters, gauge parameters, and other settings can be exported in a Golden Image for use in manufacturing the battery pack. The full .srec file can be exported and programmed on the bq40z80, Details on generating the Golden Image are included in the conclusion.

2   ChemID Identification and Programming

Texas Instruments has a database of thousands of battery profiles. Each profile has a unique number referred to as the chemistry identifier, or "ChemID". Programming a specific ChemID into an Impedance Track fuel gauge updates various public and private dataflash locations with the battery profile. This profile is then used by the IT algorithm for capacity and resistance learning as well as for capacity predictions and other features. The ChemID data includes open-circuit voltage (OCV) and resistance data as well as temperature coefficients. Each ChemID also includes a pair of voltages indicating the upper and lower bounds of the "flat voltage region" where a small error in voltage can result in a significant error in depth of discharge calculations. It is important that the proper ChemID be selected and programmed into the fuel gauge both for performing the learning cycle process and for production purposes. The ChemID selected

should either be specifically generated for the cell or battery being used or it should be a close match as determined by using the GPCCHEM tool found on *www.ti.com*. The list of cells with known ChemIDs can be searched by opening the Chem.ini file typically located in this directory: C:\ti\BatteryManagementStudio\chemistry. If you installed bqStudio in a different directory then you can search there. TI periodically updates the database with new ChemIDs and the contents of the previously mentioned folder can be updated with the latest files from ti.com found by searching for "chemistry updater". This is the direct link: http://www.ti.com/tool/gasgaugechem-sw. Note that sometimes a given cell might have multiple ChemIDs associated with it. Check for obsolete ChemIDs and generally use the most recent one. Most ChemIDs are optimized for accuracy between 0°C and 50°C, but some are noted for use at wider temperature ranges. You can also tune the resistance of an existing chemID for your specific cell across a custom temperature range by using the GPCRB tool found on *www.ti.com*. Instructions for the data collection procedure are included in that Tool folder. The ChemID is a look up table which the gauge uses for determination of state of charge during initialization. The gauge also uses this table as part of the IT algorithm to predict remaining capacity. This table consists of the open circuit voltage profile of the battery from full to empty as well as the resistance of the battery which is spit up into grid points that corresponds to different state of charges. Both the open circuit voltage (OCV) and resistance tables have the temperature dependent components which aids gauge performance at different temperatures. It is important that the ChemID programmed on the gauge was either generated by TI for that battery or a close match to an existing ChemID in TI data base for batteries is identified using our online ChemID identification tool - GPCCHEM. The ChemID identification requires running a relax-discharge-relax (rel-dis-rel) test while logging data using the gauge's GUI (bqStudio) and then using gpc chem tool with the logged data to identify a close match. If there is no match, then the cells have to be sent to TI for characterization and ChemID generation. Contact a local field applications engineer if cells have to be sent to TI. Once a ChemID has been identified or created, it has to be programmed on the fuel gauge. The user can select the new found ChemID and program it using the chemistry plug-in of bqstudio as shown in Figure 1.

NOTE: If an incorrect ChemID is used, the learning cycle may never successfully complete and the state of charge prediction may never be accurate.
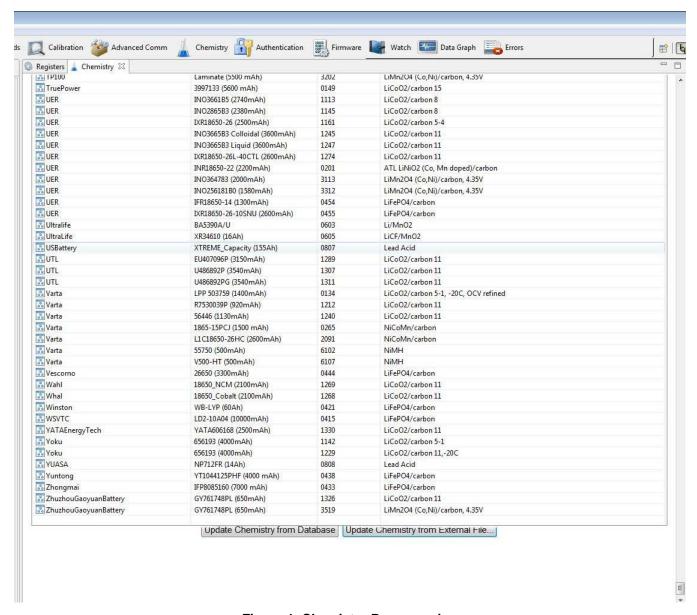

