The POWER Behind Your Designs

Battery Management Electronics

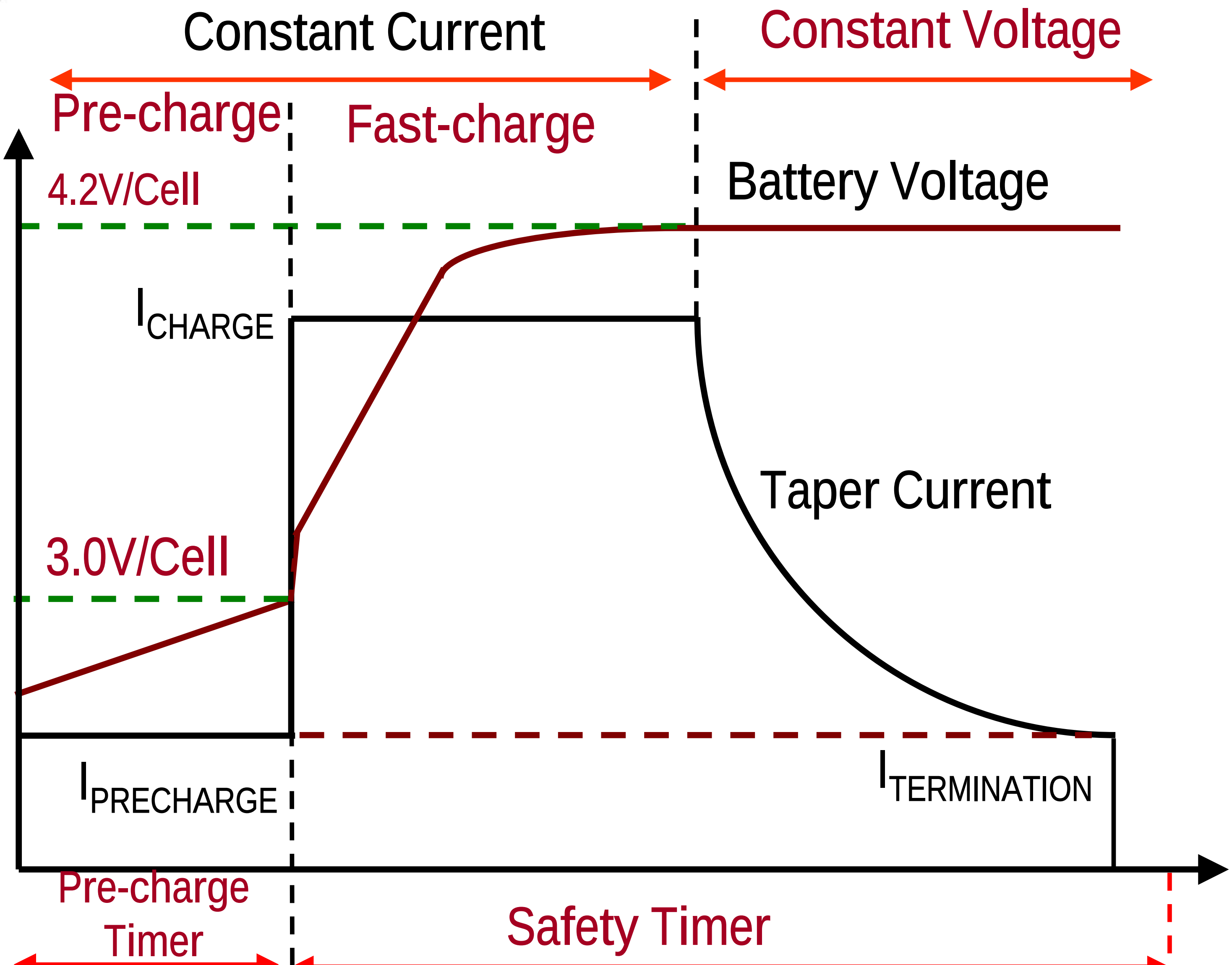
Battery Management Electronics Topics

- System-level issues with charge control circuits
  - Power Path control issues
  - Charging a battery during operation of a device
  - Thermal Regulation
  - Dynamic Power Path Management
- Linear vs. Switch-mode charger implementation examples
  - Power loss / efficiency
  - EMI considerations
- Battery Capacity Monitoring
  - Requirements for fuel-gauging solution
  - Overview of existing fuel-gauging solutions and their problems
  - How Impedance Track Technology works to address these issues

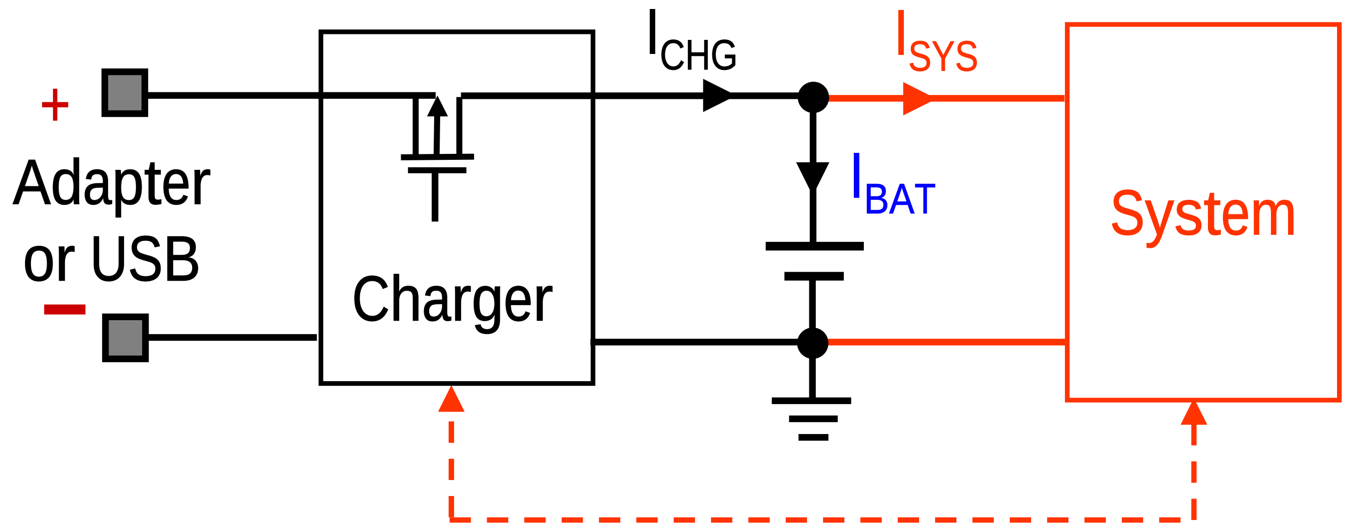
Section I

System-level issues with portable charger implementations

Li-Ion Charge CC-CV Profile



Charging with an Active System Load



I_{CHG}: Charger Output Current
I_{BAT}: Current going into the battery
(Effective charge current)

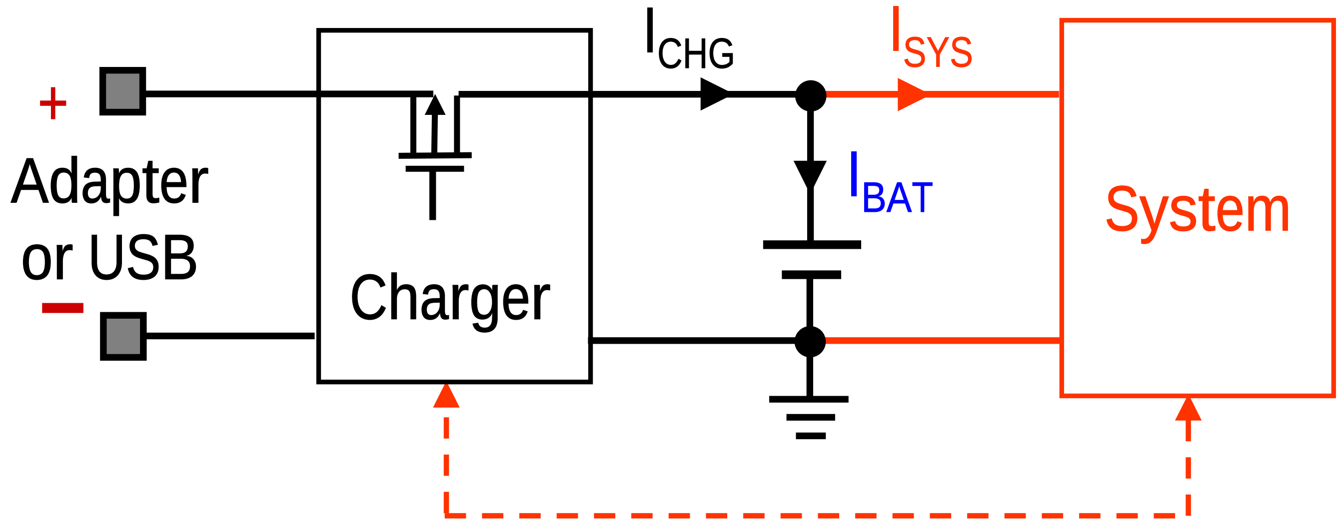
I_{SYS}: System load current

If charger is ON :

with no system load: ICHG = IBAT

with a system load, ICHG = IBAT + ISYS

Charging with an Active System Load: Potential Issues

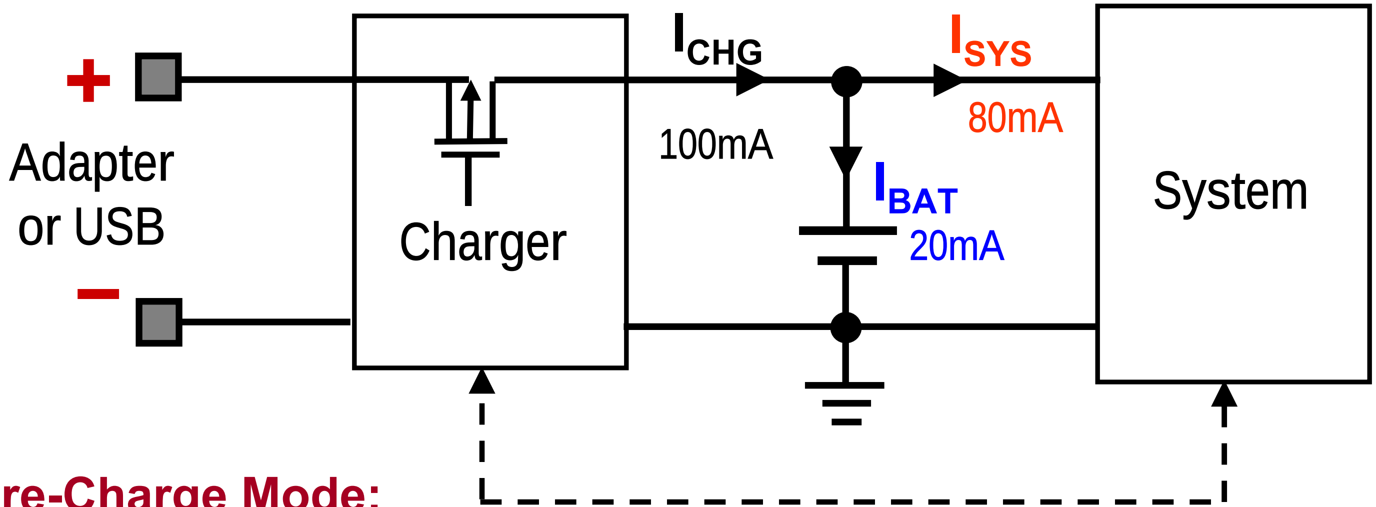


Charger output current is shared: $I_{CHG} = I_{BAT} + I_{SYS}$

Potential Issues:

- Timer fault
- No termination
- System lockup during startup

Issue 1: Pre-Charge Timer Fault



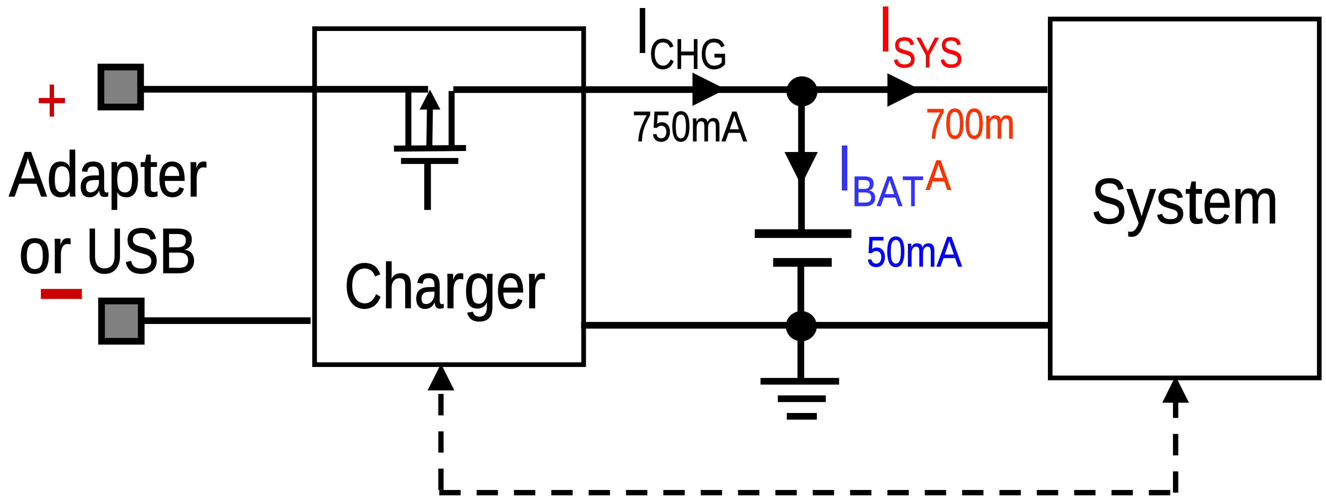
When in Pre-Charge Mode:

1. **Charger output current is limited to pre-charge current**
2. **System current "steals" charger output current**
3. **Battery is charged at a very low rate !**

- **Pre-charge timer may expire, turning off the charger**

Solution: Keep the system off or in a low-power mode during pre-charge phase !

Issue 2: Safety Timer Fault



When in Fast Charge Mode:

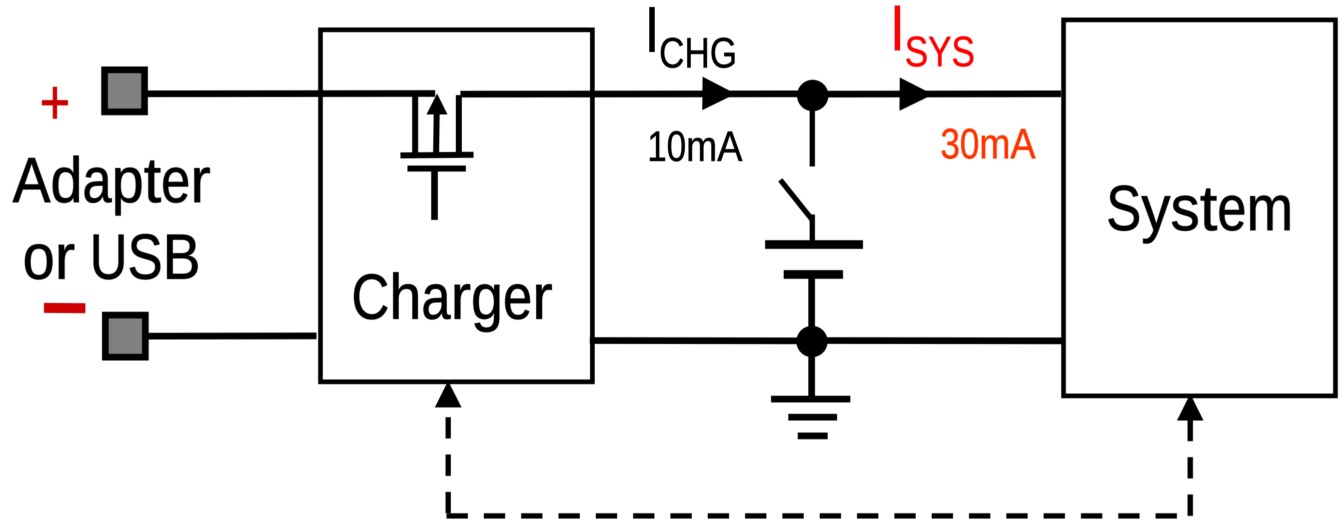
1. **Charger output current is limited to fast charge current**
2. **System current "steals" charger output current**
3. **Battery is charged at a lower rate !**

➢ **Charge safety timer may expire, turning off the charger**

Solution:

- **Increase the safety timer timeout value**
- **Increase the fast charge current value**

Issue 3: System Lockup During Initial Power-Up



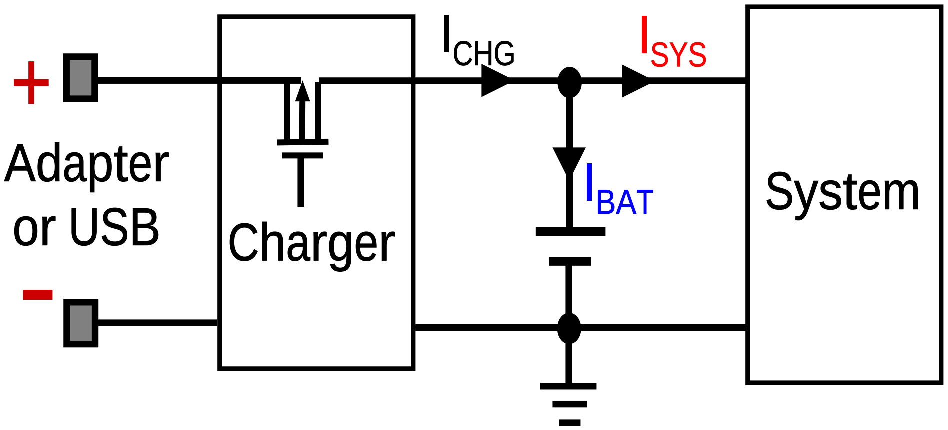
With a battery deeply depleted or no battery connected:

