Application Report

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How to Complete a Successful Learning Cycle for the bq34z100

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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. ™

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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 bq34z100, 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 bq34z100.

2 Common Considerations for All Battery Chemistries

2.1 High Cell Count and High Capacity Applications

Please refer to the app note SLUA760 to configure the gauge with current and capacity scaling for use with high cell count and high capacity applications. Once that is configured we can move on to starting the procedure for performing a learning cycle.

2.2 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 ChemID Identification and Programming www.ti.com 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-disrel) 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.

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

2.3 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. The dataflash of the bq34z100 is by default configured to learn the Li-ion chemistry.

2.3.1 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.

2.3.2 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.

2.3.3 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, but higher then maximal 1 sec averagecurrent in standby mode. When discharge current exceeds this threshold the algorithm enters the Discharge state, so it important not to set it to low, since this could cause exiting relaxed mode too often and prevent taking OCV readings which happens only in relaxed mode. A value below C/10 is usually reasonable as long as it satisfies above criteria. This setting is found in the Gas Gauging, Current Thresholds section of Data Memory.

2.3.4 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.

2.3.5 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 then minimal current that can occur in active mode for period longer than Discharge Relax time (usually 60 sec). It is usually less than C/20 and must be less than the Dsg Current Threshold and Chg Current Threshold. This setting is found in the Gas Gauging, Current Thresholds section of Data Memory.

2.3.6 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.

3 Learning Cycle for Li-ion Batteries

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.

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 bq34z100 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 < 4uV/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 CellVoltages are 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 [OCVTAKEN] 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.

Learning Cycle Procedure

- **Discharge Battery to Empty**

  - Send IT (Gauge) enable command (0x21), or use the IT_ENABLE button command to set the VOK and QEN flags in the Control 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.
  - An alternative method before starting this initial discharge would be to make sure IT is disabled. The VOK and QEN flags of the Control Status register would be cleared if IT is disabled. If the VOK flag is set, clear it by sending command 0x41 reset command.
  - Discharge the battery until the voltage at the top of stack reaches the Term Voltage.
- **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 uV/s. The voltage does 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 Flags[OCVTAKEN] flag is set when a valid OCV reading occurs.
- **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 [QEN] bit in the Control 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 Flags() 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.
- **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 uV/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 Flags[OCVTAKEN] 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. Update Status() 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.
- **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).

- **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 uV/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 Flags[OCVTAKEN] 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 data flash.
  - At this point Update Status() should be at 0x06. When the packs are deployed in the end equipment and a field update occurs, the Update Status() should hae been updated to 0x06.

4 Learning Cycle for NiMH Batteries

NOTE: Please read sections 2 through 4 before proceeding to read ahead. They explain procedures and the data flash parameters that are relevant to the learning cycle.

Best practices for NiMH batteries

Before we move on to performing a learning cycle using NiMH, here are some best practices for getting the longest possible usage from NiMH batteries.

- NiMH batteries start heating after about 70% charge, this reduces charge efficiency.
- Do not leave NiMH batteries in the charger for extended periods of time
- If trickle charging is used for charge termination, ensure that batteries cool during trickle charging.
- If batteries heat up on trickle charging, reduce the rate of charge.
- Always charge at room temperature, do not charge at hot or cold temperatures.
- NiMH batteries should not be slow charged as it reduces longevity due to memory effects.

NiMH on the bq34z100 gauge

The bq34z100 fuel gauge uses 3 different methods for charging and charge termination on all battery chemistries. They are:

1. CC/ CV charging
2. Delta T/dt charging (T=temperature, t=time)
3. NegdV charging (negative delta voltage)

NiMH batteries should ideally not use CC/CV charging. This is because self-heating can actually cause charge current to increase when the battery is near or at charge termination. Therefore this is **NOT RECOMMENDED**.

Hence, the latter two methods are only applicable for NiMH batteries. They are acted upon only on NiMH chemistries and are not applicable to Li-ion or any of the other 3 chemistries. The reason for this is the negative delta voltage phenomenon comes basically from hydrogen generation at high voltages.

Once an NiMH cell starts overcharging, it results in hydrogen generation. When the hydrogen gas recombines with oxygen, it generates heat as this is an exothermic reaction. Heating of the cell results in a reduction of impedance, and decrease of voltage as IR rise gets smaller. Therefore we can use both the heating as well as the change in impedance resulting in decrease of voltage to track charge termination.

NiMH batteries are different from Li-ion batteries because:

1. They have a very high rate of self dsg unlike Li-ion batteries.
2. The self heating effect is higher in NiMH by a large magnitude.

