Rechargeable Batteries and Their Optimized Chargers

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Battery Management Challenges

- Safety
- Battery Run-Time
  - Capacity
  - Power conversion efficiency
  - Battery charging
  - Gas Gauge Accuracy
- Size and Weight

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Agenda

- Rechargeable Battery Characteristics and Charging Requirements
- Power Path Management Battery Charger
- 3MHz switching mode USB battery charger
- Multi-cell LiFePO4 and Li-Ion switching mode battery charger
- Summary

Rechargeable Battery Characteristics and Charging Requirements

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Battery Chemistries

- **Primary battery: Non-rechargeable (Alkaline)**
- **Secondary battery: Rechargeable**
  - **NiCd: 1.0V to 1.5V**
  - **NiMH: 1.0V to 1.5V**
  - **Li-Ion**
    - ➢ **LiCoO2 - Coke: 3.0V to 4.1V**
    - ➢ **LiCoO2 - Graphite: 3.0V to 4.2V**
    - ➢ **LiMnO4 - Graphite: 3.0V to 4.4V**
    - ➢ **LiFePO4 - Graphite: 2.0V to 3.6V**

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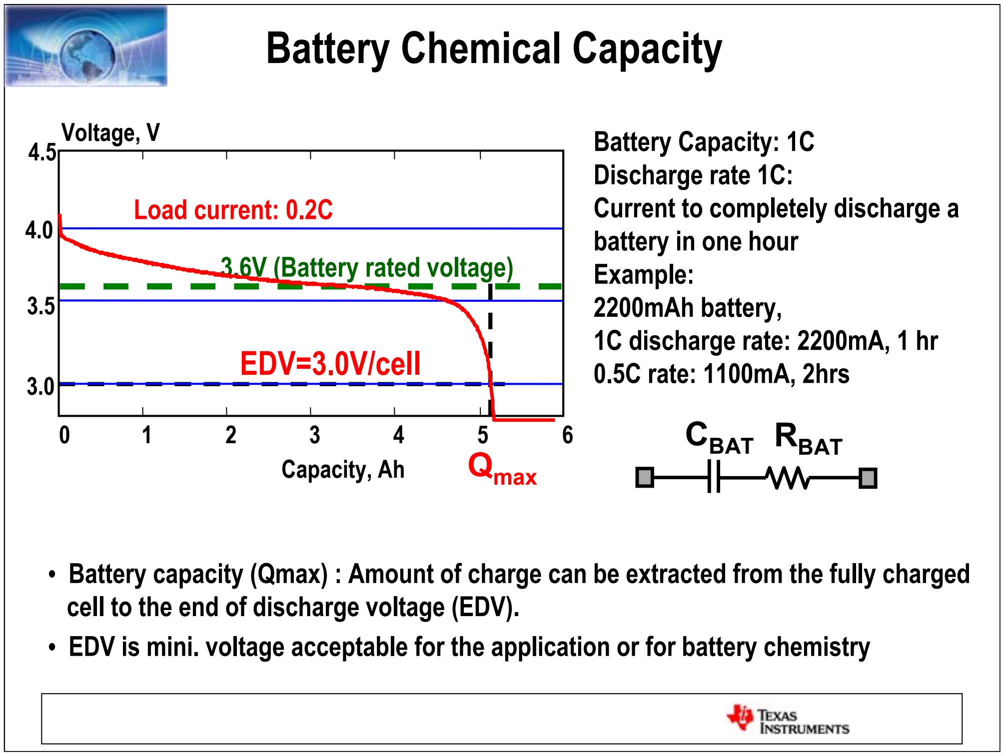
The *positive (+) electrode*, called *cathode* in batteries, is connected to aggressive oxidizing material that is capable of ripping electrons from other materials. One example of common oxidizing material is oxygen (which is indeed used in cathodes of fuel-cells) but in batteries solid oxidizing materials such as MnO2 and NiO(OH)2 are used.

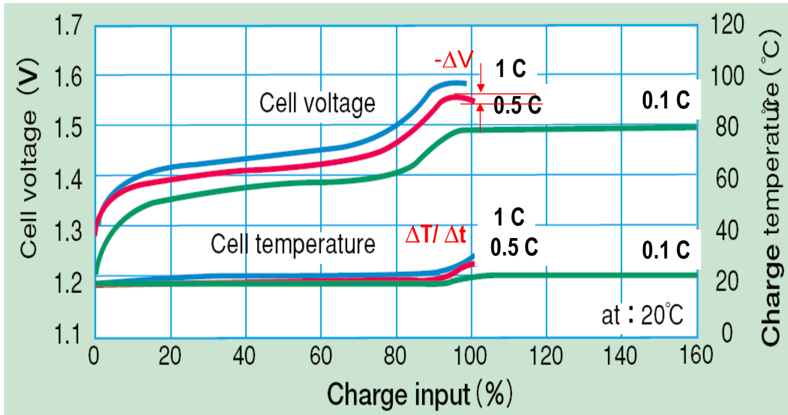
The *negative (-) electrode*, called *anode* in batteries, is connected to strong reducing material, that is rich in electrons and can easily give them away. These materials are similar to “fuel” in its function. Indeed some common fuels like natural gas can be used for anode agent of fuel-cells. In batteries it is more practical to use solid fuels, such as Cd or Zn metals, or more exotic lithium intercalated into graphite.

Both rechargeable and primary batteries have fixed amount of active materials, that are physically attached to the electrodes. Active material of fuel cells are either gas or liquid, therefore more material can be added to replace the used one. Material in primary batteries either changes its crystalline structure or becomes electrically disconnected from electrodes during discharge, therefore making recharge impossible. Rechargeable batteries retain its crystal structure and electric connecting over many charge and discharge cycles, but will also eventually degrade.



Main question regarding battery functionality in a portable application is “how long is it going to last”? This is determined by the amount of active materials, their specific capacity and voltage characteristics. When battery is discharged, its voltage will gradually decrease until it reaches minimal voltage acceptable for the device called end of discharge voltage (EDV), or the voltage where continuing discharge will cause damage to the battery. Integrating the passed charge during discharge process allows us to measure capacity Qmax that can be discharged until EDV is reached. Voltage profile during low rate lithium ion battery discharge is illustrated above.

