Battery Charging Design Considerations

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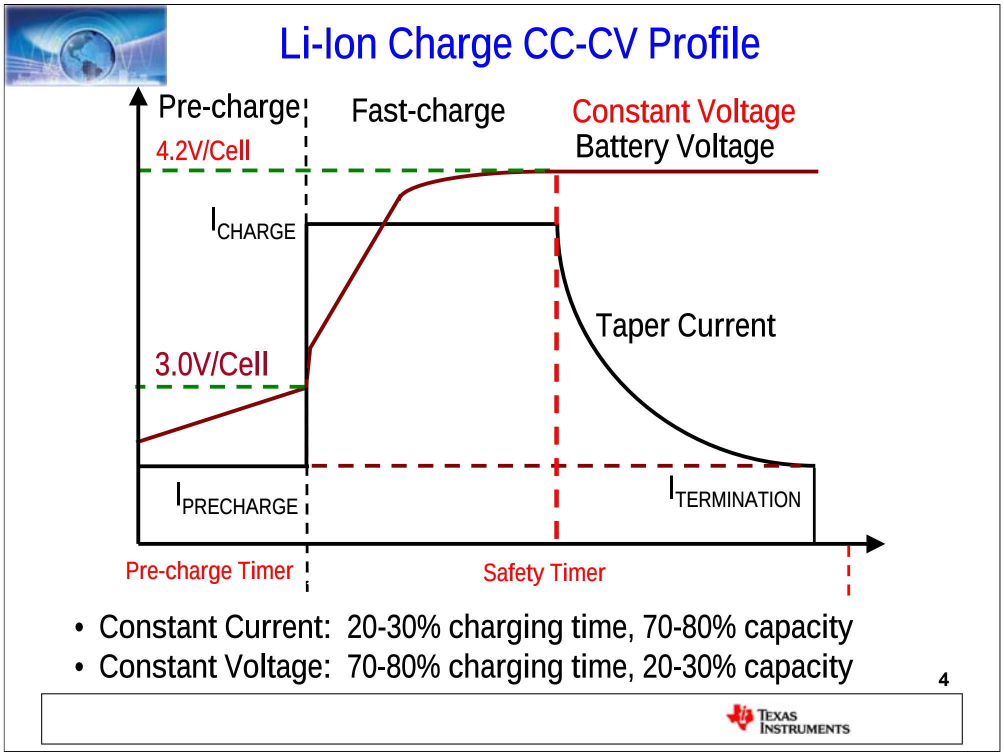
Battery Management Applications
Texas Instruments

Agenda

- Li-Ion Battery Characteristics and Charging Requirements
- Battery Charging Front-End (CFE) Protector
- Power Path Battery Management Charger
- Fast USB Switching Charger

Li-Ion Battery Characteristics and Charging Requirements



This is a typical Li-Ion battery charge profile.

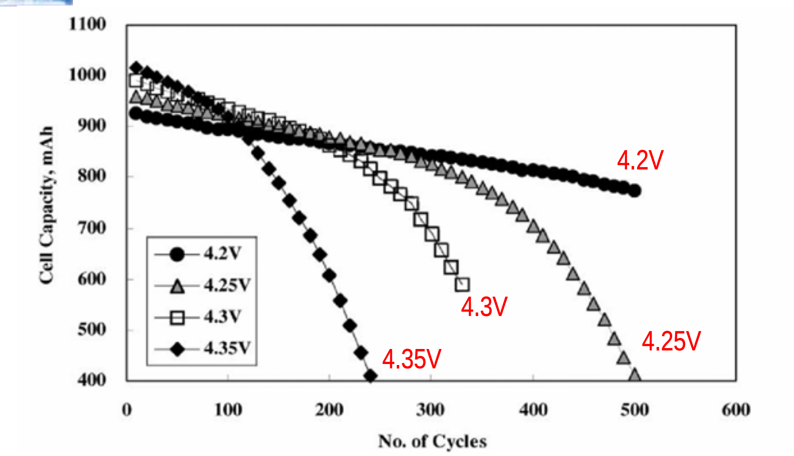
A typical Li-Ion battery charge profile has two operating modes: a current-regulation mode and a voltage regulation mode. In the current regulation mode, the charge current is dependent on the battery voltage.

For deeply discharged battery, the battery voltage is less than <3.0V. In order to prevent the battery degradation, the pre-charge current, which is usually about 10% of the fast charge current is applied to the deeply discharged battery to wake up the battery. Within pre-determined pre-charge time period, typical of 30min, if the battery voltage can not reach 3.0V, then we assume that the battery is dead and no longer can be waked. If the battery voltage reaches 3.0V, then fast charge current is applied to the battery. The fast charge current is usually about 0.5C to 1C rate. Higher than 1C charge rate will generate metallic Li and increase the battery degradation and reduce the battery cycle life time.

Once the charger output reaches the regulation voltage, typical of 4.2V(4.4V for some new chemistry such as $LiMnQ2$ cathode materials). An internal loop regulates the output voltage and the charge current tapers down as the battery is charged. Charge termination is detected when the charge current is lower than the termination threshold. Typically the termination and pre-charge thresholds are set to 10% of the fast charge rate.

During the charge process, safety timers monitor the pre-charge time and fast charge time, detecting a fault if the timers exceed a pre-defined value.

Charge Voltage Affects Battery Service Life



- 10-20% more capacity with 4.35V than 4.2V
- Over charging shortens battery cycle life

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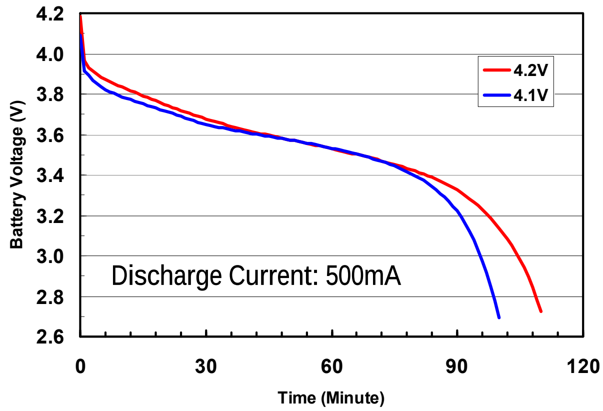
Unfortunately, for lithium ion battery self discharge in not only loss of energy, but also an indication of battery degradation. Most of lithium lost during self-discharge can no longer be recovered during charge and is stored as insoluble film on surface of the active material. This film not only binds lithium, but also increases cell impedance causing performance degradation. Unvonted reaction is accelerated at high states of charge (high voltages) as can be seen in this graph.

