

A Tutorial for Gas Gauging

Introduction

This tutorial introduces the bq2010 Gas Gauge IC (secondary battery available charge monitor). The tutorial should be used with the bq2010 data sheet when designing with or evaluating the bq2010.

The bq2010 Gas Gauge IC is a complete battery monitoring product for NiMH and NiCd batteries. The bq2010 16-pin SOIC provides significant advantages:

- A complete single-chip system solution for in-the-pack monitoring of a battery's available charge
- No battery technology expertise required
- Minimal engineering required, typically a single PCB layout specific to the application
- No software required for stand-alone battery-pack applications
- Single-wire serial interface for communication with an external processor to implement a customized display
- Direct LED display drive

This tutorial describes capacity monitoring, compares Unitrode's gas gauge solutions to microprocessor-based implementations, describes device operation in general terms, and addresses implementation issues.

Available Charge Monitoring

Rechargeable batteries are used in many different applications, from cellular phones, portable computers, and medical equipment to power tools. The operating environment of these batteries covers a wide range of temperatures; therefore, battery efficiency changes due to battery temperature and rate of charge or discharge. The bq2010 compensates for both temperature and charge/discharge rate continuously.

The battery available charge can be displayed on LEDs and can be accessed via the serial port. The calculated available charge of the battery is also compensated according to battery temperature because the actual available charge is reduced at lower temperatures. For example, if the bq2010 indicates that the battery is 60% full at a temperature of 25°C, then the bq2010 indicates 40% full when cooled to 0°C, which is the predicted available charge at that temperature. When the temperature returns to 25°C, the displayed capacity returns to 60%. This ensures that the indicated capacity is always conservatively representative of the charge available for use under the given conditions.

The bq2010 also adjusts the available charge for the approximate internal self-discharge that occurs in NiCd or NiMH batteries. The self-discharge adjustment is based on the selected rate, elapsed time, battery charge level, and temperature. This adjustment provides a conservative estimate of self-discharge that occurs naturally and that is a significant source of discharge in systems that are not charged often or are stored at elevated temperatures.

Comparing bq2010 Solution with MCU-Based Implementations

Low-power, single-chip microprocessors such as those available from Motorola, Toshiba, NEC, and others have been used to implement gas gauges in battery-powered equipment, notably camcorders and laptop computers. Although adequate, these implementations require extensive development efforts to be suitable for use in a battery pack, and even then, require significant space in the pack because of the high component count.

The bq2010 by comparison offers efficiency, ease of use, simplicity of design, and low component count. With careful PCB layout, the bq2010 system can fit in the space between AA batteries. Table 1 compares the bq2010 and a typical MCU gas gauge implementation.

bq2010 Tutorial

bq2010 Operation

Gas gauging is accomplished by measuring the charge input to and subsequently removed from a battery. This is done by monitoring the voltage drop across a low-value resistor (typically 20 to 100mΩ) during charge and discharge. This voltage is integrated over time, scaled, and used to drive two 16-bit internal counters:

- Nominal Available Charge (NAC) counter—represents the amount of charge available from the battery.
- Discharge Count Register (DCR)—represents the amount of charge removed from the battery since it was last full.

Also, the Last Measured Discharge (LMD) register is an eight-bit register used to store the most recent count value representing “battery full.”

In a typical situation, the Unitrode Gas Gauge ICs are installed in a battery pack containing unconditioned batteries with an unknown charge state.

On application of power to the bq2010, the following assumptions are made:

- The battery is empty; therefore, the NAC is zero.
- The battery's storage capacity is the Programmed Full Count (PFC) as specified by the programming inputs, which are loaded into the LMD.

The actual storage capacity of the battery has yet to be determined. The battery capacity can be learned by charging the battery until NAC = LMD (LMD = PFC on initialization) and then discharging the battery until the cell voltage reaches the End-of-Discharge Voltage (EDV1) threshold (1.05V for the bq2010). As discharge occurs, the bq2010 tracks the amount of charge removed from the battery in the DCR. The new battery capacity (DCR) is transferred to the LMD if no partial charges have occurred, the temperature is above 10°C, and self-discharge accounts for less than 8 to 18% of the DCR when EDV1 was reached. The valid discharge flag (VDQ) in the bq2010 indicates whether the present discharge is valid for LMD update.

