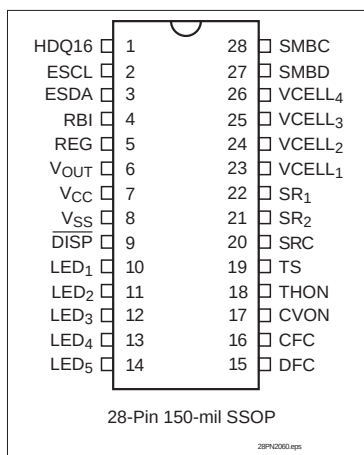


SBS v1.1-Compliant Gas Gauge IC

Features

- Provides accurate measurement of available charge in NiCd, NiMH, Li-Ion, and lead-acid batteries
- Supports SBS Smart Battery Data Specification v1.1
- Supports the 2-wire SMBus v1.1 interface with PEC or 1-wire HDQ16
- Reports individual cell voltages
- Monitors and provides control to charge and discharge FETs in Li-Ion protection circuit
- Provides 15-bit resolution for voltage, temperature, and current measurements
- Measures charge flow using a V-to-F converter with offset of less than 16µV after calibration
- Consumes less than 0.5mW operating
- Drives a 4- or 5-segment LED display for remaining capacity indication
- 28-pin 150-mil SSOP

Pin Connections



SLUS035D–SEPTEMBER 2001

General Description

The bq2060 SBS-Compliant Gas Gauge IC for battery pack or in-system installation maintains an accurate record of available charge in rechargeable batteries. The bq2060 monitors capacity and other critical battery parameters for NiCd, NiMH, Li-Ion, and lead-acid chemistries. The bq2060 uses a V-to-F converter with automatic offset error correction for charge and discharge counting. For voltage, temperature, and current reporting, the bq2060 uses an A-to-D converter. The onboard ADC also monitors individual cell voltages in a Li-Ion battery pack and allows the bq2060 to generate control signals that may be used in conjunction with a pack supervisor to enhance pack safety.

The bq2060 supports the smart battery data (SBDat) commands and charge-control functions. It communicates data using the system management bus (SMBus) 2-wire protocol or the Benchmark 1-wire HDQ16 protocol. The data available include the battery's remaining capacity, temperature, voltage, current, and remaining run-time predictions. The bq2060

provides LED drivers and a push-button input to depict remaining battery capacity from full to empty in 20% or 25% increments with a 4 or 5-segment display.

The bq2060 works with an external EEPROM. The EEPROM stores the configuration information for the bq2060, such as the battery's chemistry, self-discharge rate, rate compensation factors, measurement calibration, and design voltage and capacity. The bq2060 uses the programmable self-discharge rate and other compensation factors stored in the EEPROM to accurately adjust remaining capacity for use and standby conditions based on time, rate, and temperature. The bq2060 also automatically calibrates or learns the true battery capacity in the course of a discharge cycle from near full to near empty levels.

The REG output regulates the operating voltage for the bq2060 from the battery cell stack using an external JFET.

Pin Names

HDQ16	Serial communication input/output	DFC	Discharge FET control
ESCL	Serial memory clock	CFC	Charge FET control
ESDA	Serial memory data and address	VON	Cell voltage divider control
RBI	Register backup input	THON	Thermistor bias control
REG	Regulator output	TS	Thermistor voltage input
VO _{UT}	EEPROM supply output	SRC	Current sense input
V _{CC}	Supply voltage	SR ₁ –SR ₂	Charge-flow sense resistor inputs
V _{SS}	Ground	VCELL ₁ –VCELL ₄	Single-cell voltage inputs
DISP	Display control input	SMBD	SMBus data
LED ₁ –LED ₅	LED display segment outputs	SMBC	SMBus clock

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Pin Descriptions

HDQ16	Serial communication input/output Open-drain bidirectional communications port	DFC	Discharge FET control output Output to control the discharge FET in the Li-Ion pack protection circuitry
ESCL	Serial memory clock Output to clock the data transfer between the bq2060 and the external nonvolatile configuration memory	CFC	Charge FET control output Output to control the charge FET in the Li-Ion pack protection circuitry
ESDA	Serial memory data and address Bidirectional pin used to transfer address and data to and from the bq2060 and the external nonvolatile configuration memory	CVON	Cell voltage divider control output Output control for external FETs to connect the cells to the external voltage dividers during cell voltage measurements
RBI	Register backup input Input that provides backup potential to the bq2060 registers during periods of low operating voltage. RBI accepts a storage capacitor or a battery input.	THON	Thermistor bias control output Output control for external FETs to connect the thermistor bias resistor during a temperature measurement
REG	Regulator output Output to control an n-JFET for V _{CC} regulation to the bq2060 from the battery potential	TS	Thermistor voltage input Input connection for a thermistor to monitor temperature
V_{OUT}	Supply output Output that supplies power to the external EEPROM configuration memory	SRC	Current sense voltage input Input to monitor instantaneous current
V_{CC}	Supply voltage input	SR₁–SR₂	Sense resistor inputs Input connections for a small value sense resistor to monitor the battery charge and discharge current flow
V_{SS}	Ground	VCELL₁–VCELL₄	Single-cell voltage inputs Inputs that monitor the series element cell voltages
DISP	Display control input Input that controls the LED drivers LED ₁ –LED ₅	SMBD	SMBus data Open-drain bidirectional pin used to transfer address and data to and from the bq2060
LED₁–LED₅	LED display segment outputs Outputs that each may drive an external LED	SMBC	SMBus clock Open drain bidirectional pin used to clock the data transfer to and from the bq2060

Functional Description

General Operation

The bq2060 determines battery capacity by monitoring the amount of charge input or removed from a rechargeable battery. In addition to measuring charge and discharge, the bq2060 measures battery voltage, temperature, and current, estimates battery self-discharge, and monitors the battery for low-voltage thresholds. The bq2060 measures charge and discharge activity by monitoring the voltage across a small-value series sense resistor between the battery's negative terminal and the negative terminal of the battery pack. The available battery charge is determined by monitoring this voltage and correcting the measurement for environmental and operating conditions.

Figure 1 shows a typical bq2060-based battery pack application. The circuit consists of the LED display, voltage and temperature measurement networks, EEPROM connections, a serial port, and the sense resistor. The EEPROM stores basic battery pack configuration information and measurement calibration values. The EEPROM must be programmed properly for bq2060 operation. Table 10 shows the EEPROM memory map and outlines the programmable functions available in the bq2060.

The bq2060 accepts an NTC thermistor (Semitec 103AT) for temperature measurement. The bq2060 uses the thermistor temperature to monitor battery pack temperature, detect a battery full charge condition, and compensate for self-discharge and charge/discharge battery efficiencies.

Measurements

The bq2060 uses a fully differential, dynamically balanced voltage-to-frequency converter (VFC) for charge measurement and a sigma delta analog-to-digital converter (ADC) for battery voltage, current, and temperature measurement.

Voltage, current, and temperature measurements are made every 2–2.5 seconds, depending on the bq2060 operating mode. Maximum times occur with compensated EDV, mWh mode, and maximum allowable discharge rate. Any AtRate computations requested or scheduled (every 20 seconds) may add up to 0.5 seconds to the time interval.

Charge and Discharge Counting

The VFC measures the charge and discharge flow of the battery by monitoring a small-value sense resistor between the SR₁ and SR₂ pins as shown in Figure 1.

The VFC measures bipolar signals up to 250mV. The bq2060 detects charge activity when $V_{SR} = V_{SR2} - V_{SR1}$ is positive and discharge activity when $V_{SR} = V_{SR2} - V_{SR1}$ is negative. The bq2060 continuously integrates the signal over time using an internal counter. The fundamental rate of the counter is 6.25μVh.

Offset Calibration

The bq2060 provides an auto-calibration feature to cancel the voltage offset error across SR₁ and SR₂ for maximum charge measurement accuracy. The calibration routine is initiated by issuing a command to ManufacturerAccess(). The bq2060 is capable of automatic offset calibration down to 6.25μV. Offset cancellation resolution is less than 1μV.

Digital Filter

The bq2060 does not measure charge or discharge counts below the digital filter threshold. The digital filter threshold is programmed in the EEPROM and should be set sufficiently high to prevent false signal detection with no charge or discharge flowing through the sense resistor.

Voltage

While monitoring SR₁ and SR₂ for charge and discharge currents, the bq2060 monitors the battery-pack potential and the individual cell voltages through the VCELL₁–VCELL₄ pins. The bq2060 measures the pack voltage and reports the result in Voltage(). The bq2060 can also measure the voltage of up to four series elements in a battery pack. The individual cell voltages are stored in the optional Manufacturer Function area.

The VCELL₁–VCELL₄ inputs are divided down from the cells using precision resistors, as shown in Figure 1. The maximum input for VCELL₁–VCELL₄ is 1.25V with respect to V_{SS}. The voltage dividers for the inputs must be set so that the voltages at the inputs do not exceed the 1.25V limit under all operating conditions. Also, the divider ratios on VCELL₁–VCELL₂ must be half of that of VCELL₃–VCELL₄. To reduce current consumption from the battery, the CVON output may be used to connect the divider to the cells only during measurement period. CVON is high impedance for 250ms (12.5% duty cycle) when the cells are measured, and driven low otherwise. See Table 1.

Current

The SRC input of the bq2060 measures battery charge and discharge current. The SRC ADC input converts the current signal from the series sense resistor and stores the result in Current(). The full-scale input range to SRC is limited to ±250mV as shown in Table 2.

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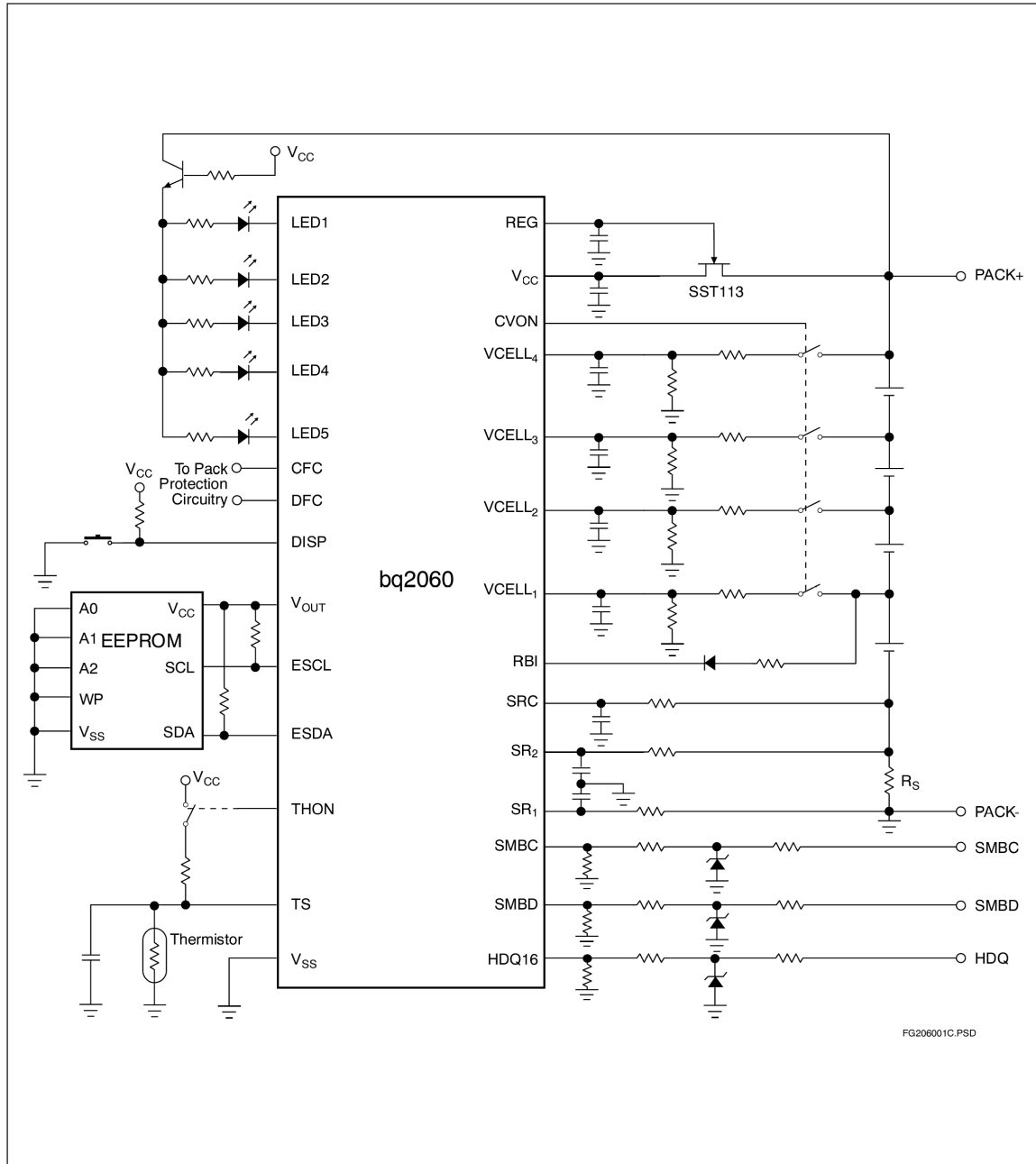


Figure 1. Battery Pack Application Diagram–LED Display and Series Cell Monitoring

Table 1. Example VCELL₁–VCELL₄ Divider and Input Range

Voltage Input	Voltage Division Ratio	Full-Scale Input (V)
VCELL ₄	16	20.0
VCELL ₃	16	20.0
VCELL ₂	8	10.0
VCELL ₁	8	10.0

Temperature

The TS input of the bq2060 in conjunction with an NTC thermistor measures the battery temperature as shown in Figure 1. The bq2060 reports temperature in Temperature(). THON may be used to connect the bias source to the thermistor when the bq2060 samples the TS input. THON is high impedance for 60ms when the temperature is measured, and driven low otherwise.

Gas Gauge Operation

General

The operational overview in Figure 2 illustrates the gas gauge operation of the bq2060. Table 3 describes the bq2060 registers.

The bq2060 accumulates a measure of charge and discharge currents and estimates self-discharge of the battery. The bq2060 compensates the charge current measurement for temperature and state-of-charge of the battery. The bq2060 also adjusts the self-discharge estimation based on temperature.

The main counter RemainingCapacity() (RM) represents the available capacity or energy in the battery at any

Table 2. SRC Input Range

Sense Resistor (Ω)	Full-Scale Input (A)
0.02	± 12.5
0.03	± 8.3
0.05	± 5.0
0.10	± 2.5

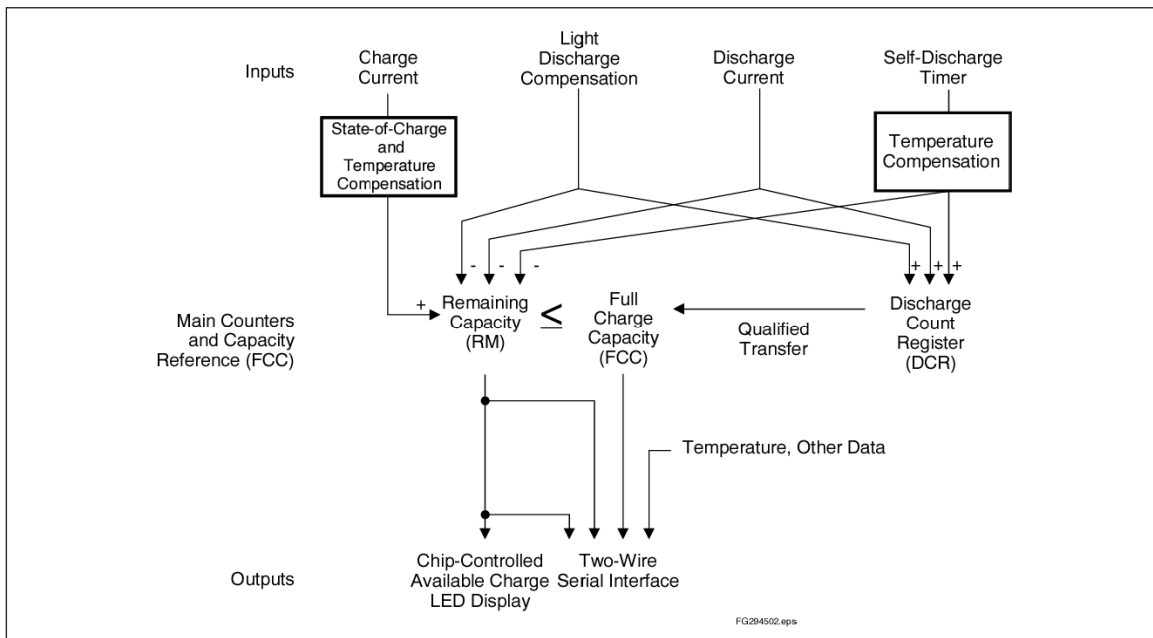


Figure 2. bq2060 Operational Overview

bq2060

given time. The bq2060 adjusts RM for charge, self-discharge, and leakage compensation factors. The information in the RM register is accessible through the communications ports and is also represented through the LED display.

The FullChargeCapacity() (FCC) register represents the last measured full discharge of the battery. It is used as the battery's full-charge reference for relative capacity indication. The bq2060 updates FCC when the battery undergoes a qualified discharge from nearly full to a low battery level. FCC is accessible through the serial communications ports.

The Discharge Count Register (DCR) is a non-accessible register that only tracks discharge of the battery. The bq2060 uses the DCR register to update the FCC register if the battery undergoes a qualified discharge from nearly full to a low battery level. In this way, the bq2060 learns the true discharge capacity of the battery under system use conditions.

Main Gas Gauge Registers

RemainingCapacity() (RM)

RM represents the remaining capacity in the battery. The bq2060 computes RM in either mAh or 10mWh depending on the selected mode.

On initialization, the bq2060 sets RM to 0. RM counts up during charge to a maximum value of FCC and down during discharge and self-discharge to 0. In addition to charge and self-discharge compensation, the bq2060 calibrates RM at three low-battery-voltage thresholds, EDV2, EDV1, and EDV0 and three programmable midrange thresholds VOC25, VOC50, and VOC75. This provides a voltage-based calibration to the RM counter.

DesignCapacity() (DC)

The DC is the user-specified battery full capacity. It is calculated from *Pack Capacity* EE 0x3a–0x3b and is represented in mAh or 10mWh. It also represents the full-battery reference for the absolute display mode.

FullChargeCapacity() (FCC)

FCC is the last measured discharge capacity of the battery. It is represented in either mAh or 10mWh depending on the selected mode. On initialization, the bq2060 sets FCC to the value stored in *Last Measured Discharge* EE 0x38–0x39. During subsequent discharges, the bq2060 updates FCC with the last measured discharge capacity of the battery. The last measured discharge of the battery is based on the value in the DCR register after a qualified discharge occurs. Once updated, the bq2060 writes the new FCC value to EEPROM in mAh to *Last Measured Discharge*. FCC represents the full battery reference for the relative display mode and relative state of charge calculations.

Discharge Count Register (DCR)

The DCR register counts up during discharge, independent of RM. DCR can continue to count even after RM has counted down to 0. Prior to RM = 0, discharge activity, light discharge estimation and self-discharge increment DCR. After RM = 0, only discharge activity increments DCR. The bq2060 initializes DCR to FCC – RM when RM is within twice the programmed value in *Near Full* EE 0x55. The DCR initial value of FCC – RM is reduced by FCC/128 if SC = 0 (bit 2 in Control Mode) and is not reduced if SC = 1. DCR stops counting when the battery voltage reaches the EDV2 threshold on discharge.

Capacity Learning (FCC Update) and Qualified Discharge

The bq2060 updates FCC with an amount based on the value in DCR if a qualified discharge occurs. The new value for FCC equals the DCR value plus the programmable nearly full and low battery levels, according to the following equation:

$$\begin{aligned} \text{FCC}(\text{new}) = & \text{DCR}(\text{final}) = \\ & \text{DCR}(\text{initial}) + \text{measured discharge to EDV2} \\ & + (\text{FCC} \times \text{BatteryLow\%}) \end{aligned} \quad (1)$$

where

$$\text{BatteryLow\%} = (\text{value stored in EE 0x54}) \div 2.56$$

A qualified discharge occurs if the battery discharges from $\text{RM} \geq \text{FCC} - \text{Near Full} * 2$ to the EDV2 voltage threshold with the following conditions:

- No valid charge activity occurs during the discharge period. A valid charge is defined as an input of 10mAh into the battery.
- No more than 256mAh of self-discharge and/or light discharge estimation occurs during the discharge period.
- The temperature does not drop below 5°C during the discharge period.
- The battery voltage reaches the EDV2 threshold during the discharge period and the voltage was less than the EDV2 threshold minus 256mV when the bq2060 detected EDV2.
- No midrange voltage correction occurs during the discharge period.

FCC cannot be reduced by more than 256mAh or increased by more than 512mAh during any single update cycle. The bq2060 saves the new FCC value to the EEPROM within 4s of being updated.