NiMH, and NiCd Battery Charge Characteristics



Charge Termination

- **-ΔV, PVD, ΔT/Δt for >0.5C**
- **Timer for <0.5C**

Charging of NiMH battery is the same as for NiCd battery. In calculation of charging current value it is necessary to considered that for the same size, NiMH battery has about twice the capacity of NiCd battery. Because of that, chargers designed for AA (or other fixed format) NiCd batteries are not suitable for NiMh because they would undercharge them or charging would take too long (charge current too low).

Charge Management ICs Charge Phases for NiCd/NiMH

- Discharge Before Charge for the NiCd to eliminate battery memory
- If the temperature is out of the LTF to HTF range, or if the battery voltage is out of the EDV to max range, start with trickle charge
- Fast charge when temperature and voltage are qualified
- Fast Charge Termination
  – $\Delta T / \Delta t$. Requires temperature sensor. Recommended for the NiMH, because
    1) the voltage depression is smaller and harder to detect than NiCad
    2) a new NiMH battery has false peaks early in the charge cycle.
  2. PVD, $-\Delta V$. Work well with the NiCd for >0.5C charge rate.
  3. Safety backup: max voltage, max temperature, max time for <0.5C
- Top-off at a reduced charge rate; usually used only with NiMH batteries, which tend to fill only 80 to 95% during fast charge
- Maintenance Charge keeps the battery full against the battery's self-discharge rate

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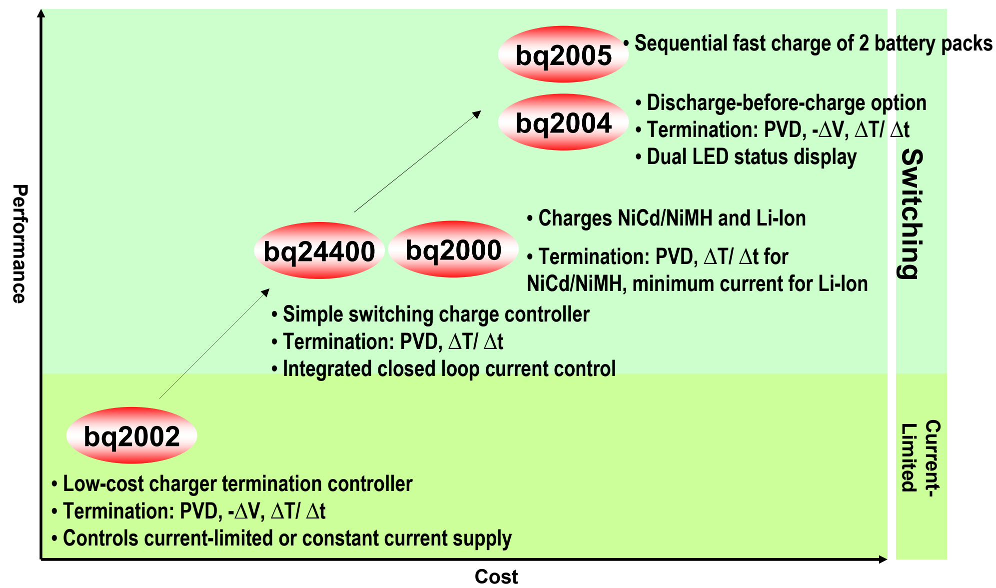
Focus Charger Products – NiCd/NiMH



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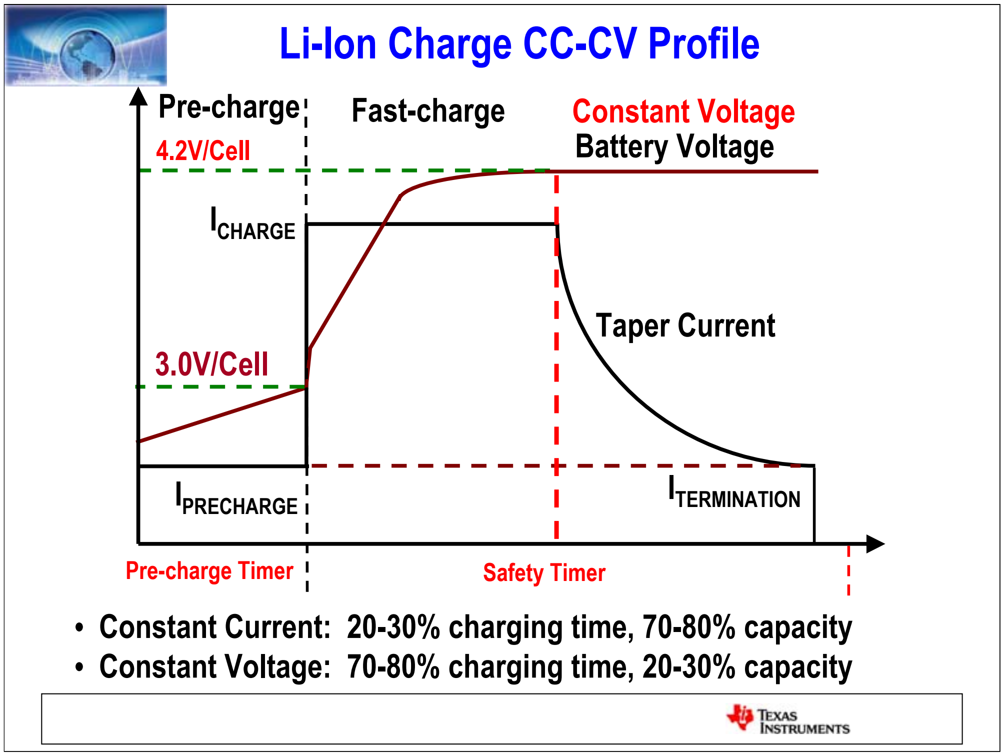