Table 1. Comparing bq2010 and MCU Implementations

Feature	MCU Implementation	bq2010 Solution
Small size	>> 1 square inch; requires extra battery pack space	≤ 1 square inch; fits between batteries
Operating current (not including LEDs)	Typically ≥ 1mA awake; as low as 10μA asleep	125μA typical
LED display	Yes	Yes
Serial I/O	Depends on programming	Yes
Programmable capacity	Depends on programming	Yes
Self-discharge	Generally not implemented	Yes, with temperature compensations
Charge, discharge rate compensations	Generally not available but depends on programming	Yes
Charge, discharge temperature compensations	Generally not available but depends on programming; requires a thermistor	Yes, uses internal temperature sensor
Programming requirements	Extensive MCU programming required for gas gauge functions; possible host programming, algorithm de- velopment, and software testing	No programming for stand-alone applications; small host code for serial I/O applications
Hardware design requirements	Extensive low-power-design, op amp, analog switch, MCU, resonator, low- power regulator, LEDs, sense resistor; component count = 56 typical	No engineering required; component count = 23 typical: bq2010, nFET, LEDs, sense resistor, pro- gramming resistors and capacitors

Discharging Before the First Charge

Most battery pack manufacturers will assemble their packs with the bq2010 and ship the packs without charging. When the customer receives a new pack, the gas gauge indicates EMPTY, and the customer then charges the pack until it indicates full. It is possible that fast-charge terminates before the gas gauge shows full because the available capacity of the battery was not zero.

The battery pack manufacturer may want to instruct the user to discharge the battery to EDV before charging. Once this condition is reached, the battery can be fast-charged until termination—allowing NAC to count up to LMD. Now, the gas gauge is synchronized with the battery and learns the true battery capacity on the next valid discharge cycle.

For applications with LED displays, the complete discharge of the battery pack is indicated by LED₁ blinking. For applications using the serial I/O port, complete discharge is indicated when the final end-of-discharge voltage (EDVF) flag is set.

To ensure that the bq2010 accurately predicts the amount of available charge, battery pack manufacturers should instruct their end-users to completely discharge a new battery pack and then charge it until the charger terminates.

Alternatively, the NAC can be written with an estimated battery capacity during pack assembly or testing. The user may then charge the battery so NAC = LMD. The actual capacity is “learned” on the next valid discharge. The appropriate value must be written into the NAC register for proper operation.

Using the bq2010

The bq2010 IC is simple to use and implement into a system. Figure 1 shows the bq2010 configured for full functionality. Almost all of the external connections and components are *optional*, as indicated by the dotted lines. For example, most stand-alone applications do not need the EMPTY pin connection or the DQ port.

All the external components can be surface-mounted. The sense resistor could fit in the space between most cells, and the populated PCB may fit in that space with the correct layout. A bq2010 Gas Gauge IC could, therefore, be added to existing battery packs with little re-tooling of plastics.

Monitoring the Battery

To determine and track the charge state of the battery, the bq2010 monitors both the divided battery voltage and the voltage drop across the sense resistor.

The divided battery voltage (V_{SB}) is provided by a resistor-divider that divides the battery pack voltage down to a single-cell voltage. V_{SB} is primarily used to determine when the battery has reached the EDV1 threshold so that the new battery capacity determined during discharge may be saved in the LMD. V_{SB} is also used for EDVF determination, battery-removed indication, and battery-replaced indication.

The battery current is monitored using a low-value sense resistor attached to the negative terminal of the battery. The current through the resistor generates a proportional voltage drop, V_{SR} , which is provided to the SR input of the bq2010.

Picking a Sense Resistor

The sense resistor is used to measure the current flowing into or out of the battery. The sense resistor value depends on the currents being measured. The bq2010 specification for V_{SR} ranges from a maximum of 2.0V for charging to -300mV for discharging. The offset error for the bq2010 relative to V_{SR} is $\pm 150\mu\text{V}$.

In general, a sense resistor should be selected so that: (a) the voltage drop across that resistor exceeds 5 to 7mV for the lowest current representing the majority of the battery drain, and (b) the lowest practical V_{SR} voltage drop is achieved to maximize the useful voltage available from the battery pack.

For example, Table 2 summarizes the approximate current requirements for a laptop computer application. The majority of the battery capacity is used in run (no disks) mode. The next largest amount of battery capacity is used in run (with disks) mode, with suspend mode consuming the least amount of battery capacity, even though it makes up the largest block of time.

