Application Report

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Key Design Considerations for the bq27500 and bq27501

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ABSTRACT

This application report provides the basic operating theory and key design considerations for the bq27500 and bq27501 single-cell, Li-ion fuel gauge ICs with the Impedance Track™ algorithm. The bq27500/501 ICs are designed to reside on the system's main board in applications with an embedded or removable battery pack. To achieve best results, the fuel gauge ICs must work properly with the battery charge circuit and the system power sequencing methodology. The application report reviews the basics on fuel gauge system integration including system design, thermistor support, sense-resistor selection, and layout considerations.

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1 Theory of Operation

1.1 Introduction

The bq27500 and bq27501 battery fuel gauges from Texas Instruments are microcontroller peripherals designed to accurately predict remaining battery capacity in single cell Li-ion applications. Designed to reside on the system's main printed-circuit board (PCB), the bq27500/501 work in systems with an embedded or removable battery pack. The bq27500/501 uses the patented Impedance Track™ fuel-gauging algorithm to calculate remaining battery capacity and system run-time. The algorithm continuously measures and stores real-time battery impedance values to construct and predict the battery pack's discharge curve under any use condition. Because the prediction uses the latest impedance values measured by the bq27500/501, the predictions are accurate with batteries of any age (new or used). The bq27500/501 employs a patented *arbitration* algorithm along with stored resistance profiles to automatically adjust the fuel gauge to a newly inserted battery pack

1.2 Basic Circuit

The bq27500 acts as a microcontroller peripheral. It resides on the system's I^2C™ bus and has an address of AAh.

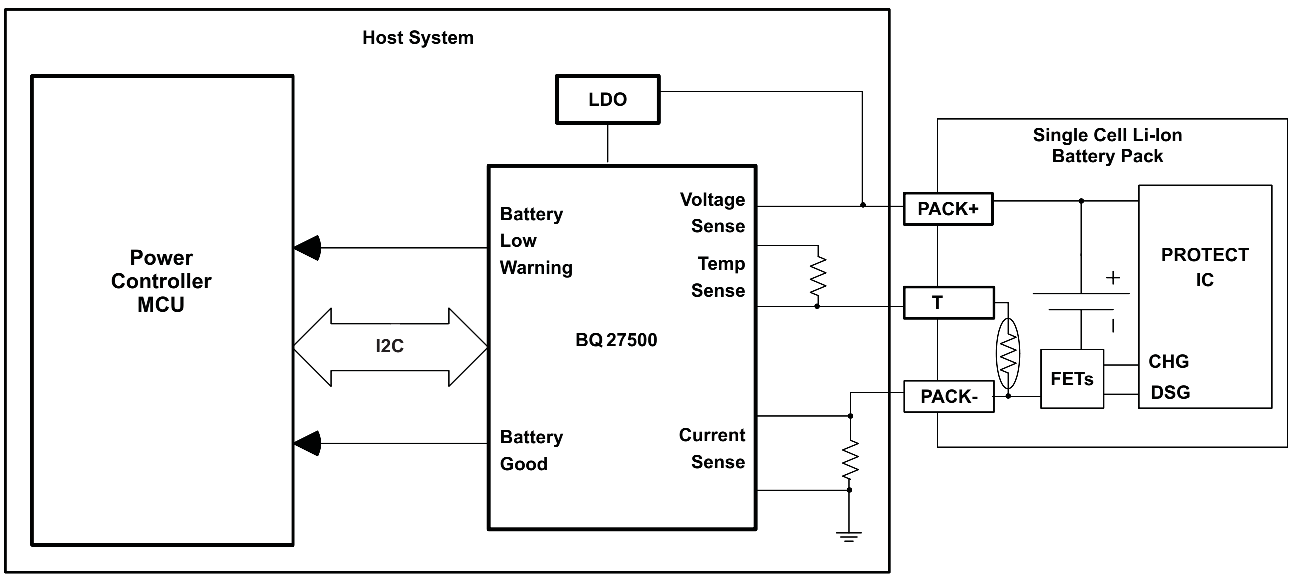

Figure 1. bq27500 Host-Side Battery Fuel Gauge

1.3 Differences Between bq27500 and bq27501

Both the bq27500 and the bq27501 work in systems with an embedded or removable battery pack. The key difference between the two parts is that the bq27501 supports an identification (ID) resistor in the battery pack. By measuring the voltage across the ID resistor on battery pack insertion, the bq27501 quickly configures itself for the type of Li-ion battery.

The bq27500 works in designs that accept one fundamental type of battery, i.e., one anode/cathode combination (chemistry). The bq27501 works with up to two types (two chemistries).

Impedance Track is a trademark of Texas Instruments.
I^2C is a trademark of Philips Electronics.