Battery Capacity at Different Charge Voltage

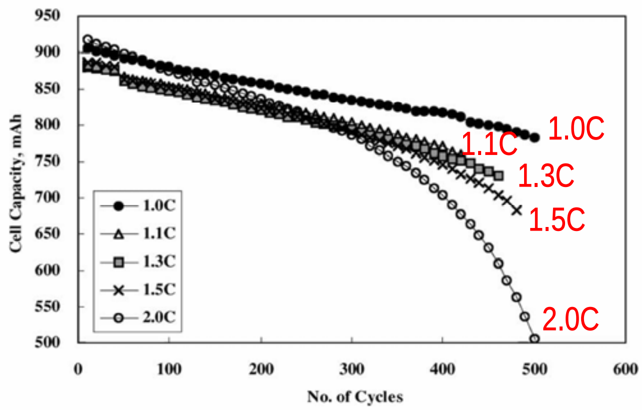


- 800mAh @4.1V, 10% less than @4.2V
- 875mAh @ 4.2V

Charge Current vs Battery Degradation

Charge Current

Current should be limited to 1C rate to prevent overheating



“Factors that affect cycle-life and possible degradation mechanisms of a Li-ion cell based on LiCoO2”, Journal of Power Sources 111 (2002) 130-136

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Higher charge current also accelerates degradation of the cells because it causes part of the lithium to be deposited as metall on the surface of anode instead of being intercalated. Even though lithium is eventually intercalated, part of it reacts with electrolyte and builds insoluble products causing degradation of battery performance.

Li-Ion Battery Charging Requirements

Charge Voltage

- 4.1V for Coke Based Anode (1990's)
- 4.2V for Graphite Anode
- 4.4V for $LiNiMnCoO_2$ cathode.
- 3.6V for $LiFePO_4$ cathode
- Charging lower voltage improves cycle life and safety

Charge Current

- $\leq$ 1C rate; preferred 0.7C to prevent overheating and resulting accelerated degradation

Li-Ion Charging Requirements (Cont.)

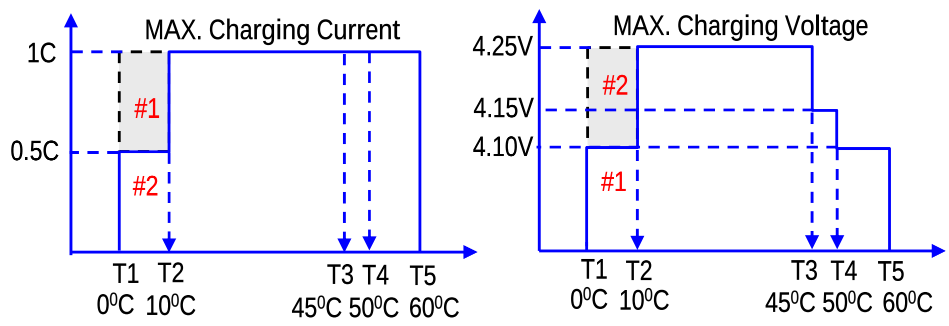
Battery charging Temperature Qualification
0°C to 45°C. Charging at higher temperature results in accelerated aging

Low-Voltage Battery Pack Charge
Pre-charge current: < 0.1C for VCELL < 3.0V

Charging Termination
In Constant Voltage Mode, Charge current < 0.1C

Charge Timer
3-5 hrs.

What are New Charging Requirements for Portable EEs?



Note: $LiCoO_2$ Type Battery Cell

- Low charge current or voltage @ low temperature
- Low charge voltage @ high temperature

Battery Charging Front-End (CFE) Protector
bq243xx

Battery Charging System Requirements

- Safety and Reliability
  - Adapter Hot Plug-in
  - Adapter Reverse Input to the charger
  - Short Circuit and Overcharging Protection

