

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

October 2017

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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?

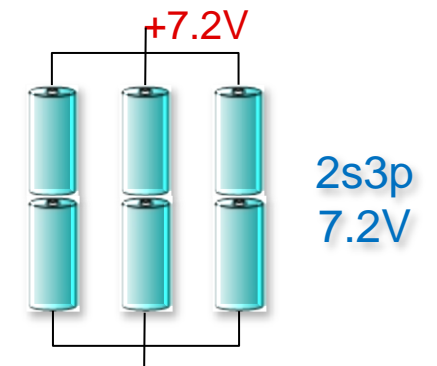
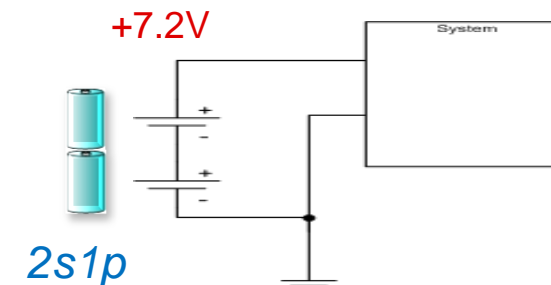
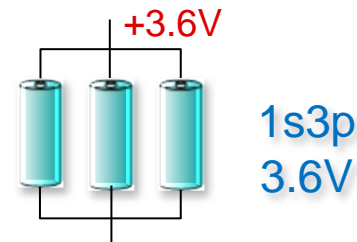
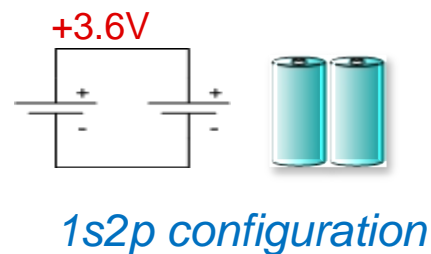
- **Battery management circuits**

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

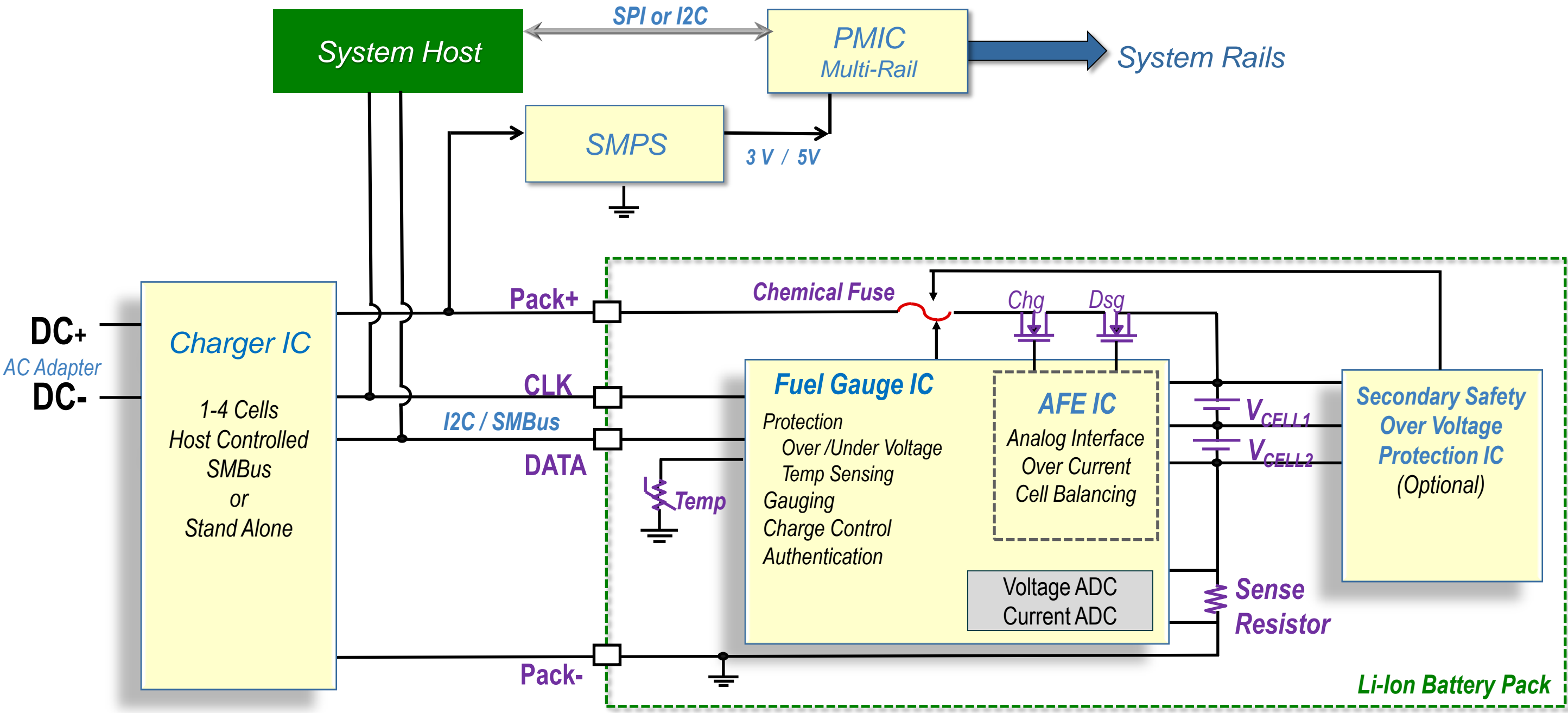


- **Systems require battery management to extend run-times, ensure safety, and maximize battery service life**
- **Degrees of implementation vary, but should include three main functions : charging, gauging (monitoring), and protection**

Pack Configurations



Li-Ion Battery Management Components

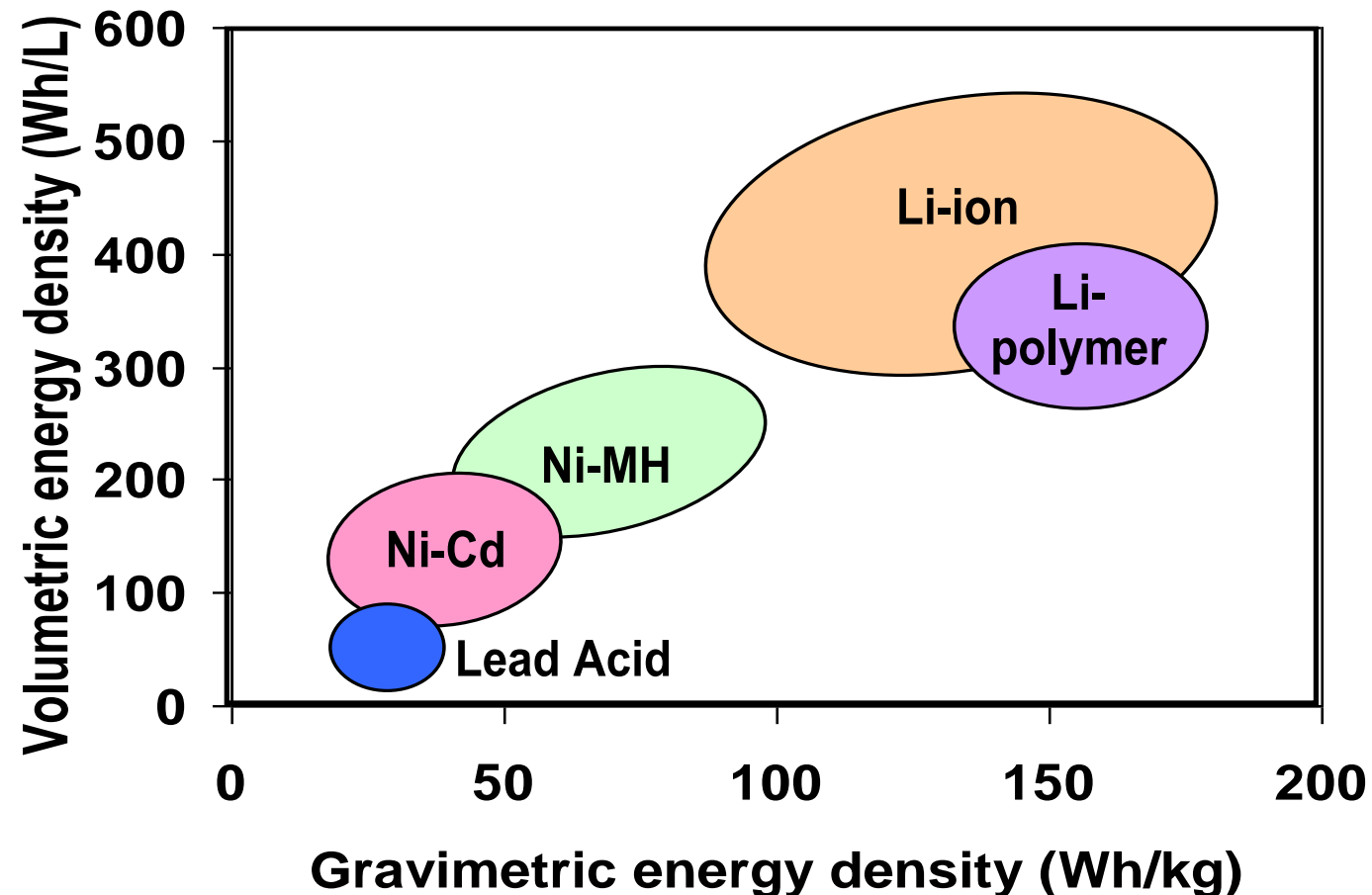


Rechargeable Battery Options

- **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

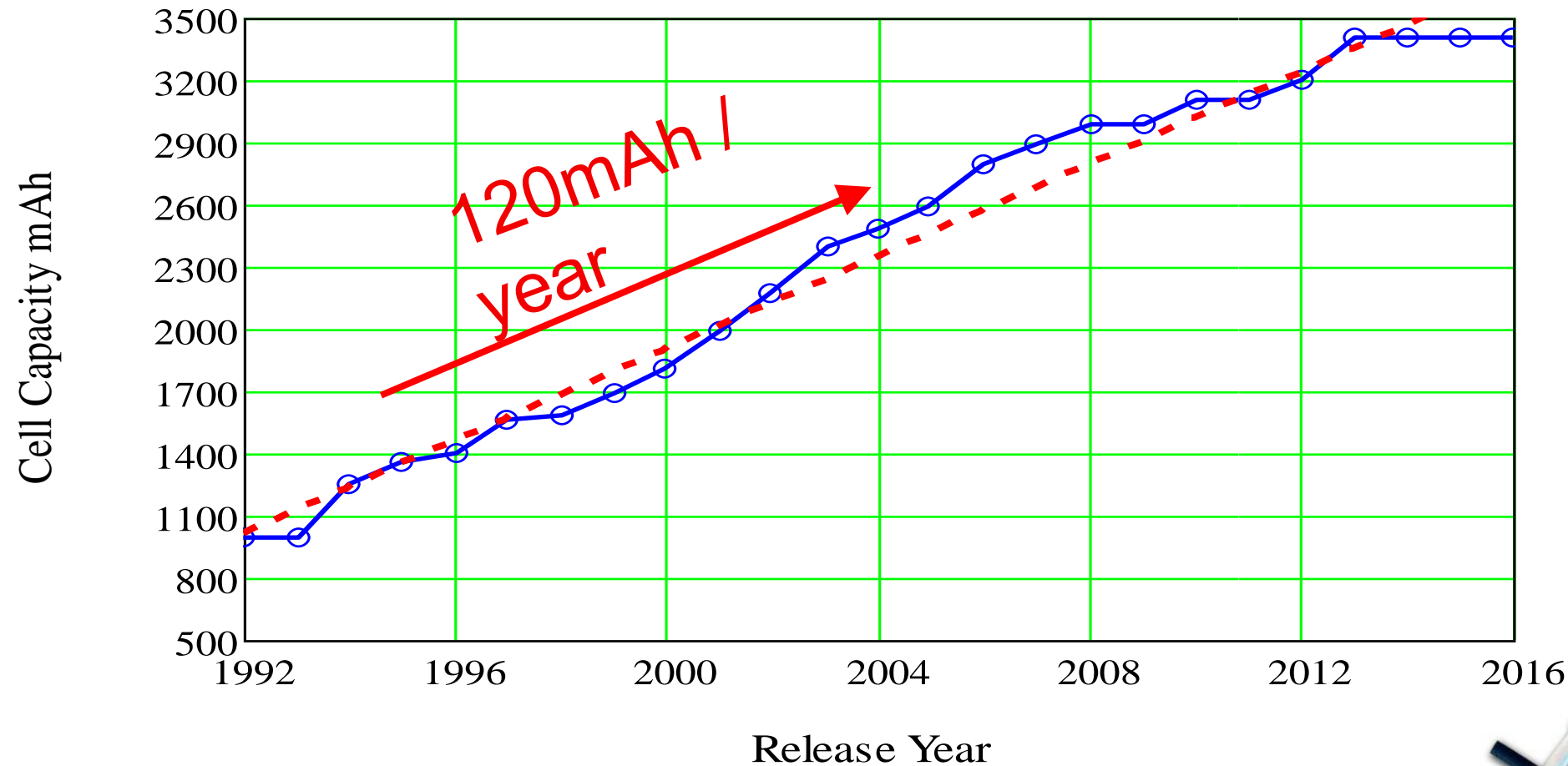
Why is Li-Ion popular?

- 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

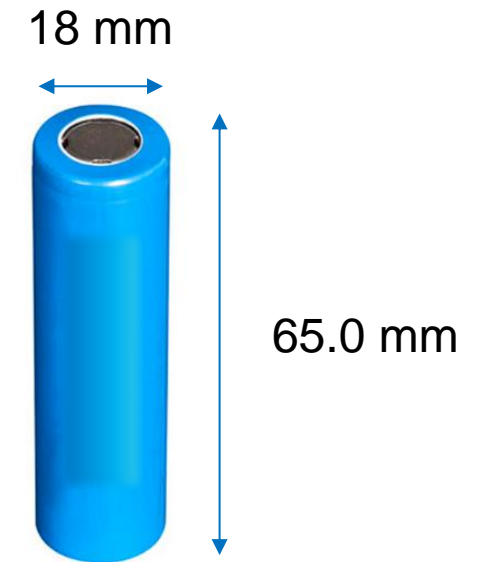
Group →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
Lanthanides				57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides				89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

18650 Li-Ion Cell Capacity Development Trend

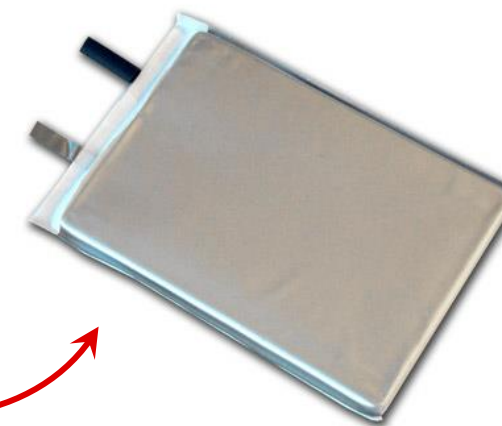
Capacity trend of 18650 cells



“18650:” Li-Ion Standard Cell



- 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 ₂ O 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!