TP100	Laminate (5500 mAh)	3202	LiMn2O4 (Co,Ni)/carbon, 4.35V
TruePower	3997133 (5600 mAh)	0149	LiCoO2/carbon 15
UER	INO3661B5 (2740mAh)	1113	LiCoO2/carbon 8
UER	INO2865B3 (2380mAh)	1145	LiCoO2/carbon 8
UER	IXR18650-26 (2500mAh)	1161	LiCoO2/carbon 5-4
UER	INO3665B3 Colloidal (3600mAh)	1245	LiCoO2/carbon 11
UER	INO3665B3 Liquid (3600mAh)	1247	LiCoO2/carbon 11
UER	IXR18650-26L-40CTL (2600mAh)	1274	LiCoO2/carbon 11
UER	INR18650-22 (2200mAh)	0201	ATL LiNiO2 (Co, Mn doped)/carbon
UER	INO364783 (2000mAh)	3113	LiMn2O4 (Co,Ni)/carbon, 4.35V
UER	INO256181B0 (1580mAh)	3312	LiMn2O4 (Co,Ni)/carbon, 4.35V
UER	IFR18650-14 (1300mAh)	0454	LiFePO4/carbon
UER	IXR18650-26-10SNU (2600mAh)	0455	LiFePO4/carbon
Ultralife	BA5390A/U	0603	Li/MnO2
UltraLife	XR34610 (16Ah)	0605	LiCF/MnO2
USBattery	XTREME_Capacity (155Ah)	0807	Lead Acid
UTL	EU407096P (3150mAh)	1289	LiCoO2/carbon 11
UTL	U486892P (3540mAh)	1307	LiCoO2/carbon 11
UTL	U486892PG (3540mAh)	1311	LiCoO2/carbon 11
Varta	LPP 503759 (1400mAh)	0134	LiCoO2/carbon 5-1, -20C, OCV refined
Varta	R7530039P (920mAh)	1212	LiCoO2/carbon 11
Varta	56446 (1130mAh)	1240	LiCoO2/carbon 11
Varta	1865-15PCJ (1500 mAh)	0265	NiCoMn/carbon
Varta	L1C18650-26HC (2600mAh)	2091	NiCoMn/carbon
Varta	55750 (500mAh)	6102	NiMH
Varta	V500-HT (500mAh)	6107	NiMH
Vescorno	26650 (3300mAh)	0444	LiFePO4/carbon
Wahl	18650_NCM (2100mAh)	1269	LiCoO2/carbon 11
Whal	18650_Cobalt (2100mAh)	1268	LiCoO2/carbon 11
Winston	WB-LYP (60Ah)	0421	LiFePO4/carbon
WSVTC	LD2-10A04 (10000mAh)	0415	LiFePO4/carbon
YATAEnergyTech	YATA606168 (2500mAh)	1330	LiCoO2/carbon 11
Yoku	656193 (4000mAh)	1142	LiCoO2/carbon 5-1
Yoku	656193 (4000mAh)	1229	LiCoO2/carbon 11,-20C
YUASA	NP712FR (14Ah)	0808	Lead Acid
Yuntong	YT1044125PHF (4000 mAh)	0438	LiFePO4/carbon
Zhongmai	IFP8085160 (7000 mAh)	0433	LiFePO4/carbon
ZhuzhouGaoyuanBattery	GY761748PL (650mAh)	1326	LiCoO2/carbon 11
ZhuzhouGaoyuanBattery	GY761748PL (650mAh)	3519	LiMn2O4 (Co,Ni)/carbon, 4.35V

Update Chemistry from Database   Update Chemistry from External File...