Table 3. bq2060 Register Functions

Function	Command Code		SMBus Access	Units
	SMBus	HDQ16		
ManufacturerAccess	0x00	0x00	read/write	n/a
RemainingCapacityAlarm	0x01	0x01	read/write	mAh, 10mWh
RemainingTimeAlarm	0x02	0x02	read/write	minutes
BatteryMode	0x03	0x03	read/write	n/a
AtRate	0x04	0x04	read/write	mA, 10mW
AtRateTimeToFull	0x05	0x05	read	minutes
AtRateTimeToEmpty	0x06	0x06	read	minutes
AtRateOK	0x07	0x07	read	Boolean
Temperature	0x08	0x08	read	0.1°K
Voltage	0x09	0x09	read	mV
Current	0x0a	0x0a	read	mA
AverageCurrent	0x0b	0x0b	read	mA
MaxError	0x0c	0x0c	read	percent
RelativeStateOfCharge	0x0d	0x0d	read	percent
AbsoluteStateOfCharge	0x0e	0x0e	read	percent
RemainingCapacity	0x0f	0x0f	read	mAh, 10mWh
FullChargeCapacity	0x10	0x10	read	mAh, 10mWh
RunTimeToEmpty	0x11	0x11	read	minutes
AverageTimeToEmpty	0x12	0x12	read	minutes
AverageTimeToFull	0x13	0x13	read	minutes
ChargingCurrent	0x14	0x14	read	mA
ChargingVoltage	0x15	0x15	read	mV
Battery Status	0x16	0x16	read	n/a
CycleCount	0x17	0x17	read	cycles
DesignCapacity	0x18	0x18	read	mAh, 10mWh
DesignVoltage	0x19	0x19	read	mV
SpecificationInfo	0x1a	0x1a	read	n/a
ManufactureDate	0x1b	0x1b	read	n/a
SerialNumber	0x1c	0x1c	read	integer
Reserved	0x1d–0x1f	0x1d - 0x1f	-	-
ManufacturerName	0x20	0x20–0x25	read	string
DeviceName	0x21	0x28–0x2b	read	string
DeviceChemistry	0x22	0x30–0x32	read	string
ManufacturerData	0x23	0x38–0x3b	read	string
Pack Status	0x2f (LSB)	0x2f (LSB)	read/write	n/a
Pack Configuration	0x2f (MSB)	0x2f (MSB)	read/write	n/a
VCELL4	0x3c	0x3c	read/write	mV
VCELL3	0x3d	0x3d	read/write	mV
VCELL2	0x3e	0x3e	read/write	mV
VCELL1	0x3f	0x3f	read/write	mV

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Table 4. State of Charge Based on Low Battery Voltage

Threshold	State of Charge in RM
EDV0	0%
EDV1	3%
EDV2	Battery Low %

End-of-Discharge Thresholds and Capacity Correction

The bq2060 monitors the battery for three low-voltage thresholds, EDV0, EDV1, and EDV2. The EDV thresholds are programmed in *EDVF/EDV0* EE 0x72–0x73, *EMF/EDV1* EE 0x74–0x75, and *EDV C1/C0 Factor/EDV2* EE 0x78–0x79. If the CEDV bit in *Pack Configuration* is set, automatic EDV compensation is enabled and the bq2060 computes the EDV0, EDV1, and EDV2 thresholds based on the values in EE 0x72–0x7d, 0x06, and the battery's current discharge rate, temperature, capacity, and cycle count. The bq2060 disables EDV detection if *Current()* exceeds the *Overload Current* threshold programmed in EE 0x46 - EE 0x47. The bq2060 resumes EDV threshold detection after *Current()* drops below the overload current threshold. Any EDV threshold detected will be reset after 10mAh of charge are applied.

The bq2060 uses the thresholds to apply voltage-based corrections to the RM register according to Table 4.

The bq2060 adjusts RM as it detects each threshold. If the voltage threshold is reached before the corresponding capacity on discharge, the bq2060 reduces RM to the appropriate amount as shown in Table 4. If RM reaches the capacity level before the voltage threshold is reached on discharge, the bq2060 prevents RM from decreasing until the battery voltage reaches the corresponding threshold.

Self-Discharge

The bq2060 estimates the self-discharge of the battery to maintain an accurate measure of the battery capacity during periods of inactivity. The algorithm for self-discharge estimation takes a programmed estimate for the expected self-discharge rate at 25°C stored in EEPROM and makes a fixed reduction to RM of an amount equal to *RemainingCapacity()/256*. The bq2060 makes the fixed reduction at a varying time interval that is adjusted to achieve the desired self-discharge rate. This method maintains a constant granularity of 0.39% for each self-discharge adjustment, which may be performed multiple times per day, instead of once per day with a potentially large reduction.

The self-discharge estimation rate for 25°C is doubled for each 10 degrees above 25°C or halved for each 10 degrees below 25°C. The following table shows the relation

of the self-discharge estimation at a given temperature to the rate programmed for 25°C (Y% per day):

Temperature (C)	Self-Discharge Rate
Temp < 10	$\frac{1}{4}Y\%$ per day
$10 \leq \text{Temp} < 20$	$\frac{1}{2}Y\%$ per day
$20 \leq \text{Temp} < 30$	Y% per day
$30 \leq \text{Temp} < 40$	2Y% per day
$40 \leq \text{Temp} < 50$	4Y% per day
$50 \leq \text{Temp} < 60$	8Y% per day
$60 \leq \text{Temp} < 70$	16Y% per day
$70 \leq \text{Temp}$	32Y% per day

The interval at which RM is reduced is given by the following equation, where n is the appropriate factor of 2 ($n = \frac{1}{4}, \frac{1}{2}, 1, 2, \dots$):

(2)

$$\text{Self - Discharge Update Time} = \frac{640 \cdot 13500}{256 \cdot n \cdot (Y\% \text{ per day})} \text{ seconds}$$

The timer that keeps track of the self-discharge update time is halted whenever charge activity is detected. The timer is reset to zero if the bq2060 reaches the *RemainingCapacity()=FullChargeCapacity()* condition while charging.

Example: If $T = 35^\circ\text{C}$ ($n = 2$) and programmed self-discharge rate Y is 2.5 (2.5% per day at 25°C), the bq2060 reduces RM by RM/256 (0.39%) every

(3)

$$\frac{640 \cdot 13500}{256 \cdot n \cdot (Y\% \text{ per day})} = 6750 \text{ seconds}$$

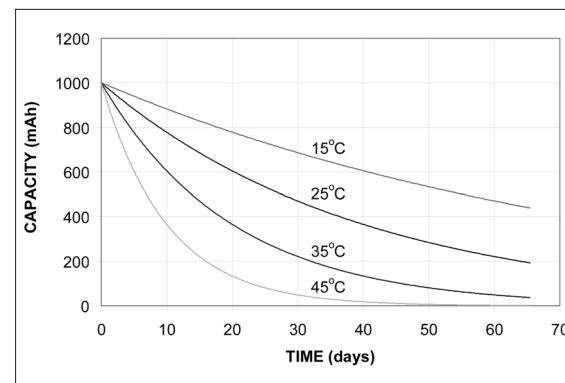


Figure 3. Self-Discharge at 2.5%/Day @25C

This means that a 0.39% reduction of RM will be made 12.8 times per day to achieve the desired 5% per day reduction at 35°C.

Figure 3 illustrates how the self-discharge estimate algorithm adjusts RemainingCapacity() vs. temperature.

Light Discharge or Suspend Current Compensation

The bq2060 can be configured in two ways to compensate for small discharge currents that produce a signal below the digital filter. First, the bq2060 can decrement RM and DCR at a rate determined by the value stored in *Light Discharge Current* EE 0x2b when it detects no discharge activity and the SMBC and SMBD lines are high. *Light Discharge Current* has a range of 44µA to 11.2mA.

Alternatively, the bq2060 can be configured to disable the digital filter for discharge when the SMBC and SMBD lines are high. In this way, the digital filter will not mask the leakage current signal. The bq2060 is configured in this mode by setting the NDF bit in *Control Mode*.

Midrange Capacity Corrections

The bq2060 applies midrange capacity corrections when the VCOR bit is set in *Pack Configuration*. The bq2060 adjusts RM to the associated percentage at three different voltage levels VOC25, VOC50, and VOC75. The VOC values represent the open circuit battery voltage at which RM corresponds to the associated state of charge for each threshold.

Threshold	Associated State of Charge
VOC25	25%
VOC50	50%
VOC75	75%

For the midrange corrections to occur, the temperature must be in the range of 19°C to 31°C inclusive and the Current() and AverageCurrent() must both be between -64mA and 0. The bq2060 makes midrange corrections as shown in Table 5.

Charge Control

Charging Voltage and Current Broadcasts

The bq2060 supports SBS charge control by broadcasting the ChargingCurrent() and ChargingVoltage() to the Smart Charger address. The bq2060 broadcasts the requests every 10s. The bq2060 updates the values used in the charging current and voltage broadcasts based on the battery's state of charge, voltage, and temperature. The fast-charge rate is programmed in *Fast-Charging Current* EE 0x1a - 0x1b while the charge voltage is programmed in *Charging Voltage* EE 0x0a-0x0b.

The bq2060 internal charge control is compatible with popular rechargeable chemistries. The primary charge-termination techniques include a change in temperature over a change in time ($\Delta T/\Delta t$) and current taper, for nickel-based and Li-Ion chemistries, respectively. The bq2060 also provides pre-charge qualification and a number of safety charge suspensions based on current, voltage, temperature, and state of charge.

Alarm Broadcasts to Smart Charger and Host

If any of the bits 8–15 in BatteryStatus() is set, the bq2060 broadcasts an AlarmWarning() message to the Host address. If any of the bits 12–15 in BatteryStatus() are set, the bq2060 also sends an AlarmWarning() message to the Smart Charger address. The bq2060 repeats the AlarmWarning() message every 10s until the bits are cleared.

Pre-Charge Qualification

The bq2060 sets ChargingCurrent() to the pre-charge rate as programmed in *Pre-Charge Current* EE 0x1e-0x1f under the following conditions:

Table 5. Midrange Corrections

Condition		Result
Voltage()	$\geq \text{VOC75}$ and $\text{RelativeStateOfCharge}() \leq 63\%$	$\text{RelativeStateOfCharge}() \rightarrow 75\%$
	$< \text{VOC75}$ and $\text{RelativeStateOfCharge}() \geq 87\%$	$\text{RelativeStateOfCharge}() \rightarrow 75\%$
	$\geq \text{VOC50}$ and $\text{RelativeStateOfCharge}() \leq 38\%$	$\text{RelativeStateOfCharge}() \rightarrow 50\%$
	$< \text{VOC50}$ and $\text{RelativeStateOfCharge}() \geq 62\%$	$\text{RelativeStateOfCharge}() \rightarrow 50\%$
	$\geq \text{VOC25}$ and $\text{RelativeStateOfCharge}() \leq 13\%$	$\text{RelativeStateOfCharge}() \rightarrow 25\%$
	$< \text{VOC25}$ and $\text{RelativeStateOfCharge}() \geq 37\%$	$\text{RelativeStateOfCharge}() \rightarrow 25\%$

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- **Voltage:** The bq2060 requests the pre-charge charge rate when Voltage() drops below the EDV0 threshold (compensated or fixed EDVs). Once requested, a pre-charge rate remains until Voltage() increases above the EDVF threshold. The bq2060 also broadcasts the pre-charge value immediately after a device reset until Voltage() is above the EDVF threshold. This threshold is programmed in EDVF/EDV0 EE 0x72-0x73.
- **Temperature:** The bq2060 requests the pre-charge rate when Temperature() is between 0°C and 5°C. Temperature() must rise above 5°C before the bq2060 requests the fast-charge rate.

Charge Suspension

The bq2060 may temporarily suspend charge if it detects a charging fault. A charging fault includes the following conditions.

- **Overcurrent:** An overcurrent condition exists when the bq2060 measures the charge current to be more than the *Overcurrent Margin* above the ChargingCurrent(). *Overcurrent Margin* is programmed in EE 0x49. On detecting an overcurrent condition, the bq2060 sets the ChargingCurrent() to zero and sets the TERMINATE_CHARGE_ALARM bit in BatteryStatus(). The overcurrent condition and TERMINATE_CHARGE_ALARM are cleared when the measured current drops below the ChargingCurrent plus the *Overcurrent Margin*.
- **Overvoltage:** An overvoltage condition exists when the bq2060 measures the battery voltage to be more than the *Overvoltage Margin* above the ChargingVoltage() or a Li-Ion cell voltage has exceeded the overvoltage limit programmed in *Cell Under-/Overvoltage*. *Overvoltage Margin* is programmed in EE 0x48 and *Cell Under-/Over Voltage* in EE 0x4a (least significant nibble). On detecting an overvoltage condition, the bq2060 sets the ChargingCurrent() to zero and sets the TERMINATE_CHARGE_ALARM bit in BatteryStatus(). The bq2060 clears the TERMINATE_CHARGE_ALARM bit when it detects that the battery is no longer being charged (DISCHARGING bit set in BatteryStatus()). The bq2060 continues to broadcast zero charging current until the overvoltage condition is cleared. The overvoltage condition is cleared when the measured battery voltage drops below the ChargingVoltage() plus the *Overvoltage Margin* or when the CVOV bit is reset.
- **Over-Temperature:** An over-temperature condition exists when Temperature() is greater than or equal to the *Max T* value programmed in EE 0x45 (most significant nibble). On detecting an over-temperature condition, the bq2060 sets the ChargingCurrent() to zero and sets the OVER_TEMP_ALARM and TERMINATE_CHARGE_ALARM bit in BatteryStatus() and the CVOV bit in Pack Status.

The over-temperature condition is cleared when Temperature() is equal to or below (*Max T* – 5°C).

- **Overcharge:** An overcharge condition exists if the battery is charged more than the *Maximum Overcharge* value after RM = FCC. *Maximum Overcharge* is programmed in EE 0x2e–0x2f. On detecting an overcharge condition, the bq2060 sets the ChargingCurrent() to zero and sets the OVER_CHARGED_ALARM, TERMINATE_CHARGE_ALARM, and FULLY_CHARGED bits in BatteryStatus(). The bq2060 clears the OVER_CHARGED_ALARM and TERMINATE_CHARGE_ALARM when it detects that the battery is no longer being charged. The FULLY_CHARGED bit remains set and the bq2060 continues to broadcast zero charging current until RelativeStateOfCharge() is less than *Fully Charged Clear%* programmed in EE 0x4c. The counter used to track overcharge capacity is reset with 2mAh of discharge.
- **Under-Temperature:** An under-temperature condition exists if Temperature() < 0°C. On detecting an under temperature condition, the bq2060 sets ChargingCurrent() to zero. The bq2060 sets ChargingCurrent() to the appropriate pre-charge rate or fast-charge rate when Temperature() ≥ 0°C.

Primary Charge Termination

The bq2060 terminates charge if it detects a charge-termination condition. A charge-termination condition includes the following.

- **$\Delta T/\Delta t$:** For $\Delta T/\Delta t$, the bq2060 detects a change in temperature over many seconds. The $\Delta T/\Delta t$ setting is programmable in both the temperature step, *DeltaT* (1.6°C - 4.6°C), and the time step, *DeltaT Time* (20s-320s). Typical settings for 1°C/minute include 2°C/120s and 3°C/180s. Longer times are required for increased slope resolution. The *DeltaT* value is programmed in EE 0x45 (least significant nibble) and the *Delta T Time* in EE 0x4e.

In addition to the $\Delta T/\Delta t$ timer, a hold-off timer starts when the battery is being charged at more than 255mA and the temperature is above 25°C. Until this timer expires, $\Delta T/\Delta t$ detection is suspended. If Current() drops below 256mA or Temperature() below 25°C, the hold-off timer resets and restarts only when the current and temperature conditions are met again. The hold-off timer is programmable (20s – 320s) with *Holdoff Time* value in EE 0x4f.

- **Current Taper:** For current taper, ChargingVoltage() must be set to the pack voltage desired during the constant-voltage phase of charging. The bq2060 detects a current taper termination when the pack voltage is greater than the voltage determined by *Current Taper Qual Voltage* in EE 0x4f and the charging current is below a threshold determined by *Current Taper*

Threshold in EE 0x4e, for at least 40s. The bq2060 uses the VFC to measure current for current taper termination. The current polarity must remain positive as measured by the VFC during this time.

Once the bq2060 detects a primary charge termination, the bq2060 sets the `TERMINATE_CHARGE_ALARM` and `FULLY_CHARGED` bits in `BatteryStatus()`, and sets the `ChargingCurrent()` to the maintenance charge rate as programmed in *Maintenance Charging Current* EE 0x1c–0x1d. On termination, the bq2060 also sets RM to a programmed percentage of FCC, provided that `RelativeStateOfCharge()` is below the desired percentage of FCC and the CSYNC bit in *Pack Configuration* EE 0x3f is set. If the CSYNC bit is not set and `RelativeStateOfCharge()` is less than the programmed percentage of FCC, the bq2060 clears the `FULLY_CHARGED` bit in `BatteryStatus()`. The programmed percentage of FCC, *Fast Charge Termination %*, is set in EE 0x4b. The bq2060 clears the `FULLY_CHARGED` bit when `RelativeStateOfCharge()` is less than the programmed *Fully Charged Clear %*. The bq2060 broadcasts the fast-charge rate when the `FULLY_CHARGED` bit is cleared and voltage and temperature permit. The bq2060 clears the `TERMINATE_CHARGE_ALARM` when it no longer detects that the battery is being charged or it no longer detects the termination condition. See Table 6 for a summary of `BatteryStatus()` alarm and status bit operation.

Display Port

General

The display port drives a 4 or 5 LED bar-graph display. The display is activated by a logic signal on the DISP input. The bq2060 can display RM in either a relative or absolute mode with each LED representing a percentage of the full-battery reference. In relative mode, the bq2060 uses FCC as the full-battery reference; in absolute mode, it uses DC.

The DMODE bit in *Pack Configuration* programs the bq2060 for the absolute or relative display mode. The LED bit in *Control Mode* programs the 4 or 5 LED option. A 5th LED can be used with the 4 LED display option to show when the battery capacity is $\geq$ to 100%.

Activation

The display may be activated at any time by a high-to-low transition on the DISP input. This is usually accomplished with a pullup resistor and a pushbutton switch. Detection of the transition activates the display and starts a four-second display timer. The timer expires and turns off the display whether DISP was brought low momentarily or held low indefinitely. Reactivation of the display requires that the DISP input return to a logic-high state and then transition low again. The second high-to-low transition must occur after the

display timer expires. The bq2060 requires the DISP input to remain stable for a minimum of 250ms to detect the logic state.

If the EDV0 bit is set, the bq2060 disables the LED display. The display is also disabled during a VFC calibration and should be turned off before entering low-power storage mode.

Display Modes

In relative mode, each LED output represents 20% or 25% of the `RelativeStateOfCharge()` value. In absolute mode, each LED output represents 20% or 25% of the `AbsoluteStateOfCharge()` value. Table 7 shows the display operation.

In either mode, the bq2060 blinks the LED display if `RemainingCapacity()` is less than `RemainingCapacityAlarm()`. The display is disabled if EDV0 = 1.

Secondary Protection for Li-Ion

Undervoltage and overvoltage thresholds may be programmed in the byte value *Cell Under/Over Voltage* EE 0x4a to set a secondary level of protection for Lithium Ion cells. The bq2060 checks individual cell voltages for undervoltage and overvoltage conditions. The bq2060 displays the results in the Pack Status register and controls the state of the FET control outputs CFC and DFC. If any cell voltage is less than the V_{uv} threshold, the bq2060 sets the CVUV bit in Pack Status and pulls the DFC pin to a logic low. If any cell voltage is greater than the V_{ov} threshold, the bq2060 sets the CVOV bit in Pack Status and pulls the CFC pin to a logic low.

Low-Power Storage Mode

The bq2060 enters low-power mode 5–8s after receiving the Enable Low-Power command. In this mode the bq2060 consumes less than 10 μ A. A rising edge on SMBC, SMBD, or HDQ16 restores the bq2060 to the full operating mode. The bq2060 does not perform any gas gauge functions during low-power storage mode.