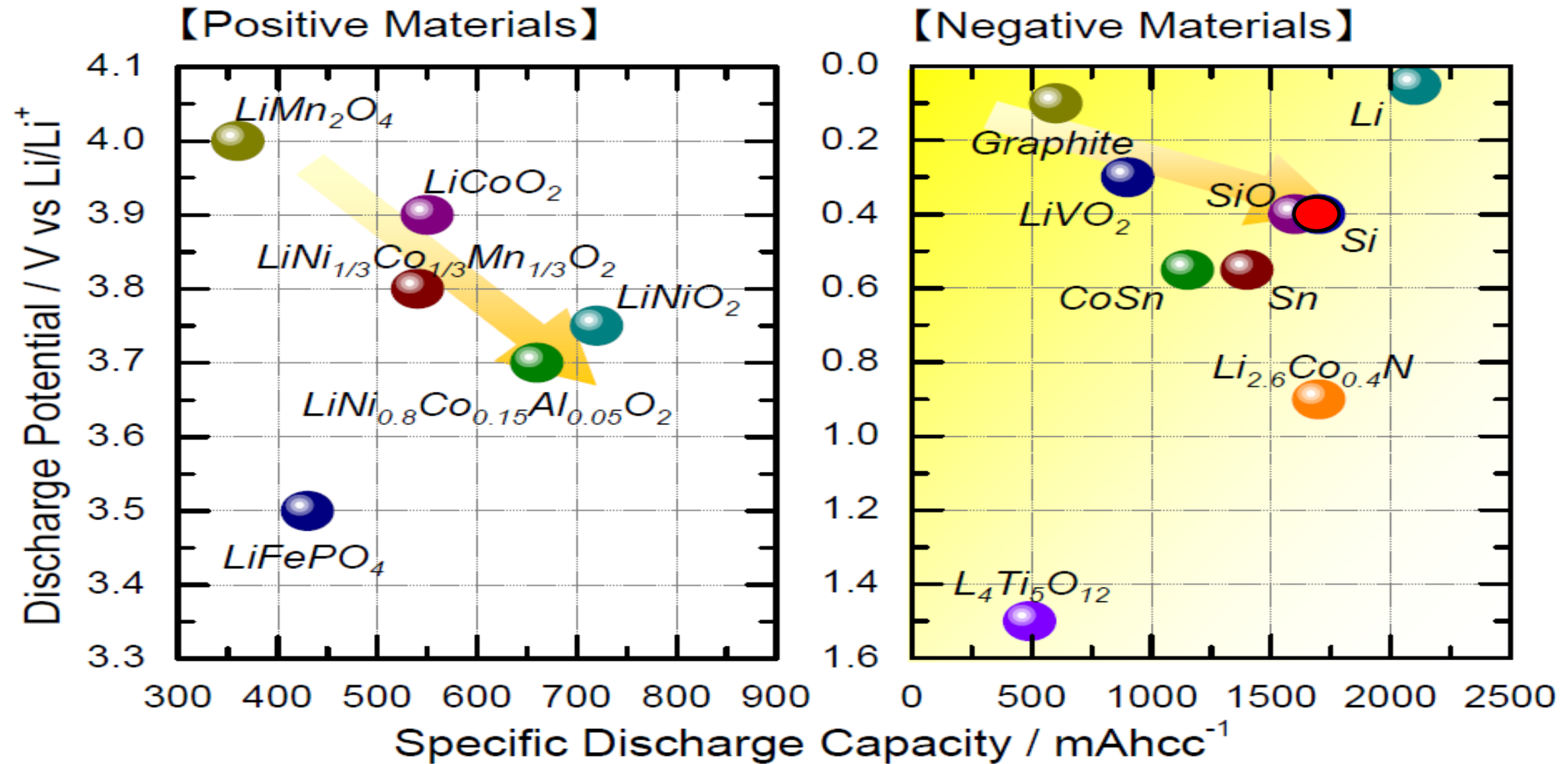
Periodic Table of the Elements

1 1IA 11A H Hydrogen 1.0079	2 IIA 2A He Helium 4.00260																
3 Li Lithium 6.941	4 Be Beryllium 9.01218											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.998403	10 Ne Neon 20.1797
11 Na Sodium 22.989768	12 Mg Magnesium 24.305	13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948										
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9072	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [209]	85 At Astatine 209	86 Rn Radon 222
87 Fr Francium 223	88 Ra Radium 226	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Uuq Ununquadium [289]	115 Uup Ununpentium unknown	116 Uuh Ununhexium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
			57 La Lanthanum 138.9055	58 Ce Cerium 140.115	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.9655	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
			89 Ac Actinium 227	90 Th Thorium 232	91 Pa Protactinium 231	92 U Uranium 238	93 Np Neptunium 237	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium [254]	100 Fm Fermium [257]	101 Md Mendelevium [261]	102 No Nobelium [259]	103 Lr Lawrencium [262]

Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetals
Nonmetals
Halogens
Noble Gas
Lanthanides
Actinides

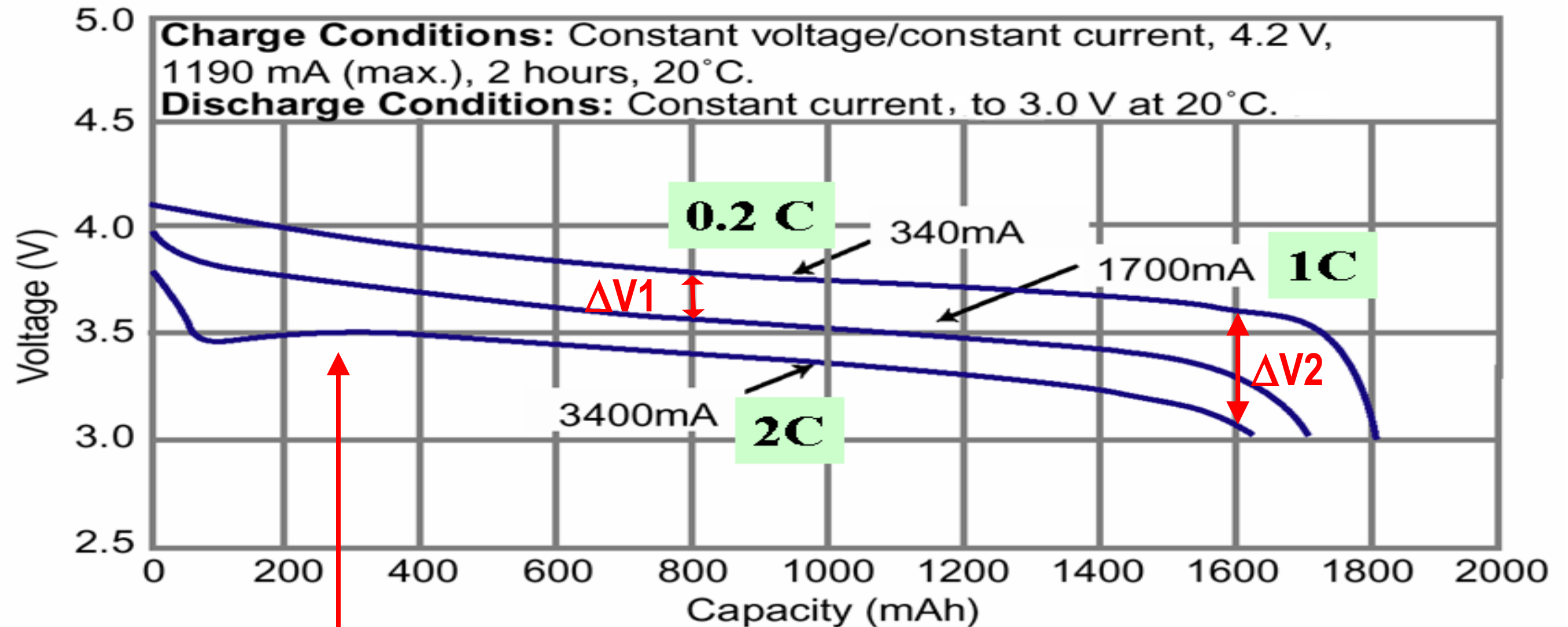
- Pick anode from top (lightest) left (strongest electron donor)
- Pick cathode from top (lightest) right (strongest electron acceptor)

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?

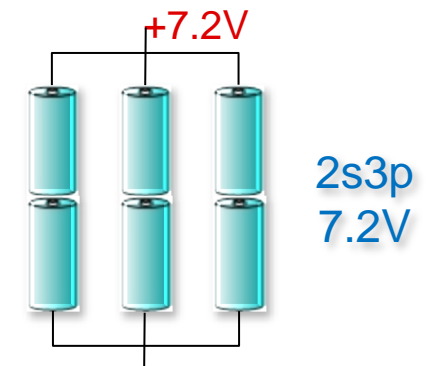
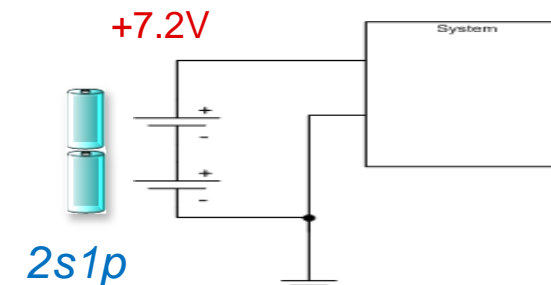
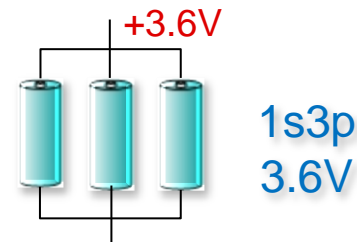
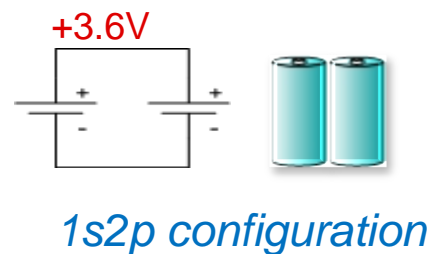
- **Battery management circuits**

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

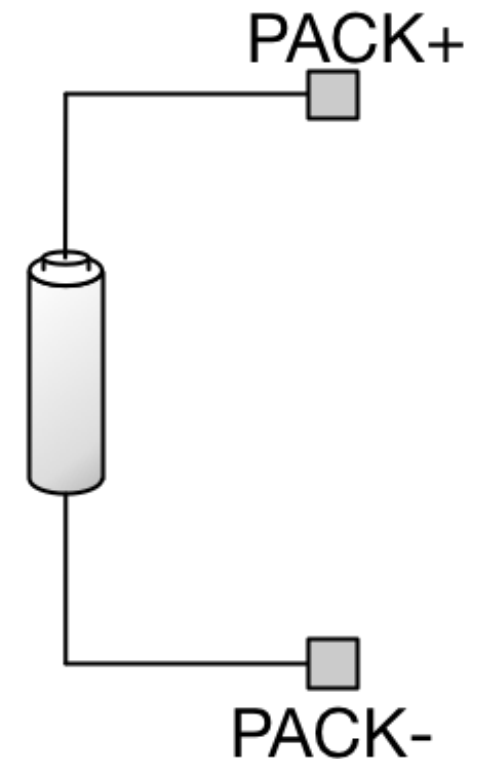
Pack Configurations



Agenda

The use of batteries is simple, but protecting them is not always straight forward as one might imagine. This discussion will 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**

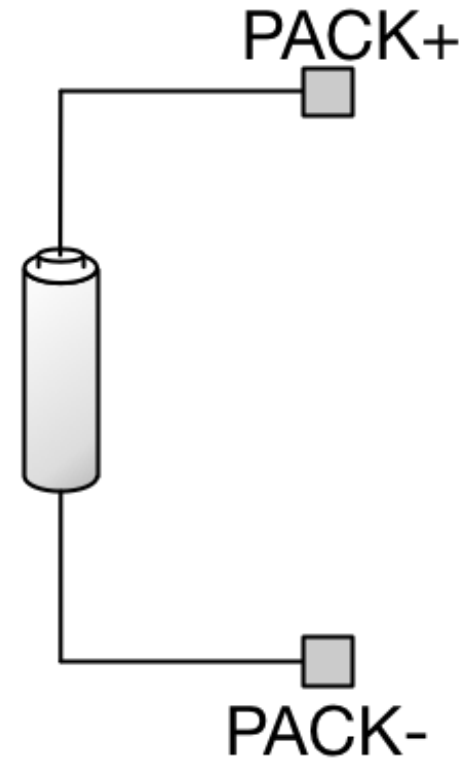


The goal is to avoid catastrophic failure



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:

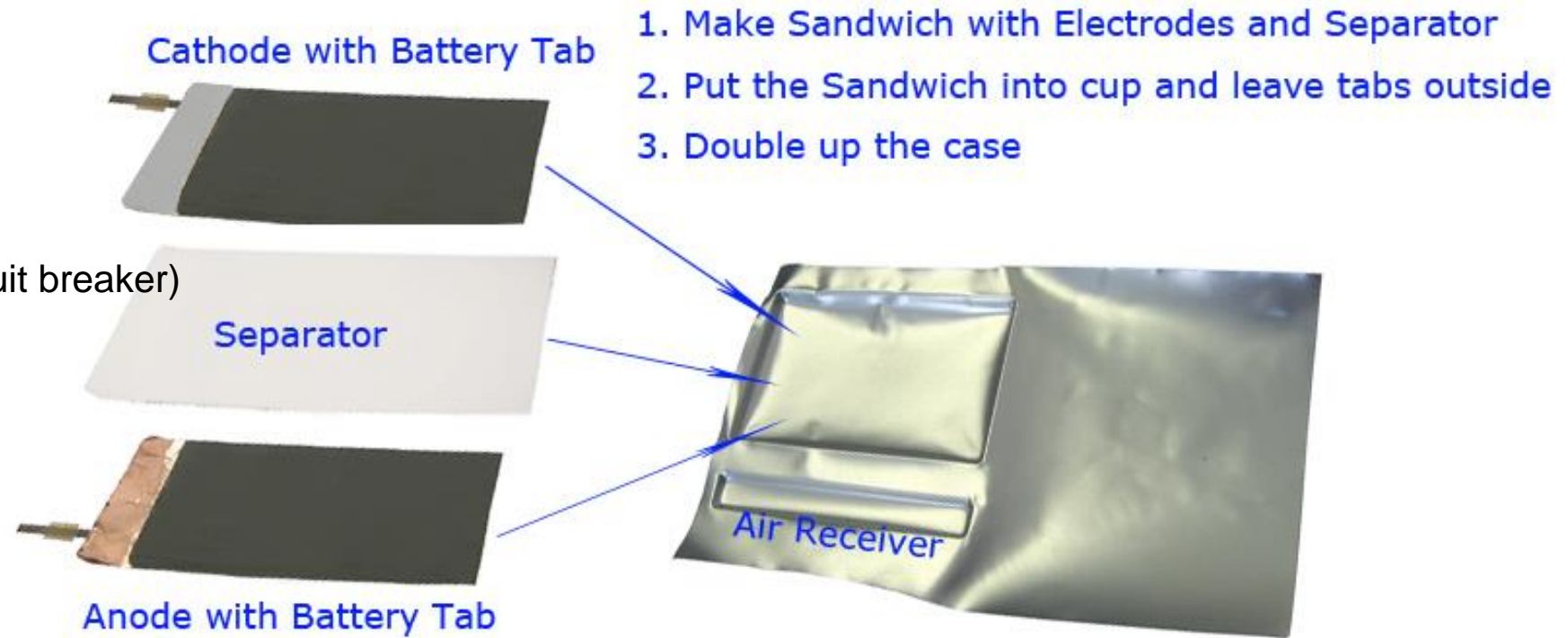
- Safety by design - UL1642 compliance
- cell-internal safety devices: Separator, PTC, Vent, CID (circuit breaker)
- compliant manufacturing processes
- factory quality control (QC)

- On pack manufacturing site:

- Safe pack design - IEEE 1625/1725 compliance
- Manufacturing QC

- Industrial Design

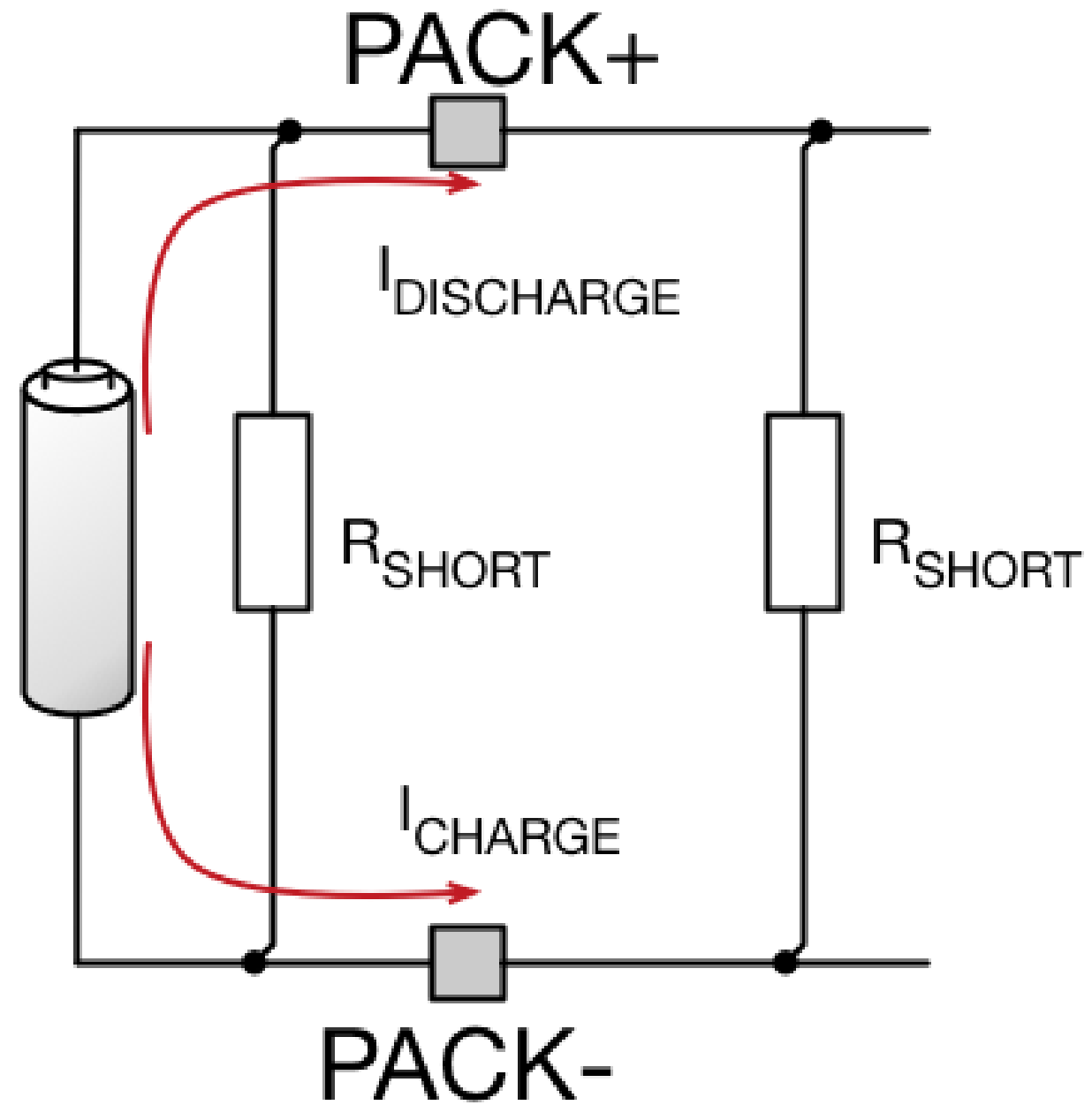
- Allowances for pack swelling
- Manufacturing QC



