

This charger solution is simple and discrete but has many limitations and few safety features. Adding any safety feature will quickly drive up the solution cost but often may offset the liability cost of an unprotected design. LDOs are typically not highly accurate regulators, especially with external programmable resistors. If the regulation was set lower to ensure that the maximum battery voltage was not exceeded, the typical voltage and capacity would be lower. The crude current-limit resistor would allow more current at lower battery voltages and would not provide a conditioning current to help recover depleted cells or to prevent cell damage from excessive charging.

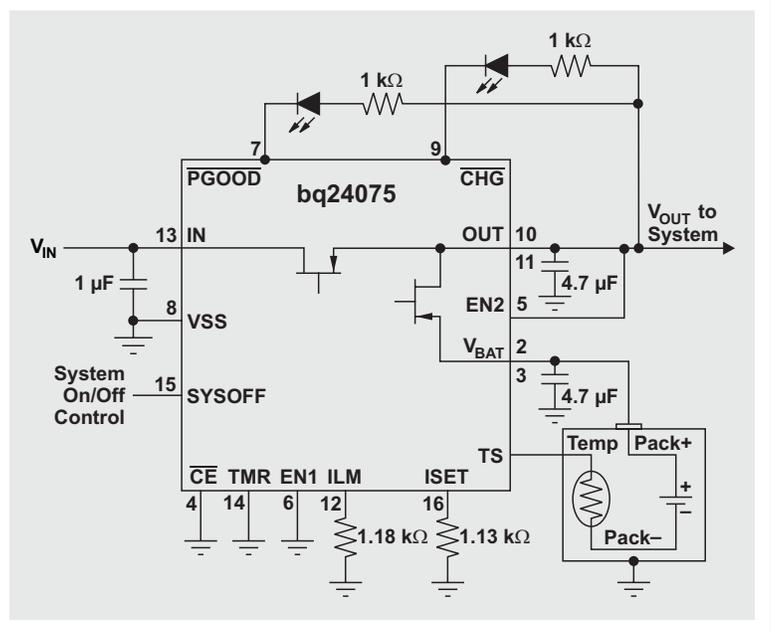
Typical integrated application

Figure 3 shows the Texas Instruments (TI) bq24075, a charger with a highly integrated power path in a 3 × 3-mm, 16-pin QFN package. The only external components required are two external programming resistors and three capacitors for the power sources.

Programmed input-source protection

The input-current limit is programmed with the EN1/2 pins to one of four states: 100 mA, 500 mA, ILIM, or Suspend, as shown in Figure 4. A resistor can be used to program ILIM at any level up to the device's maximum input current. When current-limited, the input FET restricts the current to the OUT pin, causing the system voltage to drop to the DPPM threshold or to the battery voltage where the charge current will be reduced. Assuming that the protection was designed for the applied

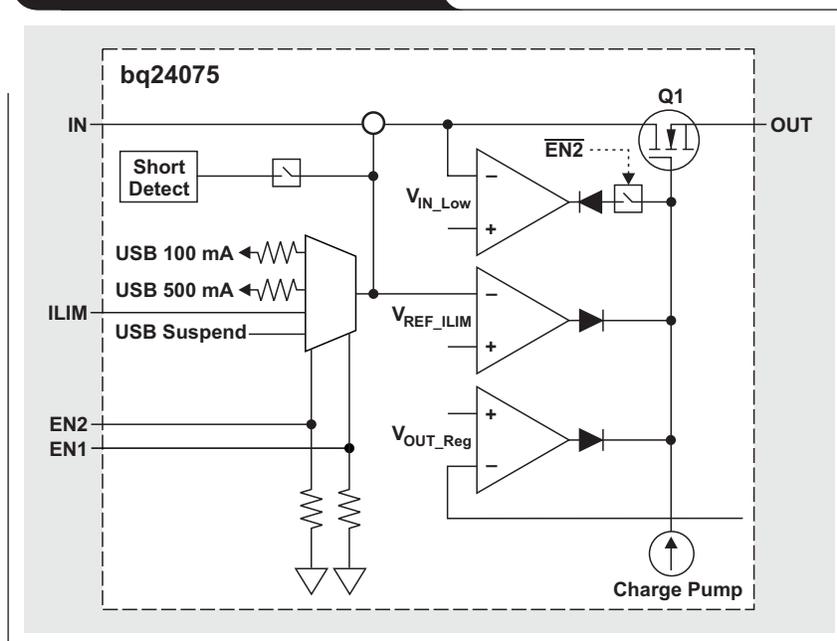
Figure 3. Typical integrated application with bq24075 charger