If a 0.1 Ω sense resistor is used, the voltage input to SR is as shown. This means that for both run modes, the integrator repeatability error is a maximum of 2% because $|V_{SR}|$ is well above 30mV. Although the repeatability error associated with suspend mode is approximately 5%, its total error contribution is only 0.5% because suspend mode is responsible for only 10% of the total consumption.

bq2010 Tutorial

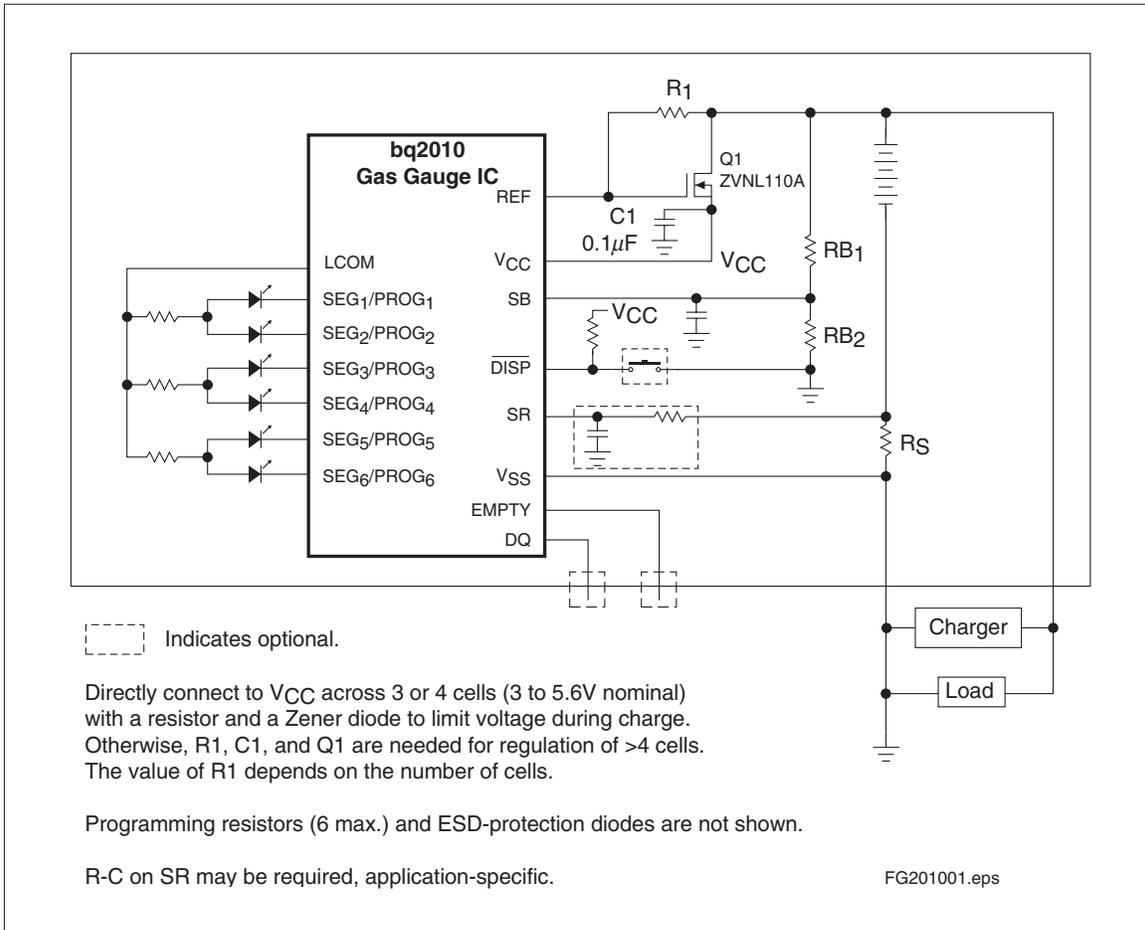


Figure 1. bq2010 Application Diagram—LED Display

Table 2. Approximate Laptop Computer Current Requirements

Mode	Current (A)	0.1Ω Voltage Drop (mV)	Time (min.)	% of Battery Usage
Run (with disks)	1	100.0	20	16.7
Run (no disks)	0.5	50.0	175	72.9
Suspend	0.05	5	250	10.4

Selecting PFCs

When the bq2010 is first connected to the battery pack, a Programmed Full Count (PFC) representing the initial full battery capacity is loaded into the LMD. To select this PFC, determine the initial full battery capacity value in mVh by multiplying the manufacturer's battery capacity rating in mAh by the sense resistor value:

$$\text{mVh} = \text{mAh} * R_{\text{SNS}}$$

Find the nearest corresponding value in Table 3 that is *less than* the calculated mVh value, and then set the programming pin levels to select the Programmed Full Count (PFC), scale, and scale multiplier associated with that value.

Nine PFC settings are available using PROG₁ and PROG₂, which together with scale (PROG₃ and PROG₄) settings provide a wide range of initial full battery values. (PROG₅ is used to select the self-discharge compensations for either NiMH or NiCd batteries; PROG₆ is used to determine the display mode of the bq2010 as described on page 6.)