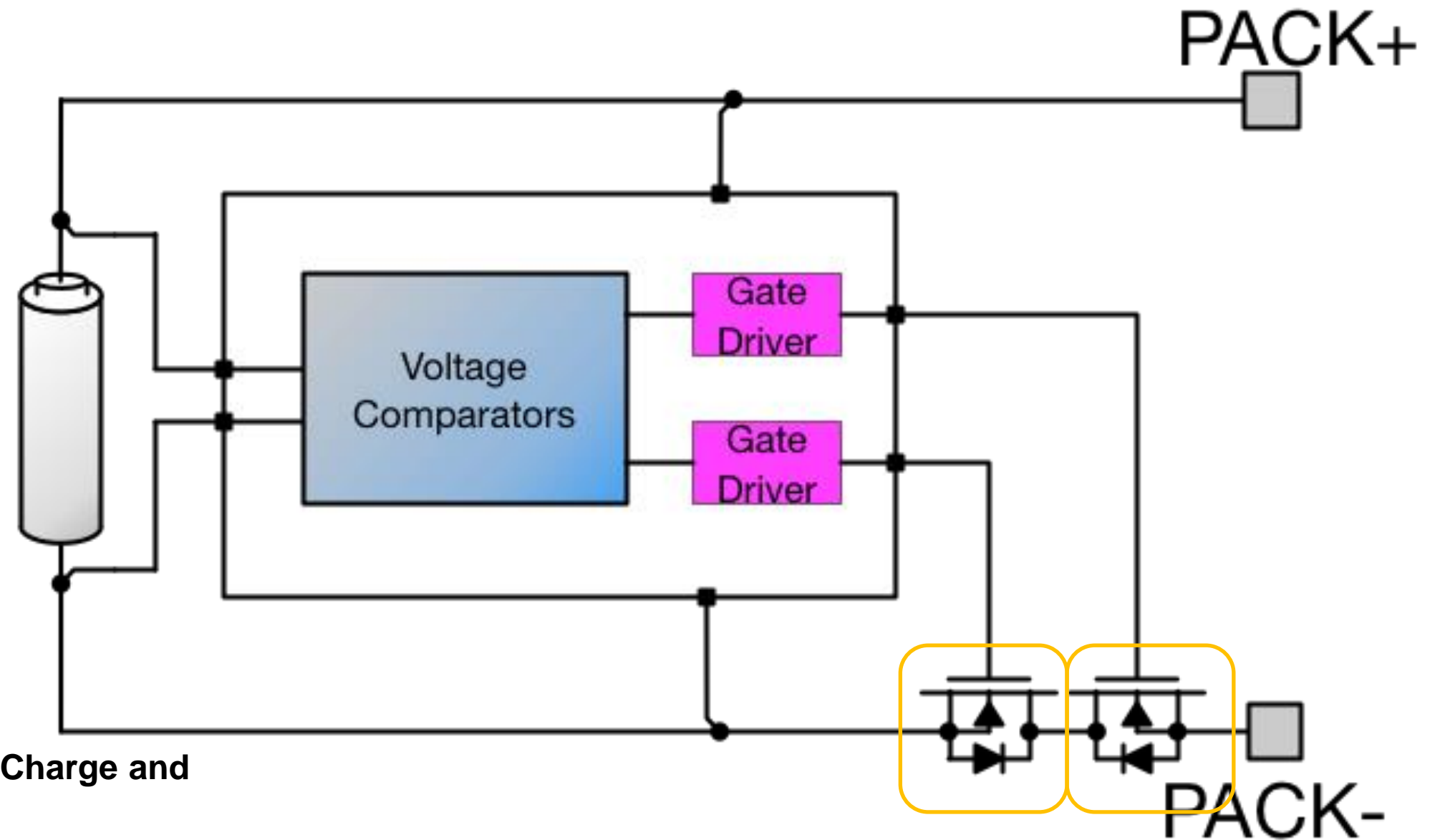
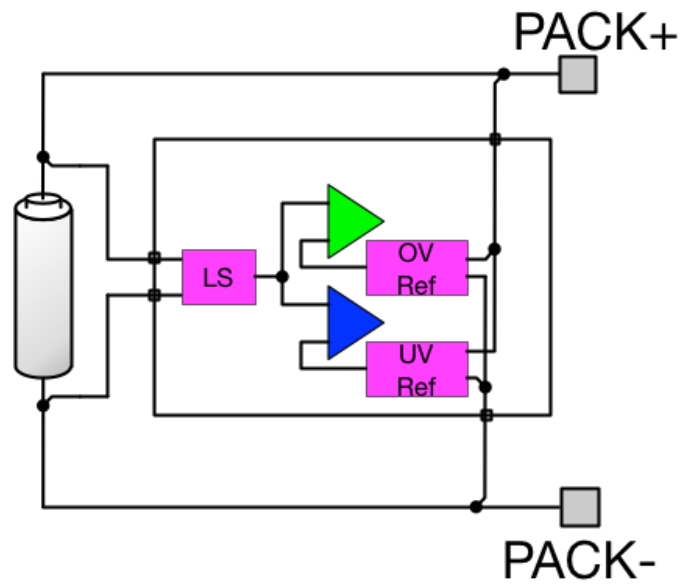
Preventing this class of failure requires good design/manufacturing practices.
Once a cell fails internally, little can be done to stop it!

Possible Battery System Malfunctions

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



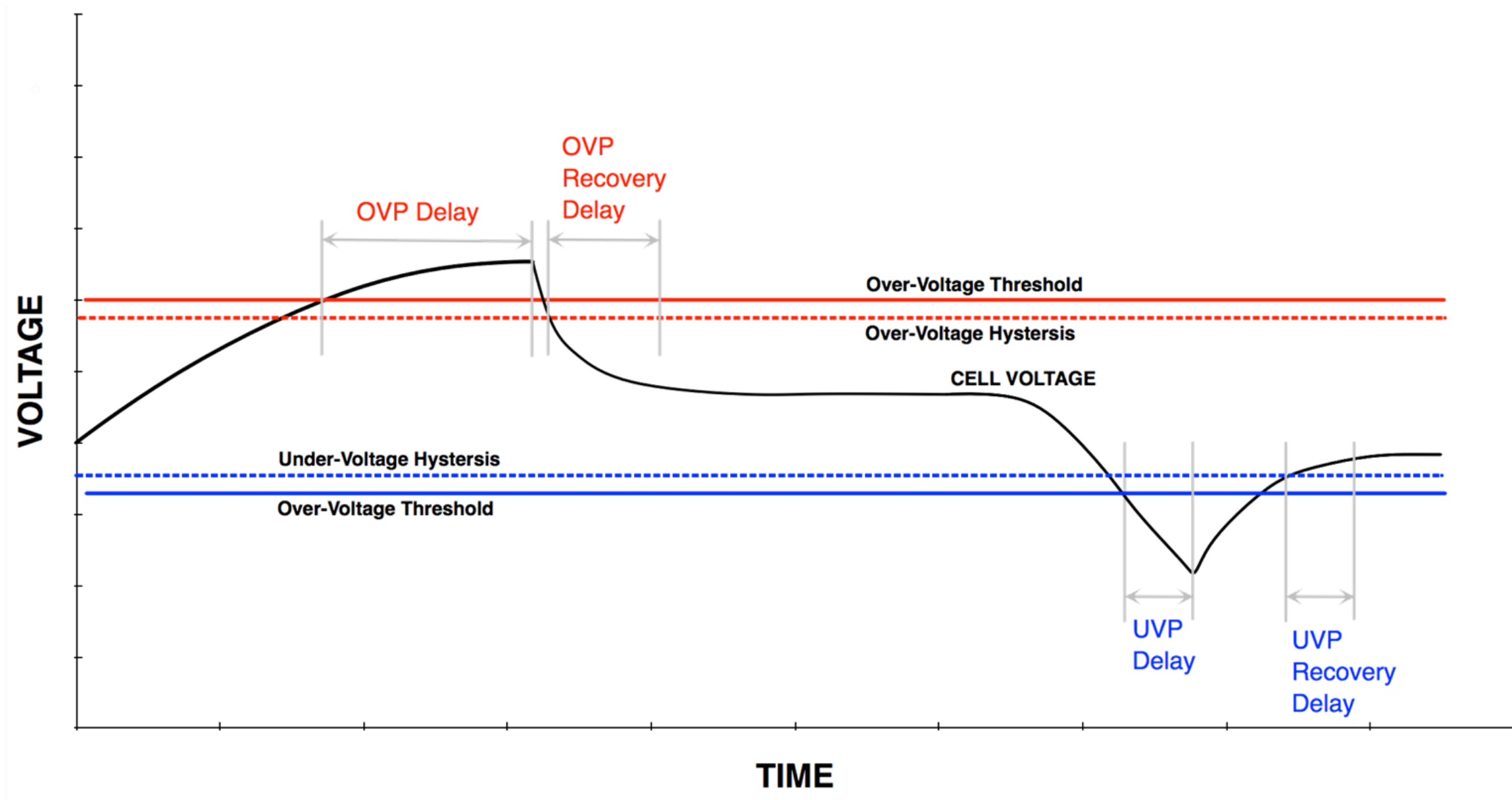
Handling Over-Charge/Discharge



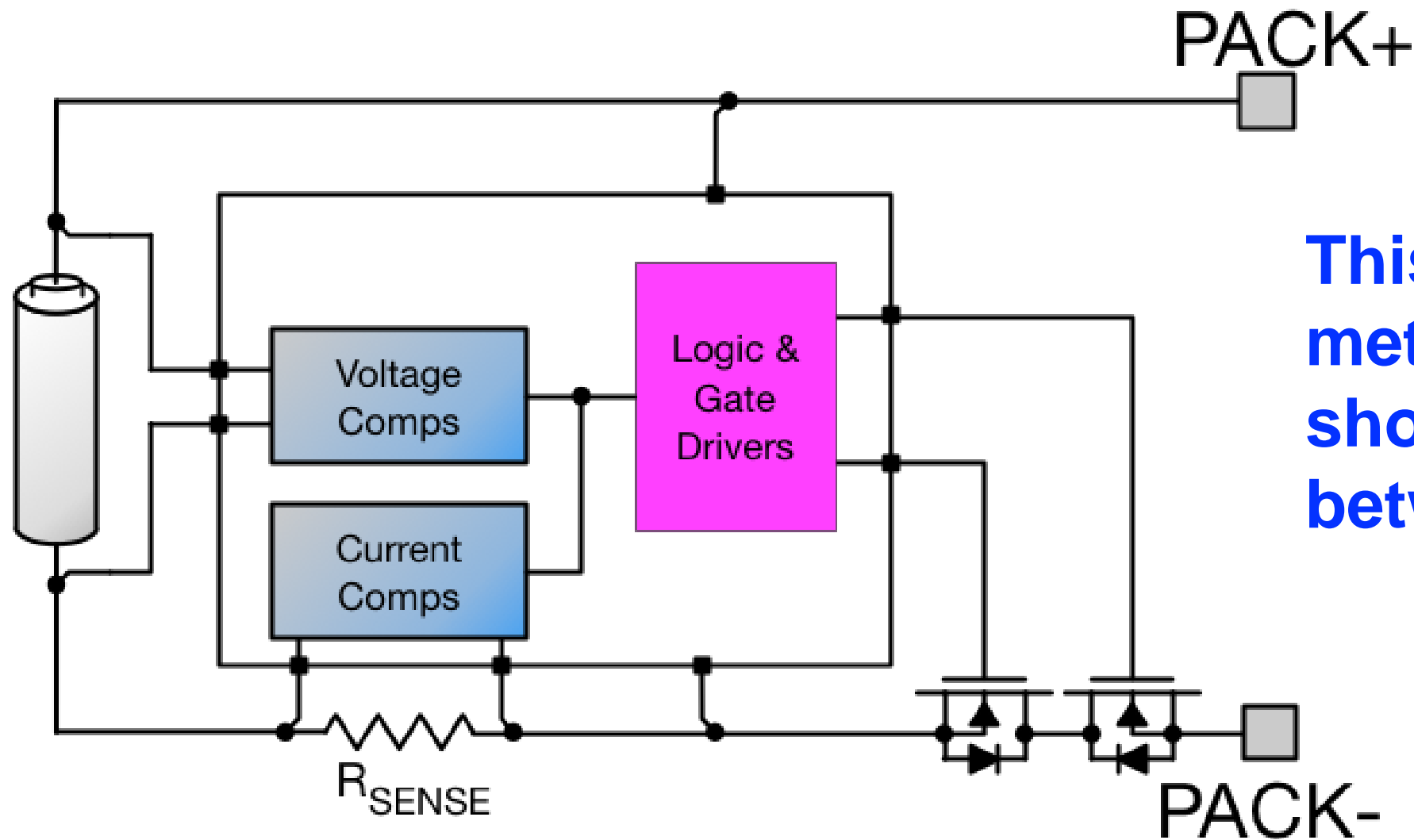
FETs are added to protect against Over-Charge and Over-Discharge

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

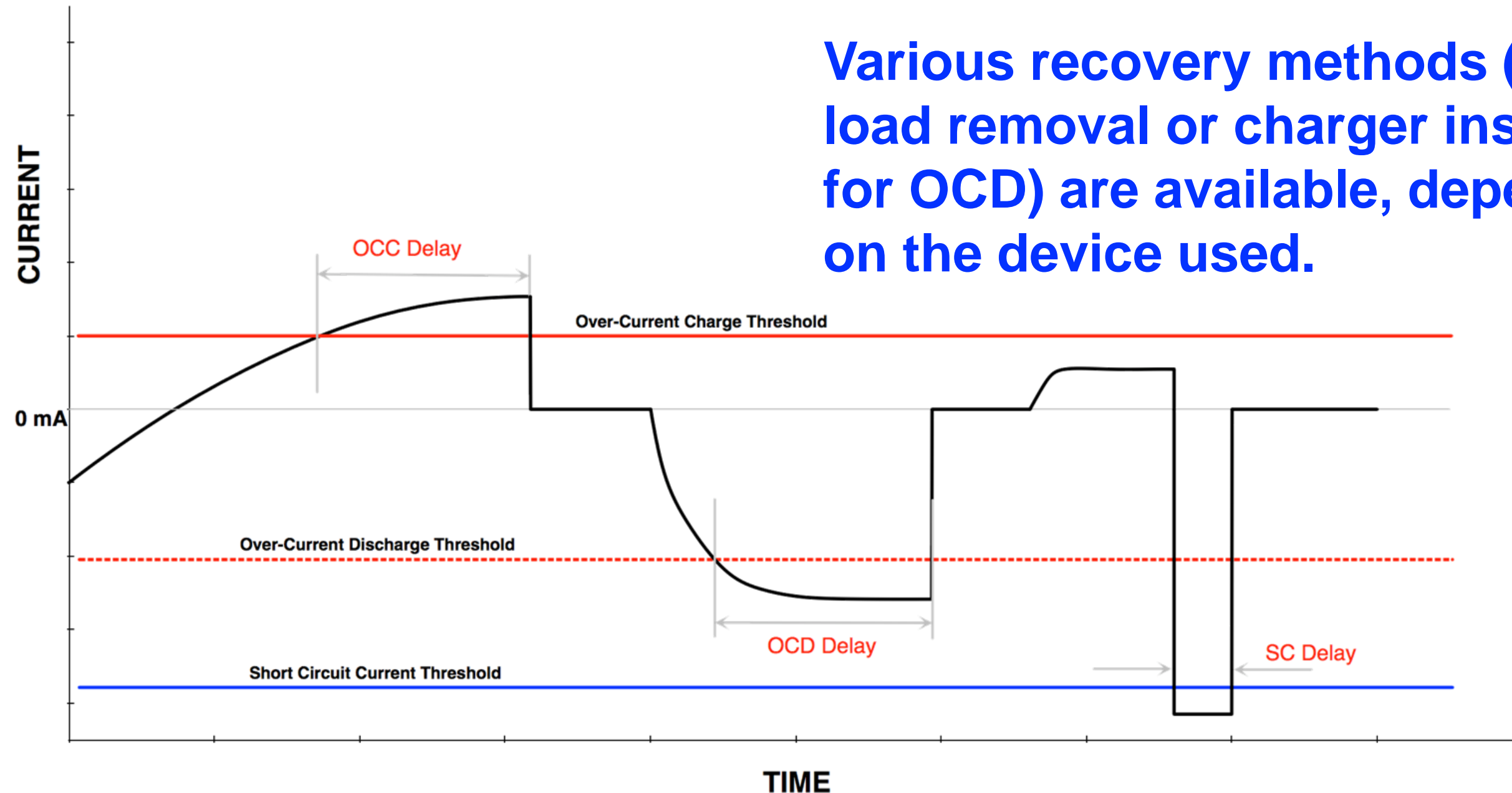


This allows detection and a method to de-energize any short that might develop between the $PACK\pm$ pins!