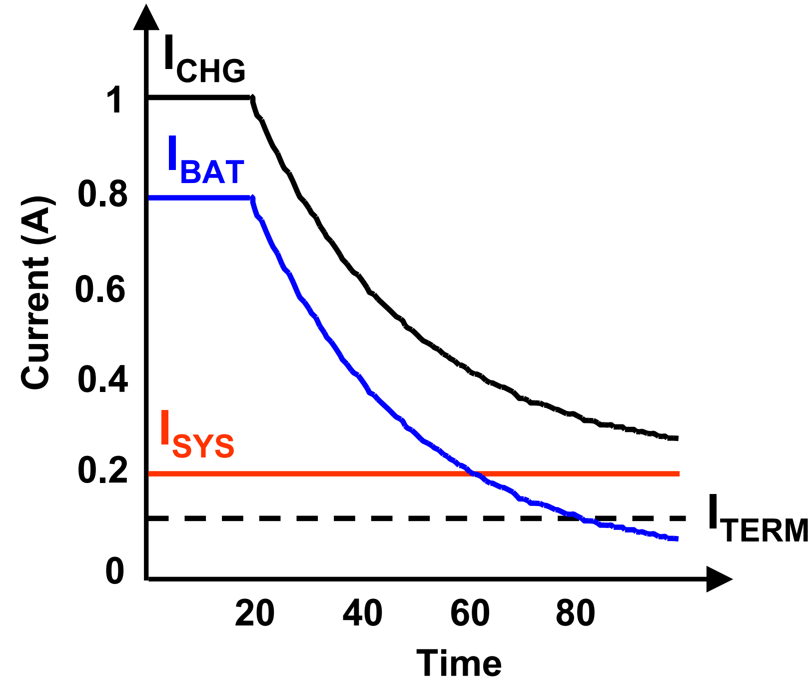
1. **System voltage is initially at zero volts (pack open or no battery)**
2. **Charger circuit detects a battery "short" and limits charge current**
3. **System current needed for power-up exceeds available charge current**
4. **System voltage stuck at very low value …..**

➢ **System never starts**

Solution: **Reduce system start-up current**

Issue 4: Charge Termination NOT Detected





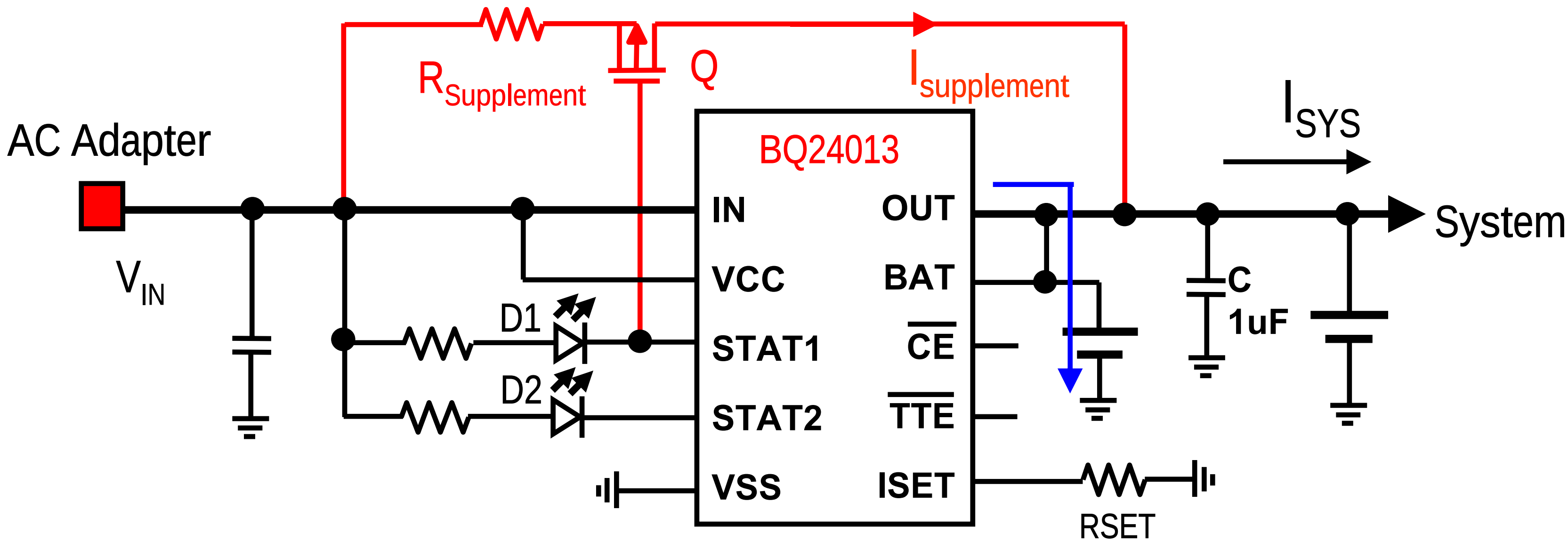
With the charger in regulation mode :

1. Charge current will taper down
2. System current exceeds termination threshold
3. Charger regulates system rail at charge voltage, $I_{CHG} > I_{TERM}$
   - ➢ Termination is not detected
   - ➢ Charger safety timer fault

Solution:

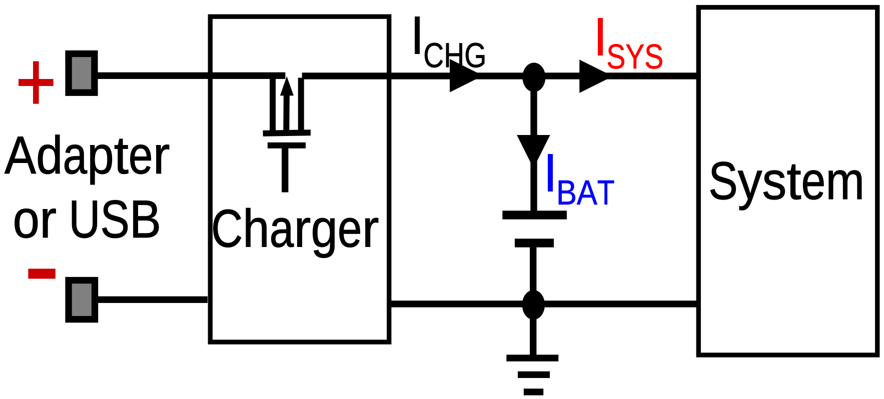
Disable safety timer or supply additional current to the system

Supplying Additional Current to System

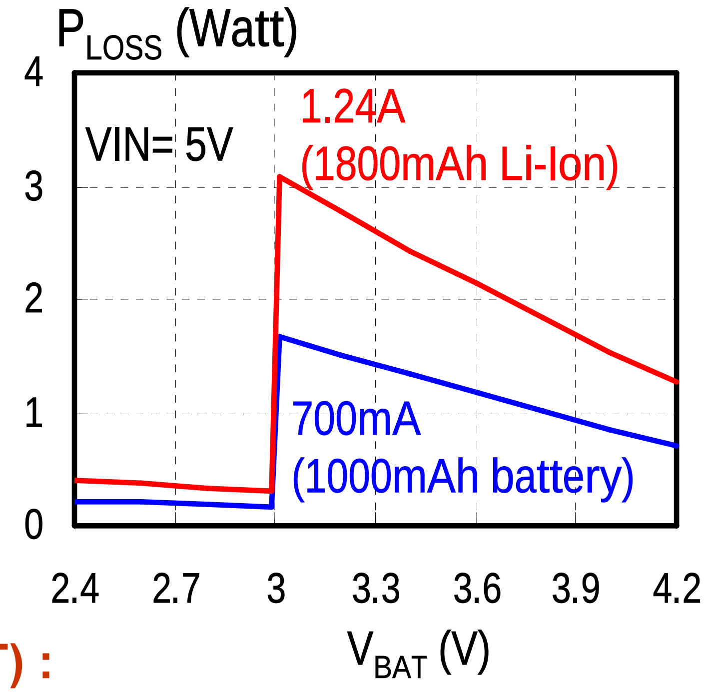


- A new circuit supplies the system load current **directly** from the input source during voltage regulation ; $I_{CHG} \approx I_{BAT}$
- When charging is terminated, the STAT1 pin goes high and disconnects the supplement circuit.
- Design Example: V_{IN} = 5V, V_{OUT} = 4.2V, I_{SYS} = 0.2A,
  Voltage drop across Rsupplement = 5 - 4.2 = 0.8V, Rsupplement = 0.8 / 0.2 = 4 Ω

Thermal Analysis of the Charger Stage



$$P_{LOSS} = (V_{IN} - V_{BAT}) \cdot I_{CHG}$$



Under worst case conditions (high VIN, low BAT) :

Charger IC junction temperature is excessive:

Tj = 130^{0}C @700mA, Tj = 192C @1.24A, 50^{0}C ambient temperature

- **Potential oscillatory behavior if charger has thermal shutdown**
- **Charger IC damage if charger has no thermal shutdown**

Solution: Add thermal management to charger IC !

Thermal Management

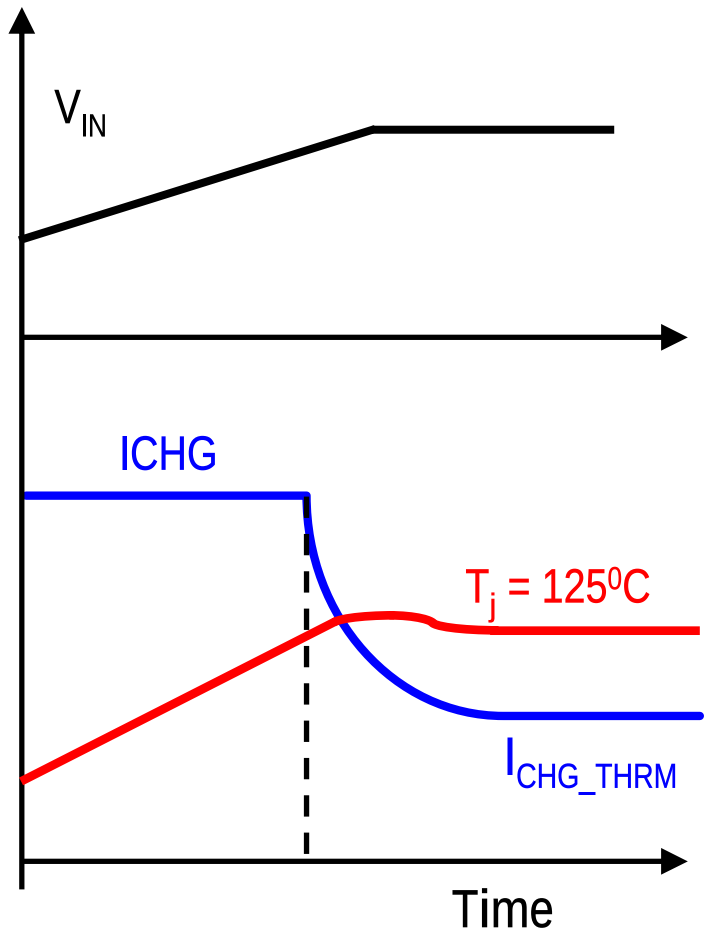
The POWER Behind Your Designs

Thermal management functions:

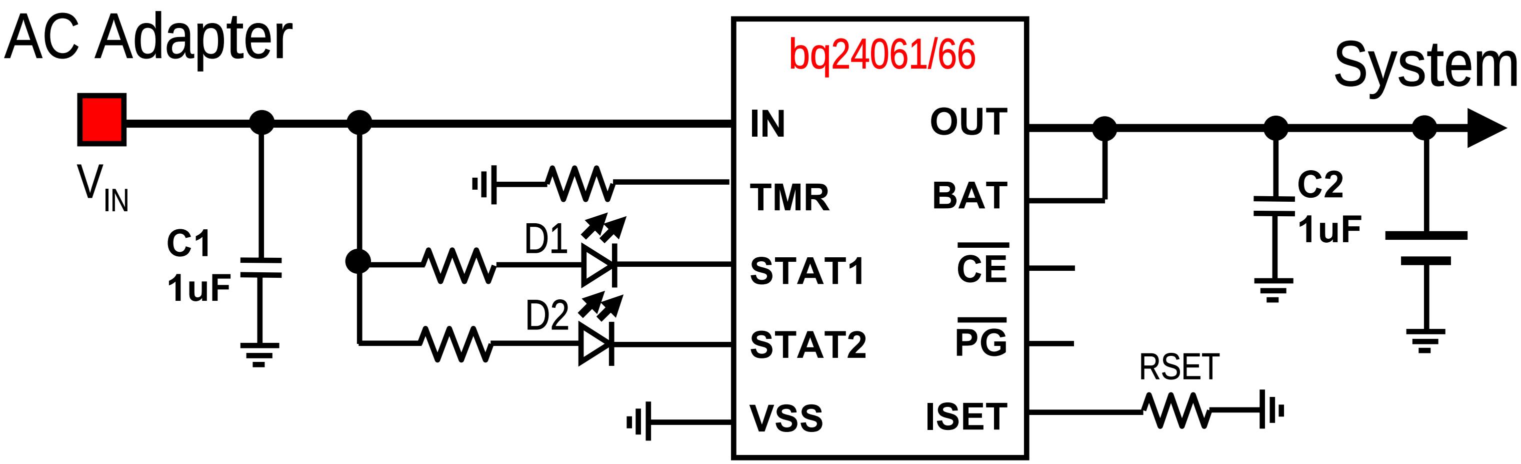
- Regulate IC junction temperature by reducing charge current , AND
- Turn off the charger when IC junction temperature
- is excessive
- Slows down the safety timers when the charge current is reduced by the thermal loop, avoiding a false safety timer fault

Common implementations:

- The IC junction temperature is regulated to a value just below the maximum operating junction temperature, 125⁰C typical
- The charger is turned off when the Charger IC
- junction temperature is excessive, 150⁰C typical

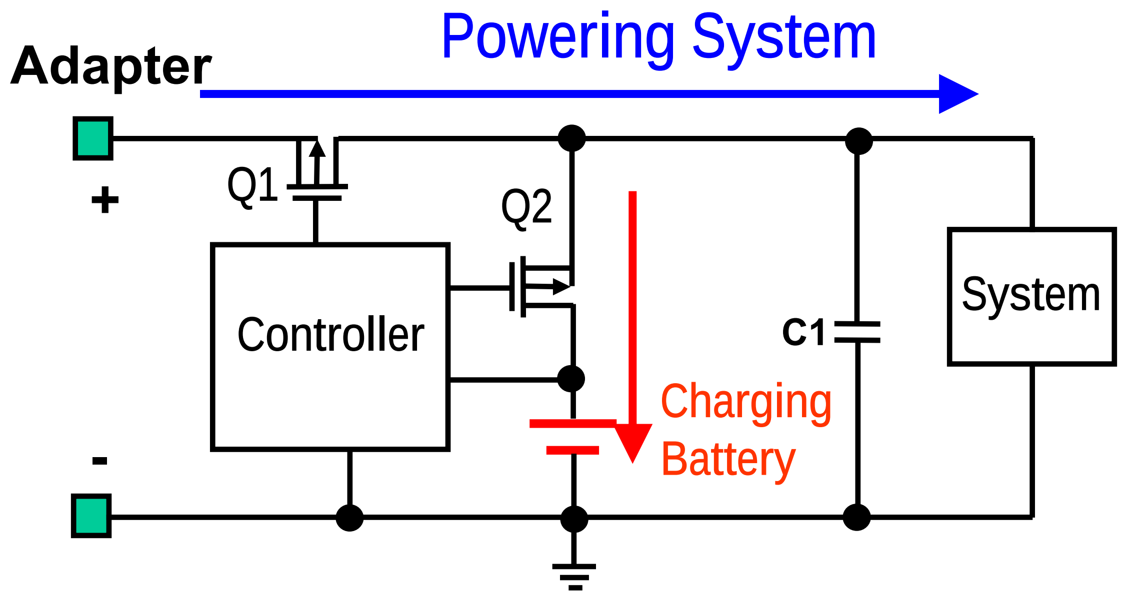


Battery Charger with Thermal Management



- Charger on/off control
- Programmable timer – can be disabled by leaving TMR pin floating
- Programmable charge current rate
- Charger status: pre-charge, fast charge and fault detected
- Integrated thermal loop
- Charge Safety timer adjusted dynamically when thermal loop is active
- Input over-voltage protection

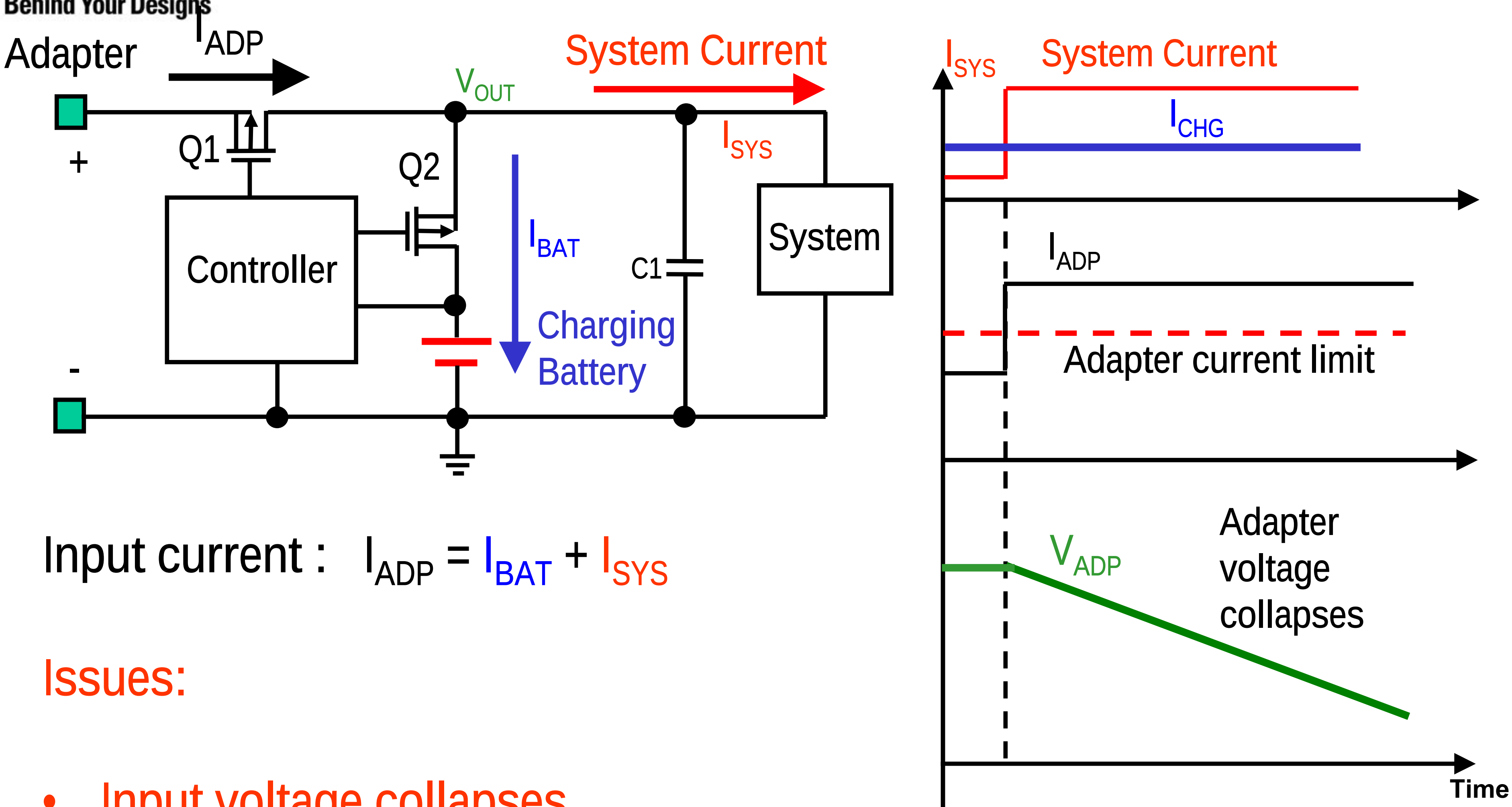
Adding Power Path Management to a System