Table 1. bq27500/501 Comparison

Part Number	Supports Removable Battery Packs or Embedded Batteries	Maximum Number of Different Cell Types (Chemistries) Supported (1)	Maximum Number of Capacity Ratings (2)	Number of Physically Different Battery Packs Supported (3)	Ungradable in System for New Chemistry and Capacity	Example Battery Packs Number of Battery Packs = 1 to N
bq27500	Y	1	One range	Any number	Y	1. 800 mAh, lithium cobalt oxide 2. 780 mAh, lithium cobalt oxide 3. A battery of type (1) or (2) . . N
bq27501	Y	2	Two ranges	Any number	Y	1. 800 mAh, lithium cobalt oxide 2. 1200 mAh, lithium nickel oxide 3. 780 mAh, lithium cobalt oxide 4. 1000 mAh, lithium nickel oxide 5. A battery of type (1), (2), (3), or (4) . . N

(1) Each battery pack that is plugged into a bq27500 application must be the same chemistry. Each battery pack that is plugged into a bq27501 application must be one of two chemistry types.
(2) Each battery pack that is plugged into a bq27500 application must be of similarly rated capacities (within 10%). Each battery pack that is plugged into a bq27501 application must be similar to one of the two predetermined capacity values.
(3) The number of individual battery packs that can be plugged into a bq27500/501 application.

1.4 Fuel Gauge Operation

The bq27500/501 uses the Impedance Track™ algorithm for its accurate fuel gauging. The bq27500/501 measures and stores in real-time the battery pack's resistance as a function of state of charge (SOC). The real-time resistance profiles along with the stored open-circuit voltage (OCV) tables (OCV versus SOC) enables the bq27500/501 to predict the battery pack's discharge curve under any system use condition and temperature to accurately calculate the battery pack's remaining discharge capacity and the system's run time to empty. The algorithm uses current integration (coulomb counting) and OCV measurement to adjust remaining state of charge (RSOC) up or down (for charge or discharge) the predicted discharge curve.

The fuel gauge has four different operational modes. With the system *ON* the bq27500/501 transitions between NORMAL and SLEEP modes depending on the system's load current. If the system's load current is greater than approximately C/20 (a programmable threshold), the bq27500/501 is in NORMAL mode where all measurements are taken (voltage, temperature, and current), and the battery pack's resistance is calculated and updated at various SOC points. The bq27500/501 also periodically runs the simulation to predict the battery pack's discharge curve and calculate remaining battery capacity under the present use conditions. If the system is in a low power mode (STANDBY) with a load current less than approximately C/20, the bq27500/501 enters a SLEEP mode where it wakes up periodically to measure battery pack voltage and correlates the relaxed battery voltage to the corresponding SOC in the stored OCV tables. In this way, RSOC remains accurate and current consumption is minimized. The system's current consumption must be below C/20 for SLEEP mode to work properly.

Table 2. bq27500/501 Power Modes

Fuel Gauge Mode	Battery Inserted	System State	Current Consumption	Measurements Taken	Primary Gauge Method	Resistance Updated
NORMAL	Yes	System ON with load > C/20	<100 µA	Voltage, temperature, and current once per second	Coulomb counting	Yes

Table 2. bq27500/501 Power Modes (continued)

Fuel Gauge Mode	Battery Inserted	System State	Current Consumption	Measurements Taken	Primary Gauge Method	Resistance Updated
SLEEP	Yes	System ON in a STANDBY mode with current <C/20	<15 µA	Voltage and current once per 20 seconds	OVC correlation to RSOC	No
HIBERNATE	Yes	System OFF with load <<< C/20	1 µA	None	NA	No
BATTERY INSERT CHECK MODE	No	System ON with any load, AC adapter inserted	<10 µA	None	NA	No

The two other power modes are HIBERNATE and BATTERY INSERT CHECK. The system can put the bq27500/501 in HIBERNATE mode when the system is turned OFF and system current consumption is in its lowest state. In HIBERNATE mode, the bq27500/501 consumes less than 1 µA and can be waked up with a pin transition (e.g., a system ON pushbutton) or by the system's CPU.

If the system is designed such that the bq27500/501 is powered even when there is no battery inserted, the bq27500/501 resides in the BATTERY INSERT CHECK mode. In this mode, the bq27500/501 consumes less than 15 µA and only checks for battery pack insertion and updates its internal temperature reading.