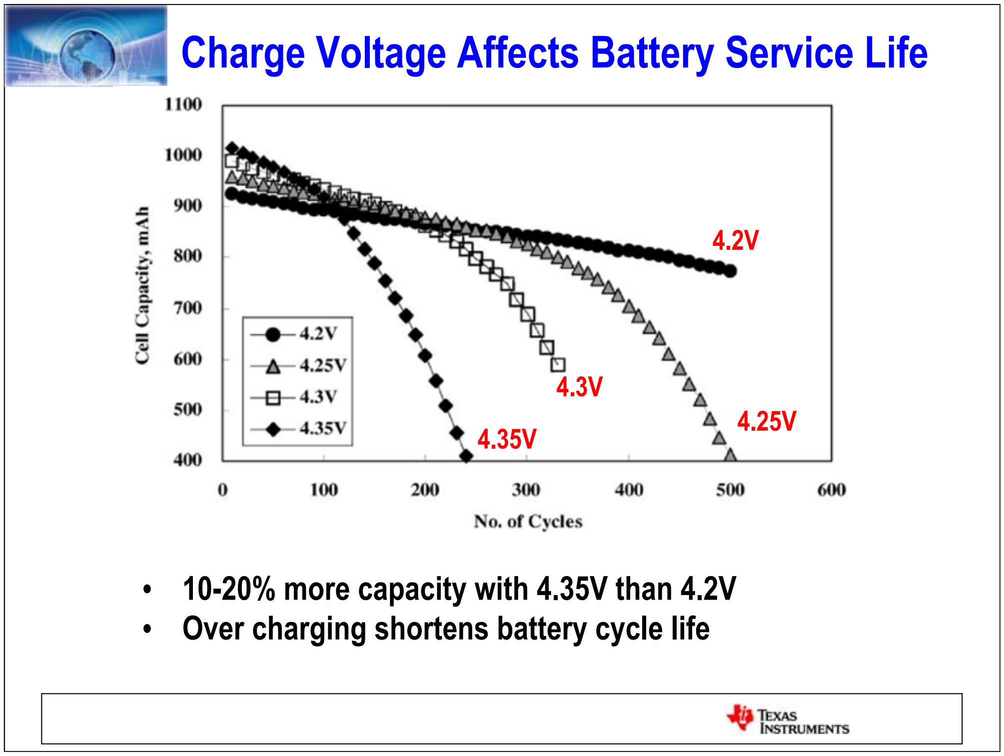
This is a typical Li-Ion battery charge profile.

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.

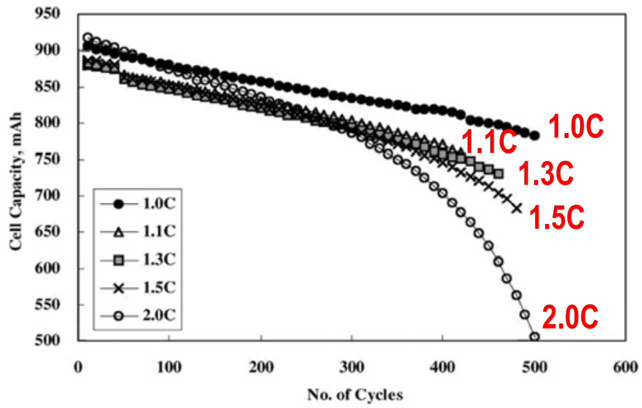


Unfortunately, for lithium ion battery self discharge in not only loss of energy, but also an indication of battery degradation. Most of lithium lost during self-discharge can no longer be recovered during charge and is stored as insoluble film on surface of the active material. This film not only binds 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.

Charge Current vs Battery Degradation

Charge Current

Current should be limited to 1C rate to prevent overheating and resulting accelerated degradation.



"Factors that affect cycle-life and possible degradation mechanisms of a Li-ion cell based on $LiCoO_2$", 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 $LiMnO_4$ 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

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Li-Ion Charging Requirements (Cont.)

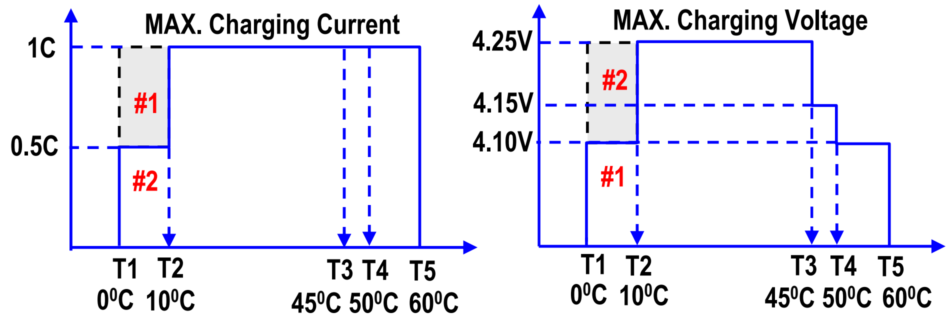
Battery charging Temperature Qualification
0°C to 45°C. Charging at higher temperature results in accelerated aging

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.

New Charging Requirements for Portable EEs

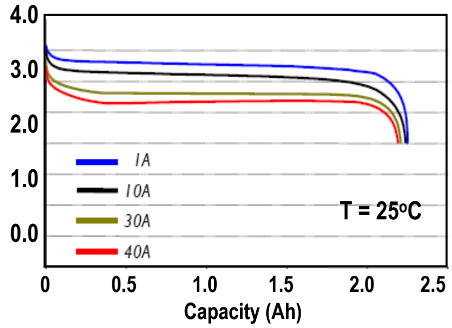


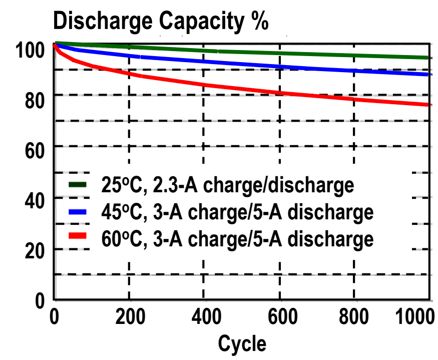
Note: $LiCoO_2$ Type Battery Cell

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

LiFePO4 Battery

- Fine-tune the cell for either high discharge rate or high capacity. 10C rate discharge are available with Ni/Co/Mn hybrid cathodes.
- Example: A123 Systems company: 26650A LiFePO4,
  - Safety: 350°C Thermal Runaway
  - 10 mΩ at 1 Hz
- Suggest charge voltage 3.6V



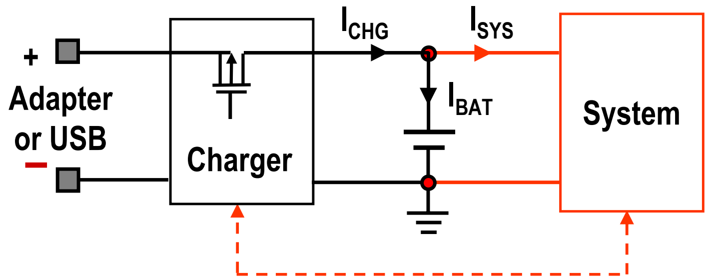


http://www.a123systems.com

More radical improvement of rate capability can be improved by using anodes with very low impedance because their voltage is not as low and so no passivating layer has to be build to stop reaction with electrolyte. Example of this approach is use of Li titanate anode.