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

The POWER Behind Your Designs

Power Path Management: Potential Issues

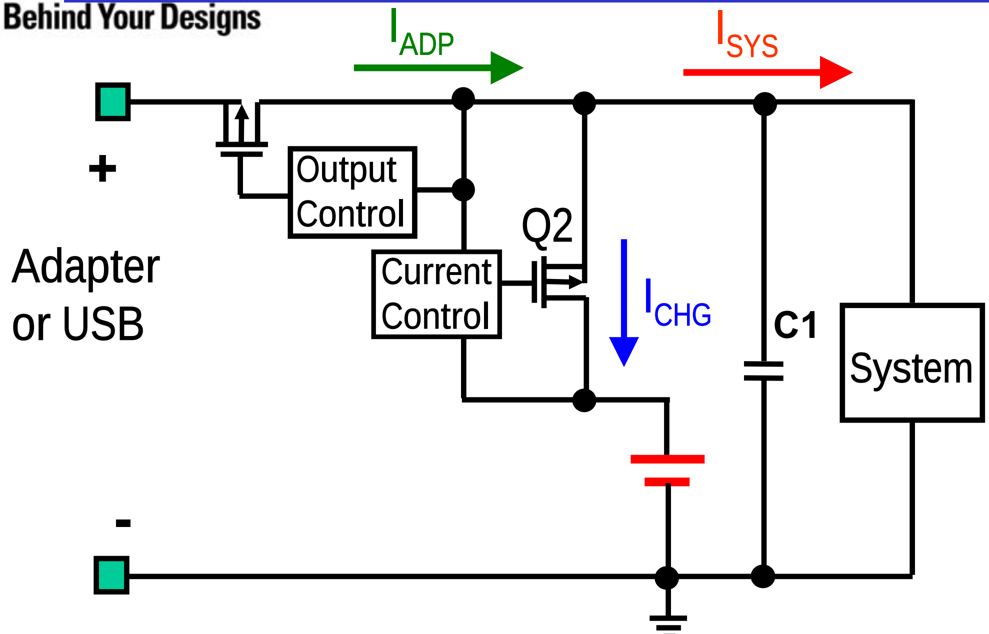


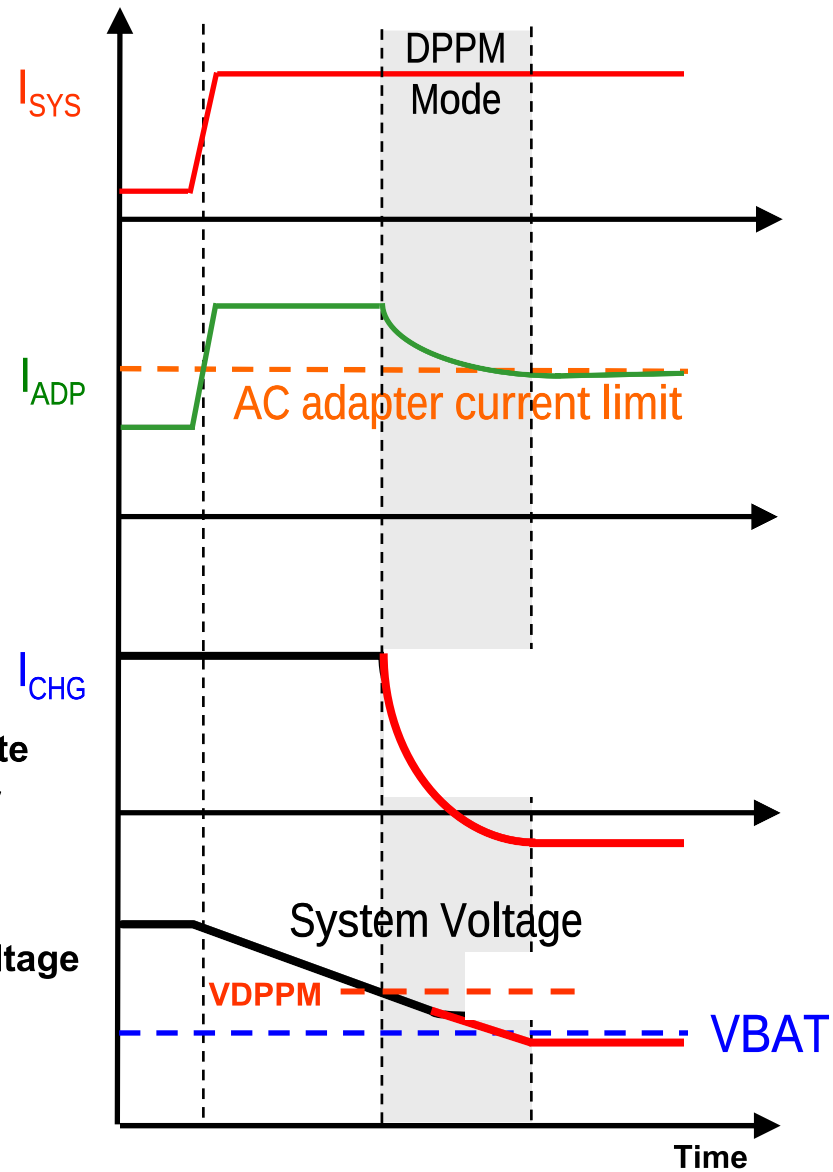
Input current : $I_{ADP} = I_{BAT} + I_{SYS}$

Issues:

- Input voltage collapses

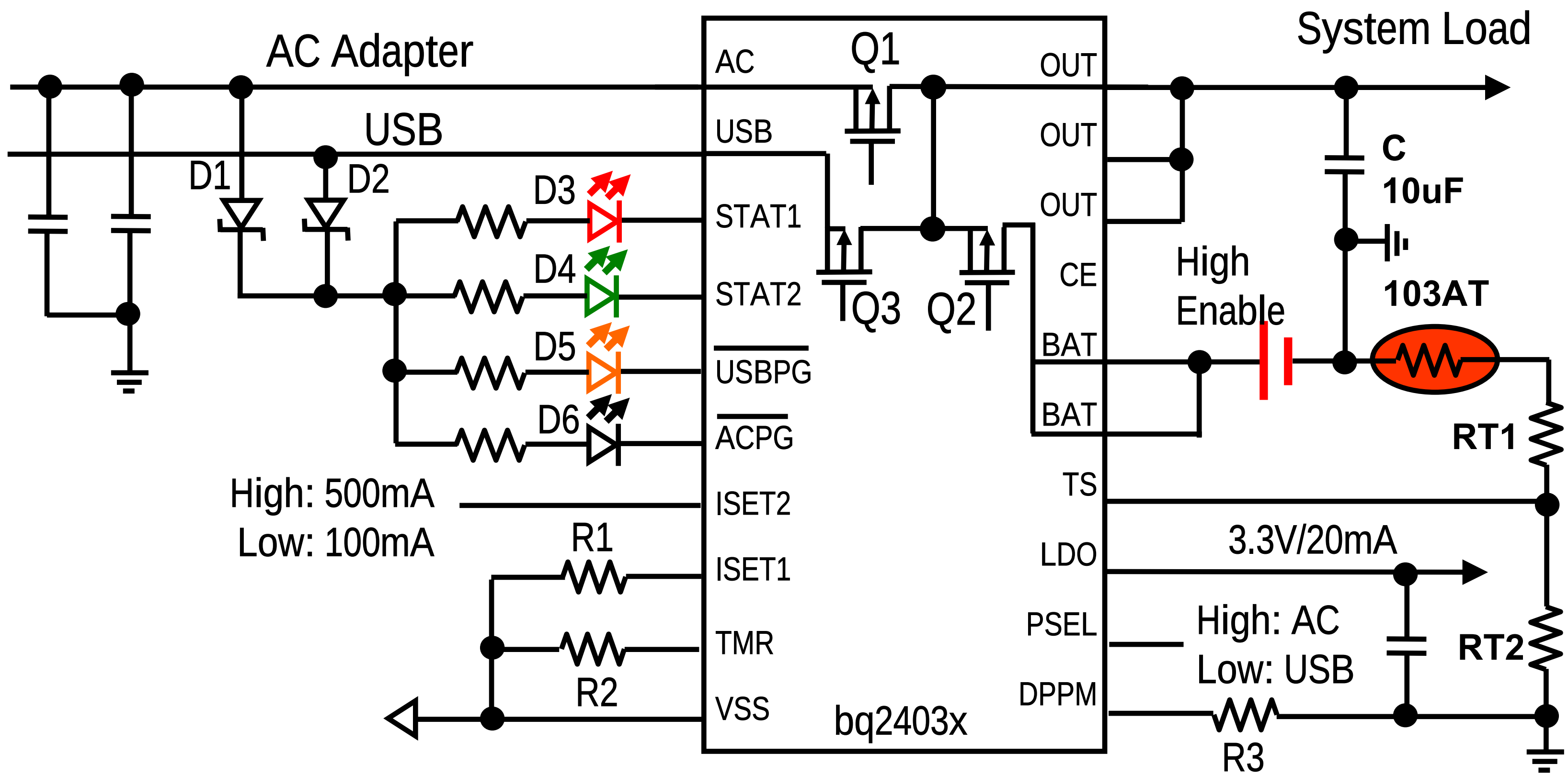
Dynamic Power Path Management (DPPM)





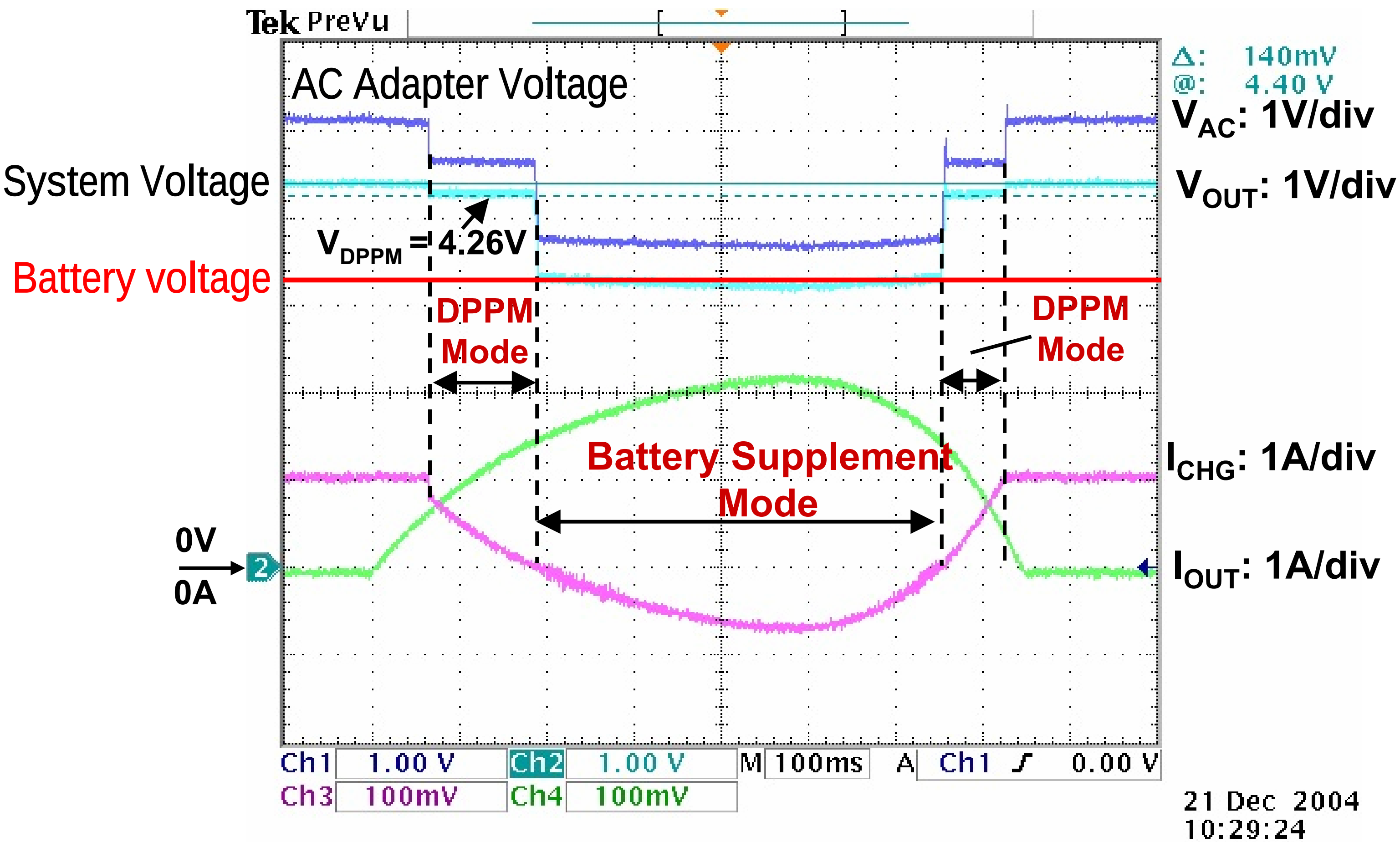
- **System voltage drops if $(I_{SYS} + I_{CHG}) > I_{AC\_LIMIT}$**
- **Large voltage drops due to system load pulses generate undesired ripple at system power rail, causing reset or degrading system performance**
- **DPPM function :**
  - **Reduces the charge current when the system voltage is below the user-defined Voltage threshold VDPPM**
  - **"Finds" maximum adapter power !!!**
- **Battery Supplement Mode**

Dynamic Power-Path Management Charger



- AC adapter or USB port can power the system and charge the battery simultaneously
- Dynamically reduces the charge rate to maximize adapter to system current
- Battery Supplement enables use of "weak" adapters
- Selectable charge current limits : USB 100/500mA, AC adapter up to 1.5A
- Battery Management features maximize battery capacity, cycle life and safety

bq24032A Test Results



Summary – Section 1

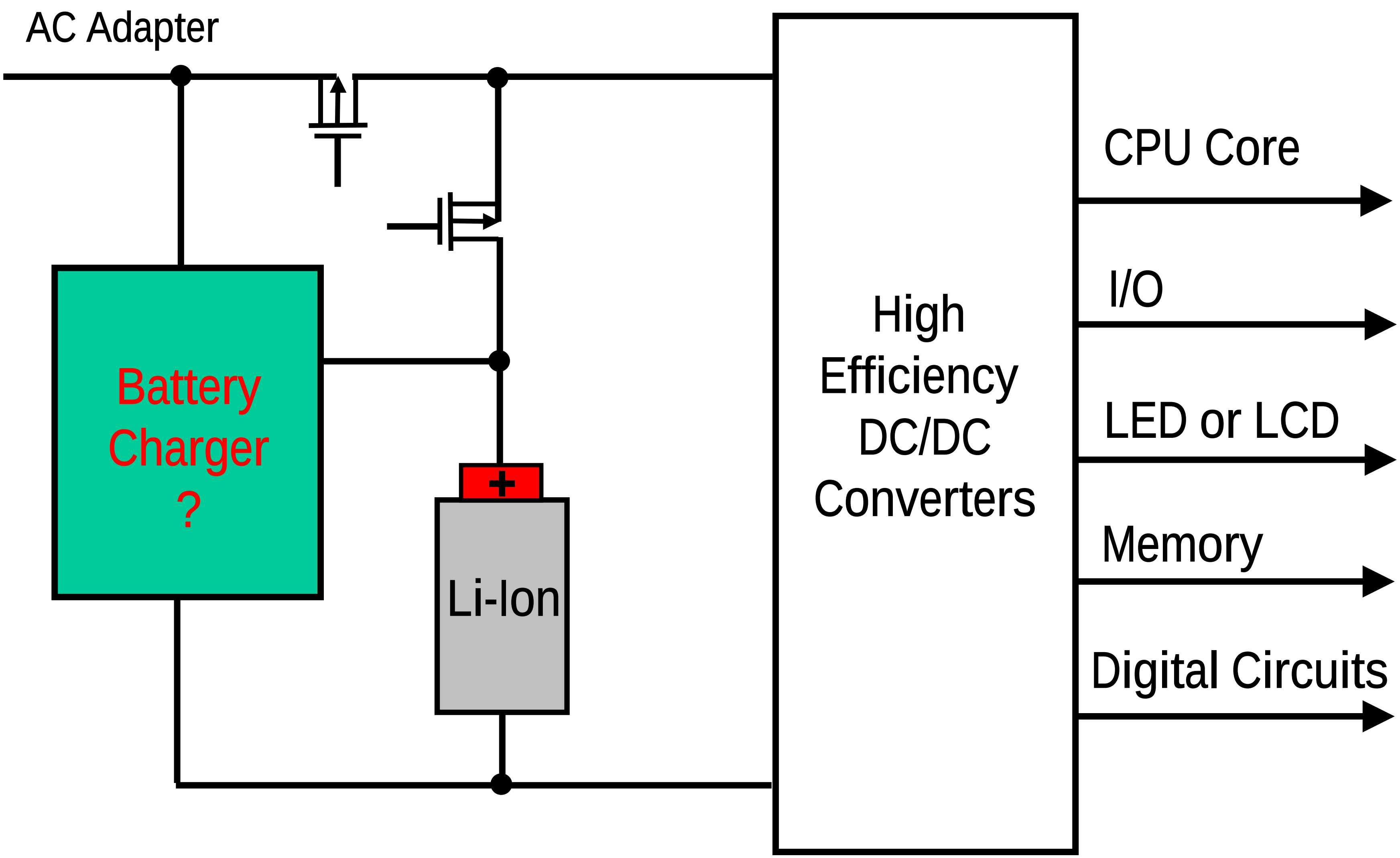
- Basic Configuration: system is directly connected to the battery
  - System rail interacts with battery charger
- Power Path: powers the system directly from the input
  - Eliminate charger-system rail interaction issues
- Dynamic Power Path Management and battery supplement mode
  - Prevent system issues during large system current load transients
  - Prevent battery MOSFET Body-diode conduction during large system current load transients
  - Enable use of low cost wall adapters
- Thermal management