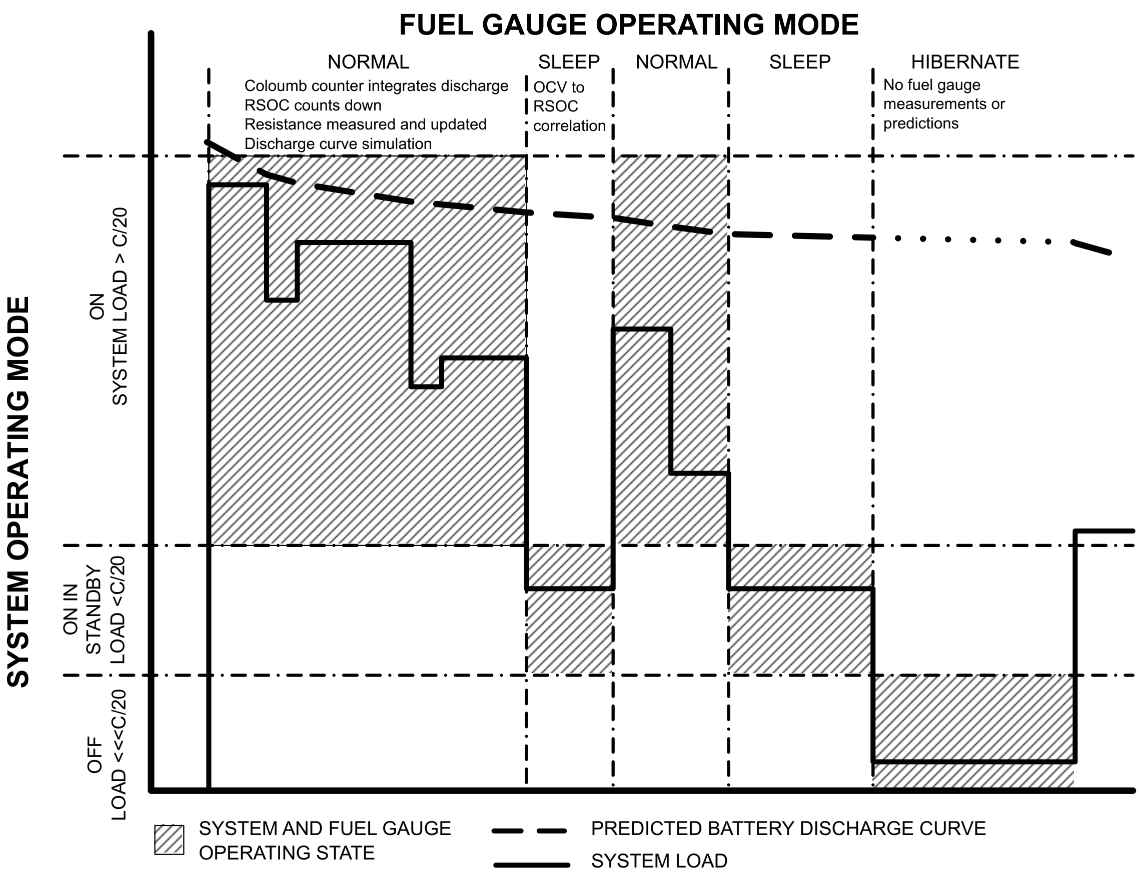

Figure 2. Fuel Gauge Power Modes Versus System Power Modes

1.5 Arbitration Algorithm

The bq27500/501 works in systems with an embedded battery or a removable battery pack. One of the keys to working with a removable battery pack is the bq27500/501 *arbitration* algorithm. This is an algorithm that allows the bq27500/501 to quickly adjust its fuel-gauging parameters to match the characteristics of the inserted battery pack.

The bq27500/501 stores default battery profiles on the chip in flash memory. The Default Profiles consist of the OCV table, the resistance profile, and the battery packs low-rate discharge capacity (Table 3).

Table 3. Default Profile Contents

Profile Parameter	Description
OCV Table	The OCV Table stores the battery pack's OCV versus capacity curve. The bq27500/501 algorithm discounts this curve by the resistance values to simulate the battery pack's discharge curve under the present system use conditions (rate and temperature).
Resistance Profile	The resistance profile is the resistance versus SOC curve used to discount the OCV curve based on the present use conditions.
Low-Rate Discharge Capacity	QMAX is the low-rate or theoretical maximum discharge capacity of the battery pack.

On battery insertion in a system for the first time, the bq27500/501 copies the programmed Default Profile to another flash storage area on the chip, creating a specific Cell Profile. The Cell Profile consists of the copied OCV Table, Resistance Profile, and QMAX. The bq27500/501 then updates the Resistance Profile and QMAX in the Cell Profile during NORMAL operating mode and uses the Cell Profile to run the discharge curve simulations. As long as the battery pack remains in system, the bq27500/501 uses the created Cell Profile as the basis for its fuel gauging. If the battery pack is removed and subsequently re-inserted or a new battery is inserted, the bq27500/501 arbitration algorithm compares the measured characteristics of the inserted battery pack with the Default Profiles and the previously created Cell Profiles and chooses the profile that most closely matches the characteristics of the battery pack.

