Advanced Charge Algorithm Application Note

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ABSTRACT

This document details the various features and options available in bq40z50-R2 that can be used to control a Li-ion charger voltage and current settings. Various advanced charging algorithms can be implemented by configuring the data flash values in the fuel gauge accordingly.

Contents

1 Introduction ................................................................. 1
2 Dataflash Configuration Overview .................................... 2
3 Charging Loss compensation ........................................... 7
4 Battery Degradation ...................................................... 8
5 SMBus Broadcast .......................................................... 9
6 Acronym ......................................................................... 10

List of Figures

1 Charging profile example ................................................ 2
2 Charge Current vs Voltage Range ..................................... 6
3 IR Compensation ........................................................... 7
4 SMBus Connection ........................................................ 9

List of Tables

1 DF Parameters .................................................................. 3
2 Voltage ........................................................................... 3
3 Voltage Range ............................................................... 4
4 Temp Charging .................................................................. 5
5 SOC Range ...................................................................... 5
6 Charging Current ............................................................ 6
7 Degrade Mode ................................................................... 8

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1 Introduction

The bq40z5x family of battery gauge devices provides Advanced Charge Algorithm options which allow the user to implement flexible custom charging profiles based on the Temperature(), Voltage(), RSoC(), CycleCount() and StateOfHealth() information. It can minimize charging time and prolong battery lifetime by using the recommended values reported in the ChargingVoltage() and ChargingCurrent() gauge registers. This application note details how to configure the values in Data Flash to obtain optimized ChargingVoltage() and ChargingCurrent() by showing a few examples.
2 Dataflash Configuration Overview

Lithium-ion cells can become damaged and possibly dangerous if they are overcharged, especially at extreme temperatures. To improve the safety of charging lithium-ion batteries, some vendors have their own charging profiles based on a segmented temperature range. Figure 1 shows an example for recommended charge current and charge voltage over temperature adhere the following conditions.

- \( T_1 \leq T_2 \leq T_5 \leq T_6 \leq T_3 \leq T_4 \)

In Figure 1, \( T_5 = T_6 \) since both have the same charging voltage and current:
- \( T_1 \sim T_4 \) are located in Temperature Ranges: \( T_1 \) Temp... \( T_4 \) Temp

![Figure 1. Charging profile example](image)

2.1 Temperature Configuration

Determine Temperature Ranges: \( T_x \) Temp based on the charging profile.

Set the temperature values as follows:
- \( T_1 \) Temp = 0
- \( T_2 \) Temp = 10
- \( T_5 \) Temp = 45
- \( T_6 \) Temp = 45
- \( T_3 \) Temp = 50
- \( T_4 \) Temp = 60
The Low Temp Charging range is between $T_1$ Temp and $T_2$ Temp.

Standard Temp Low Charging range is between $T_2$ Temp and $T_5$ Temp.

Rec Temp Charging range is between $T_5$ Temp and $T_6$ Temp

Standard Temp High Charging range is between $T_6$ Temp and $T_3$ Temp.

High Temp Charging range is between $T_3$ Temp and $T_4$ Temp.

Over $T_4$ Temp is Over Temp Charging.

See Table 1 for the DF parameters:

### Table 1. DF Parameters

<table>
<thead>
<tr>
<th>Class</th>
<th>Subclass</th>
<th>Name</th>
<th>Type</th>
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<td>°C</td>
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<td>°C</td>
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<td>Temperature Ranges</td>
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<td>°C</td>
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<td>Advanced Charging Algorithm</td>
<td>Temperature Ranges</td>
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<td>127</td>
<td>45</td>
<td>°C</td>
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<tr>
<td>Advanced Charging Algorithm</td>
<td>Temperature Ranges</td>
<td>$T_3$ Temp</td>
<td>I1</td>
<td>$-128$</td>
<td>127</td>
<td>50</td>
<td>°C</td>
</tr>
<tr>
<td>Advanced Charging Algorithm</td>
<td>Temperature Ranges</td>
<td>$T_4$ Temp</td>
<td>I1</td>
<td>$-128$</td>
<td>127</td>
<td>60</td>
<td>°C</td>
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</tbody>
</table>

### 2.2 Charge Voltage Configuration

Determine Temp Charging: Voltage

The $ChargingVoltage( )$ is determined based on Temperature Ranges.