For example, if a 0.1Ω sense resistor is being used, and the battery is rated at 1100mAh, then the initial full battery value is 110mVh. The nearest available value that is less than 110mVh from Table 3 is 106mVh,

which corresponds to PROG₁ = Z, PROG₂ = Z, PROG₃ = L, and PROG₄ = L.

Note that some cells in Table 3 have identical initial full battery values. For example, 141mVh can be found two places:

- Example 1: PROG₁ = L, PROG₂ = L, PROG₃ = Z, PROG₄ = L = 141mVh
- Example 2: PROG₁ = H, PROG₂ = Z, PROG₃ = L, PROG₄ = L = 141mVh

Example 1 corresponds to a PFC of 22528 of 65535 possible counts (34.4%). This means that, in all likelihood, a majority of the counter range will remain unused. Counter resolution could be increased by using the settings in example 2. In this case, the PFC is 45056 of 65535 counts (68.8% of range). In general, when faced with a choice, it is better to pick the finer resolution (that is, a larger PFC).

PROG₃ and PROG₄ inputs determine the scale to be used by the bq2010. Together these two pins determine the mVh value of a single NAC count. Thus, for any given PFC selected by PROG₁ and PROG₂, the capacity represented by that PFC (in mVh) is given by:

$$\text{PFC} * \text{scale}$$

Note that the scale value is given for a PROG₃, PROG₄ pair at the top of each column in Table 3.

Table 3. bq2010 Programmed Full Count mVh Selections

PROG _x		Pro-grammed Full Count (PFC)	PROG ₄ = L			PROG ₄ = Z			Units
			PROG ₃ = H	PROG ₃ = Z	PROG ₃ = L	PROG ₃ = H	PROG ₃ = Z	PROG ₃ = L	
-	-	-	Scale = 1/80	Scale = 1/160	Scale = 1/320	Scale = 1/640	Scale = 1/1280	Scale = 1/2560	mVh/ count
H	H	49152	614	307	154	76.8	38.4	19.2	mVh
H	Z	45056	563	282	141	70.4	35.2	17.6	mVh
H	L	40960	512	256	128	64.0	32.0	16.0	mVh
Z	H	36864	461	230	115	57.6	28.8	14.4	mVh
Z	Z	33792	422	211	106	53.0	26.4	13.2	mVh
Z	L	30720	384	192	96.0	48.0	24.0	12.0	mVh
L	H	27648	346	173	86.4	43.2	21.6	10.8	mVh
L	Z	25600	320	160	80.0	40.0	20.0	10.0	mVh
L	L	22528	282	141	70.4	35.2	17.6	8.8	mVh
VSR equivalent to 2 counts/sec. (nom.)			90	45	22.5	11.25	5.6	2.8	mV

bq2010 Tutorial

Using the Programming Pins

The bq2010 is programmed through the LED display pins during a special programming cycle that occurs during power-up or during a device reset.

Programming Without LED Display

In applications where the LED display is not used, programming is very simple. The bq2010 may be programmed by tying each programming pin directly to the appropriate level:

$$H = V_{CC}$$

$$Z = \text{open}$$

$$L = V_{SS}$$

LED outputs must be disabled by tying $\overline{\text{DISP}}$ to V_{CC} . LCOM may remain open.

Programming With LED Display

When the LED display is used, it is necessary to provide programming information with either a pull-up resistor to V_{CC} , a pull-down resistor to V_{SS} (200K Ω value in either case), or no resistor at all. The logic states are set as follows:

$$H \leq 200K \text{ to } V_{CC}$$

$$Z = \text{no resistor}$$

$$L \leq 200K \text{ to } V_{SS}$$

LCOM must be used to provide power to the LEDs so that they may be disabled during reading of the programming resistors (see Figure 1).

Selecting Battery Chemistry

PROG₅ is used during power-up to select self-discharge compensations for either NiMH or NiCd batteries. PROG₅ = Z for NiCd and L for NiMH batteries.

Using the LED Display

The bq2010 supports 6 LEDs that display a gauge of available battery charge. LEDs 1 through 5 provide 20% step indication of charge, while the sixth LED indicates “overfull” when the display is operating in absolute mode (PROG₆ = Z).

Selecting Display Mode

PROG₆ is used during power-up to determine the display mode of the bq2010. The bq2010 uses either absolute or relative battery charge state as described below (PROG₆ = Z or L, respectively).

The display indicates available battery charge as a percentage of “battery full.” This is based on the current LMD value (“relative” mode) or on the PFC value (the initial battery capacity value programmed, “absolute” mode). Relative mode is for applications where the customer does not want to see on the display the decline in battery capacity following many charge/discharge cycles. Absolute mode is for applications when the customer wants each segment to represent a fixed amount of charge.