Device Reset

The bq2060 can be reset with commands over the HDQ16 or SMBus. Upon reset, the bq2060 initializes its internal registers with the information contained in the configuration EEPROM. The following command sequence initiates a full bq2060 reset:

```
Write 0x4f to 0xff5a
Write 0x7d to 0x0000
Write 0x7d to 0x0080
```

Table 6. Alarm and Status Bit Summary

Battery State	Conditions	CC() State and BatteryStatus Bits Set	CC() = Fast or Pre-charge Current and/or Bits Cleared
Overcurrent	$C() \geq CC() + \text{Overcurrent Margin}$	CC() = 0, TCA = 1	$C() < CC() + \text{Overcurrent Margin}$
Overvoltage	$V() \geq CV() + \text{Overvoltage Margin}$ $VCELL1, 2, 3, \text{ or } 4 > \text{Cell Over Voltage}$	TCA = 1	DISCHARGING = 1
		CC() = 0, CVOV = 1	$V() < CV() + \text{Overvoltage Margin}$ Li-Ion cell voltage $\leq$ Cell Over Voltage
Overtemperature	$T() \geq \text{Max } T$	CC() = 0, OTA = 1, TCA = 1, CVOV = 1	$T() \leq \text{Max } T - 5^\circ\text{C}$ or $T() \leq 43^\circ\text{C}$
Overcharge	Capacity added after $RM() = FCC() \geq \text{Maximum Overcharge}$	CC() = 0, FC = 1	RSOC() < Fully Charged Cleared %
		OCA = 1, TCA = 1	DISCHARGING = 1
Undertemperature	$T() < 0^\circ\text{C}$	CC() = 0	$0^\circ\text{C} \leq T() < 5^\circ\text{C}$, CC() = Pre-Charge Current $T() \geq 5^\circ\text{C}$, CC() = Fast-Charging Current
Fast charge termination	$\Delta T/\Delta t$ or Current Taper	CC() = Maintenance Charging Current, FC = 1	RSOC() < Fully Charged Cleared %
		TCA = 1	DISCHARGING = 1 or termination condition is no longer valid.
Fully discharged	$V() \leq EDV2$	FD = 1	RSOC() > 20%
Overdischarged	$V() \leq EDV0$	TDA = 1	$V() > EDV0$
	$VCELL1, 2, 3 \text{ or } 4 < \text{Cell Under Voltage}$	TDA = 1, CVUV = 1	$VCELL1, 2, 3, \text{ or } 4 \geq \text{Cell Under Voltage}$
Low capacity	$RM() < RCA()$	RCA = 1	$RM() \geq RCA()$
Low run-time	$ATTE() < RTA()$	RTA = 1	$ATTE() \geq RTA()$

Note: C() = Current(), CV() = ChargingVoltage(), CC() = ChargingCurrent(), V() = Voltage(), T() = Temperature(), TCA = TERMINATE_CHARGE_ALARM, OTA = OVER_TEMPERATURE_ALARM, OCA = OVER_CHARGED_ALARM, TDA = TERMINATE_DISCHARGE_ALARM, FC = FULLY_CHARGED, FD = FULLY_DISCHARGED, RSOC() = RelativeStateOfCharge(). RM() = RemainingCapacity(), RCA = REMAINING_CAPACITY_ALARM, RTA = REMAINING_TIME_ALARM, ATTE() = AverageTimeToEmpty(), RTA() = RemainingTimeAlarm(), RCA() = RemainingCapacityAlarm(), FCC() = FullChargeCapacity.

Table 7A. Display Mode

Condition Relative or Absolute StateOfCharge()	5 LED Display Option				
	LED1	LED2	LED3	LED4	LED5
EDV0 = 1	OFF	OFF	OFF	OFF	OFF
<20%	ON	OFF	OFF	OFF	OFF
≥20%, <40%	ON	ON	OFF	OFF	OFF
≥40%, <60%	ON	ON	ON	OFF	OFF
≥60%, <80%	ON	ON	ON	ON	OFF
≥80%	ON	ON	ON	ON	ON

Communication

The bq2060 includes two types of communication ports: SMBus and HDQ16. The SMBus interface is a 2-wire bidirectional protocol using the SMBC (clock) and SMBD (data) pins. The HDQ16 interface is a 1-wire bidirectional protocol using the HDQ16 pin. All three communication lines are isolated from V_{CC} and may be pulled-up higher than V_{CC} . Also, the bq2060 will not pull these lines low if V_{CC} to the part is zero. HDQ16 should be pulled down with a 100KΩ resistor if not used.

The communication ports allow a host controller, an SMBus compatible device, or other processor to access the memory registers of the bq2060. In this way a system can efficiently monitor and manage the battery.

SMBus

The SMBus interface is a command-based protocol. A processor acting as the bus master initiates communication to the bq2060 by generating a START condition. A START condition consists of a high-to-low transition of the SMBD line while the SMBC is high. The processor then sends the bq2060 device address of 0001011 (bits 7–1) plus a R/W bit (bit 0) followed by an SMBus command code. The R/W bit and the command code instruct the bq2060 to either store the forthcoming data to a register specified by the SMBus command code or output the data from the specified register. The processor completes the access with a STOP condition. A STOP condition consists of a low-to-high transition of the SMBD line while the SMBC is high. With SMBus, the most significant bit of a data byte is transmitted first.

In some instances, the bq2060 acts as the bus master. This occurs when the bq2060 broadcasts charging requirements and alarm conditions to device addresses 0x12 (SBS Smart Charger) and 0x10 (SBS Host Controller.)

Table 7B. Display Mode

Condition Relative or Absolute StateOfCharge()	4 LED Display Option			
	LED1	LED2	LED3	LED4
EDV0 = 1	OFF	OFF	OFF	OFF
<25%	ON	OFF	OFF	OFF
≥25%, <50%	ON	ON	OFF	OFF
≥50%, <75%	ON	ON	ON	OFF
≥75%	ON	ON	ON	ON

SMBus Protocol

The bq2060 supports the following SMBus protocols:

- Read Word
- Write Word
- Read Block

A processor acting as the bus master uses the three protocols to communicate with the bq2060. The bq2060 acting as the bus master uses the Write Word protocol.

The SMBD and SMBC pins are open drain and require external pullup resistors.

SMBus Packet Error Checking

The bq2060 supports Packet Error Checking as a mechanism to confirm proper communication between it and another SMBus device. Packet Error Checking requires that both the transmitter and receiver calculate a Packet Error Code (PEC) for each communication message. The device that supplies the last byte in the communication message appends the PEC to the message. The receiver compares the transmitted PEC to its PEC result to determine if there is a communication error.

PEC Protocol

The bq2060 can receive or transmit data with or without PEC. Figure 4 shows the communication protocol for the Read Word, Write Word, and Read Block messages without PEC. Figure 5 includes PEC.

In the Write Word protocol, the bq2060 receives the PEC after the last byte of data from the host. If the host does not support PEC, the last byte of data is followed by a STOP condition. After receipt of the PEC, the bq2060 compares the value to its calculation. If the PEC is correct, the bq2060 responds with an ACKNOWLEDGE. If it is not correct, the bq2060 responds with a NOT ACKNOWLEDGE and sets an error code.

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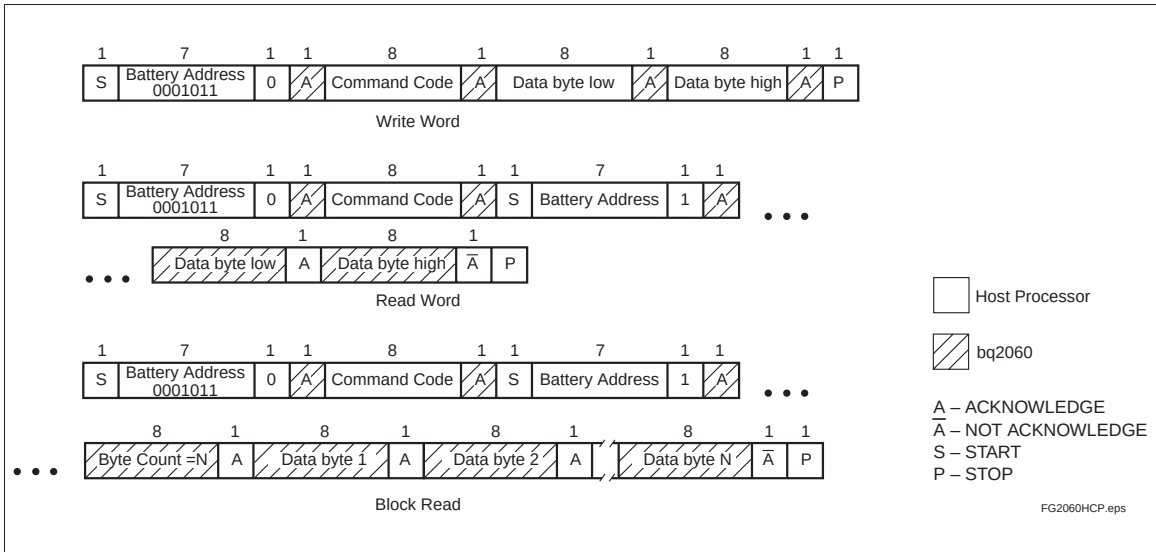


Figure 4. SMBus Communication Protocol without PEC

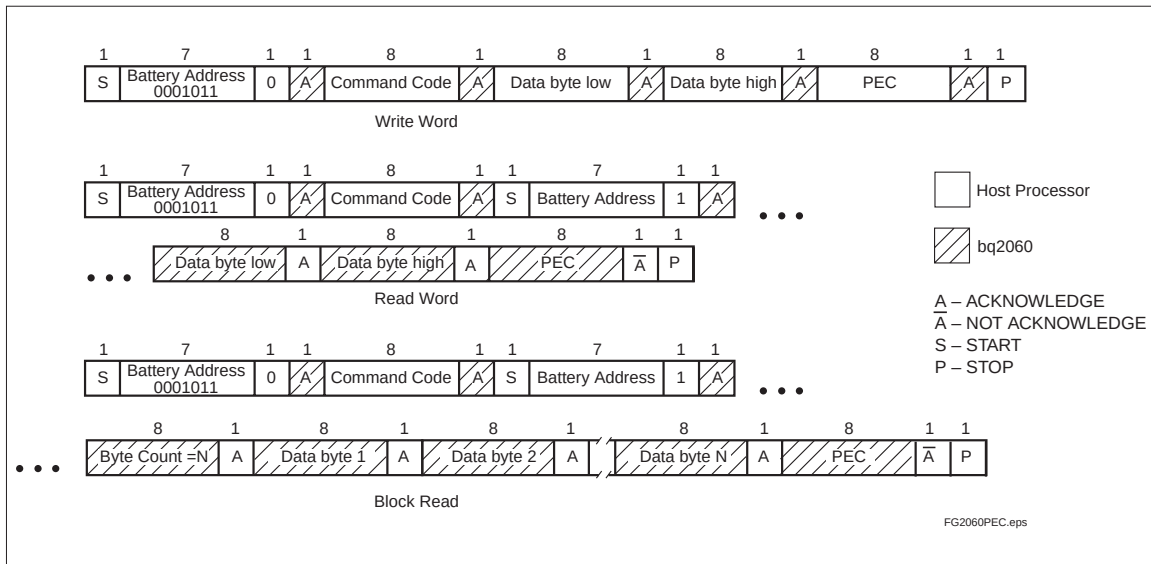


Figure 5. SMBus Communication Protocol with PEC

In the Read Word and Block Read, the host generates an ACKNOWLEDGE after the last byte of data sent by the bq2060. The bq2060 then sends the PEC and the host acting as a master-receiver generates a NOT ACKNOWLEDGE and a STOP condition.

PEC Calculation

The basis of the PEC calculation is an 8-bit Cyclic Redundancy Check (CRC-8) based on the polynomial $C(X) = X^8 + X^2 + X^1 + 1$. The PEC calculation includes all bytes in the transmission, including address, command, and data. The PEC calculation does not include ACKNOWLEDGE, NOT ACKNOWLEDGE, START, STOP, and Repeated START bits.

For example, the host requests RemainingCapacity() from the bq2060. This includes the host following the Read Word protocol. The bq2060 calculates the PEC based on the following 5 bytes of data, assuming the remaining capacity of the battery is 1001mAh.

- Battery Address with $R/\overline{W} = 0$: 0x16
- Command Code for RemainingCapacity(): 0x0f
- Battery Address with $R/\overline{W} = 1$: 0x17
- RemainingCapacity(): 0x03e9

For 0x160f17e903, the bq2060 transmits a PEC of 0xe8 to the host.

PEC Enable in Master Mode

PEC for master mode broadcasts to the charger, host, or both can be enabled/disabled with the combination of the bits HPE and CPE in *Control Mode*.

SMBus On and Off State

The bq2060 detects whether the SMBus enters the Off State" by monitoring the SMBC and SMBD lines. When both signals are continually low for at least 2.5s, the bq2060 detects the Off State. When the SMBC and SMBD lines go high, the bq2060 detects the On State and can begin communication within 1ms. One-M Ω pulldown resistors on SMBC and SMBD are recommended for reliable Off State detection.

HDQ16

The HDQ16 interface is a command-based protocol. (See Figure 6.) A processor sends the command code to the bq2060. The 8-bit command code consists of two fields, the 7-bit HDQ16 command code (bits 0–6) and the 1-bit R/W field. The R/W field directs the bq2060 either to

- Store the next 16 bits of data to a specified register or
- Output 16 bits of data from the specified register

With HDQ16, the least significant bit of a data byte (command) or word (data) is transmitted first.

A bit transmission consists of three distinct sections. The first section starts the transmission by either the host or the bq2060 taking the HDQ16 pin to a logic-low state for a period $t_{STRH;B}$. The next section is the actual data-transmission, where the data bit is valid by the time, $t_{DSU;B}$ after the negative edge used to start communication. The data bit is held for a period $t_{DH;DV}$ to allow the host processor or bq2060 to sample the data bit.

The final section is used to stop the transmission by returning the HDQ16 pin to a logic-high state by at least the time $t_{SSU;B}$ after the negative edge used to start communication. The final logic-high state should be until a period $t_{CYCH;B}$ to allow time to ensure that the bit transmission was stopped properly.

If a communication error occurs (e.g., $t_{CYCB} > 250\mu s$), the host sends the bq2060 a BREAK to reinitiate the serial interface. The bq2060 detects a BREAK when the HDQ16 pin is in a logic-low state for a time t_B or greater. The HDQ16 pin is then returned to its normal ready-high logic state for a time t_{BR} . The bq2060 is then ready to receive a command from the host processor.

The HDQ16 pin is open drain and requires an external pullup resistor.

Command Codes

The SMBus Command Codes are in (), the HDQ16 in []. Temperature(), Voltage(), Current(), and AverageCurrent(), performance specifications are at regulated V_{CC} (V_{RO}) and a temperature of 0–70°C.

ManufacturerAccess() (0x00); [0x00–0x01]

Description:

This function provides writable command codes to control the bq2060 during normal operation and pack manufacture. These commands can be ignored if sent within one second after a device reset. The following list of commands are available.

0x0618 Enable Low-Power Storage Mode: Activates the low-power storage mode. The bq2060 enters the storage mode after a 5–8s delay. The bq2060 accepts other commands to ManufacturerAccess() during the delay before entering low-power storage mode. The LEDs must be off before entering the low-power storage mode as the display state remains unchanged. During the delay following the low-power storage command, a VFC Calibration command may be issued.

The bq2060 clears the ManufacturerAccess() command within 900ms of acknowledging the Enable Low-Power Storage command. The VFC Calibration command must be sent 900–1600ms after SMBus acknowledgment of the Enable Low-Power Storage command. In this case, the bq2060 delays entering storage mode until the calibration process completes and the bq2060 stores the new calibration values in EEPROM.

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0x062b SEAL Command: Instructs the bq2060 to restrict access to those functions listed in Table 3. **Note:** The SEAL Command does not change the state of the SEAL bit in *Pack Configuration* in EEPROM. The bq2060 completes the seal function and clears ManufacturerAccess() within 900ms of acknowledging the command.

0x064d Charge Synchronization: Instructs the bq2060 to update RM to a percentage of FCC as defined in *Fast Charge Termination %*. The bq2060 updates RM and clears ManufacturerAccess() within 900ms of acknowledging the command.

0x0653 Enable VFC Calibration: Instructs the unsealed bq2060 to begin VFC calibration. With this command the bq2060 deselects the SR₁ and SR₂ inputs and calibrates for IC offset only. It is best to avoid charge or discharge currents through the sense resistor during this calibration process.

0x067e Alternate VFC Calibration: Instructs the unsealed bq2060 to begin VFC calibration. With this command the bq2060 deselects the SR₁ and SR₂ inputs and calibrates for IC and PCB offset. **During this procedure no charge or discharge currents**

During VFC calibration, the bq2060 disables the LED display and accepts only the Stop VFC Calibration and the SEAL Command to ManufacturerAccess(). The bq2060 disregards all other commands. SMBus communication should be kept to a minimum during VFC calibration to reduce the noise level and allow a more accurate calibration.

Once started, the VFC calibration procedure completes automatically. When complete, the bq2060 saves the calibration values in EEPROM. The calibration normally takes about 8 to 10 minutes. The calibration time is inversely proportional to the bq2060 VFC (and PCB) offset

error. The bq2060 caps the calibration time at one hour in the event of calibrating zero offset error. The VFC calibration can be done as the last step in a battery pack test procedure since the calibration can complete automatically after removal from a test setup.

The bq2060 clears ManufacturerAccess() within 900ms and starts calibration within 3.2s of acknowledging the command.

0x0660 Stop VFC Calibration: Instructs the bq2060 to abort a VFC calibration procedure. If aborted, the bq2060 disables offset correction. The bq2060 stops calibration within 20ms of acknowledging the command.

0x0606 Program EEPROM: Instructs the unsealed bq2060 to connect the SMBus to the EEPROM I²C bus. The bq2060 applies power to the EEPROM within 900ms of acknowledging the command. After issuing the program EEPROM command, the bq2060 monitoring functions are disabled until the I²C bus is disconnected. The bq2060 disconnects the I²C bus when it detects that the Battery Address 0x16 is sent over the SMBus. The Battery Address 0x16 to disconnect the I²C bus should not be sent until 10ms after the last write to the EEPROM.

Example: The following sequence of actions is an example of how to use the ManufacturerAccess() commands in an efficient manner to take a battery pack that has completed all testing and calibration except for VFC calibration and to make it ready for shipment in the SEALED state and in low-power storage mode:

1. Complete testing and calibration with desired final values stored in EEPROM. This process includes setting the SEAL bit in *Pack Configuration*. Sending a reset command to the bq2060 during test ensures that RAM values correspond to the final EEPROM values

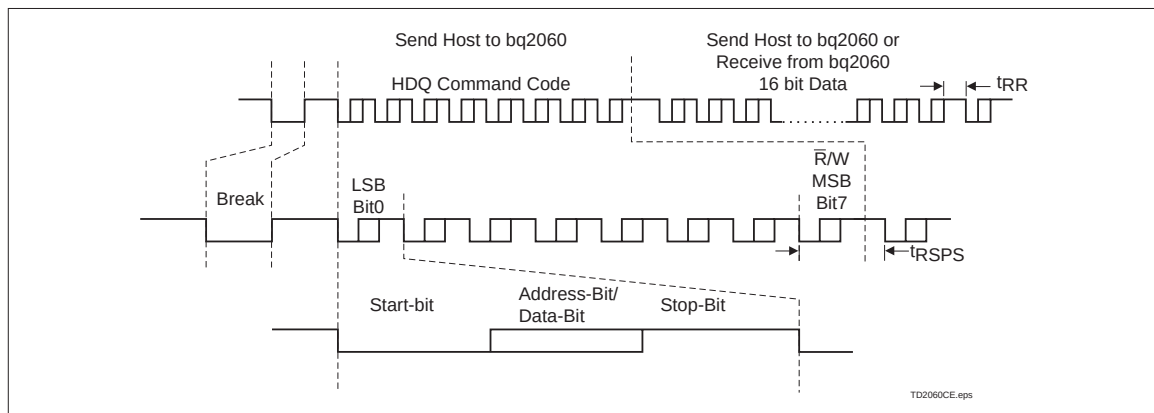


Figure 6. HDQ16 Communication Example

2. If the initial value of RemainingCapacity() must be non-zero, the desired value may be written to Command 0x26 with the pack unsealed. A reset sent after this step resets RM to zero.
3. Issue the Enable Low-Power Storage Mode command.
4. Within 900–1600ms after sending the Enable Low-Power command, issue the Enable VFC Calibration command. This delays the low-power storage mode until after VFC calibration completion.
5. Issue the SEAL Command subsequent to the VFC Calibration command. The bq2060 must receive the SEAL Command before VFC calibration completes. The bq2060 resets the OCE bit in Pack Status when calibration begins and sets the bit when calibration successfully completes.

After VFC calibration completes automatically, the bq2060 saves the VFC offset cancellation values in EEPROM and enters the low-power storage mode in about 20s. In addition, the bq2060 is sealed, allowing access as defined in Table 3 only.

Purpose:

The ManufacturerAccess() function provides the system host access to bq2060 functions that are not defined by the SBD.

SMBus Protocol: Read or Write Word

Input/Output: Word

RemainingCapacityAlarm() (0x01); [0x01]

Description:

Sets or gets the low-capacity threshold value. Whenever the RemainingCapacity() falls below the low capacity value, the bq2060 sends AlarmWarning() messages to the SMBus Host with the REMAINING_CAPACITY_ALARM bit set. A low-capacity value of 0 disables this alarm. The bq2060 initially sets the low-capacity value to *Remaining Capacity Alarm* value programmed in EE 0x04 - 0x05. The low-capacity value remains unchanged until altered by the RemainingCapacityAlarm() function. The low-capacity value may be expressed in either current (mA) or power (10mWh) depending on the setting of the BatteryMode()'s CAPACITY_MODE bit.