Figure 1. Chemistry Programming

3   Data Flash Configuration Settings Pertinent to Learning Cycle Completion

In order to have learning cycle successfully complete, certain parameters need to be configured specific to the application and the battery type in the gauge data flash. These parameters are Design Capacity, Design Voltage, Charge Term Taper Current, Dsg Current Threshold, Chg Current Threshold, Quit Current and Term Voltage. The gauging algorithm state machine has three modes: charge, discharge, and relax. More background on how Dsg Current Threshold, Chg Current Threshold, and Quit Current are used can be found by referring to Figure 1 of SLUA364.

3.1   Design Capacity

There are three parameters which should be set to match the target battery pack's nominal capacity. Design Capacity mAh and Design Capacity cWh should be set to the nominal capacity of the total pack with their respective units. Often this can be copied from the battery pack label or datasheet, or calculated based on the number of series and parallel cells. Design Capacity mAh is also used for state of health (SOH) calculations, so if a project uses a different charging voltage or discharge current than that which was used for the cell datasheet design capacity, this parameter should be customized to that actual amount of capacity that can be extracted under the applications real conditions. For example, if a cell datasheet specifies a nominal capacity based on charging to 4.2 V and discharging with 500 mA, but the target application actually only charge to 4.1 V and discharge with a 1000 mA load, then Design Capacity should not be based on the datasheet but should be determined through testing using the application charge and discharge conditions. Design Voltage should be set to the nominal or average voltage of your battery pack. Most Li-ion cells have an average voltage of 3.6 V to 3.8 V and may be specified on the cell datasheet or label. Design Voltage = (number of series cells) x average cell voltage. For example, a pack with five cells in series might use Design Voltage = 5 x 3700 mV = 18500 mV. All three of these data flash parameters can be found in the Gas Gauging subsection in the Data Memory plugin in bqStudio.

3.2   Charge Term Taper Current

Most battery chargers have a ±10% error in taper current threshold at which point the charger cuts off charging. It is important to set the taper current programmed in the data flash of the gauge slightly higher than the taper current threshold of the charger. This ensures that the gauge detects the battery is fully charged before the charger cuts off charge. For example, if the charger taper current is 50 mA, it is recommended to set the charge termination taper current in data flash greater than 50 mA. A good value to use is 70 mA. Also, it is recommended that the taper current should be less than C/10 to ensure that the battery gets properly fully charged. This setting is found in the Advanced Charge Algorithm, Termination Config section of Data Memory.

3.3   Dsg Current Threshold

This is the current threshold above which the gauge detects that it is in discharge mode. A positive number should be entered and the firmware automatically interpret it as a negative (discharge) current threshold. The default value is suitable for many applications, but if customized it should be set to a value lower than the minimum system draw when in active mode. When discharge current exceeds this threshold the algorithm enters the Discharge state. A value below C/10 is generally reasonable. This setting is found in the Gas Gauging, Current Thresholds section of Data Memory.

3.4   Chg Current Threshold

This is the current above which the gauge detects that it is in charge mode. This value should be set lower than the Charge Term Taper Current. When positive current exceeds this value the algorithm enters the Charge state. This setting is found in the Gas Gauging, Current Thresholds section of Data Memory.

3.5   Quit Current

This is the threshold that determines that the gauge enters relax mode. This mode is important because this is where the gauge takes OCV readings which are used for Qmax calculations. It is recommended that the quit current be less than C/20 and must be less than the Dsg Current Threshold and Chg Current Threshold. This setting is found in the Gas Guaging, Current Thresholds section of Data Memory.