Set the temperature values as follows:

- **Low Temp Charging**: $Voltage = 4150$ mV
- **Standard Temp Low Charging**: $Voltage = 4350$ mV
- **Rec Temp Charging**: $Voltage = 4350$ mV
- **Standard Temp High Charging**: $Voltage = 4300$ mV
- **High Temp Charging**: $Voltage = 4200$ mV

### Table 2. Voltage

<table>
<thead>
<tr>
<th>Class</th>
<th>Subclass</th>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Charging Algorithm</td>
<td>Low Temp Charging</td>
<td>Voltage</td>
<td>I2</td>
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<td>32767</td>
<td>4150</td>
<td>mV</td>
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<tr>
<td>Advanced Charging Algorithm</td>
<td>Standard Temp Low Charging</td>
<td>Voltage</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>4350</td>
<td>mV</td>
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<tr>
<td>Advanced Charging Algorithm</td>
<td>Rec Temp Charging</td>
<td>Voltage</td>
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<td>mV</td>
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<td>4300</td>
<td>mV</td>
</tr>
<tr>
<td>Advanced Charging Algorithm</td>
<td>High Temp Charging</td>
<td>Voltage</td>
<td>I2</td>
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<td>32767</td>
<td>4200</td>
<td>mV</td>
</tr>
</tbody>
</table>

The $ChargingVoltage( )$ changes depending on the detected Temperature( ) and Cell numbers configured in DA Configuration[CC1:CC0] bits combination.

For example, if [CC1:CC0] is set to 1,0 which is 3 cells configuration,$ChargingVoltage( ) = X$ Temp charging$Voltage \times 3$. 
2.3 Charge Current Configuration

The ChargingCurrent() is determined based on Voltage Range and Temperature Ranges. So, ChargingCurrent() is set according to Voltage Range at each Temperature Range.

The ChargingCurrent() is set based on temperature only regardless of battery voltage level.

If ChargeCurrent() is set regardless of battery voltage level, Voltage Range is not important except for Precharge Start Voltage and Charging Voltage Low in normal charging.

Use the following conditions to set Voltage Range:

- CVL ≤ CVM ≤ CVH

Precharge Start Voltage is minimum cell voltage to enter Precharge mode from Fast Charge mode. The gauge enters Precharge mode if Min Cell Voltage 1..4 < a Precharge Start Voltage. Charging Voltage Low is maximum Precharge Voltage range before entering Fast charge mode from Precharge mode. The gauge enters Fast Charge mode if Max Cell Voltage 1..4 > Charging Voltage Low.


2.4 Voltage Range Configuration

Determine the Voltage Range:

- Precharge Start Voltage = 2500 mV
- Charging Voltage Low = 3000 mV
- Charging Voltage Med = 3600 mV
- Charging Voltage High = 4000 mV

<table>
<thead>
<tr>
<th>Class</th>
<th>Subclass</th>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>Advanced Charging Algorithm</td>
<td>Voltage Range</td>
<td>Precharge Start Voltage</td>
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<td>Advanced Charging Algorithm</td>
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<td>Charging Voltage Low</td>
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<td>3000</td>
<td>mV</td>
</tr>
<tr>
<td>Advanced Charging Algorithm</td>
<td>Voltage Range</td>
<td>Charging Voltage Med</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>3600</td>
<td>mV</td>
</tr>
<tr>
<td>Advanced Charging Algorithm</td>
<td>Voltage Range</td>
<td>Charging Voltage High</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>4000</td>
<td>mV</td>
</tr>
</tbody>
</table>

2.5 Set X Temp Charging

Current Low, Med and High at each Temp Charging as followings:

- Low Temp Charging: Current Low = 2000 mA,
- Low Temp Charging: Current Med = 2000 mA,
- Low Temp Charging: Current High = 2000 mA
- Standard Temp Low Charging: Current Low = 4000 mA,
- Standard Temp Low Charging: Current Med = 4000 mA
- Standard Temp Low Charging: Current High = 4000 mA
- Rec Temp Charging: Current Low = 4000 mA
- Rec Temp Charging: Current Med = 4000 mA
- Rec Temp Charging: Current High = 4000 mA
- Standard Temp High Charging: Current Low = 4000 mA,
- Standard Temp High Charging: Current Med = 4000 mA
- Standard Temp High Charging: Current High = 4000 mA
- High Temp Charging: Current Low = 1200 mA,
• High Temp Charging: Current Med = 1200 mA
• High Temp Charging: Current High = 1200 mA

Table 4. Temp Charging

<table>
<thead>
<tr>
<th>Class</th>
<th>Subclass</th>
<th>Name</th>
<th>Type</th>
<th>Min</th>
<th>Max</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Charging</td>
<td>Low Temp Charging</td>
<td>Current Low</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>2000</td>
<td>mA</td>
</tr>
<tr>
<td>Advanced Charging</td>
<td>Low Temp Charging</td>
<td>Current Med</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>2000</td>
<td>mA</td>
</tr>
<tr>
<td>Advanced Charging</td>
<td>Low Temp Charging</td>
<td>Current High</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>2000</td>
<td>mA</td>
</tr>
<tr>
<td>Advanced Charging</td>
<td>Standard Temp Low</td>
<td>Charging</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>2000</td>
<td>mA</td>
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<tr>
<td>Advanced Charging</td>
<td>Standard Temp Low</td>
<td>Charging</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>4000</td>
<td>mA</td>
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<tr>
<td>Advanced Charging</td>
<td>Rec Temp Charging</td>
<td>Current Low</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>4000</td>
<td>mA</td>
</tr>
<tr>
<td>Advanced Charging</td>
<td>Rec Temp Charging</td>
<td>Current Med</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>4000</td>
<td>mA</td>
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<tr>
<td>Advanced Charging</td>
<td>Rec Temp Charging</td>
<td>Current High</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
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<td>mA</td>
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<tr>
<td>Advanced Charging</td>
<td>Standard Temp High</td>
<td>Charging</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>4000</td>
<td>mA</td>
</tr>
<tr>
<td>Advanced Charging</td>
<td>Standard Temp High</td>
<td>Charging</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>4000</td>
<td>mA</td>
</tr>
<tr>
<td>Advanced Charging</td>
<td>High Temp Charging</td>
<td>Current Low</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>1200</td>
<td>mA</td>
</tr>
<tr>
<td>Advanced Charging</td>
<td>High Temp Charging</td>
<td>Current Med</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>1200</td>
<td>mA</td>
</tr>
<tr>
<td>Advanced Charging</td>
<td>High Temp Charging</td>
<td>Current High</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>1200</td>
<td>mA</td>
</tr>
</tbody>
</table>

2.6 **SoC Based ChargingCurrent( ) Configuration**

When using specific SoC ranges instead of voltages to determine the charging current, then the Charging Configuration[SOC_CHARGE] bit should be set to "1". The voltage thresholds is replaced by SoC thresholds.

The *voltage range* is still important since transitions happen if both the voltage range and Charging SoC : Mid and High conditions are met.

The transition happens at the following condition:

a. [LV] state and RelativeStateOfCharge( ) > Charging SoC Mid; move to [MV].

b. [MV] state and RelativeStateOfCharge( ) > Charging SoC High; move to [HV].