Section II: Switch-Mode Charger Issues

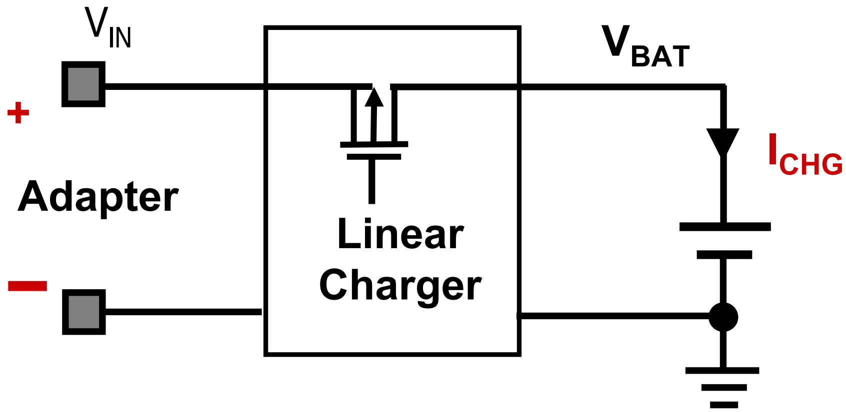
Switch-Mode vs. Linear Charger Implementation

- Linear Battery Charger Challenges
- Why Switching Charger?
- EMI Analysis
- Loss Calculation and Analysis
- Switching Charger Example and Measurement Results
- Summary

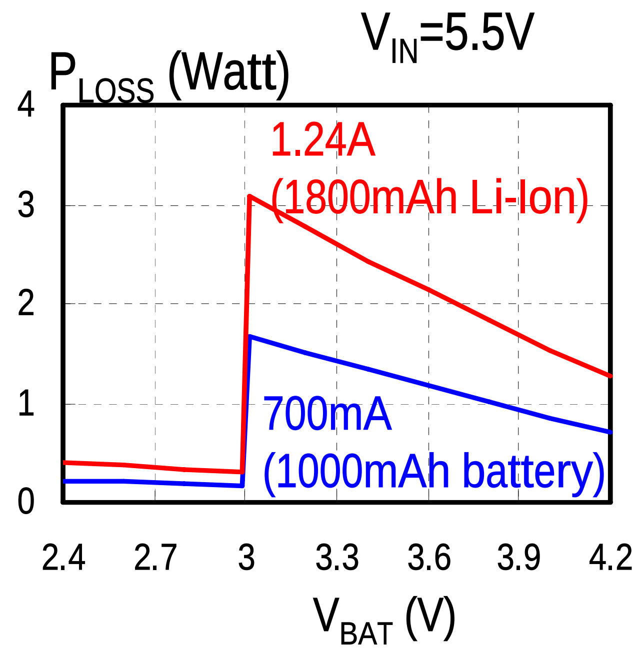
Typical Battery Operated System



Linear Battery Charger



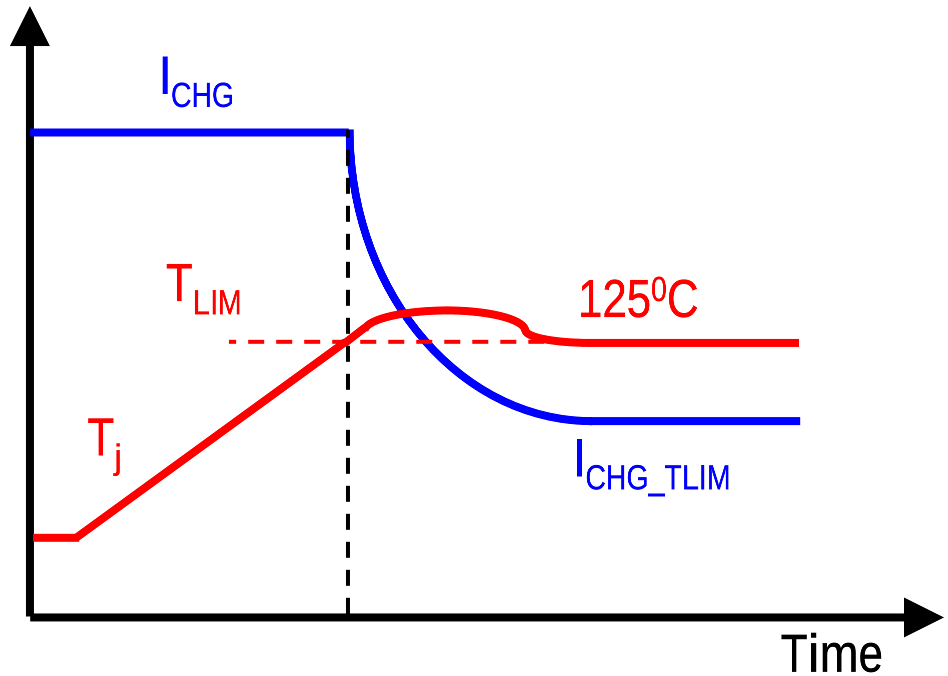
$$P_{LOSS} = (V_{IN} - V_{BAT}) \bullet I_{CHG}$$



- Simple and low cost
- Highest power dissipation from pre-charge to fast charge mode transition
- Ideal for low charge current < 800mA
- Thermal issue for ≥ 800mA charge current
- For high charge current applications (Portable DVD, PMP)

What's the solution?

Solution 1: Thermal Regulation



- Regulate the junction temperature
- Thermal fold-back at 125^0C by reducing charge current
- Drawback: Increase the charge time, may expire the safety timer

Solution 2: High Efficiency Switching Charger

- **Switching Charger: Higher than 90% Efficiency**

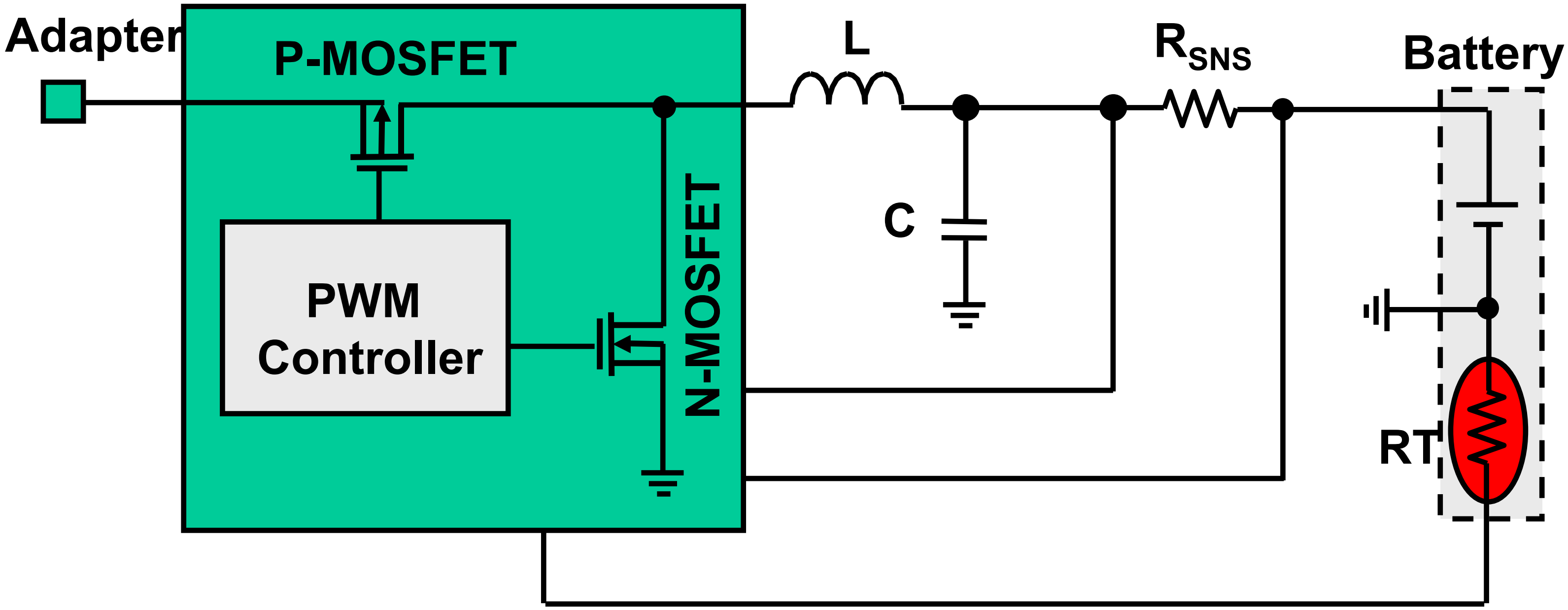
  For V_{IN}=5.5V, V_{BAT}=3.0V, I_{CHG}=1.24A (1800mAh, 0.7C)

- **Power Dissipation:**

	Linear Charger	Switching Charger
Power Dissipation	3.1-Watt	0.4-Watt
Junction Temp Rise	142^{0}C	18.4^{0}C

- **Ideal for ≥1000mA charge current, high input and output voltage difference**
- **Typical Applications: Portable DVD Players, MP3 Players,….**

Synchronous Switching Charger Design Considerations



- Higher Efficiency but Larger Size and Higher Cost Compared to Linear Charger
- Small Passive Component Size Needed: Increased Switching Frequency (Consideration #1)
- High Switching Frequency: EMI issues (Consideration #2)

- Integrated Power MOSFETs: Smaller Size, Higher Die Temperature
- Loss and Thermal Analysis (Consideration #3)

Inductor Size and Selection

Inductance value and switching frequency relationship:

$$L = \frac{V_{IN} - V_{BAT}}{\Delta I_{ripple}} \frac{V_{BAT}}{V_{IN}} \frac{1}{f_s} \qquad \Delta_{ripple} = 30\% \, I_{CHG}$$

$$I_{Peak} = I_{Charge} + \frac{1}{2} I_{Ripple}$$

$$\boldsymbol{I_{SATURATION} \sim 1.5 \times I_{Peak\_max}}$$

Design Tradeoff

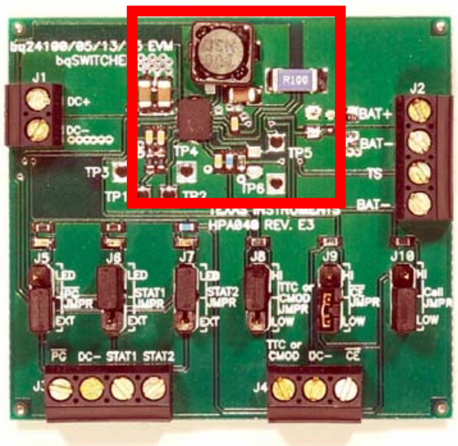
Higher switching frequency, the smaller the inductor

Higher switching frequency, the higher the switching losses

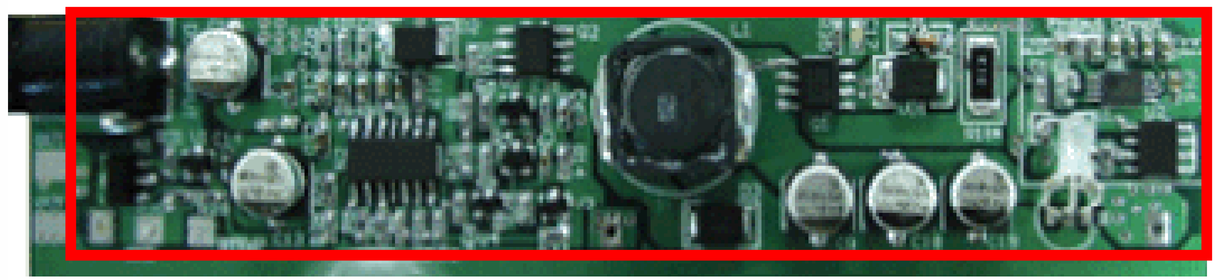
50 kHz vs 1.1 MHz Area Comparison

Total Active Area Size Comparison

Bq2410x EVM



1.1 MHz Solution



50 KHz Solution

EMI Considerations

EMI Definition

The interference of one piece of electronic equipment on the operation of another by means of electromagnetic energy transfer.

- **A generator of electromagnetic energy: (a source)**
- **Transmission of that energy between equipments: (a coupling means)**
- **A receptor circuit whose operation is negatively impacted by the transmitted energy: (a victim circuit)**

EMI Principles:

	Inductive Coupling	Capacitive Coupling
EMI Principles:	$e = M\dfrac{di}{dt}$	$i = C\dfrac{dv}{dt}$

Solutions to Reduce EMI

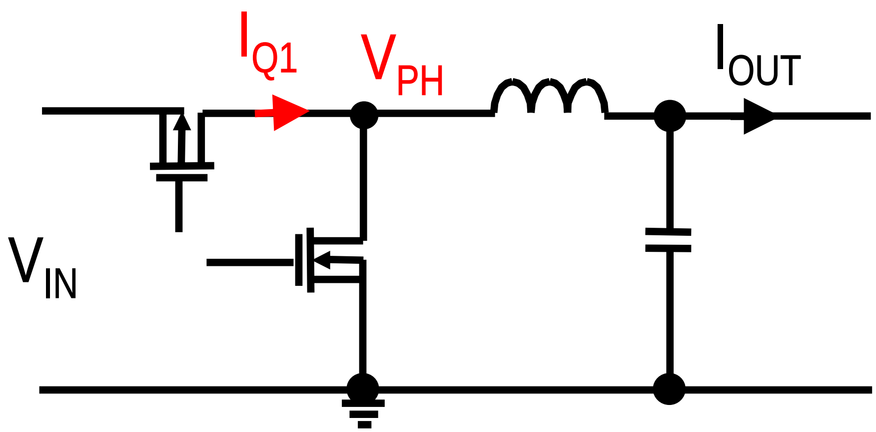
- **Adding filter (cost! may not work for radiated EMI)**
- **Adding snubber (cost!)**
- **Excellent layout (design difficulty)**
- **Slower switching speed**

  - No extra cost

  - Reduce both conducted and radiated EMI

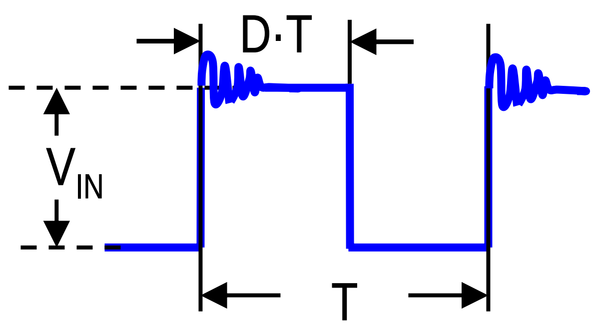
  - May impact efficiency

Major EMI Source of a Converter

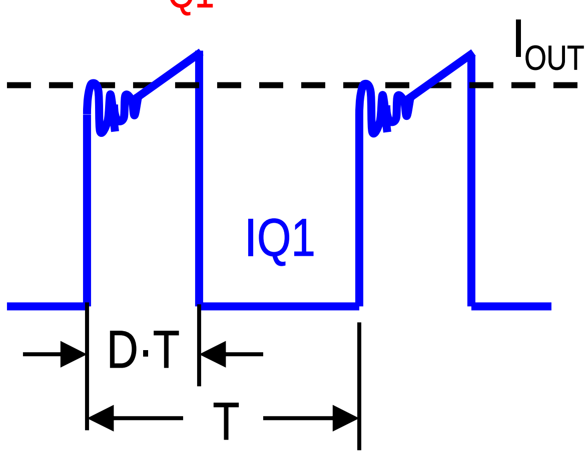


High dv/dt and di/dt switching on the phase node is the major EMI source in a Buck converter