3.6 Term Voltage

Also called Terminate Voltage, this is essentially the empty pack voltage where the gauge should ensure 0% state of charge is reported. For learning cycle purposes, this should be set to the minimum voltage of the battery as specified in the manufacturer's data sheet. After the learning cycle is completed, this value can be adjusted upwards if there is a need for the gauge to report 0% at a higher voltage. If the cell is rated to operate from 3 V to 4.2 V and if the application is a 5s application, the term voltage should be set to 3 V x 5 cells = 15000 mV. This setting is in the Gas Gauging, IT Cfg section of Data Memory.

Note that in normal operation the gauge may report 0% at a voltage higher than Term Voltage because it learns the voltage spikes seen by your system. The adds the average of those spikes to Term Voltage in order to predict empty at an earlier voltage so that a sudden spike does not cause a drop to 0%. These learned average spikes are kept in RAM but occasionally updated in the dataflash parameter Delta Voltage. Additionally, if Reserve Cap-mAh and Reserve Cap-cWh are not zero then the gauge further buffers the voltage at which 0% is reported in order to ensure that the reserve capacity is still available for shutdown before Term Voltage+Delta Voltage is actually reached.

4 Learning Cycle

The learning cycle is needed for the gauge to update the total chemical capacity (Qmax) and the resistance (Ra) tables in data flash. It is also needed for the LStatus() which the gauge controls to change indicating that a learning cycle has been completed. When running a learning cycle it is recommended to log all of the RAM values in the Registers plugin in bqStudio. This enables the data to be analyzed later for troubleshooting purposes and it can also be used for processing in the GPCRA tool if necessary. Furthermore, it can also assist debug if the Data Memory plugin is set to AutoExport .gg.csv files periodically. The rate of autoexporting .gg.csv files can be customized in the Window->Preferences->Data Memory settings. A period of 10-30 minutes is generally frequent enough without resulting in creation of too many files. When troubleshooting a failed learning cycle attempt, the register values can be analyzed and the progress of the data flash updates can be checked using the time stamps of the data points and the file creation dates.

4.1 Initial Qmax Update Criteria

QMax update is enabled when gauging is enabled, which is done by sending the MAC subcommand GAUGE_EN. This can be done manually, by using the Advanced Comm SMB plugin in bqStudio, or by clicking the GAUGE_EN button in the Commands plugin on the right side of the bqStudio screen. The bq40z80 updates the no-load full capacity (QMax) when two open circuit voltage (OCV) readings are taken. These OCV readings are taken when the battery is in a RELAXED state before and after charge or discharge activity. A RELAXED state is achieved if the battery voltage has a dV/dt of < 4 μV/s. Typically it takes 2 hours in a CHARGED state and 5 hours in a DISCHARGED state to ensure that the dV/dt condition is satisfied. If 5 hours are exceeded, a reading is taken even if the dV/dt condition was not satisfied. If a valid DOD0 (taken at a previous QMax update) is available, then QMax is also updated when a valid charge termination is detected. Qmax is not updated if the following occurs:

- **Temperature** — If Temperature is outside of the range 10°C to 40°C.
- **Delta Capacity** — If the capacity change between suitable battery rest periods is less than 90% of the full scale range of the OCV table during the initial QMax Update and 37% during field updates (2nd and subsequent updates) of QMax.
- **Voltage** — If CellVoltage7..1 is inside the flat voltage region. This flat region is different for each ChemID. The GaugingStatus[OCVFR] flag indicates if the cell voltage is inside this flat region.
- **Offset Error** — If offset error accumulated during time passed from previous OCV reading exceeds 1% of Design Capacity, update is disqualified. Offset error current is calculated as CC Deadband/sense resistor value.

Several flags in ITStatus() are helpful to track for QMax update conditions. The [REST] flag indicates an OCV is taken in RELAX mode. The [VOK] flag indicates the last OCV reading is qualified for the QMax update. The [VOK] is set when charge or discharge starts. It is cleared when the QMax update occurs, when the offset error for a QMax disqualification is met, or when there is a full reset. The [QMax] flag is toggled when the QMax update occurs.

