TECH DAYS
Texas Instruments

Battery Technology Overview:
Lithium-Ion Battery Technology, Charging, and Capacity Monitoring

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INTRODUCTION TO BATTERY MANAGEMENT

- Battery Technology Overview
  - Li-Ion vs. other batteries
  - Li-Ion technology trends
- Li-Ion Pack Protection – brief overview
- Li-Ion Battery Charging
  - Typical (CCCV) Li-Ion Charging method – ideal & real implementations
  - Power Path & Dynamic Power Management
  - "Universal" Charging with Buck-Boost charger
- Appendix / Reference Material
  - Introduction to Battery Gauging Concepts

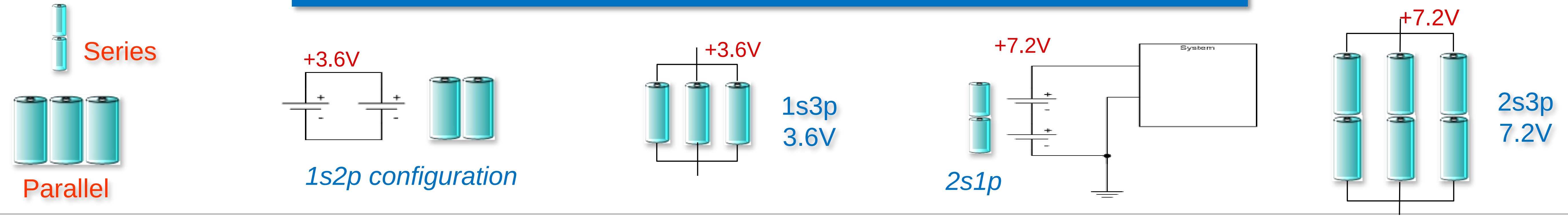
What is Battery Management?

- **Battery management circuits**
  - *Control charge flow into battery*
  - *Prevent abuse conditions*
  - *Monitor critical parameters*
  - *Communicate information*

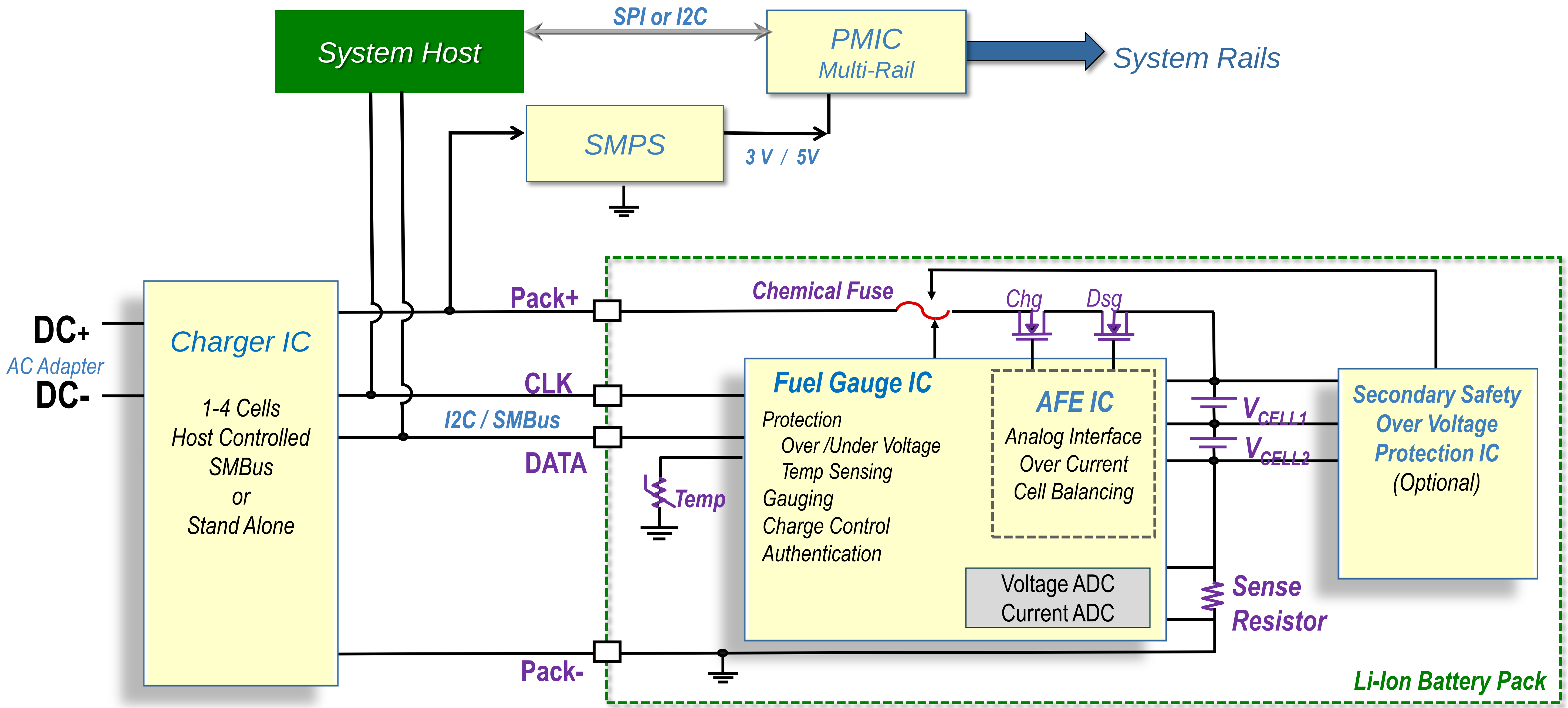
- **Systems require battery management to extend run-times, ensure safety, and maximize battery service life**

- **Degrees of implementation vary, but should include three main functions : charging, gauging (monitoring), and protection**

Pack Configurations

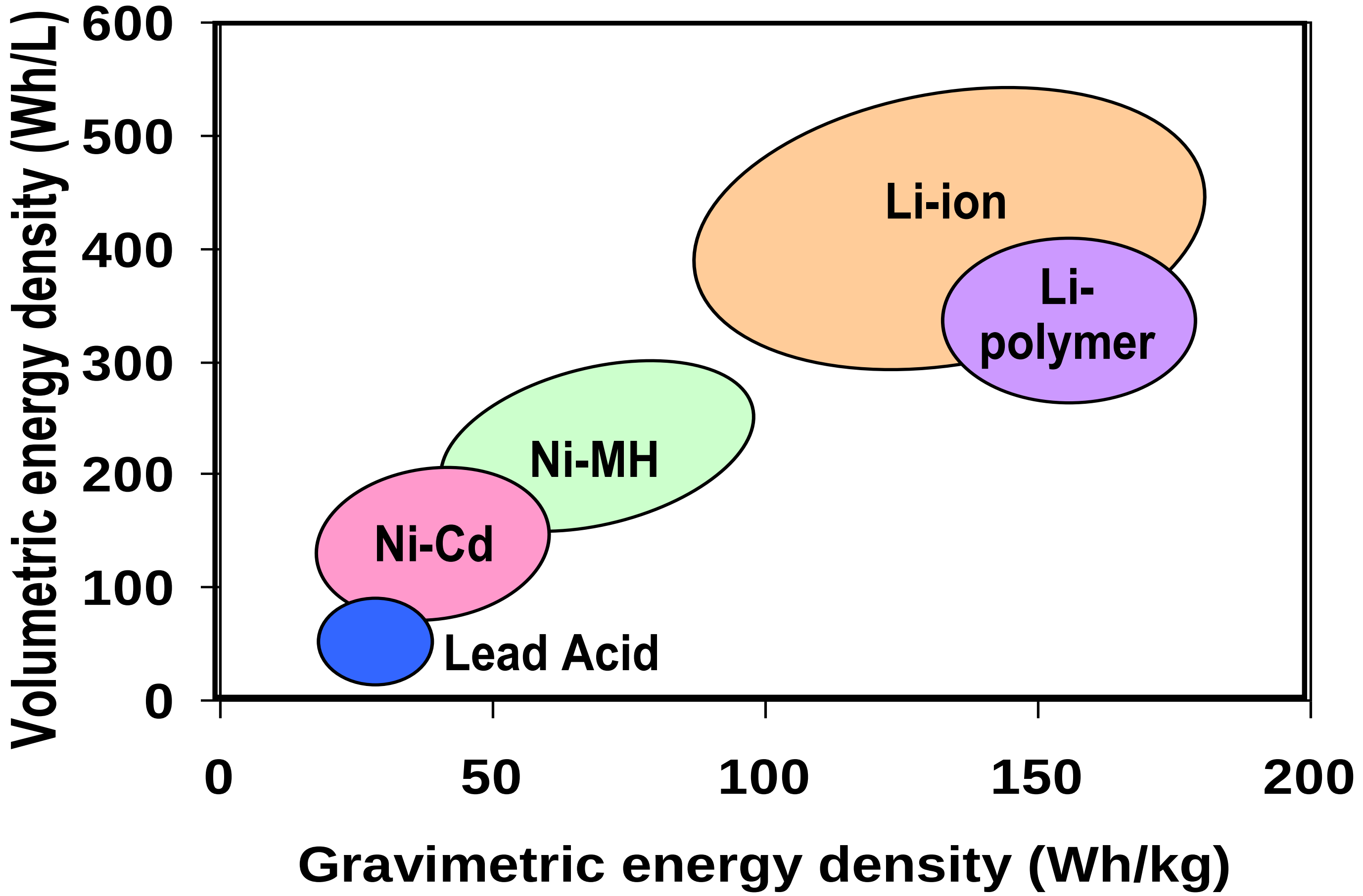


Li-Ion Battery Management Components



Rechargeable Battery Options

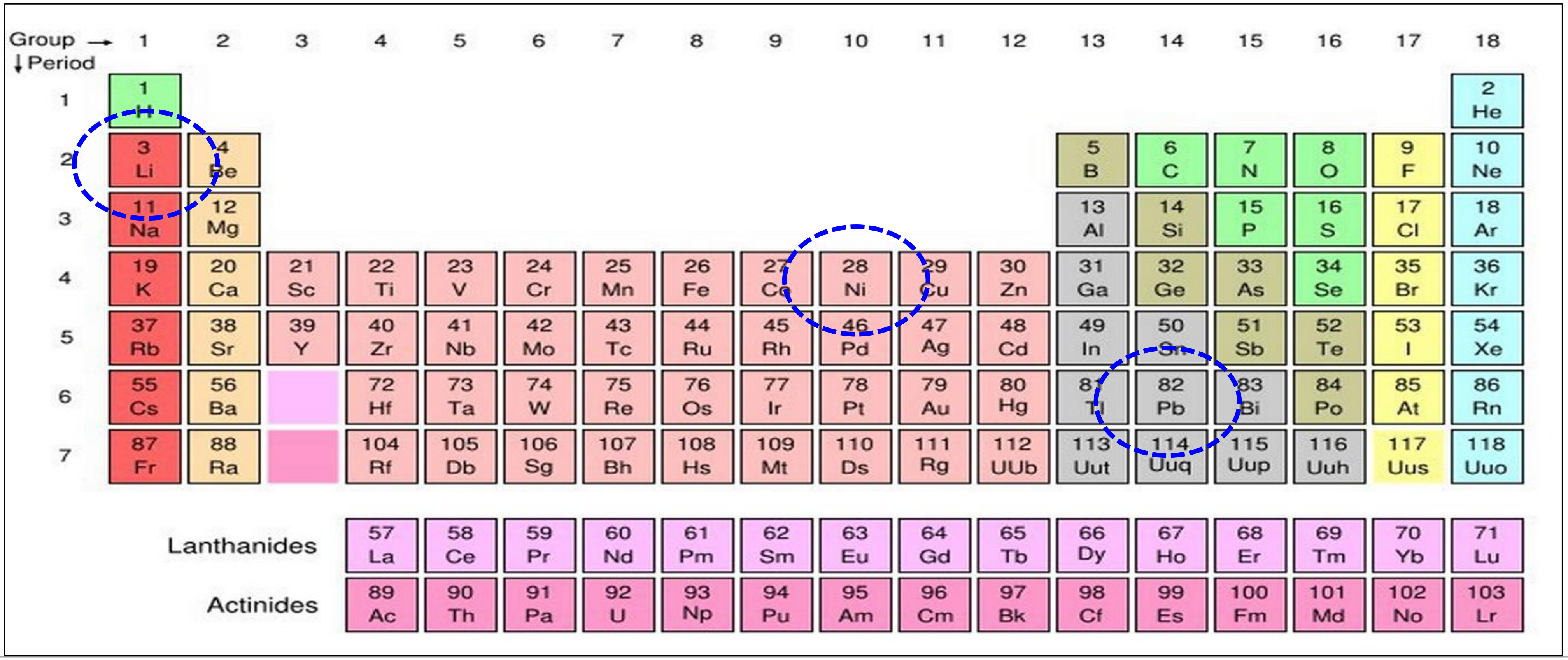
- **Lead Acid**
  - ↑ 100 years of fine service!
  - ↓ Heavy, low energy density, toxic materials



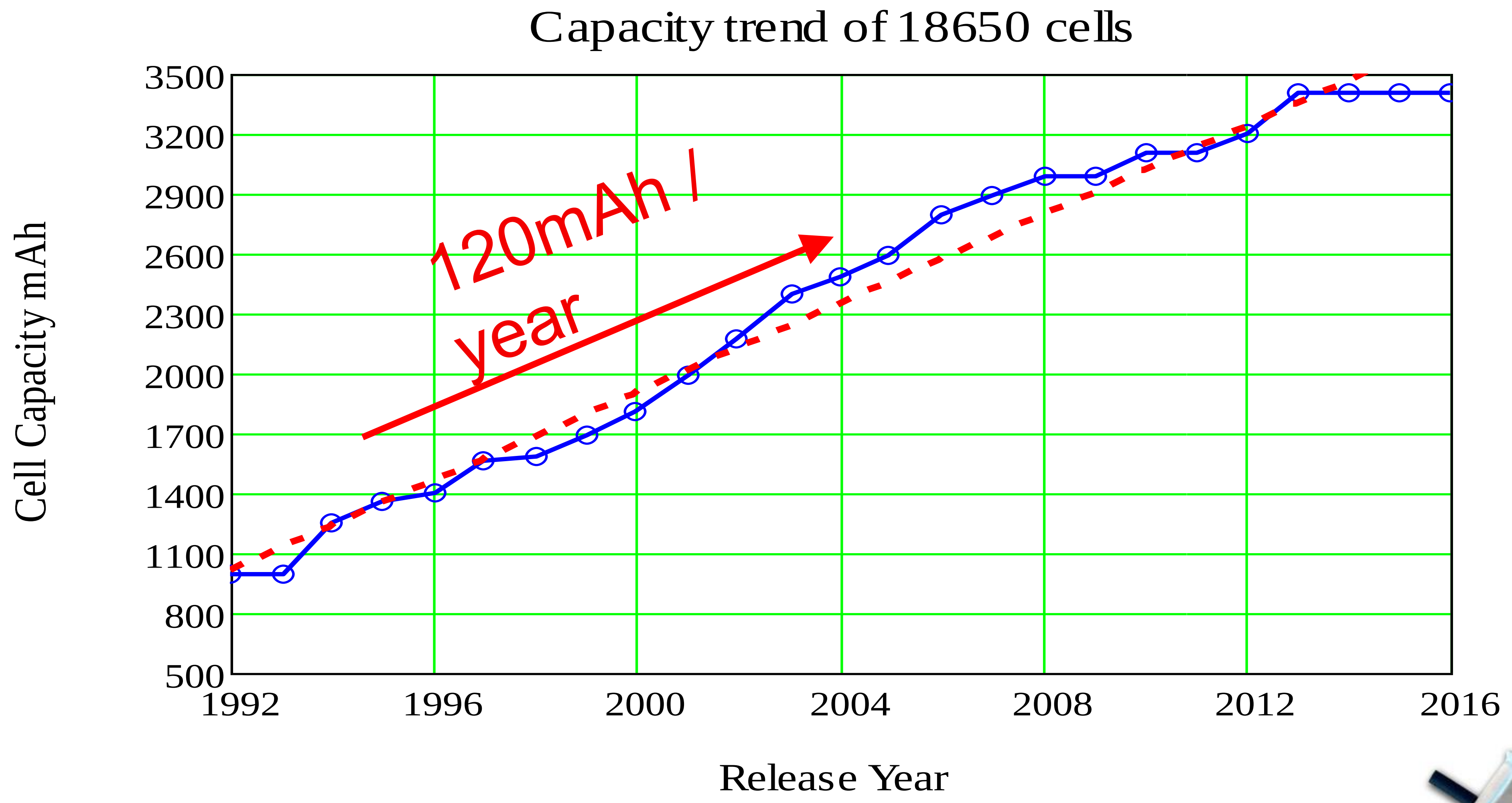
- **NiCd**
  - ↑ High cycle count, low cost
  - ↓ Toxic heavy metal, low energy density
- **NiMH**
  - ↑ Improvement in capacity over NiCd
  - ↓ High self-discharge
- **Lithium Ion / Polymer**
  - ↑ High Energy density, low self-discharge
  - ↓ Cost, external electronics required for battery management

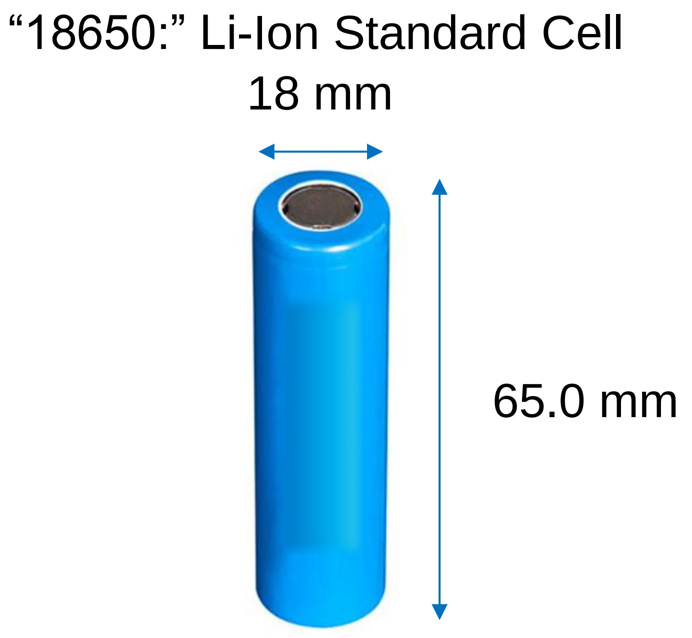
Why is Li-Ion popular?