Power Path Management Battery Charger

Charging with an Active System Load: Issues



Charger output current is shared:

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

Issues:

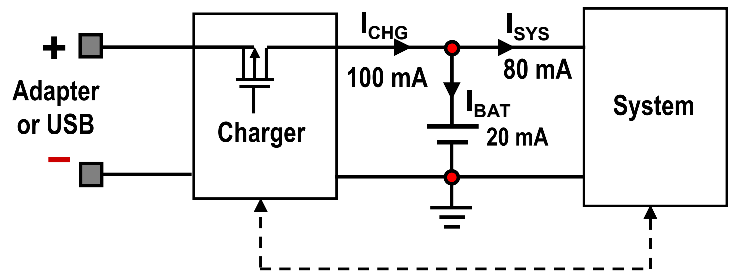
- **Safety Timer False Expiration**
- **Termination Detection**

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.

Issue : Pre-charge and Safety Timer Fault



Pre-Charge Mode:

Battery voltage may not reach the fast charge voltage threshold

- **Pre-charge timer may expire**

Solution: keep system off or in low-power mode in pre-charge mode

Drawback: Can not operate the system while charging a deeply discharged battery simultaneously

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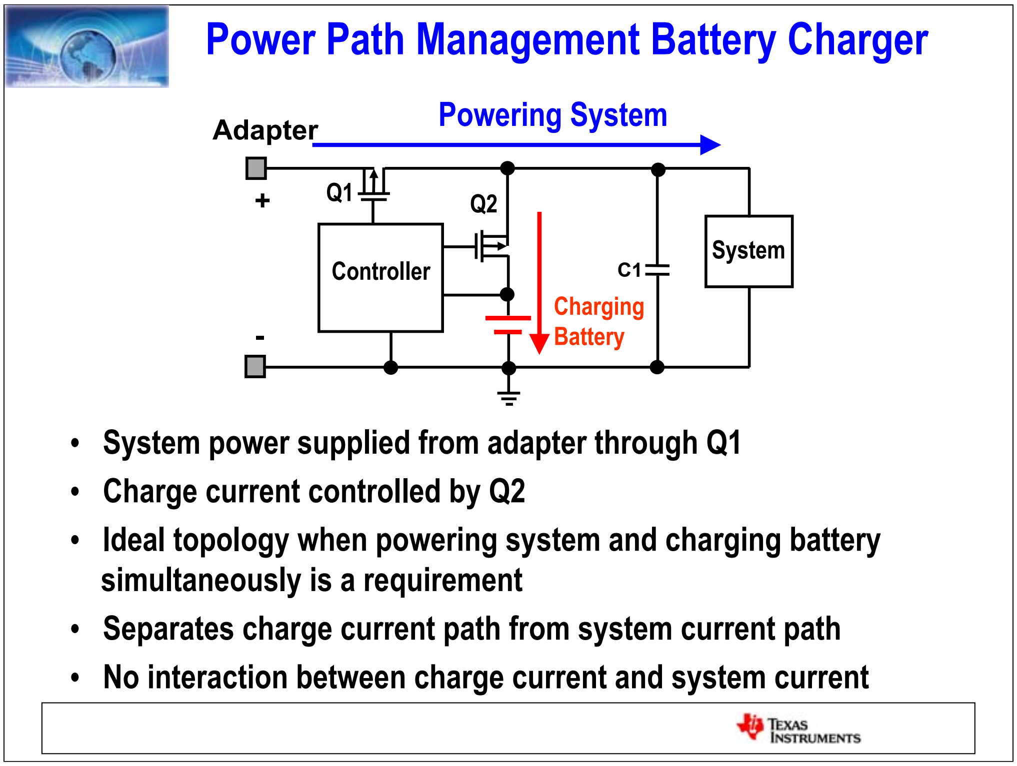
As I've mentioned, during pre-charge phase, the charge current is very small, typically 1/10 of the maximum chargin current. The power delivered will be this small current times a low battery voltage. The system's average load most likely will be greater than this value.

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.



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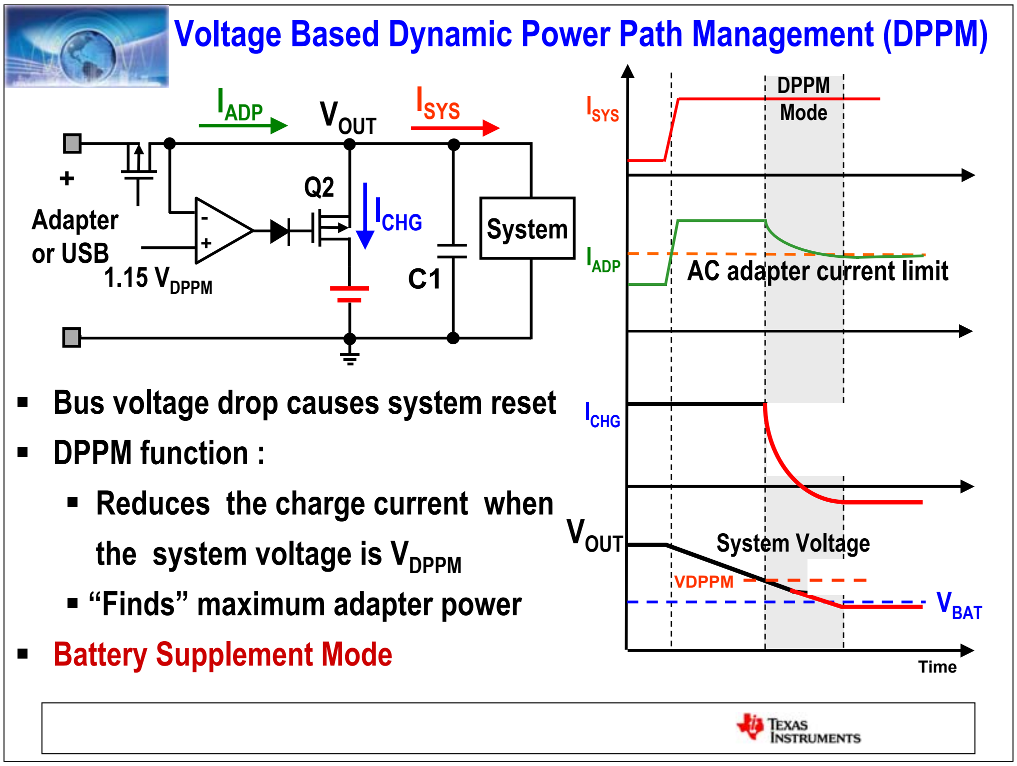
This new topology is ideal when powering system while charging the battery, as no interaction occurs between the charge current and system current.