4.2 Learning Cycle Procedure

4.2.1 Discharge Battery to Empty

- Before beginning the discharge, turn on the charge and discharge FETs by sending command 0x22, or by sending the CHG_FET_TOGGLE and DSG_FET_TOGGLE commands until both the CHG and DSG bits are shown as red in the Bit Registers. Next send IT (Gauge) enable command (0x21), or use the GAUGE_EN command to set the GAUGE_EN in manufacturing status register and QEN flags in IT Status register. Then send the reset command (0x41), or select RESET, to set the RDIS flag and disable resistance updates during this initial discharge cycle. In this case, since IT has already been enabled, there is no need to disable it again during the entire learning cycle. Once IT has been enabled, verify the LStatus() has changed to 04 in the Gas Gauging, State section of Data Memory.
- An alternative method before starting this initial discharge would be to make sure IT is disabled. The GAUGE_EN flag of the manufacturing status register would be cleared if IT is disabled. If the GAUGE_EN flag is set, clear it by sending command 0x21 or clicking the GAUGE_EN button in the command window. This is different from earlier gauges in that IT enable command can be toggled on and off. In earlier gauges, once IT is enabled, it can never be disabled via command. Disabling

impedance track prevents resistance updates from occurring during this initial discharge.

- Discharge the battery until the voltage at the top of stack reaches the Term Voltage.

4.2.2 Relax for at least 5 Hours

- This relaxation time allows for a valid OCV reading to be taken and stored for the Qmax update. The valid OCV reading occurs when the dV/dt of the battery is < 4 µV/s. The voltages does not need to be monitored, the gauge monitors for this condition and takes the OCV reading once met.
- The [VOK] and [RDIS] bits in the IT status() register clear once the gauge has taken an OCV reading and qualified it for a Qmax update.
- The 5 hour wait time is a recommendation; the most accurate time is determine when the [VOK] and [RDIS] bits are clear, which can occur sooner than 5 hours. If the alternative method of disabling IT was used, IT enable command should be sent after the 5 hour wait time. This forces an OCV measurement to be taken, and because the cells are sufficiently rested, this OCV value is qualified for a Qmax update.
- The GaugingStatus[REST] flag is set when a valid OCV reading occurs

4.2.3 Charge Battery to Full

- A typical C/2 charge rate is recommended; however, the charge rate is of no consequence.
- Make sure IT is already enabled at this point before the start of charge (the [Gauge_EN] bit in the manufacturing status() register should be set).
- At the start of charge, the [VOK] bit in the IT status () register sets automatically.
- At the end of charge the [FC] bit in the Battery Status () register should be set automatically. If it did not set then a full charge was not properly detected and the learning cycle fails. Correct either the charging conditions or the relevant dataflash settings to ensure the [FC] bit gets set and try again from the beginning.

4.2.4 Relax for at least 2 Hours

- This relaxation time allows for a valid OCV reading to be taken and stored for the Qmax update. The valid OCV reading occurs when the dV/dt of the battery pack is < 4 µV/s. Again, the gauge monitors for this condition.
- The [VOK] bit in the IT status() register clears once the gauge has taken an OCV reading and qualified it for a Qmax update.
- The GaugingStatus[REST] flag is set when a valid OCV reading occurs
- The 2 hour wait time is a recommendation; the most accurate time is checking to determine when the [VOK] and [RDIS] bits are clear, which can occur sooner than 2 hours.
- At this point, the first Qmax update should have occurred. The [QMax] flag is toggled when the QMax update occurs. LStatus() would now be 0x05. New values for Qmax should also be observable in the Gas Gauging section of the Data Memory view or in the autoexported .gg.csv files.
- Note that it takes less time for a battery to relax once it is fully charged than it does when it is discharged.