Purpose:

The RemainingCapacityAlarm() function can be used by systems that know how much power they require to save their operating state. It enables those systems to more finely control the point at which they transition into suspend or hibernate state. The low-capacity value can be read to verify the value in use by the bq2060's low capacity alarm.

SMBus Protocol: Read or Write Word

Input/Output: Unsigned integer—value below which Low Capacity messages are sent.

Battery Modes		
	CAPACITY_MODE bit = 0	CAPACITY_MODE bit = 1
Units	mAh @ C/5	10mWh @ P/5
Range	0–65,535mAh	0–65,535 10mWh
Granularity	Not applicable	
Accuracy	See RemainingCapacity()	

RemainingTimeAlarm() (0x02); [0x02]

Description:

Sets or gets the remaining time alarm value. Whenever the AverageTimeToEmpty() falls below the remaining time value, the bq2060 sends AlarmWarning() messages to the SMBus Host with the REMAINING_TIME_ALARM bit set. A remaining time value of 0 effectively disables this alarm. The bq2060 initially sets the remaining time value to the *Remaining Time Alarm* value programmed in EE 0x02 - 0x03. The remaining time value remains unchanged until altered by the RemainingTimeAlarm() function.

Purpose:

The RemainingTimeAlarm() function can be used by systems that want to adjust when the remaining time alarm warning is sent. The remaining time value can be read to verify the value in use by the bq2060's RemainingTimeAlarm().

SMBus Protocol: Read or Write Word

Input/Output:

Unsigned integer—the point below which remaining time messages are sent.

Units: minutes

Range: 0 to 65,535 minutes

Granularity: Not applicable

Accuracy: see AverageTimeToEmpty()

BatteryMode() (0x03); [0x03]

Description:

This function selects the various battery operational modes and reports the battery's mode and requests.

Defined modes include

- Whether the battery's capacity information is specified in mAh or 10mWh (CAPACITY_MODE bit)
- Whether the ChargingCurrent() and ChargingVoltage() values are broadcast to the Smart Battery Charger

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when the bq2060 detects the battery requires charging (CHARGER_MODE bit)

- Whether all broadcasts to the Smart Battery Charger and Host are disabled

The defined request condition is the battery requesting a conditioning cycle (RELEARN_FLAG).

Purpose:

The CAPACITY_MODE bit allows power management systems to best match their electrical characteristics with those reported by the battery. For example, a switching power supply represents a constant power load, whereas a linear supply is better represented by a constant current model. The CHARGER_MODE bit allows a SMBus Host or Smart Battery Charger to override the Smart Battery's desired charging parameters by disabling the bq2060's broadcasts. The RELEARN_FLAG bit allows the bq2060 to request a conditioning cycle.

SMBus Protocol: Read or Write Word

Input/Output:

Unsigned integer —bit mapped— see below.

Units: not applicable

Range: 0–1

Granularity: not applicable

Accuracy: not applicable

The BatteryMode() word is divided into two halves, the most significant bit (bits 8–15) which is read/write and the

least significant bit (bits 0–7) which is read only. The bq2060 forces bits 0–6 to zero and prohibits writes to bit 7.

Table 8 summarizes the meanings of the individual bits in the BatteryMode() word and specifies the default values, where applicable, are noted.

INTERNAL_CHARGE_CONTROLLER bit is not used by the bq2060.

PRIMARY_BATTERY_SUPPORT bit is not used by the bq2060.

RELEARN_FLAG bit set indicates that the bq2060 is requesting a capacity relearn cycle for the battery. The bq2060 sets the RELEARN_FLAG on a full reset and if it detects 20 cycle counts without an FCC update. The bq2060 clears this flag after a learning cycle has been completed.

CHARGE_CONTROLLER_ENABLED bit is not used by the bq2060. The bq2060 forces this bit to zero.

PRIMARY_BATTERY bit is not used by the bq2060. The bq2060 forces this bit to zero.

ALARM_MODE bit is set to disable the bq2060's ability to master the SMBus and send AlarmWarning() messages to the SMBus Host and the Smart Battery Charger. When set, the bq2060 does NOT master the SMBus, and AlarmWarning() messages are NOT sent to the SMBus Host and the Smart Battery Charger **for a period of no more than 65s and no less than 45s**. When cleared (default), the Smart Battery sends the AlarmWarning()

Table 8. Battery Mode Bits and Values

Battery Mode() Bits	Bits Used	Format	Allowable Values
INTERNAL_CHARGE_CONTROLLER	0	Read only bit flag	
PRIMARY_BATTERY_SUPPORT	1	Read only bit flag	
Reserved	2–6		
RELEARN_FLAG	7	Read only bit flag	0—Battery OK 1—Relearn cycle requested
CHARGE_CONTROLLER_ENABLED	8	R/W bit flag	
PRIMARY_BATTERY	9	R/W bit flag	
Reserved	10–12		
ALARM_MODE	13	R/W bit flag	0—Enable alarm broadcast (default) 1—Disable alarm broadcast
CHARGER_MODE	14	R/W bit flag	0—Enable charging broadcast (default) 1—Disable charging broadcast
CAPACITY_MODE	15	R/W bit flag	0—Report in mA or mAh (default) 1—Report in 10mW or 10mWh

messages to the SMBus Host and the Smart Battery Charger any time an alarm condition is detected.

- The bq2060 polls the ALARM_MODE bit at least every 150ms. Whenever the ALARM_MODE bit is set, the bq2060 resets the bit and starts or restarts a 55s (nominal) timer. After the timer expires, the bq2060 automatically enables alarm broadcasts to ensure that the accidental deactivation of broadcasts does not persist. To prevent the bq2060 from becoming a master on the SMBus, an SMBus host must therefore continually set this bit at least once per 50s to keep the bq2060 from broadcasting alarms.
- The ALARM_MODE bit defaults to a cleared state within 130ms after the bq2060 detects the SMBus Off-State.
- The condition of the ALARM-MODE bit does NOT affect the operation or state of the CHARGER_MODE bit which is used to prevent broadcasts of ChargingCurrent() and ChargingVoltage() to the Smart Battery Charger.

CHARGER_MODE bit enables or disables the bq2060's transmission of ChargingCurrent() and ChargingVoltage() messages to the Smart Battery Charger. When set, the bq2060 does NOT transmit ChargingCurrent() and ChargingVoltage() values to the Smart Battery Charger. When cleared, the bq2060 transmits the ChargingCurrent() and ChargingVoltage() values to the Smart Battery Charger. The CHARGER_MODE bit defaults to a cleared state within 130ms after the bq2060 detects the SMBus Off-State.

CAPACITY_MODE bit indicates if capacity information is reported in mA/mAh or 10mW/10mWh. When set, the bq2060 reports capacity information in 10mW/10mWh as appropriate. When cleared, the bq2060 reports capacity information in mA/mAh as appropriate. The CAPACITY_MODE bit defaults to a cleared state within 130ms after the bq2060 detects the SMBus Off-State.

Note 1: The following functions are changed to accept or return values in mA/mAh or 10mW/10mWh depending on the CAPACITY_MODE bit:

- RemainingCapacityAlarm()
- AtRate()
- RemainingCapacity()
- FullChargeCapacity()
- DesignCapacity()

Note 2: The following functions are calculated on the basis of capacity and may be calculated differently depending on the CAPACITY_MODE bit:

- AtRateOK()
- AtRateTimeToEmpty()
- AtRateTimeToFull()
- RunTimeToEmpty()
- AverageTimeToEmpty()
- AverageTimeToFull()
- Remaining Time Alarm()
- BatteryStatus()

The bq2060 updates the non-AtRate related register values within 3s of changing the state of the CAPACITY_MODE bit. The AtRate() values will be updated after the next AtRate value is written to the bq2060 (or after the next 20s scheduled refresh calculation).

AtRate() (0x04); [0x04]

Description:

The AtRate() function is the first half of a two-function call-set used to set the AtRate value used in calculations made by the AtRateTimeToFull(), AtRateTimeToEmpty(), and AtRateOK() functions. The AtRate value may be expressed in either current (mA) or power (10mW) depending on the setting of the BatteryMode()'s CAPACITY_MODE bit.

Purpose:

Since the AtRate() function is the first half of a two-function call-set, it is followed by the second function of the call-set that calculates and returns a value based on the AtRate value and the battery's present state. A delay of up to 1.3s is required after writing AtRate() before the bq2060 can acknowledge the requested AtRate function.

- When the AtRate() value is positive, the AtRateTimeToFull() function returns the predicted time to full-charge at the AtRate value of charge.
- When the AtRate() value is negative, the AtRateTimeToEmpty() function returns the predicted operating time at the AtRate value of discharge.
- When the AtRate() value is negative, the AtRateOK() function returns a Boolean value that predicts the battery's ability to supply the AtRate value of *additional* discharge energy (current or power) for 10 seconds.

The default value for AtRate() is zero. Writing AtRate() values over the HDQ16 serial port does NOT trigger a re-calculation of AtRateTimeToFull(), AtRateTimeToEmpty(), and AtRateOK() functions.

It is recommended that AtRate() requests should be limited to one request every 4s.

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SMBus Protocol: Read or Write Word

Input/Output: Signed integer—charge or discharge; the `AtRate()` value is positive for charge, negative for discharge, and zero for neither (default).

Battery Mode		
	CAPACITY_MODE bit = 0	CAPACITY_MODE bit = 1
Units	mA	10mW
Charge Range	1–32,767mA	1–32,768 10mW
Discharge Range	-1– -32,768mA	-1– -32,768 10mW
Granularity	1 Unit	
Accuracy	NA	

`AtRateTimeToFull() (0x05);[0x05]`

Description:

Returns the predicted remaining time to fully charge the battery at the `AtRate()` value (mA).

Purpose:

The `AtRateTimeToFull()` function is part of a two-function call-set used to determine the predicted remaining charge time at the `AtRate` value in mA. The bq2060 updates `AtRateTimeToFull()` within 1.3s after the SMBus Host sets the `AtRate` value. If read before this delay, the command is No Acknowledged and the error code in `BatteryStatus` is set to *not ready*. The bq2060 automatically updates `AtRateTimeToFull()` based on the `AtRate()` value every 20s.

SMBus Protocol: Read Word

Output:

Unsigned integer—predicted time in minutes to fully charge the battery.

Units: minutes

Range: 0 to 65,534 min

Granularity: 2 min or better

Accuracy: $\pm \text{MaxError}() * \text{FullChargeCapacity}() / |\text{AtRate}()|$

Invalid Data Indication: 65,535 indicates the battery is not being charged.

`AtRateTimeToEmpty() (0x06); [0x06]`

Description:

Returns the predicted remaining operating time if the battery is discharged at the `AtRate()` value.

Purpose:

The `AtRateTimeToEmpty()` function is part of a two-function call-set used to determine the remaining operating time at the `AtRate()` value. The bq2060 updates `AtRateTimeToEmpty()` within 1.3s after the SMBus Host sets the `AtRate()` value. If read before this delay, the command is No Acknowledged, and the error code in `BatteryStatus` is set to *not ready*. The bq2060 automatically updates `AtRateTimeToEmpty()` based on the `AtRate()` value every 20s.

SMBus Protocol: Read Word

Output:

Unsigned integer — estimated operating time left.

Units: minutes

Range: 0 to 65,534 min

Granularity: 2 min or better

Accuracy: $-0, +\text{MaxError}() * \text{FullChargeCapacity}() / |\text{AtRate}()|$

Invalid Data Indication: 65,535 indicates the battery is not being discharged.

`AtRateOK() (0x07); [0x07]`

Description:

Returns a Boolean value that indicates whether or not the battery can deliver the `AtRate()` value of *additional* energy for 10 seconds (Boolean). If the `AtRate` value is zero or positive, the `AtRateOK()` function ALWAYS return-true.

Purpose:

The `AtRateOK()` function is part of a two-function call-set used by power management systems to determine if the battery can safely supply enough energy for an additional load. The bq2060 updates `AtRateOK()` within 1.3s after the SMBus Host sets the `AtRate()` value. If read before this delay, the command is No Acknowledged, and the error code in `BatteryStatus` is set to *not ready*. The bq2060 automatically updates `AtRateOK()` based on the `AtRate()` value every 20s.

SMBus Protocol: Read Word

Output:

Boolean—indicates if the battery can supply the *additional* energy requested.

Units: Boolean

Range: TRUE, FALSE

Granularity: not applicable

Accuracy: not applicable

Temperature() (0x08); [0x08]

Description:

Returns the temperature (K) measured by the bq2060.

Purpose:

The Temperature() function provides accurate cell temperatures for use by battery chargers and thermal management systems. A battery charger can use the temperature as a safety check. Thermal management systems may use the temperature because the battery is one of the largest thermal sources in a system.

SMBus Protocol: Read Word

Output:

Unsigned integer—cell temperature in tenth-degree Kelvin increments.

Units: 0.1°K

Range: 0 to +6553.5°K {real range}

Granularity: 0.1°K

Accuracy: $\pm 1.5^\circ\text{K}$ (from ideal 103AT thermistor performance, after calibration)

Voltage() (0x09); [0x09]

Description:

Returns the cell-pack voltage (mV).

Purpose:

The Voltage() function provides power management systems with an accurate battery terminal voltage. Power management systems can use this voltage, along with battery current information, to characterize devices they control. This ability helps enable intelligent, adaptive power-management systems.

SMBus Protocol: Read Word

Output:

Unsigned integer—battery terminal voltage in mV.

Units: mV

Range: 0 to 20,000 mV

Granularity: 1mV

Accuracy: $\pm 0.65\%$ (after calibration)

Current() (0x0a); [0x0a]

Description:

Returns the current being supplied (or accepted) through the battery's terminals (mA).

Purpose:

The Current() function provides a snapshot for the power management system of the current flowing into or out of the battery. This information is of particular use in power-management systems because they can characterize individual devices and tune their operation to actual system power behavior.

SMBus Protocol: Read Word

Output:

Signed integer—charge/discharge rate in mA increments—positive for charge, negative for discharge.

Units: mA

Range: $(\pm 250\text{mV}/R_S)$ mA

Granularity: $0.038\text{mV}/R_S$ (integer value)

Accuracy: $\pm 1\text{mV}/R_S$ (after calibration)

AverageCurrent() (0x0b); [0x0b]

Description:

Returns a value that approximates a one-minute rolling average of the current being supplied (or accepted) through the battery's terminals (mA). The AverageCurrent() function will return meaningful values during the battery's first minute of operation.

Purpose:

The AverageCurrent() function provides the average current flowing into or out of the battery for the power management system.

SMBus Protocol: Read Word

Output:

Signed integer—charge/discharge rate in mA increments—positive for charge, negative for discharge.

Units: mA

Range: $(\pm 250\text{mV}/R_S)$ mA

Granularity: $0.038\text{mV}/R_S$ (integer value)

Accuracy: $\pm 1\text{mV}/R_S$ (after calibration)

MaxError() (0x0c); [0x0c]

Description:

Returns the expected margin of error (%) in the state of charge calculation. For example, when MaxError() re-

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turns 10% and `RelativeStateOfCharge()` returns 50%, the `Relative StateOfCharge()` is more likely between 50 and 60%. The bq2060 sets `MaxError()` to 100% on a full reset. The bq2060 sets `MaxError()` to 2% on completion of a learning cycle, unless the bq2060 limits the learning cycle to the +512/-256mAh maximum adjustment values. If the learning cycle is limited, the bq2060 sets `MaxError()` to 8% unless `MaxError()` was already below 8%. In this case `MaxError()` does not change. The bq2060 increments `MaxError()` by 1% after four increments of `CycleCount()` without a learning cycle.

If voltage-based corrections are applied to the coulomb counter, `MaxError()` is set to 25%.

Purpose:

The `MaxError()` function has real value in two ways: first, to give the user a confidence level about the state of charge and second, to give the power management system information about how aggressive it should be, particularly as the battery nears the end of its life.

SMBus Protocol: Read Word

Output:

Unsigned integer—percent uncertainty for selected information.

Units: %

Range: 2 to 100%

Granularity: 1%

Accuracy: not applicable

RelativeStateOfCharge() (0x0d); [0x0d]

Description:

Returns the predicted remaining battery capacity expressed as a percentage of `FullChargeCapacity()` (%).

Purpose:

The `RelativeStateOfCharge()` function is used to estimate the amount of charge remaining in the battery relative to the last learned capacity.

SMBus Protocol: Read Word

Output:

Unsigned integer—percent of remaining capacity.

Units: %

Range: 0 to 100%

Granularity: 1%

Accuracy: -0, +`MaxError()`

AbsoluteStateOfCharge()(0x0e); [0x0e]

Description:

Returns the predicted remaining battery capacity expressed as a percentage of `DesignCapacity()` (%). Note that `AbsoluteStateOfCharge()` can return values greater than 100%.

Purpose:

The `AbsoluteStateOfCharge()` function is used to estimate the amount of charge remaining in the battery relative to the nominal or `DesignCapacity()`.

SMBus Protocol: Read Word

Output:

Unsigned integer—percent of remaining capacity.

Units: %

Range: 0 to 100+%

Granularity: 1%

Accuracy: -0, +`MaxError()`

RemainingCapacity() (0x0f); [0x0f]

Description:

Returns the predicted charge or energy remaining in the battery. The `RemainingCapacity()` value is expressed in either charge (mAh at a C/5 discharge rate) or energy (10mWh at a P/5 discharge rate) depending on the setting of the `BatteryMode()`'s `CAPACITY_MODE` bit.

Purpose:

The `RemainingCapacity()` function returns the battery's remaining capacity. This information is a numeric indication of remaining charge or energy given by the `Absolute` or `Relative StateOfCharge()` functions and may be in a better form for use by power management systems.

SMBus Protocol: Read Word

Output:

Unsigned integer—remaining charge in mAh or 10mWh.

Battery Mode		
	CAPACITY_MODE bit = 0	CAPACITY_MODE bit = 1
Units	mAh	10mWh
Range	0–65,535mAh	0–65,535 10mWh
Granularity	mAh	10mWh
Accuracy	-0, + <code>MaxError()</code> * <code>FullChargeCapacity()</code>	

FullChargeCapacity() (0x10); [0x10]**Description:**

Returns the predicted pack capacity when it is fully charged. The FullChargeCapacity() value is expressed in either current (mAh at a C/5 discharge rate) or power (10mWh at a P/5 discharge rate) depending on the setting of the BatteryMode()'s CAPACITY_MODE bit.

Purpose:

The FullChargeCapacity() function provides the user with a means of understanding the tank size of their battery. This information, along with information about the original capacity of the battery, can be presented to the user as an indication of battery wear.

SMBus Protocol: Read Word

Output:

Unsigned integer—estimated full-charge capacity in mAh or 10mWh.

Battery Mode		
	CAPACITY_MODE bit = 0	CAPACITY_MODE bit = 1
Units	mAh	10mWh
Range	0–65,535mAh	0–65,535 10mWh
Granularity	mAh	10mWh
Accuracy	-0, +MaxError() * FullChargeCapacity()	

RunTimeToEmpty() (0x11); [0x11]**Description:**

Returns the predicted remaining battery life at the present rate of discharge (minutes). The RunTimeToEmpty() value is calculated based on either current or power depending on the setting of the BatteryMode()'s CAPACITY_MODE bit.

Purpose:

The RunTimeToEmpty() provides the power management system with information about the relative gain or loss in remaining battery life in response to a change in power policy. This information is NOT the same as the AverageTimeToEmpty(), which is not suitable to determine the effects that result from a change in power policy.

SMBus Protocol: Read Word

Output:

Unsigned integer—minutes of operation left.

Units: minutes

Range: 0 to 65,534 min

Granularity: 2 min or better

Accuracy: -0, +MaxError() * FullChargeCapacity() / Current()

Invalid Data Indication: 65,535 indicates battery is not being discharged.

AverageTimeToEmpty() (0x12); [0x12]

Description: Returns a one-minute rolling average of the predicted remaining battery life (minutes). The AverageTimeToEmpty() value is calculated based on either current or power depending on the setting of the BatteryMode()'s CAPACITY_MODE bit.

Purpose:

The AverageTimeToEmpty() displays state-of-charge information in a more useful way. It averages the instantaneous estimations so the remaining time does not appear to jump around.

SMBus Protocol: Read Word

Output:

Unsigned integer — minutes of operation left.

Units: minutes

Range: 0 to 65,534 min

Granularity: 2 min or better

Accuracy: -0, +MaxError() * FullChargeCapacity() / AverageCurrent()

Invalid Data Indication: 65,535 indicates battery is not being discharged.

AverageTimeToFull() (0x13); [0x13]

Description: Returns a one-minute rolling average of the predicted remaining time until the battery reaches full charge (minutes).

Purpose: The AverageTimeToFull() function can be used by the SMBus Host's power management system to aid in its policy. It may also be used to find out how long the system must be left on to achieve full charge.

SMBus Protocol: Read Word

Output:

Unsigned integer —remaining time in minutes.

Units: minutes

Range: 0 to 65,534 minutes

Granularity: 2 minutes or better

Accuracy: MaxError() * FullChargeCapacity() / AverageCurrent()

Invalid Data Indication: 65,535 indicates the battery is not being charged.