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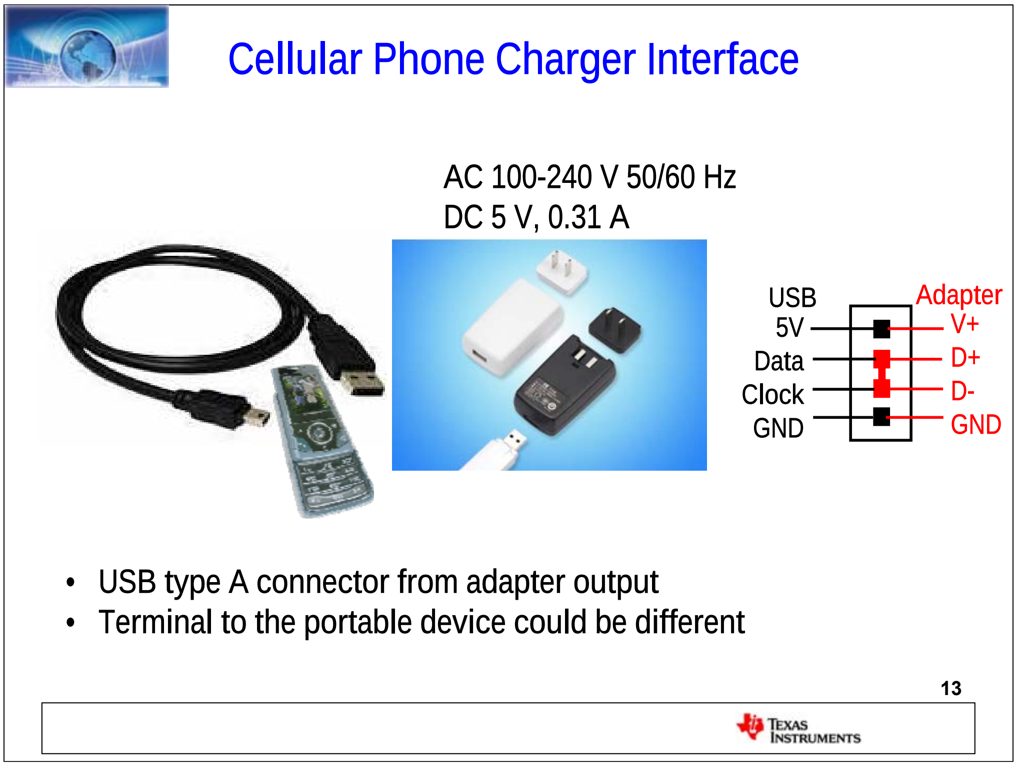
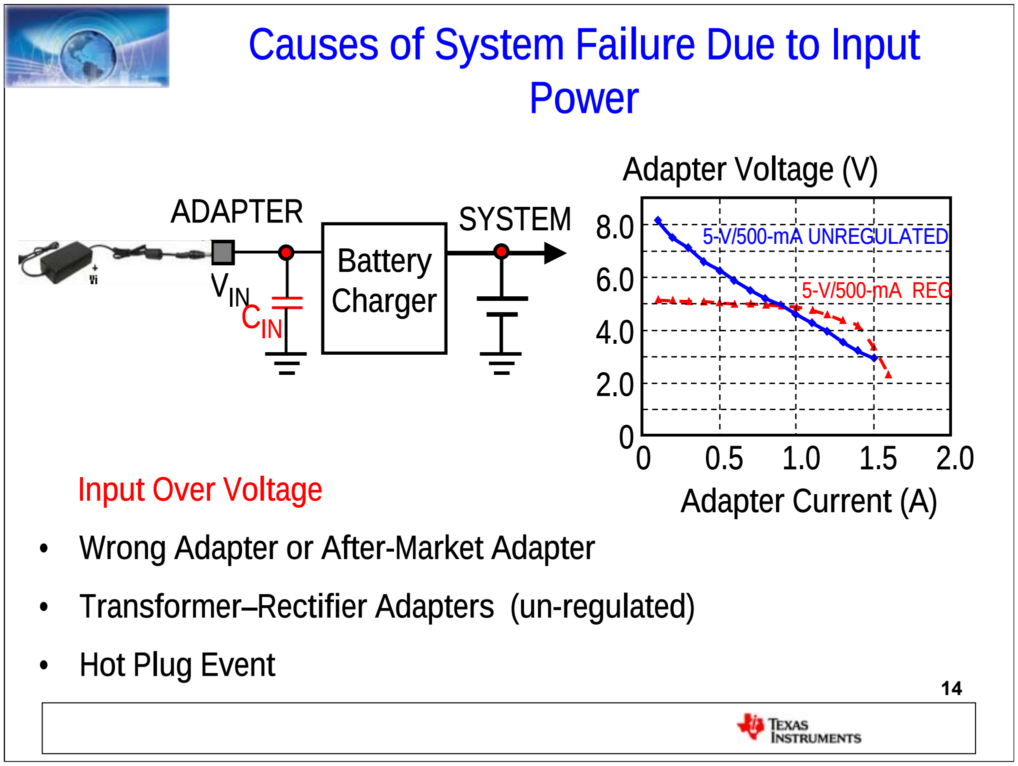
As we said before, safety and reliability are critical for the end-users. There are many kinds of adapters powering the portable devices under many different conditions. Hot plug-in of an adapter with charged output is one of worst operation conditions that we have to consider. I believe that many of us here have done many tests to make sure that system is still alive after the hot plug-in test.

The second one is the adapter reverse polarity which a negative adapter voltage is applied to the charger.

The last one is the short circuit and battery over charging protection.

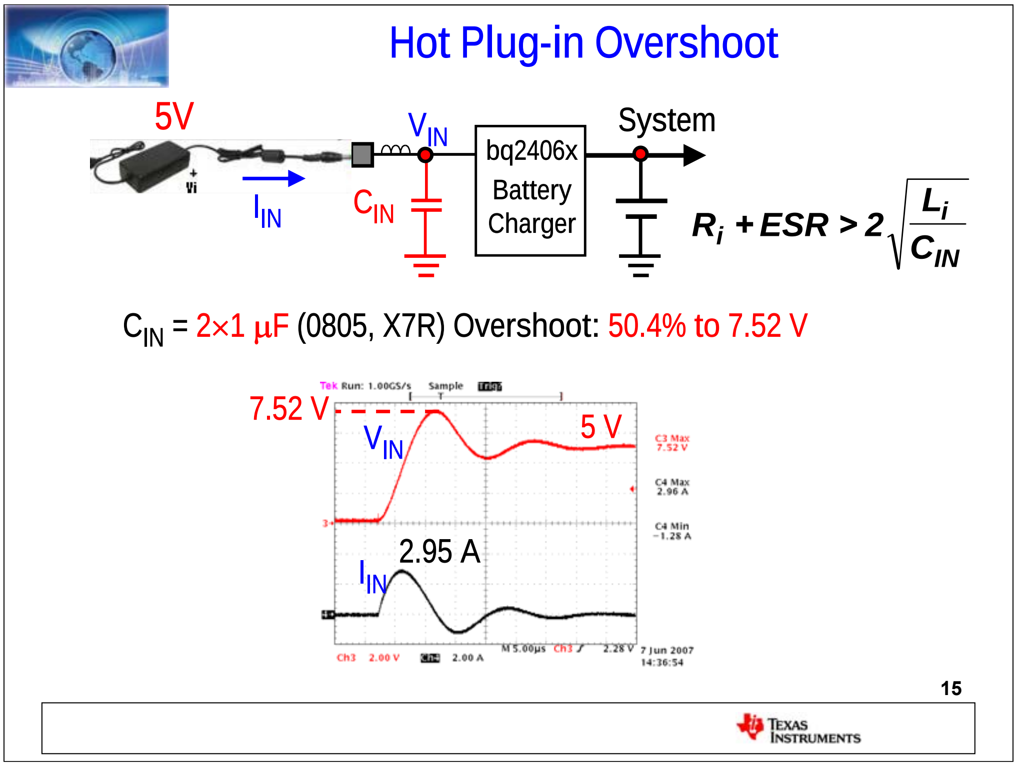


As we know that there are thousands of adapters available, and their connectors are all different and electrical specifications are different as well. Each major OEM has its own specs which cause a lot of problems for our end users and system designers. How do we make a system more reliable to meet all these adapter specifications in our portable devices.



Cost is one of the main driving factors in consumer market. A cheap adapter may have a very poor output voltage regulation. This figure shows the adapter output voltage regulation over load current. For simple diode rectification adapter without active voltage regulation loop, it has high output voltage under light load like before the adapter is plugged in. wrong adapter of after market adapter from unauthorized adapter vendors may also have different output voltage, which may cause over voltage damage to the device.