4.2.5 Discharge Battery to Empty

- A typical C/5 rate is recommend, but the rate can be as low as C/10. If using a C/10 load, make sure the gauge sees that the current is at least C/10, if the current is any lower, resistance updates can not occur.
- During the discharge, the resistance tables are updated as each grid point is reached (the resistance tables for each cell are stored in 15 grid points along the discharge curve). The updates can be observed in the Ra Table section in Data Memory in bqStudio, or in the autoexported .gg.csv files.
- Update Status shouldn't change until the second Qmax update occurs during relaxation (assuming Ra was also updated during the discharge).

4.2.6 Relax for at least 5 Hours

• This relaxation time allows for a valid OCV reading to be taken and stored for the Qmax update. The valid OCV reading occurs when the dV/dt of the battery is < 4 µV/s

• The [VOK] bit in the Control() register clears once the gauge has taken an OCV reading and qualified it for a Qmax update.

• The GaugingStatus[REST] flag is set when a valid OCV reading occurs

• The 5 hour wait time is a recommendation. The most accurate time is determined by observing when the [VOK] bit clears, which can occur sooner than 5 hours.

• There is another Qmax update at this point, and this should be reflected in dataflash

• At this point LStatus() should be at 0x06. When the packs are deployed in the end equipment and a field update occurs, the LStatus() updates to 0x0E, which means that cell balancing has been enabled. If an LStatus() of 0E is not obtained, the device can be charged to full, relaxed for 2 hours and then discharged to empty, at which point it should be 0E.

5 Learning Cycle Summary in Graphical Form

Figure 2. Overview of the Complete Step

Figure 3. Breakdown of the Steps 1 and 2

Figure 4. Breakdown of the Steps 3 and 4

Figure 5. Breakdown of the Steps 5 and 6

6 Conclusion

The learning cycle is a critical and integral part of ensuring the proper functionality of a battery pack using the Impedance Track algorithm. The bq40z80 uses Impedance Track and this step by step procedure for learning ensures the golden flash image extracted for mass production is fully optimized. The summary of the discussed steps are as follows:

- Program the ChemID that matches the cell to be used in the application

- Configure the data flash parameters for the application. The pertinent data flash parameters that are required for successful learning cycle are Design Capacity, Design Voltage, Charge Term Taper Current, Dsg Current Threshold, Chg Current Threshold, Quit Current, and Term Voltage. The following conditions must be met:

  – Charge Term Taper Current > Chg Current Threshold > Quit Current

  – At least, 90% passed charge of DOD is needed to occur during the initial charge.

- To complete a full learning cycle, the battery must complete a full charge-relax-discharge-relax cycle. The battery should be charged to the max voltage specified by the cell manufacturer and discharged to the min voltage specified as well to ensure the 90% passed charge condition is met. After a successful learning cycle, the Term Voltage and the voltage the cells are charged to can be adjusted to suit the application specifications.

  – Discharge the cells to empty and let them relax for at least 5 hours.

  – Enable Impedance Track (0x21), issue a reset command (0x41). LStatus() changes from 00 to 04

  – Charge the cells to full ensuring that the [FC] bit gets set and let it relax for at least two hours. Qmax updates at this point and LStatus() goes to 05.

  – Discharge the cells to empty using the typical discharge rate of your application. It must be between C/5 to C/10 rate, otherwise, learning fails. Resistance tables are updated during this discharge cycle.

  – Let the cells relax for 5 hours during which the LStatus() would change to 06.

  – For multi-cell applications, another charge-relax-discharge- relax cycle may be run to ensure LStatus() changes to 0E to activate cell balancing.

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- Before saving the Golden File, set LStatus() bit to 02 to disable IT gauging, set the Qmax Cycle Count to 0, and set the Cycle Count to 0. This ensures that when the pack is assembled and gauging and lifetime data is enabled, the cycle counts start from 0.