- A high performance battery for high performance devices!
  - *Gravimetric energy density → High Capacity, Light weight battery*
  - *Volumetric density energy → High Capacity, Thin battery*
  - *Low self-discharge → Stays charged when not in use*

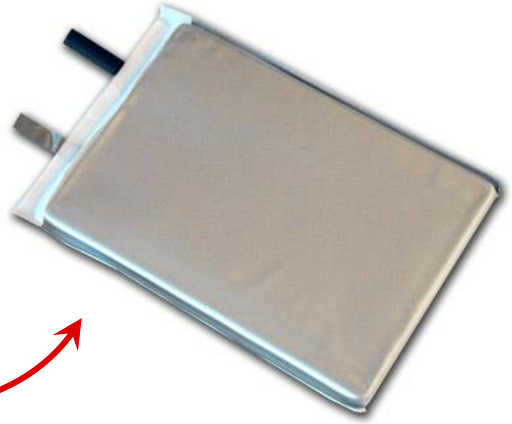


18650 Li-Ion Cell Capacity Development Trend





- 18650: Cylindrical, 65mm length, 18mm diameter
- 120mAh/year average increase rate until 2012
- 3.4Ah remains highest capacity for 18650 Cell
- New developments are focusing on pouch cells

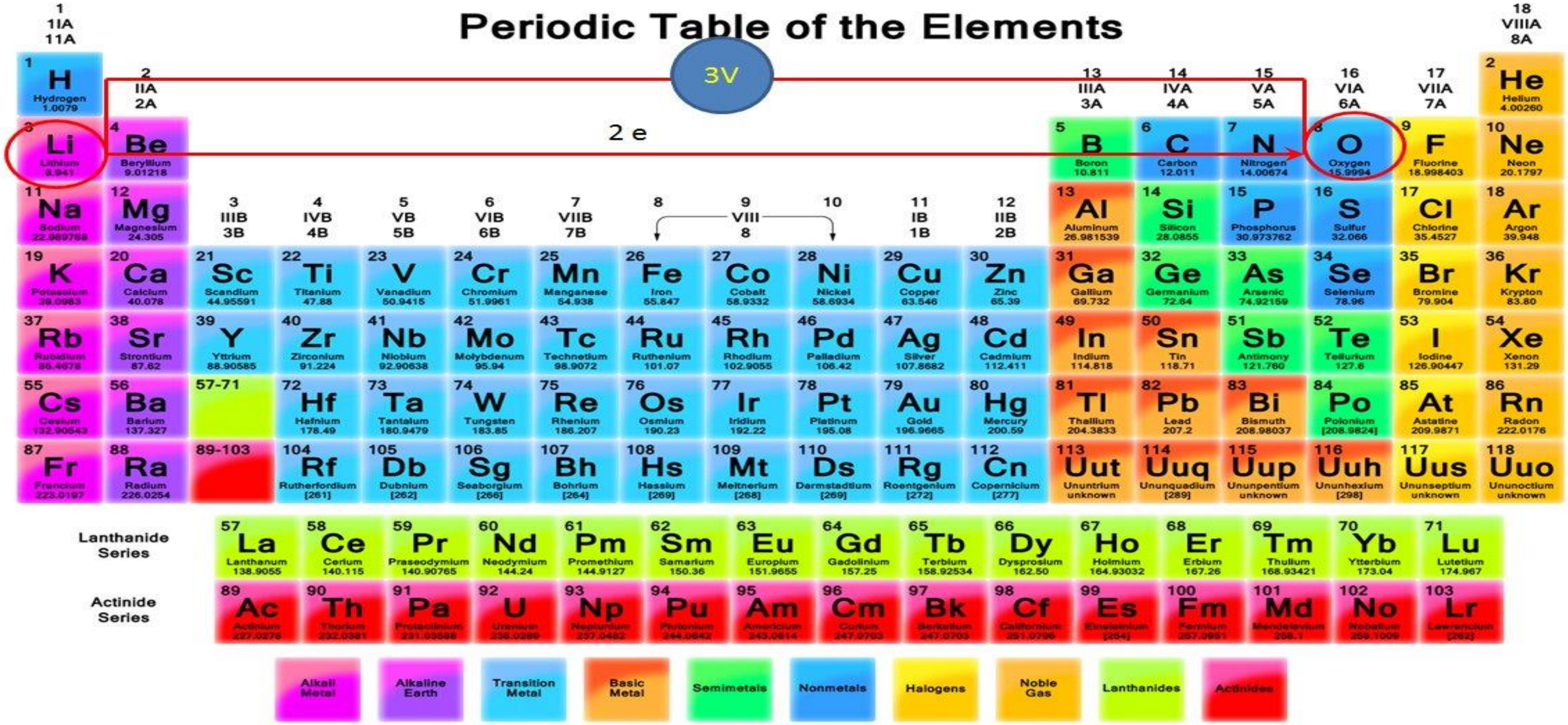


There are many variations of "Li-Ion" Batteries!

Cathode Material (LI+)	Li - CoO_2	Li - Mn_2O_4	Li - $FePO_4$	Li - NMC	Li - NCA	Li -CoO_2 - NMC	Li - MnO - NMC	Li -CoO_2	Li -CoO_2
Anode Material	Graphite							Hard Carbon	LTO ("Titanate")
V_{max}	4.20	4.20	3.60	4.20	4.20	4.35	4.20	4.20	2.70
V_{mid}	3.60	3.80	3.30	3.65	3.60	3.70	3.75	3.75	2.30
V_{min}	3.00	2.50	2.00	2.50	2.50	3.00	2.00	2.50	1.50

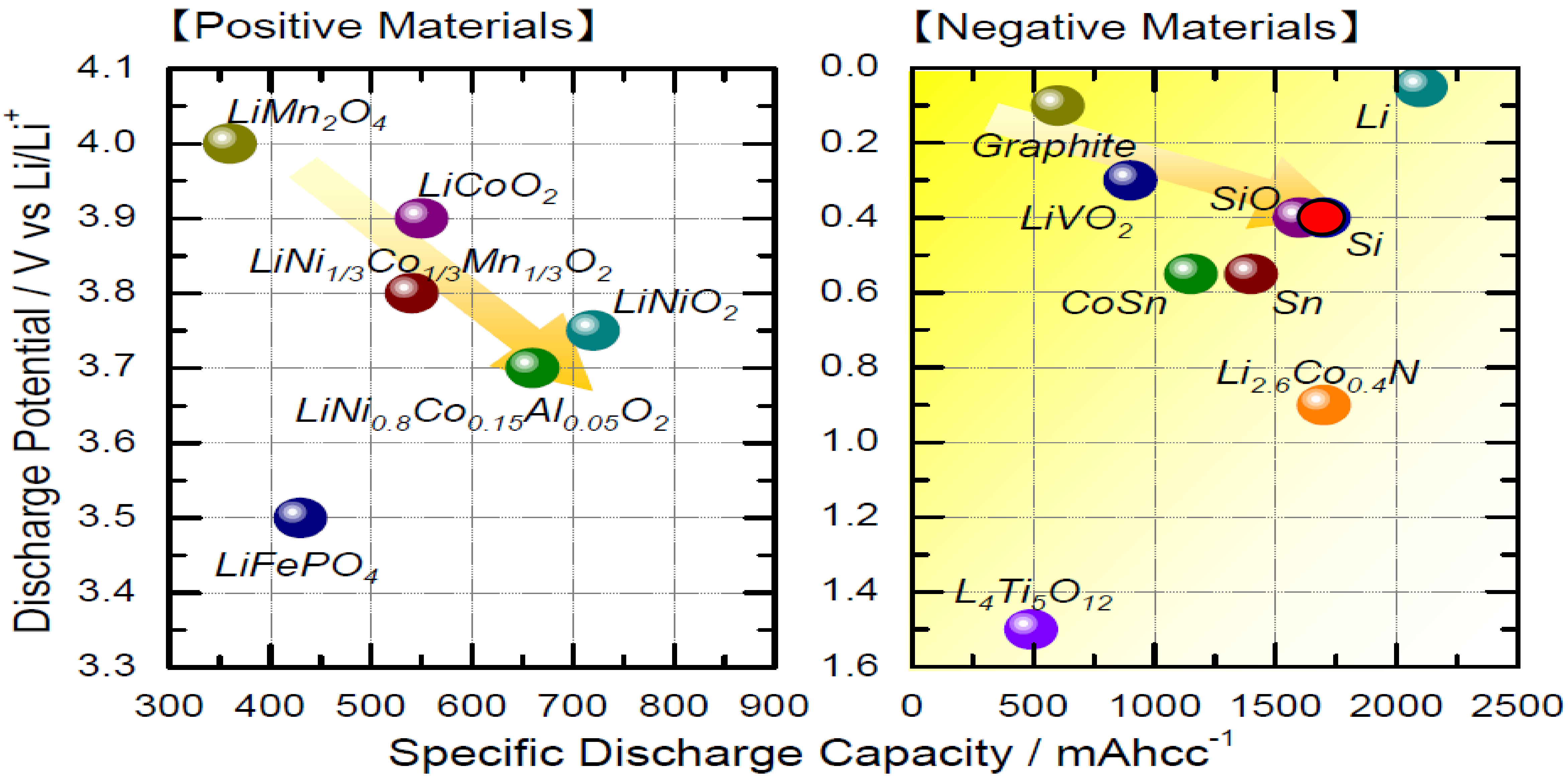
Typical Anode and Cathode Materials used for Li-Ion Cells

- *All the above cells are considered "Li-Ion" despite chemical variations shown*
- *In addition to different voltage ranges, they may also have different capacity, cycle life, and charge/discharge rate performance (not shown)*
- *Specific performance parameters can be optimized based on chemistry and physical design of a cell*
  - *The "important" parameters depend on the application!*



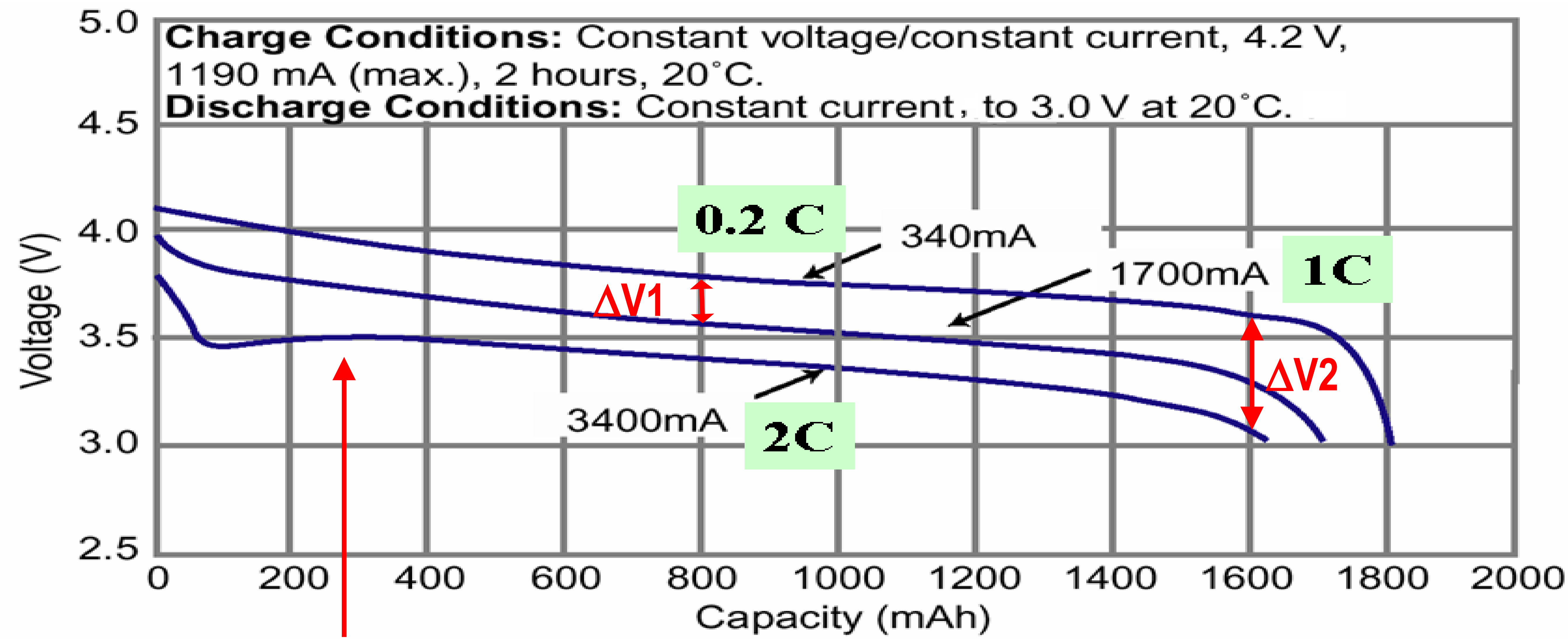
- Pick anode from top (lightest) left (strongest electron donor)
- Pick cathode from top (lightest) right (strongest electron acceptor)

Choices in Materials determine capacity and voltage



*Source: Maxell Energy conference presentation

Li-Ion 18650 Discharge at Various Rates



Self-heating Effect Lowers the Internal Impedance

$$\Delta V = \Delta I \times R_{BAT}$$

What is Battery Management?

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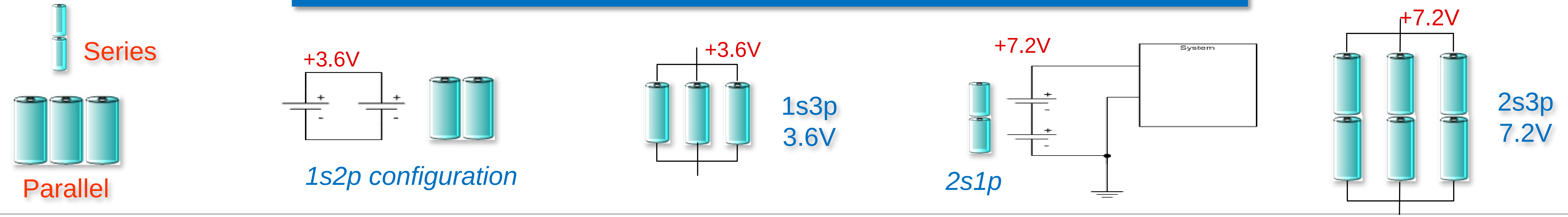
  - *Control charge flow into battery*
  - *Prevent abuse conditions*
  - *Monitor critical parameters*
  - *Communicate information*

- **Systems require battery management to extend run-times, ensure safety, and maximize battery service life**

- **Degrees of implementation vary, but should include three main functions : charging, gauging (monitoring), and protection**

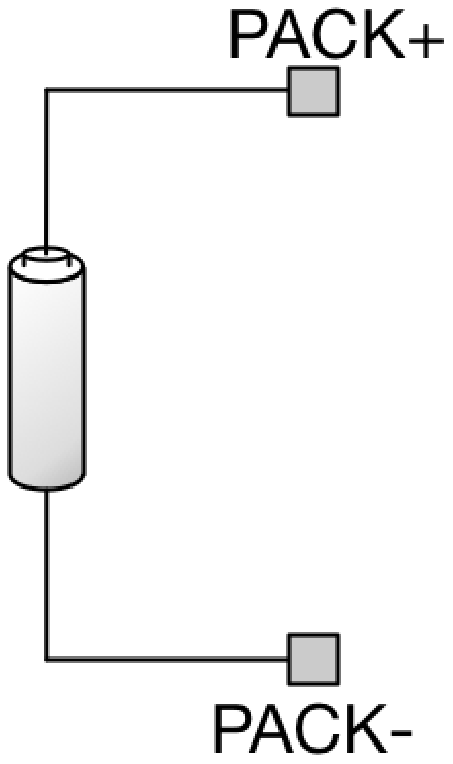
Pack Configurations



Agenda

The use of batteries is simple, but protecting them is not always straight forward as one might imagine. This discussion with cover the basics of battery protection from keeping them from over-charging and over-heating to what needs to be done at the system to implement battery authentication.

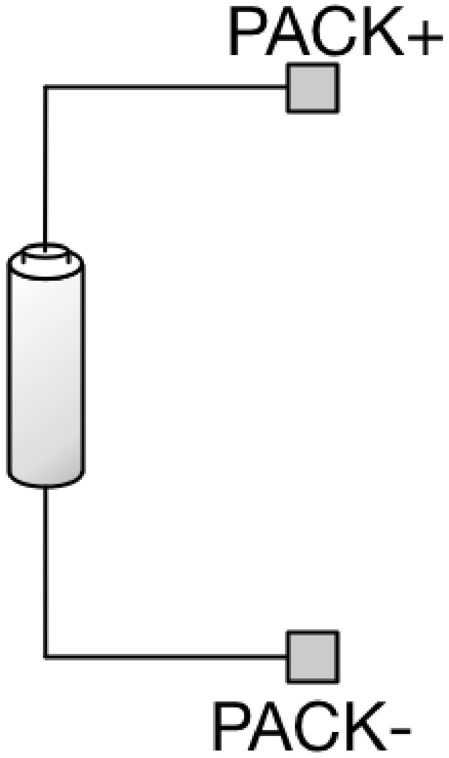
- **What can be protected and what cannot be protected?**
- **Protection Overview**
- **Battery/Cable Authentication**



The goal is to avoid catastrophic failure

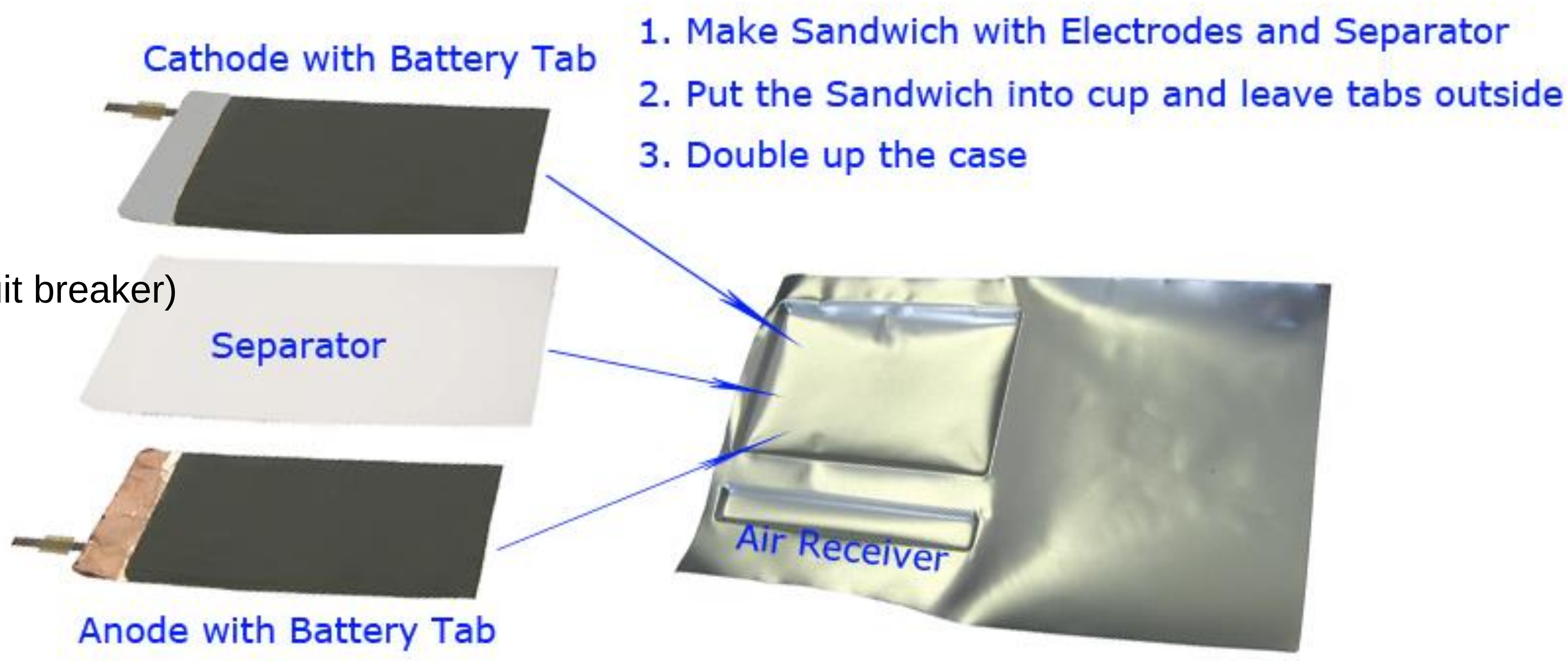
Possible Battery System Malfunctions

- Short Circuits:
  - cell internal
  - pack internal
  - pack external
- Over-charge
- Over-discharge
- Over-heating