Hot plug in is another important real event, which can results in two times of the input voltage and it may cause over voltage damage as well.



This is a battery charger and it is powered by a 5V adapter.

The first case is that we use two 1uF ceramic capacitors. This waveform is the voltage across the decoupling capacitor which is applied to the batery charger. We see that there is over 50% overshoot. This over-voltage is from the resonance between the cable inductance and input decoupling capacitance.

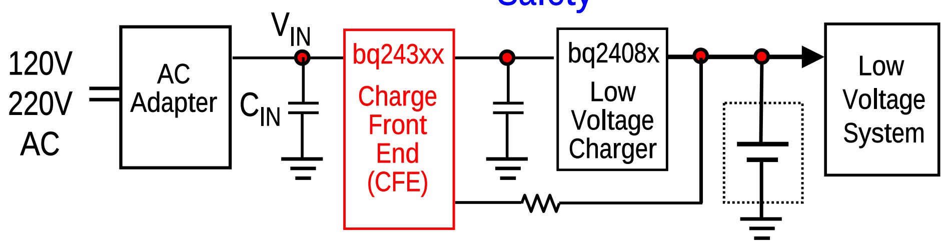
What happens if we increase the input decoupling capacitance by 4 times. From this waveform, the input voltage overshoot is reduced, by not too much while it significantly increases the inrush current by two times.

In order to reduce the overshoot, we have to increase the damping factor. The total resistance should be big enough to reduce the output voltag eovershoot. The higher the series resistance, the lower the overshoot. From this equation, we increase the input capacitance, we equivalently increase the characteristic impedance, which generates less overshoot.

So the conclusion is that increasing the input capacitance is not effective way to minimize the input overshoot in adapter hot plug-in.

How about increase the ESR of the capacitor?

TI Solution: Charge Front End (CFE) Improves Safety



CFE Provide System Level Protections

- Input Transient Over-Voltage
- Steady state over voltage
- Over-Current Protection, Latch or Hiccup
- Adapter Reverse Polarity
- Battery Over-voltage

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So far, we all talked about the discrete solutions to minimize the input voltage overshoot. Overall these solutions are still not enough to safely protect the charging system. if the charger is damaged due to over voltage, then the adapter voltage will be directly applied to the battery which may cause a serious problem although there is a over voltage protector in the battery pack. However, this high voltage will damage the whole low voltage system such as micro processor or low voltage DC-DC converters. Therefore, there is a necessity to add a charge front end device to improve the system safety. the main function of the CFE is to isolate the high voltage from the low voltage operating system so that the operating system will be see any high voltage. As a result, the system with CFE can significantly improve its ssytem safety and reliability due to any extreme conditions such as adapter hot plug in, third party adapter.

Our TI CFE solution provides many other function as well such as robust over current limiting with latch or hiccup mode, reverse adapter voltage protection, and accurate battery protection.

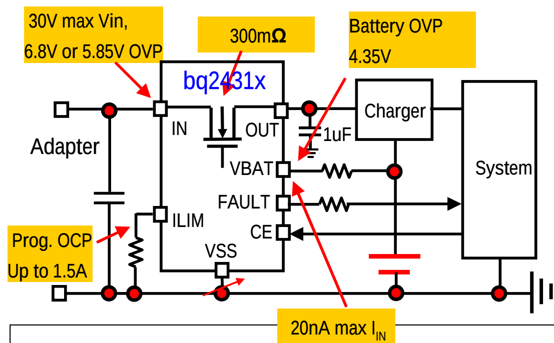
Charger Front End Protector IC bq2431x

Features

- Input over-voltage
- User-programmable input over-current
- Battery over-voltage (EEPROM versions)
- 30V maximum input voltage
- Supports up to 1.5A input current limit
- <1us response against input over-voltage
- Status Indication – Fault condition
- Small 2mm x 2mm 8pin SON package

Benefits

- Maximum safety protection
- Protects against voltage transients
- Quick turn-off of integrated switch
- Small and recoverable solution



Applications

- Mobile Phones
- Bluetooth Headsets
- Portable Navigation Devices
- Portable Media Players

EVM

bq2431xEVM

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Summary of bqCFE Protection Features

		INPUT OVP			OCP		Battery OVP	
Part #	Package	V_{OVP}	$V_{O(REG)}$	$t_{BLANK(OVP)}$	I_{OCP}	$t_{BLANK(OCP)}$	BV_{OVP}	Counter
bq24300	2x2 mm	10.5	5.5	64 μs	300 mA	5 ms	4.35	HICCUP
bq24304	2x2 mm	10.5	4.5	64 μs	300 mA	5 ms	4.35	HICCUP
bq24305	2x2 mm	10.5	5.0	64 μs	300 mA	5 ms	4.35	HICCUP
bq24314	2x2 mm 4x3 mm	5.8		0	PROG	176 μs	4.35	LATCH
bq24316	2x2 mm 4x3 mm	6.8		0	PROG	176 μs	4.35	LATCH
bq24380	2x2 mm	6.3	5.5	0	No		4.35	Hiccup
bq24381	2x2 mm	7.1	5.0	0	No		4.35	Hiccup

- Latch: After 15 times OCP or OVP, then latch

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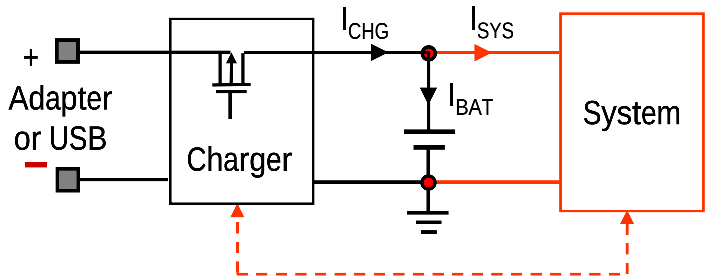
We provide many CFEs in terms of different input OVP thresholds, OCP threshold, and OCP hiccup and latch functions, different package size.