source, this feature solves the problem of the system overloading the adapter or the USB source, which could potentially damage the source or device. More power-management details are presented later under “DPPM protection of output voltage.”

If a current-limited source such as a weak or wrong adapter or USB is used, the adapter and system voltages

Figure 4. Input-FET control loops



will drop, causing the IC to enter DPPM mode or battery-supplement mode. Basing DPPM on the output voltage solves most loading issues by reducing the charge current, giving priority to the system load, and allowing operation with a weak power source or minor AC brownouts. Other input-current-management solutions without DPPM would not detect the weak source or reduce the charging current, and the system would crash.

The V_{IN_Low} input loop provides additional protection for a weak source when in USB 100/500-mA mode. This loop monitors the voltage on the USB input pin; and, if it drops to ~ 4.5 V, Q2 enters its linear range to keep the USB input voltage from dropping any further, as shown in Figure 5. This voltage loop is independent of the input-current-limit loop. This feature adds protection for the USB host in the event that it cannot deliver the load current because of a weak source or failed communication. In Figure 5, I_{OUT} starts with no load and, at ~ 250 mA, the current limit of the weak source causes the source voltage to fall to 4.5 V, where the V_{IN_Low} loop kicks in and the system output voltage drops about 100 mV to the DPPM threshold. The charge current is reduced as the load is increased to maintain the input at 4.5 V. As the load is reduced, the system returns to normal operation.

DPPM protection of output voltage

The output voltage powering the system will drop if the system load current and the battery charge current exceed the available input current. The input current can

be restricted by the source, the V_{IN_Low} loop, or the input-current-limit setting of the IC. If the output voltage drops to the DPPM threshold, the charge current will be reduced to keep the voltage from further decay. This allows the use of a less expensive adapter because the charging current is reduced during peak loads.

If the system current exceeds the available input current, the output voltage will drop to the battery voltage and enter battery-supplement mode, in which the battery FET turns on and supplements the input current going to the system. This allows use of the battery to supplement large current pulses to the system, which the charger is not capable of supplying. Figures 6 through 8 show the waveforms of the TI bq24072/3/4/5 where the output voltage drops first into DPPM mode and then into battery-supplement mode.

Figure 6 shows the waveforms of the bq24072 with V_{OUT} initially regulated to about 225 mV above the battery voltage. Upon reaching the input-current limit after the first load step, the IC enters DPPM mode, which reduces the charge current to keep the output voltage from dropping below the DPPM threshold. After the second load step, the system load is greater than the input limit. The output voltage drops to just below the battery voltage, and the battery FET turns on and supplements the input current to the system load. Note that the voltage transitions between modes are very small and are best for applications that are sensitive to voltage changes.