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ChargingCurrent() (0x14); [0x14]

Description: Returns the desired charging rate in mA.

Purpose: The ChargingCurrent() function sets the maximum charge current of the battery. The ChargingCurrent() value should be used in combination with the ChargingVoltage() value to set the charger's operating point. Together, these functions permit the bq2060 to dynamically control the charging profile (current/voltage) of the battery. The bq2060 can effectively turn off a charger by returning a value of 0 for this function. The charger may be operated as a constant-voltage source above its maximum regulated current range by returning a ChargingCurrent() value of 65,535.

SMBus Protocol: Read Word

Output:

Unsigned integer—maximum charger output current in mA.

Units: mA

Range: 0 to 65,535mA

Granularity: 1mA

Accuracy: not applicable

Invalid Data Indication: 65,535 indicates that a charger should operate as a voltage source outside its maximum regulated current range.

ChargingVoltage() (0x15); [0x15]

Description: Returns the desired charging voltage in mV.

Purpose: The ChargingVoltage() function sets the maximum charge voltage of the battery. The ChargingVoltage() value should be used in combination with the ChargingCurrent() value to set the charger's operating point. Together, these functions permit the bq2060 to dynamically control the charging profile (current/voltage) of the battery. The charger may be operated as a constant-current source above its maximum regulated voltage range by returning a ChargingVoltage() value of 65,535.

SMBus Protocol: Write Word

Output:

Unsigned integer—charger output voltage in mV.

Units: mV

Range: 0 to 65,535mV

Granularity: 1mV

Accuracy: not applicable

Invalid Data Indication: 65,535 indicates the charger should operate as a current source outside its maximum regulated voltage range.

BatteryStatus()(0x16); [0x16]

Description: Returns the bq2060's status word (flags). Some of the BatteryStatus() flags (REMAINING_CAPACITY_ALARM and REMAINING_TIME_ALARM) are calculated based on either current or power depending on the setting of the BatteryMode()'s CAPACITY_MODE bit. This is important because use of the wrong calculation mode may result in an inaccurate alarm.

Purpose: The BatteryStatus() function is used by the power-management system to get alarm and status bits, as well as error codes from the bq2060. This is basically the same information broadcast to both the SMBus Host and the Smart Battery Charger by the AlarmWarning() function except that the AlarmWarning() function sets the Error Code bits all high before sending the data.

SMBus Protocol: Read Word

Output:

Unsigned integer—Status Register with alarm conditions bit mapped as follows:

Alarm Bits	
0x8000	OVER CHARGED ALARM
0x4000	TERMINATE CHARGE ALARM
0x2000	reserved
0x1000	OVER TEMP ALARM
0x0800	TERMINATE DISCHARGE ALARM
0x0400	reserved
0x0200	REMAINING CAPACITY ALARM
0x0100	REMAINING TIME ALARM
Status Bits	
0x0080	INITIALIZED
0x0040	DISCHARGING
0x0020	FULLY CHARGED
0x0010	FULLY DISCHARGED
Error Codes	
0x0007	Unknown Error
0x0006	BadSize
0x0005	Overflow/Underflow
0x0004	AccessDenied
0x0003	UnsupportedCommand
0x0002	ReservedCommand
0x0001	Busy
0x0000	OK

Alarm Bits

OVER_CHARGED_ALARM bit is set whenever the bq2060 detects that the battery is being charged beyond the *Maximum Overcharge* limit. This bit is cleared when the bq2060 detects that the battery is no longer being charged (i.e., the bq2060 detects discharge activity or no activity for the digital filter timeout periods. The digital filter timeout period (seconds) equates to 10 times the value shared in *Digital Filter EE0x52*.)

TERMINATE_CHARGE_ALARM bit is set when the bq2060 detects that one or more of the battery's charging parameters are out of range (e.g., its voltage, current, or temperature is too high) or when the bq2060 detects a primary charge termination. This bit is cleared when the parameter falls back into the allowable range, the termination condition ceases, or when the bq2060 detects that the battery is no longer being charged.

OVER_TEMP_ALARM bit is set when the bq2060 detects that the internal battery temperature is greater than or equal to the *MaxT* limit. This bit is cleared when the internal temperature falls back into the acceptable range.

TERMINATE_DISCHARGE_ALARM bit is set when the bq2060 detects that Voltage() is less than EDV0 or when the CVUV bit in Pack Status is set indicating that a Li-Ion cell voltage has dropped below the limit programmed in *Cell Under / Over Voltage*. The bit is cleared when Voltage() is greater than EDV0 or when the CVUV bit is cleared.

REMAINING_CAPACITY_ALARM bit is set when the bq2060 detects that RemainingCapacity() is less than that set by the RemainingCapacityAlarm() function. This bit is cleared when either the value set by the RemainingCapacityAlarm() function is lower than the RemainingCapacity() or when the RemainingCapacity() is increased by charging.

REMAINING_TIME_ALARM bit is set when the bq2060 detects that the estimated remaining time at the present discharge rate is less than that set by the RemainingTimeAlarm() function. This bit is cleared when either the value set by the RemainingTimeAlarm() function is lower than the AverageTimeToEmpty() or when the AverageTimeToEmpty() is increased by charging.

Status Bits

INITIALIZED bit is set when the bq2060 has detected a valid load of EEPROM. It is cleared when the bq2060 detects an improper EEPROM load.

DISCHARGING bit is set when the bq2060 determines that the battery is not being charged. This bit is cleared when the bq2060 detects that the battery is being charged.

FULLY_CHARGED bit is set when the bq2060 detects a primary charge termination or an overcharged condition. It is cleared when RelativeStateOfCharge() is less than or equal to the programmed *Fully Charged Clear %* in EE 0x4c.

FULLY_DISCHARGED bit is set when Voltage() is less than the EDV2 threshold. This bit is cleared when the Relative StateOfCharge() is greater than or equal to 20%.

Error Codes	Description
OK	The bq2060 processed the function code without detecting any errors.
Busy	The bq2060 is unable to process the function code at this time.
Reserved	The bq2060 detected an attempt to read or write to a function code reserved by this version of the specification. The bq2060 detected an attempt to access an unsupported optional manufacturer function code.
Unsupported	The bq2060 does not support this function code which is defined in this version of the specification.
AccessDenied	The bq2060 detected an attempt to write to a read-only function code.
Over/Underflow	The bq2060 detected a data overflow or underflow.
BadSize	The bq2060 detected an attempt to write to a function code with an incorrect data block.
UnknownError	The bq2060 detected an unidentifiable error.

CycleCount()(0x17); [0x17]

Description: Returns the number of cycles the battery has experienced. The mAh value of each count is determined by programming the *Cycle Count Threshold* value in EE 0x3c–0x3d. The bq2060 saves the cycle count value to *Cycle Count* EE 0x0e–0x0f after an update to CycleCount().

Purpose: The CycleCount() function provides a means to determine the battery's wear. It may be used to give advanced warning that the battery is nearing its end of life.

SMBus Protocol: Read Word

Output:

Unsigned integer—count of total charge removed from the battery over its life.

Units: cycle

Range: 0 to 65,534 cycles 65,535 indicates battery has experienced 65,535 or more cycles.

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Granularity: 1 cycle

Accuracy: absolute count

DesignCapacity() (0x18); [0x18]

Description: Returns the theoretical or nominal capacity of a new pack. The DesignCapacity() value is expressed in either current (mAh at a C/5 discharge rate) or power, (10mWh at a P/5 discharge rate) depending on the setting of the BatteryMode()'s CAPACITY_MODE bit.

Purpose: The DesignCapacity() function is used by the SMBus Host's power management in conjunction with FullChargeCapacity() to determine battery wear. The power management system may present this information to the user and also adjust its power policy as a result.

SMBus Protocol: Read Word

Output:

Unsigned integer—battery capacity in mAh or 10mWh.

Battery Mode		
	CAPACITY_MODE bit = 0	CAPACITY_MODE bit = 1
Units	mAh	10mWh
Range	0–65,535mAh	0–65,535 10mWh
Granularity	Not applicable	
Accuracy	Not applicable	

DesignVoltage() (0x19); [0x19]

Description: Returns the theoretical voltage of a new pack (mV). The bq2060 sets DesignVoltage() to the value programmed in *Design Voltage* EE0x12–0x13.

Purpose: The DesignVoltage() function can be used to give additional information about a particular Smart Battery's expected terminal voltage.

SMBus Protocol: Read Word

Output:

Unsigned integer—the battery's designed terminal voltage in mV

Units: mV

Range: 0 to 65,535 mV

Granularity: not applicable

Accuracy: not applicable

SpecificationInfo() (0x1a); [0x1a]

Description: Returns the version number of the Smart Battery specification the battery pack supports, as well as voltage and current scaling information in a packed unsigned integer. Power scaling is the product of the voltage scaling times the current scaling. The SpecificationInfo is packed in the following fashion: (SpecID_H * 0x10 + SpecID_L) + (VScale + IPScale * 0x10) * 0x100.

The bq2060 VScale (voltage scaling) and IPScale (current scaling) should always be set to zero. The bq2060 sets SpecificationInfo() to the value programmed in *Specification Information* EE 0x14–0x15.

Purpose: The SpecificationInfo() function is used by the SMBus Host's power management system to determine what information the Smart Battery can provide.

SMBus Protocol: Read Word

Output:

Unsigned integer—packed specification number and scaling information.

Field	Bits Used	Format	Allowable Values
SpecID_L	0...3	4-bit binary value	0–15
SpecID_H	4...7	4-bit binary value	0–15
VScale	8...11	4-bit binary value	0 (multiplies voltage by $10^{\wedge}$ VScale)
IPScale	12...15	4-bit binary value	0 (multiplies current by $10^{\wedge}$ IPScale)

ManufactureDate() (0x1b); [0x1b]

Description: This function returns the date the cell pack was manufactured in a packed integer. The date is packed in the following fashion: (year-1980) * 512 + month * 32 + day. The bq2060 sets ManufactureDate() to the value programmed in *Manufacture Date* EE 0x16–0x17.

Purpose: The ManufactureDate() provides the system with information that can be used to uniquely identify a particular battery pack when used in conjunction with SerialNumber().

SMBus Protocol: Read Word

Output:

Unsigned integer—packed date of manufacture.

Field	Bits Used	Format	Allowable Values
Day	0...4	5-bit binary value	0–31 (corresponds to date)
Month	5...8	4-bit binary value	1–12 (corresponds to month number)
Year	9...15	7-bit binary value	0–127 (corresponds to year biased by 1980)

SerialNumber() (0x1c); [0x1c]

Description: This function is used to return a serial number. This number, when combined with the ManufacturerName(), the DeviceName(), and the ManufactureDate(), uniquely identifies the battery (unsigned int). The bq2060 sets SerialNumber() to the value programmed in *Serial Number* EE 0x18–0x19.

Purpose: The SerialNumber() function can be used to identify a particular battery. This may be important in systems that are powered by multiple batteries where the system can log information about each battery that it encounters.

SMBus Protocol: Read Word

Output:

Unsigned integer

ManufacturerName() (0x20); [0x20-0x25]

Description: This function returns a character array containing the battery's manufacturer's name. For example, MyBattCo would identify the Smart Battery's manufacturer as MyBattCo. The bq2060 sets ManufacturerName() to the value programmed in *Manufacturer Name* EE 0x20–0x2a.

Purpose: The ManufacturerName() function returns the name of the Smart Battery's manufacturer. The manufacturer's name can be displayed by the SMBus Host's power management system display as both an identifier and as an advertisement for the manufacturer. The name is also useful as part of the information required to uniquely identify a battery.

SMBus Protocol: Read Block

Output:

String—character string with maximum length of 11 characters (11+length byte).

DeviceName() (0x21); [0x28-0x2b]

Description: This function returns a character string that contains the battery's name. For example, a DeviceName() of BQ2060A would indicate that the battery is a model BQ2060A. The bq2060 sets DeviceName() to the value programmed in *Device Name* EE 0x30–0x37.

Purpose: The DeviceName() function returns the battery's name for identification purposes.

SMBus Protocol: Read Block

Output:

String—character string with maximum length of 7 characters (7+length byte).

DeviceChemistry() (0x22); [0x30-0x32]

Description: This function returns a character string that contains the battery's chemistry. For example, if the DeviceChemistry() function returns *NiMH*, the battery pack would contain nickel metal hydride cells. The bq2060 sets DeviceChemistry() to the value programmed in *Device Chemistry* EE 0x40–0x44.

Purpose: The DeviceChemistry() function gives cell chemistry information for use by charging systems. The bq2060 does not use DeviceChemistry() values for internal charge control or fuel gauging.

SMBus Protocol: Read Block

Output:

String—character string with maximum length of 4 characters (4+length byte).

Note: The following is a partial list of chemistries and their expected abbreviations. These abbreviations are NOT case sensitive.

Lead acid	PbAc
Lithium ion	LION
Nickel cadmium	NiCd
Nickel metal hydride	NiMH
Nickel zinc	NiZn
Rechargeable alkaline-manganese	RAM
Zinc air	ZnAr

ManufacturerData() (0x23); [0x38-0x3a]

Description: This function allows access to the manufacturer data contained in the battery (data). The bq2060 stores seven critical operating parameters in this data area.

Purpose: The ManufacturerData() function may be used to access the manufacturer's data area. The data fields of this command reflect the programming of five critical EEPROM locations and can be used to facilitate evaluation bq2060 under various programming sets. The ManufacturerData() function returns the following information in order: *Control Mode*, *Digital Filter*, *Self-Discharge Rate*, *Battery Low %*, *Near Full*, and the pending EDV threshold voltage (low byte and high byte.)

SMBus Protocol: Read Block

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Output:

Block data—data that reflects EEPROM programming as assigned by the manufacturer with maximum length of 7 characters (7+length byte).

Pack Status and Pack Configuration (0x2f); [0x2f]

This function returns the Pack Status and Pack Configuration registers. The Pack Status register contains a number of status bits relating to bq2060 operation. The Pack Status register is the least significant byte of the word. The Pack Configuration register is the most significant byte of the word. The byte reflects how the bq2060 is configured as defined by the value programmed in *Pack Configuration* in EE 0x3f.

The Pack Status Register consists of the following bits:

b7	b6	b5	b4	b3	b2	b1	b0
OCE	EDV2	EINT	VDQ	COK	DOK	CVOV	CVUV

OCE

The OCE bit indicates that offset cancellation is enabled. The bq2060 sets this bit after VFC offset calibration is complete.

- 0 Offset calibration is not enabled
- 1 Offset calibration is enabled

EDV2

The EDV2 bit indicates that Voltage() is less than the EDV2 threshold.

- 0 Voltage() > EDV2 threshold (discharging)
- 1 Voltage() ≤ EDV2 threshold

EINT

The EINT bit indicates that the VFC has detected a charge or discharge pulse.

- 0 No charge/discharge activity detected
- 1 Charge/discharge activity detected.

VDQ

The VDQ bit indicates if the present discharge cycle is valid for an FCC update.

- 0 Discharge cycle is not valid
- 1 Discharge cycle is valid

COK

The COK bit indicates the status of the CFC pin of the bq2060.

- 0 CFC pin is low
- 1 CFC pin is high

DOK

The DOK bit indicates the status of the DFC pin of the bq2060.

- 0 DFC pin is low
- 1 DFC pin is high

CVOV

The CVOV bit indicates that a secondary Li-Ion protection limit has been exceeded. It is set if any individual cell exceeds the programmed high voltage limit, if the pack voltage exceeds the overvoltage threshold, or if an over temperature condition occurs. The bit is not latched and merely reflects the present overvoltage status.

- 0 No secondary protection limits exceeded
- 1 A secondary protection limit exceeded

CVUV

The CVUV bit indicates if any individual cell falls below the programmed low-voltage limit. The bit applies to lithium batteries only. The bit is not latched and merely reflects the present undervoltage status.

- 0 All series cells are above the low-voltage limit
- 1 A series cell is below the low voltage limit

VCELL4–VCELL1 (0x3c–0x3f); [0x3c–0x3f]

These functions return the calculated voltages in mV at the VCELL₄ through VCELL₁ inputs.

EEPROM

General

The bq2060 accesses the external EEPROM during a full reset and when storing historical data. During an EEPROM access, the V_{OUT} pin becomes active and the bq2060 uses the ESCL and ESDA pins to communicate with the EEPROM. The EEPROM stores basic configuration information for use by the bq2060. The EEPROM must be programmed correctly for proper bq2060 operation.

Memory Map

Table 10 shows the memory map for the EEPROM. It also contains example data for a 10 series NiMH and a 3s3p Li-Ion battery pack with a 0.05Ω sense resistor.

Table 10. EEPROM Memory Map

EEPROM Address		Name	Chemistry	NiMH Example	Data		Li-Ion Example	Data	
					MSB	LSB		MSB	LSB
0x00	0x01	Check Byte 1	Li-Ion, Nickel	15487	3c	7f	15487	3c	7f
0x02	0x03	Remaining Time Alarm	Li-Ion, Nickel	10 minutes	00	0a	10 minutes	00	0a
0x04	0x05	Remaining Capacity Alarm	Li-Ion, Nickel	350mAh	01	5e	400mAh	01	90
0x06		EDV A0 Impedance Age Factor	Li-Ion, Nickel	0	-	00	0	-	00
0x07		Reserved	-	0	-	00	0	-	00
0x08	0x09	Reserved	-	0	00	00	0	00	00
0x0a	0x0b	Charging Voltage	Li-Ion, Nickel	18000mV	46	50	12600mV	31	38
0x0c	0x0d	Reserved	-	128	00	80	128	00	80
0x0e	0x0f	Cycle Count	Li-Ion, Nickel	0	00	00	0	00	00
0x10	0x11	Reserved	-	0	00	00	0	00	00
0x12	0x13	Design Voltage	Li-Ion, Nickel	12000mV	2e	e0	10800mV	2a	30
0x14	0x15	Specification Information	Li-Ion, Nickel	v1.1/PEC	00	31	v1.1/PEC	00	31
0x16	0x17	Manufacture Date	Li-Ion, Nickel	2/25/99=9817	26	59	2/25/99=9817	26	59
0x18	0x19	Serial Number	Li-Ion, Nickel	1	00	01	1	00	01
0x1a	0x1b	Fast-Charging Current	Li-Ion, Nickel	4000mA	0f	a0	3000mA	0b	b8
0x1c	0x1d	Maintenance Charging Current	Li-Ion, Nickel	200mA	00	c8	0mA	00	00
0x1e	0x1f	Pre-Charge Current	Li-Ion, Nickel	800mA	03	20	100mA	00	64
0x20		Manufacturer Name Length	Li-Ion, Nickel	9	-	09	9	-	09
0x21		Character 1	Li-Ion, Nickel	B	-	42	B	-	42
0x22		Character 2	Li-Ion, Nickel	E	-	45	E	-	45
0x23		Character 3	Li-Ion, Nickel	N	-	4e	N	-	4e
0x24		Character 4	Li-Ion, Nickel	C	-	43	C	-	43
0x25		Character 5	Li-Ion, Nickel	H	-	48	H	-	48
0x26		Character 6	Li-Ion, Nickel	M	-	4d	M	-	4d
0x27		Character 7	Li-Ion, Nickel	A	-	41	A	-	41
0x28		Character 8	Li-Ion, Nickel	R	-	52	R	-	52
0x29		Character 9	Li-Ion, Nickel	Q	-	51	Q	-	51
0x2a		Character 10	Li-Ion, Nickel	0	-	00	0	-	00
0x2b		Light Discharge Current	Li-Ion, Nickel	0	-	00	0	-	00
0x2c	0x2d	Reserved	-	0	00	00	0	00	00
0x2e	0x2f	Maximum Overcharge	Li-Ion, Nickel	200mAh	ff	38	256mAh	ff	00
0x30		Device Name Length	Li-Ion, Nickel	7	-	07	7	-	07
0x31		Character 1	Li-Ion, Nickel	B	-	42	B	-	42
0x32		Character 2	Li-Ion, Nickel	Q	-	51	Q	-	51
0x33		Character 3	Li-Ion, Nickel	2	-	32	2	-	32
0x34		Character 4	Li-Ion, Nickel	0	-	30	0	-	30

(Continued on next page)

Note: Reserved locations must be set as shown. Locations marked with an * are calibration values that can be adjusted for maximum accuracy. For these locations the table shows the appropriate default or initial setting.