Li-Ion Battery Charger

Linear Battery Charger Design Considerations

- Charge voltage
- Charge current
- Input voltage range (USB, adapter)
- Input current limit
- Internal or external power FET
- Charge cycle management
  - Pre-charge voltage, pre-charge current
  - Termination current, status reporting
  - Safety timer
- Thermal management
  - Battery charging temperature qualification
  - Power dissipation: IC junction temperature and Protection
- Package

Charging with an Active System Load: Issues



Charger output current is shared:

$I_{CHG} = I_{BAT} + I_{SYS}$

Issues:

- Safety Timer False Expiration
- Termination Detection

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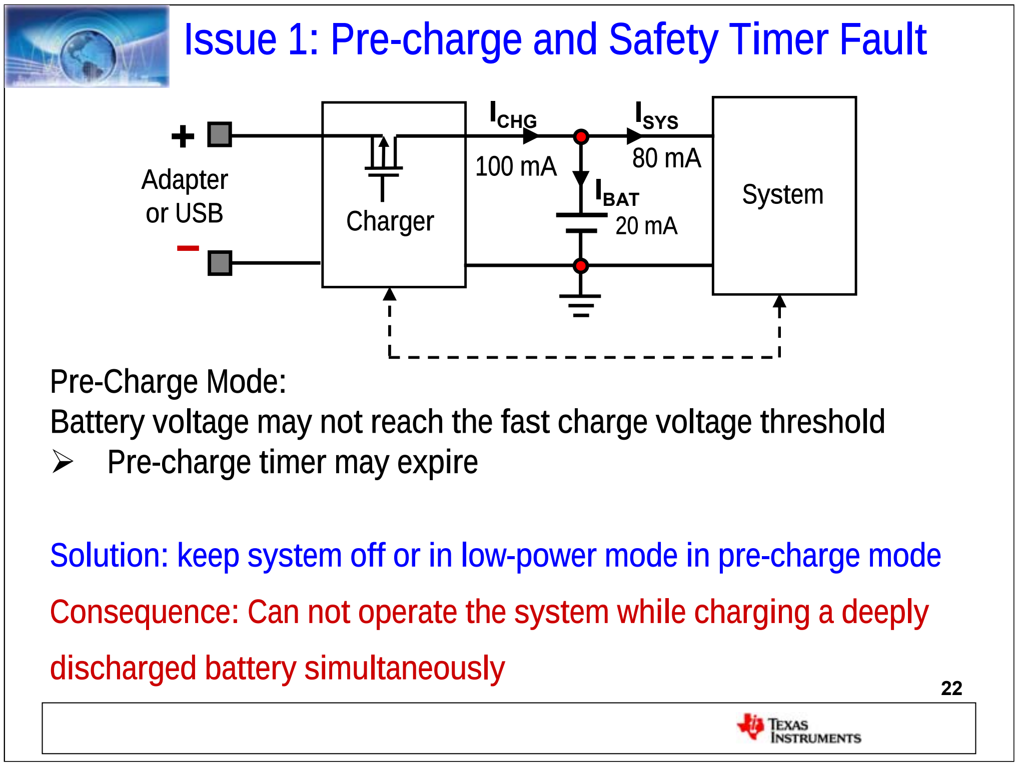
This is a stand alone battery charger. The charger output is dedicated to charge a battery, and it will make a right charging decision. However, things are not so simple. The system is usually connected to the charge output . This scheme is straight forward and no additional cost is added. However, this power architecture will cause various design challenges.

The root cause of the system-charger interaction issues is that the charger output current is not dedicated to the battery, but shared between the system and the battery. Ichg is the current the charger sees, and it makes charging decision based on this current. Even though the system load steals away some portion of this current and the charger is not able to tell.

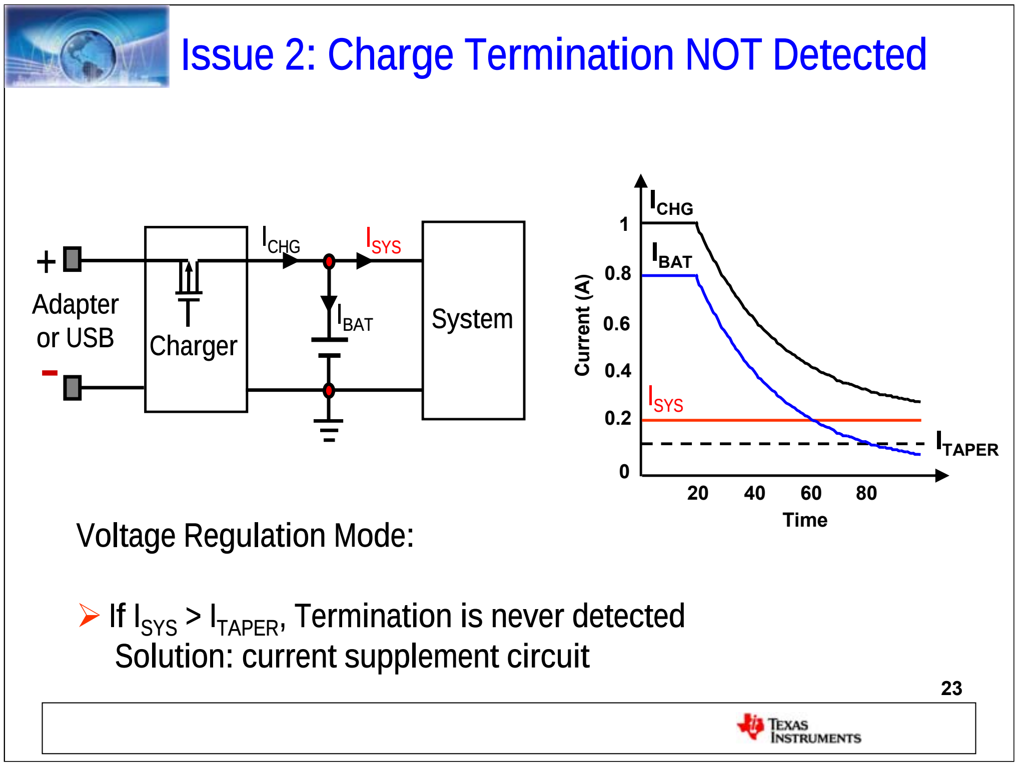
This design infrastructure has issues with timer and termination.



As I've mentioned, during pre-charge phase, the charge current is very small, typically 1/10 of the maximum chargin current. The power delivered will be this small current times a low battery voltage. The system's average load most likely will be greater than this value.

Because the effective current to charge the battery is too small, the battery voltage may never rise to 3V, then the pre-charge timer would expire. It's even possible that the system current is larger than the precharge current, then the battery would be discharged in stead of being charged!