Figure 5. V_{IN_Low} USB protection with source-current limit at 250 mA

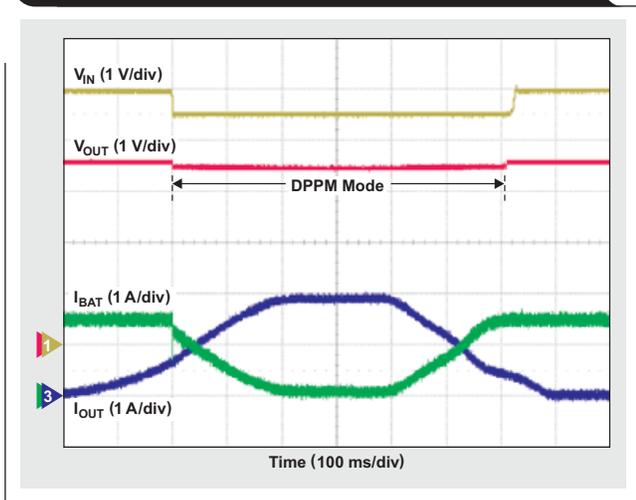
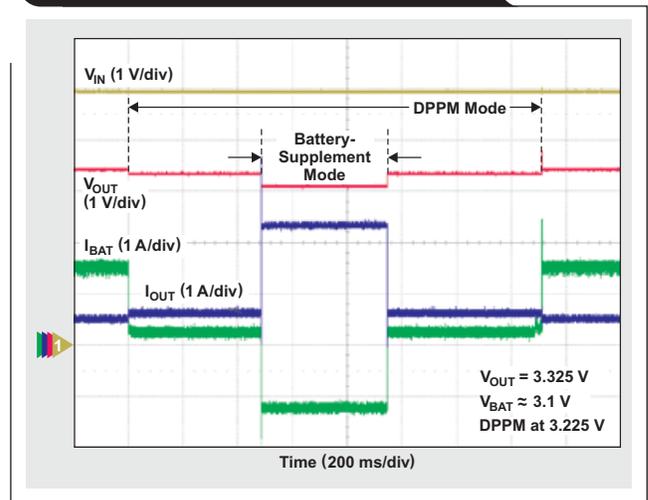


Figure 6. bq24072 DPPM and battery-supplement modes with $V_{BAT} \approx 3.1$ V



The waveforms of the bq24073/4 in Figure 7 were generated under the same conditions as for the bq24072 in Figure 6, except that the bq24073/4 regulates V_{OUT} at 4.4 V and the DPPM threshold at 4.3 V. Upon entering battery-supplement mode, the output voltage drops to just below the battery voltage; so the lower the battery voltage is, the larger the drop. For an application sensitive to system voltage drops, the system load should not exceed the available input current in order to stay out of battery-supplement mode. An alternative is to use the bq24072.

The bq24075 waveforms in Figure 8 were generated under the same conditions as for the bq24072 in Figure 6, except that the bq24075 regulates V_{OUT} at 5.5 V and the DPPM threshold at 4.3 V. The transition between modes is larger and dependent on the input voltage and battery voltage. If the input voltage is less than 5.5 V, then the regulator is switched fully on to deliver what voltage is available.

Protection from shorting system V_{OUT}

Shorting the V_{OUT} pin can cause excessive current from the battery or the V_{IN} power source. Battery short-circuit protection disables the battery FET if the voltage drop from V_{BAT} to V_{OUT} is greater than 250 mV for a duration longer than the specified deglitch time. The battery FET is turned on periodically to check whether the short is still present, and this hiccup mode will continue until the short is removed. This prevents damage to the IC and solves reliability issues.

For V_{IN} protection, the input FET limits the input current to 100 mA when the output voltage is less than 1 V. Once the excessive load is removed, the output will charge above 1 V and start delivering the programmed input current. This feature reduces the power dissipation during the output short, which also improves reliability. Figure 9 shows the waveforms of an output short and the IC's recovery.

Figure 9 shows the waveforms that occur when the bq24072's output is shorted, causing the battery FET and input FET to turn off. The input source supplies about

90 mA to the output via the input control loop; and, approximately every 64 ms, the battery FET is turned on for 250 μ s to check whether the short is still present.