Therefore, we need additional factors to account for compensation of heating losses during charging.

Charge Efficiency

To more accurately track state of charge and Time-to-Full during the charge phase, the bq34z100-G1 uses four charge-efficiency factors to compensate for charge acceptance. These factors are ***Charge Efficiency***, ***Charge Eff Reduction Rate***, ***Charge Eff Drop Off***, and ***Charge Eff Temperature Compensation***.

The bq34z100-G1 applies the ***Charge Efficiency*** when *RelativeStateOfCharge()* is less than the value stored in ***Charge Efficiency Drop Off***. When *RelativeStateOfCharge()* is > or equal to the value coded in ***Charge Efficiency Drop Off***, ***Charge Efficiency*** and ***Charge Efficiency Reduction Rate*** determine the charge efficiency rate. ***Charge Efficiency Reduction Rate*** defines the percent efficiency reduction per percentage point of *RelativeStateOfCharge()* over ***Charge Efficiency Drop Off***. The ***Charge Efficiency Reduction Rate*** has units of 0.1%.

The bq34z100-G1 also adjusts the efficiency factors for temperature. ***Charge Efficiency Temperature Compensation*** defines the percent efficiency reduction per degree C over 25°C. ***Charge Efficiency Temperature Compensation*** has units of 0.01%.

Applying the four factors:

Effective Charge Efficiency % = ***Charge Efficiency*** – ***Charge Eff Reduction Rate*** [*RSOC()* – ***Charge Efficiency Drop Off***] – ***Charge Efficiency Temperature Compensation*** [***Temperature*** – 25°C] Where: *RSOC()* ≥ ***Charge Efficiency*** and ***Temperature*** ≥ 25°C

Setting up the learning cycle for NiMH

Setup to perform the learning cycle:

1. Obtain the chem ID using the GPCCHEM tool as per the steps here: http://www.ti.com/tool/GPCCHEM
2. Update the gauge with the chem ID obtained in Step 1.
3. Update the gauging settings per Sections 2. Look at the datasheet of the battery to know the limits to which the battery can be charged and discharged.
4. Update the settings for protections and permanent failure appropriately.
5. If dT/dt is the chosen method for charge termination, update ***NiMH Delta Temp***, ***NiMH Delta Temp Time***, ***NiMH Hold Off Current***, ***NiMH Hold Off Time***, ***NiMH Hold Off Temp*** per cell data sheet to appropriate values.
6. If NdV is the charge termination method, update the ***NiMH Cell Negative Delta Time***, ***NiMH Cell Negative Delta Volt***, ***NiMH Cell Negative Delta Qual Volt*** per cell data sheet to appropriate values.

Performing the learning cycle for NiMH

Now to perform the learning cycle:

1. Set charging current to at least C/5 rate but never more than C/2 rate
2. Charge the cell to full. For charge termination either of the following methods can be used,
   a. a. Delta Temperature (ΔT/Δt) method—For ΔT/Δt, the bq34z100-G1 detects an increase in temperature over many seconds. The ΔT/Δt setting is programmable in the temperature step, ***Delta Temp*** (0°C – 25.5°C), and the time step, ***Delta Temp Time*** (0 s–1000 s). Typical settings for 1°C/minute include 2°C/120 s and 3°C/180s (default). Longer times may be used for increased slope resolution. In addition to the ΔT/Δt timer, a holdoff timer starts when the battery is charged at more than ***Holdoff Current*** (default is 240 mA), and the temperature is above Holdoff Temp.Until this timer expires, ΔT/Δt detection is suspended. If *Current()* drops below Holdoff Current or *Temperature()* below ***Holdoff Temp***, the holdoff timer resets and restarts only when the current and temperature conditions are met again. .
   b. b. Negative Delta Voltage (–ΔV) method—For negative delta voltage, the bq34z100-G1 detects a charge termination when the pack voltage drops during charging by ***Cell Negative Delta Volt*** for a period of ***Cell Negative Delta Time*** during which time *Voltage()* must be greater than ***Cell Negative Qual Volt***. If the charger is not capable of detecting or supporting NegDV method, we can also set charge termination to be detected at ***Cell Negative Qual Volt*** by setting ***Cell Negative Delta Volt*** to 0.
3. Relax until the first DOD is taken.
4. Set discharge current to at least C/5 rate but never more than C/2 rate.
5. Discharge the NiMH cell until it is at least 100mV below terminate voltage.