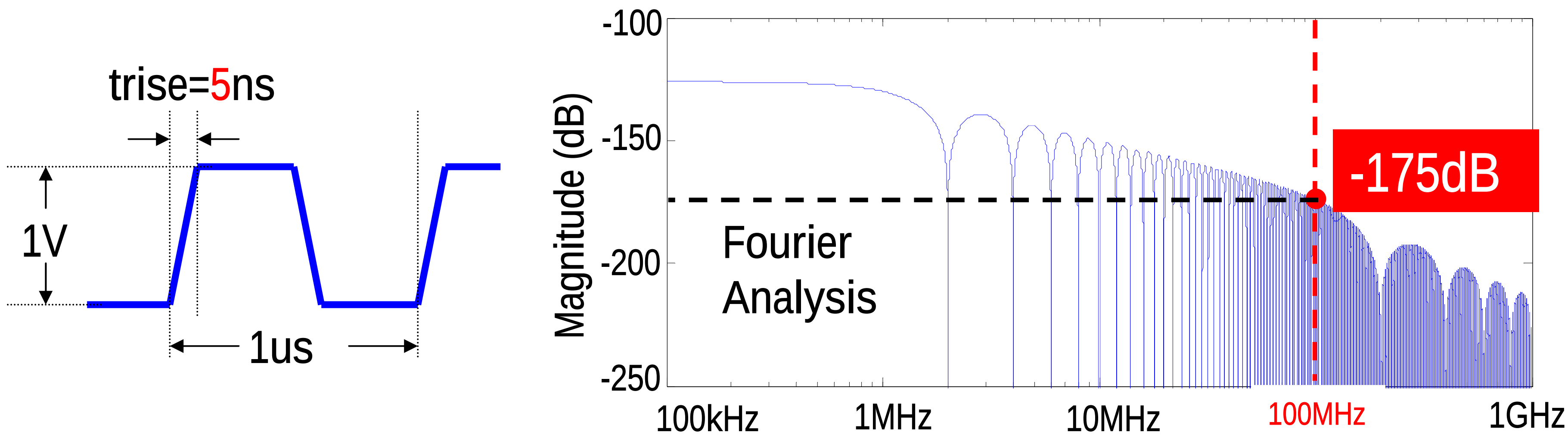
V_{PH} Waveform

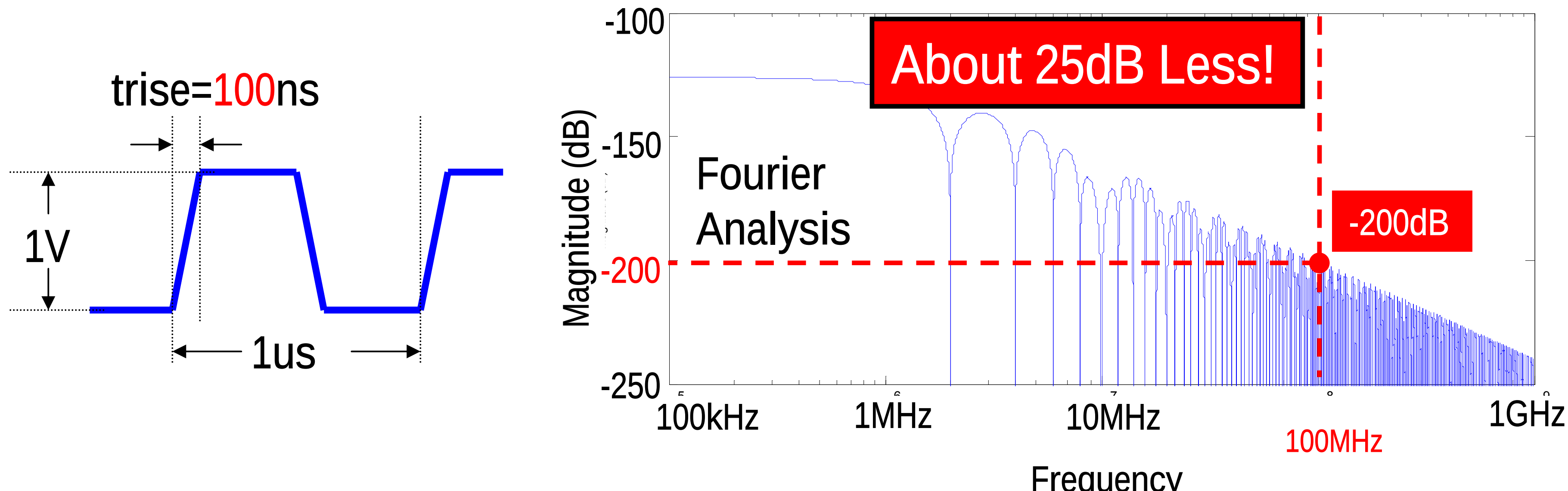


I_{Q1} Waveform

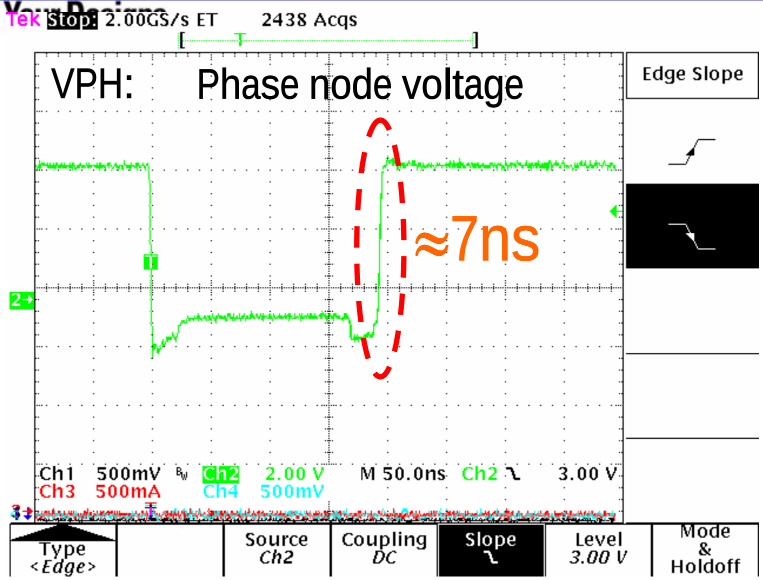


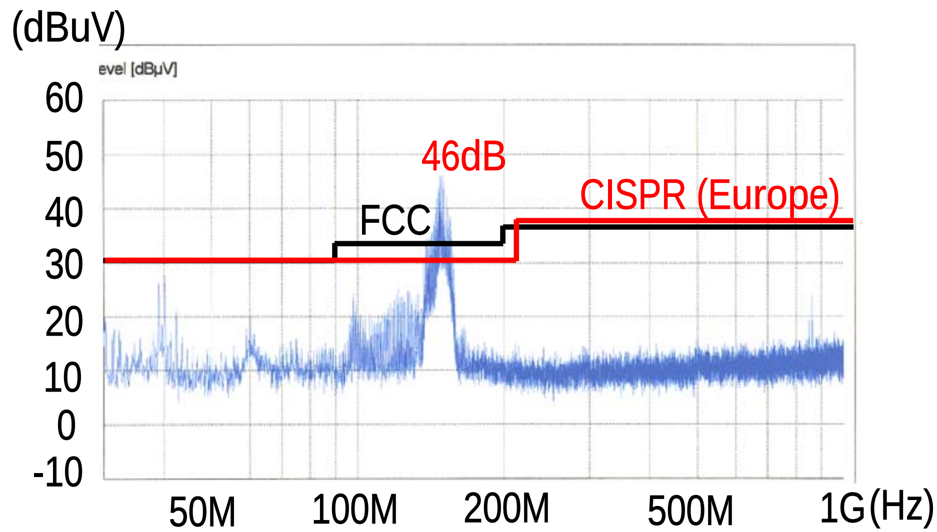
Why Slower Switching Helps

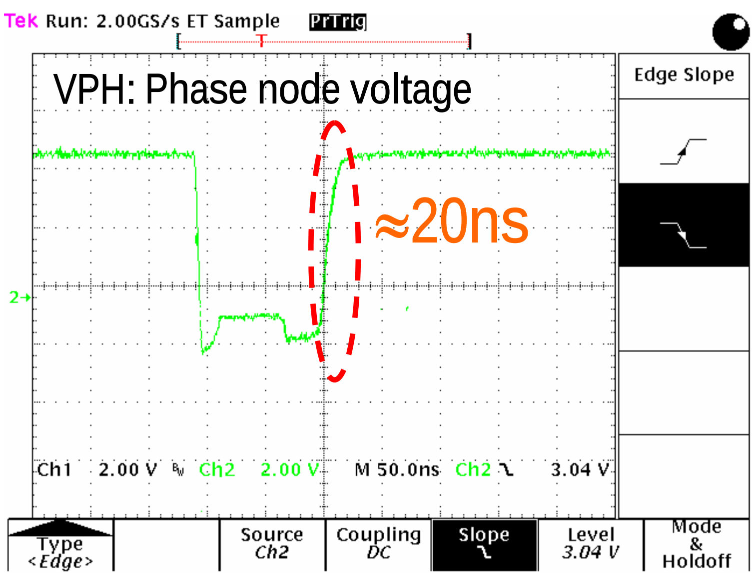


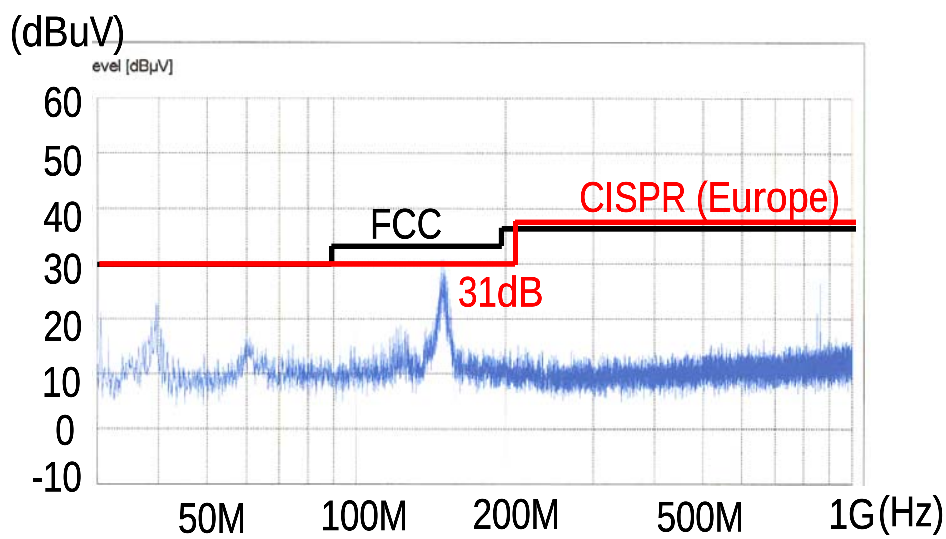


Switching Waveforms and EMI Spectrum @ Vin=9V Ichrg=1A



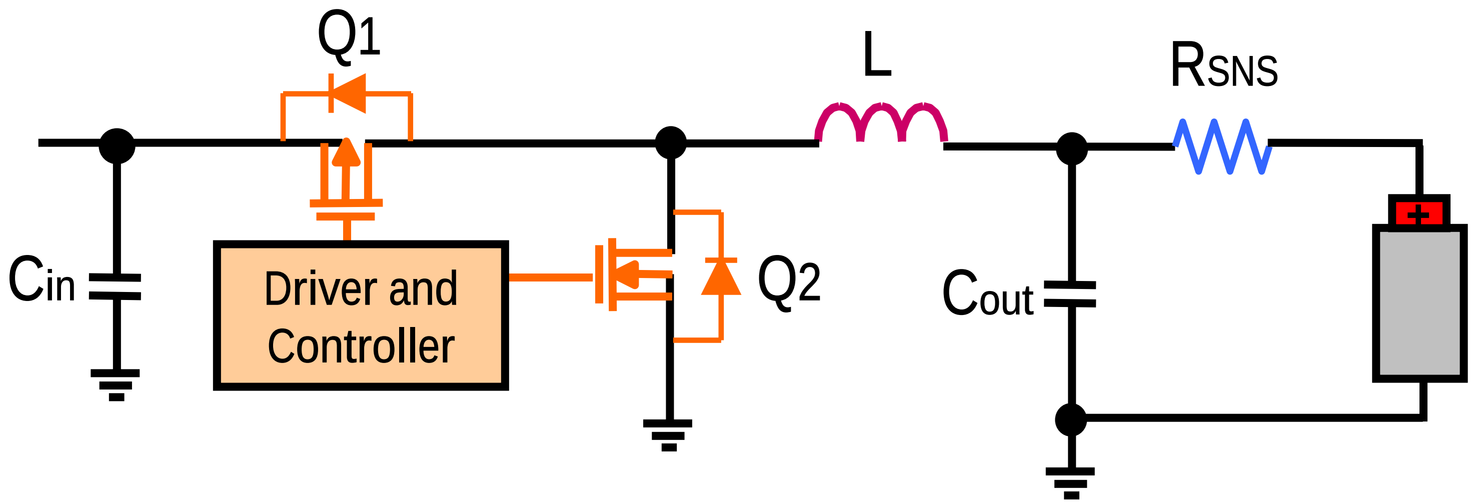






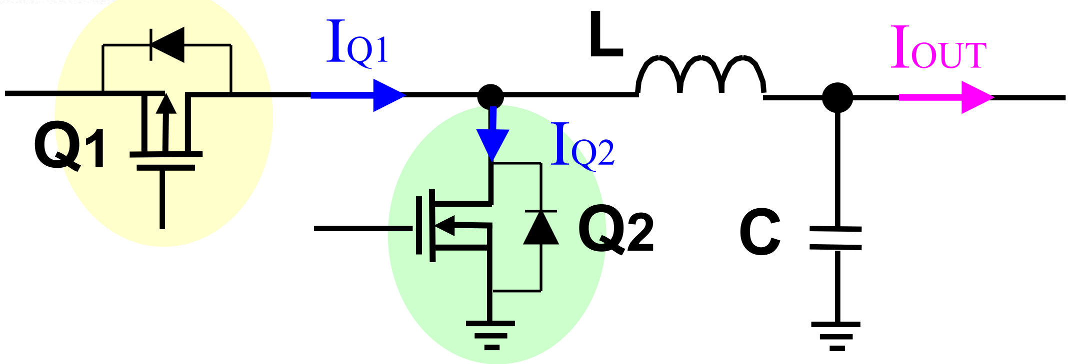
- 15dB reduction around 150MHz

Loss Analysis: Synchronous Switching Charger



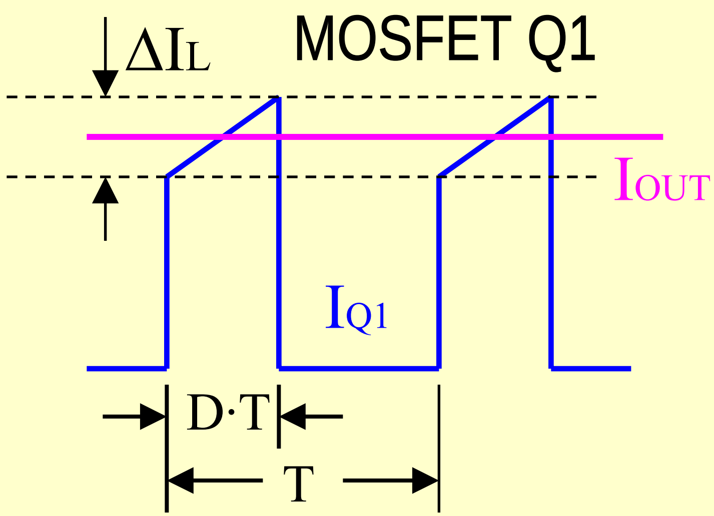
- MOSFETs — Conduction losses; Switching Losses; Body Diode Conduction Losses; Gate Drive Losses
- Inductor — Winding Losses; Core Losses
- RSNS — Resistive losses
- Others — Cap ESR Losses, IC losses …; PCB Trace Conduction Losses

MOSFET Conduction Losses

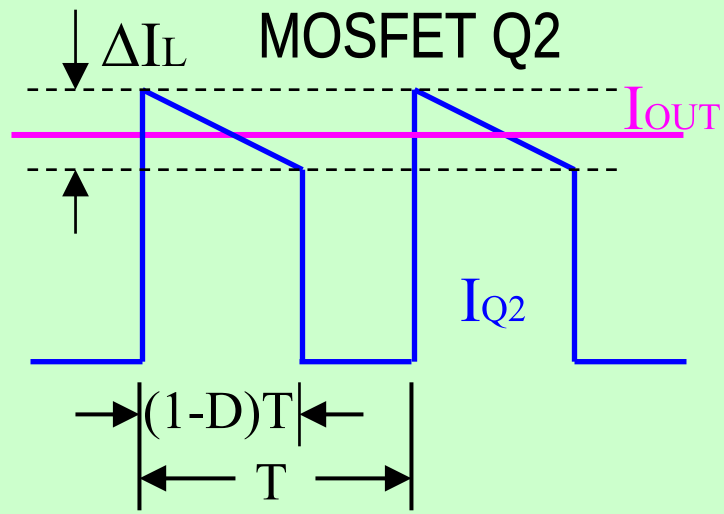


$$P_{COND} = I_{RMS}^2 \cdot R_{DSON}$$

RDSON is a function of temperature, normally increases by 0.39%/°C

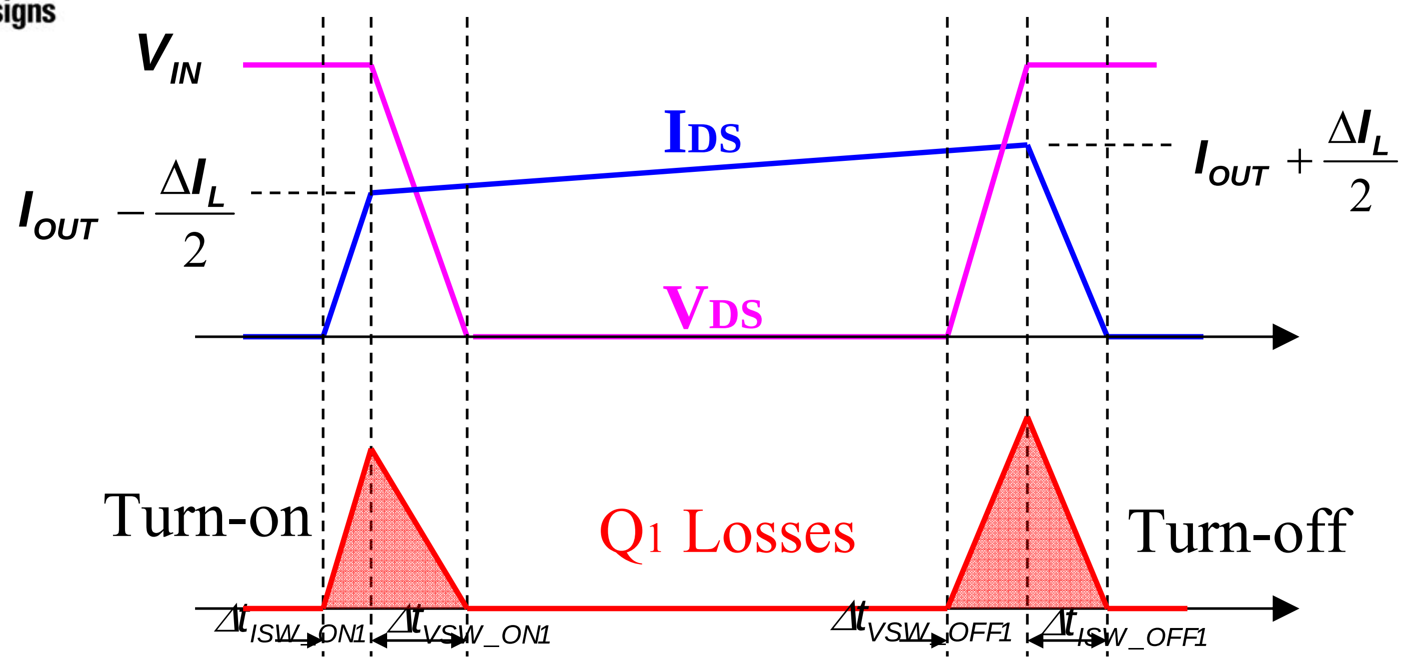


$$I_{RMS\_Q1} = \sqrt{D\left(I_{OUT}^2 + \frac{1}{12}\Delta I_L^2\right)}$$



$$I_{RMS\_Q2} = \sqrt{(1-D)\left(I_{OUT}^2 + \frac{1}{12}\Delta I_L^2\right)}$$

Upper MOSFET – Switching Losses

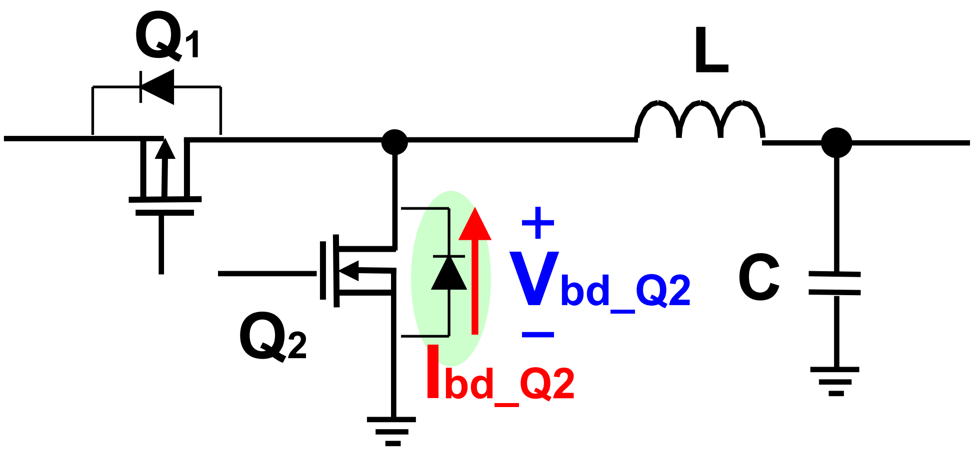


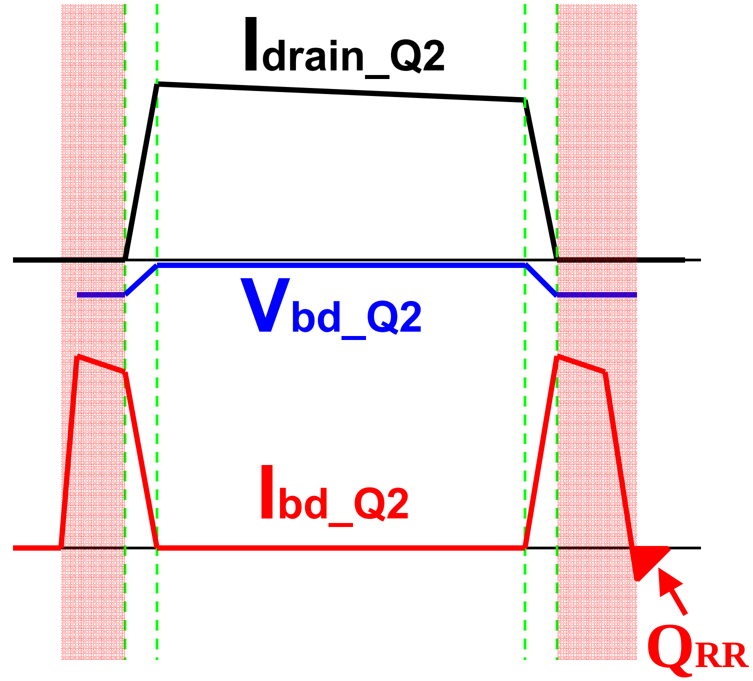
$$P_{swon\_Q1} = 0.5 \cdot V_{IN} \cdot (I_{OUT} - \frac{\Delta I_L}{2}) \cdot (\Delta t_{ISW\_ON1} + \Delta t_{VSW\_ON1}) \cdot f_{SW}$$

$$P_{swoff\_Q1} = 0.5 \cdot V_{IN} \cdot (I_{OUT} + \frac{\Delta I_L}{2}) \cdot (\Delta t_{VSW\_OFF1} + \Delta t_{ISW\_OFF1}) \cdot f_{SW}$$