Picking the right charger IC

The bq24072/3/4/5 ICs all charge a single-cell Li-Ion battery properly, but they have various values for the overvoltage-protection (OVP) threshold, the V_{OUT} regulation, and the DPPM threshold (see Table 1). Each IC also has an

Figure 8. bq24075 DPPM and battery-supplement modes with $V_{OUT} = 5.5$ V

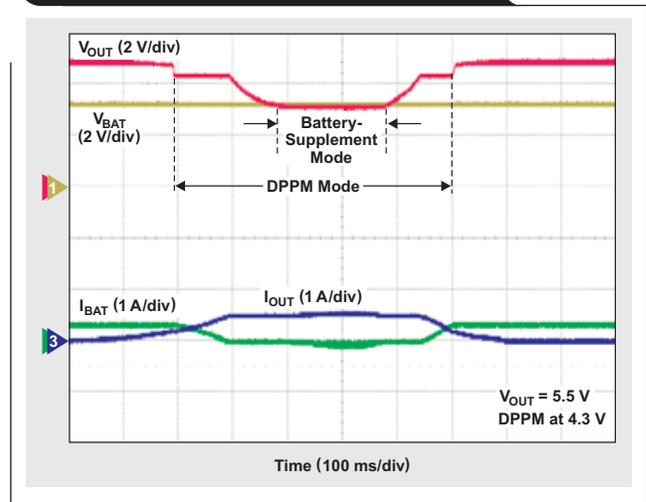


Figure 9. Output short-circuit protection

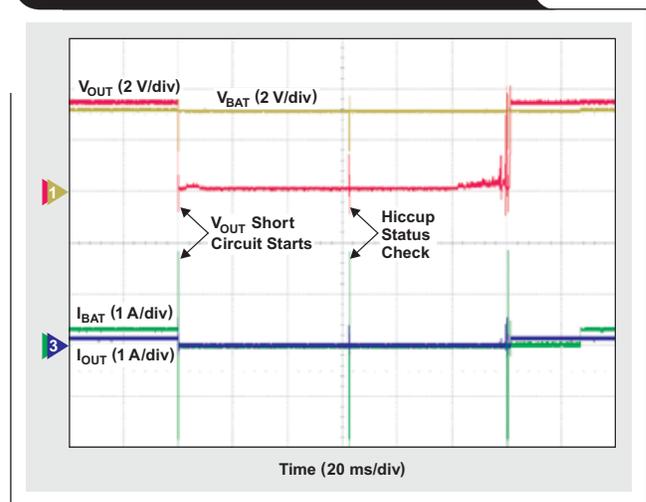


Figure 7. bq24073/4 DPPM and battery-supplement modes with $V_{OUT} = 4.4$ V

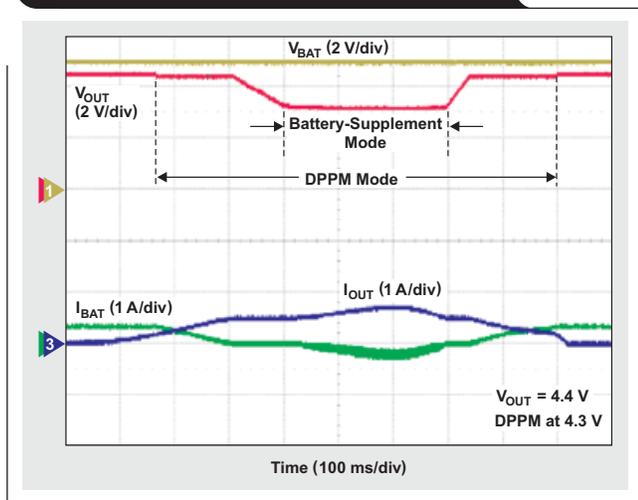


Table 1. Differences between bq24072/3/4/5 ICs

DEVICE	V_{OVP}	V_{OUT}	V_{DPPM}	OPTIONAL FUNCTION
bq24072	6.6 V	$V_{BAT} + 225$ mV	$V_{O(REG)} - 100$ mV	TD
bq24073	6.6 V	4.4 V	$V_{O(REG)} - 100$ mV	TD
bq24074	10.5 V	4.4 V	$V_{O(REG)} - 100$ mV	ITERM
bq24075	6.6 V	5.5 V	4.3 V	SYSOFF

optional control function such as termination disable (TD), programmable termination current (ITERM), or system off (SYSOFF). The 10.5-V OVP is for a nonregulated 5-V adapter where the unloaded source is above 6.6 V. To minimize power dissipation, during fast charge the optimum input voltage should be between 4.5 and 5.5 V.