Display Activation

The LED display is normally maintained in the OFF state to conserve battery power. It is activated during a high rate of battery charge and discharge if $\overline{\text{DISP}}$ is floating, or continuously if the $\overline{\text{DISP}}$ pin is pulled to V_{SS} . When the display is not used, the $\overline{\text{DISP}}$ pin can be tied to V_{CC} to disable the display and allow the pins to be used strictly as programming pins.

LED Supply

The current source for the LEDs is provided through the LCOM pin in all applications, because the programming inputs and the LED outputs share common pins. When the bq2010 is initially powered-up, the LCOM output is disabled, thus allowing the pins to be sensed for the presence of programming resistors tied to V_{CC} or V_{SS} (see Figure 1).

Standard LEDs such as the Sharp PR series should provide adequate performance at low cost. For better results, customers could use a high-brightness LED (low current) such as the more expensive Sharp LR or UR series. The suitability of any particular LED depends not only on its luminosity at rated current, but also the packaging and lensing technique used (very important in concentrating viewable energy, especially for high-ambient-light conditions).

Using the DQ Serial Port

The bq2010 is also equipped with a bidirectional single-line serial I/O port (DQ) that allows it to conveniently communicate with a host processor.

Data Interface

The DQ serial port allows the implementation of gas gauge functions without the need for the LED display. For example, in cellular telephone and laptop computer applications, the LED display is not needed because an LCD is available. The host processor in these cases can simply obtain the gas gauge display step and the temperature over the serial port and use these to indicate available charge. The gas gauge step data is a 4-bit value that represents 1 of 16 possible steps (6.25% of full per step), giving a greater possible display accuracy than is possible with the LED display.

In a more sophisticated approach, the host may obtain the NAC, LMD, temperature, and operational status flags, and then use these to customize and display functions and features.

Battery Pack Testing

The DQ serial port is also useful for final testing of assembled battery packs. The bq2010 can be exercised from a host processor over the DQ serial port—allowing the host to directly control the state of the LED output pins and the EMPTY pin. The state of the programming pins may also be checked. A battery ID byte (stored in on-chip RAM) allows the manufacturer to identify battery types.

Using the EMPTY Pin

The EMPTY pin provides external control for automatic load disconnection on low battery, preventing deep discharge. It activates when V_{SB} drops below the EDVF threshold.

Supplying Power to the Part

The V_{CC} specification for the bq2010 is:

$$3.0V \leq V_{CC} \leq 6.5V$$

This may be achieved in several ways under various battery configurations.

Direct Battery Power

The bq2010 may be powered directly from the batteries in configurations of 3 or 4 cells. When using unregulated direct battery power, ensure that the battery voltage does not exceed the maximum of 6.5V or fall below the minimum operational value of 3.0V.

Direct unregulated power supply should be limited to situations where varying or pulsed load conditions during discharge or charge do not cause battery voltage spikes. Such spikes typically result when batteries drive switching power supplies that use inductive storage, or when start-up transients in motors produce significant voltage spikes on the battery.

Low-Cost nFET Regulator

Most applications require some kind of voltage regulator to supply V_{CC} within specifications over a broad range of battery voltage conditions. The bq2010 provides support for a low-cost regulator circuit consisting of an nFET and the on-chip reference voltage V_{REF} .

Across temperature, V_{REF} ranges from 4.5V to 7.5V, given an I_{REF} of 5 μ A, where:

$$V_{CC} = V_{REF} - V_{GS}$$

where V_{GS} is the gate-source voltage of the nFET, Q1. When the battery voltage drops below V_{REF} , the $R1/R_{REF}$ divider determines V_{CC} . A low-threshold nFET exhibiting a maximum V_{GS} of 0.8 to 1.5V may be adequate for this circuit. An example is the BSS138ZX from Zetex. The correct choice for $R1$ is a function of the number of cells in the battery pack. Table 4 lists different values for $R1$ for various battery packs.

Table 4. Reference Bias Resistor $R1$ Selection

Assuming a Nominal Q1 $V_{GS} = 1.5V$

Number of Cells	$R1$ (Ω)
5	33K
6	100K
7	180K
8	240K
9	300K
10	390K
11	430K

Split Battery Configurations

When a battery pack contains a large number of cells, the bq2010 may be operated from a small number of cells inside the larger pack. This is possible as long as the current required for LED operation does not significantly reduce the available charge of the small cell cluster relative to the available charge of the other cells in the pack. Generally, it is best not to use the bq2010 display in this configuration.

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