The solution is to keep the system off or in low power mode so the pre-charge current can do its job and bring the battery into fast charge.



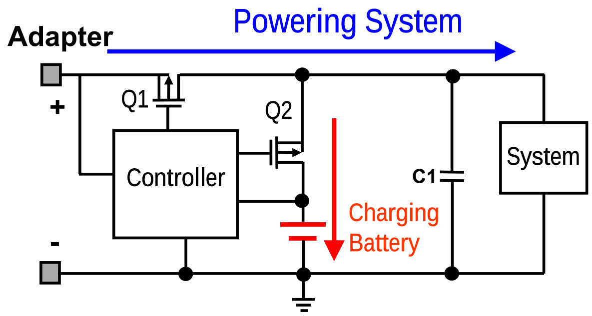
During constant-voltage phase, termination is typically based on 1/10 of max charge current, which will not occur if the system load is larger than the taper threshold. The solution is a supplemental circuit. We'll talk about it the next slide.

This plot shows how the system load keeps the current above the taper threshold. Ichg = Ibat + Isys.

At time=20, the charger goes into constant voltage mode from constant current mode. The battery charging current actually falls below the taper threshold at time=80, but the charger can't see that. The current the charger sees is way above the taper detect because the system load keeps it high.

Another scenario is the taper threshold is reached but dynamic load resets it. For example, the current waveform of a cell phone in use would typically show irregular spikes. Those spikes would cause the taper timer to reset. The solution is to filter the spikes with a capacitor.

Power Path Management Battery Charger



- System power supplied from adapter through Q1
- Charge current controlled by Q2
- Power Path Topology – Powers System & Charges Battery
  - Independent functions
  - No interaction

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To overcome all the issues that we discussed so far we can isolate the battery from the system power rail. To do that we need to add a power path network, as shown in this circuit.

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Here Q1 connects the external supply to the system rail, with Q2 being controlled by the charger to regulate the charge current and charge voltage. When the battery is fully charged Q2 is turned OFF, isolating the battery from the system. When the battery must be connected to the system Q1 turns off and Q2 turns on.

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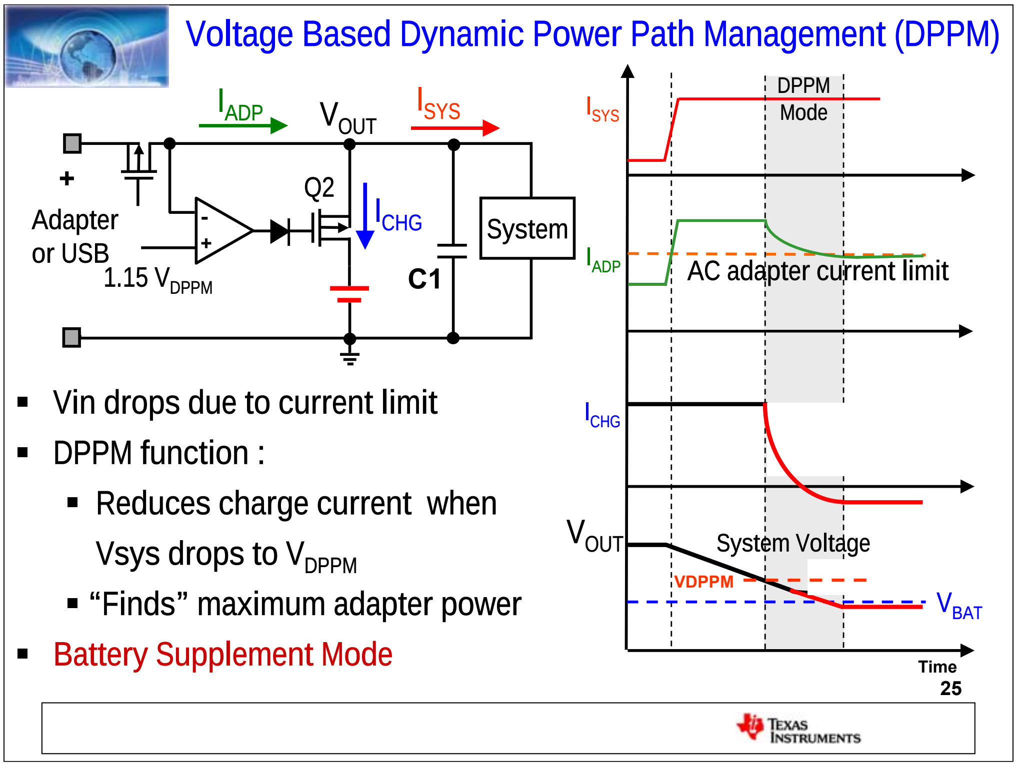
This new topology is ideal when powering system while charging the battery, as no interaction occurs between the charge current and system current.



A dynamic power management function monitors, on real time, the current going to different power paths and reduces the charge current when the external supply capacity has been reached. The dynamic power path management circuit prioritizes the use of the input power to run the system .

Without a dynamic power management funtion the system voltage will collapse when the combined system and charger current exceed the exteranl supply capability.

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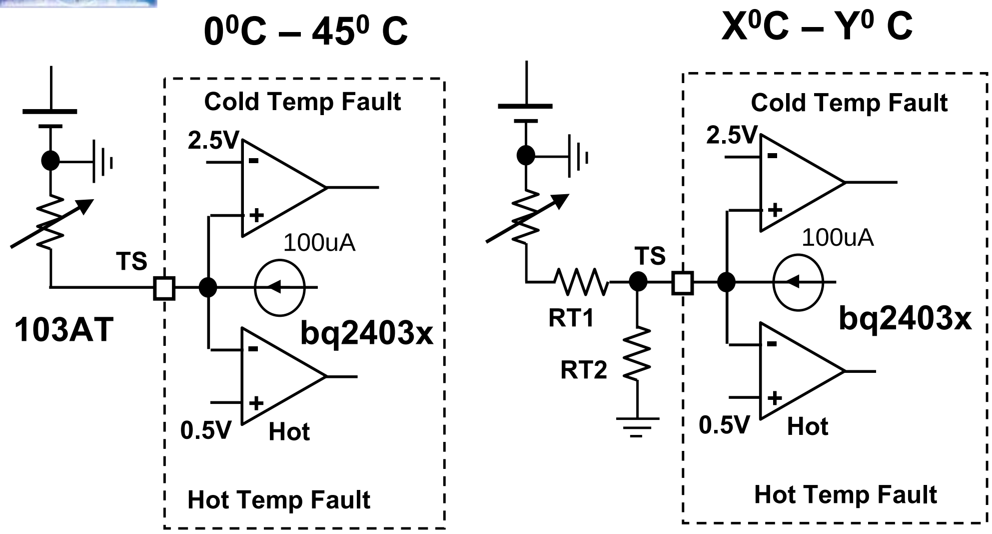
One method of dynamic power control is the DPPM, which checks the system voltage and reduces charging current when the voltage drops below a programmed threshold. This method enables finding the maximum external supply capability. In the plot, the gray area shows the DPPM, which brings the system voltage back to the DPPM level by reducing the charging current.