The bq27500 stores one Default Profile (for the one chemistry supported) and can create up to two Cell Profiles. The bq27501 stores two Default Profiles (for the two chemistries supported) and can create up to two Cell Profiles. The bq27501 reads the battery pack's ID resistor on battery pack insertion and chooses the profile assigned to the pack's resistor value.

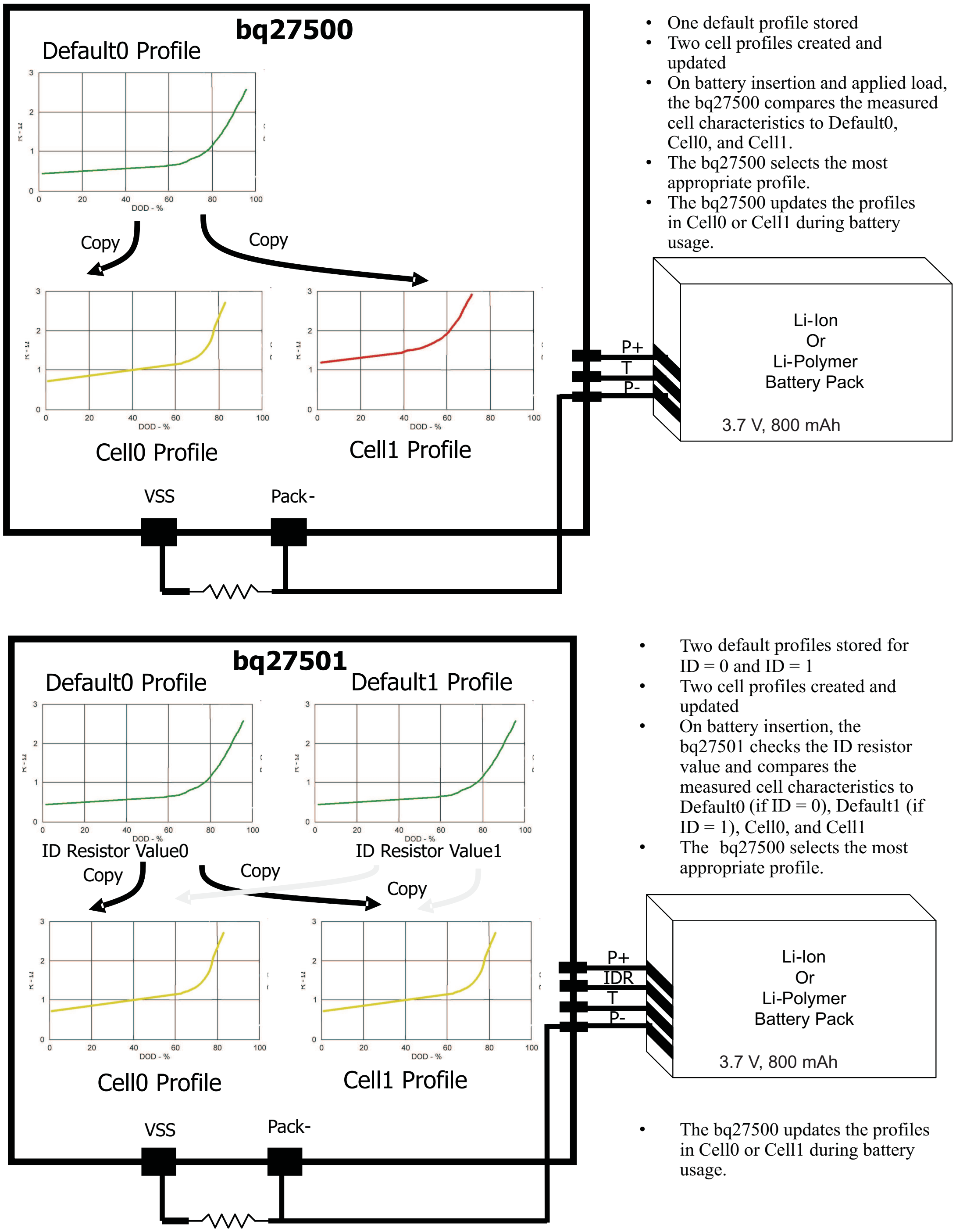

Figure 3. bq27500/501 Profile Arbitration

2 Design Considerations

Designers should consider the following important design considerations when integrating a bq27500/501 in a system.