Cell Related Failures

- On cell manufacturer site:
  - Safety by design - UL1642 compliance
  - cell-internal safety devices: Separator, PTC, Vent, CID (circuit breaker)
  - compliant manufacturing processes
  - factory quality control (QC)
- On pack manufacturing site:
  - Safe pack design - IEEE 1625/1725 compliance
  - Manufacturing QC

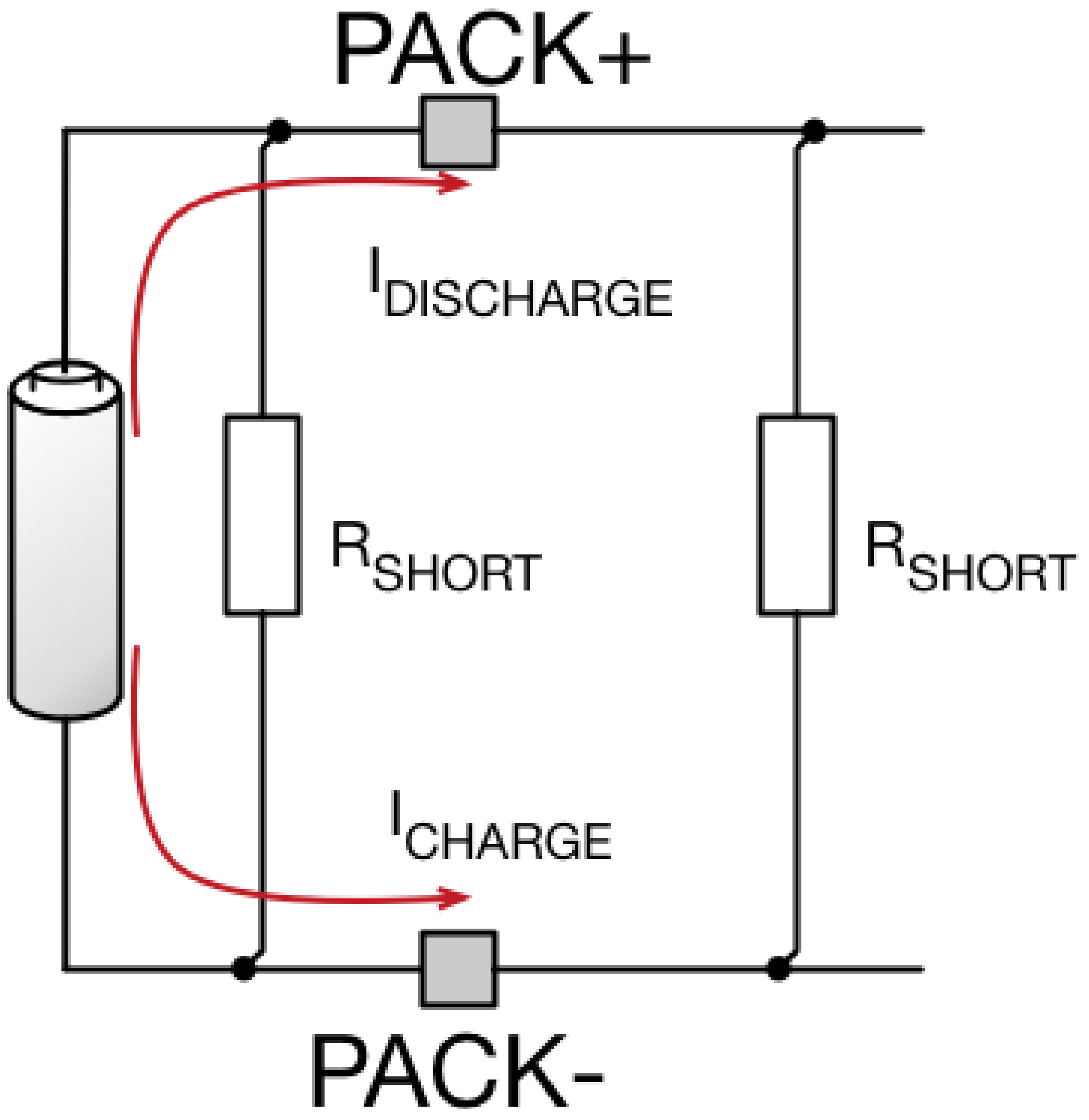


Preventing this class of failure requires good design/manufacturing practices.
Once a cell fails internally, little can be done to stop it!

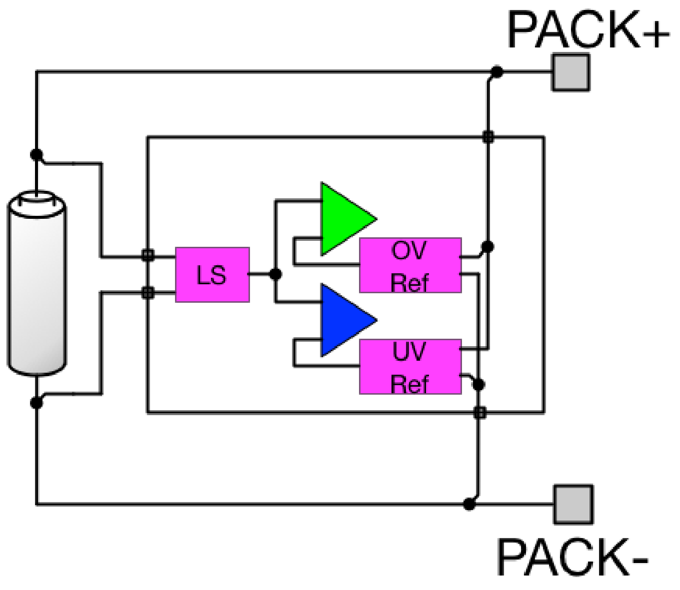
- Industrial Design
  - Allowances for pack swelling
  - Manufacturing QC

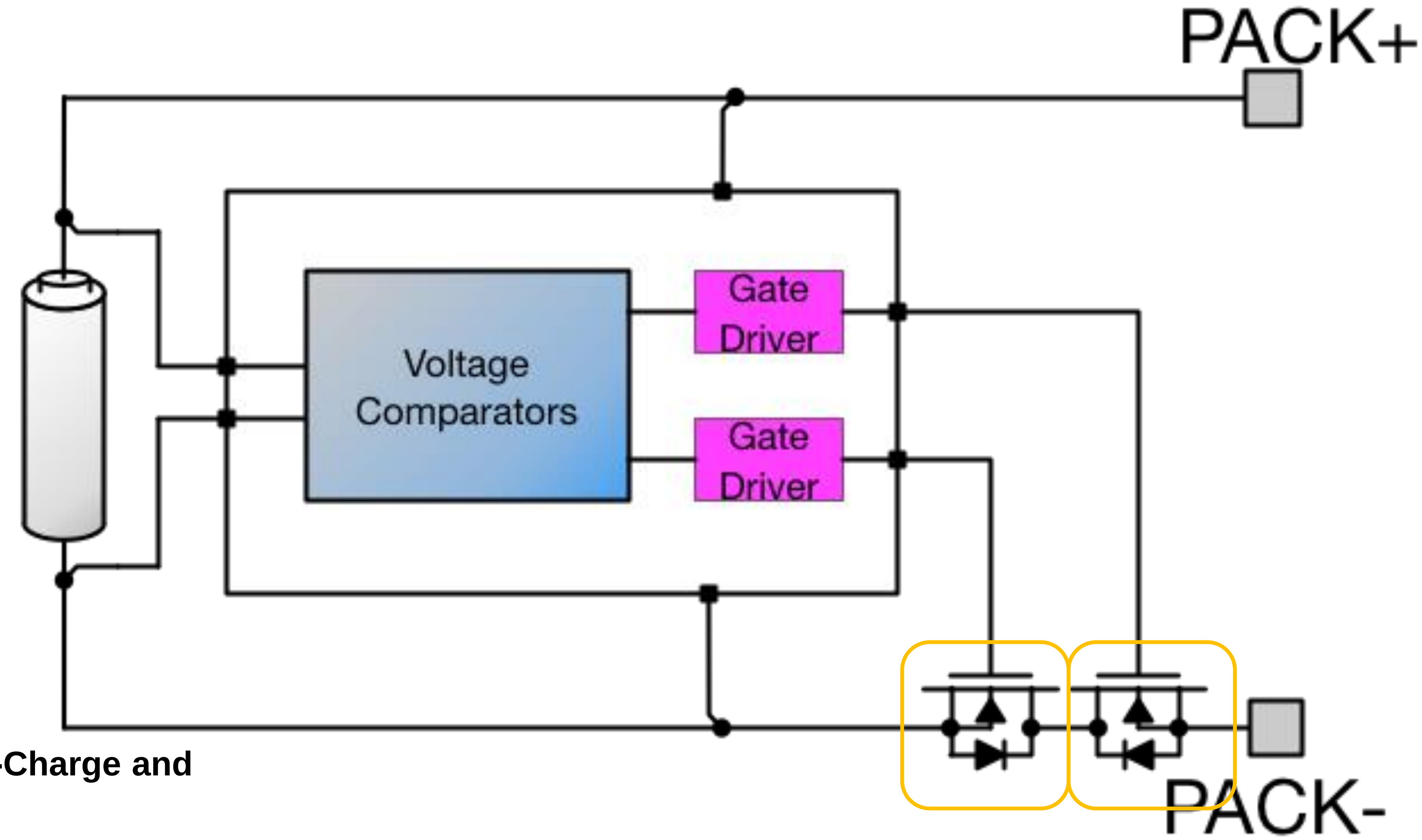
Possible Battery System Malfunctions

- Short Circuits
  - cell internal
  - pack internal
  - pack external
- Over-charge
- Over-discharge
- Over-heating



Handling Over-Charge/Discharge

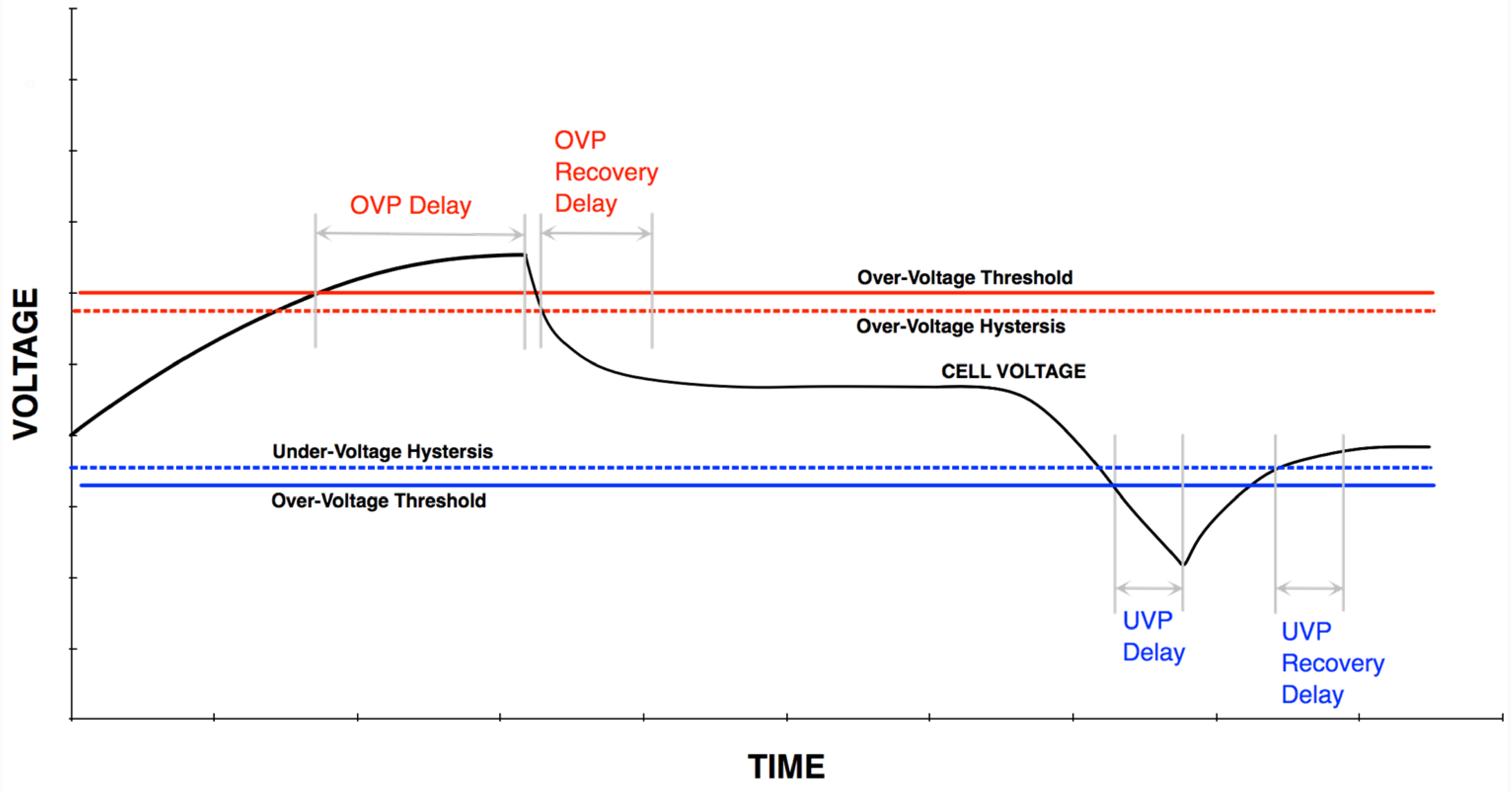




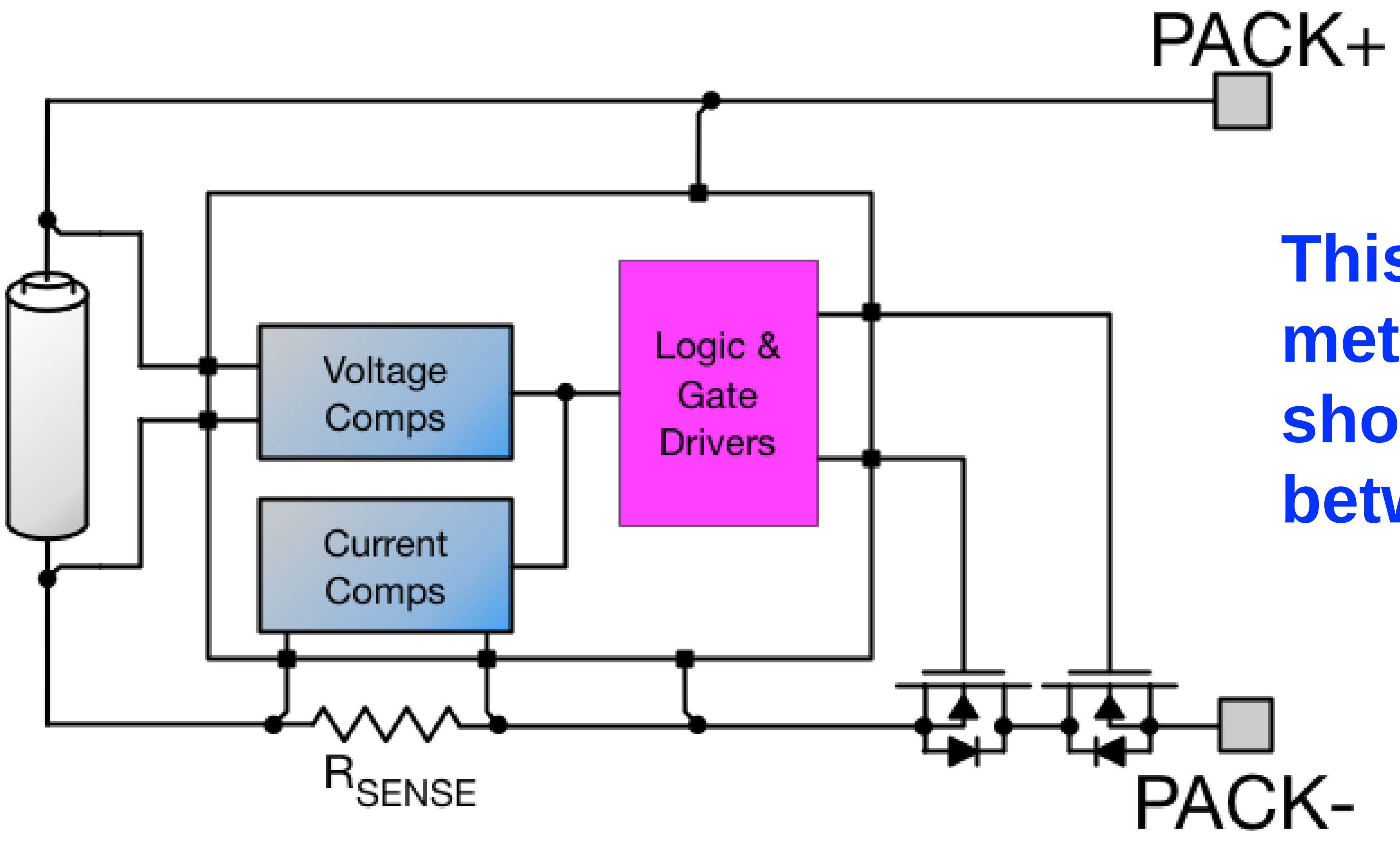
FETs are added to protect against Over-Charge and Over-Discharge

Over/Under Voltage

By measuring voltage and disabling the current flow, we can stop the cell of reaching a damaging threshold!