The total switching losses of Q1: $P_{sw\_Q1} = P_{swon\_Q1} + P_{swoff\_Q1}$

Lower MOSFET – Body Diode Conduction & Reverse Recovery Losses



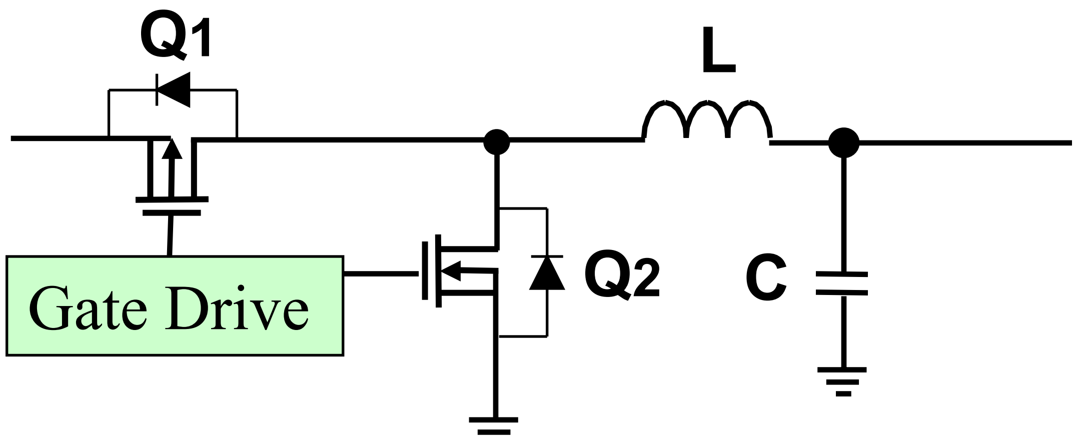


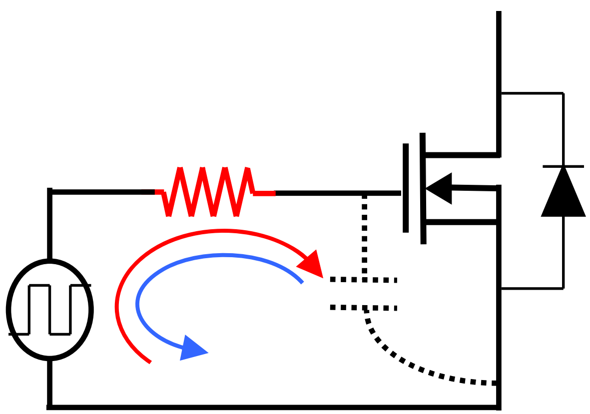
- **Relates to the short periods of conduction before and after the on-time of Q2.**
- **Dead time -- 20–60ns typically**

$$P_{BD\_Q2} = 2 \cdot V_{BD} \cdot I_{OUT} \cdot t_{DT} \cdot f_{SW}$$

$$P_{QRR} = Q_{RR} \cdot V_{IN} \cdot f_{SW}$$

Gate Drive Losses



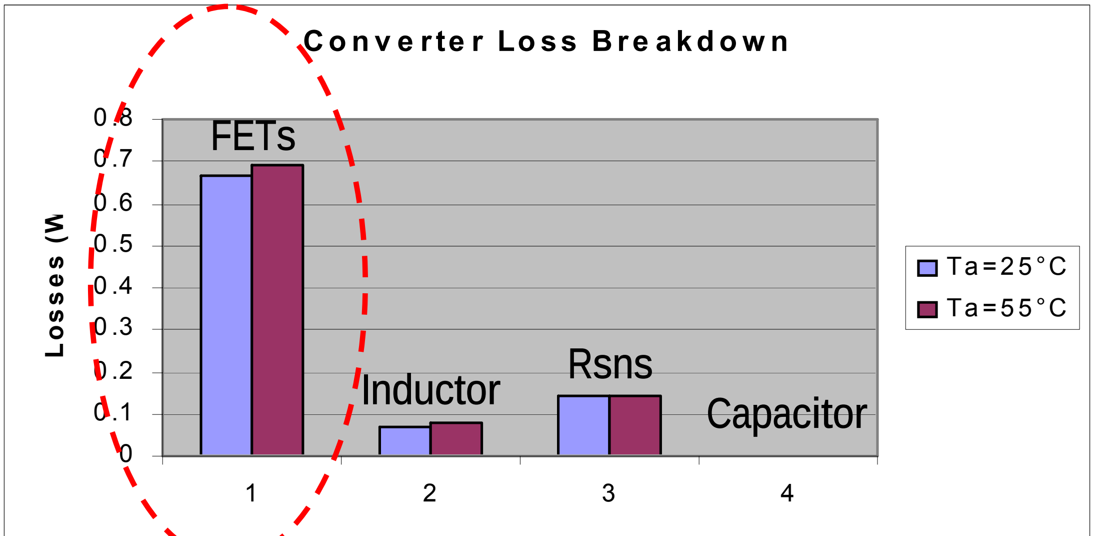


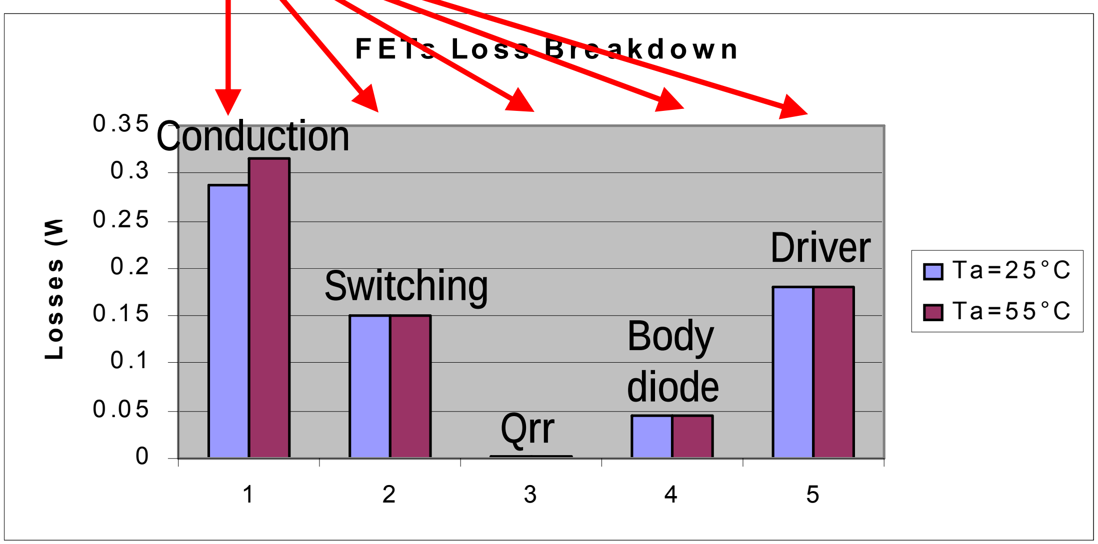
$$P_{DRV\_Q1} = Q_{g\_Q1} \cdot V_{DRV\_Q1} \cdot f_{SW}$$

$$P_{DRV\_Q2} = Q_{g\_Q2} \cdot V_{DRV\_Q2} \cdot f_{SW}$$

$$P_{DRV} = P_{DRV\_Q1} + P_{DRV\_Q2}$$

Loss Breakdown @ VIN=12V, VBAT=8.4V, ICHG=1.2A

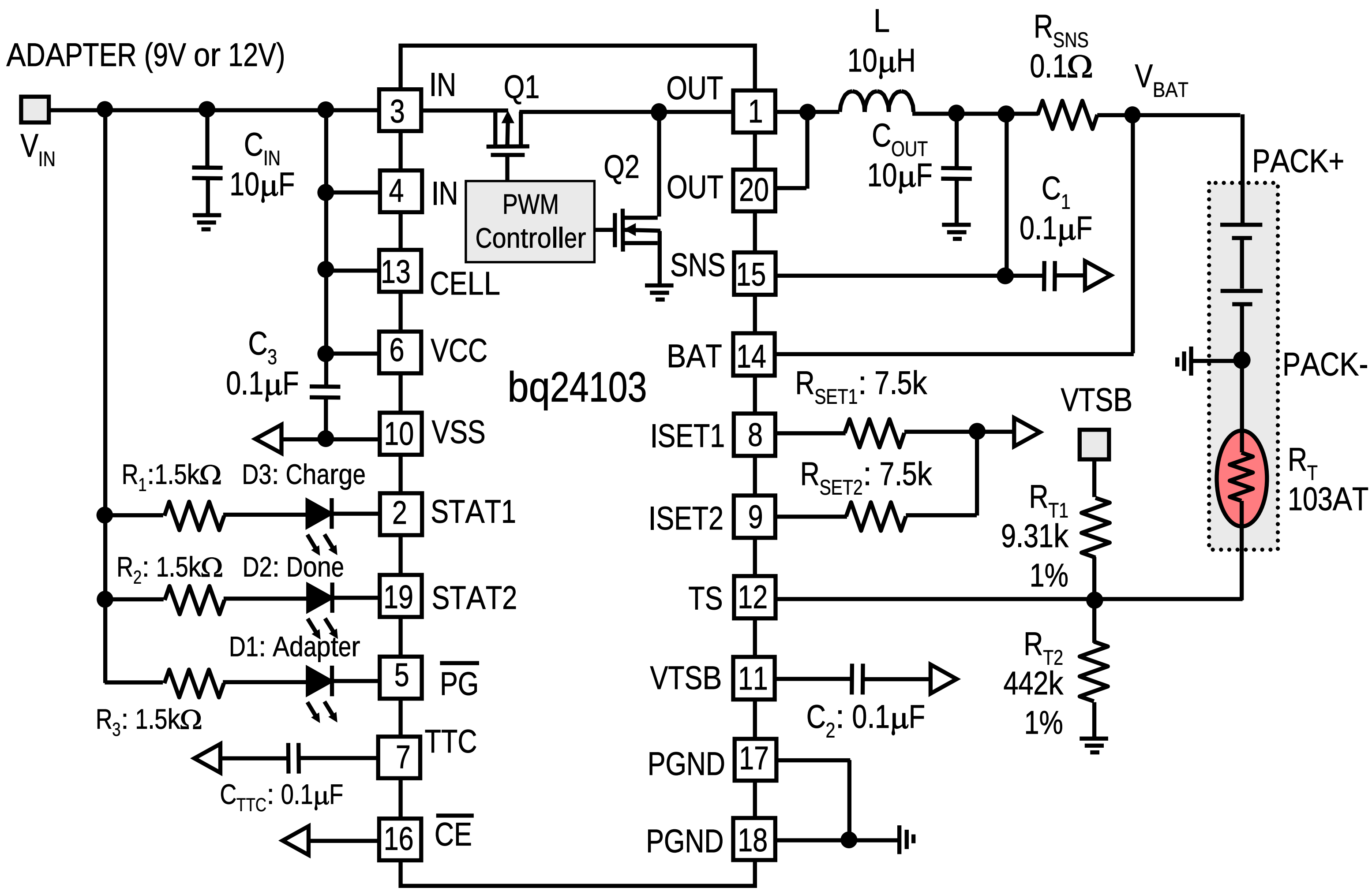




	Linear T_{am}=55°C	Switching T_{am}=55°C
Total Losses	4.32W	0.911W
Efficiency	57.1%	91.72%
Temperature rise	153.6°C	32.4°C
IC Junction Temperature	208.6°C	87.4°C

Typical Applications Circuit

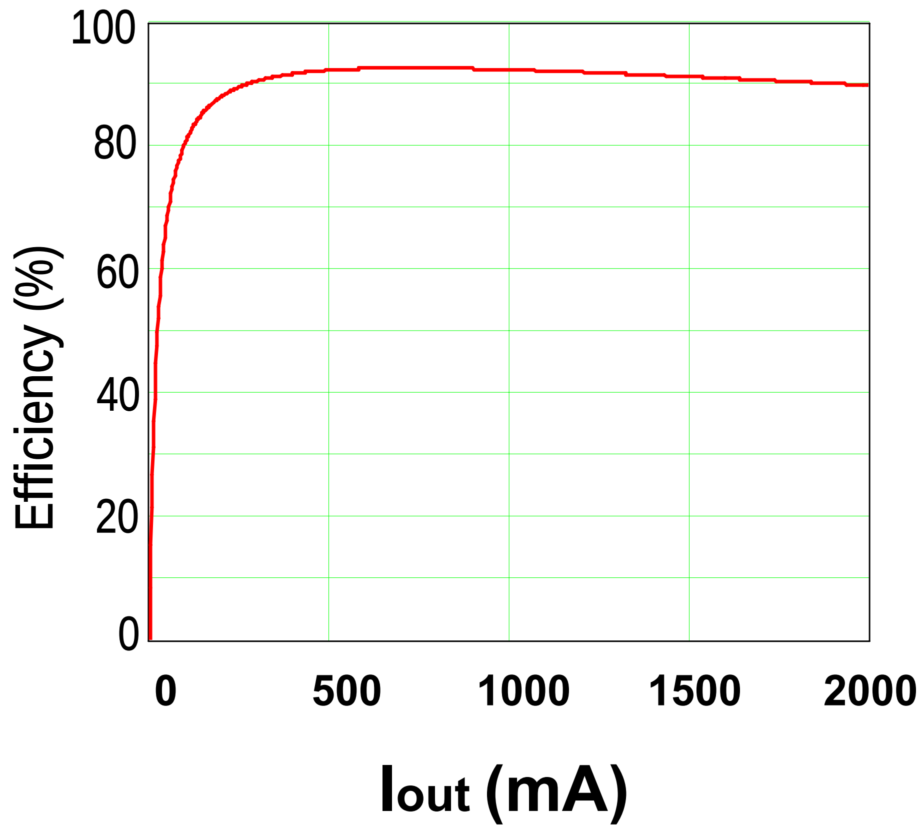
VIN=9V, Battery: 2-cell in series, ICHG=1.25A, Safety timer: 5 hours, I_{PRECHG} = 125mA, Temperature range: 0-45C