1. System power path and charger design
2. Thermistor support
3. Power consumption

4. Sense-resistor selection
5. Layout and radio frequency (RF) considerations
6. Battery-low warning implementation

2.1 System Power Path and Charger Design

With the bq27500/501, both the battery-charging and fuel-gauging subsystems are located in the host-side motherboard. They have to work together to optimize the system performance in terms of safety, charging, and gauging. Most of the applications are required to operate the system while simultaneously charging the battery.

Figure 4 shows a circuit diagram of the host-side battery management system including the battery charger and the fuel gauge. The bq24032A is a power path management battery charger which is able to power the system while charging the battery simultaneously. Several considerations of the host-side gauging system design follow.

The first consideration is to obtain the battery initial capacity when a new battery is inserted. Because a solid correlation exists between the battery OCV and SOC, the bq27500/501 needs to measure the OCV before high rate (>C/20) battery charging or discharging starts. In order to accurately measure the OCV, the battery cannot be charged or discharged at >C/20 after it is inserted. The bq27500/501 first determines if the battery is present or not. The fuel gauge puts the BI/TOUT in high-impedance mode. No battery presence is detected if the BI/TOUT pin voltage is high. Battery insertion is detected when this pin voltage is pulled low. Battery charging is disabled by pulling the temperature monitoring pin to ground by turning on MOSFET QT to allow reading the OCV to get the initial battery capacity information when the adapter is present. After the OCV reading is finished and the initial battery capacity is accurately learned, $\overline{\text{BAT\_GD}}$ is pulled low, which turns off MOSFET QT and allows charging of the battery. When the battery is inserted without an adapter, the system turns on in a low-power state (<C/20) for a few ms (to allow for an accurate OCV reading) before fully powering the system.

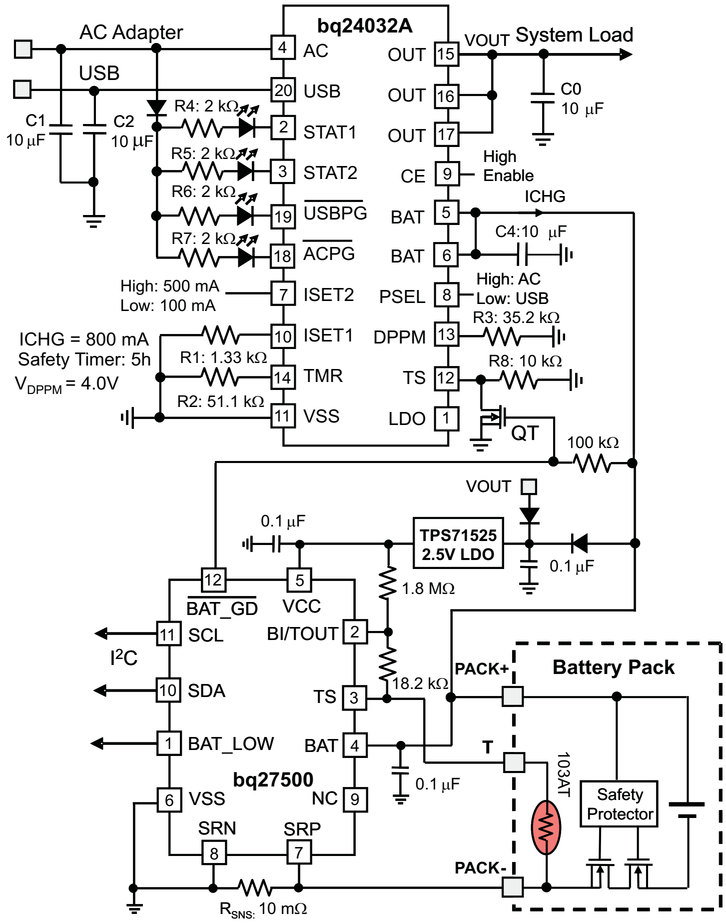

Figure 4. bq27500 Typical Implementation

2.2 Thermistor Support

The second design consideration is how to monitor the battery temperature for charging qualification and adjusting the battery capacity. To minimize the battery degradation, the battery charging is prohibited when the cell temperature is typically out of the 0°C–45°C range. On the other hand, the fuel gauge also has to monitor the cell temperature for adjusting the battery impedance and capacity. The fuel gauge bq27500/501 can be configured to monitor the cell temperature through its TS pin, and the temperature threshold to qualify charging can be set through the data flash constants. In order to minimize the power consumption, the cell temperature is measured every one second by internally pulling BI/TOUT high and measuring the voltage across the TS pin. If the cell temperature falls outside of the preset range, $\overline{\text{BAT\_GD}}$ is pulled high and turns on the MOSFET QT so that the battery charger is disabled until the cell temperature recovers. In the mean time, the temperature information is used for normalizing the cell impedance and adjusting the capacity.