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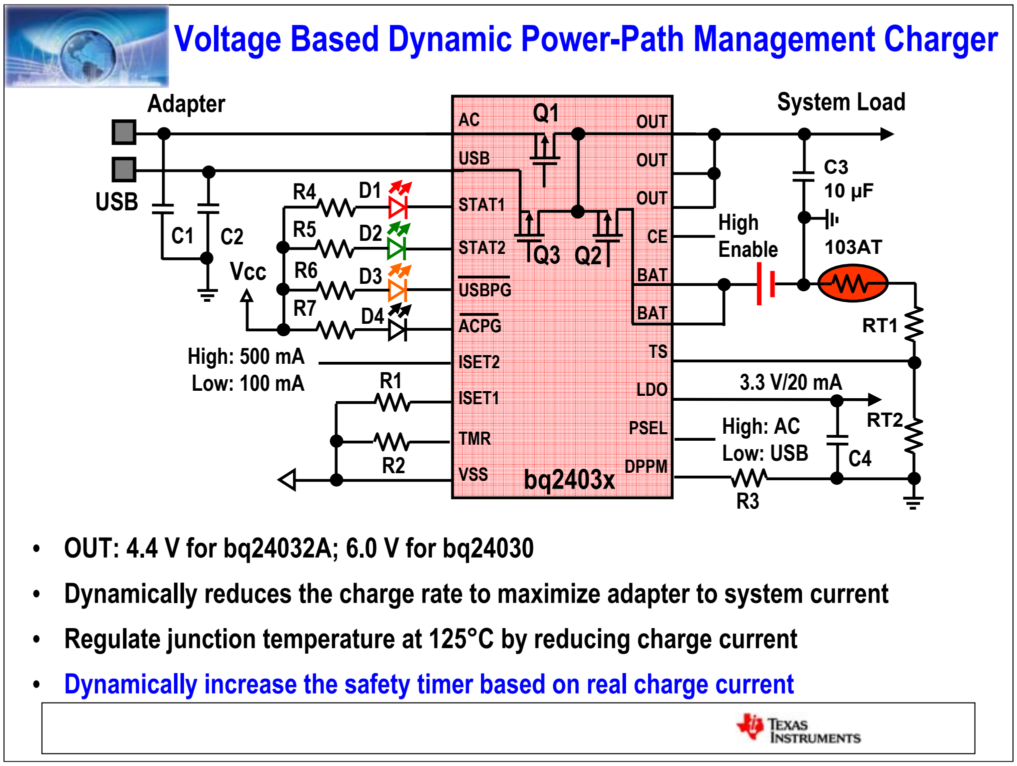
One method of dynamic power control is the DPPM, which checks the system voltage and reduces charging current when the voltage drops below a programmed threshold. This method enables finding the maximum external supply capability. In the plot, the gray area shows the DPPM, which brings the system voltage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



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

bqTINY™-II	bqHYBRID	bqTINY™-III
bq24020	bq2501x	bq2403x
$7V_{IN}$ – 1A 2 Status Pins Temp Sensor 3x3 QFN	$7V_{IN}$ – 1A 2 Status Pins Temp Sensor Integrated DC/DC Converter (300mA) 3.5x4.5 QFN	$18V_{IN}$ – 1.5A 2 Status Pins DPPM Thermal Regulation 3.5x4.5 QFN

Single Input

	bqTINY™-I	bqTPOD	bqMicro-Lite	bqTINY™-III
bq24080/1	bq24010	bq24060	bq24085/6/7	Bq24070/1
$7V_{IN}$ – 1A 2 Status Pins 3x3 QFN	$18V_{IN}$ – 1A 2 Status Pins 3x3 QFN	$26V_{IN}$ – 1A 2 Status Pins LDO Mode Thermal Regulation Input OVP 3x3 QFN	$26V_{IN}$ – 0.75A 2 Status Pins LDO Mode Thermal Regulation Input OVP 3x3 QFN	$18V_{IN}$ – 1.5A 2 Status Pins DPPM Thermal Regulation 3.5x4.5 QFN

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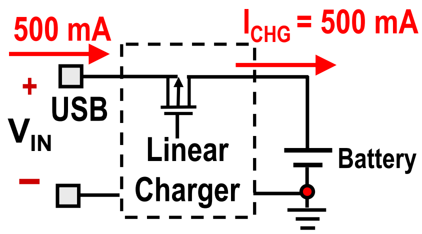
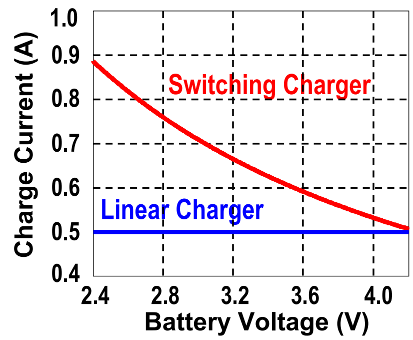
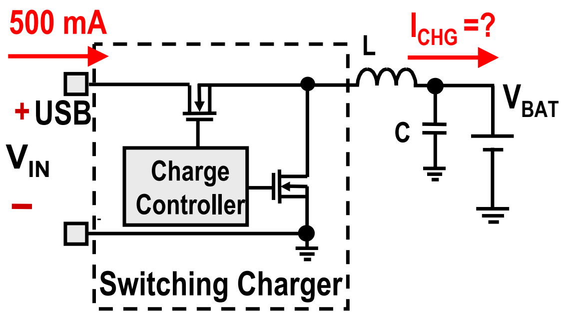
Fully Integrated Switch-Mode Li-Ion Battery Charger with Full USB Compliance and USB-OTG Support