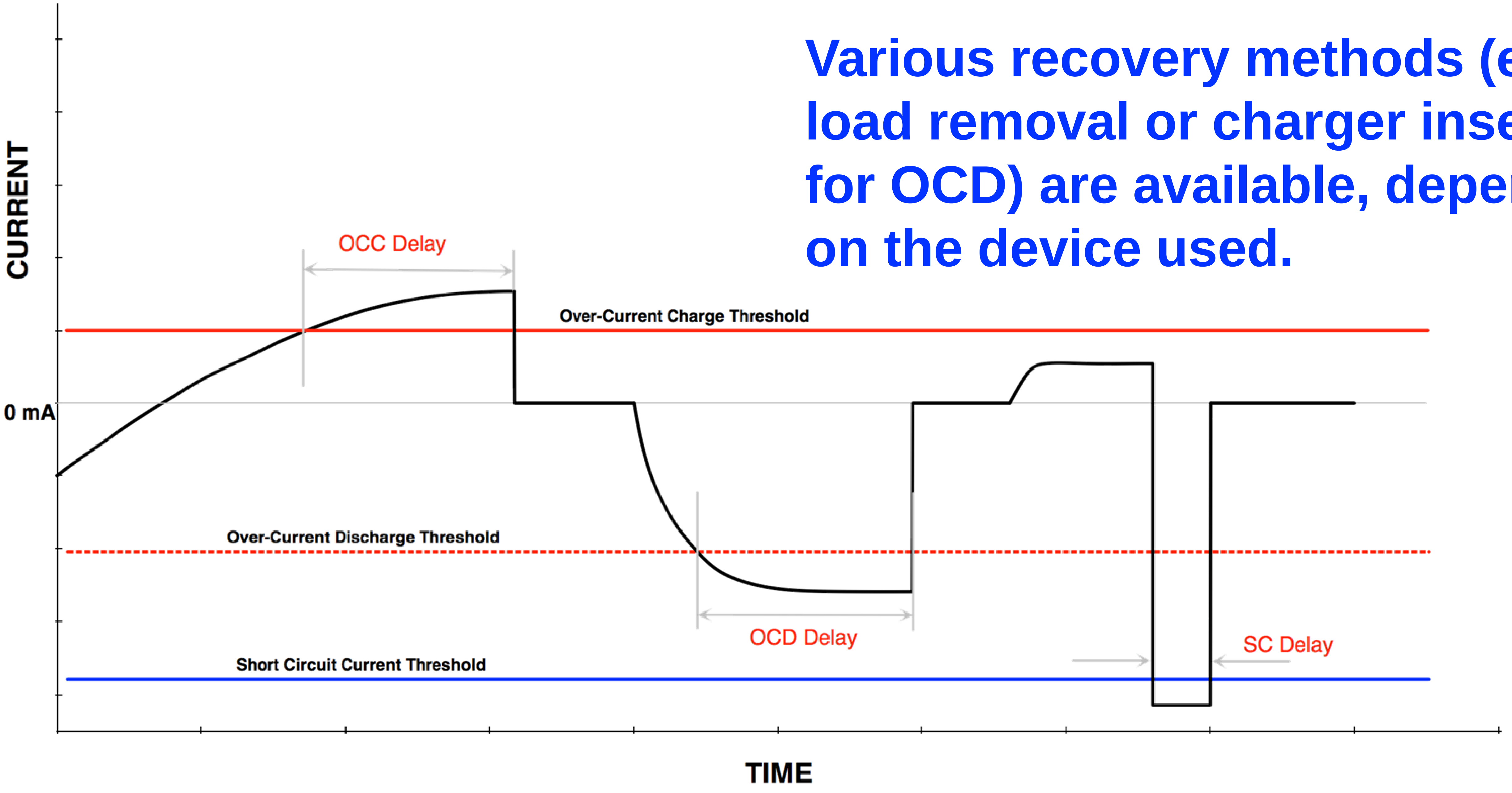
Addressing Over-Current Conditions



This allows detection and a method to de-energize any short that might develop between the PACK± pins!

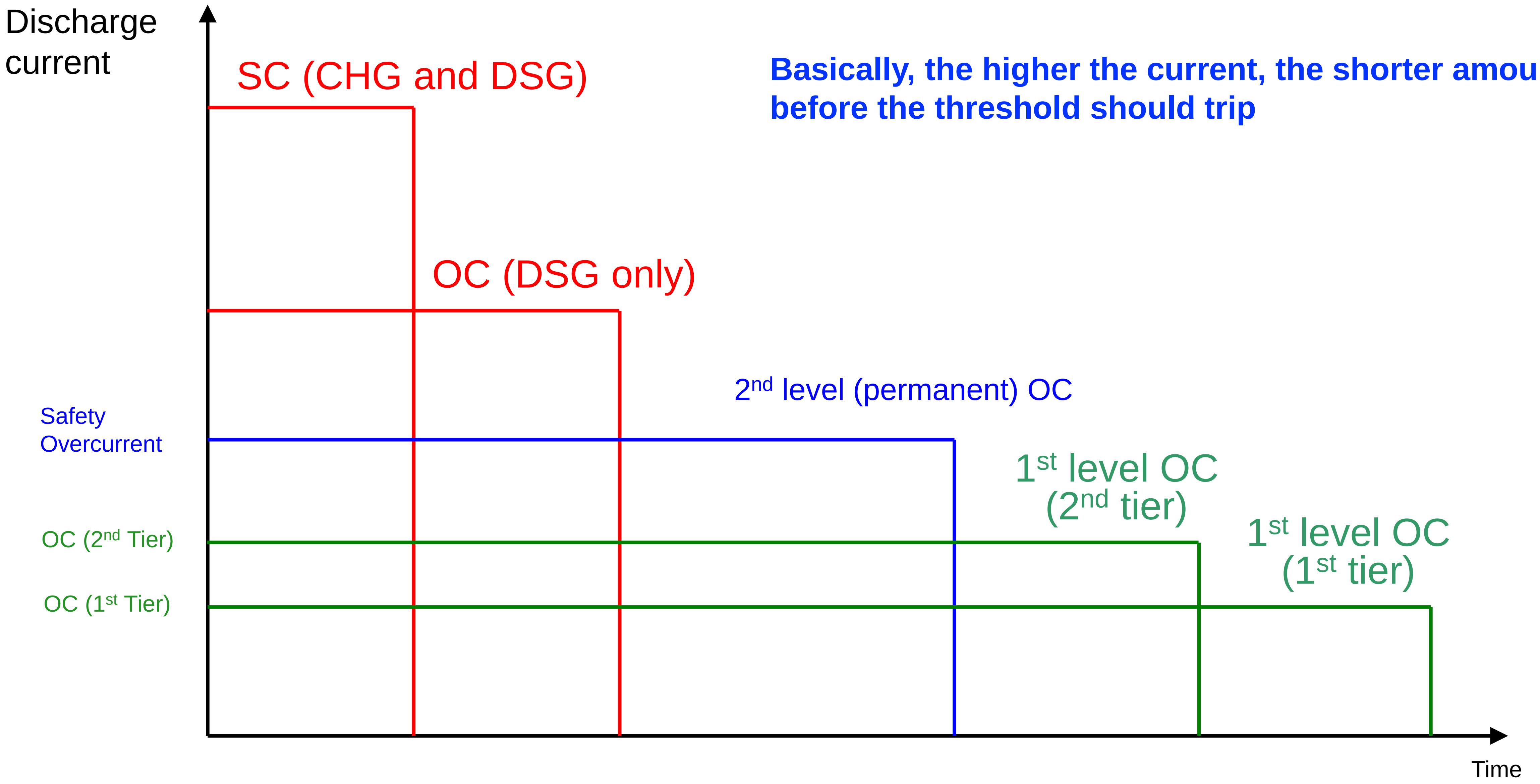
Charge/Discharge Overcurrent and Short Circuit

Over Current, or OC, can be in either the Charge or Discharge direction!



Various recovery methods (e.g. load removal or charger insertion for OCD) are available, depending on the device used.

Time/Current Relationships

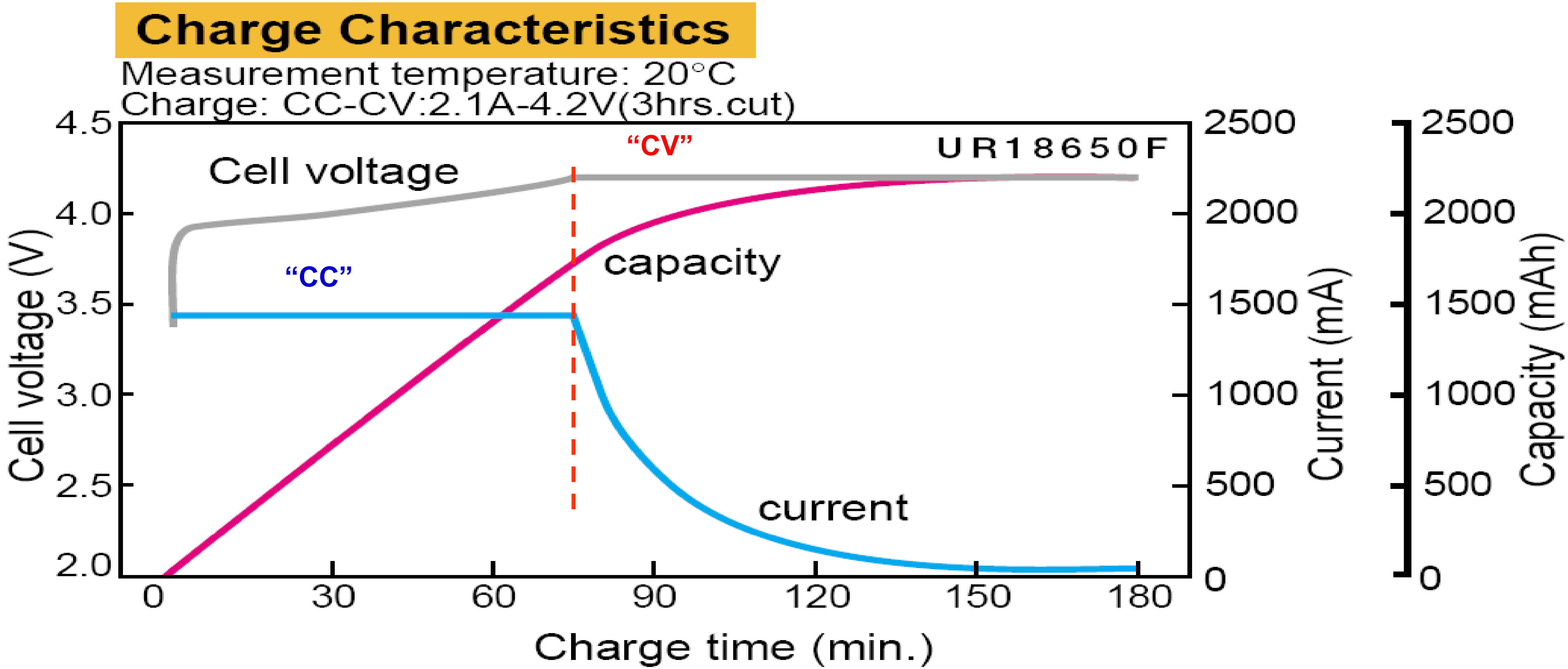


Basically, the higher the current, the shorter amount of delay before the threshold should trip

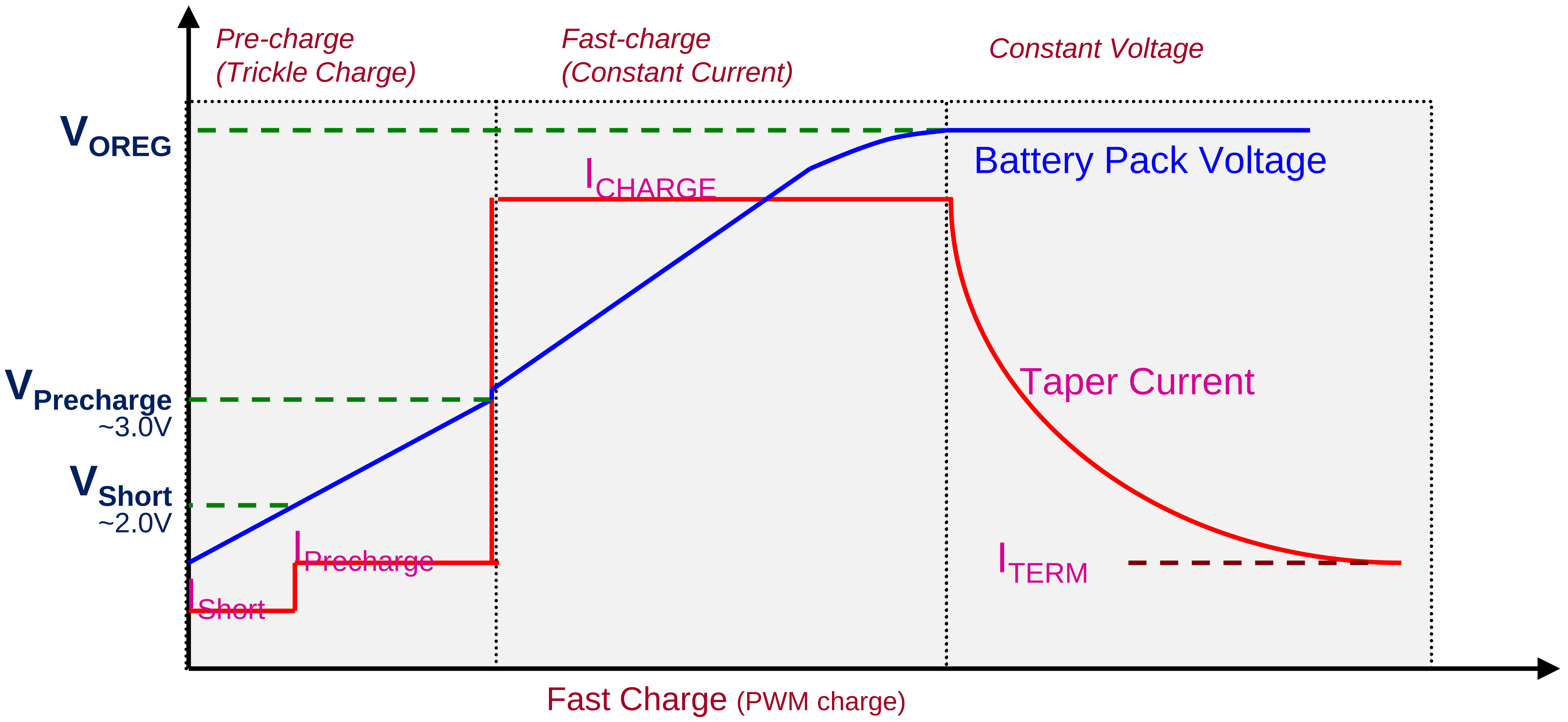
Li-Ion Charging

- Numerous ICs are available for charging Li-Ion batteries
- In order to choose the best device, the system designer needs to consider a number of factors beyond the simple power requirements associated with a given battery pack.
- This section will review some basic issues such as:
  - Li-Ion Charging Profile, and how charger accuracy can affect the service life of the battery
  - When to use a linear or switch-mode charger
  - The benefit of “power path management” in a system with an internal battery pack

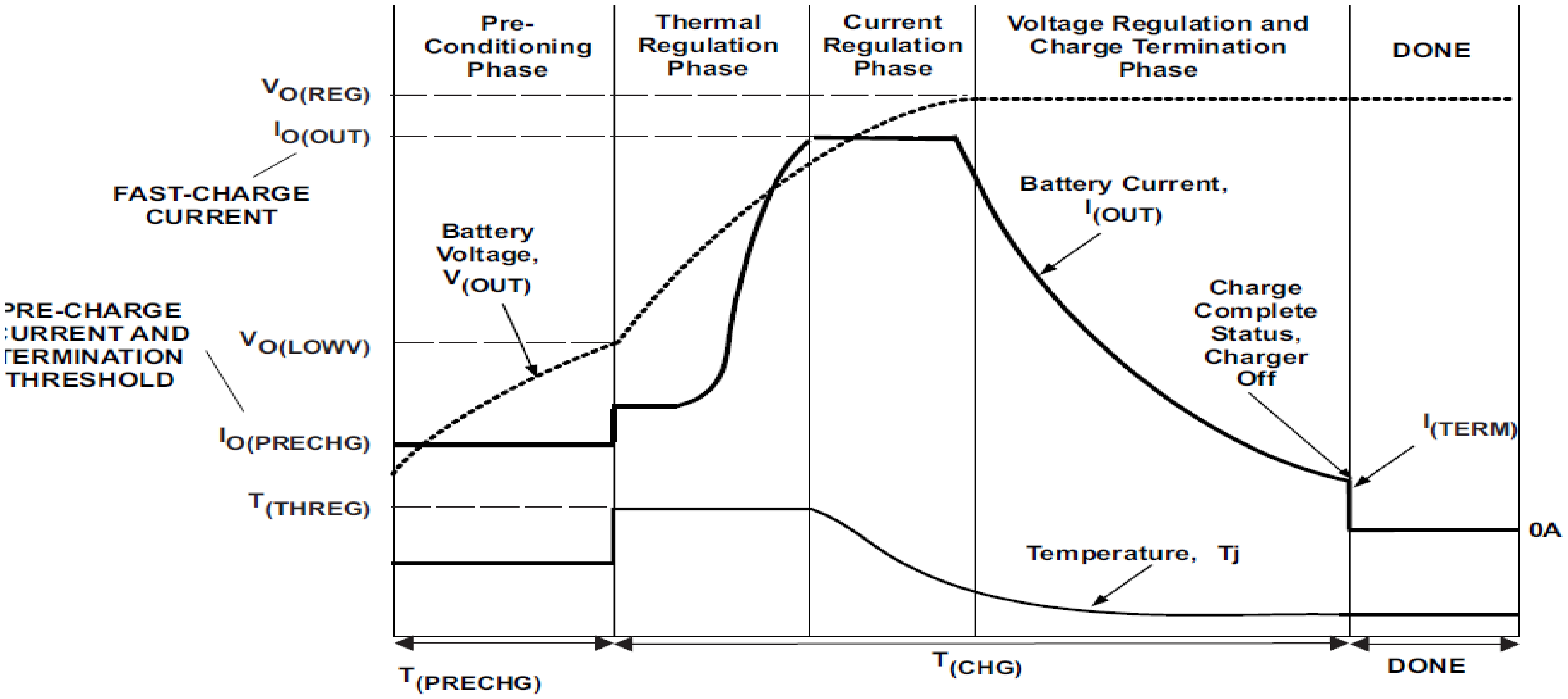
Review: “Ideal” Li-Ion CC-CV Charge Curve



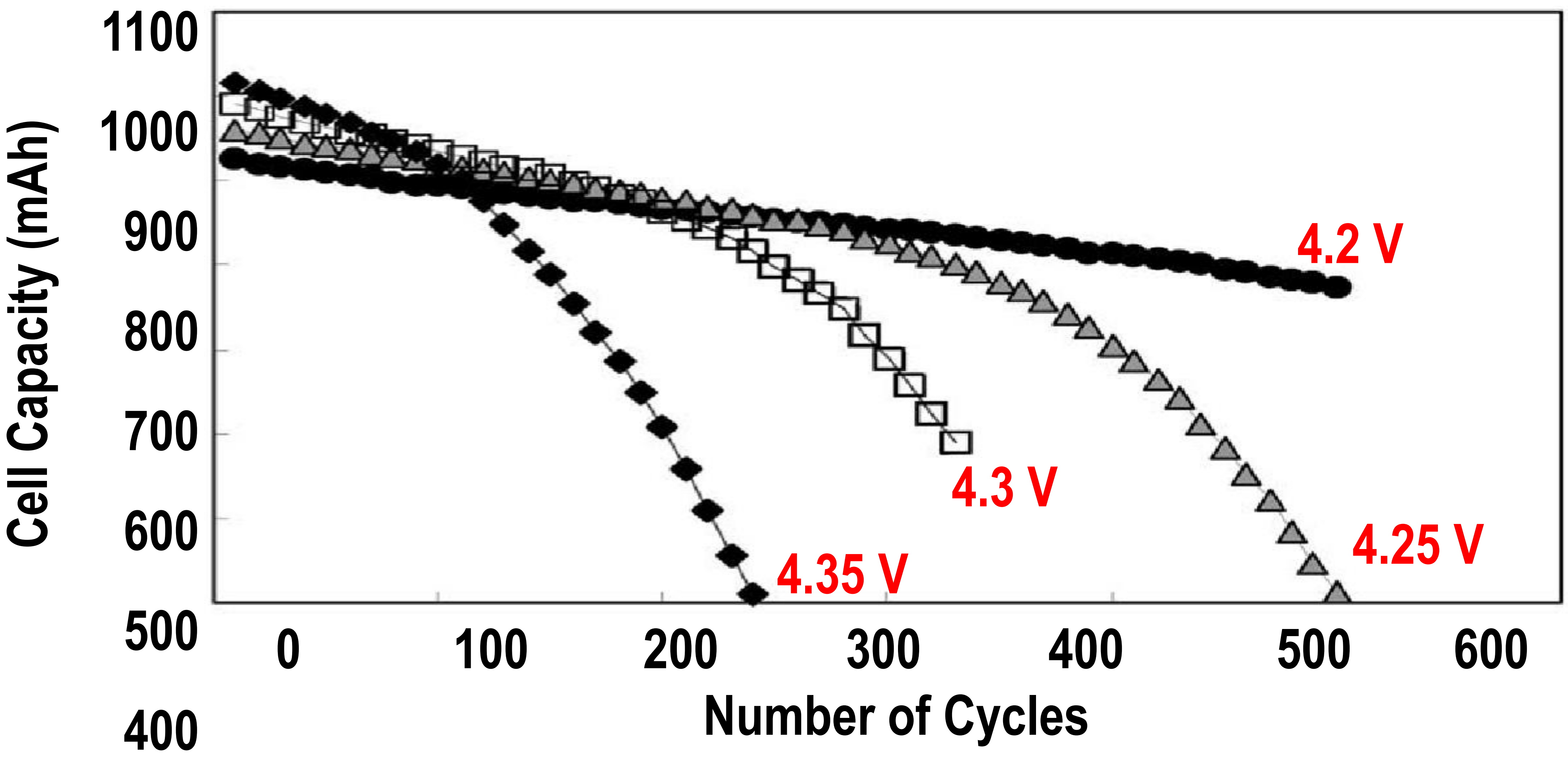
Practical "CC-CV" – allows for fault conditions