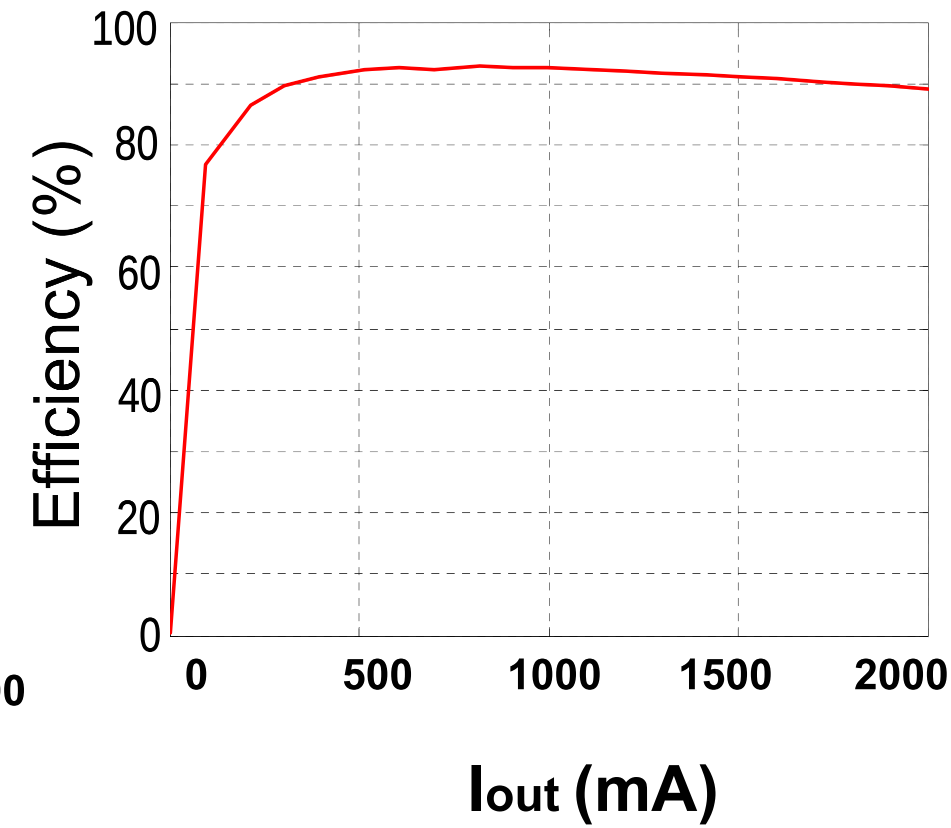
Efficiency - Calculation vs Measurement

VIN=12V, VBAT=8.4V

Calculation Results



Measurement Results



Summary – Switching Chargers

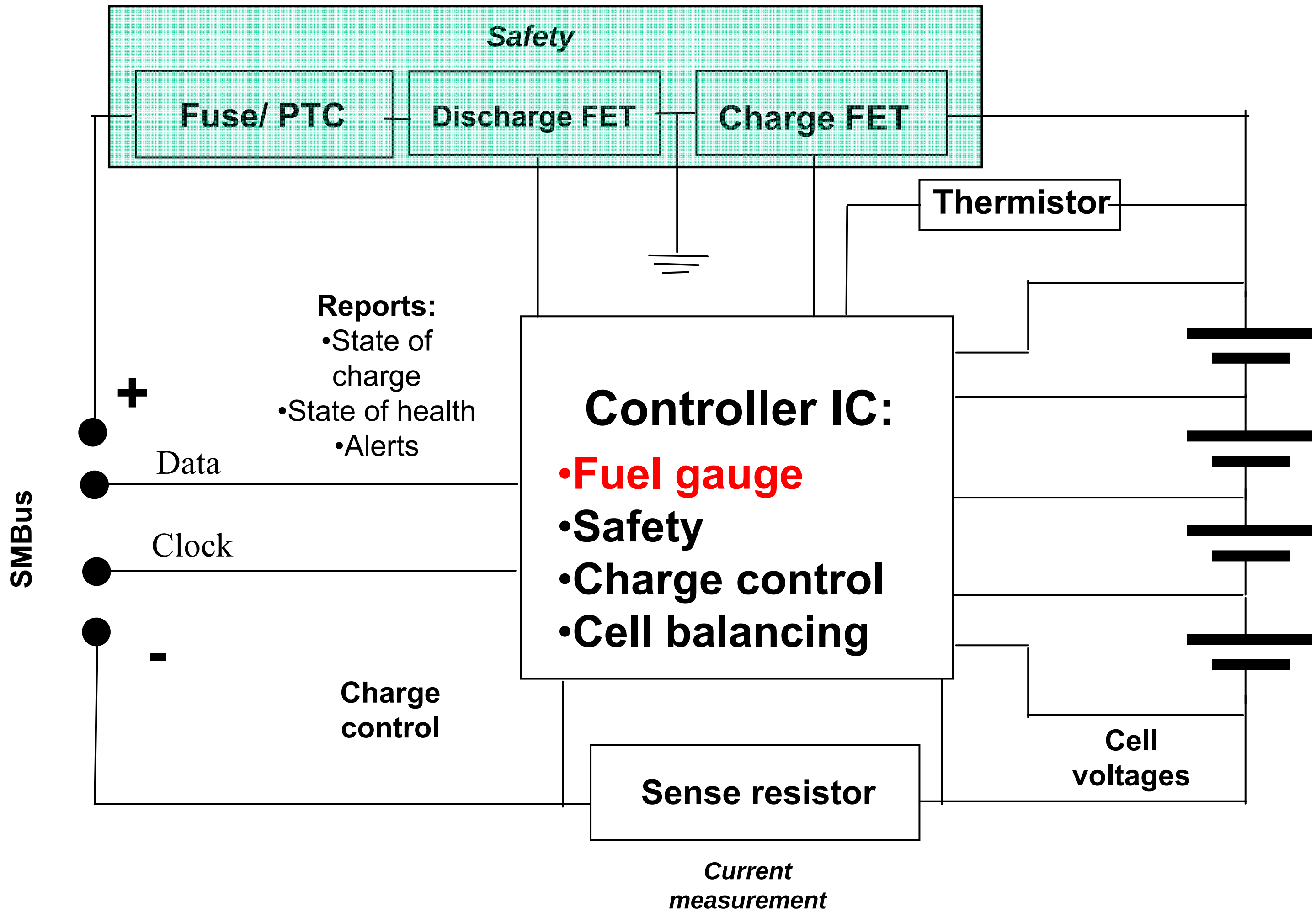
- Linear Charger: Low cost, low charge current
- Switching Charger: Ideal Solution for higher charge current
- More complex than Linear Charger
- Reducing the voltage slew rate dV/dt can reduce EMI
- Loss analysis helps thermal design

Section III: Battery Capacity Monitoring

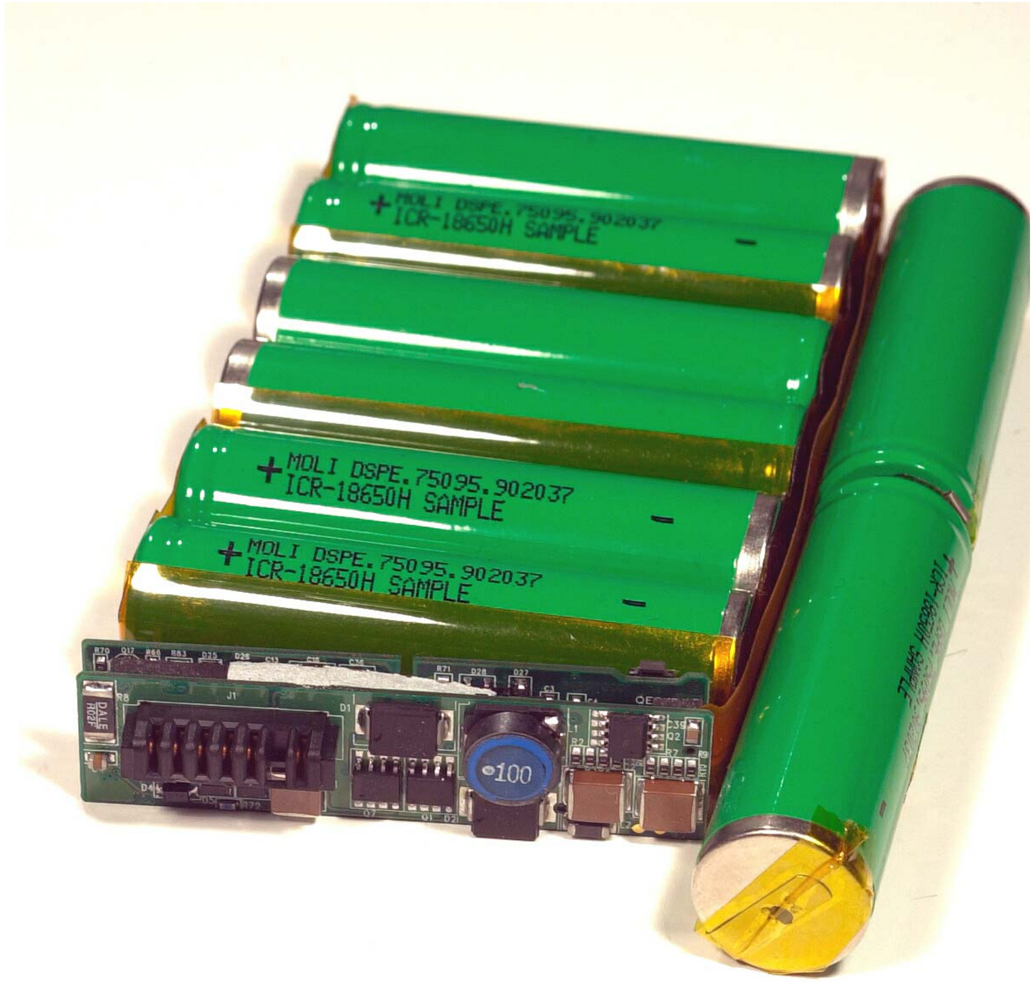
What is a capacity-gauge and why it is needed?

- Early portable devices used fuel-gauging for giving raw estimate to end-user, typically 4 LED based
- Notebooks, PDAs, smart phones and increasingly camera phones need to prevent data loss due to battery failure
- System needs to use remaining capacity information to perform software shut-down to prevent data loss
- Requirement to gauge precision is highly increased, because premature software-directed shut down is equivalent to degraded battery.
- 10% wrong fuel gauge means 10% of battery is not used

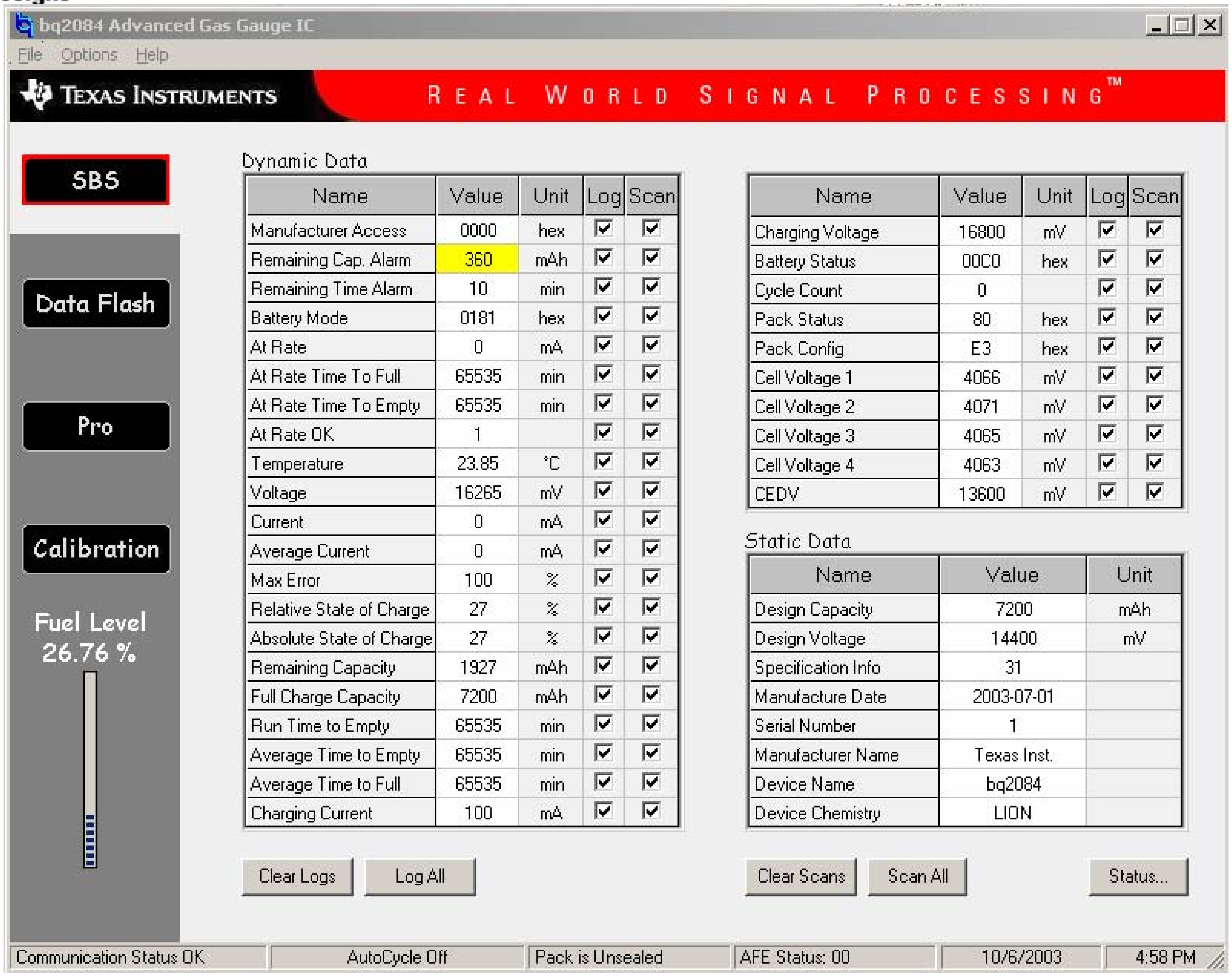
Example of capacity gauge and protector solution



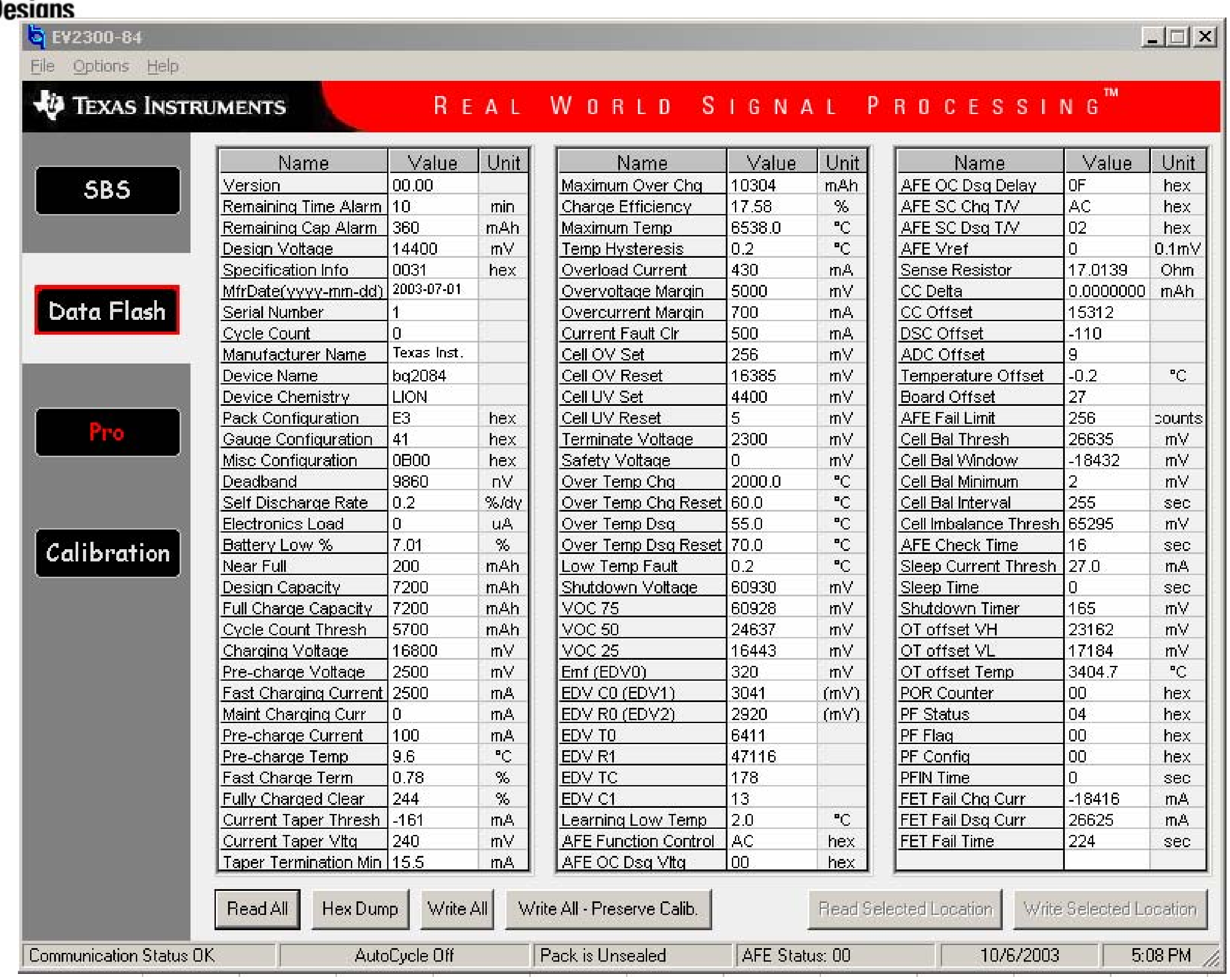
Example of capacity gauge and protector solution



Typical parameters reported to host through SMBus



Typical parameters needed for algorithm

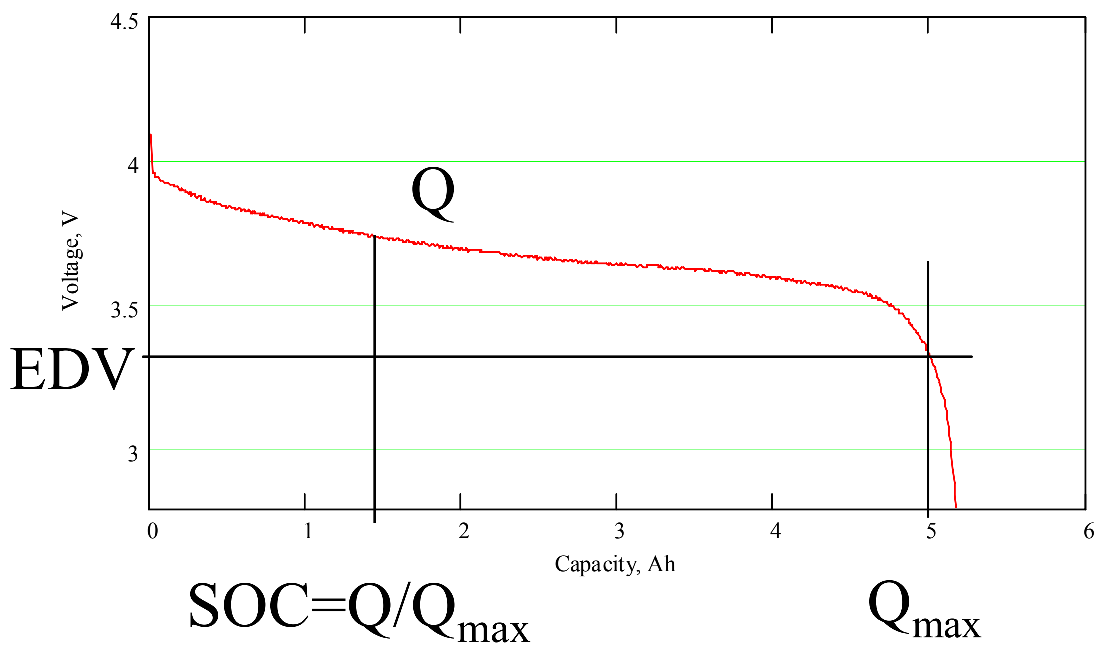


Name	Value	Unit
Version	00.00	
Remaining Time Alarm	10	min
Remaining Cap Alarm	360	mAh
Design Voltage	14400	mV
Specification Info	0031	hex
MfrDate(yyyy-mm-dd)	2003-07-01	
Serial Number	1	
Cycle Count	0	
Manufacturer Name	Texas Inst.	
Device Name	bq2084	
Device Chemistry	LION	
Pack Configuration	E3	hex
Gauge Configuration	41	hex
Misc Configuration	0B00	hex
Deadband	9860	nV
Self Discharge Rate	0.2	%/dy
Electronics Load	0	uA
Battery Low %	7.01	%
Near Full	200	mAh
Design Capacity	7200	mAh
Full Charge Capacity	7200	mAh
Cycle Count Thresh	5700	mAh
Charging Voltage	16800	mV
Pre-charge Voltage	2500	mV
Fast Charging Current	2500	mA
Maint Charging Curr	0	mA
Pre-charge Current	100	mA
Pre-charge Temp	9.6	°C
Fast Charge Term	0.78	%
Fully Charged Clear	244	%
Current Taper Thresh	-161	mA
Current Taper Vltg	240	mV
Taper Termination Min	15.5	mA