Fast USB Battery Charging



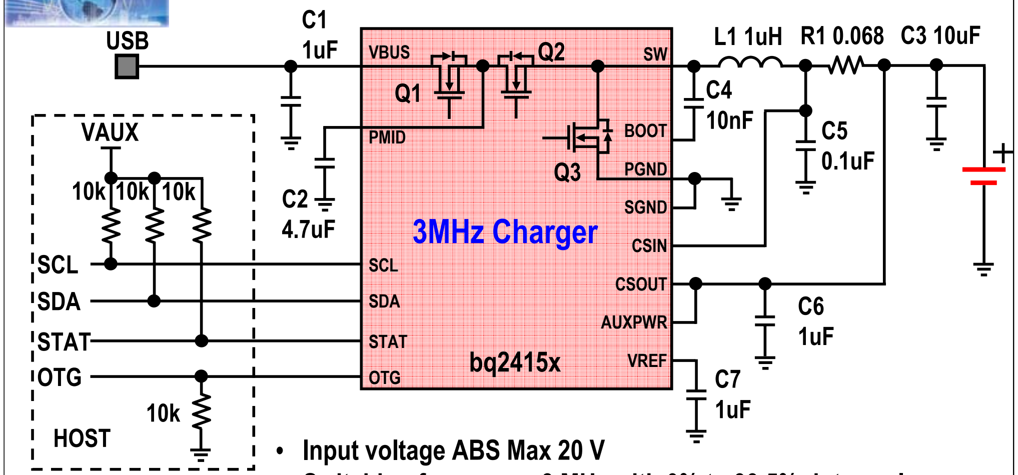




- 500-mA Current Limit
- 40% more charge current
- Full use of USB Power
- Short battery charging time

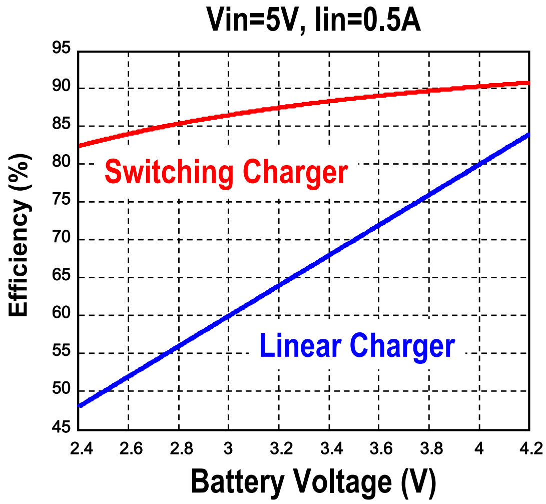
$$I_{CHG} = \frac{V_{IN}}{V_{BAT}} \cdot \eta \cdot 500\text{mA}$$

BQ2415x Typical Application Circuit



- Input voltage ABS Max 20 V
- Switching frequency: 3 MHz with 0% to 99.5% duty cycle
- Programmable charge parameters by I2C interface
  - Charge current up to 1.25A
  - Charge voltage: 3.5—4.42V, step 20mV
  - Termination current