6. Relax again until the DOD is taken, this is indicated by the VOK flag being cleared.
7. At this point Qmax for the cell will be updated.
8. Repeat the cycle again to get a subsequent Qmax and Ra table update.

This will complete characterization of the battery. The learning cycle for the bq34z100 on the NiMH cell will be complete

Trickle Charging

It is recommended that trickle charging not be used with the bq34z100 gauge. While trickle charging compensates for self discharge, such a compensation mechanism is not compatible with the DOD Error Weighting used in the gauge.

The DOD Error Weighting (DODEW) option allows a combination of the DODs from coulomb counting and from taking an OCV value to obtain a more accurate DOD. However, because NiMH batteries have a high rate of self discharge, this overcompensates for DOD taken from the OCV. Therefore the passed charge compensation is not weighted correctly until trickle charging stops and an OCV is taken.

However, since typical use cases start to discharge batteries once they are fully charged, an OCV is not readily available. Therefore it is recommended that if

1. Trickle charging is used, DODEW be disabled in the dataflash configuration options.
2. 2. If DODEW is used, trickle charging be avoided.

5 Learning Cycle for Lead-Acid (PbA) Batteries

PbA batteries are commonly used in areas that require low cost, low maintenance, high specific output across temperature. However as limitations they also have low specific energy, take longer to charge, have limited life and have limited depth of discharge if longevity is desired.

Best practices for PbA batteries

Before we move on to performing a learning cycle using LFP, here are some best practices for getting the longest possible usage from LFP batteries.

- Use CC/CV mode for charging.
- Charge to a nominal voltage of 2.4-2.45V.
- Use charge saturation to prevent sulfation.
- Keep charge floating voltage at 2.25-2.3V.
- Always keep battery cool while charging as heating causes heavy charge losses.
- Do not discharge batteries to high DOD (depth of discharge).
- When possible try to store batteries fully charged. If not possible, maintain batteries above 2.1V.
- When possible try to avoid loading the battery while charging.
- Apply topping charge to avoid sulfation every 5-6 months when battery is in storage.
- For charging either do not use a rate greater than C/3 or less than C/10.

PbA on the bq34z100 gauge

The bq34z100 fuel gauge uses 3 different methods for charging and charge termination on all battery chemistries. They are:

1. CC/ CV charging
2. Delta T/dt charging (T=temperature, t=time)
3. NegdV charging (negative delta voltage)

PbA batteries should ideally only use CC/CV charging. In addition to this, we should also account for charging losses that are typical to PbA batteries. Hence we should calculate the charging efficiency.

Lead acid batteries are also prone to gassing (flooded lead acid batteries). Therefore once they have been fully charged (completing the CC/CV) mode, if a topping charge were to be applied, it should be done at a slightly lower voltage.

Charge efficiency

When PbA batteries are charged, they lose a certain portion of the charging current to I2R and chemical losses. Hence, to more accurately track state of charge and Time-to-Full during the charge phase, the bq34z100-G1 uses four charge-efficiency factors to compensate for charge acceptance. These factors are ***Charge Efficiency***, ***Charge Eff Reduction Rate***, ***Charge Eff Drop Off***, and ***Charge Eff Temperature Compensation***.

The bq34z100-G1 applies the ***Charge Efficiency*** when *RelativeStateOfCharge()* is less than the value stored in ***Charge Efficiency Drop Off***. When *RelativeStateOfCharge()* is > or equal to the value coded in ***Charge Efficiency Drop Off***, ***Charge Efficiency*** and ***Charge Efficiency Reduction Rate*** determine the charge efficiency rate. ***Charge Efficiency Reduction Rate*** defines the percent efficiency reduction per percentage point of *RelativeStateOfCharge()* over ***Charge Efficiency Drop Off***. The ***Charge Efficiency Reduction Rate*** has units of 0.1%.

The bq34z100-G1 also adjusts the efficiency factors for temperature. ***Charge Efficiency Temperature Compensation*** defines the percent efficiency reduction per degree C over 25°C. ***Charge Efficiency Temperature Compensation*** has units of 0.01%.

Applying the four factors:

Effective Charge Efficiency % = ***Charge Efficiency*** – ***Charge Eff Reduction Rate*** [*RSOC()* – ***Charge Efficiency Drop Off***] – ***Charge Efficiency Temperature Compensation*** [***Temperature*** – 25°C] Where: *RSOC()* ≥ ***Charge Efficiency*** and ***Temperature*** ≥ 25°C

Setting up the learning cycle for PbA

Setup to perform the learning cycle:

1. Obtain the chem ID using the GPCCHEM tool as per the steps here: http://www.ti.com/tool/GPCCHEM
2. Update the gauge with the chem ID obtained in Step 1.
3. Update the gauging settings per Sections 2. Look at the datasheet of the battery to know the limits to which the battery can be charged and discharged.
4. Update the settings for protections and permanent failure appropriately.