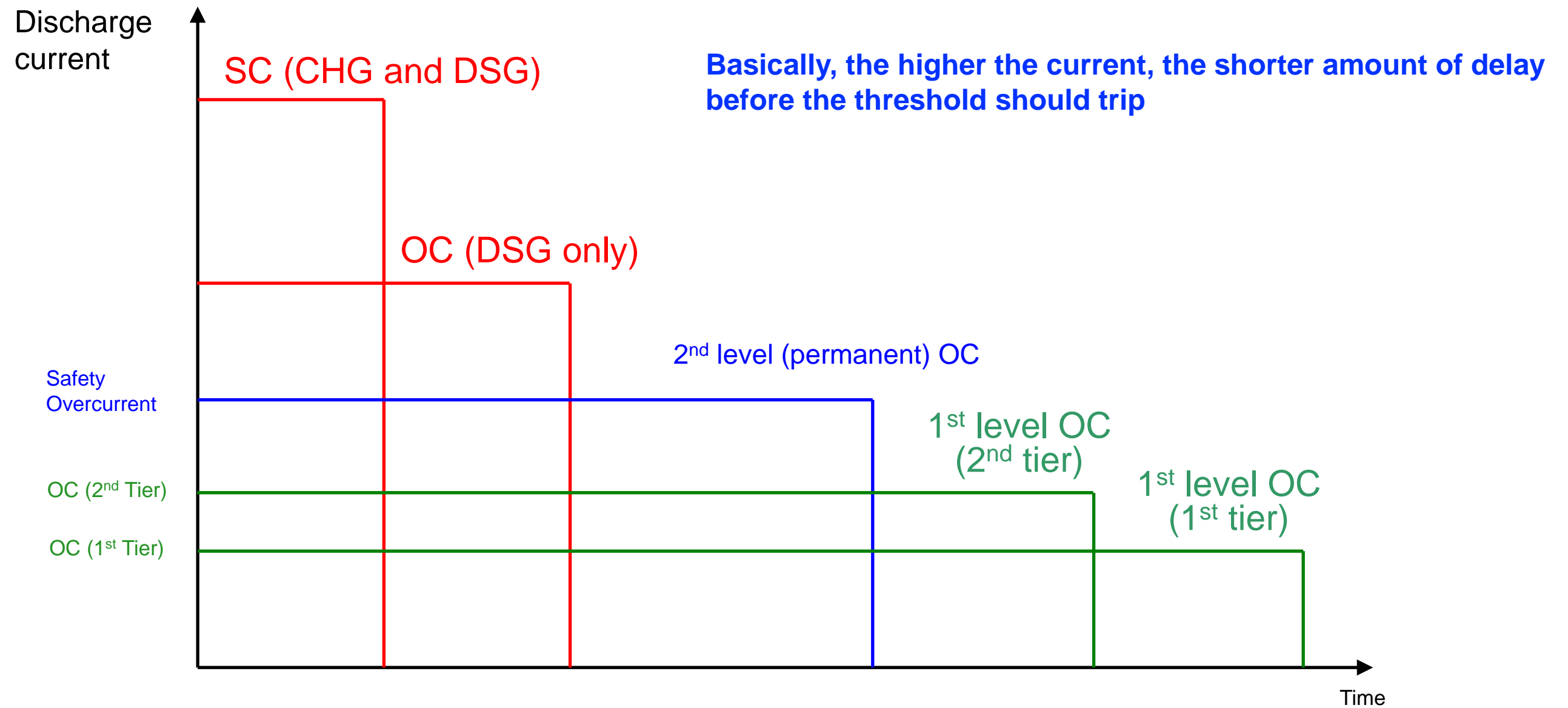
Charge/Discharge Overcurrent and Short Circuit

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.



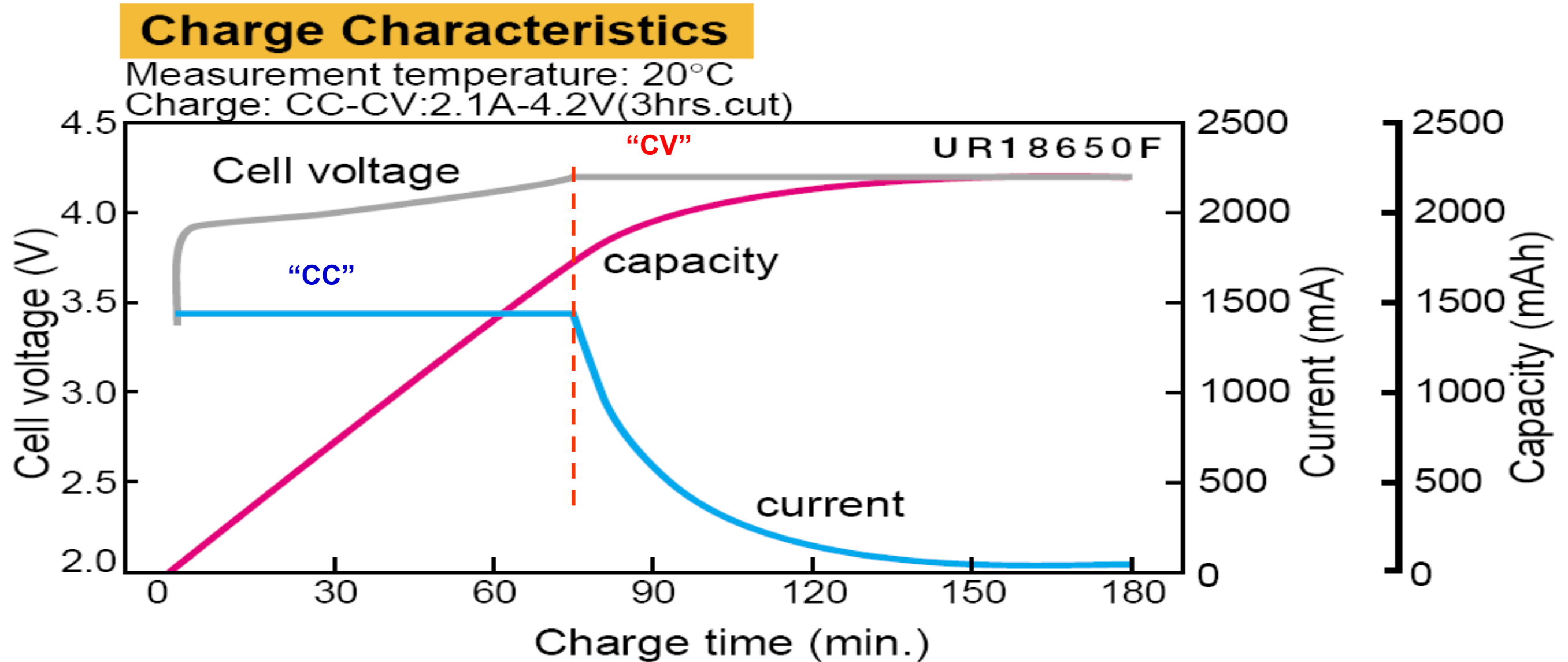
Time/Current Relationships



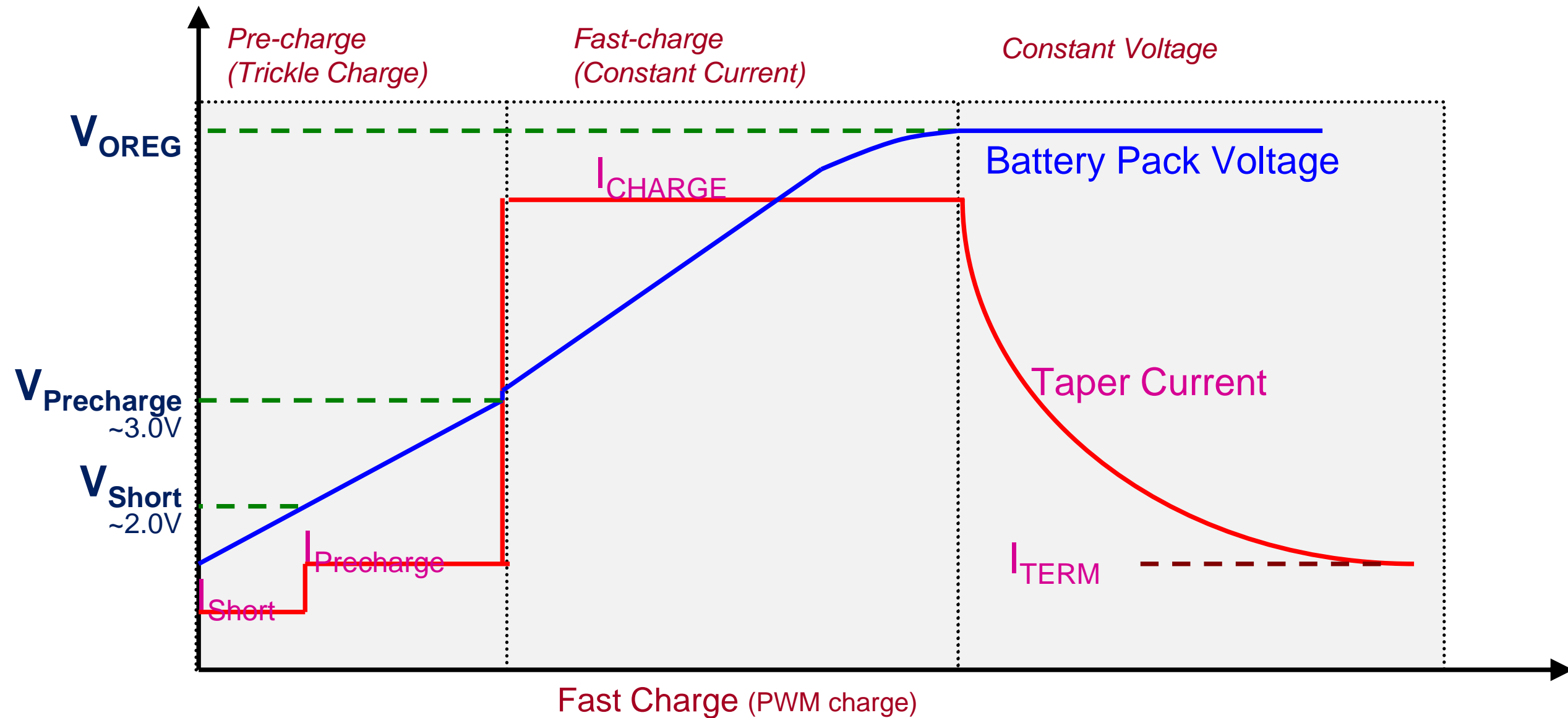
Li-Ion Charging

- 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

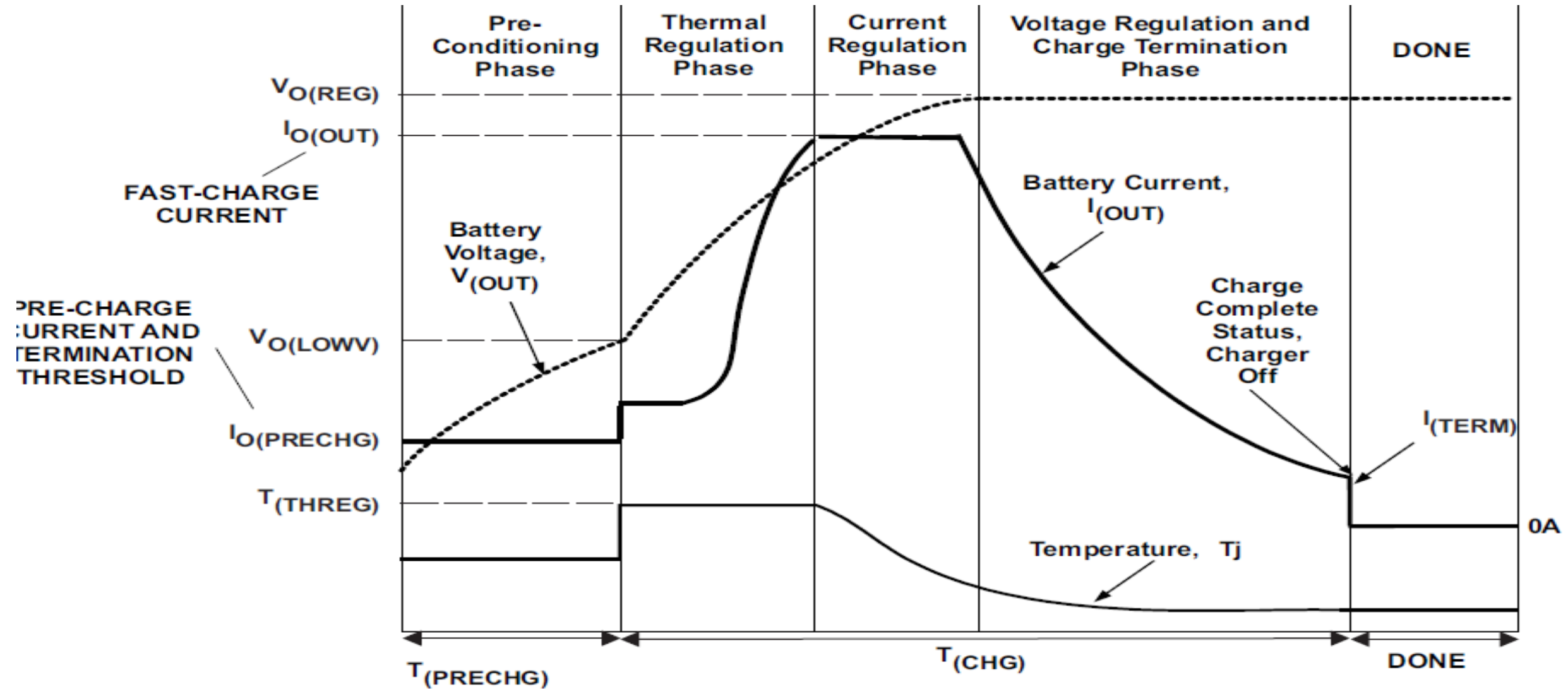
Review: “Ideal” Li-Ion CC-CV Charge Curve



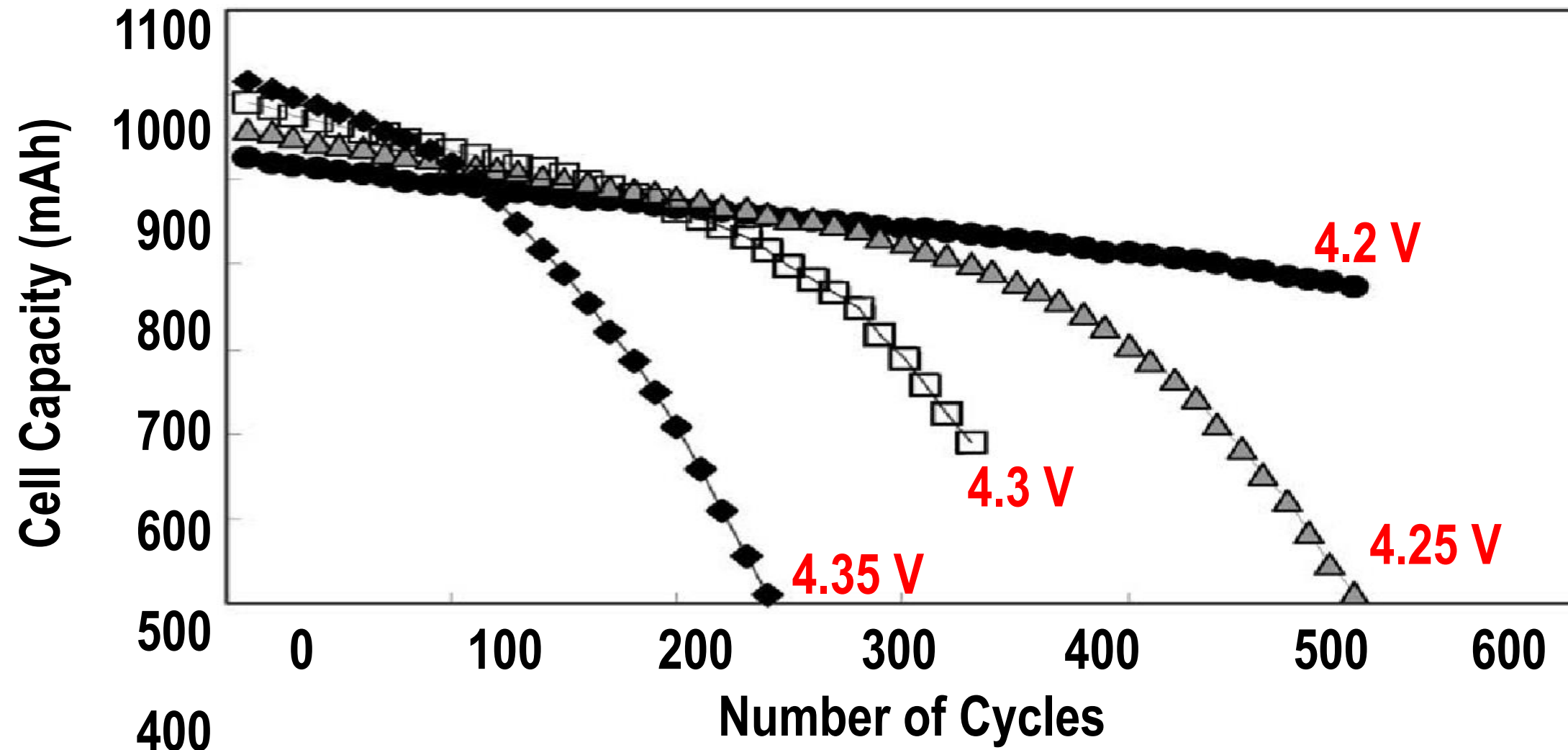
Practical “CC-CV” – allows for fault conditions



CCCV - From an actual data sheet...