The bar chart in Figure 10 shows graphically how the charger output voltage changes from one operational mode to another for each charger. If the system is sensitive to changes in the output voltage and the peak system load exceeds the input current, the bq24072 minimizes these changes since it regulates the output voltage to within 225 mV of the battery voltage. The bq24073/4 regulates the output voltage to 4.4 V and the DPPM threshold to 4.3 V. Depending on the battery voltage, the voltage drop can be large when the charger enters battery-supplement mode. The bq24075 regulates the output voltage to 5.5 V for inputs greater than 5.5 V and passes through lower voltages. If the charger output current plus the charge current exceed the input current, the output voltage will drop much more than 100 mV, as shown in Figure 10. A further increase in output current may put the device in battery-supplement mode, where another large drop will occur.

Figure 11 shows the efficiency of the power topology. Efficiency for a linear topology is

$$\eta = \frac{V_{IN} - V_{OUT}}{V_{IN}} \times 100.$$

Each charger mode has an efficiency factor. For the bq24072/3/4/5, the efficiency during battery-supplement mode is the same given the same input voltage and battery voltage.

The bq24072 has the least change in output voltage between modes, but the efficiency drops as the battery discharges. The bq24073/4 is more efficient in normal and DPPM modes but may have a larger internal voltage drop upon entering battery-supplement mode. The bq24075 has high efficiency in normal mode and good efficiency in DPPM mode, but it may have a large change in output voltage after switching from normal to DPPM to battery-supplement mode.

The decision for the designer is whether the charger should be sensitive to system voltage changes, have lower efficiency, or both. If the charger is sensitive to voltage changes, will the system operations cause changes between

Figure 10. Output voltage with changes in operational mode and part number ($V_{IN} = 5\text{ V}$)

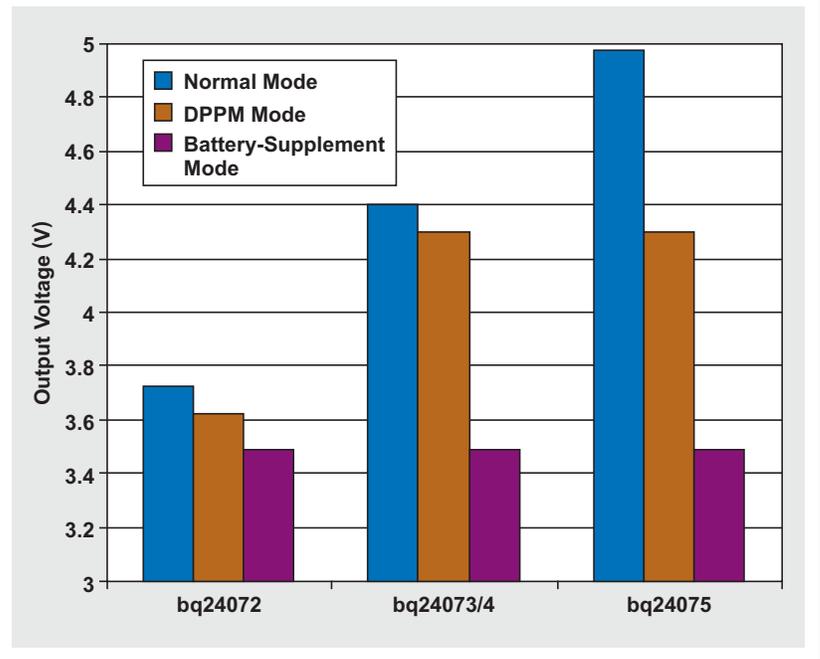
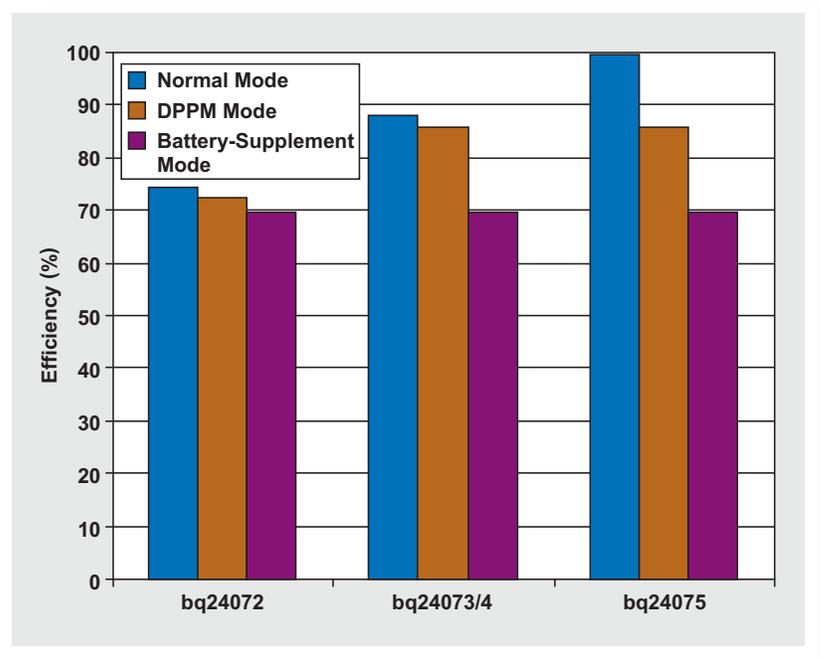