Battery Charger Efficiency



Switch Mode Charger

Fs=3Meg Hz

L=1uH

DCR=0.1 ohm

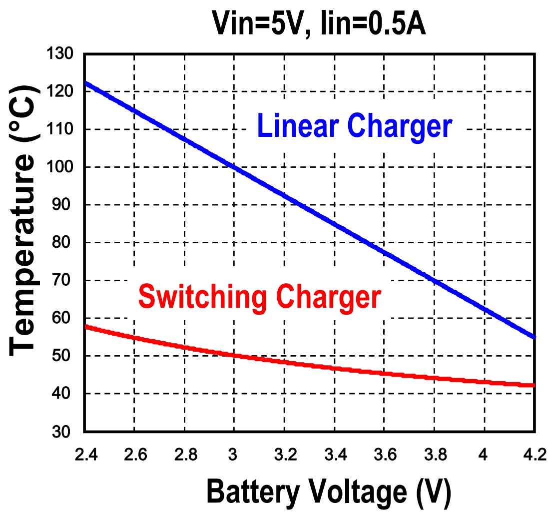
Rsns=0.068 ohm

Linear Mode Charger

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

- Higher efficiency

Junction Temperature



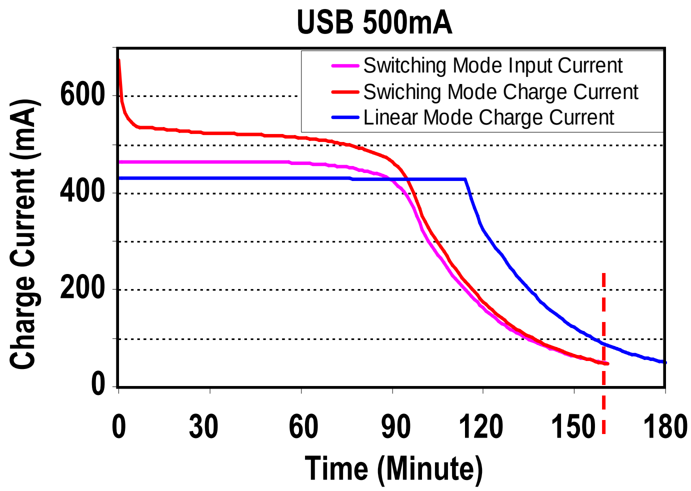
$T_A = 25°C$

$\theta_{JA} = 75°C/W$ for 2x2mm QFN

$$T_j = R_{\theta JA} \times P_{loss} + T_A$$

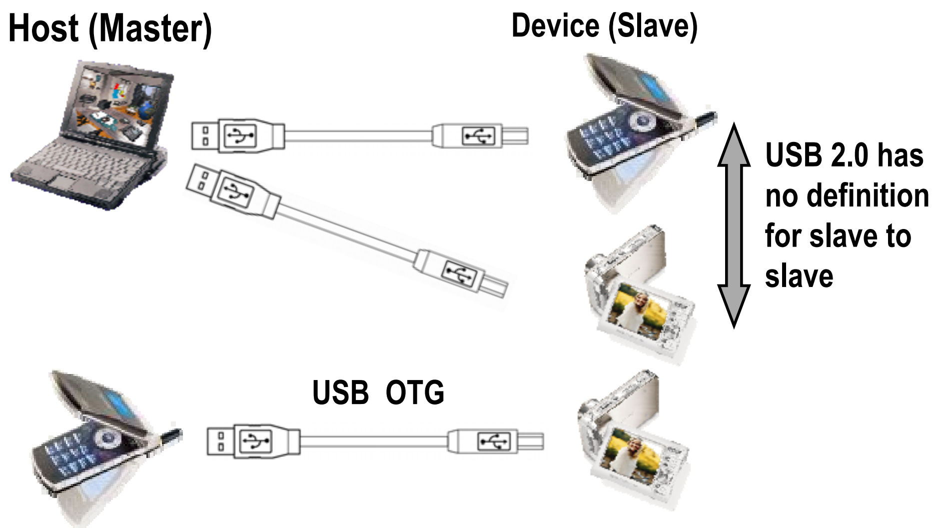
Linear Charger:
Thermal regulation effectively
Reduce the charge current and
Slow charging

Charging Time Comparison



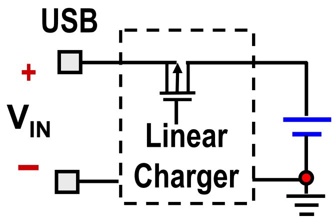
• **Total charging time save 10% (about 20 minutes).**

USB On-The-Go Defines a New Connection Paradigm

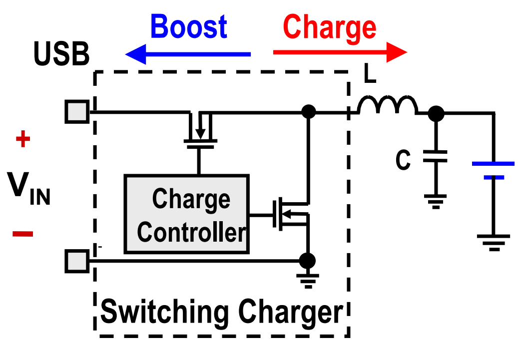


• USB OTG provides a STANDARD USB connection for mobile devices.

How to Support OTG?



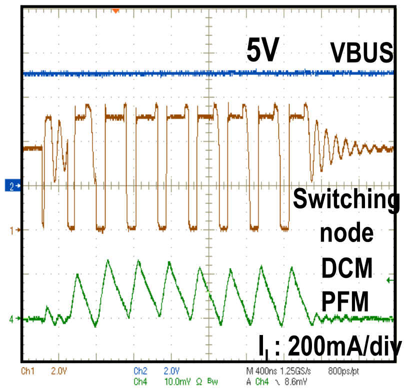
- Can not provide 5V VBUS
- Have to add boost converter

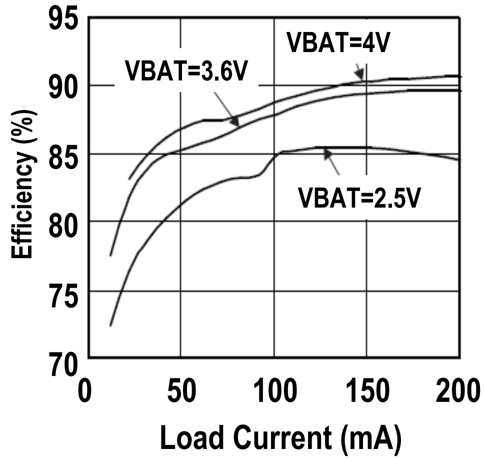


- Buck mode for charging
- Boost mode for OTG
- No additional cost

Boost Converter Light Load PFM Mode

VBAT=3.6V, No load





- Boost converter: PFM mode at light load to increase efficiency

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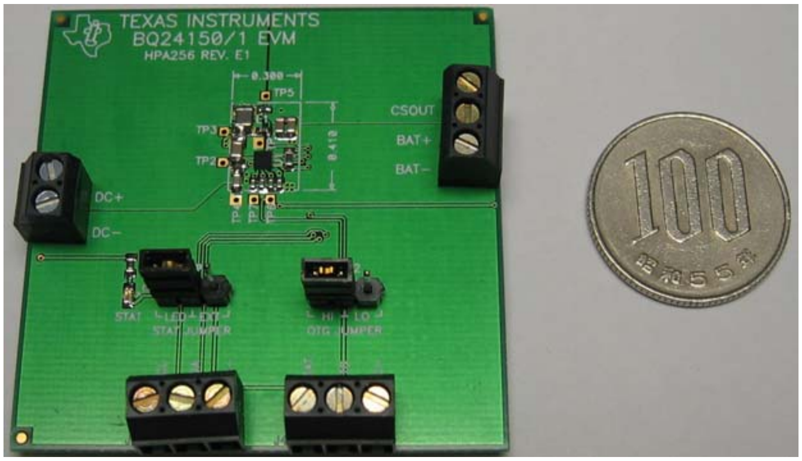
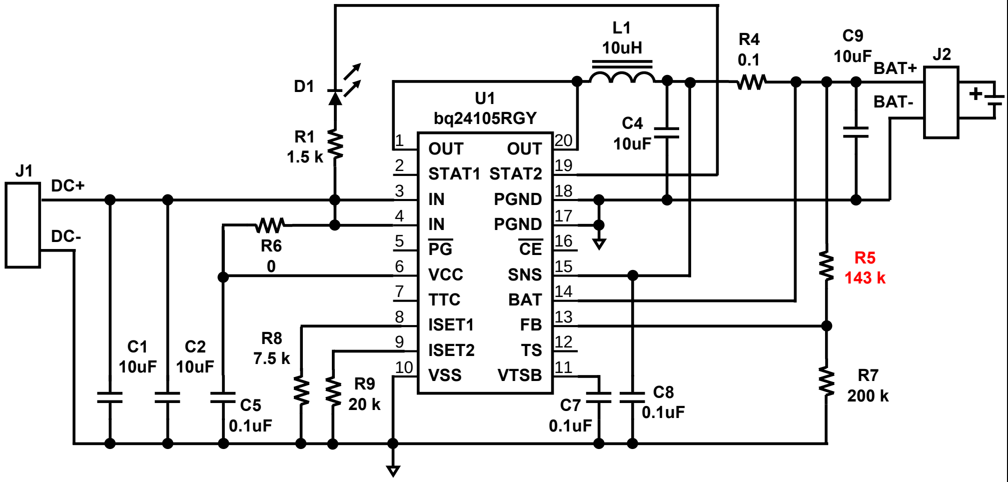
EVM Hardware