Charge Voltage Accuracy Affects Battery Service Life

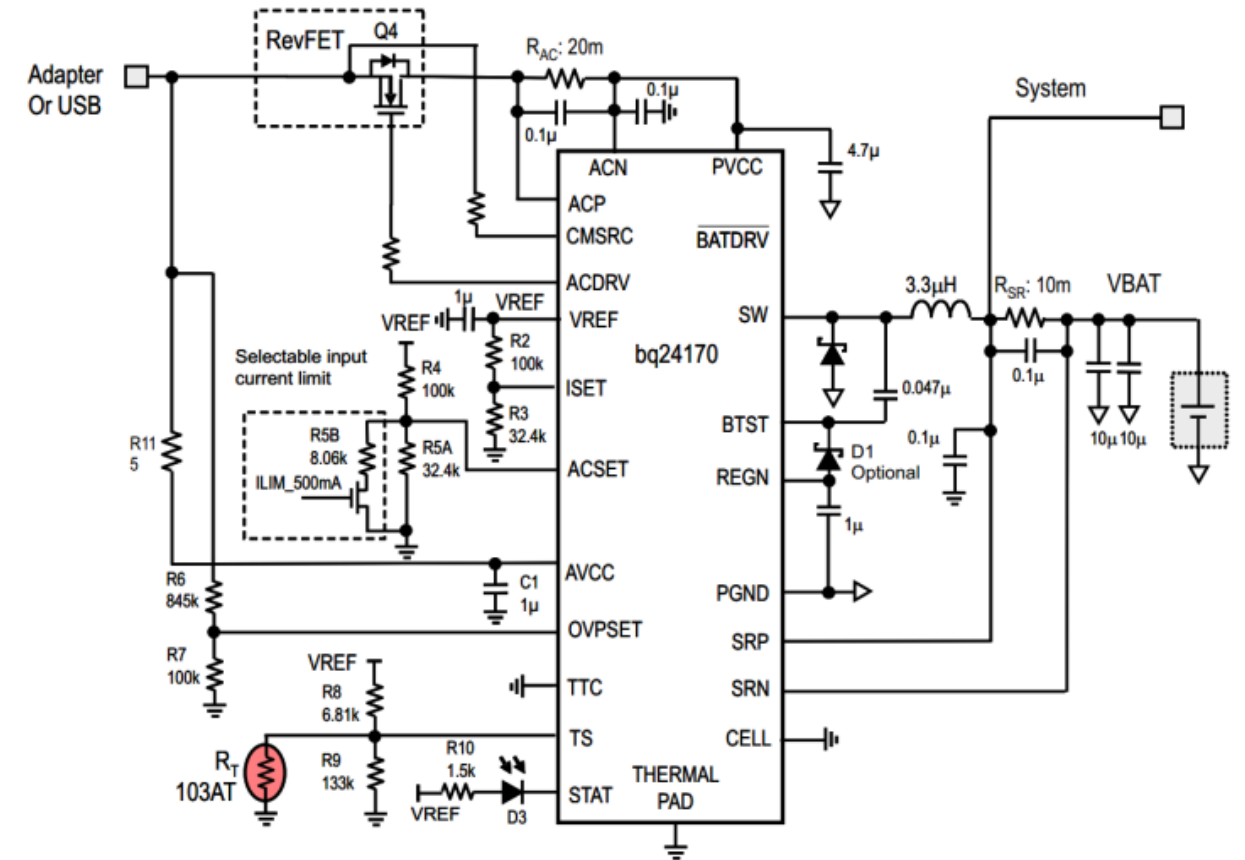
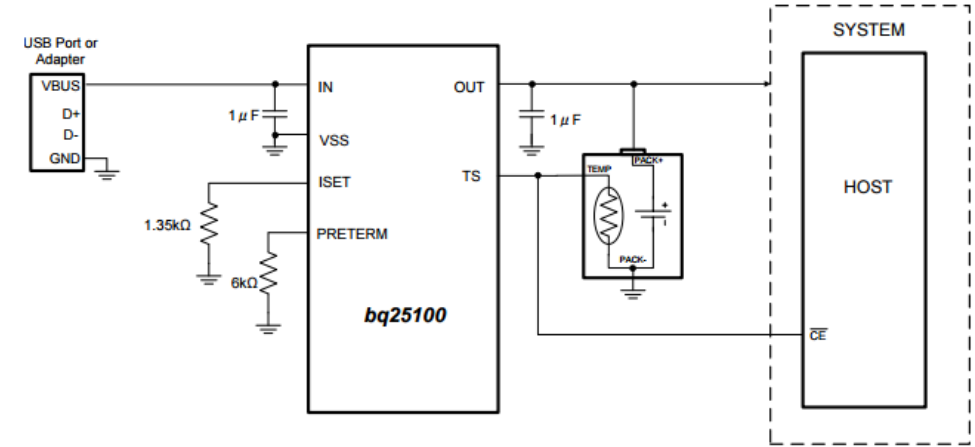


- The higher the voltage, the higher the initial capacity
- Overcharging shortens battery cycle life

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

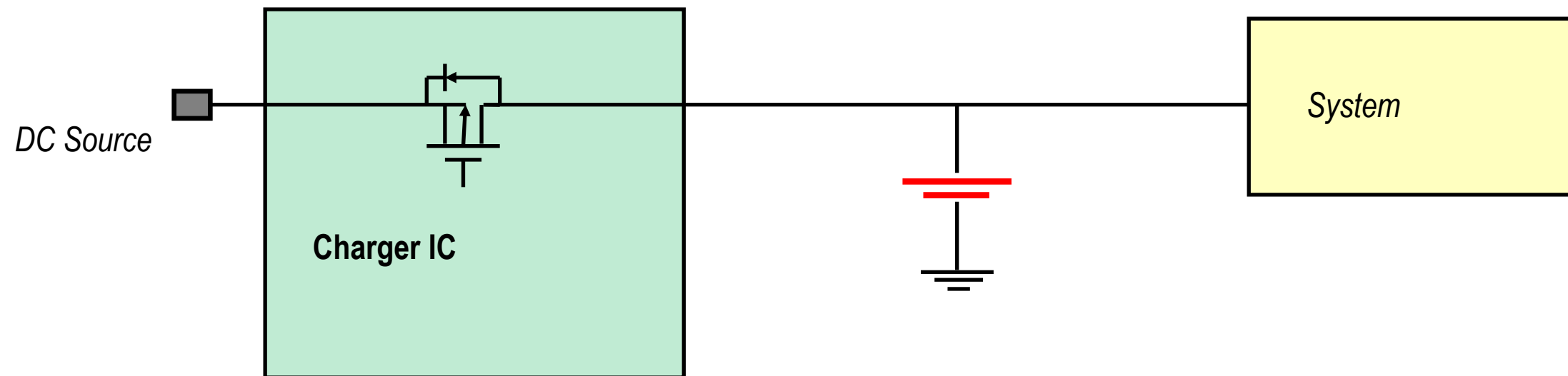
CHARGING CIRCUIT IMPLEMENTATION: Linear or Switch-Mode Charger?

- 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



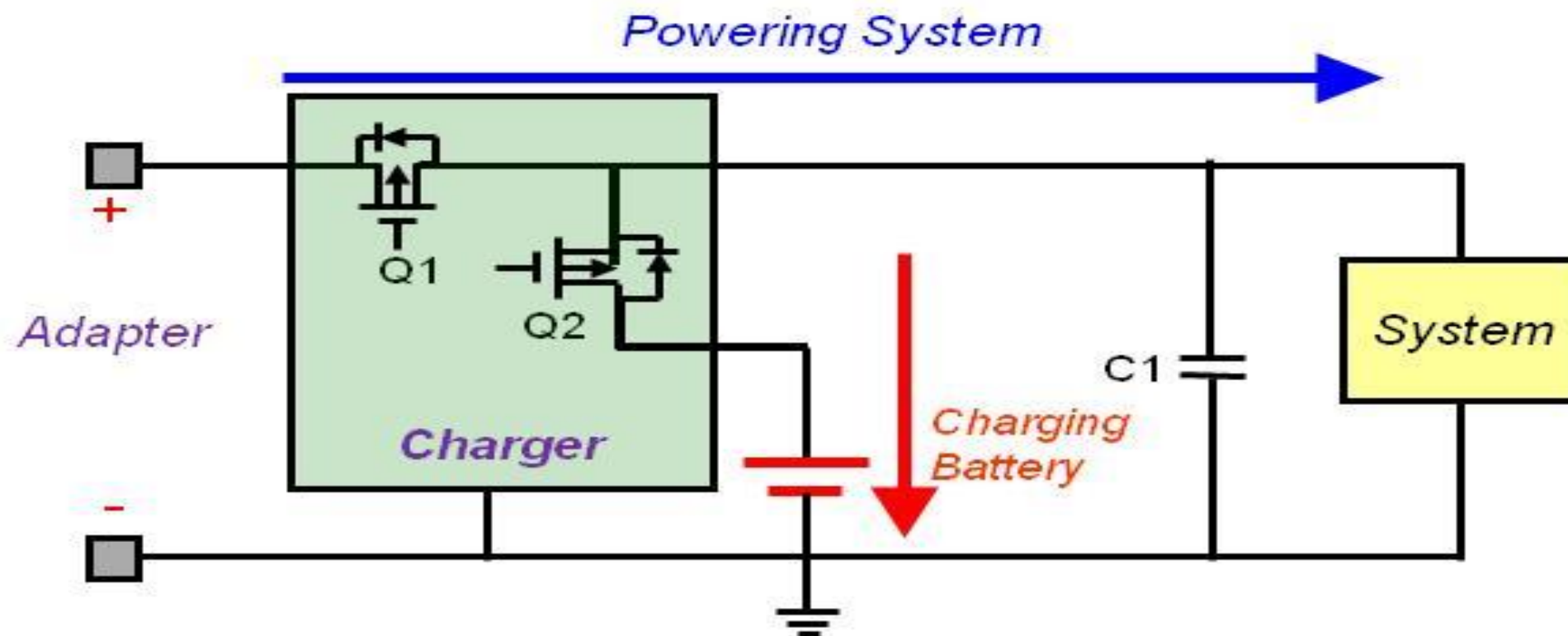
Simplest Charger Architecture

- 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

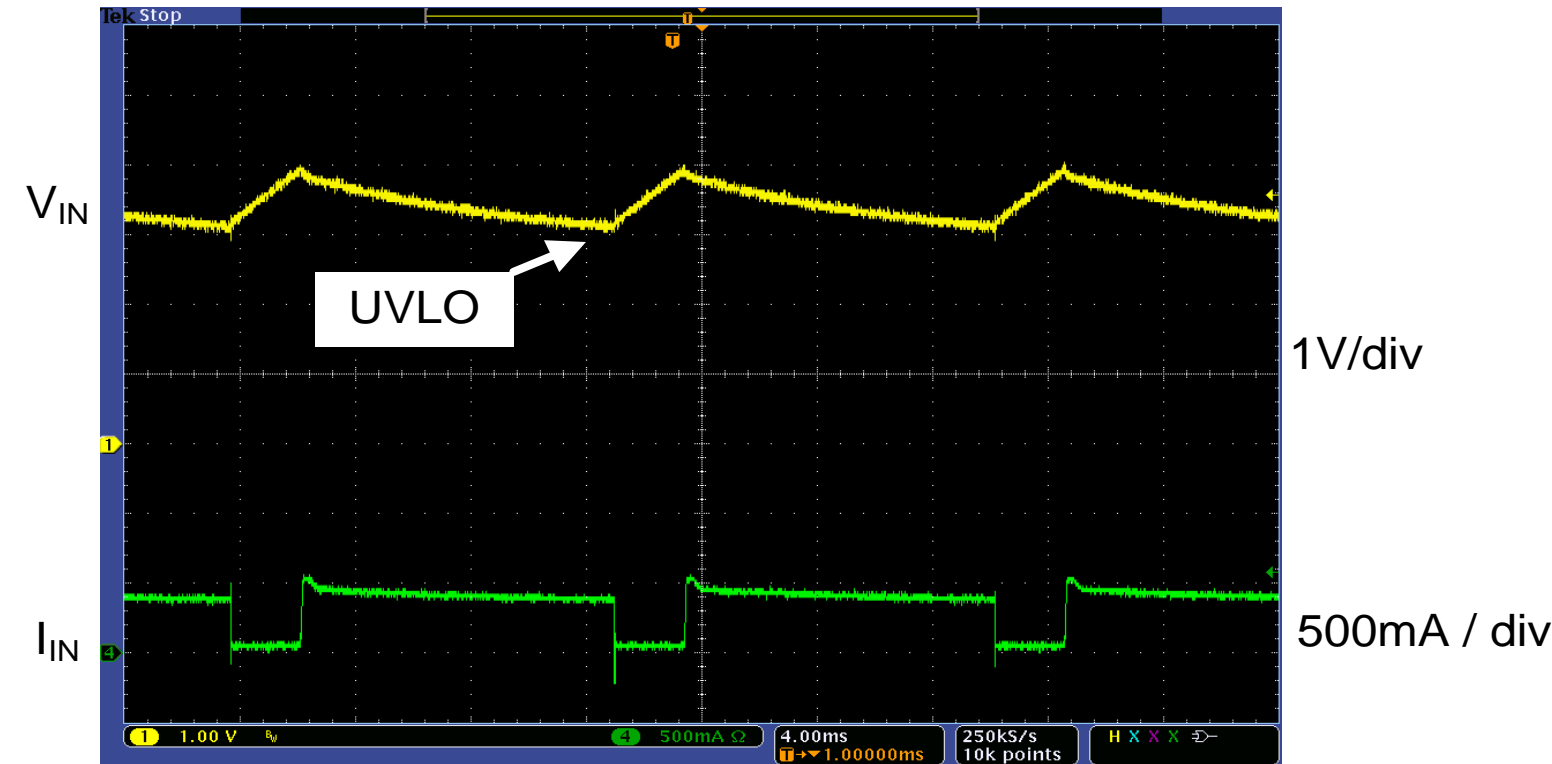
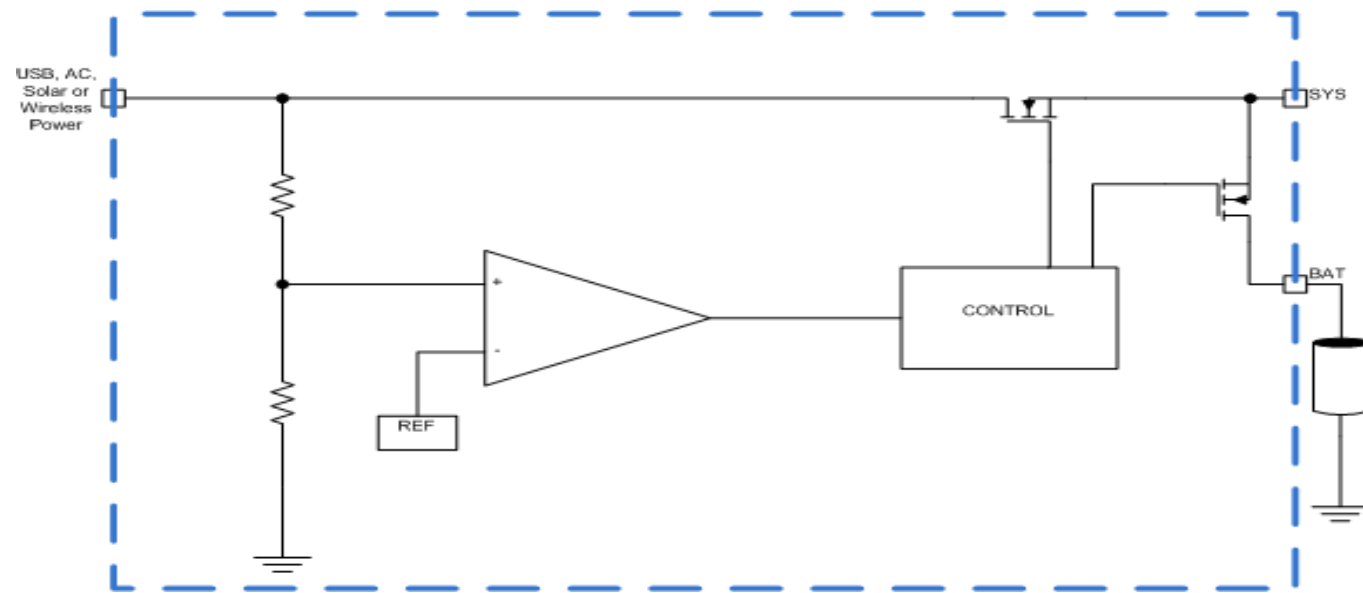