CCCV - From an actual data sheet…



Charge Voltage Accuracy Affects Battery Service Life

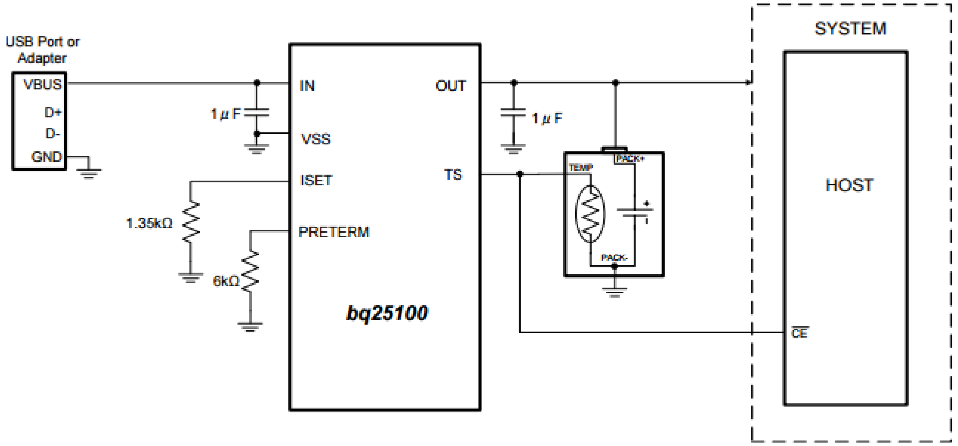


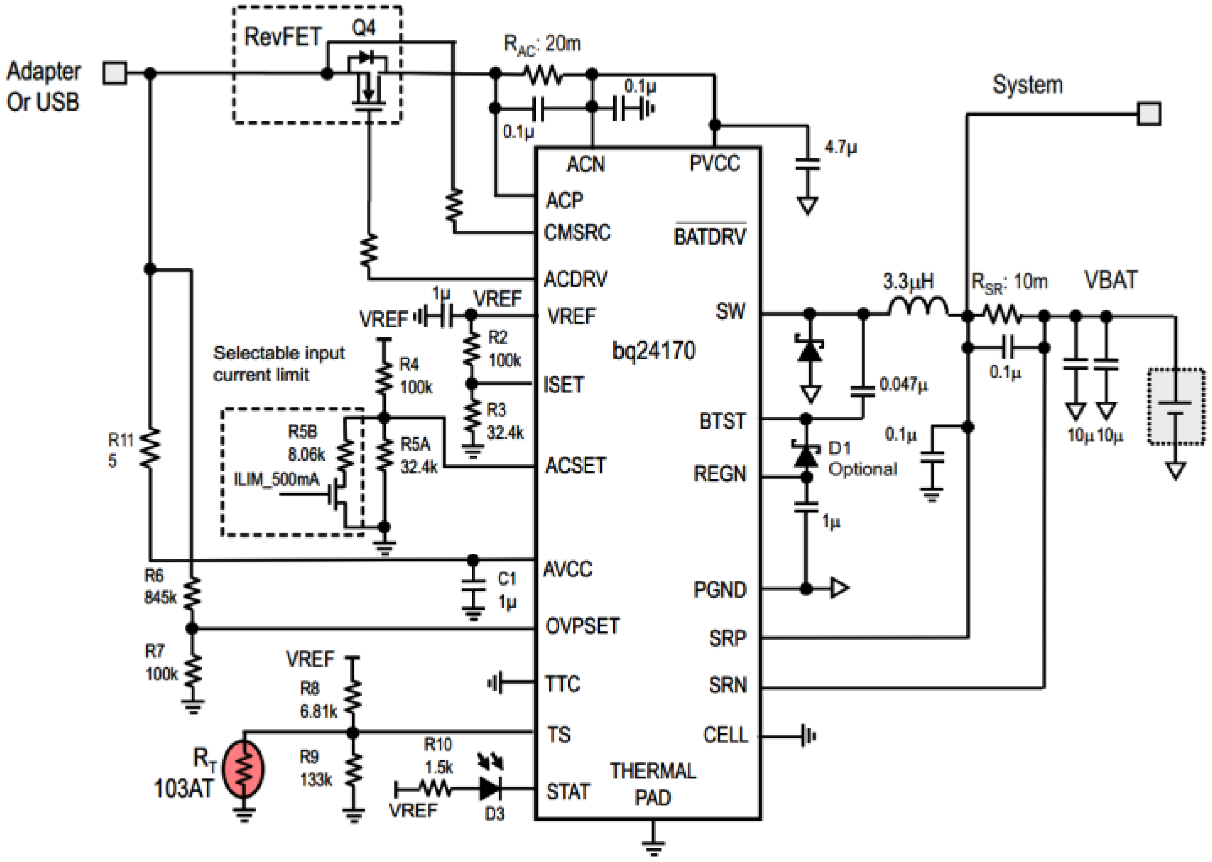
- The higher the voltage, the higher the initial capacity
- Overcharging shortens battery cycle life

Source: "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

CHARGING CIRCUIT IMPLEMENTATION:
Linear or Switch-Mode Charger?

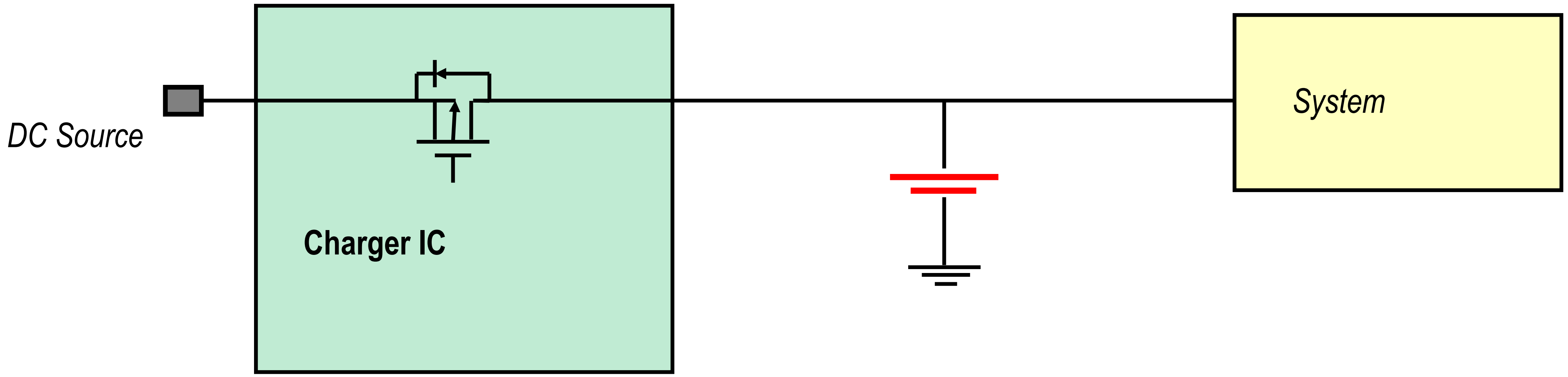
- Same type of decision as whether to use an LDO or a DC/DC converter
  - Low current, simplest solution → Linear Charger
  - High Current, high efficiency → Switch-Mode Charger
- General Guideline: Use switch mode charger for
  - Current > 1 to 1.5A
  - High density products that need minimum thermal rise
  - Applications that need to get maximum charge current from current-limited DC source





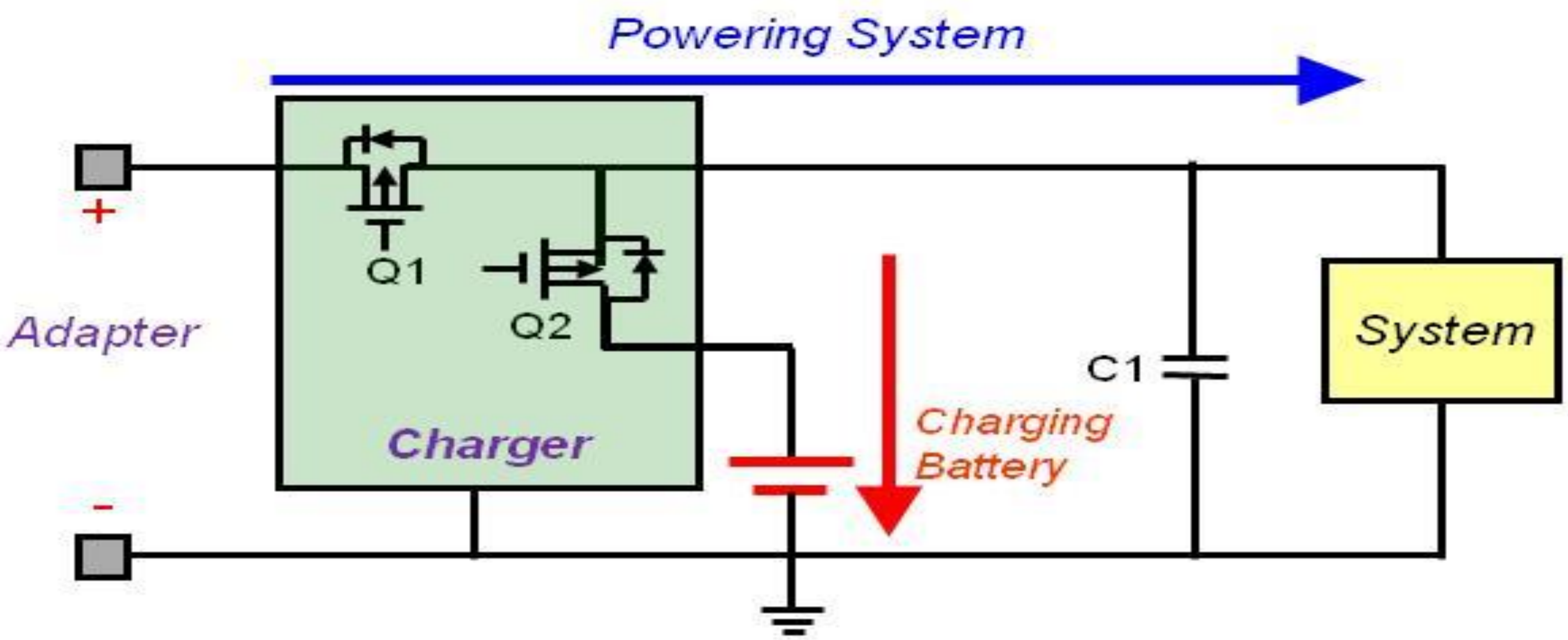
Simplest Charger Architecture

- Some possible concerns / issues:
  - What happens when battery is very low?
  - What happens if battery is missing or defective?
  - If system is operating, how can charger determine if battery current has reached a termination level?



Power Path Management

- Power supplied from adapter through Q1; Charge current controlled by Q2
- Separates charge current path from system current path; No interaction between charge current and system current
- Ideal topology when powering system and charging battery simultaneously is a requirement

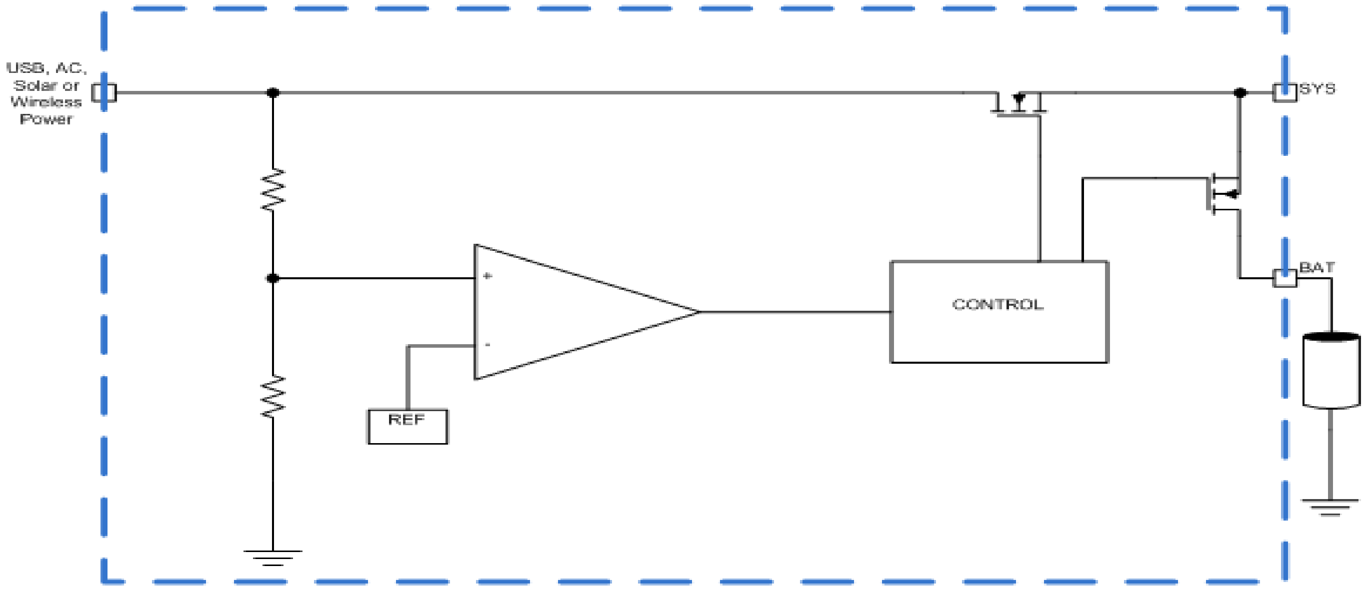


Current Capabilities of Adapters

- Power sources have their limits
  - There are situations where the input power source does not have enough power to supply what the portable device demands
  - Becoming increasingly important with the standardization of input connectors (Micro USB Type A, USB Type C) – the device being charged may need to work with various (and possibly unknown) types of adapters
  - Input current limits and Input Voltage Dynamic Power Management (V_{INDPM}) provide the functions needed to solve this problem

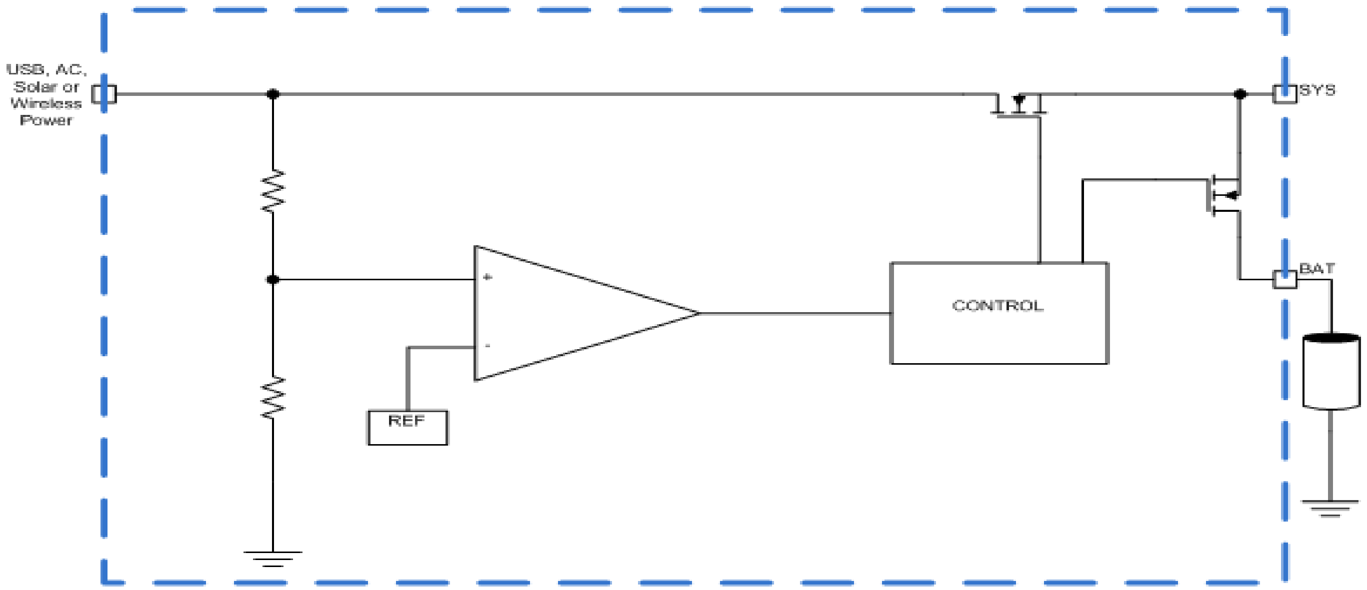
Voltage Input: Dynamic Power Management (V_{INDPM})

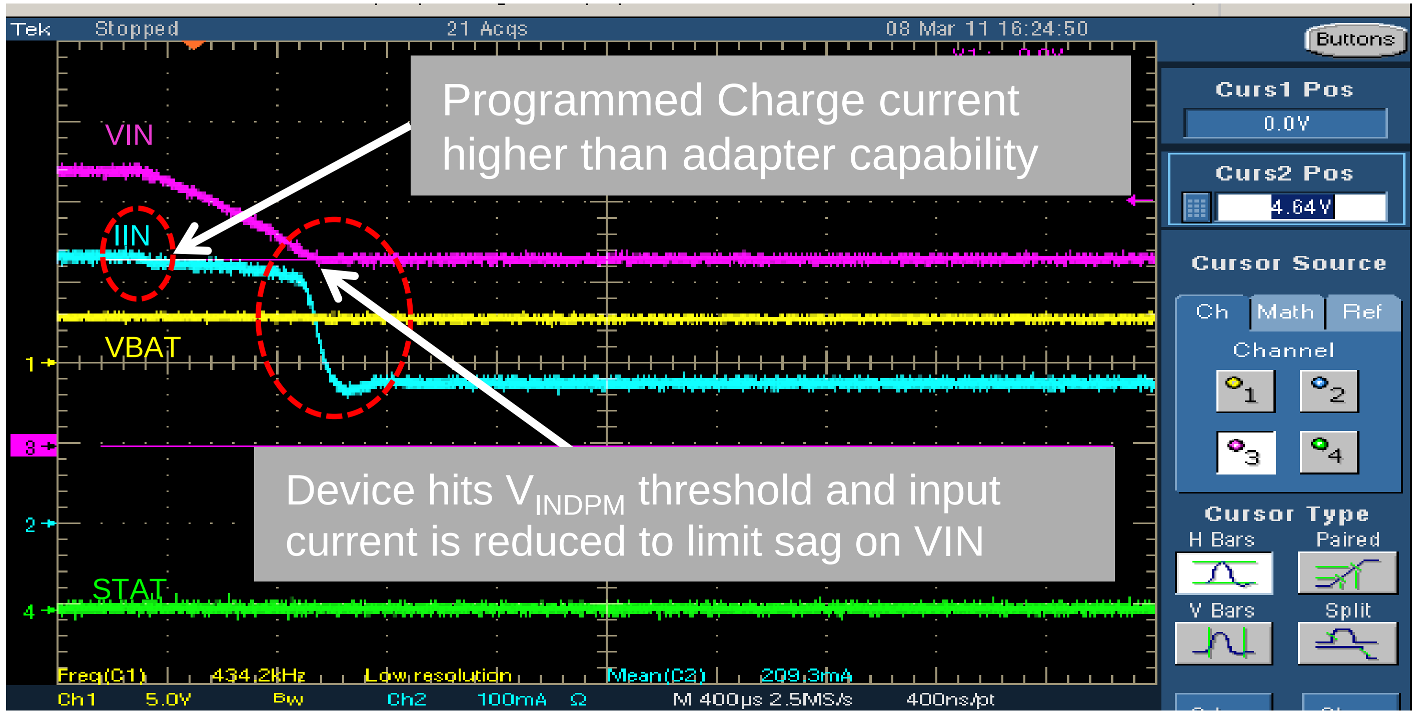
- Avoid adapter overload:
  - –Continuously monitor the input voltage to the charger
  - –Without V_{INDPM} : the device can enter a “hiccup mode” if the input source is overloaded (V_{IN} falls to UVLO trip level)