The DPPM function enables cost savings when in choosing an AC adapter, as it enables selecting an AC adapter that needs to be capable of supplying the maximum system current ONLY, as opposed to an AC adapter that must be capable of supplying the combined maxumu system load + fast charge current.

Temperature Qualification

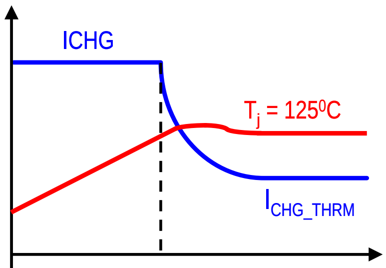


RT1 and RT2 calculation from the Temp sense software
http://focus.ti.com/docs/toolsw/folders/print/tempsense-sw.html

Thermal Fold-back Function

- Temperature Rise, in IC, is function of Power Dissipation – P = (Vin-Vout)*Iout
- Thermal Regulation is active when the IC reaches ~125°C, due to:
  - Increased Input voltage
  - Low Battery Voltage
  - High Current to Battery & System
  - Thermal Design - Layout
  - High Ambient Temperatures
- Thermal Management reduces Charge Current at 125°C – Reduces Power Dissipated

- Safety timer duration is increased.
- Charge termination is disabled



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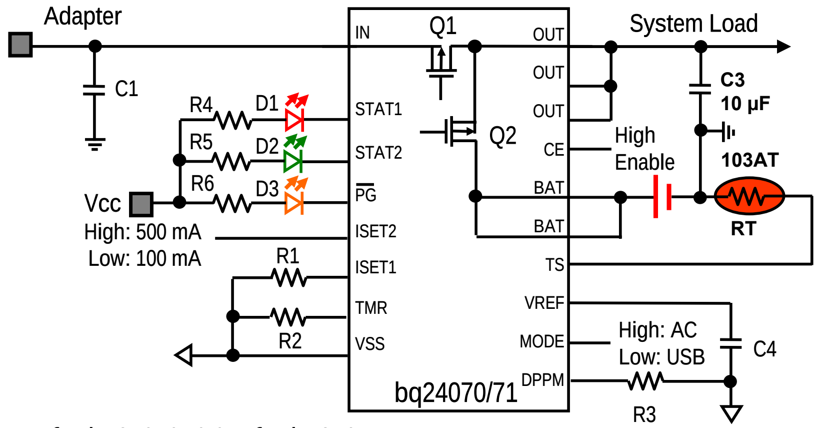
Voltage Based Dynamic Power-Path Management Charger



- OUT: 4.4 V for bq24070; 6.0 V for bq24071
- DPPM – Reduces Charge Current if input Power is limited – System Priority
- Thermal Regulation when at 125°C by reducing charge current
- Dynamically increase the safety timer based on real charge current

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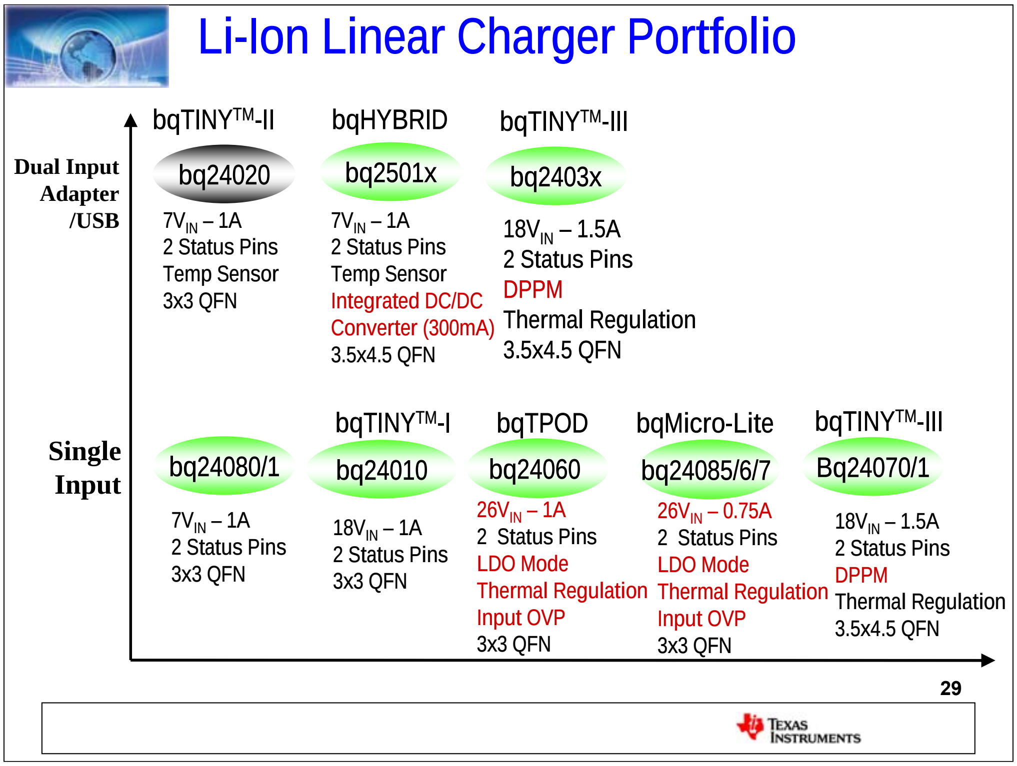
If you are interested in a charger with integrated dynamic power path, here is the part number: bq24030 series.

It has dual inputs for AC adapter and USB port. The input source can power the system and charge the battery simultaneously on two separate paths.

Charge rate is dynamically adjusted to supply sufficient system current, and an automatic battery supplement mode is integrated.