Table 10. EEPROM Memory Map (Continued)

EEPROM Address		Name	Chemistry	NiMH Example	Data		Li-Ion Example	Data	
					MSB	LSB		MSB	LSB
0x35		Character 5	Li-Ion, Nickel	6	-	36	6	-	36
0x36		Character 6	Li-Ion, Nickel	0	-	30	0	-	30
0x37		Character 7	Li-Ion, Nickel	A	-	41	A	-	41
0x38	0x39	Last Measured Discharge	Li-Ion, Nickel	4000mAh	0f	a0	4050mAh	0f	d2
0x3a	0x3b	Pack Capacity	Li-Ion, Nickel	4000mAh	0f	a0	4050mAh	0f	d2
0x3c	0x3d	Cycle Count Threshold	Li-Ion, Nickel	500mAh	fe	0c	3240mAh	f3	58
0x3e		Reserved	-	0	-	00	0	-	00
0x3f		Pack Configuration	Li-Ion, Nickel	232	-	e8	246	-	f6
0x40		Device Chemistry Length	Li-Ion, Nickel	4	-	04	4	-	04
0x41		Character 1	Li-Ion, Nickel	N	-	4e	L	-	4c
0x42		Character 2	Li-Ion, Nickel	I	-	49	I	-	49
0x43		Character 3	Li-Ion, Nickel	M	-	4d	O	-	4f
0x44		Character 4	Li-Ion, Nickel	H	-	48	N	-	4e
0x45		MaxT DeltaT	Li-Ion, Nickel	50C, 3.0	-	c7	50C, 4.6	-	cf
0x46	0x47	Overload Current	Li-Ion, Nickel	6000mA	17	70	6000mA	17	70
0x48		Overvoltage Margin	Li-Ion, Nickel	0	-	00	800mV	-	32
0x49		Overcurrent Margin	Li-Ion, Nickel	512mA	-	20	512mA	-	20
0x4a		Reserved	Nickel	0	-	00	-	-	-
		Cell Under/Over Voltage	Li-Ion	-	-	-	118	-	76
0x4b		Fast Charge Termination %	Li-Ion, Nickel	96%	-	a0	100%	-	9c
0x4c		Fully Charged Clear %	Li-Ion, Nickel	90%	-	a6	95%	-	a1
0x4d		Charge Efficiency	Li-Ion, Nickel	97%	-	el	100%	-	ff
0x4e		Current Taper Threshold	Li-Ion	-	-	-	200mA	-	12
		DeltaT Time	Nickel	180s	-	07	-	-	-
0x4f		Holdoff Time	Nickel	240s	-	04	-	-	-
		Current Taper Qual Voltage	Li-Ion	-	-	-	128mV	-	40
0x50		Manufacturers Data Length	Li-Ion, Nickel	7	-	07	7	-	07
0x51		Control Mode	Li-Ion, Nickel	4		04	4		04
0x52		Digital Filter	Li-Ion, Nickel	50μV	-	2d	50μV	-	2d
0x53		Self-Discharge Rate	Li-Ion, Nickel	1%	-	cb	0.21%	-	05
0x54		Battery Low %	Li-Ion, Nickel	7%	-	12	7%	-	12
0x55		Near Full	Li-Ion, Nickel	200mAh	-	64	200mAh	-	64
0x56	0x57	Reserved	-	0	-	00	0	-	00
0x58	0x59	Reserved	-	0	-	00	0	-	00
0x5a	0x5b	Reserved	-	0	-	00	0	-	00

(Continued on next page)

Note: Reserved locations must be set as shown. Locations marked with an * are calibration values that can be adjusted for maximum accuracy. For these locations the table shows the appropriate default or initial setting.

Table 10. EEPROM Memory Map (Continued)

EEPROM Address		Description	Chemistry	NiMH Example	Data		Li-Ion Example	Data	
					MSB	LSB		MSB	LSB
0x5c	0x5d	Reserved	-	0	00	00	0	00	00
0x5e	0x5f	VFC Offset*	Li-Ion, Nickel	0	00	00	0	00	00
0x60		VFC Offset*	Li-Ion, Nickel	0	-	00	0	-	00
0x61		Temperature Offset*	Li-Ion, Nickel	0	-	00	0	-	00
0x62		ADC Offset*	Li-Ion, Nickel	0	-	00	0	-	00
0x63		Cell 2 Calibration Factor*	Li-Ion	-	-	-	0	-	00
		Efficiency Temperature Compensation	Nickel	0.25%	-	20	-	-	-
0x64		Cell 3 Calibration Factor*	Li-Ion	-	-	-	0	-	00
		Efficiency Drop Off Percentage	Nickel	96%	-	a0	-	-	-
0x65		Cell 4 Calibration Factor*	Li-Ion	-	-	-	0	-	00
		Efficiency Reduction Rate	Nickel	1%	-	50	-	-	-
0x66	0x67	ADC Voltage Gain*	Li-Ion, Nickel	16 : 1	4e	20	16 : 1	4e	20
0x68	0x69	ADC Sense Resistor Gain*	Li-Ion, Nickel	0.05Ω	30	d4	0.05Ω	30	d4
0x6a	0x6b	VFC Sense Resistor Gain*	Li-Ion, Nickel	0.05Ω	20	00	0.05Ω	20	00
0x6c	0x6d	VOC 25%	Li-Ion, Nickel	11500mV	d3	14	10550mV	d6	ca
0x6e	0x6f	VOC 50%	Li-Ion, Nickel	12500mV	cf	2c	10750mV	d6	02
0x70	0x71	VOC 75%	Li-Ion, Nickel	13500mV	cb	44	11200mV	d4	40
0x72	0x73	EDVF / EDV0	Li-Ion, Nickel	9500mV	25	1c	10265mV	28	19
0x74	0x75	EMF / EDV1	Li-Ion, Nickel	10000mV	27	10	11550	2d	1e
0x76	0x77	EDV T0 Factor	Li-Ion, Nickel	0	00	00	4475	11	7b
0x78	0x79	EDV C1 / C0 Factor / EDV2	Li-Ion, Nickel	10500mV	29	04	C1 = 0 C0 = 235	00	eb
0x7a	0x7b	EDV R0 Factor	Li-Ion, Nickel	0	00	00	5350	14	e6
0x7c	0x7d	EDV R1 Factor	Li-Ion, Nickel	0	-	00	250	00	fa
0x7e	0x7f	Check Byte 2	Li-Ion, Nickel	42330	a5	5a	42330	a5	5a

Note: Reserved locations must be set as shown. Locations marked with an * are calibration values that can be adjusted for maximum accuracy. For these locations the table shows the appropriate default or initial setting.

EEPROM Programming

The following sections describes the function of each EEPROM location and how the data is to be stored.

Fundamental Parameters

Sense Resistor Value

Two factors are used to scale the current related measurements. The 16-bit *ADC Sense Resistor Gain* value in EE 0x68–0x69 scales *Current()* to mA. Adjusting *ADC Sense Resistor Gain* from its nominal value provides a method to calibrate the current readings for system errors and the sense resistor value (R_s). The nominal value is set by

$$ADC\ Sense\ Resistor\ Gain = \frac{625}{(R_s)} \quad (4)$$

The 16-bit *VFC Sense Resistor Gain* in EE 0x6a–0x6b scales each VFC interrupt to mAh. *VFC Sense Resistor Gain* is based on the resistance of the series sense resistor. The following formula computes a nominal or starting value for *VFC Sense Resistor Gain* from the sense resistor value.

$$VFC\ Sense\ Resistor\ Gain = \frac{409.6}{(R_s)} \quad (5)$$

Sense resistor values are limited to the range of 0.00916 to 0.100Ω.

Digital Filter

The digital filter threshold, VDF (μV), is set by the value stored in *Digital Filter* EE 0x52.

$$Digital\ Filter = \frac{2250}{VDF} \quad (6)$$

Cell Characteristics

Battery Pack Capacity and Voltage

Pack capacity in mAh units is stored in *Pack Capacity* EE 0x3a–0x3b. In mAh mode, the bq2060 copies *Pack Capacity* to *DesignCapacity()*. In mWh mode, the bq2060 multiplies *Pack Capacity* by *Design Voltage* EE 0x12–0x13 to calculate *DesignCapacity()* scaled to 10mWh. *Design Voltage* is stored in mV.

The initial value for *Last Measured Discharge* in mAh is stored in EE 0x38–0x39. *Last Measured Discharge* is modified over the course of pack usage to reflect cell aging under the particular use conditions. The bq2060 updates *Last Measured Discharge* in mAh after a capacity

learning cycle. The bq2060 uses the *Last Measured Discharge* value to calculate *FullChargeCapacity()* in mAh or 10mWh mode.

EDV Thresholds and Near Full Percentage

The bq2060 uses three pack voltage thresholds to provide voltage-based warnings of low battery capacity. The bq2060 uses the values stored in EEPROM for the EDV0, EDV1, and EDV2 values or calculates the three thresholds from a base value and the temperature, capacity, and rate adjustment factors stored in EEPROM. If EDV compensation is disabled then EDV0, EDV1, and EDV2 are stored directly in mV in EE 0x72–0x73, EE 0x74–0x75, and EE 0x78–0x79, respectively.

For capacity correction at EDV2, *Battery Low %* EE 0x54 can be set at a desired state-of-charge, *STATEOFCHARGE%*, in the range of 5 to 20%. Typical values for *STATEOFCHARGE%* are 7–12% representing 7–12% capacity.

$$Battery\ Low\ \% = STATEOFCHARGE\% * 2.56 \quad (7)$$

The bq2060 updates FCC if a qualified discharge occurs from a near-full threshold to EDV2. The desired near-full threshold window, NFW (mAh), is programmed in *Near Full* in EE 0x55.

$$Near\ Full = \frac{NFW}{2} \quad (8)$$

EDV Discharge Rate and Temperature Compensation

If EDV compensation is enabled, the bq2060 calculates battery voltage to determine EDV0, EDV1, and EDV2 thresholds as a function of battery capacity, temperature, and discharge load. The general equation for EDV0, EDV1, and EDV2 calculation is

$$EDV_{0,1,2} = EMF * F_{BL} - |I_{LOAD}| * R_0 * F_{TZ} * F_{CY} \quad (9)$$

where

- EMF is a no-load battery voltage that is higher than the highest EDV threshold that is computed. EMF is programmed in mV in *EMF/EDV1* EE 0x74–0x75.
- I_{LOAD} is the current discharge load.

F_{BL} is the factor that adjusts the EDV voltage for battery capacity and temperature to match the no-load characteristics of the battery.

$$F_{BL} = f(C_0, C + C_1, T) \quad (10)$$

where

- C (0%, 3%, or *Battery Low %* for EDV0, EDV1, and EDV2, respectively) and C0 are the capacity related EDV adjustment factors. C0 is programmed in the lower 11 bits of *EDV C0 Factor/EDV2 EE 0x78–79*. The *Residual Capacity Factor* is stored in the upper 5 bits of EE 0x78–0x79.

$$\text{Residual Capacity Factor } C1 = \text{RESIDUAL\%} * 2.56$$

RESIDUAL % is the desired battery capacity remaining at EDV0 (RM = 0).

- T is the current temperature in °K

$R0 * F_{TZ}$ represents the resistance of the battery as a function of temperature and capacity.

$$F_{TZ} = f(R1, T0, T, C + C1) \quad (11)$$

- R0 is the first order rate dependency factor stored in *EDV R0 Factor EE 0x7a–0x7b*.
- T is the current temperature; C is the battery capacity relating to EDV0, EDV1, and EDV2; and C1 is the desired residual battery capacity remaining at EDV0 (RM = 0).
- R1 adjusts the variation of impedance with battery capacity. R1 is programmed in *EDV R1 Rate Factor EE 0x7c–0x7d*.
- T0 adjusts the variation of impedance with battery temperature. T0 is programmed in *EDV T0 Rate Factor EE 0x76–0x77*.

F_{CY} is the factor that adjusts for changing cell impedance as the battery pack is cycled.

where

$$F_{CY} = f(A0, \text{CycleCount}()) \quad (12)$$

- A0 is the EDV aging factor that is stored in *EDV A0 Factor EE 0x06*. It should be set to 0 for most applications.

Typical values for the EDV compensation factors for a Li-Ion 3s3p 18650 pack are

$$\text{EMF} = 11550$$

$$T0 = 4475$$

$$C0 = 235$$

$$C1 = 0$$

$$R0 = 5350$$

$$R1 = 250$$

$$A0 = 0$$

The graphs in Figures 7 and 8 show the calculated EDV0, EDV1, and EDV2 thresholds versus capacity using the typical compensation values for different temperatures and loads for a Li-Ion 3s3p 18650 pack. The compensation values vary widely for different cell types and manufacturers and must be matched exactly to the unique characteristics for optimal performance.

Overload Current Threshold

The *Overload Current* threshold is a 16-bit value stored in EE 0x46–0x47 in mA units.

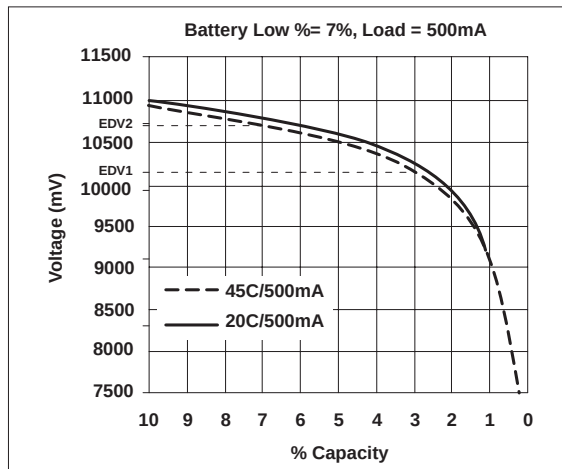


Figure 7. EDV Calculations vs. Capacity for Various Temperatures

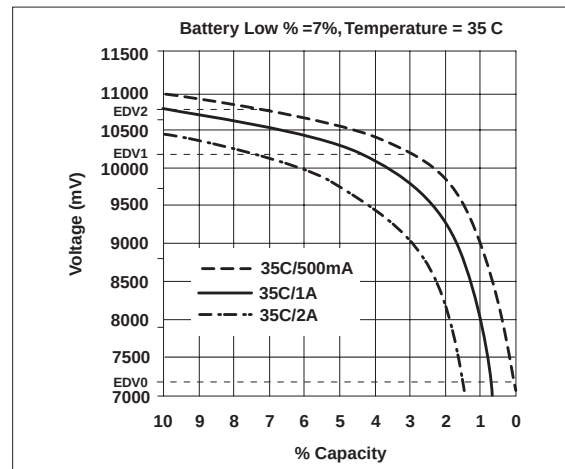


Figure 8. EDV Calculations vs. Capacity for Various Loads

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Midrange Capacity Corrections

Three voltage-based thresholds, *VOC25* EE 0x6c–0x6d, *VOC50* EE 0x6e–0x6f, and *VOC75* EE 0x70–0x71, are used to test the accuracy of the RM based on open-circuit pack voltages. These thresholds are stored in the EEPROM in 2's complement of voltage in mV. The values represent the open-circuit battery voltage at which the battery capacity should correspond to the associated state of charge for each threshold.

Self-Discharge Rate

The nominal self-discharge rate, %PERDAY (% per day), is programmed in an 8-bit value *Self-Discharge Rate* EE 0x53 by the following relation:

$$\text{Self-Discharge Rate} = 256 - \left(\frac{52.73}{\% \text{PERDAY}} \right) \quad (13)$$

Light Load Current

The amount of light load current in mA, ILEAK, used for compensation is stored in *Light Discharge Current* in EE 0x2b as follows:

$$\text{Light Discharge Current} = \frac{\text{ILEAK} * 1024}{45} \quad (14)$$

ILEAK is between 0.044 and 11.2mA.

Charge Efficiency

The bq2060 uses four charge-efficiency factors to compensate for charge acceptance. These factors are coded in *Charge Efficiency*, *Efficiency Reduction Rate*, *Efficiency Drop Off Percentage*, and *Efficiency Temperature Compensation*.

The bq2060 applies the efficiency factor, EFF%, when *RelativeStateOfCharge()* is less than the value coded in *Efficiency Drop Off Percentage* EE 0x64. When *RelativeStateOfCharge()* is greater than or equal to the value coded in *Efficiency Drop Off Percentage*, EFF% and ERR% determine the charge efficiency rate. ERR% defines the percent efficiency reduction per percentage point of *RelativeStateOfCharge()* over *Efficiency Drop Off Percentage*. EFF% is encoded in *High Charge Efficiency* EE 0x4d according to the following equation:

$$\text{Charge Efficiency} = 10 * (\text{EFF\%} - 74.5) \quad (15)$$

where

$$74.5 \leq \text{EFF\%} \leq 100$$

ERR% is encoded in *Efficiency Reduction Rate* EE 0x65 according to the following equation:

$$\text{Efficiency Reduction Rate} = \frac{\text{ERR\%}}{0.0125} \quad (16)$$

where

$$0 \leq \text{ERR\%} \leq 3.19$$

The *Efficiency Drop Off Percentage* is stored in 2's complement of percent.

The bq2060 also adjusts the efficiency factors for temperature. TEFF% defines the percent efficiency reduction per degree C over 25°C. TEFF% is encoded in *Efficiency Temperature Compensation* EE 0x63 according to the following equation

$$\text{Efficiency Temperature Compensation} = \frac{\text{TEFF\%} * 1.6}{0.0125} \quad (17)$$

where

$$0 \leq \text{TEFF\%} \leq 1.99$$

The bq2060 applies all four charge-compensation factors when the CHEM bit in *Pack Configuration* is not set denoting a nickel pack.

$$\text{Effective Charge Efficiency Reduction (nickel only)} \quad (18)$$

$$= \text{ERR\%}[\text{RSOC}() - \text{EFF\%}] + \text{TEFF\%}[\text{T}(\text{°C}) - 25]$$

where

$$\text{RSOC}() \geq \text{EFF\%} \text{ and } \text{T} \geq 25^\circ\text{C}$$

If CHEM is set denoting a Li-Ion pack, the bq2060 applies only the value coded in *High Charge Efficiency* and makes no other adjustments for charge acceptance.

Charge Limits and Termination Techniques

Charging Voltage

The 16-bit value, *Charging Voltage* EE 0x0a–0x0b programs the *ChargingVoltage()* value broadcast to a Smart Charger. It is also sets the base value for determining overvoltage conditions during charging and voltage compliance during a constant-voltage charging methodology. It is stored in mV.

Overvoltage

The 8-bit value, *Overvoltage Margin* EE 0x48, sets the limit over *ChargingVoltage()* that is to be considered as an overvoltage charge-suspension condition. The voltage in mV above the *ChargingVoltage()*, VOVM, that should

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trigger a charge suspend is encoded in *Overvoltage Margin* as follows:

$$\text{Overvoltage Margin} = \frac{\text{VOVM}}{16} \quad (19)$$

VOVM is between 0 and 4080mV.

Charging Current

ChargingCurrent() values are either broadcast to a Level 2 Smart Battery Charger or read from the bq2060 by a Level 3 Smart Battery Charger. The bq2060 sets the value of ChargingCurrent(), depending on the charge requirements and charge conditions of the pack.

When fast charge is allowed, the bq2060 sets ChargingCurrent() to the rate programmed in *Fast Charging Current* EE 0x1a-0x1b.

When fast charge terminates, the bq2060 sets ChargingCurrent() to zero and then to the *Maintenance Charging Current* EE 0x1c-0x1d when the termination condition ceases.

When Voltage() is less than EDV0, the bq2060 sets ChargingCurrent() to *Pre-charge Current* EE 0x1e-0x1f. Typically this rate is larger than the maintenance rate to charge a deeply depleted pack up to the point where it may be fast charged.

Fast Charging Current, *Maintenance Charging Current*, and *Pre-Charge Current* are stored in mA.

Charge Suspension

During charge, the bq2060 compares the current to the ChargingCurrent() plus the value IOIM. If the pack is charged at a current above the ChargingCurrent() plus IOIM, the bq2060 sets ChargingCurrent() set to zero to stop charging. IOIM is programmed in the EEPROM value, *Overcurrent Margin*, encoded as

$$\text{Overcurrent Margin} = \frac{\text{IOIM}}{16} \quad (20)$$

Overcurrent Margin EE 0x49 may be used to program IOIM values of 0 to 4080mA in 16mA steps.

The desired temperature threshold for charge suspension, MAXTEMP, may be programmed between 45°C and 69°C in 1.6°C steps. *MaxT DeltaT* EE 0x45 (most significant nibble) is stored in a 4-bit value as shown:

$$\text{MaxT} = \left\lceil \frac{69 - \text{MAXTEMP}}{1.6} \right\rceil \quad (21)$$

The bq2060 suspends fast charge when fast charge continues past full by the amount programmed in *Maximum Overcharge* EE 0x2e-0x2f. *Maximum Overcharge* is programmed in 2s complement form of charge in mAh.

FULLY_CHARGED Bit Clear Threshold

The bq2060 clears the FULLY_CHARGED bit in BatteryStatus() when RelativeStateOfCharge() reaches the value, *Fully Charged Clear %* EE 0x4c. *Fully Charged Clear %* is an 8-bit value and is stored as a 2's complement of percent.

Fast Charge Termination Percentage

The bq2060 sets RM to a percentage of FCC on charge termination if the CSYNC bit is set in the Pack Configuration register. The percentage of FCC is stored in *Fast Charge Termination %* in EE 0x4b. The value is stored in 2's complement of percent.

Cycle Count Threshold

Cycle Count Threshold 0x3c–0x3d sets the number of mAh that must be removed from the battery to increment CycleCount(). Cycle Count Threshold is a 16-bit value stored in 2's complement of charge in mAh.