2.3 Power Consumption

Another design consideration is how to minimize the total power consumption by the fuel gauge because the fuel gauge is always connected to the battery as long as the battery is inserted. The four operation modes of the fuel gauge are NORMAL, SLEEP, HIBERNATE , and BAT INSERT CHECK (see Figure 2). In NORMAL mode, current, voltage, and temperature measurements are taken, and the interface data set is updated periodically. Decisions to change states also are made. NORMAL mode consumes the most power (100 µA, typical). When the SLEEP mode bit is set in the CONTROL STATUS register and the average current is below a programmable sleep current (Sleep Current data flash location), the bq27500 enters the SLEEP mode. It periodically wakes to take data measurements and then returns to sleep as long as the system load is below the sleep level. The sleep current threshold should be set to correlate with the system's low power mode such as a standby mode in a smart phone application. The default sleep threshold is 10 mA.

To further reduce the current consumption, the fuel gauge can be put in a HIBERNATE mode by setting the HIBERNATE bit in the CONTROL STATUS register. The bq27500/501 transitions from SLEEP mode to HIBERNATE mode if this bit is set and sufficient relaxation time has passed to take an OCV reading. When in HIBERNATE mode, the bq27500/501 consumes 1 μA, typical. The bq27500/501 wakes from HIBERNATE mode by any transitions on the I^2C communication lines.

The bq27500/501 enters the BAT INSERT CHECK mode when the battery is removed, but the fuel gauge is still powered (by the charger, for example). In this mode, the bq27500/501 is in the SLEEP mode (<15 μA) checking for battery insertion with the BI/TOUT pin. No gauging occurs in this mode. Once battery insertion is detected and OCV readings are complete, the gauge proceeds to NORMAL mode.

2.4 Sense-Resistor Selection

The typical sense-resistor value used in bq27500/501 applications is 10 mΩ. Most applications should choose a sense resistor with a temperature coefficient of no more than 100 ppm per degree Celsius. A tight tolerance (±1%) part is recommended for best performance. The following text discusses the several factors to consider in choosing the optimal sense resistor for an application.

2.5 Sense-Resistor Value

The sense-resistor value should be sized to accurately integrate the charge and discharge current that the system draws in its *ON* state as Figure 5 shows .

The maximum sense-resistor voltage that can be measured accurately by the coulomb counter is +/-125 mV. The designer should ensure that the voltage across the sense resistor at maximum currents is less than this limit. It is often the power dissipation in the resistor at maximum load currents that sets the maximum acceptable sense-resistor value, particularly when space considerations restrict the maximum size allowable for the resistor. The physical size, power dissipation, and insertion loss (voltage drop) considerations of the sense resistor dictate that the smallest possible sense-resistor value be used. This has to be balanced against the accuracy requirements at low currents (slightly above the SLEEP threshold), where the sense-resistor voltage at minimum load currents might not be much larger than the measurement offset error if the sense-resistor value is too small. If the bq27500/501 is configured to SLEEP (use OCV-to-RSOC correlation) when the system is in STANDBY, then it is unnecessary to optimize the sense-resistor value to integrate the low standby system current levels. The system STANDBY mode average current must be less than C/20 while the bq27500/501 is in SLEEP mode.