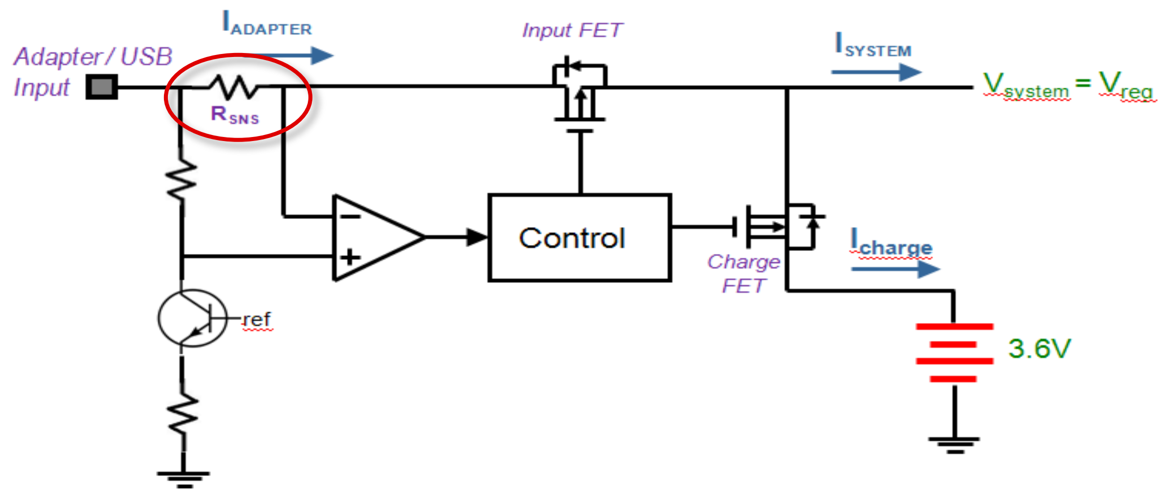
V_{INDPM} Operation

- Choose thresholds such that $V_{INDPM} > V_{BATT\_MAX} > V_{UVLO}$
- For "most" adapter types, the adapter output voltage (VIN to the charger IC) will start to sag as it is overloaded
- VINDPM control loop will not allow the adapter voltage to sag below the chosen VINDPM threshold
- When input voltage drops, device will limit the input current
- VINDPM may not be enough by itself! (see next slide…)

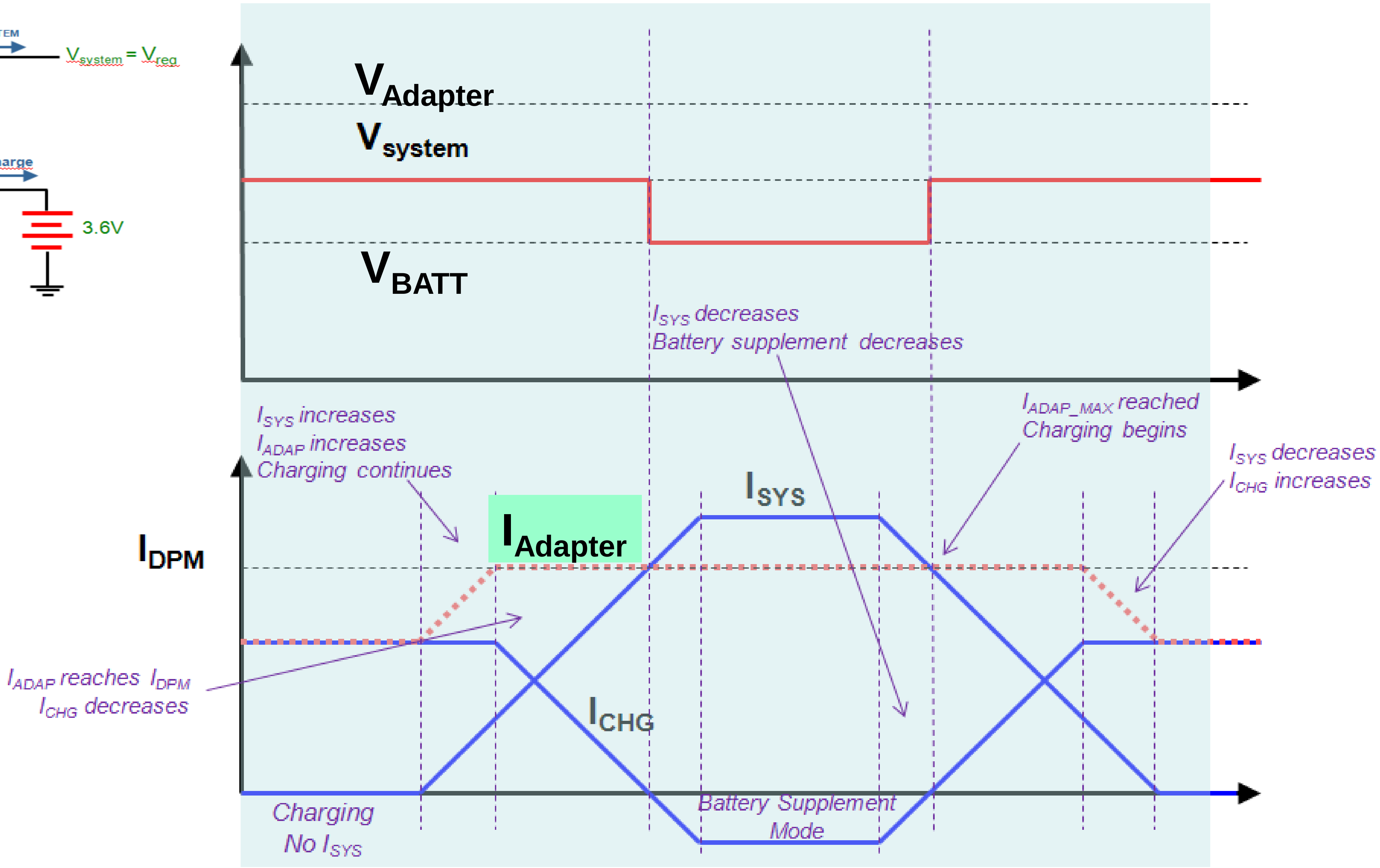




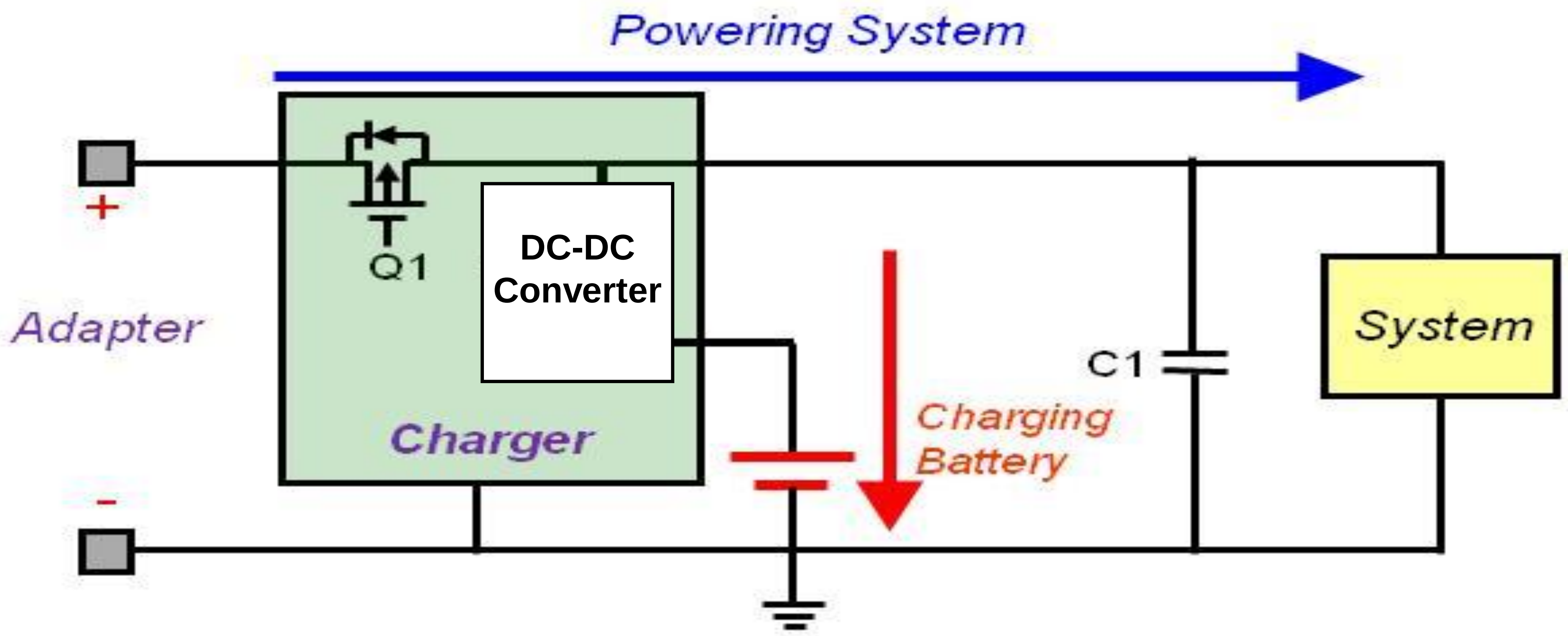
I_{IN_DPM} – Limits Input Current



- Input FET limits TOTAL current from adaptor
- Allows the device to extract the maximum <u>rated</u> adapter current
- Allows selection (spec) of a lower cost and/or smaller size adapter

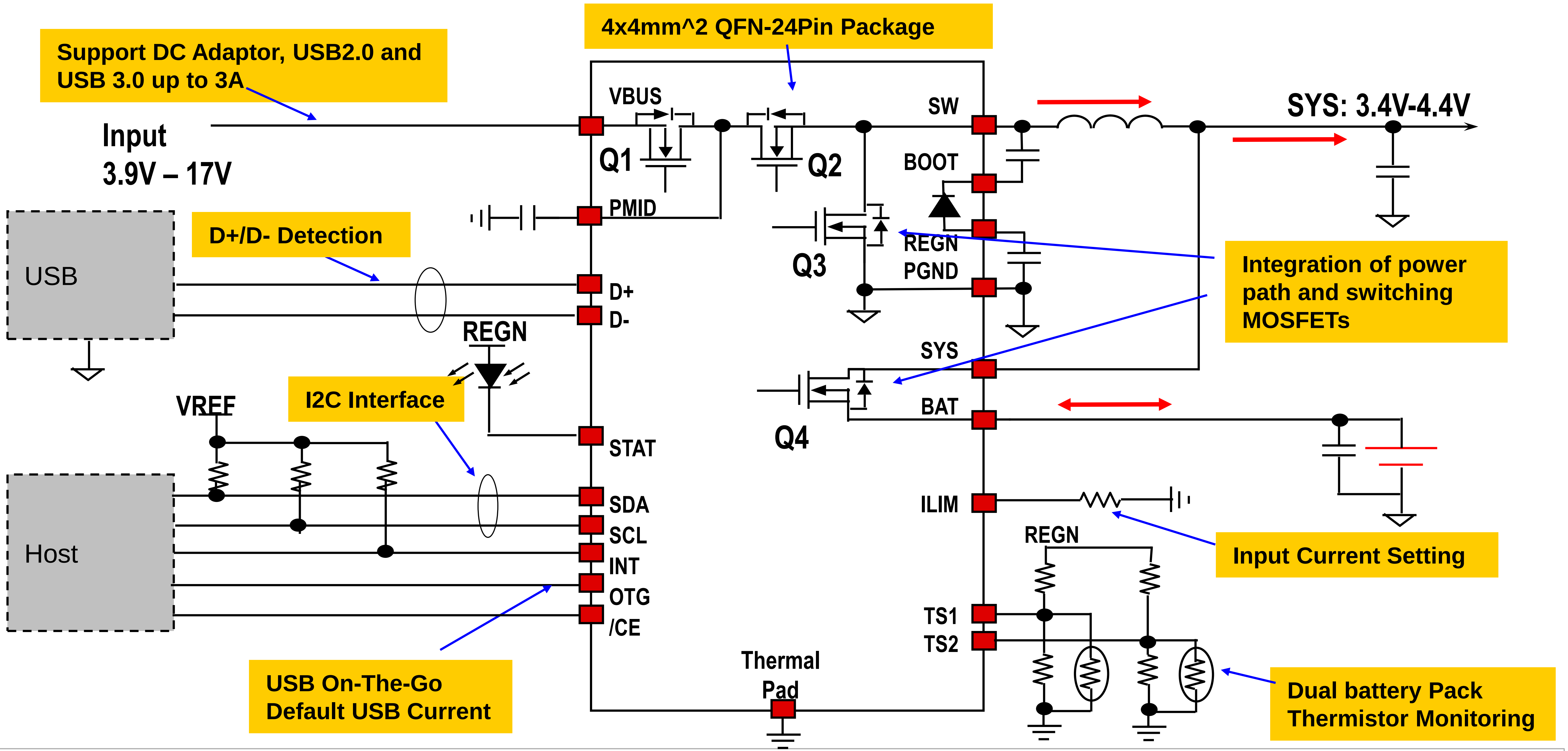


Traditional power path (switch-mode) charger



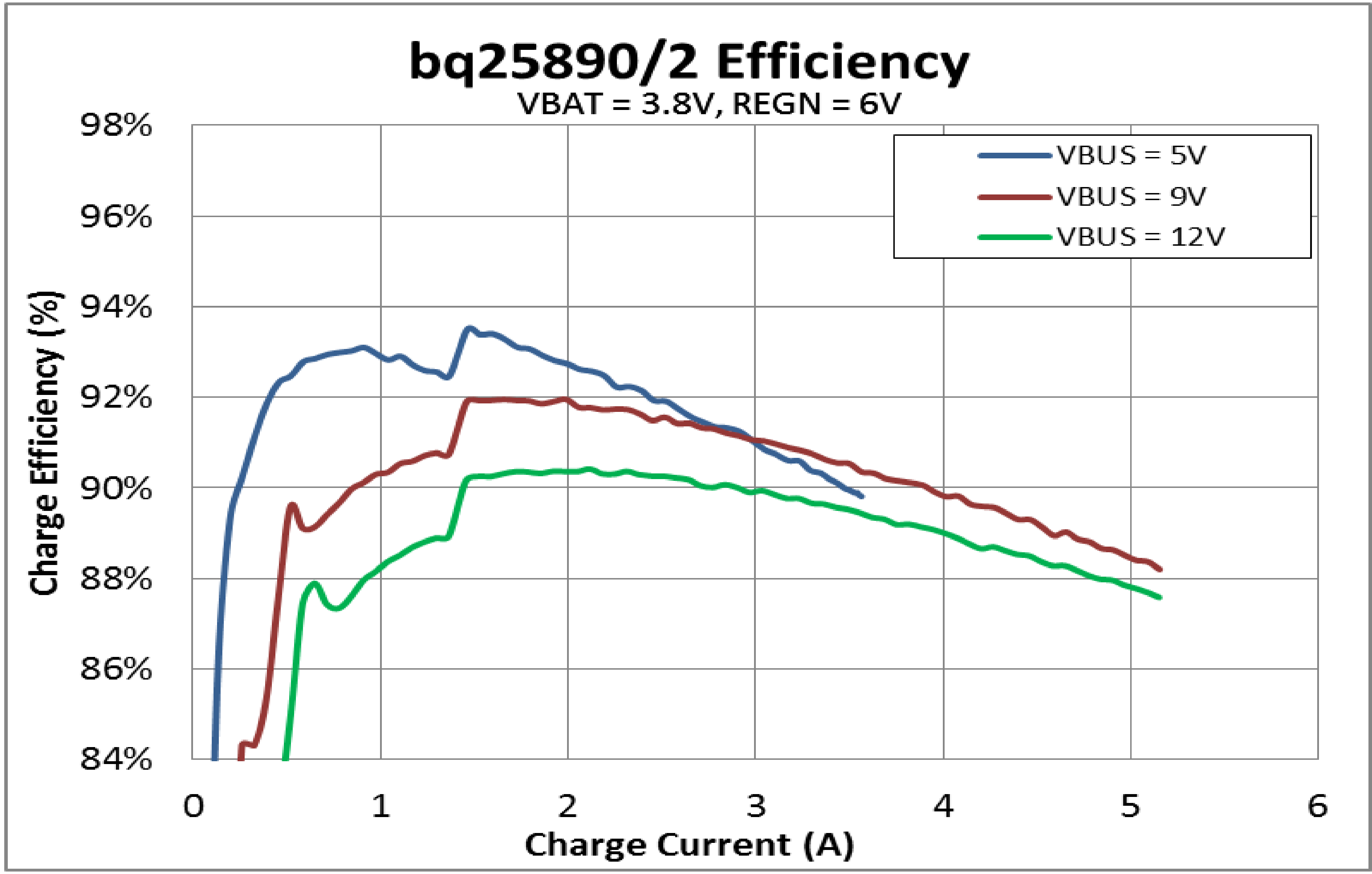
- When operating from adapter power source: system rail can go as high as max adapter voltage (5V, 9V, etc.)
- When operating from battery, system voltage can go as low as minimum battery voltage – RDS drop (e.g. < 3V)
- Wide swing on system rail especially if higher voltage input source is used (often to reduce input current for fast charging thru switch mode charger)

Integrated NVDC Charger Application
(e.g. bq2419x, bq2429x, bq2589x)