Figure 11. System efficiency with changes in operational mode and part number ($V_{IN} = 5\text{ V}$. For V_{OUT} , see Figure 10.)



the modes with large voltage steps? Because of the low power drain from the adapter or USB source, efficiency is not typically a cost concern, but it can be a heat-dissipation issue in the device.

Simple, single-cell, integrated Li-Ion chargers

For designs where power-path control is not necessary, the TI bq2401x, bq2402x, and bq2406x families of single-cell Li-Ion chargers perform complete charging with all the necessary safety features.

The bq2406x family incorporates many of the same features found in the bq24072/3/4/5 family, but without the power-path management. The bq2406x performs standard three-phase charging—battery conditioning, constant current, and voltage regulation—followed by termination. The safety features include input OVP, a precharge safety timer, a fast-charge safety timer, and IC thermal regulation. The OVP circuit disables the input pass FET if the input voltage exceeds the OVP threshold. This helps to protect against wrong or damaged power sources. The safety timers, once expired, will disable charging. Typically, if the design is done properly, a good battery will exit precharge or reach termination long before the safety timers declare a fault. Typically intended for operation in extremely hot environments where the IC junction temperature reaches 125°C, the thermal-regulation loop reduces the charge level to prevent further heating of the charger IC. Further details on these features can be found in the data sheet.

Conclusion

An inexpensive discrete charger can be implemented that performs the charging and manages basic power-path connections but does not address any of the safety and reliability issues that may occur. A brief description has

been given of the safety features of a simple charger, followed by a more detailed description of DPPM. The bq24072/3/4/5 chargers provide three levels of input-current-limiting protection that can be programmed to protect the specified source. The USB V_{IN_Low} loop provides additional protection by detecting weak USB sources and restricting the input current. The output DPPM loop reduces the charging current at the first sign of a drop in the system voltage and enters battery-supplement mode if the system load exceeds what the adapter can handle. This article has also discussed how the IC protects against a system short circuit and then recovers. Finally, for each part number in the bq24072/3/4/5 family, changes in output voltage and efficiency that occur with changes in operational mode were compared.

The bq24072/3/4/5 family of Li-Ion battery chargers is a fully integrated solution that performs Li-Ion charging and DPPM and reduces application size. It solves many issues with power sources by allowing use of less expensive adapters, managing loading, giving priority to the system, increasing reliability, and incorporating many safety features for a lower total system price.

Related Web sites

power.ti.com

www.ti.com/sc/device/partnumber

Replace *partnumber* with bq24010, bq24020, bq24060, bq24072, bq24073, bq24074, or bq24075

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