In addition to the dynamic power path, bq24030 also has the latest generation charger, with high-accuracy Voltage and Current Regulation, Temperature Sensing, Timer, etc. The charge status, AC power present, USB power present etc. provide users the complete charge and power path status.


Li-Ion Linear Charger Portfolio
Dual Input Adapter /USB
bqTINYTM-II
bq24020
7VIN – 1A
2 Status Pins
Temp Sensor
3x3 QFN
bqHYBRID
bq2501x
7VIN – 1A
2 Status Pins
Temp Sensor
Integrated DC/DC Converter (300mA)
3.5x4.5 QFN
bqTINYTM-III
bq2403x
18VIN – 1.5A
2 Status Pins
DPPM
Thermal Regulation
3.5x4.5 QFN
Single Input
bq24080/1
7VIN – 1A
2 Status Pins
3x3 QFN
bqTINYTM-I
bq24010
18VIN – 1A
2 Status Pins
3x3 QFN
bqTPOD
bq24060
26VIN – 1A
2 Status Pins
LDO Mode
Thermal Regulation
Input OVP
3x3 QFN
bqMicro-Lite
bq24085/6/7
26VIN – 0.75A
2 Status Pins
LDO Mode
Thermal Regulation
Input OVP
3x3 QFN
bqTINYTM-III
Bq24070/1
18VIN – 1.5A
2 Status Pins
DPPM
Thermal Regulation
3.5x4.5 QFN
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Fast USB Battery Charger

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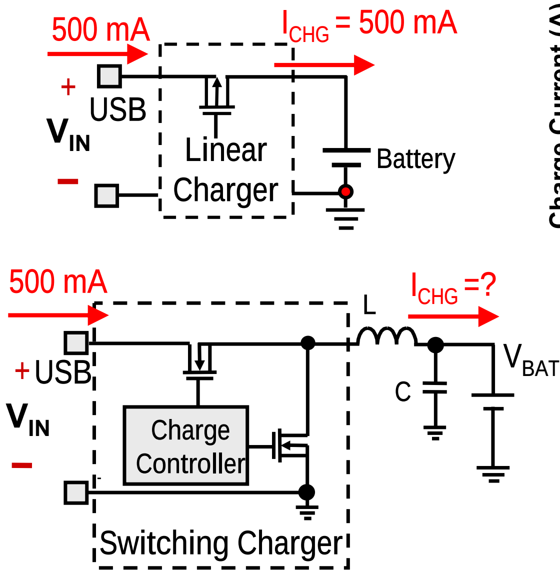
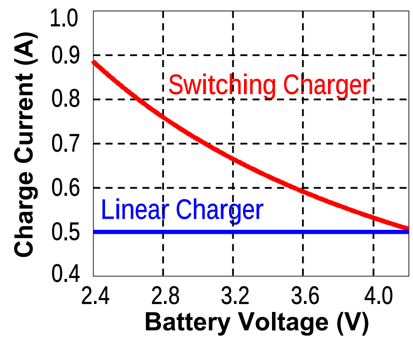
Fast USB Battery Charging





- 500-mA Current Limit
- 40% more charge current
- Full use of USB Power
- Short battery charging time

$$\boxed{I_{CHG} = \frac{V_{IN}}{V_{BAT}} \cdot \eta \cdot 500\text{mA}}$$

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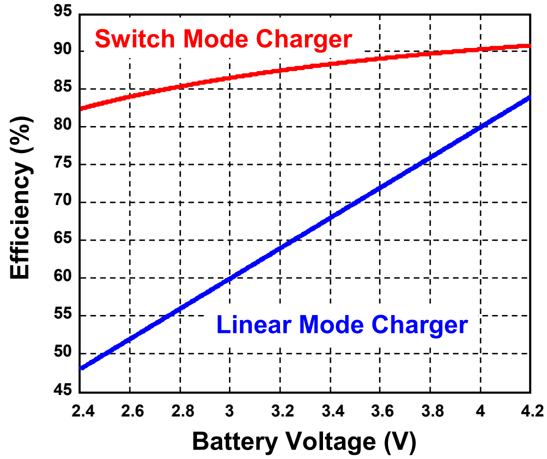
Charger Comparison: Efficiency

Vin=5V, Iin=0.5A



Switch Mode Charger

Fs=3Meg Hz

L=1uH

DCR=0.1 ohm

Rsns=0.068 ohm

Linear Mode Charger

$$Eff_{Linear} = \frac{V_{BAT}}{V_{IN}} \quad 100\%$$

Switch mode charger:

- Higher efficiency
- More suitable for power limited source application, e.g. USB battery charging

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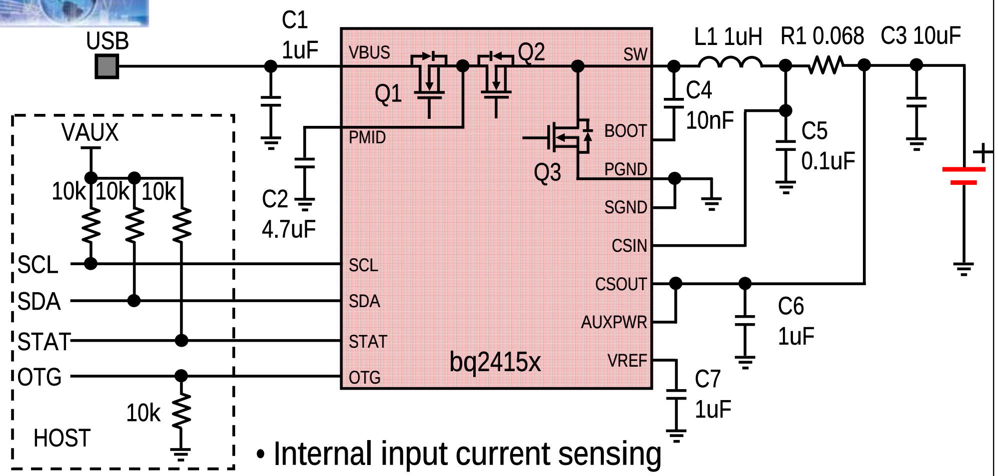
BQ2415x Typical Application Circuit



- Internal input current sensing
- Input current limiting: current loop
- Charge in constant current and constant voltage mode
- Automatic termination with internal safety timer
- Boost mode operation for USB OTG

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