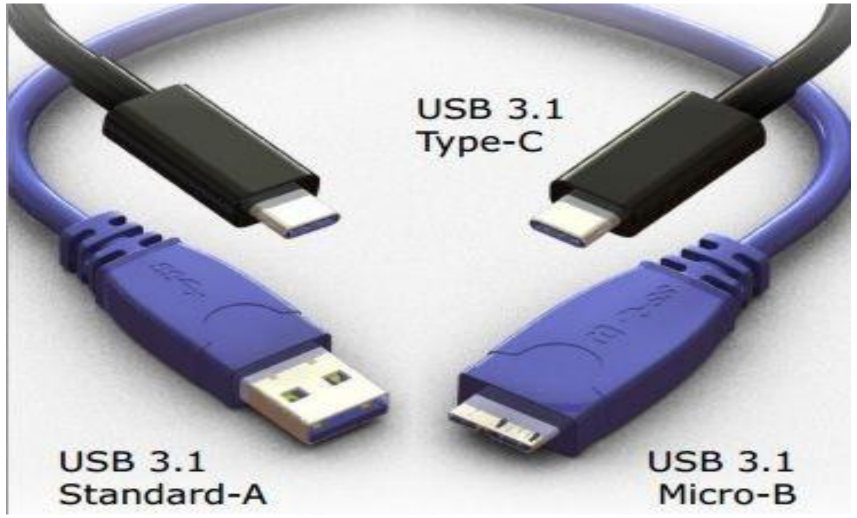


High Efficiency / Low R_{DS_ON} is essential

- For NVDC architecture to provide best performance, the charger must have high efficiency over wide VIN range
- FET performance in an integrated switching converter (charger) is fundamental to the overall performance of the device
- bq2589x has best efficiency for high current charging
  - 91%@3A, 90% @ 4A
  - Inductor = IHLP2525CZ 1uH (DCR=10m)



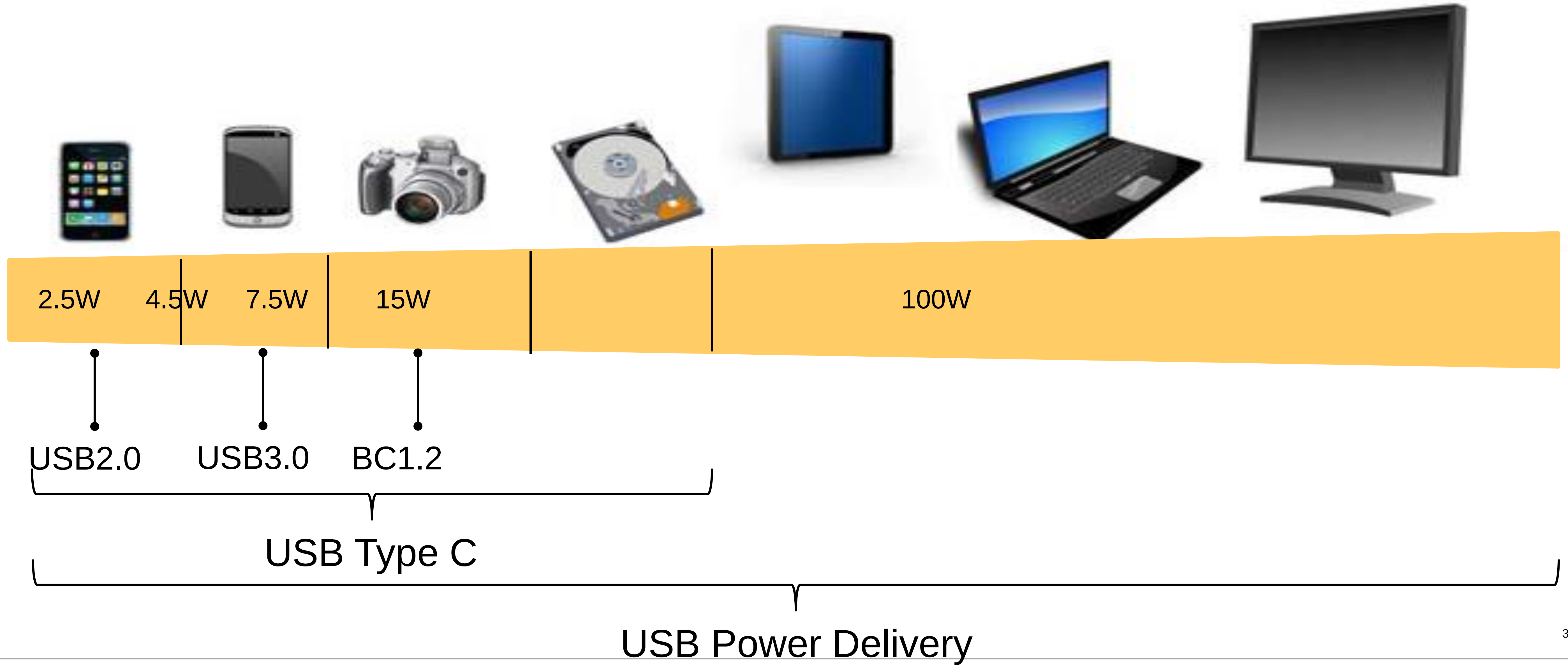
USB Type C Connector



- USB Type-C
  - A USB specification for a small 24-pin reversible-plug connector for USB devices and USB cabling.
  - Work seamlessly with existing USB host and device silicon solutions (USB2.0, USB3.1, bc1.2, USB PD).
  - Ease of use with focus on minimizing user confusion for plug and cable orientation
- Maximum power from USB type C connector reaches 15W (5V @ 3A)
  - Most of the portable devices, including notebook PC, tablet, cell phone, digital camera, can be quickly charged through USB charger.

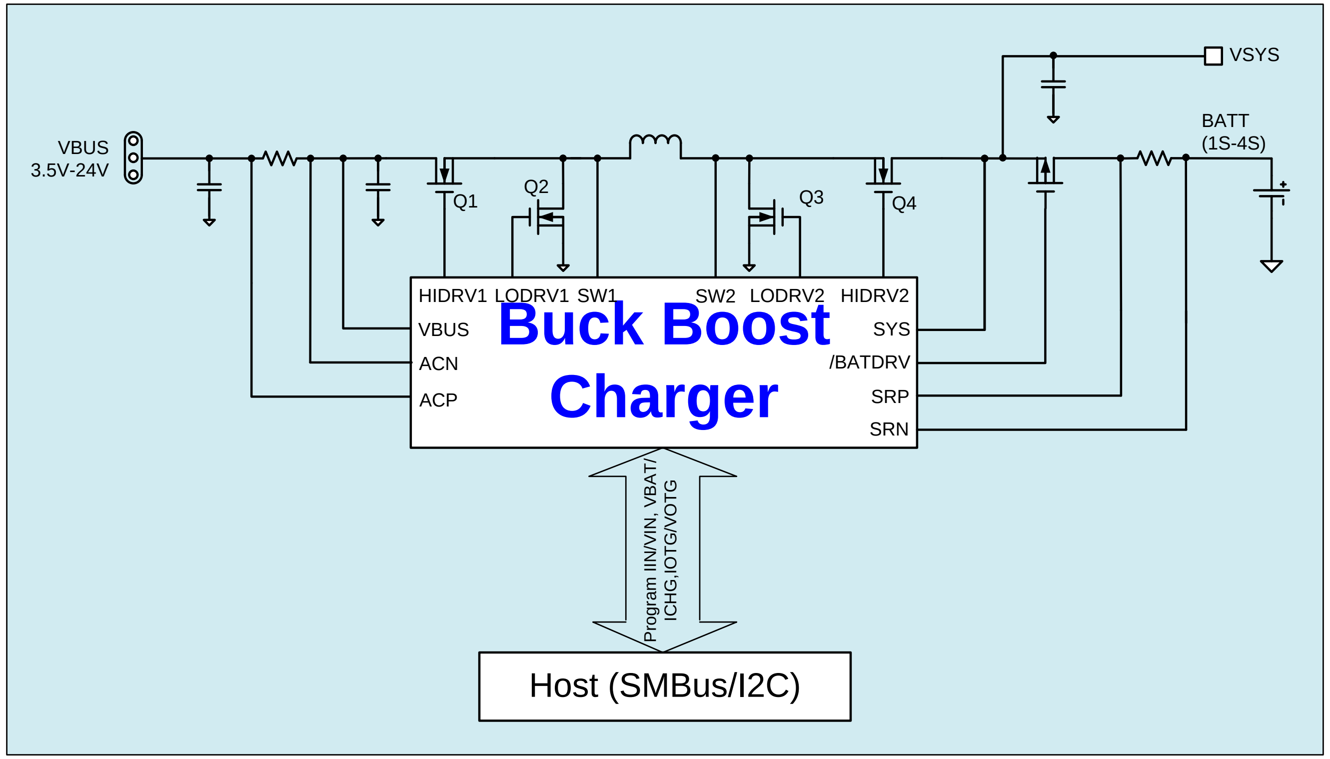
USB Power Delivery Device Spectrum

- USB Power Delivery is a single-wire protocol leveraging new USB-C standard & cable. It expands USB to deliver up to 100W (20V, 5A) of power.

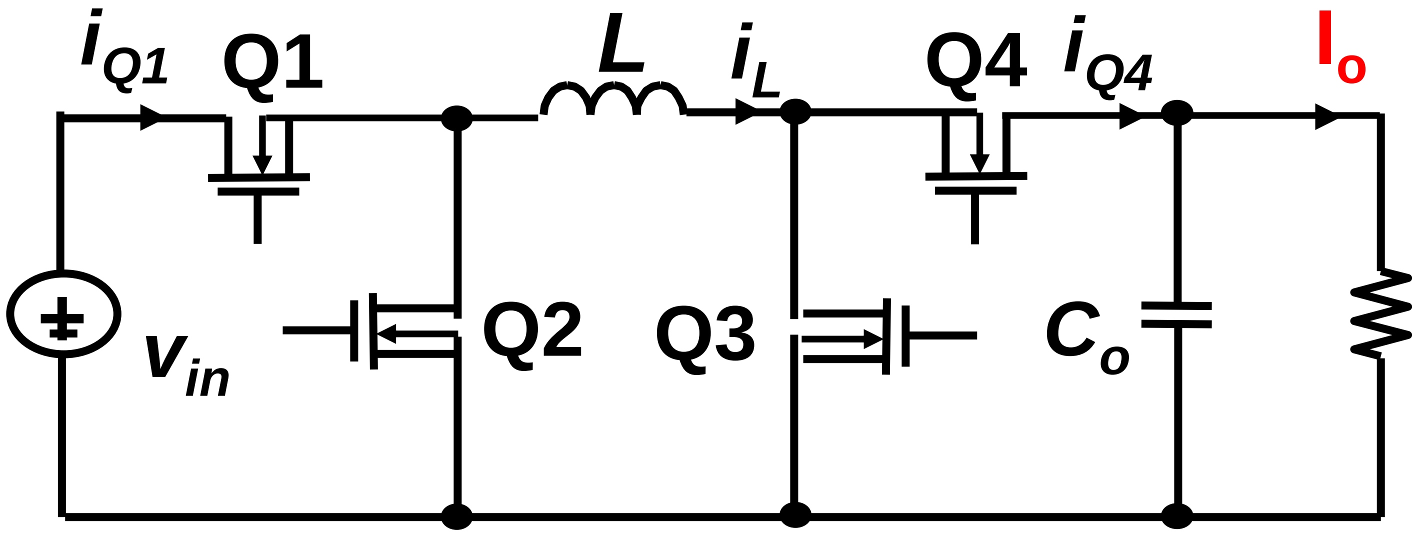


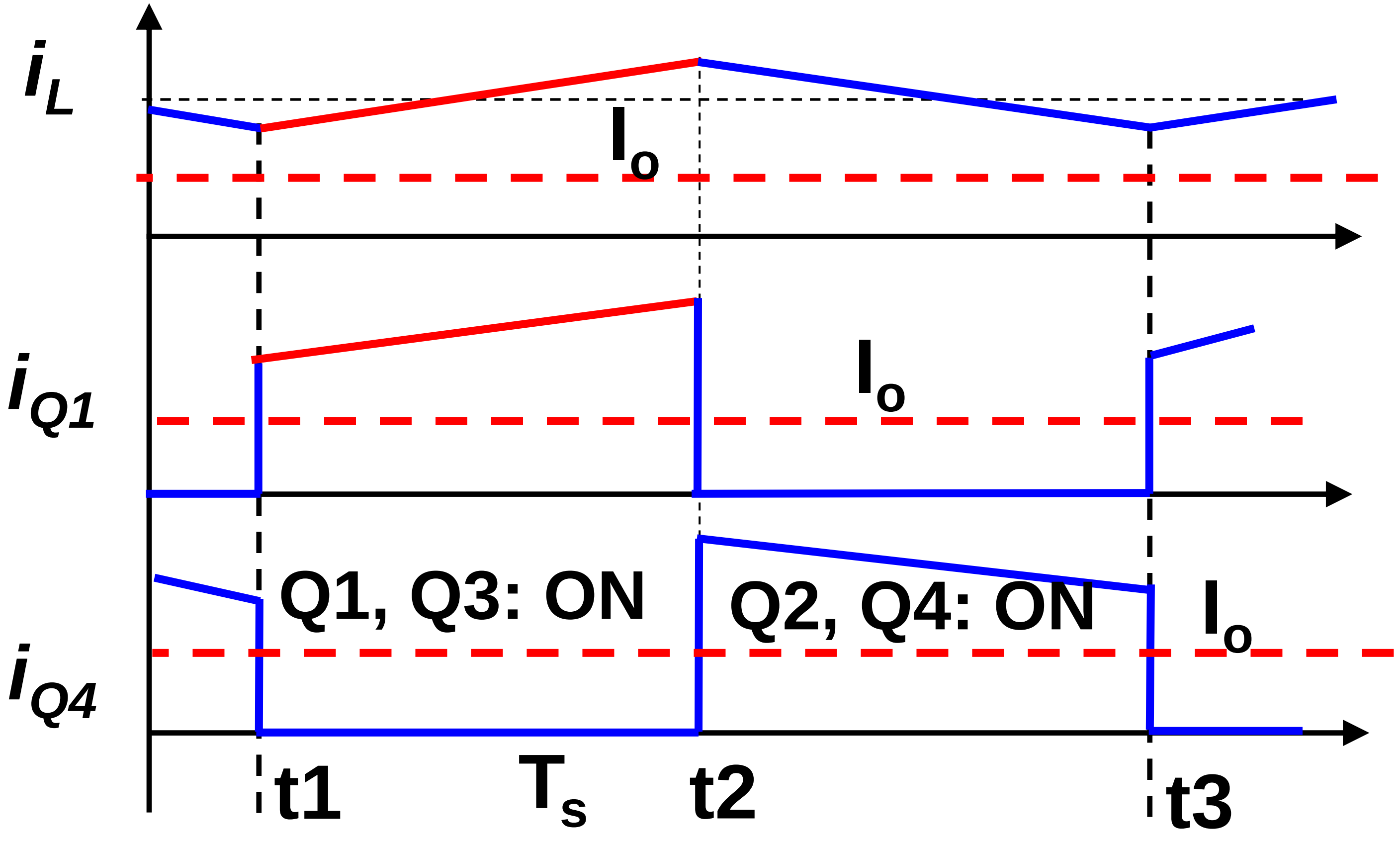
Universal Charging

- USB - PD output voltage can be 5 – 20V
- 1S battery pack typical 4V range; 4S battery pack 16.8 ~ 18V full charge
- bq2570x can charge any 1 – 4S pack across full USB VBUS range
- Bidirectional converter can generate USB OTG output over full USB PD range from any battery



Issues with Classical Buck-Boost Converter



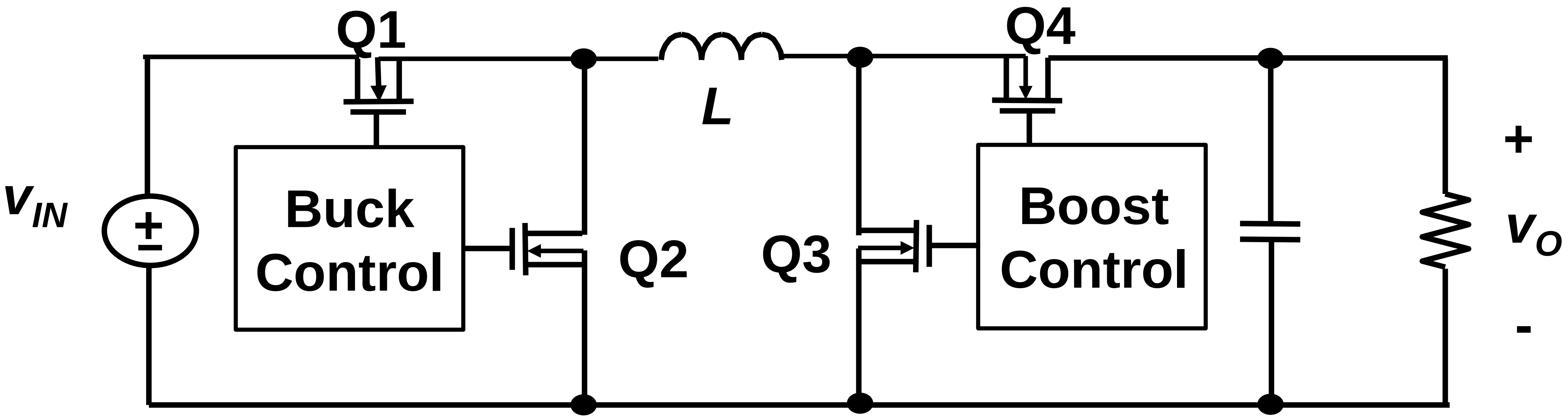


$$\textbf{Average Inductor Current} = \frac{I_O}{1-D}$$

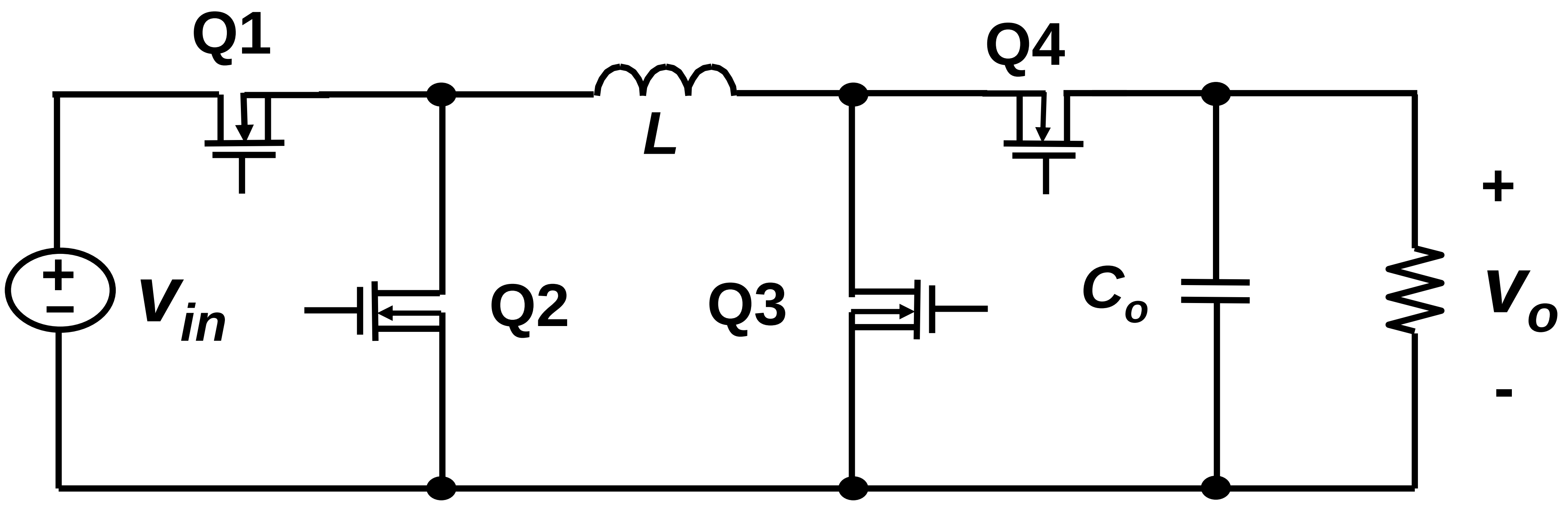
- ✓ Buck and Boost Mode Transition at D = 0.5
- × Discontinuous input and output current
- × Inductor Current: 2 times higher than output or input current, Boost at D = 0.5
- × Higher conduction and switching loss due to 4 MOSFETs Actively Switching
- × Lower efficiency compared with Buck or Boost Converter

TI Proposed Buck-Boost Converter

- The bq25700 operates as Buck or Boost
- Automatically transitions between buck mode and boost mode.
- Innovative control topology uses only two switches at a time.