Current Capabilities of Adapters

- 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

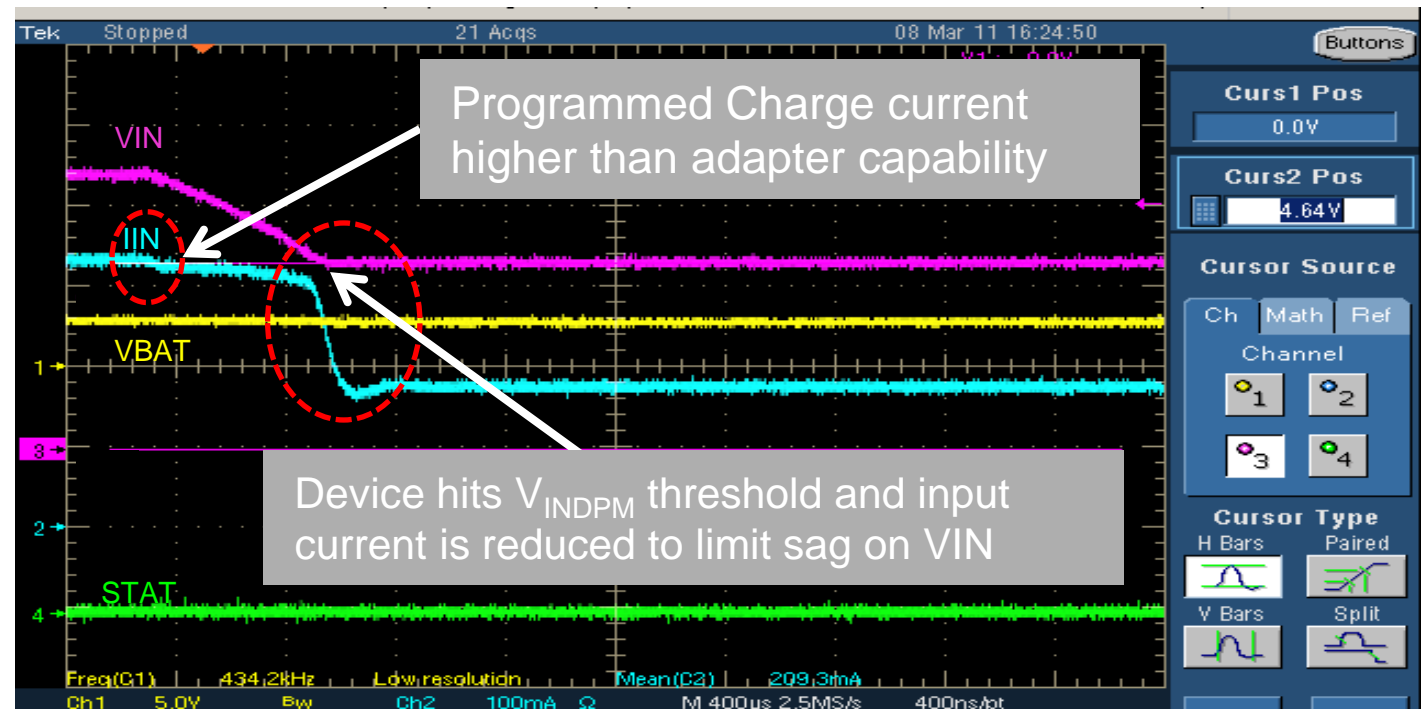
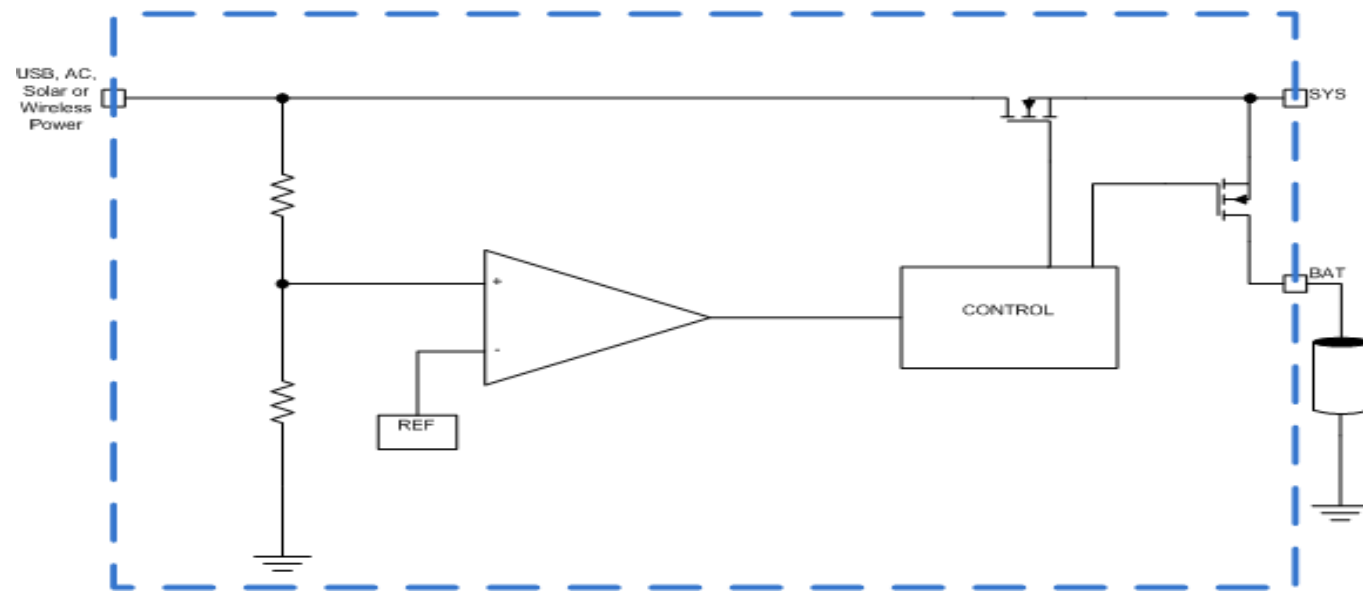
Voltage Input: Dynamic Power Management (V_{INDPM})

- 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)

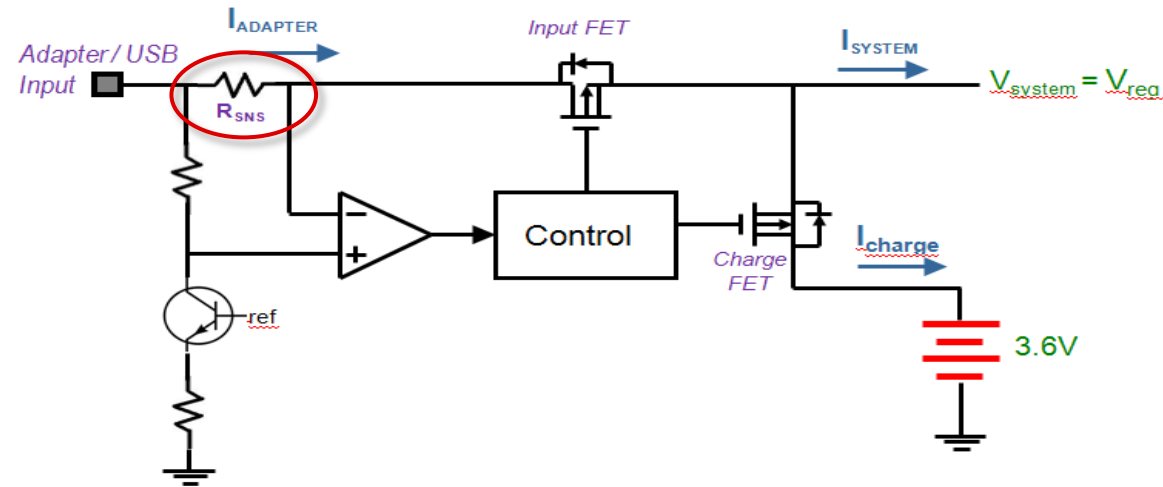


V_{INDPM} Operation

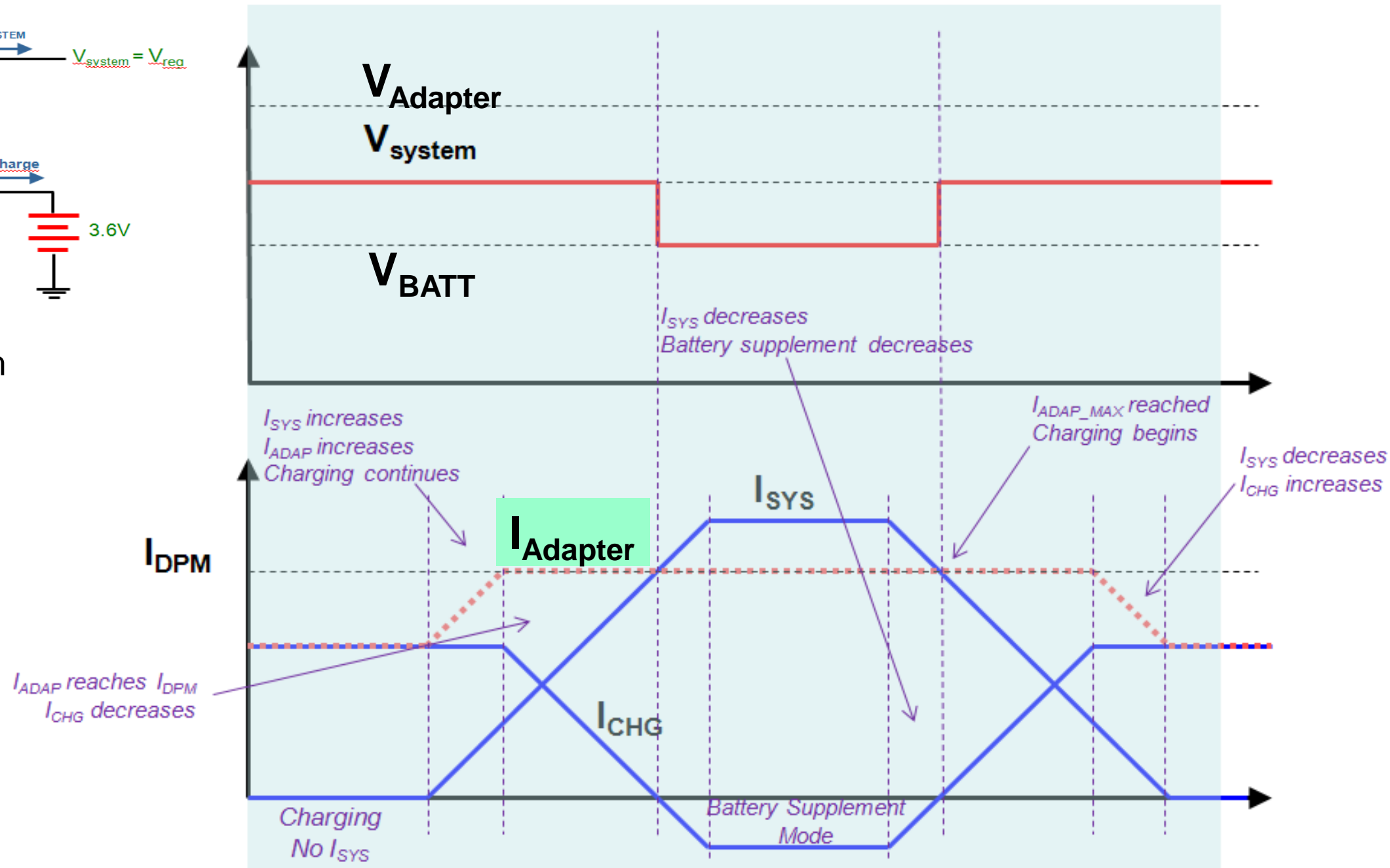
- Choose thresholds such that $V_{INDPM} > V_{BATT_MAX} > V_{UVLO}$
- For “most” adapter types, the adapter output voltage (V_{IN} to the charger IC) will start to sag as it is overloaded
- V_{INDPM} control loop will not allow the adapter voltage to sag below the chosen V_{INDPM} threshold
- When input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