Performing the learning cycle for PbA

Now to perform the learning cycle:

1. Set charging current to at least C/5 rate but never more than C/2 rate
2. Charge the cell to full. For charge termination the current taper method is used:
   - During two consecutive periods of ***Current Taper Window***, the *AverageCurrent()* is less than ***Taper Current*** AND
   - During the same periods, the accumulated change in capacity > 0.25 mAh /***Taper Current Window*** AND
   - *Voltage()* is > ***Charging Voltage*** – ***Charging Taper Voltage***. When this occurs, the [CHG] bit of *Flags()* is cleared. Also, if the [RMFCC] bit of Pack Configuration is set, and *RemainingCapacity()* is set equal to *FullChargeCapacity()*.
3. Relax until the first DOD is taken.
4. Set discharge current to at least C/5 rate but never more than C/2 rate.
5. Discharge the PbA cell until it is at least 10mV below terminate voltage.
6. Relax again until the DOD is taken, this is indicated by the VOK flag being cleared.
7. At this point Qmax for the cell will be updated.
8. Repeat the cycle again to get a subsequent Qmax and Ra table update.

This will complete characterization of the battery. The learning cycle for the bq34z100 on the PbA cell will be complete.

6 Learning Cycle for NiCD Batteries

NiCD batteries are similar in behavior to NiMH batteries. Therefore their characteristics are similar.

Best practices for NiCD batteries

Before we move on to performing a learning cycle using NiCD, here are some best practices for getting the longest possible usage from NiCD batteries:

- NiCD batteries start heating after about 70% charge, this reduces charge efficiency.
- Do not leave NiCD batteries in the charger for extended periods of time.
- If trickle charging is used for charge termination, ensure that batteries cool during trickle charging.
- If batteries heat up on trickle charging, reduce the rate of charge.
- Always charge at room temperature, do not charge at hot or cold temperatures.
- NiCD batteries should not be slow charged as it reduces longevity due to memory effects.

NiCD on the bq34z100 gauge

The bq34z100 fuel gauge uses 3 different methods for charging and charge termination on all battery chemistries. They are:

1. CC/ CV charging
2. Delta T/dt charging (T=temperature, t=time)
3. NegdV charging (negative delta voltage)

The bq34z100 supports CC/CV charging on NiCD batteries. NiCD batteries are different from Li-ion batteries because:

1. They have a very high rate of self dsg unlike Li-ion batteries.
2. 2. The self-heating effect is higher in NiCD by a large magnitude.

Setting up the learning cycle for NiCD Therefore, we need additional factors to account for compensation of heating losses during charging.

Charge Efficiency

To more accurately track state of charge and Time-to-Full during the charge phase, the bq34z100-G1 uses four charge-efficiency factors to compensate for charge acceptance. These factors are ***Charge Efficiency***, ***Charge Eff Reduction Rate***, ***Charge Eff Drop Off***, and ***Charge Eff Temperature Compensation***.

The bq34z100-G1 applies the ***Charge Efficiency*** when *RelativeStateOfCharge()* is less than the value stored in ***Charge Efficiency Drop Off***. When *RelativeStateOfCharge()* is > or equal to the value coded in ***Charge Efficiency Drop Off***, ***Charge Efficiency*** and ***Charge Efficiency Reduction Rate*** determine the charge efficiency rate. ***Charge Efficiency Reduction Rate*** defines the percent efficiency reduction per percentage point of *RelativeStateOfCharge()* over ***Charge Efficiency Drop Off***. The ***Charge Efficiency Reduction Rate*** has units of 0.1%.

The bq34z100-G1 also adjusts the efficiency factors for temperature. ***Charge Efficiency Temperature Compensation*** defines the percent efficiency reduction per degree C over 25°C. ***Charge Efficiency Temperature Compensation*** has units of 0.01%.

Applying the four factors:

Effective Charge Efficiency % = ***Charge Efficiency*** – ***Charge Eff Reduction Rate*** [*RSOC()* – ***Charge Efficiency Drop Off***] – ***Charge Efficiency Temperature Compensation*** [***Temperature*** – 25°C] Where: *RSOC()* ≥ ***Charge Efficiency*** and ***Temperature*** ≥ 25°C

Setting up the learning cycle for NiCD

Setup to perform the learning cycle:

1. Obtain the chem ID using the GPCCHEM tool as per the steps here: http://www.ti.com/tool/GPCCHEM
2. Update the gauge with the Chem ID obtained in Step 1.
3. Update the gauging settings per Sections 2. Look at the datasheet of the battery to know the limits to which the battery can be charged and discharged.
4. Update the settings for protections and permanent failure appropriately.