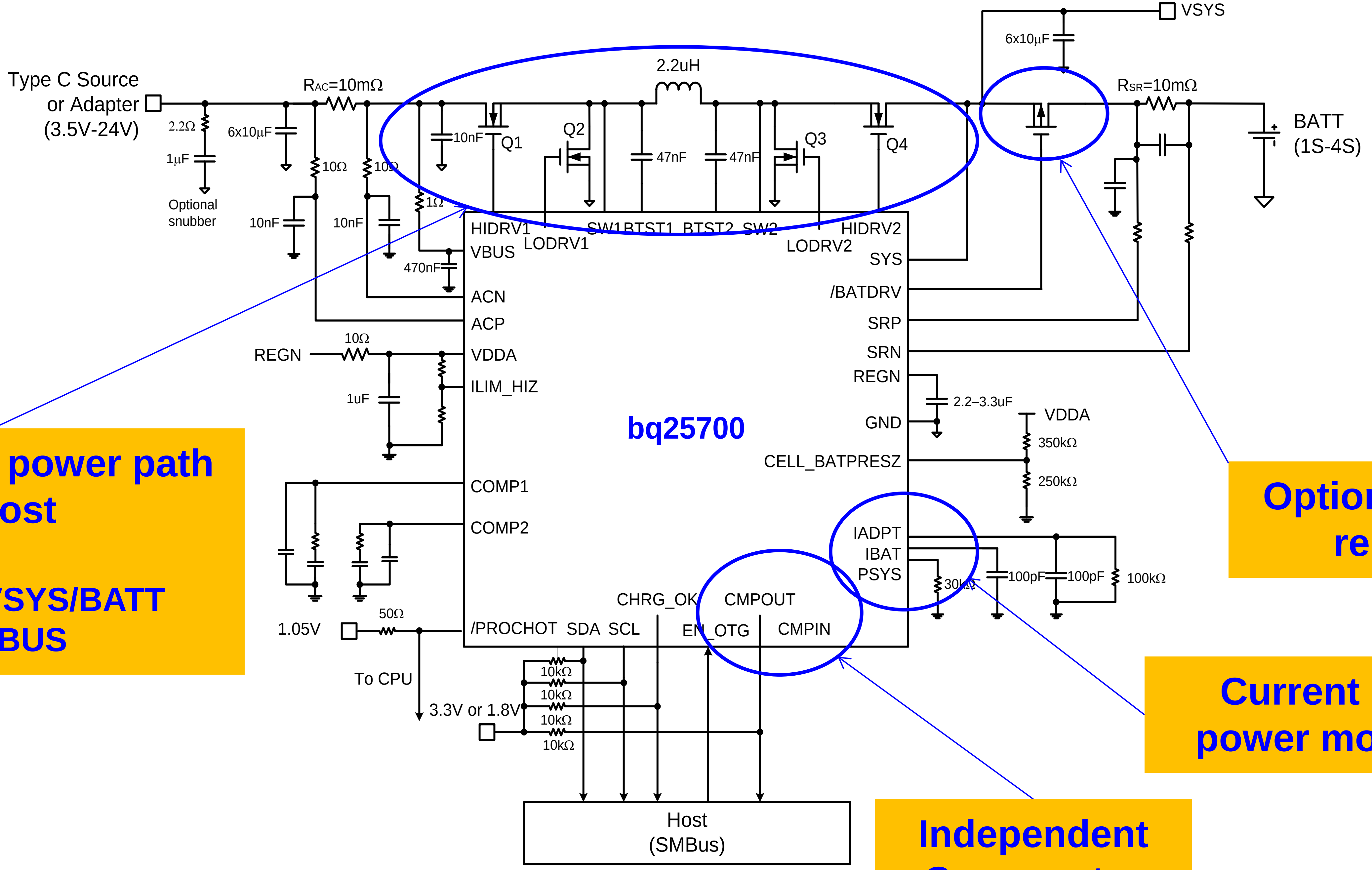
TI Proposed Buck-Boost Converter Control Method



	Q1	Q2	Q3	Q4	Voltage Gain
Buck	Switching	Switching	OFF	ON	D
Boost	ON	OFF	Switching	Switching	1 / (1-D)

- Operate either Buck or Boost
- Traditional buck-boost: D/(1-D): higher loss, and lower efficiency

Application Diagram



Bidirectional power path with buck boost operation:

1. **VBUS to VSYS/BATT**
2. **BATT to VBUS**

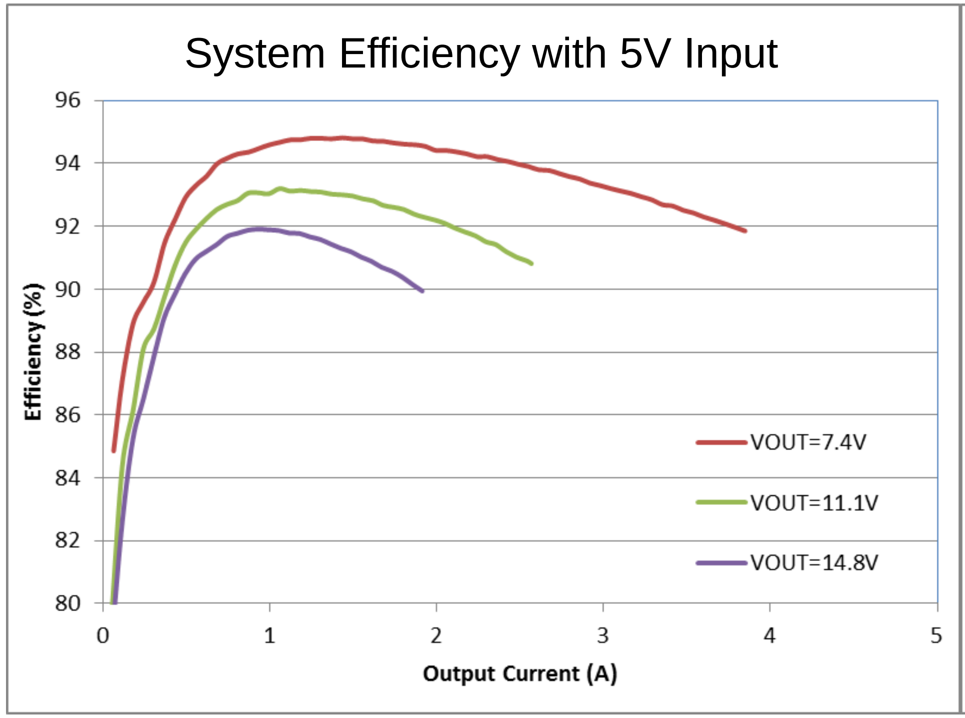
Optional, can be removed

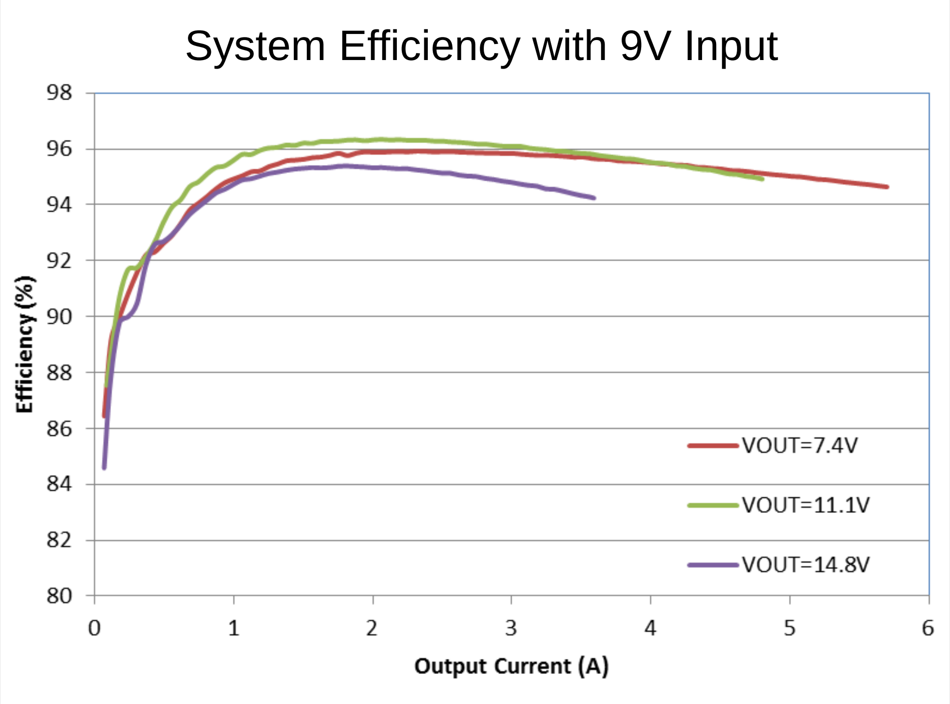
Current and power monitor

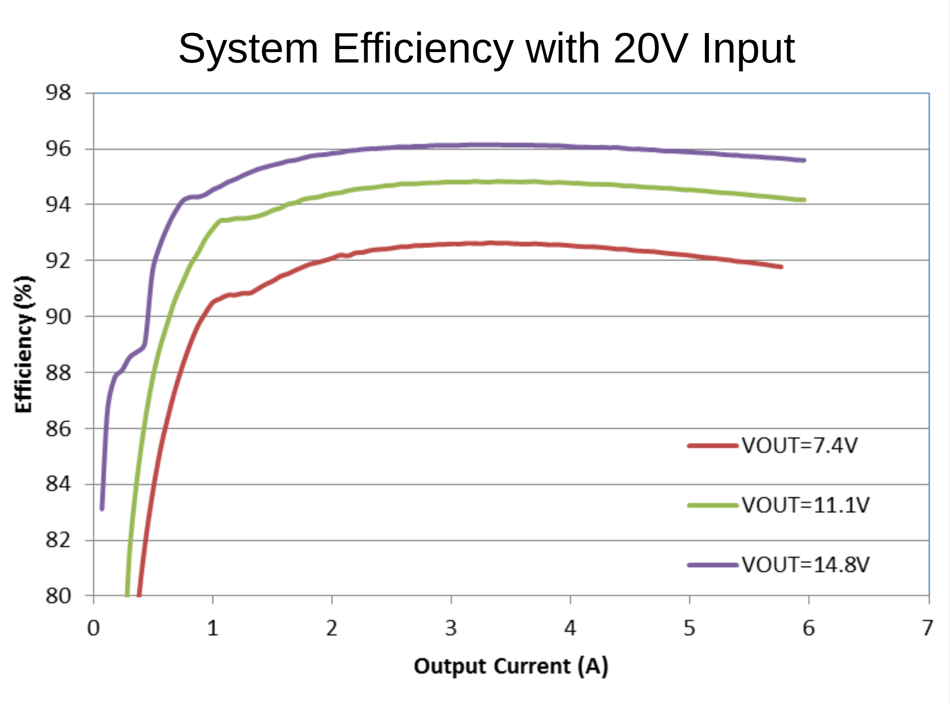
Independent Comparator

Forward Charging Efficiency

- Measured on EVM
  - –Switching FET CSD17551
  - –Inductor 2.2uH (IHLP3232CZ)
  - –Switching frequency 800kHz

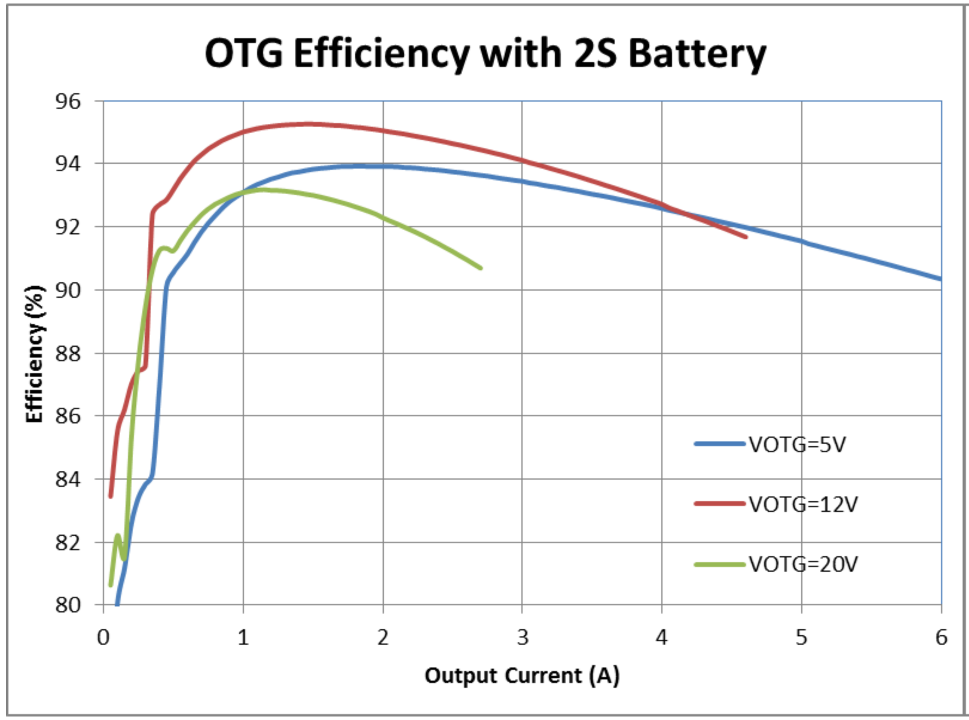


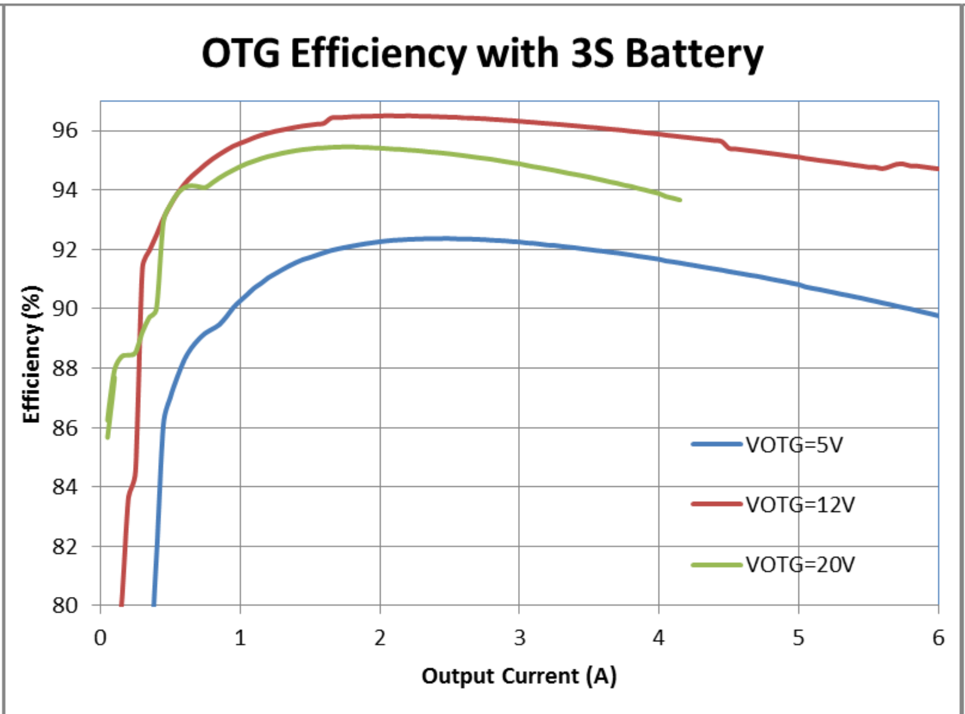


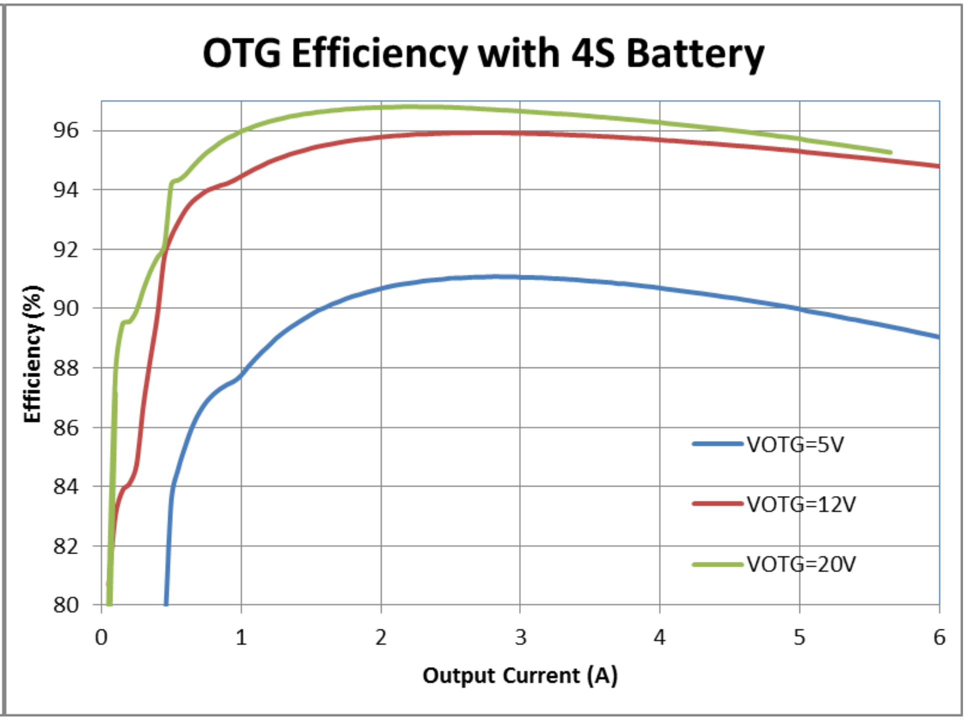


Reverse OTG Efficiency

- Measured on EVM
  - Switching FET CSD17551
  - Inductor 2.2uH (IHLP3232CZ)
  - Switching frequency 800kHz







Summary – Battery Charging

- Charge control algorithm must be matched to the battery type you are using

- IC selection criteria starts with power requirements:
  - output power: “volts and amps” like any other power supply
  - Linear regulator, switch mode buck, buck-boost options exist

- Consider other application requirements to decide if you should use power path system, standalone charger, or host-controlled charger – more resources at www.ti.com/chargers

- See additional appnotes and “E2E Forum” at www.ti.com/battery

APPENDIX / ADDITIONAL MATERIAL

- TI – Battery Management “Deep Dive” Annual Seminars Oct 2016 and Oct 2017
- Complete set of presentations available here for download (ZIP files):
- www.ti.com/deepdive