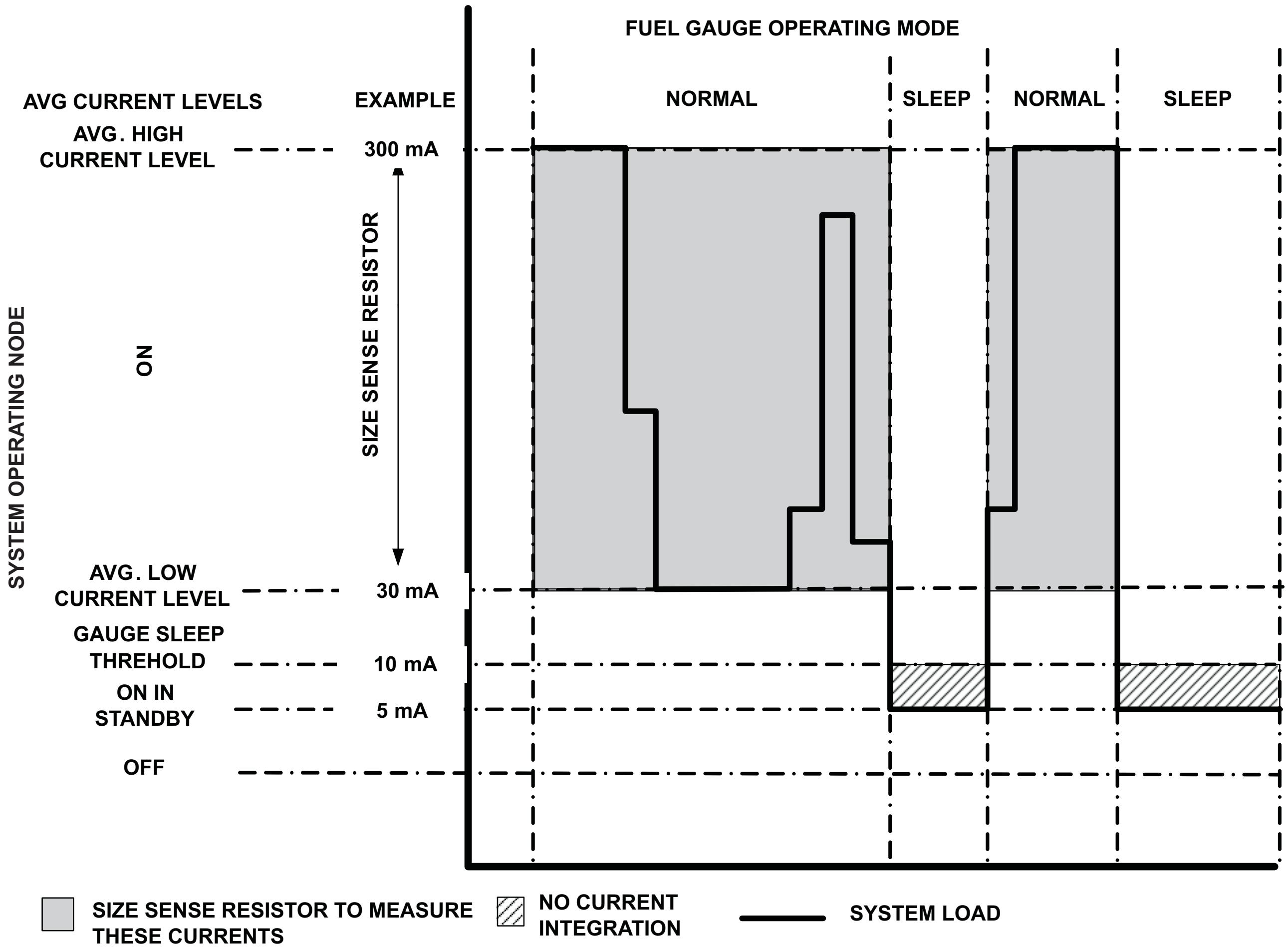

Figure 5. Sizing the bq27500 Sense Resistor

Example: A handheld device uses an 800-mAh Li-ion battery. In use, the average operating current ranges between 30 mA and 300 mA with pulse current spike (e.g., GSM pulse) of 1.2 A. If the system is unused for a time, it enters a STANDBY mode with an average current of 5 mA, including the periodic current spikes. The bq27500 has a voltage current sense range maximum of |125 mV| and a current measurement offset of 10 µV. The maximum battery charge current is 700 mA.

Battery capacity:	800 mAh
System ON mode current consumption:	30 mA to 300 mA (average)
System peak pulse current:	1.2 A (pulse)
Charge current maximum:	700 mA
System standby current:	5 mA (average) = (~C/160)
Target sleep threshold:	10 mA
Current measurement offset:	10 µV
Device input voltage range:	125 mV

Table 4. Sense-Resistor Trade-Offs

Sense-Resistor Nominal Value	Max Sense Voltage at 1.2 A	Avg Sense Range (30 mA to 700 mA)	Max Power Dissipation at 700 mA	Max. Power Dissipation at Max Discharge Load (300 mA)	Worst-Case, Low- Discharge Current Error (at 30 mA)	STANDBY Threshold Wake-Up Range
5 mΩ	6 mV	150 µV to 3.5 mV	2.45 mW	0.45 mW	7%	8 mA to 12 mA
10 mΩ	12 mV	300 µV to 7 mV	4.90 mW	0.90 mW	3%	9 mA to 11 mA
25 mΩ	30 mV	750 µV to 17.5 mV	12.25 mW	2.25 mW	1%	9.6 mA to 10.4 mA
50 mΩ	60 mV	1.5 mV to 35 mV	24.50 mW	4.50 mW	0.1%	9.8 mA to 10.2 mA

2.6 Temperature Coefficient

Ambient temperature changes as well as power dissipation in the sense resistor can cause the sense-resistor temperature to change. If the sense-resistor temperature coefficient is large, these temperature changes make noticeable changes in the measured current and capacity changes. Use of a sense resistor with a 100 ppm (0.01%) per degree Celsius or better temperature coefficient minimizes this issue. Even if a low temperature coefficient sense resistor is used, overall temperature accuracy can be degraded if the PCB layout allows some of the PCB copper etch resistance to become part of the effective sense-resistor value. The temperature coefficient of copper etch is 0.39% per degree Celsius. If the connections from the gauge to the sense resistor do not measure the sense-resistor voltage directly at the sense-resistor connection points, but connect to the high-current etch run some distance from the sense resistor, then any etch resistance between the sense voltage connection and the sense-resistor connection is effectively added to the sense-resistor value. This increases the resistance and degrades the temperature coefficient of the effective sense resistor as compared with the physical sense-resistor characteristics.