ΔT/Δt Rate Programming

The ΔT portion of the ΔT/Δt rate is programmed in *DeltaT*, the low nibble of *MaxT DeltaT* EE 0x45 (least significant nibble). The Δt portion is programmed in *DeltaT Time* EE 0x4e.

$$\Delta T / \Delta t = \frac{[\text{DeltaT} * 2 + 16] / 10}{[320 - \text{DeltaT Time} * 20]} \left[\frac{^{\circ}\text{C}}{\text{s}} \right] \quad (22)$$

<i>DeltaT</i>	<i>Δ(°C)</i>	<i>DeltaT Time</i>	<i>t (s)</i>
0	1.6	00	320
1	1.8	01	300
2	2.0	02	280
3	2.2	03	260
4	2.4	04	240
5	2.6	05	220
6	2.8	06	200
7	3.0	07	180
8	3.2	08	160
9	3.4	09	140
a	3.6	0a	120
b	3.8	0b	100
c	4.0	0c	80
d	4.2	0d	60
e	4.4	0e	40
f	4.6	0f	20

ΔT/Δt Hold-off Timer Programming

The hold-off timer is programmed in the lower nibble of *Holdoff Time* EE 0x4f. The hold-off time is 320s minus 20 times the *Holdoff Time* value.

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Hold-off Time	Hold-off Time (s)	Hold-off Time	Hold-off Time (s)
00	320	08	160
01	300	09	140
02	280	0a	120
03	260	0b	100
04	240	0c	80
05	220	0d	60
06	200	0e	40
07	180	0f	20

Current Taper Termination Characteristics

Two factors in the EEPROM set the current taper termination for Li-Ion battery packs. The two coded locations are *Current Taper Qual Voltage* EE 0x4f and *Current Taper Threshold* EE 0x4e. Current taper termination occurs during charging when the pack voltage is above the charging voltage minus CELLV (mV) and the charging current is below the threshold coded in *Current Taper Threshold* for at least 40s.

$$\text{Current Taper Qual Voltage} = \frac{\text{CELLV}}{2} \quad (23)$$

$$\text{Current Taper Threshold} = \frac{R_S \cdot i}{0.5625} \quad (24)$$

where i = the desired current termination threshold in mA, and R_S = VFC sense resistor in ohms.

Pack Options

Pack Configuration

Pack Configuration EE 0x3f contains bit-programmable features.

b7	b6	b5	b4	b3	b2	b1	b0
DMODE	SEAL	CSYNC	CEDV	VCOR	CHEM	LCC1	LCC0

DMODE

The DMODE bit determines whether the LED outputs will indicate `AbsoluteStateOfCharge()` or `RelativeStateOfCharge()`

- 0 LEDs reflect `AbsoluteStateOfCharge()`
- 1 LEDs reflect `RelativeStateOfCharge()`

SEAL

The SEAL bit determines the SMBus access state of the bq2060 on reset

- 0 SMBus commands (0x00–0xff) are accessible for both read and write.

- 1 SMBus read access is limited to commands (0x05–0x1c) and (0x20–0x23). SMBus read/write access is limited to commands (0x00–0x04), (0x2f), and (0x3c–0x3f).

CSYNC

In usual operation of the bq2060, the CSYNC bit is set so that the coulomb counter is adjusted when a fast charge termination is detected. In some applications, especially those where an externally controlled charger is used, it may be desirable NOT to adjust the coulomb counter. In these cases the CSYNC bit should be cleared.

- 0 The bq2060 does not alter RM at the time of a valid charge termination.
- 1 The bq2060 updates RM with a programmed percentage of FCC at a valid charge termination.

CEDV

The CEDV bit determines whether the bq2060 implements automatic EDV compensation to calculate the EDV0, EDV1 and EDV2 thresholds base on rate, temperature, and capacity. If reset, the bq2060 uses the fixed values programmed in EEPROM for EDV0, EDV1 and EDV2. If set the bq2060 calculates EDV0, EDV1 and EDV2.

- 0 EDV compensation disabled
- 1 EDV compensation enabled

VCOR

The VCOR bit enables the midrange voltage correction algorithm. When set, the bq2060 compares the pack voltage to RM and may adjust RM according to the values programmed in *VOC25*, *VOC50*, and *VOC75*.

- 0 Midrange corrections disabled
- 1 Midrange corrections enabled

CHEM

The CHEM bit configures the bq2060 for nickel packs (NiCd or NiMH) or Li-Ion packs. When set the bq2060 employs the configuration parameters in EEPROM designated for Li-Ion. When not set, the bq2060 employs the configuration parameters designated for nickel.

- 0 The bq2060 uses nickel configuration parameters.
- 1 The bq2060 uses Li-Ion configuration parameters.

LCC0 and LCC1

The LCC0 and LCC1 bits configure the cell voltage inputs (VCELL1–4).

No. of Series Cells	LCC1 LCC0	Cell Voltage Inputs
NA	00	VCELL ₄ = Cell Stack
2	01	VCELL ₁ = Cell 1 VCELL ₂ = Cell 2
3	10	VCELL ₁ = Cell 1 VCELL ₂ = Cell 2 VCELL ₃ = Cell 3
4	11	VCELL ₁ = Cell 1 VCELL ₂ = Cell 2 VCELL ₃ = Cell 3 VCELL ₄ = Cell 4

For Li-Ion packs with individual measurements, LCC0 and LCC1 define the number of series elements and their voltage measurement inputs. In each case (2, 3, or 4), the bq2060 uses the highest numbered cell voltage input to measure the pack voltage measurement as returned with Voltage(). For nickel chemistries or Li-Ion without single-cell measurements, LCC0 and LCC1 must be set to 00. VCELL₄ is the pack voltage input for this programming.

Remaining Time and Capacity Alarms

Remaining Time Alarm in EE 0x02–0x03 and *Remaining Capacity Alarm* in 0x04–0x05 set the alarm thresholds used in the SMBus command codes 0x01 and 0x02, respectively. *Remaining Time Alarm* is stored in minutes and *Remaining Capacity Alarm* in mAh.

Secondary Protection Limits for Li-Ion

The cell undervoltage (V_{uv}) and overvoltage (V_{ov}) limits are programmed in *Cell Undervoltage/Over Voltage* EE 0x4a according to the equations:

$$\text{Cell Undervoltage/Overvoltage (lower)} = \frac{V_{ov} - 4096}{32} \quad (25)$$

$$\text{Cell Undervoltage/Overvoltage (upper)} = \frac{V_{uv} - 2048}{64} \quad (26)$$

Cell Under/Over Voltage (upper nibble)	V _{uv} (mV)	Cell Under/Over Voltage (lower nibble)	V _{ov} (mV)
0	2048	0	4096
1	2112	1	4128
2	2176	2	4160
3	2240	3	4192
4	2304	4	4224
5	2368	5	4256
6	2432	6	4288
7	2496	7	4320
8	2560	8	4352
9	2624	9	4384

a	2688	a	4416
b	2752	b	4448
c	2816	c	4480
d	2880	d	4512
e	2944	e	4544
f	3008	f	4576

Cycle Count Initialization

Cycle Count EE 0x0e–0x0f stores the initial value for the CycleCount() function. It should be programmed to 0x0000.

Control Modes

Control Mode EE0x51 contains additional bit programmable features.

b7	b6	b5	b4	b3	b2	b1	b0
NDF	-	HPE	CPE	LED	SC	-	SM

NDF

The NDF bit disables the digital filter during discharge if the SMBC and SMBD lines are high.

- 0 Digital filter enabled all the time
- 1 Digital filter disabled if SMBC and SMBD are high

HPE

The HPE bit enables/disables PEC transmissions to the Smart Battery host for master mode alarm messages.

- 0 No PEC byte on alarm warning to host
- 1 PEC byte on alarm warning to host

CPE

The CPE bit enables/disables PEC transmissions to the Smart Battery Charger for master mode alarm messages.

- 0 No PEC byte on broadcasts to charger
- 1 PEC byte on broadcasts to charger

LED

The LED bit configures the bq2060 for 4 or 5 LED indication

- 0 Selects the 5 LED indication mode
- 1 Selects the 4 LED indication mode

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SC

The SC bit enables learning cycle optimization for a Smart Charger or independent charge

- 0 Learning cycle optimized for independent charger
- 1 Learning cycle optimized for Smart Charger

SM

The SM bit enables/disables master mode broadcasts by the bq2060

- 0 Broadcasts to host and charger enabled
- 1 Broadcasts to host and charger disabled

If the SM bit is set, modifications to bits in BatteryMode() will not re-enable broadcasts.

Measurement Calibration

ADC

To describe how the bq2060 calculates reported battery and individual cell voltages, the following abbreviations and designations are used:

- VCELL₁₋₄ = voltages at the input pins of the bq2060
- VCELL₁₋₄ = reported cell voltages
- Vn₁₋₄ = voltages at the different series nodes in the battery
- Voltage() = reported battery voltage
- V_{sr} = voltage across the sense resistor

The reported voltages measurements, Voltage() and VCELL₁₋₄, may be calibrated by adjusting five 8- or 16-bit registers in EEPROM: *ADC Offset* in EE0x62, *ADC Voltage Gain* in EE 0x66–0x67, *Cell 2 Calibration Factor* in EE 0x63, *Cell 3 Calibration Factor* in EE 0x64, and *Cell 4 Calibration Factor* in EE 0x65.

The bq2060 first computes the node voltages Vn₁, Vn₂, Vn₃, and Vn₄. The node voltages are inputs to the voltage dividers to the VCELL₁ through VCELL₄ input pins of the bq2060. The bq2060 computes node voltages to calculate the five reported voltages by the bq2060: Voltage(), VCELL₁, VCELL₂, VCELL₃, and VCELL₄.

An *ADC Voltage Gain* factor of 20,000 is the nominal value when using the recommended cell-voltage division ratios of 16:1 on the VCELL₄ and VCELL₃ inputs and 8:1 on the VCELL₂ and VCELL₁ inputs. The bq2060 subtracts the voltage across the sense resistor from the measurements so that the reported voltages reflect the cell-stack voltages only.

The bq2060 compute the node voltages as

$$Vn1 = \left[\frac{VCELL1 * 32768}{1250} + ADC\ Offset \right] * \left[\frac{ADC\ Voltage\ Gain}{65536} \right] \quad (27)$$

$$Vn2 = \left[\frac{VCELL2 * 32768}{1250} + ADC\ Offset \right] * \left[\frac{ADC\ Voltage\ Gain + 8 * (Cell\ 2\ Calibration\ Factor)}{65536} \right] \quad (28)$$

$$Vn3 = \left[\frac{VCELL3 * 32768}{1250} + ADC\ Offset \right] * \left[\frac{ADC\ Voltage\ Gain + 8 * (Cell\ 3\ Calibration\ Factor)}{65536} \right] * \left[\frac{2}{65536} \right] \quad (29)$$

$$Vn4 = \left[\frac{VCELL4 * 32768}{1250} + ADC\ Offset \right] * \left[\frac{ADC\ Voltage\ Gain + 8 * (Cell\ 4\ Calibration\ Factor)}{65536} \right] * \left[\frac{2}{65536} \right] \quad (30)$$

Note: With LCC1–LCC0 = 00, *Cell 4 Calibration Factor* = 0.

ADC Offset adjusts the ADC reading for voltage and current measurements. *ADC Offset* is a signed 8-bit value that cancels offset present in the circuit with no potential or current flow. *ADC Offset* is typically set between -20 and 20.

The bq2060 uses the computed node voltages to calculate the reported voltages. It does not compute reported cell voltages greater than the selected number of nodes. If no individual cell voltages are to be measured, LCC1–LCC0 should be set to 00 and the top of the battery stack should be connected to a voltage divider to the VCELL₄ input.

The bq2060 computes the reported voltages as follows:

$$Voltage() = Vn4 (LCC1–LCC0 = 11 or 00) - V_{sr}$$

$$Voltage() = Vn3 (LCC1–LCC0 = 10) - V_{sr}$$

$$Voltage() = Vn2 (LCC1–LCC0 = 01) - V_{sr}$$

$$VCELL4 = Vn4 - Vn3$$

$$VCELL3 = Vn3 - Vn2$$

$$VCELL2 = Vn2 - Vn1$$

$$V_{CELL1} = V_{n1} - V_{sr}$$

Current

The bq2060 scales Current() to mA units by the 16-bit value *ADC Sense Resistor Gain* in EE 0x68–0x69. Adjusting *ADC Sense Resistor Gain* from its nominal value provides a method to calibrate the current readings for variances in the ADC gain, internal voltage reference, and sense resistor value. The bq2060 calculates Current() by

$$\text{Current()} = \frac{[(\text{ADC Reading} + \text{ADC Offset}) * \text{ADC Sense Resistor Gain}]}{16,384} \quad (31)$$

The nominal value for *ADC Sense Resistor Gain* is given by equation (6).

VFC

To calibrate the coulomb counting measurement for VFC gain errors and sense resistor tolerance, the value of *VFC Sense Resistor Gain* EE 0x6a–0x6b may be adjusted from its nominal value.

The nominal value of *VFC Sense Resistor Gain* is given by equation (5).

The bq2060 VFC circuit can introduce a signal opposite in sign from that of the inherent device and circuit offset to cancel this error. The offset calibration routine is initiated with commands to ManufacturerAccess().

The bq2060 calculates the offset with the calibration routine and stores the calibration value using the least 21 bits of *VFC Offset* in EE 0x5e–0x60.

The least 20 bits store the offset calibration value (OCV). The sign of the offset calibration value is positive if the 21st bit is 0.

$$\text{OCV} = \frac{0.6V}{\text{VFC Offset}_{19-0}} \quad (32)$$

Temperature

The bq2060 uses *Temperature Offset* in EE 0x61 to calibrate the Temperature() function for offset. The required offset adjustment, TOFF (C), sets *Temperature Offset* according to the equation

$$\text{Temperature Offset} = \text{TOFF} * 10 \quad (33)$$

where

$$-12.8 \leq \text{TOFF} \leq 12.7$$

Constants and String Data

EEPROM Constants

Check/Byte 1 EE 0x00–0x01 and *Check Byte 2* EE 0x7e–0x7f must be programmed to 0x3c7f and 0xa55a, respectively.

Specification Information

Specification Information EE 0x14–0x15 stores the default value for the SpecificationInfo() function. It is stored in EEPROM in the same format as the data returned by the SepcificationInfo().

Manufacture Date

Manufacture Date EE 0x16–0x17 stores the default value for the ManufactureDate() function. It is stored in EEPROM in the same format as the data returned by the ManufactureDate().

Serial Number

Serial Number EE 0x18–0x19 stores the default value for the SerialNumber() function. It is stored in EEPROM in the same format as the data returned by the SerialNumber().

Manufacturer Name Data

Manufacturer Name Length EE 0x20 stores the length of the desired string that is returned by the ManufacturerName() function. Locations EE 0x21–0x2a store the characters for ManufacturerName() in ASCII code.

Device Name Data

Device Name Length EE 0x30 stores the length of the desired string that is returned by the DeviceName() function. Locations EE 0x31–0x37 store the characters for DeviceName() in ASCII code.

Device Chemistry Data

Device Chemistry Length EE 0x40 stores the length of the desired string that is returned by the DeviceChemistry() function. Locations EE 0x41–0x44 store the characters for DeviceChemistry() in ASCII code.

Manufacturers Data Length

Manufacturers Data Length EE 0x50 stores the length of the desired number of bytes that is returned by the ManufacturersData() function. It should be set to 7.

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Absolute Maximum Ratings

Symbol	Parameter	Minimum	Maximum	Unit	Notes
V _{CC} —Supply voltage	Relative to V _{SS}	-0.3	+6.0	V	
V _{IN} —All other pins	Relative to V _{SS}	-0.3	+6.0	V	
T _{OPR}	Operating temperature	-20	+70	°C	Commercial

Note: Permanent device damage may occur if **Absolute Maximum Ratings** are exceeded. Functional operation should be limited to the Recommended DC Operating Conditions detailed in this data sheet. Exposure to

DC Electrical Characteristics (V_{CC} = 2.7–3.7V, T_{OPR} = -20–70°C, Unless Otherwise Noted)

Symbol	Parameter	Conditions	Minimum	Typical	Maximum	Unit
V _{CC}	Supply voltage		2.7	3.3	3.7	V
I _{CC}	Operating current	V _{OUT} inactive		180	235	μA
I _{SLP}	Low-power storage mode current	1.5V < V _{CC} < 3.7V		5	10	μA
I _{LVOUT}	V _{OUT} leakage current	V _{OUT} inactive	-0.2		0.2	μA
I _{VOUT}	V _{OUT} source current	V _{OUT} active, V _{OUT} = V _{CC} - 0.6V	-5.0			mA
V _{OLS}	Output voltage low: LED ₁ –LED ₅ , CFC, DFC	I _{OLS} = 5mA			0.4	V
	Output voltage low: THON, CVON	I _{OLS} = 5mA			0.36	V
V _{IL}	Input voltage low $\overline{\text{DISP}}$		-0.3		0.8	V
V _{IH}	Input voltage high $\overline{\text{DISP}}$		2.0		V _{CC} + 0.3	V
V _{OL}	Output voltage low SMBC, SMBD, HDQ16, ESCL, ESDA	I _{OL} = 1.0mA			0.4	V
V _{ILS}	Input voltage low SMBC, SMBD, HDQ16, ESCL, ESDA		-0.3		0.8	V
V _{IHS}	Input voltage high SMBC, SMBD, HDQ16, ESCL, ESDA		1.7		6.0	V
V _{AI}	Input voltage range VCELL _{1–4} , TS, SRC		V _{SS} - 0.3		1.25	V
I _{RB}	RBI data-retention input current	V _{RBI} > 3.0V, V _{CC} < 2.0V		10	50	nA
V _{RBI}	RBI data-retention voltage		1.3			V
Z _{AI1}	Input impedance: SR1, SR2	0–1.25V	10			MΩ
Z _{AI2}	Input impedance: VCELL _{1–4} , TS, SRC	0–1.25V	5			MΩ

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VFC Characteristics ($V_{CC} = 3.1\text{--}3.6\text{V}$, $T_{OPR} = 0\text{--}70^{\circ}\text{C}$ Unless Otherwise Noted)

Symbol	Parameter	Conditions	Minimum	Typical	Maximum	Unit
V_{SR}	Input voltage range, V_{SR2} and V_{SR1}	$V_{SR} = V_{SR2} - V_{SR1}$	-0.25		+0.25	V
V_{SROS}	V_{SR} input offset	$V_{SR2} = V_{SR1}$, autocorrection disabled	-250	-50	250	μV
V_{SRCOS}	Calibrated offset		-16		+16	μV
RM_{VCO}	Supply voltage gain coefficient (see Note)	$V_{CC} = 3.3\text{V}$		0.8	1.2	%/V
RM_{TCO}	Temperature gain coefficient (see note)	Slope for $T_{OPR} = -20$ to 70°C	-0.09		+0.09	%/ $^{\circ}\text{C}$
		Total Deviation $T_{OPR} = -20$ to 70°C	-1.6		0.1	%
		Slope for $T_{OPR} = -0$ to 50°C	-0.05		+0.05	%/ $^{\circ}\text{C}$
		Total Deviation $T_{OPR} = -0$ to 50°C	-0.6		0.1	%
INL	Integral nonlinearity error	$T_{OPR} = 0\text{--}50^{\circ}\text{C}$			0.21	%

Note: RM_{TCO} total deviation is from the nominal gain at 25°C .

REG Characteristics ($T_{OPR} = -20\text{--}70^{\circ}\text{C}$)

Symbol	Parameter	Conditions	Minimum	Typical	Maximum	Unit
V_{RO}	REG controlled output voltage	JFET: $R_{ds(on)} < 150\Omega$ $V_{gs}(\text{off}) < -3.0\text{V}$ @ $10\mu\text{A}$	3.1	3.3	3.6	V
I_{REG}	REG output current		1.0			μA

SMBus AC Specifications (V_{CC} = 2.7–3.7V, T_{OPR} = -20–70°C, Unless Otherwise Noted)

Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
F _{SMB}	SMBus operating frequency	Slave mode, SMBC 50% duty cycle	10		100	kHz
F _{MAS}	SMBus master clock frequency	Master mode, no clock low slave extend		51.2		kHz
T _{BUF}	Bus free time between start and stop		4.7			μs
T _{HD:STA}	Hold time after (repeated) start		4.0			μs
T _{SU:STA}	Repeated start setup time		4.7			μs
T _{SU:STO}	Stop setup time		4.0			μs
T _{HD:DAT}	Data hold time	Receive mode	0			ns
		Transmit mode	300			ns
T _{SU:DAT}	Data setup time		250			ns
T _{TIMEOUT}	Error signal/detect	See Note 1	25		35	ms
T _{LOW}	Clock low period		4.7			μs
T _{HIGH}	Clock high period	See Note 2	4.0		50	μs
T _{LOW:SEXT}	Cumulative clock low slave extend time	See Note 3			25	ms
T _{LOW:MEXT}	Cumulative clock low master extend time	See Note 4			10	ms

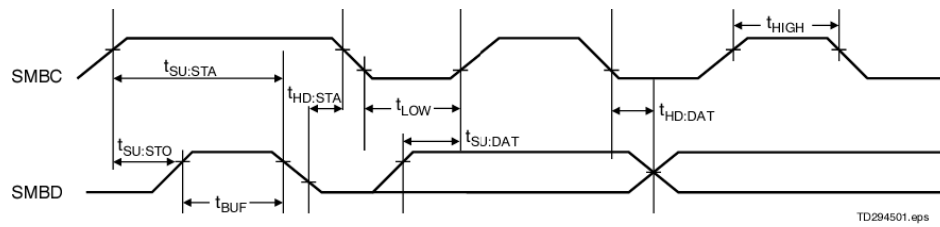
- Notes:**
1. The bq2060 will time out when any clock low exceeds T_{TIMEOUT}.
 2. T_{HIGH} Max. is minimum bus idle time. SMBC = SMBD = 1 for t > 50μs will cause reset of any transaction involving bq2060 that is in progress.
 3. T_{LOW:SEXT} is the cumulative time a slave device is allowed to extend the clock cycles in one message from initial start to the stop. The bq2060 typically extends the clock only 20μs as a slave in the read byte or write byte protocol.
 4. T_{LOW:MEXT} is the cumulative time a master device is allowed to extend the clock cycles in one message from initial start to the stop. The bq2060 typically extends the clock only 20μs as a master in the read byte or write byte protocol.