Table 5. SOC Range

<table>
<thead>
<tr>
<th>Class</th>
<th>Subclass</th>
<th>Name</th>
<th>Type</th>
<th>Min Value</th>
<th>Max Value</th>
<th>Default Value</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>Advanced Charge</td>
<td>SOC Range</td>
<td>Charging SOC Mid</td>
<td>U1</td>
<td>0</td>
<td>100</td>
<td>50</td>
<td>%</td>
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<tr>
<td>Advanced Charge</td>
<td>SOC Range</td>
<td>Charging SOC High</td>
<td>U1</td>
<td>0</td>
<td>100</td>
<td>75</td>
<td>%</td>
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<tr>
<td>Advanced Charge</td>
<td>SOC Range</td>
<td>Charging SOC Hysteresis</td>
<td>U1</td>
<td>0</td>
<td>100</td>
<td>1</td>
<td>%</td>
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</table>
2.7 Charging Current

If the ChargingCurrent( ) requires to be segmented based on Voltage Range at Section 2.4, it can be set by X Temp Charging: Current Low, Current Med and Current High value each Temperature Ranges. Here is the example to segment the value at Low Temp range in Figure 2. This method is the same for other temperature ranges.

<table>
<thead>
<tr>
<th>Class</th>
<th>Subclass</th>
<th>Name</th>
<th>Type</th>
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<th>Max</th>
<th>Value</th>
<th>Unit</th>
</tr>
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<td>Current</td>
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<td>200</td>
<td>mA</td>
</tr>
<tr>
<td>Advanced Charging Algorithm</td>
<td>Low Temp Charging</td>
<td>Current Low</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>1000</td>
<td>mA</td>
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<tr>
<td>Advanced Charging Algorithm</td>
<td>Low Temp Charging</td>
<td>Current Med</td>
<td>I2</td>
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<td>1500</td>
<td>mA</td>
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<tr>
<td>Advanced Charging Algorithm</td>
<td>Low Temp Charging</td>
<td>Current High</td>
<td>I2</td>
<td>0</td>
<td>32767</td>
<td>2000</td>
<td>mA</td>
</tr>
</tbody>
</table>

Table 6. Charging Current

![Figure 2. Charge Current vs Voltage Range](image_url)
3 Charging Loss compensation

To speed up charging cycle, it is ideal to stay in the Constant Current mode as long as possible before transitioning to Constant Voltage. In the pack, many elements like the sense resistor, CHG/DSG FETs, as well as the layout contribute to a sometimes significant IR drop between Pack and Cell. This can force the charger to move to Constant Voltage mode early which extends the charging time since the charger transitions to CV mode based on its output regulation point (Charger output Voltage). Therefore if the gauge can provide an IR compensated ChargingVoltage( ) to the system, it would shorten charge time.

The gauge can read the cell voltage very accurately by measuring the cell voltages directly. So, the gauge can compensate for IR losses caused by the elements mentioned above and minimize charge time by providing IR compensated ChargingVoltage( ) if the Configuration[CCC] bit is set to "1".

When Voltage( ) < Charging Algorithm Voltage and Current( ) > CCC Current Threshold. ChargingVoltage( ) is increased with accounting for IR drop between Pack Voltage and Cell Voltage. So, ChargingVoltage( ) reports Original ChargingVoltage( ) + (PackVoltage( ) - Voltage( )). The system can increase charger output voltage based on compensated ChargingVoltage( ) information.

ChargingVoltage( ) is clamped to the Charging Algorithm + CCC Voltage Threshold level for the maximum safety not to overcharge the cell.

![Figure 3. IR Compensation](image)
Lithium-ion battery capacity is degraded and impedance is increased as battery cell ages. If Charge Voltage and Charge Current are adjusted as battery ages, it helps to increase battery longevity. According to the Study, the battery voltage is the most important factor to speed up the degradation. The gauge provides the reduced ChargingVoltage( ) and ChargingCurrent( ) information based on either CycleCount( ) or SOH( ). Only either CycleCount( ) or SOH( ) can be used at one time.

Degraded ChargingVoltage( ) is enabled when ChargingConfiguration[CYLE_DEGRADE] or ChargingConfiguration[SOH_DEGRADE] bit is set. Degraded ChargingCurrent( ) is enabled when ChargingConfiguration[DEGRADE_CC] bit is set.