Performing the learning cycle for NiCD

Now to perform the learning cycle:

1. Set charging current to at least C/5 rate but never more than C/2 rate.

2. Charge the cell to full. For charge termination the current taper method is used:
   - During two consecutive periods of Current Taper Window, the AverageCurrent() is less than Taper Current AND
   - During the same periods, the accumulated change in capacity > 0.25 mAh /Taper Current Window AND
   - Voltage() is > Charging Voltage – Charging Taper Voltage. When this occurs, the [CHG] bit of Flags() is cleared. Also, if the [RMFCC] bit of Pack Configuration is set, and RemainingCapacity() is set equal to FullChargeCapacity().
3. Relax until the first DOD is taken
4. Set discharge current to at least C/5 rate but never more than C/2 rate.
5. Discharge the NiCD cell until it is at least 100mV below terminate voltage
6. Relax again until the DOD is taken, this is indicated by the VOK flag being cleared.
7. At this point Qmax for the cell will be updated.
8. Repeat the cycle again to get a subsequent Qmax and Ra table update.

This will complete characterization of the battery. The learning cycle for the bq34z100 on the NiCD cell will be complete.

7 Learning cycle for Lithium Iron Phosphate (LFP/LiFePO4) Batteries

LFP batteries are analogous to Li-ion batteries. Therefore their characteristics are similar. However the significant difference here is that they have a very large flat region in their characteristic curve and they also charge to a much lower voltage. However they are capable of high discharge currents, have long cycle life and are relatively much safer to use than other Li-ion chemistries.

Best practices for LFP batteries

Before we move on to performing a learning cycle using LFP, here are some best practices for getting the longest possible usage from LFP batteries.

- Do not store at high temperature as this reduces life
- The cells have a high rate of self dsg, so use balancing in system
- Do not expose battery to moisture as this will reduce life time

LFP on the bq34z100 gauge

The bq34z100 fuel gauge uses 3 different methods for charging and charge termination on all battery chemistries. They are:

1. CC/ CV charging
2. Delta T/dt charging (T=temperature, t=time)
3. NegdV charging (negative delta voltage)

The bq34z100 supports CC/CV charging on LFP batteries.

Setting up the learning cycle for LFP

Setup to perform the learning cycle:

1. Obtain the chem ID using the GPCCHEM tool as per the steps here: http://www.ti.com/tool/GPCCHEM
2. Update the gauge with the chem ID obtained in Step 1.
3. Update the gauging settings per Sections 2. Look at the datasheet of the battery to know the limits to which the battery can be charged and discharged.
4. Update the settings for protections and permanent failure appropriately.

DOD Error Weighting (DODEW)

The bq34z100 offers the DOD error weighting feature. This enables the gauge to use a combination of the DOD values taken using both the passed charge and also from the previous OCV. This is particularly useful when a percentage of charge or injected current is lost due to resistive and chemical losses. Therefore it is recommended that DODEW be enabled in the gauge settings.

Performing the learning cycle for LFP

Now to perform the learning cycle:

1. Set charging current to at least C/5 rate but never more than C/2 rate
2. Charge the cell to full. For charge termination the current taper method is used:
   - During two consecutive periods of Current Taper Window, the AverageCurrent() is less than Taper Current AND
   - During the same periods, the accumulated change in capacity > 0.25 mAh /Taper Current Window AND
   - Voltage() is > Charging Voltage – Charging Taper Voltage. When this occurs, the [CHG] bit of Flags() is cleared. Also, if the [RMFCC] bit of Pack Configuration is set, and RemainingCapacity() is set equal to FullChargeCapacity().
3. Relax for 5 hours until the first DOD is taken
4. Set discharge current to at least C/5 rate but never more than C/2 rate.
5. Discharge the LFP cell until it is at least 100mV below terminate voltage
6. Relax again for another 5 hours until the DOD is taken, this is indicated by the VOK flag being cleared.
7. At this point Qmax for the cell will be updated
8. Repeat the cycle again to get a subsequent Qmax and Ra table update

This will complete characterization of the battery. The learning cycle for the bq34z100 on the LFP cell will be complete

8 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 bq34z100 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.
- 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.

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