HDQ16 AC Specifications (V_{CC} = 2.7–3.7V, T_{OPR} = -20–70 °C, Unless Otherwise Noted)

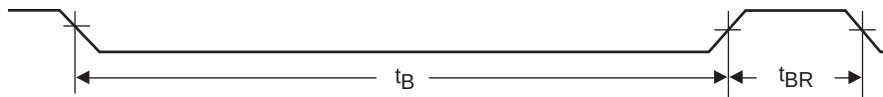
Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
t _{CYCH}	Cycle time, host to bq2060 (write)		190	-	-	μs
t _{CYCB}	Cycle time, bq2060 to host (read)		190	205	250	μs
t _{STRH}	Start hold time, host to bq2060 (write)		5	-	-	ns
t _{STRB}	Start hold time, host to bq2060 (read)		32	-	-	μs
t _{DSU}	Data setup time		-	-	50	μs
t _{DSUB}	Data setup time		-	-	50	μs
t _{DH}	Data hold time		100	-	-	μs
t _{DV}	Data valid time		80	-	-	μs
t _{SSU}	Stop setup time		-	-	145	μs
t _{SSUB}	Stop setup time		-	-	145	μs
t _{RSPS}	Response time, bq2060 to host		190	-	320	μs
t _B	Break time		190	-	-	μs
t _{BR}	Break recovery time		40	-	-	μs

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SMBus Timing Data

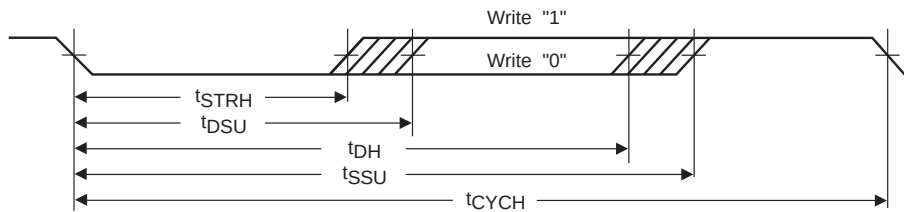


HDQ16 Break Timing

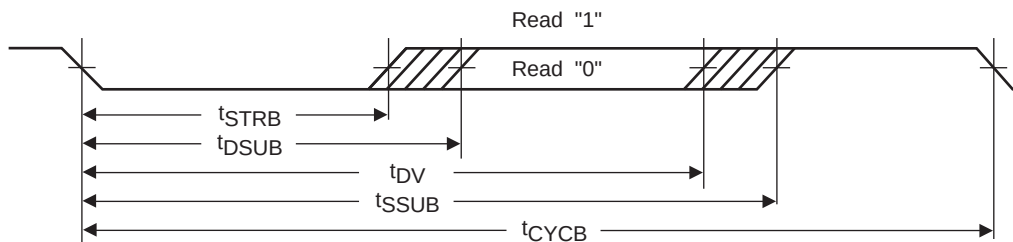


TD201803.eps

HDQ16 Host to bq2060



HDQ16 bq2060 to Host



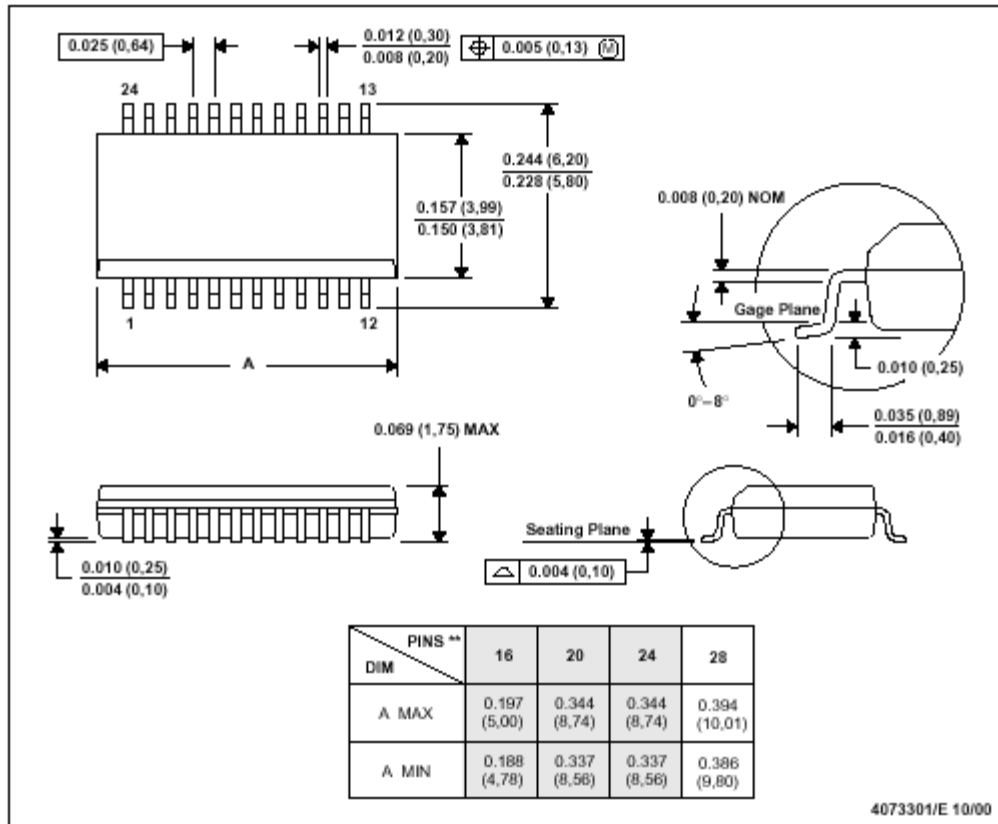
TD201805.eps

MECHANICAL DATA

DBQ (R-PDSO-G**)

PLASTIC SMALL-OUTLINE

24 PINS SHOWN



- NOTES: A. All linear dimensions are in inches (millimeters).
 B. This drawing is subject to change without notice.
 C. Body dimensions do not include mold flash or protrusion not to exceed 0.006 (0,15).
 D. Falls within JEDEC MO-137

Ordering Information

bq2060 -E411

Tape and Reel
 blank = tubes
 TR = tape and reel

Package Option:
 SS = 28-pin SSOP (DBQ)

Device:
 bq2060 SBS v1.1-Compliant Gas Gauge IC

Data Sheet Revision History

Change No.	Page No.	Description	Nature of Change
1	1	V-to-F Converter offset	Was: 20μV Is: 16μV
2	1	Calibration of true battery capacity	Was: from a programmable level of full to empty Is: from programmable near full to near empty levels
3	3	Digital filter operation	Was: does not integrate charge or discharge counts Is: does not measure charge or discharge counts Was: flowing through the sense resistor because of offset. Is: flowing through the sense resistor
4	5	Figure 2. Bq2060 Operational Overview	Add Light Discharge Compensation input. Delete Suspend Compensation box.
5	6	Equation for value of FCC	Was: $FCC(new) = DCR + (FCC * BatteryLow\%)$ Is: $FCC(new) = DCR(final) = DCR(initial) + \text{measured discharge to EDV2} + (FCC \times BatteryLow\%)$ $Battery Low\% = (\text{value stored in EE } 0x54) \div 2.56$
6	6	Battery voltage threshold for qualified discharge	Was: voltage was greater than the EDV2 threshold Is: voltage was less than the EDV2 threshold
7	6	End-of-discharge thresholds	Was: three compensated low-voltage thresholds Is: three low-voltage thresholds
8	7	Table 3 header	Was: Access Is: SMBus Access
9	8	EDV threshold reset	Was: The bq2060 resumes EDV threshold detection after Current() drops below the overload current threshold. Is: The bq2060 resumes EDV threshold detection after Current() drops below the overload current threshold. Any EDV threshold detected will be reset after 10mAh of charge are applied.
10	8	Self-discharge estimation rate	Was: estimation for 25°C Is: estimation rate for 25°C
11	8	Replace times sign with mathematical bullet	Was: $Self - Discharge Update Time = \frac{640 \cdot 13500}{256 \cdot n \times (Y\% \text{ per day})} \text{ seconds}$ Is: $Self - Discharge Update Time = \frac{640 \cdot 13500}{256 \cdot n \cdot (Y\% \text{ per day})} \text{ seconds}$ Was: $\frac{640 \cdot 13500}{256 \cdot n \times (Y\% \text{ per day})} = 6750 \text{ seconds}$ Is: $\frac{640 \cdot 13500}{256 \cdot n \cdot (Y\% \text{ per day})} = 6750 \text{ seconds}$

12	10	Typos in overcurrent condition	Was: On detecting an overcurrent condition, the bq2060 sets the ChargingCurrent() to zero and sets the TERMINATE_CHARGE_ALARM bit in Battery Status(). The overcurrent condition and TERMINATE_CHARGE_ALARM are cleared when the measured current drops below the ChargingCurrent plus the <i>Overcurrent Margin</i>. Is: On detecting an overcurrent condition, the bq2060 sets the ChargingCurrent() to zero and sets the TERMINATE_CHARGE_ALARM bit in Battery Status(). The overcurrent condition and TERMINATE_CHARGE_ALARM are cleared when the measured current drops below the ChargingCurrent plus the <i>Overcurrent Margin</i>.
13	10	Typo in Overvoltage	Was: BatteryStat-us() Is: BatteryStatus()
14	10	Overtemperature criterion	Was: An over-temperature condition exists when Temperature() exceeds the <i>Max T</i> value programmed in EE 0x45 (most significant nibble). Is: An over-temperature condition exists when Temperature() is greater than or equal to the <i>Max T</i> value programmed in EE 0x45 (most significant nibble).
15	10	Overtemperature cleared	Was: drops 5 degrees C below the <i>Max T</i> value or 43°C. Is: is equal to or below (<i>Max T</i> – 5°C) or 43°C.
16	11	Extensive changes in Table 6: Alarm and Status Bit Summary	Was: See Table 6 in SLUS035C. Is: See Table 6 in SLUS035D.
17	12	Fifth LED function	Was: A 5th LED can be used with the 4 LED display option to show when the battery capacity is equal to 100%. Is: A 5th LED can be used with the 4 LED display option to show when the battery capacity is $\geq$ to 100%.
18	12	Display activation	Was: Detection of the transition activates the display and starts a display timer that advances for four seconds. Is: Detection of the transition activates the display and starts a four-second display timer.
19	12	Display disabling	Was: Unless noted, EDV0 = 0. Is: The display is disabled if EDV0 = 1.
20	15	SMBus On and Off State	Was: <i>OH State</i> detection Is: Off State detection
21	15	Removal of t _{RR} from Figure 6	Was: See Fig. 6 in SLUS035C. Is: See Fig. 6 in SLUS035D.
22	16	ManufacturerAccess description	Was: This function provides writable command codes to control the bq2060 during normal operation and pack manufacture. Is: These commands can be ignored if sent within one second after a device reset.
23	19	Time between settings of ALARM_MODE bit	Was: An SMBus host that does not want the bq2060 to be a master on the SMBus must therefore continually set this bit at least once per 45s Is: To prevent the bq2060 from becoming a master on the SMBus, an SMBus host must therefore continually set this bit at least once per 50s

24	19	Enabling transmission of ChargingCurrent() and ChargingVoltage()	Was: When cleared, the bq2060 transmits the ChargingCurrent() and ChargingVoltage() values to the Smart Battery Charger when charging is desired. Is: When cleared, the bq2060 transmits the ChargingCurrent() and ChargingVoltage() values to the Smart Battery Charger.
25	24	ChargingCurrent()	Was: Range: 0 to 61,456mA Is: Range: 0 to 65,535mA
26	24	ChargingVoltage()	Was: Range: 0 to 61,456mV Is: Range: 0 to 65,535mV
27	25	Setting OVER_TEMP_ALARM bit	Was: temperature is greater than allowed by the <i>MaxT</i> limit Is: temperature is greater than or equal to the <i>MaxT</i> limit
28	27	Setting ManufacturerName()	Was: sets ManufacturerName() to the value programmed in <i>Manufacturer Name</i> EE 0x20–0x26 Is: sets ManufacturerName() to the value programmed in <i>Manufacturer Name</i> EE 0x20–0x2a
29	27	ManufacturerData() description	Was: critical EEPROM programming parameters Is: critical operating parameters
30	27	ManufacturerData() purpose	Was: calculated EDV threshold Is: pending EDV threshold voltage
31	28	Move paragraph from CVUV to Pack Status and Pack Configuration	Was: Is: The Pack Configuration register reflects how the bq2060 is configured as defined by the value programmed in <i>Pack Configuration</i> in EE 0x3f.
32	28	Introduce Pack Status Register table	Was: Is: The Pack Status Register consists of the following bits:
33	28	Pack Status EDV2 bit = 0	Was: Voltage() > EDV2 threshold Is: Voltage() > EDV2 threshold (discharging)
34	28	EINT bit function	Was: The EDV2 bits indicate Is: The EDV2 bit indicates
35	32	Setting the digital filter threshold, VDF (μV)	Was: The desired digital filter threshold, VDF (μV), is set by calculating the value stored in <i>Digital Filter</i> EE 0x52. Is: The digital filter threshold, VDF (μV), is set by the value stored in <i>Digital Filter</i> EE 0x52.
36	32	Pack capacity storage	Was: Pack capacity is programmed in mAh units to <i>Pack Capacity</i> in EE 0x3a–0x3b and <i>Last Measured Discharge</i> in EE 0x38–0x39. Is: Pack capacity in mAh units is stored in <i>Pack Capacity</i> EE 0x3a–0x3b.
37	32	Last Measured Discharge initial value storage	Was: Is: The initial value for <i>Last Measured Discharge</i> in mAh is stored in EE 0x38–0x39.

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38	32	EDV compensation	Was: If EDV compensation is enabled, the bq2060 calculates battery voltage to determine EDV0, EDV1, EDV2 as a function of EDV, battery capacity, temperature, and discharge load Is: If EDV compensation is enabled, the bq2060 calculates battery voltage to determine EDV0, EDV1, and EDV2 thresholds as a function of battery capacity, temperature, and discharge load.
39	33	FBL equation term definition	Was: C is 0%, 3%, or <i>Battery Low</i> % for EDV0, EDV1, and EDV2, respectively and C0 is the capacity related EDV adjustment factors. Is: C (0%, 3%, or <i>Battery Low</i> % for EDV0, EDV1, and EDV2, respectively) and C0 are the capacity related EDV adjustment factors.
40	34	Self-discharge rate	Was: $Self - Discharge Rate = 2s \left(\frac{52.73}{\%PERDAY} \right)$ Is: $Self - Discharge Rate = 256 - \left(\frac{52.73}{\%PERDAY} \right)$
41	35	Temperature threshold equation	Was: $MaxT = \text{Int} \left[\frac{69 - MAXTEMP}{1.6} + 0.5 \right]$ Is: $MaxT = \left[\frac{69 - MAXTEMP}{1.6} \right]$
42	36	CSYNC bit = 1	Was: The bq2060 sets update RM with a programmed percentage of FCC. Is: The bq2060 updates RM with a programmed percentage of FCC at a valid charge termination.
43	36	CEDV	Was: If reset, the bq2060 uses the values . . . Is: If reset, the bq2060 uses the fixed values . . .
44	38	CPE bit = 0	Was: No PEC byte on alarm warning to charger Is: No PEC byte on broadcasts to charger
45	38	CPE bit = 1	Was: PEC byte on alarm warning to charger Is: PEC byte on broadcasts to charger
46	38	ADC Offset	Was: adjusts the ADC offset Is: adjusts the ADC reading
47	38	ADC Offset	Was: <i>ADC Offset</i> is typically set between -10 and 10. Is: <i>ADC Offset</i> is typically set between -20 and 20.
48	39	VFC	Was: to calibrate the coulomb counting measurement for system errors and sense resistor error Is: to calibrate the coulomb counting measurement for VFC gain errors and sense resistor tolerance
49	39	VFC	Was: opposite in sign as Is: opposite in sign to
50	40	Extensive changes in DC Electrical Characteristics table	Was: SLUS035C version Is: SLUS035D version
51	40	VFC Characteristics table V_{SROS} minimum/typical/maximum	Was: -300/-50/250 Is: -250/-50/250
52	41	VFC Characteristics	Was: $V_{CC} = 3.1-3.5V$ Is: $V_{CC} = 3.1-3.6V$

53	41	REG Characteristics	Was: $V_{CC} = 3.5V$ (max) Is: $V_{CC} = 3.6V$ (max)
54	41	VFC Characteristics table RM_{VCO} conditions	Was: $V_{CC} = 3.5V$ Is: $V_{CC} = 3.3V$
55	41	VFC Characteristics table Note	Was: Note: RM_{TCO} total deviation is from the gain at 25°C. Is: Note: RM_{TCO} total deviation is from the nominal gain at 25°C.
56	41	REG Characteristics table title	Was: REG Characteristics Is: REG Characteristics ($T_{OPR} = -20-70^{\circ}C$)
57	42	SMBus AC Specifications table title	Was: SMBus AC Specifications ($T_A = T_{OPR}$, $2.9V < V_{CC} < 3.7V$ unless otherwise noted) Is: SMBus AC Specifications ($V_{CC} = 2.7-3.7V$, $T_{OPR} = -20-70^{\circ}C$, Unless Otherwise Noted)
58	42	HDQ16 AC Specifications table title	Was: HDQ16 AC Specifications ($T_A = T_{OPR}$, $2.9V < V_{CC} < 3.7V$ unless otherwise noted) Is: HDQ16 AC Specifications ($V_{CC} = 2.7-3.7V$, $T_{OPR} = -20-70^{\circ}C$, Unless Otherwise Noted)
59	42	HDQ16 AC Specifications table t_{DH} minimum	Was: 90μs Is: 100μs
60	42	HDQ16 AC Specifications table t_{RSPS} minimum	Was: 320μs Is: 190μs
61	42	HDQ16 AC Specifications table t_{RSPS} maximum	Was: - Is: 320ms
62	45	Replace package diagram and Ordering Information Package Option with SS = 28-pin SSOP (DBQ)	Was: SLUS035C version Is: SLUS035D version

PACKAGING INFORMATION

Orderable Device	Status ⁽¹⁾	Package Type	Package Drawing	Pins	Package Qty	Eco Plan ⁽²⁾	Lead/Ball Finish	MSL Peak Temp ⁽³⁾
BQ2060SS-E207-EP	ACTIVE	SSOP/QSOP	DBQ	28	40	None	CU NIPDAU	Level-1-220C-UNLIM
BQ2060SS-E207TR-EP	ACTIVE	SSOP/QSOP	DBQ	28	2500	None	CU NIPDAU	Level-1-220C-UNLIM
BQ2060SS-E411	ACTIVE	SSOP/QSOP	DBQ	28	40	None	CU NIPDAU	Level-1-220C-UNLIM
BQ2060SS-E411TR	ACTIVE	SSOP/QSOP	DBQ	28	2500	None	CU NIPDAU	Level-1-220C-UNLIM

⁽¹⁾ The marketing status values are defined as follows:

ACTIVE: Product device recommended for new designs.

LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.

NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.

PREVIEW: Device has been announced but is not in production. Samples may or may not be available.

OBSOLETE: TI has discontinued the production of the device.

⁽²⁾ Eco Plan - May not be currently available - please check <http://www.ti.com/productcontent> for the latest availability information and additional product content details.

None: Not yet available Lead (Pb-Free).

Pb-Free (RoHS): TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.

Green (RoHS & no Sb/Br): TI defines "Green" to mean "Pb-Free" and in addition, uses package materials that do not contain halogens, including bromine (Br) or antimony (Sb) above 0.1% of total product weight.

⁽³⁾ MSL, Peak Temp. -- The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

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