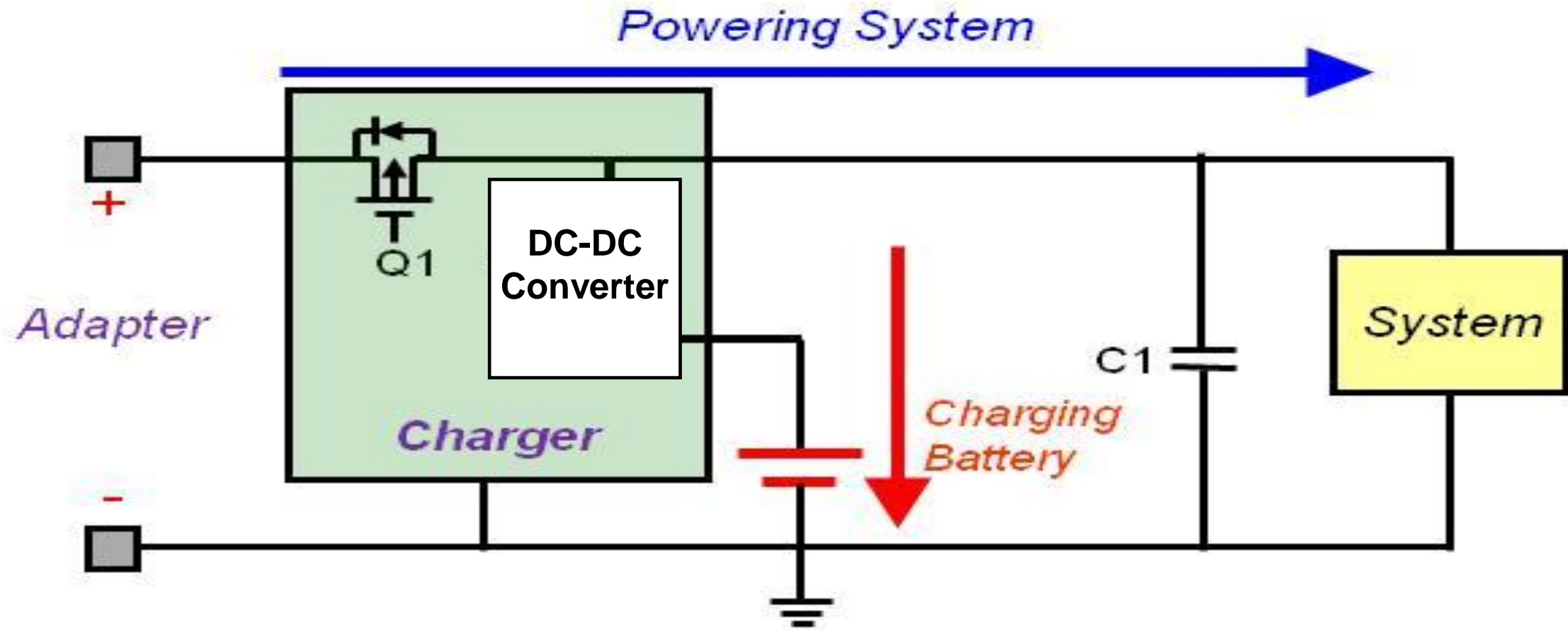
I_{IN_DPM} – Limits Input Current



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

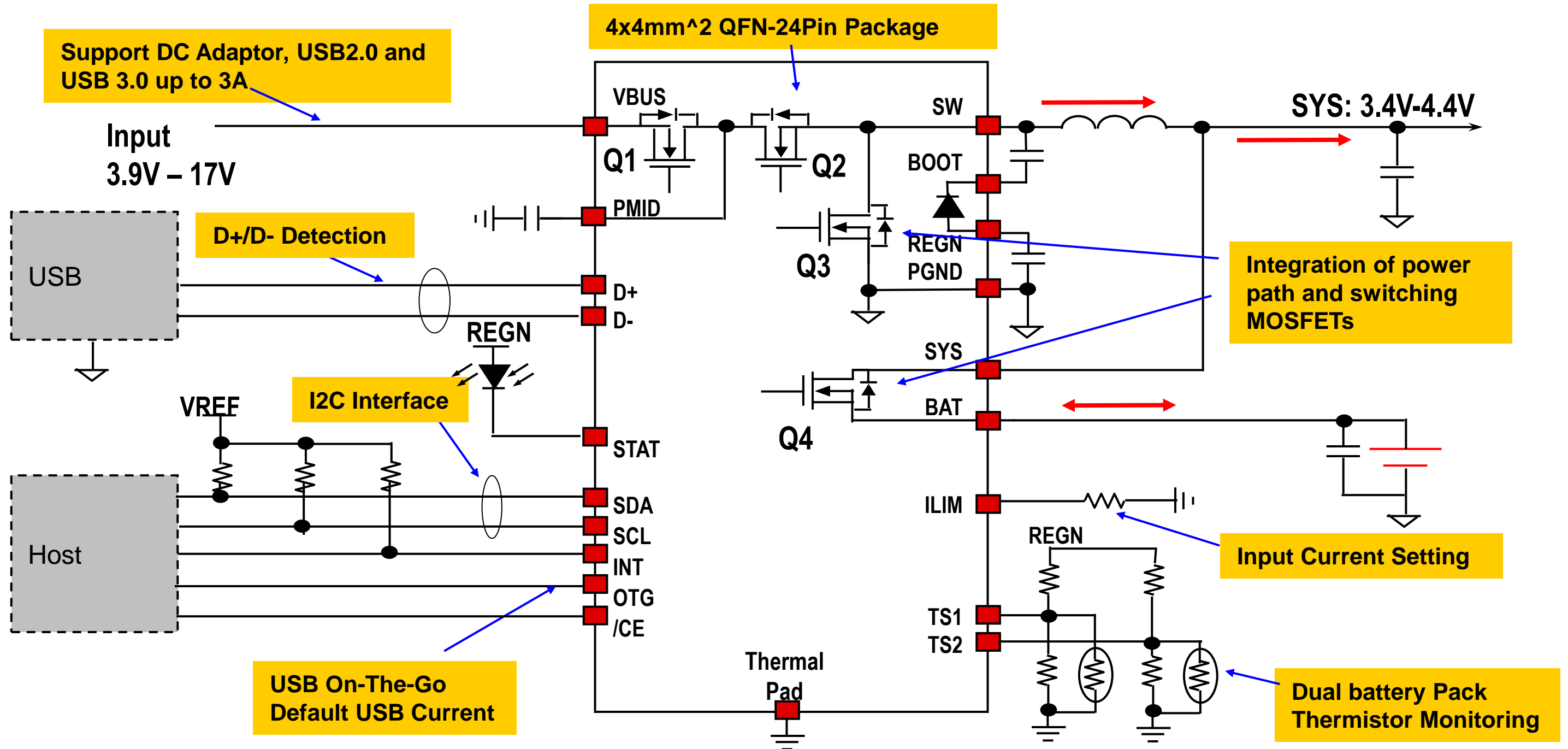


Traditional power path (switch-mode) charger



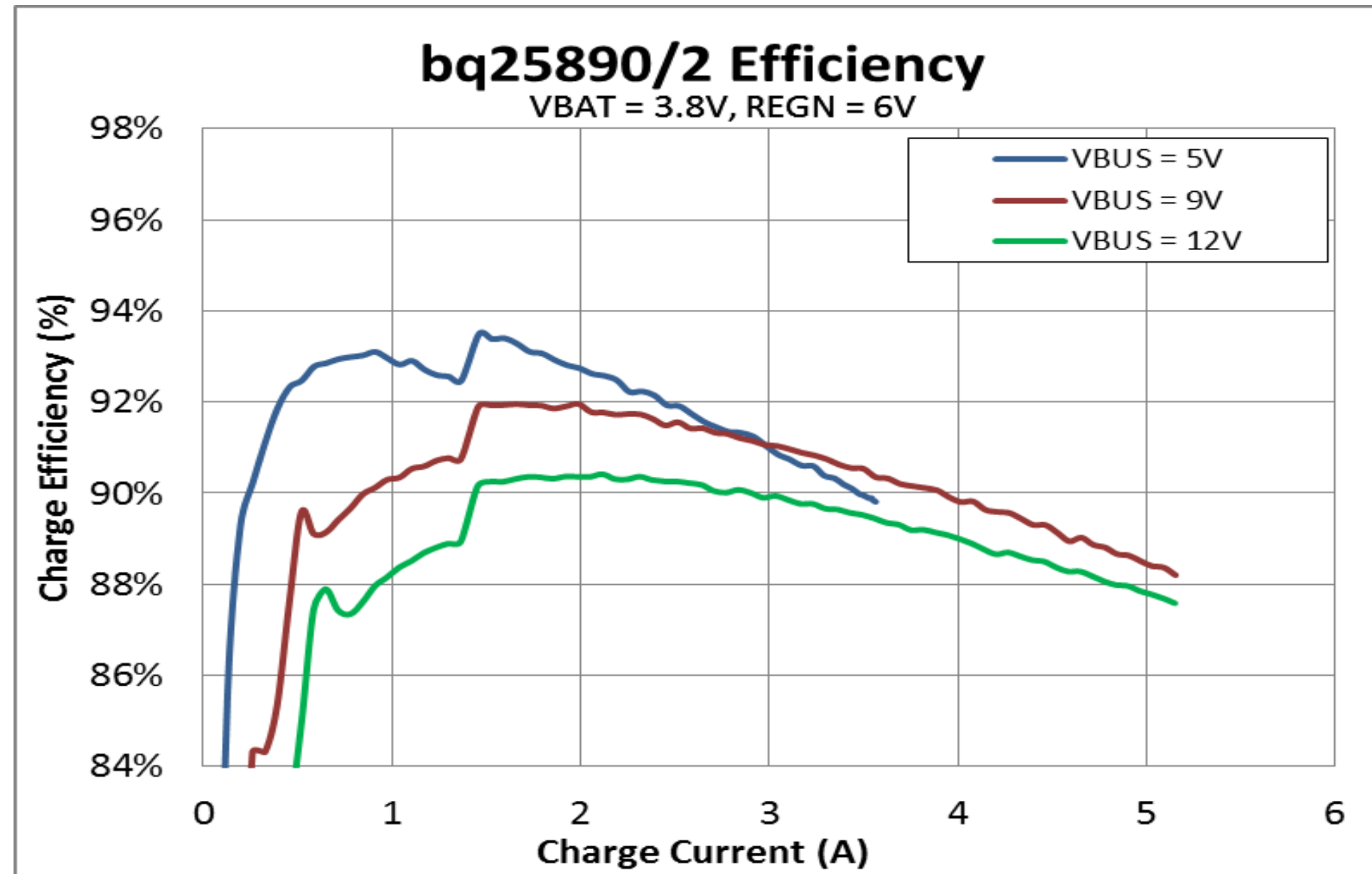
- When operating from adapter power source: system rail can go as high as max adapter voltage (5V, 9V, etc.)
- When operating from battery, system voltage can go as low as minimum battery voltage – RDS drop (e.g. < 3V)
- Wide swing on system rail especially if higher voltage input source is used (often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

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

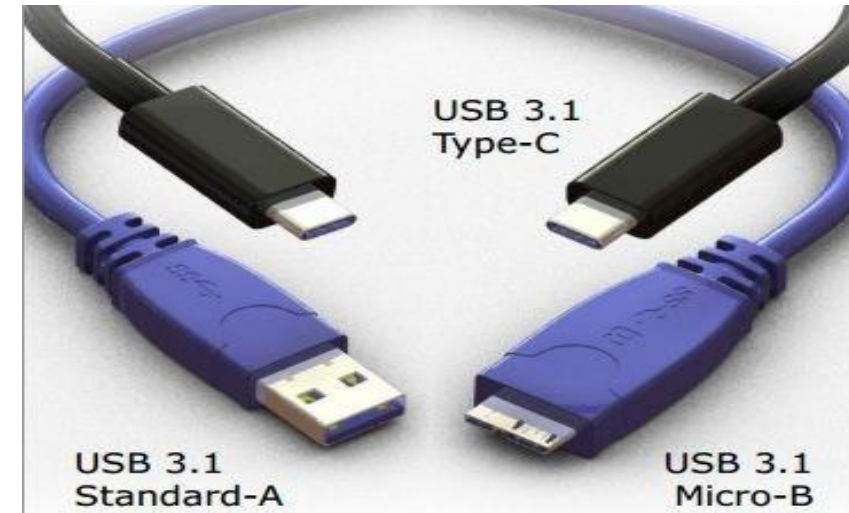


High Efficiency / Low R_{DS_ON} is essential

- 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)



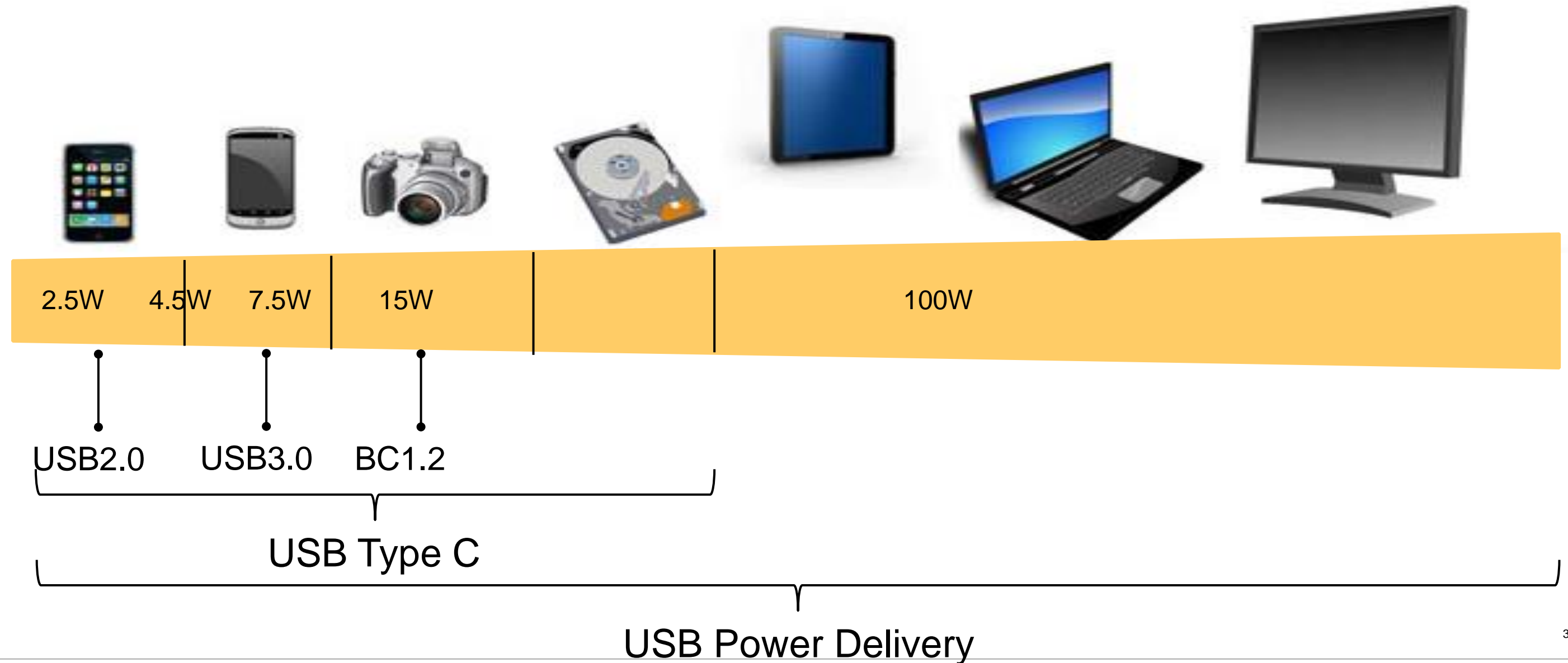
USB Type C Connector



- 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.

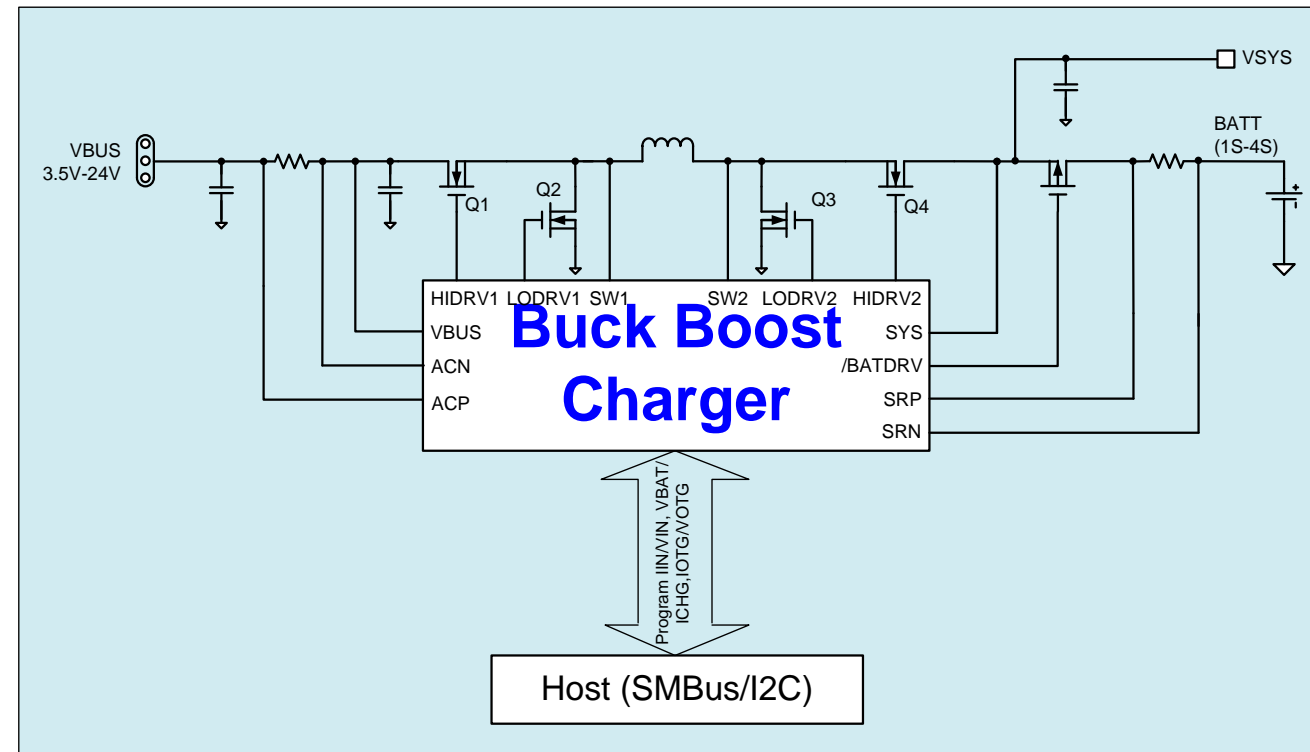
USB Power Delivery Device Spectrum

- 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.