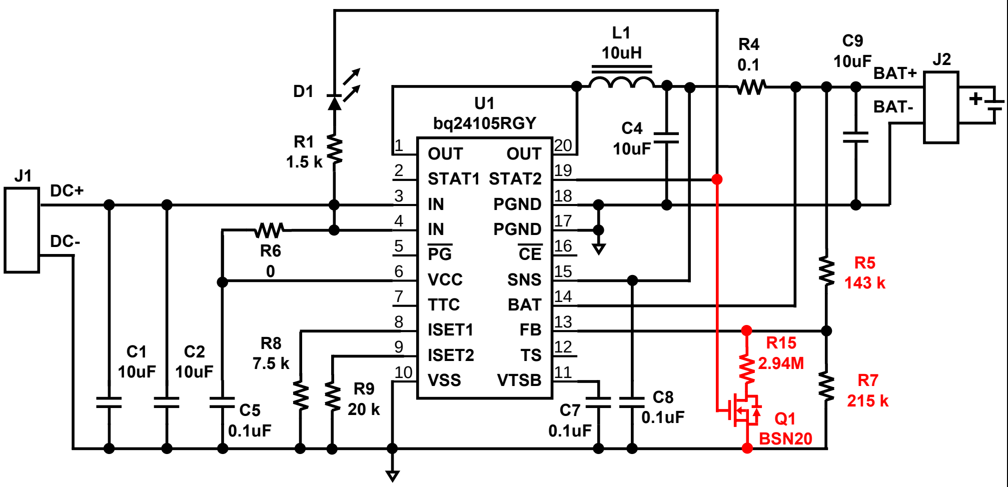
Multi Cell LiFePO4 and Li-Ion Battery Charger

LiFePO4 Battery Charger Solution 1: bq24105/125 up to 4 cell, <2A application



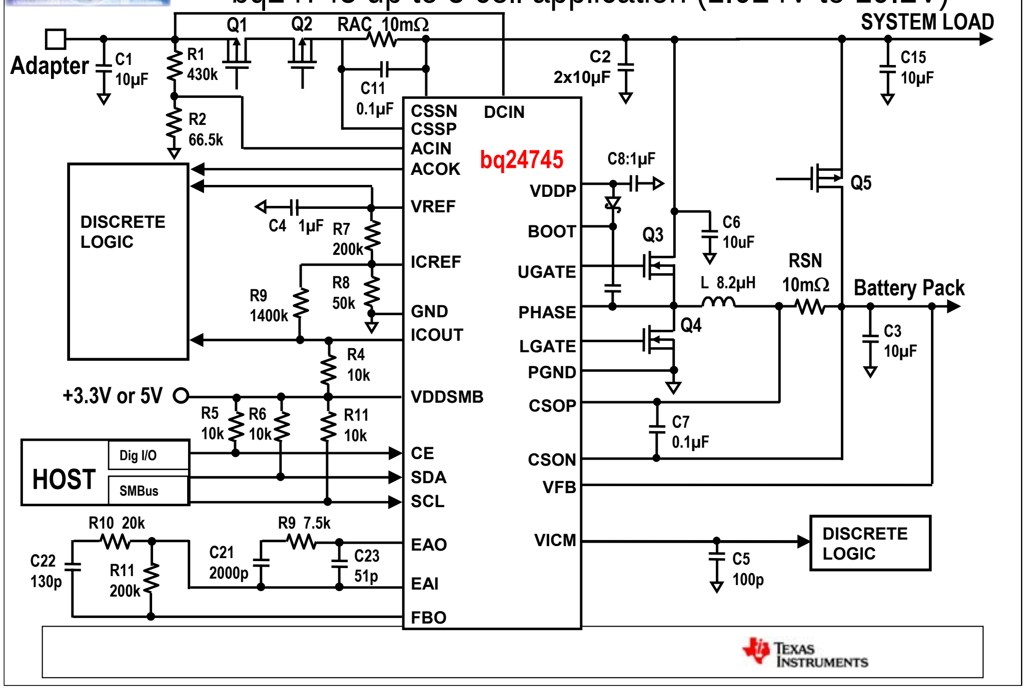
- Charge voltage change from 4.2V to 3.6V
- Refresh voltage change from 4.1V to 3.516V

bq24105 EVM Schematic and Changes



- Charge voltage change from 4.2V to 3.6V
- Refresh voltage change from 4.1V to 3.4V

LiFePO4 Battery Charger Solution 2: bq24745 up to 5 cell application (1.024V to 19.2V)



Li-Ion Switch-Mode Charger Portfolio

Stand-alone → **Host-controlled**

EMI improvement
(increase gate resistance to slow down switching)
Standalone only
2-cell for UMPC

bq24103/5
bq24113/5
bq24123/5

$18V_{IN}$ - 2A
1.1MHz Sync PWM
Integrated FETs
1 - 3 Cells in Series
3.5x4.5 QFN
Standalone & Host Controlled

Very small solution size

bq24745 (5x5)

SMBus, 1-4 cell
No power source selector

bq24705 (4x4)
bq24740 (5x5)

No power source selector

bq24721C

$30V_{IN}$ – 8A
300/500kHz Sync PWM
High V/I Accuracy
Dynamic Power Mgt
3-4 Cells in Series
5x5 QFN-28
SMBus Interface
Power source selector

bq24750/51A

$30V_{IN}$ – 8A
300kHz Sync PWM
High V/I Accuracy
Dynamic Power Mgt
2-4 Cells in Series
5x5 QFN-28
Power source selector

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Summary

- Rechargeable Battery Characteristics and Charging Requirements
- Power Path Management Battery Charger
- 3MHz switching mode USB battery charger
- Multi-cell LiFePO4 and Li-Ion switching mode battery charger