Cycle Count or SOH Threshold are configured at Degrade Mode 1,2,3. Charge Voltage Degradation level and Charge Current Degradation level are also configured at Degrade Mode 1,2,3.

For example, if it requires to reduce the ChargingVoltage( ) by 50 mV after 200 cycles, set:

- Degrade Mode 1 : Cycle Threshold = 200
- Degrade Mode 1: Voltage Degradation = 50
- Degrade Mode 1: Current Degradation = 0

After that, if it is required to reduce the ChargingVoltage( ) by 100 mV and ChargingCurrent( ) by 10 % after 300 cycles, set:

- Degrade Mode 2: Cycle Threshold = 300
- Degrade Mode 1: Voltage Degradation = 50
- Degrade Mode 2: Current Degradation = 10 since Degrade Mode 2: Voltage Degradation

- Degrade Mode 2: Current Degradation are accumulated value from Degrade Mode 1: Voltage Degradation

- Degrade Mode 1 : Current Degradation

<table>
<thead>
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<th>Table 7. Degrade Mode</th>
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<tbody>
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<tr>
<td>Advanced Charging Algorithm</td>
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<tr>
<td>Advanced Charging Algorithm</td>
</tr>
</tbody>
</table>
5 SMBus Broadcast

The gauge supports SMBus Broadcast mode which makes the gauge as a master on the bus and broadcasts the information to the System Host or Smart Battery Charger as a master. It gives the benefit that the host doesn’t need polling the registers to read ChargingVoltage() and ChargingCurrent() since the gauge sends the information periodically. An SMBus master can only start a packet if the SMBus has been idle for more than 50 µs. Once this requirement has been met, the master immediately takes control of the bus by sending a start bit. If another master controls the bus, the firmware-controlled bus does not detect that the bus is no longer busy, which causes arbitration to be lost. Make sure that CPU does not have a problem with multi-master SMBus to use Broadcast function.

When BatteryMode[CHGM] bit is "0", it enables ChargingVoltage() and ChargingCurrent() to host an smart battery charger. When BatteryMode[AM] bit is "0", it enables AlarmWarning() broadcasts to host an smart battery charger. If SBS configuration[HPE] bit is set, Master mode broadcasts to the System host address are PEC enabled. If the SBS configuration[CPE] bit is set, Master mode broadcasts to the System Charger(0x12). If the SBS configuration[BCAST] bit is set, Master mode is enabled and the gauge broadcasts ChargingVoltage(), ChargingCurrent() and AlarmWarning() to the Smart Charger (0x12) and the host.(0x10).

There are two main advantages in using the SMBus Broadcast function:

1. It provides the battery with all power it can handle without overcharging – Maximum Safe Charge
2. It correctly charges batteries with different chemistries and voltages.

The AlarmWarning() broadcast can be used to warn the System Host or Smart Battery Charger of potentially dangerous situations that are verify by reading the status registers.

bq40z50 supports PEC (Packet Error Checking) to enhance data integrity during SMBus communication. PEC is an extra byte of data added to the end of the communication packet that is derived from a simple CRC-8 checksum. In read operations, the bq40z50 is responsible for sending the PEC packet to the host which determines if the PEC is valid. In write operations, the host is responsible for sending the PEC to the slave which determines if the PEC is valid.

Make sure CPU does not have a problem with multi-master SMBus before enabling the SMBus Broadcast feature. Many CPUs do not behave properly if another SMBus master is on the same bus.

![Figure 4. SMBus Connection](image-url)
6 Acronym

UT: Under Temperature
LT: Low Temperature
STL: Standard Low Temperature
RT: Recommended Temperature
STH: Standard High Temperature
HT: High Temperature
OT: Over Temperature
CVL: Charging Voltage Low
CVM: Charging Voltage Med
CVH: Charging Voltage High
CCL: Charging Current Low
CCM: Charging Current Med
CCH: Charging Current High
FCC: Full Charge Capacity
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