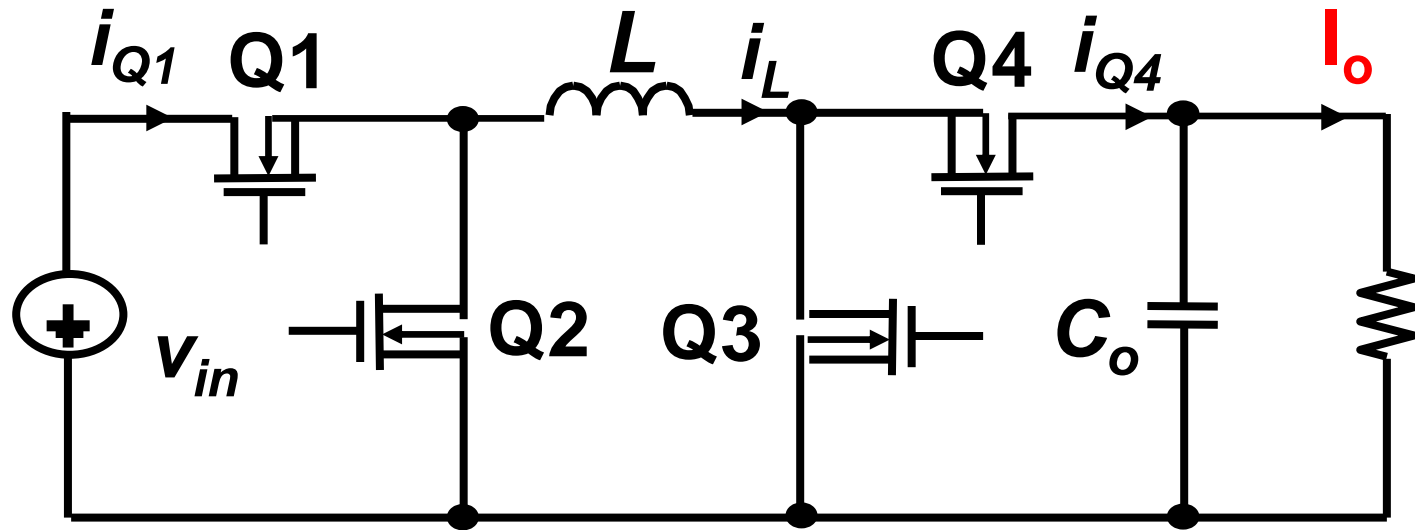


Universal Charging

- 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

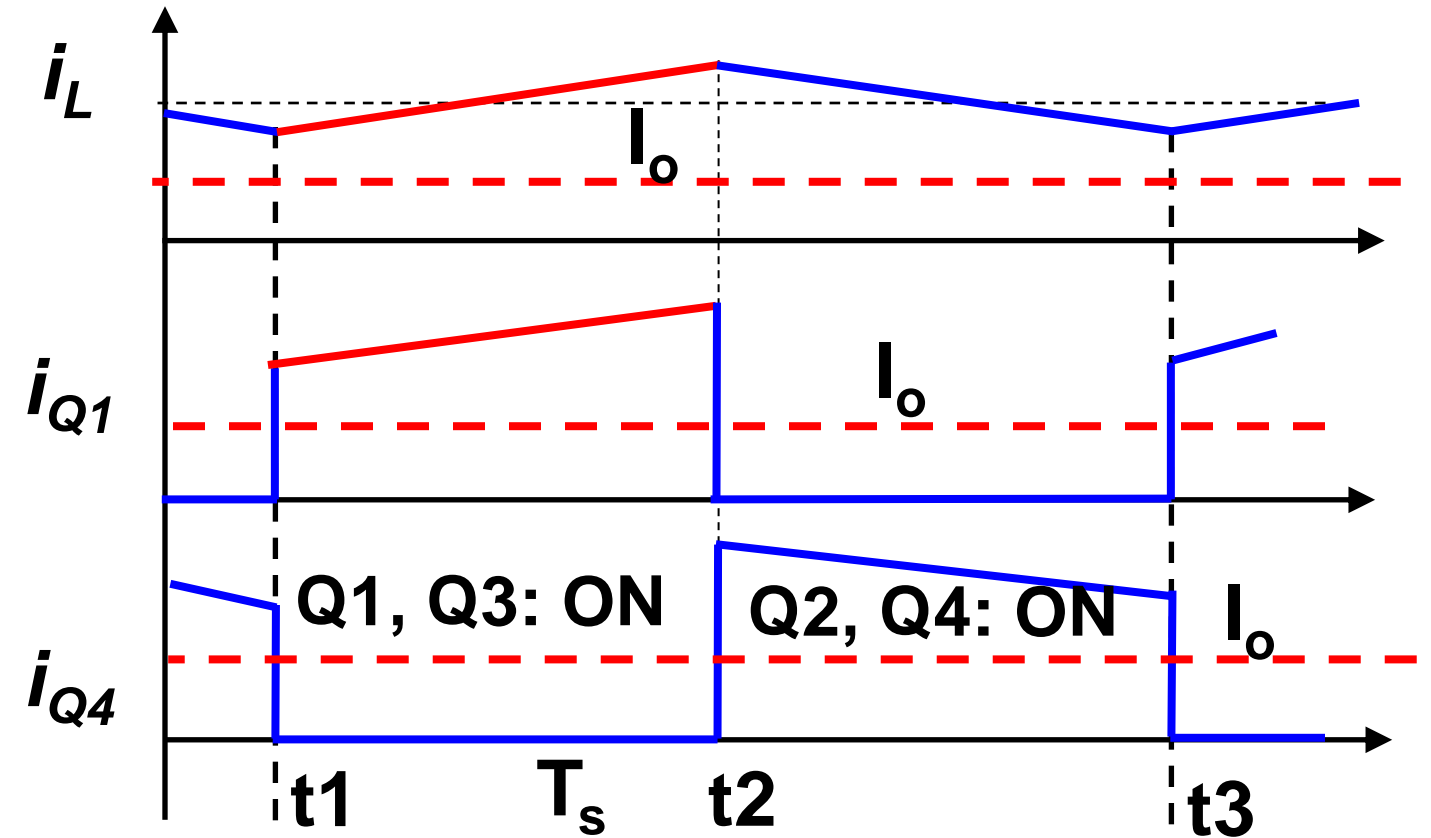


Issues with Classical Buck-Boost Converter



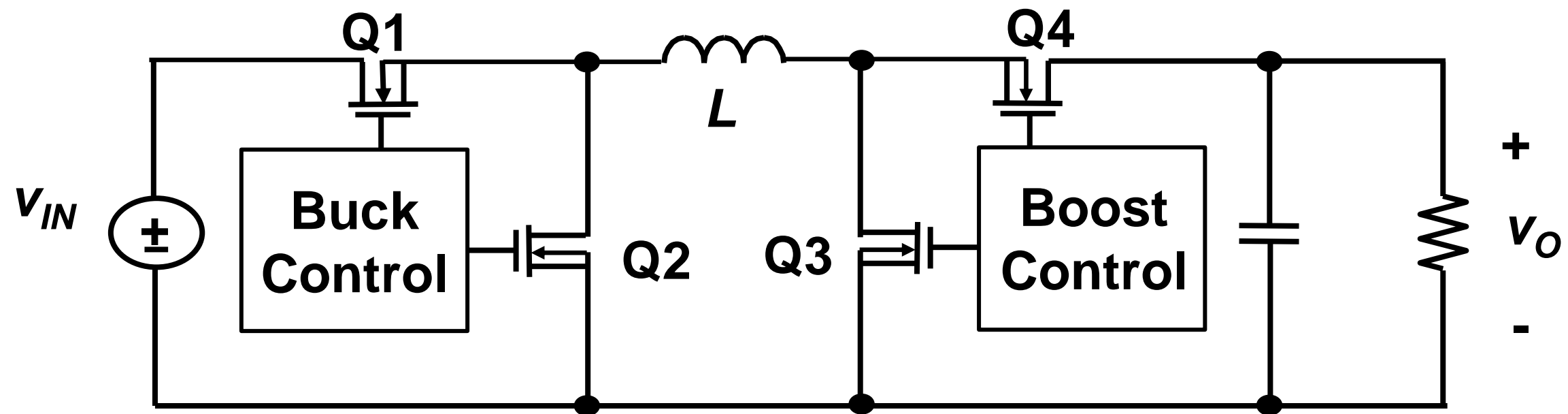
$$\text{Average Inductor Current} = \frac{I_o}{1-D}$$

- ✓ 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

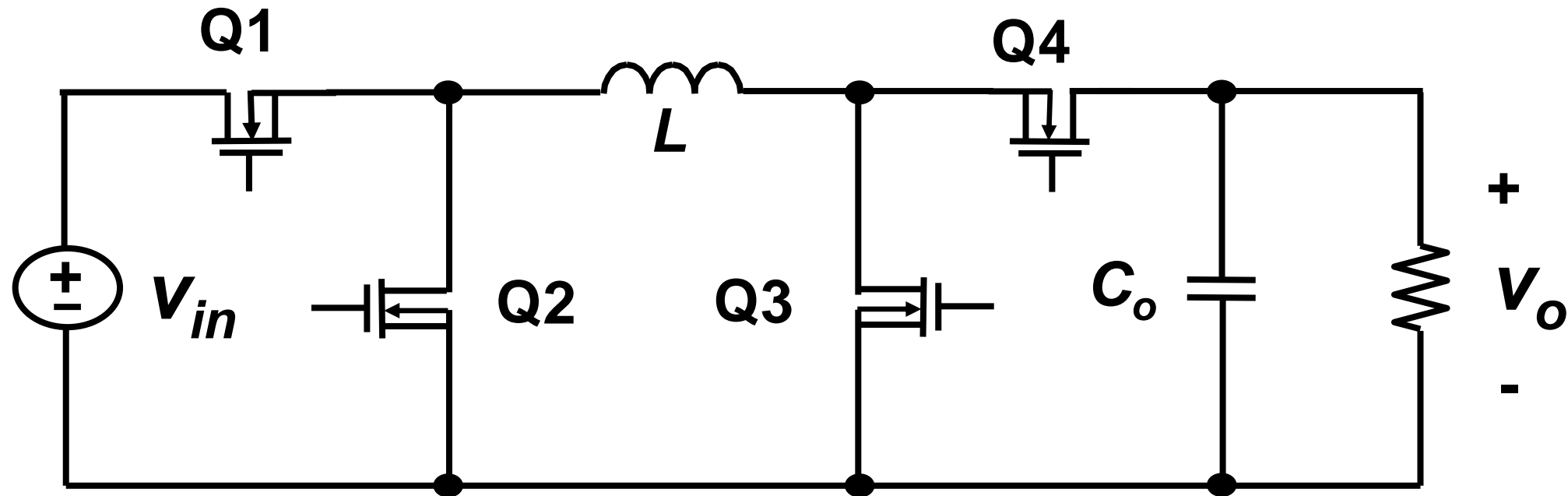


TI Proposed Buck-Boost Converter

- 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.



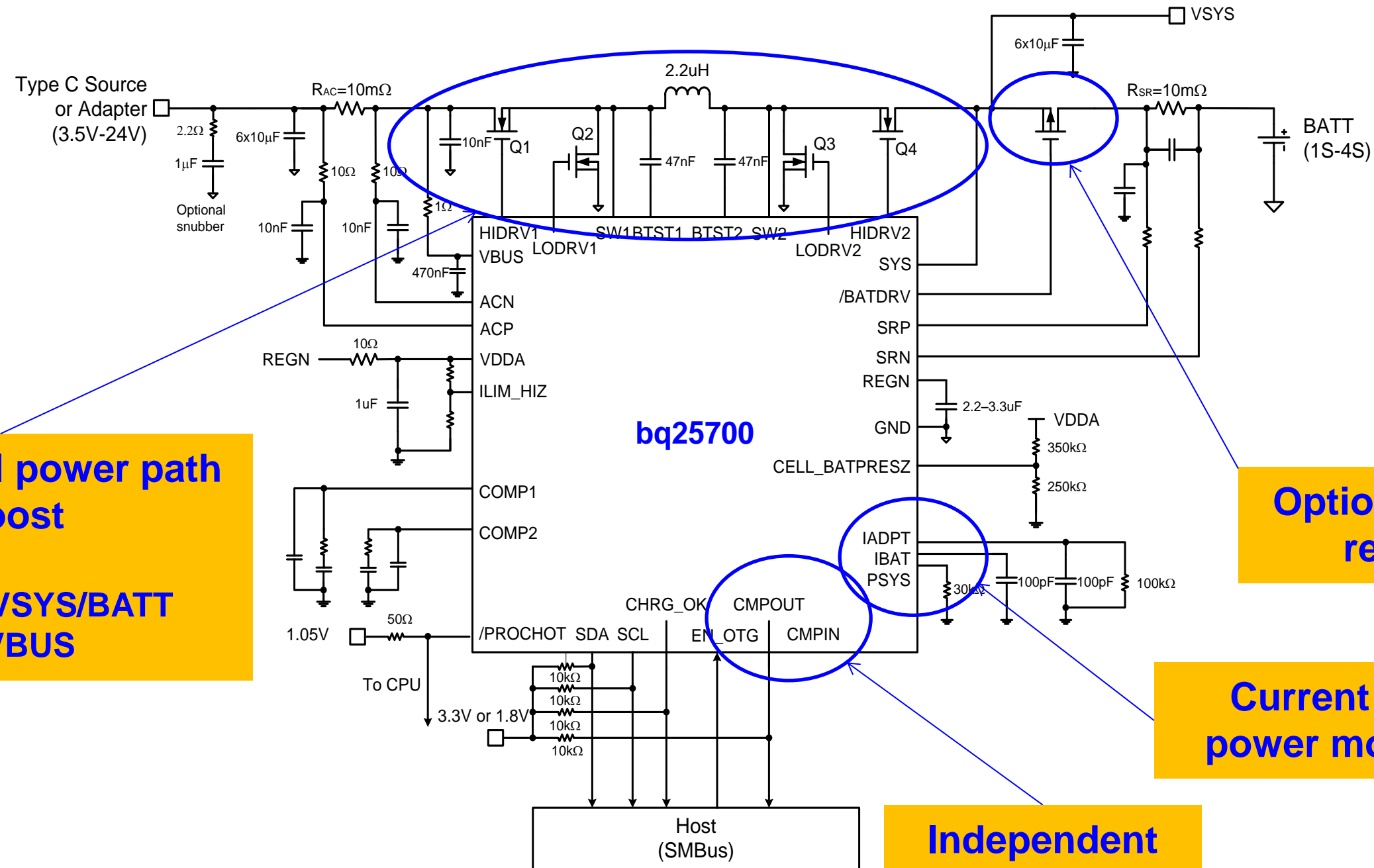
TI Proposed Buck-Boost Converter Control Method



	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

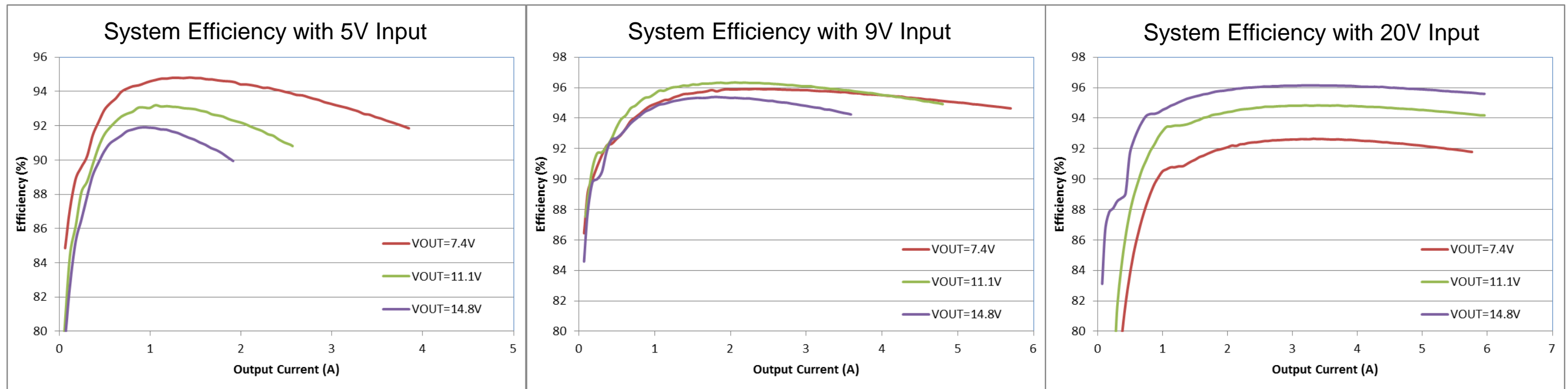
Optional, can be removed

Current and power monitor

Independent Comparator

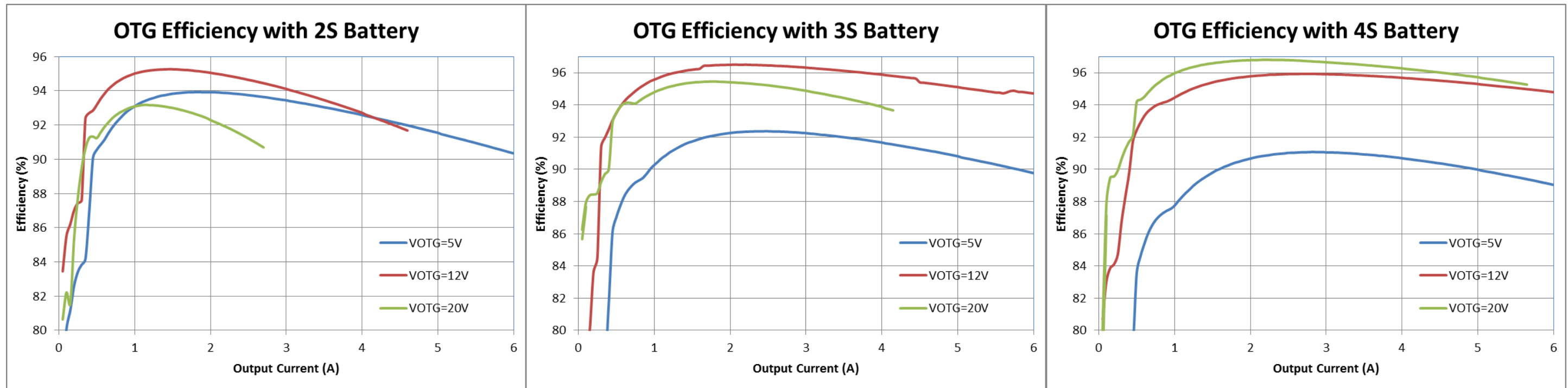
Forward Charging Efficiency

- Measured on EVM
 - Switching FET CSD17551
 - Inductor 2.2 μ H (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



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