3 Layout/RF Considerations

The PCB layout for the bq27500/501 and associated components can have a significant effect on gauge performance. The layout can cause the gauge to see some PCB etch resistance added to the actual sense-resistor value. The layout can also cause excessive measurement offset errors. Further, it can allow RF fields to affect the gauge measurements and even allow RF fields to corrupt register values in the gauge.

3.1 Sense-Resistor Connection

The sense lead connections need to be a Kelvin-style connection, so that only the voltage drop across the sense resistor is measured and any voltage drop along high-current etch runs, or plated-through-hole resistance is not included in the measurement. The two sense leads should run close to each other.

3.2 Grounding

All the bypass capacitors, Vss, and other ground connections in the gauge circuitry except for the sense-resistor connection to ground, should be tied to a ground plane or wide etch area that is separate from the system ground. A single-point connection should be made between this isolated ground and the system ground. It is best to have this connection between the grounds to be made to the ground end of the sense resistor, preferably at the same point where the sense lead is connected. This prevents any of the system load current from flowing in any portion of the low-current ground etch used by the gauge. This helps measurement offset performance.

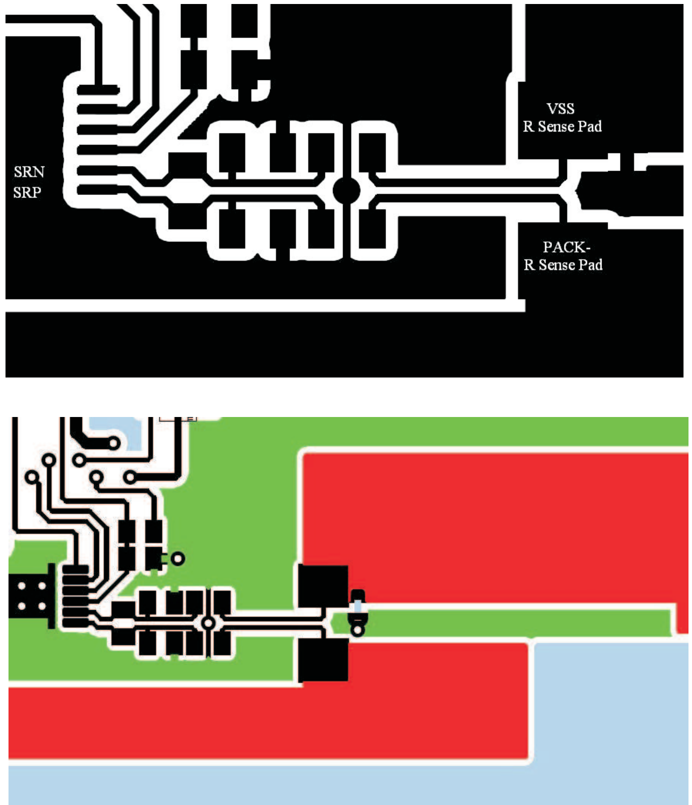

Figure 6. Sense-Resistor Connection and Grounding

3.3 Component Location

Bypass capacitors should be as close as possible to the bq27500/501, especially the capacitors on Vcc, SRP, and SRN. Both leads of each bypass or filter capacitor should be short and wide, as inductance and resistance in either lead degrades the capacitor impedance. Avoid placing the bq27500/501 integrated circuit (IC) and other gauge components close to power supply switching components (or other noise sources), hot components, or high RF field-strength sources.

3.4 RF Mitigation

RF that is coupled or conducted onto signal lines that connect to the bq27500/501 can be rectified by the electrostatic-discharge protection diodes and can create bias voltages that can upset normal gauge operation. Lines that cannot be shielded or otherwise protected from RF may need to have an RF filter capacitor added close to the bq27500. This capacitor should be a small ceramic unit with a value like 68 pf, as it has a smaller impedance at RF frequencies than larger filter capacitors. Longer etch runs can be shielded by placing them on an internal PCB layer with a ground plane or wide ground etch above and below to provide the shielding.

IMPORTANT NOTICE