Name	Value	Unit
Maximum Over Chg	10304	mAh
Charge Efficiency	17.58	%
Maximum Temp	6538.0	°C
Temp Hysteresis	0.2	°C
Overload Current	430	mA
Overvoltage Margin	5000	mV
Overcurrent Margin	700	mA
Current Fault Clr	500	mA
Cell OV Set	256	mV
Cell OV Reset	16385	mV
Cell UV Set	4400	mV
Cell UV Reset	5	mV
Terminate Voltage	2300	mV
Safety Voltage	0	mV
Over Temp Chg	2000.0	°C
Over Temp Chg Reset	60.0	°C
Over Temp Dsg	55.0	°C
Over Temp Dsg Reset	70.0	°C
Low Temp Fault	0.2	°C
Shutdown Voltage	60930	mV
VOC 75	60928	mV
VOC 50	24637	mV
VOC 25	16443	mV
Emf (EDV0)	320	mV
EDV C0 (EDV1)	3041	(mV)
EDV R0 (EDV2)	2920	(mV)
EDV T0	6411	
EDV R1	47116	
EDV TC	178	
EDV C1	13	
Learning Low Temp	2.0	°C
AFE Function Control	AC	hex
AFE OC Dsg Vltg	00	hex

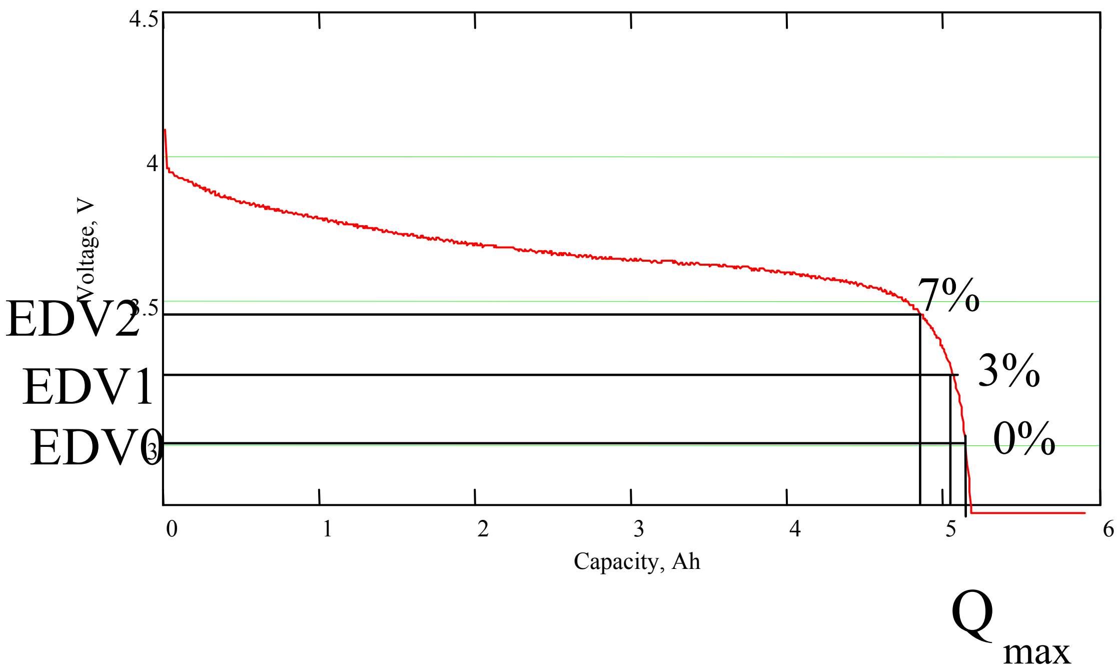
Name	Value	Unit
AFE OC Dsg Delay	0F	hex
AFE SC Chg T/V	AC	hex
AFE SC Dsg T/V	02	hex
AFE Vref	0	0.1mV
Sense Resistor	17.0139	Ohm
CC Delta	0.0000000	mAh
CC Offset	15312	
DSC Offset	-110	
ADC Offset	9	
Temperature Offset	-0.2	°C
Board Offset	27	
AFE Fail Limit	256	counts
Cell Bal Thresh	26635	mV
Cell Bal Window	-18432	mV
Cell Bal Minimum	2	mV
Cell Bal Interval	255	sec
Cell Imbalance Thresh	65295	mV
AFE Check Time	16	sec
Sleep Current Thresh	27.0	mA
Sleep Time	0	sec
Shutdown Timer	165	mV
OT offset VH	23162	mV
OT offset VL	17184	mV
OT offset Temp	3404.7	°C
POR Counter	00	hex
PF Status	04	hex
PF Flag	00	hex
PF Config	00	hex
PFIN Time	0	sec
FET Fail Chg Curr	-18416	mA
FET Fail Dsg Curr	26625	mA
FET Fail Time	224	sec

Current integration based fuel-gauging



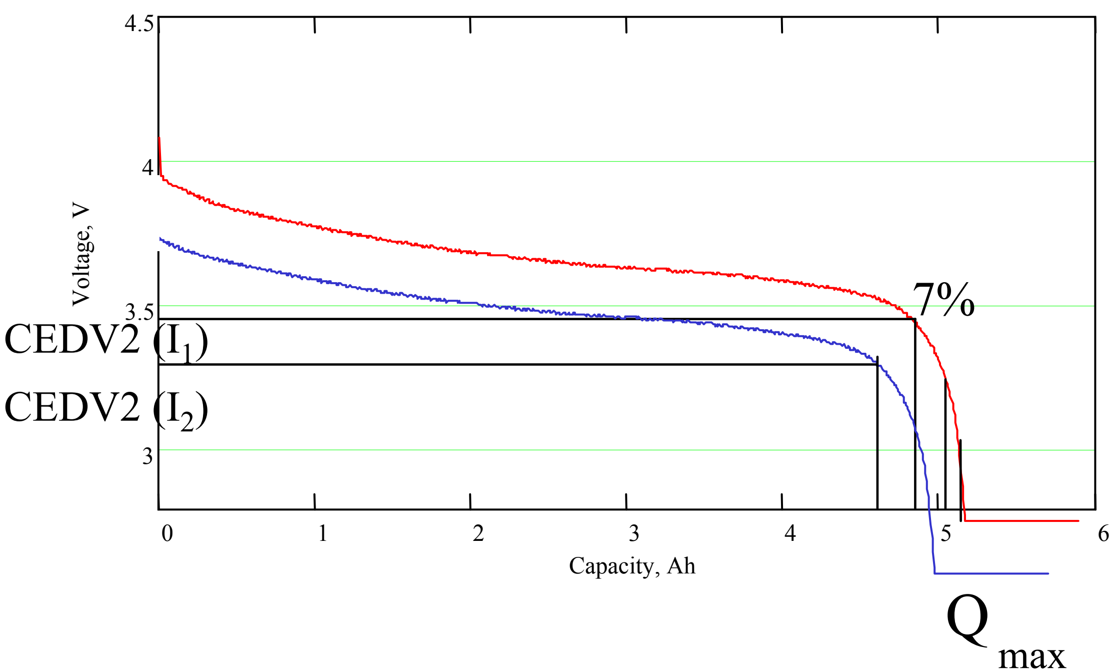
- Battery is fully charged
- During discharge capacity is integrated
- State of charge (SOC) at each moment is Q/Q_{max}
- Q_{max} is updated every time full discharge occurs

Learning before fully discharged



- It is too late to learn when 0% capacity is reached
- We can set voltage threshold that correspond to given percentage of remaining capacity
- However, true voltage corresponding to 7% depends on current and temperature

Learning before fully discharged with current and temperature compensation



- Modeling last part of discharge allows to calculate function V(SOC, I, T)
- Substituting SOC=7% allows to calculate in real time CEDV2 threshold that corresponds to 7% capacity at any current and temperature

Effect of aging on current integration based fuel-gauging

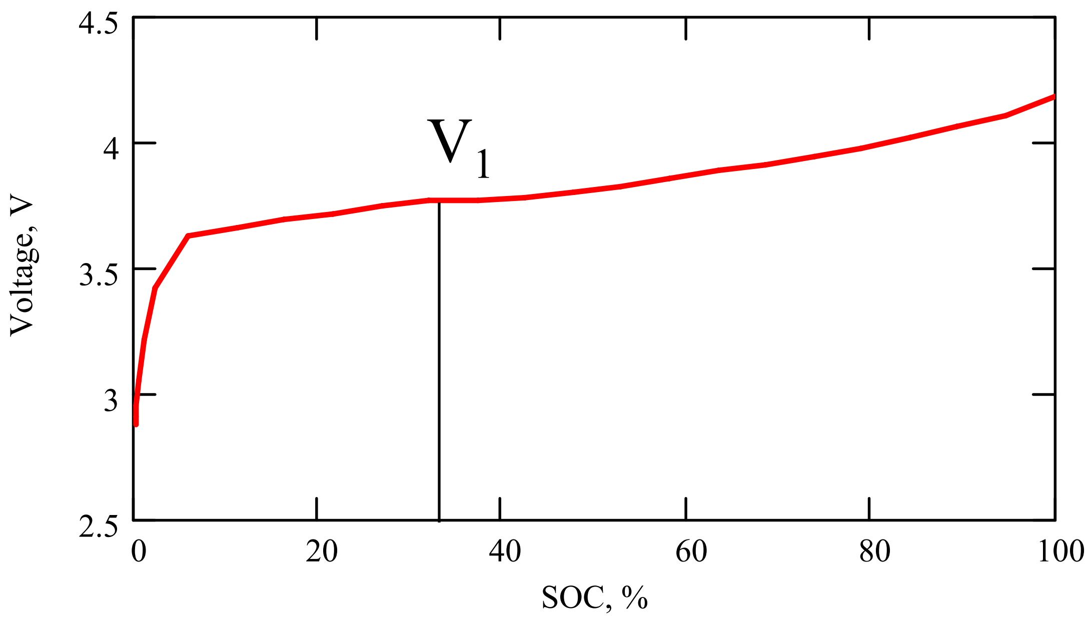
- If learning discharge occurs every cycle, accuracy does not degrade with aging
- However, in usual applications full discharge occurs rarely
- Every 10 cycles without learning increase error by about 1%, but can be worse
- With increasing impedance increases difference between Q_{max} value learned at different discharge rates
- Voltage modeling done for learning at 7% SOC suffers from impedance increase error

Current integration based fuel-gauging

Advantages
- Transparent procedure, minimal data collection
- Not influenced by distortions of voltage measurement during operation
- Accuracy is defined by current integration hardware

Disadvantages
- Learning cycle needed to update Q_{max}
- Self-discharge has to be modeled during inactivity periods
- Additional data collection is needed if Q_{max} learning has to occur earlier then EDV
- Additional modeling suffers from impedance increase

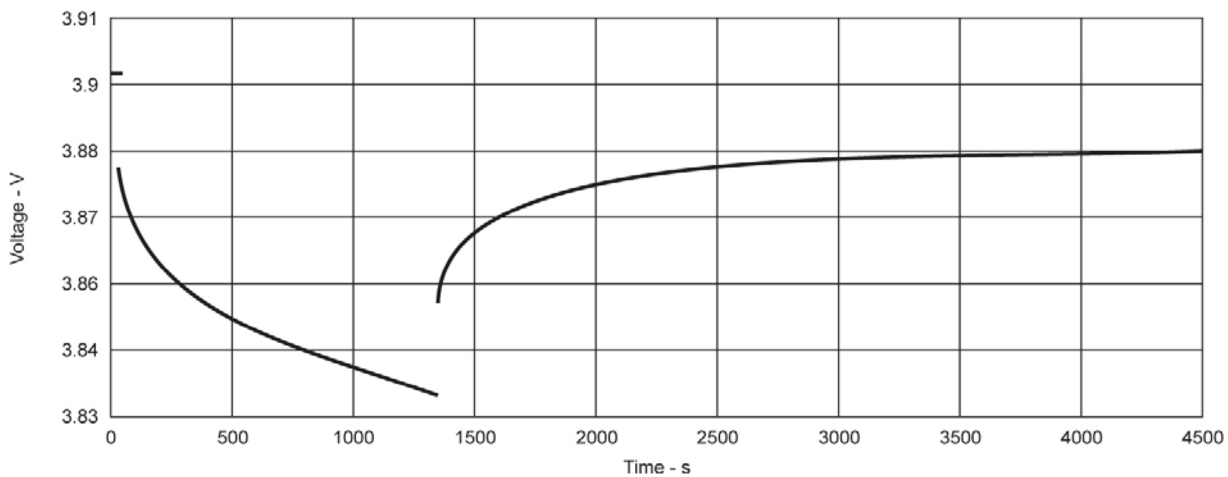
Voltage correlation based fuel gauging



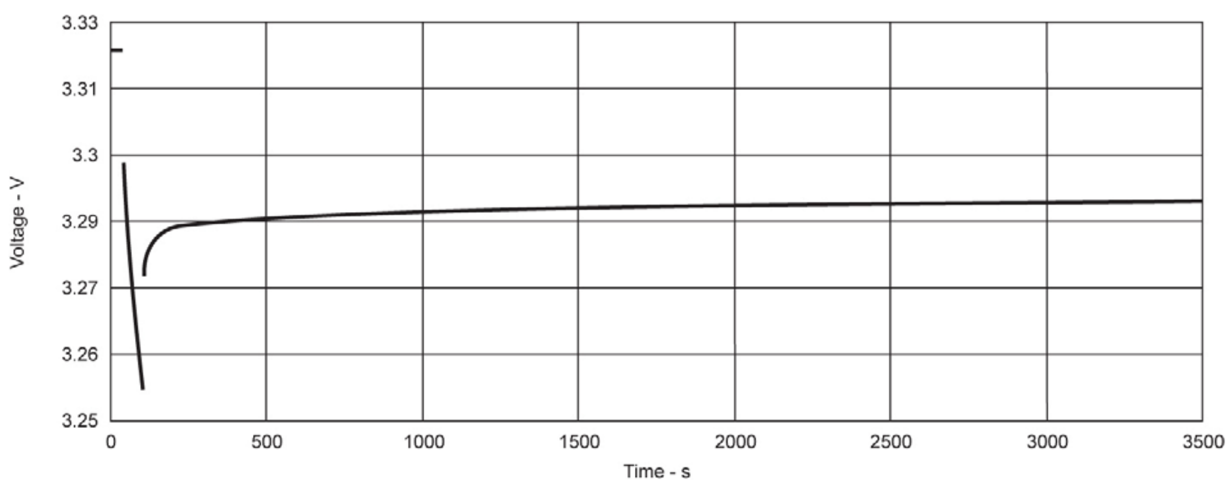
- Voltage is measured during discharge
- Voltage is corrected by IR drop. R is used as fixed value or from a database R=f(SOC, T)
- Resulting corrected voltage is correlated with SOC using a database SOC=f(V,T)
- Alternatively, 3d database SOC=f(V,I,T) can be used for correlation

$$SOC=f(V_1-I\cdot R)$$

Battery – Transient Response



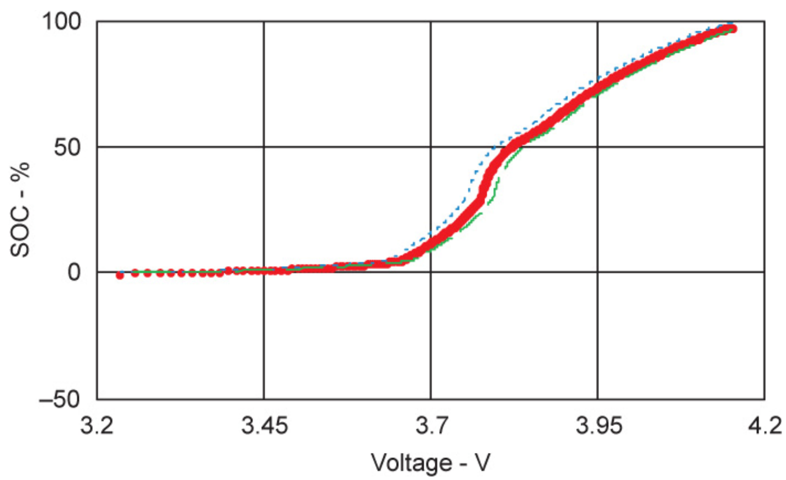
- ◆ Charged state
  - ■ Complete relaxation takes about 3000 seconds
  - ■ Voltage difference between 20 and 3000 seconds is 20 mV

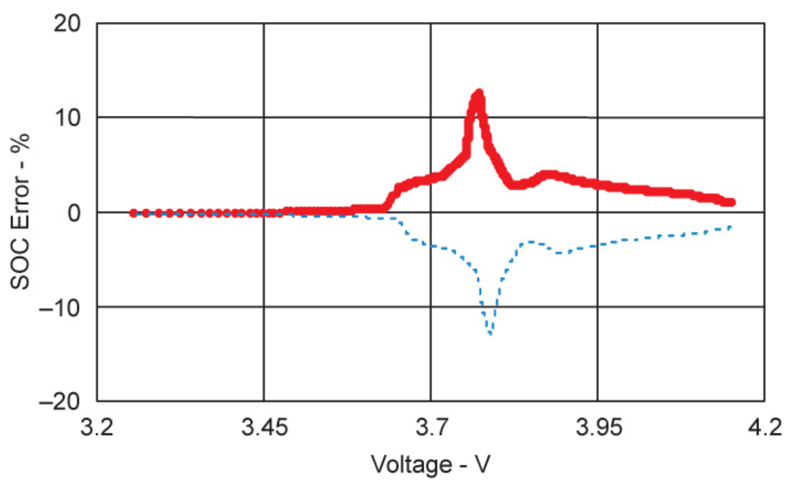


- ◆ Discharged state
  - ■ Impedance is much higher, therefore fast drop
  - ■ Despite small passed charge, complete relaxation takes about 3000 seconds
  - ■ Voltage difference between 20 and 3000 seconds is 40 mV

***C/3 rate current used for both tests**

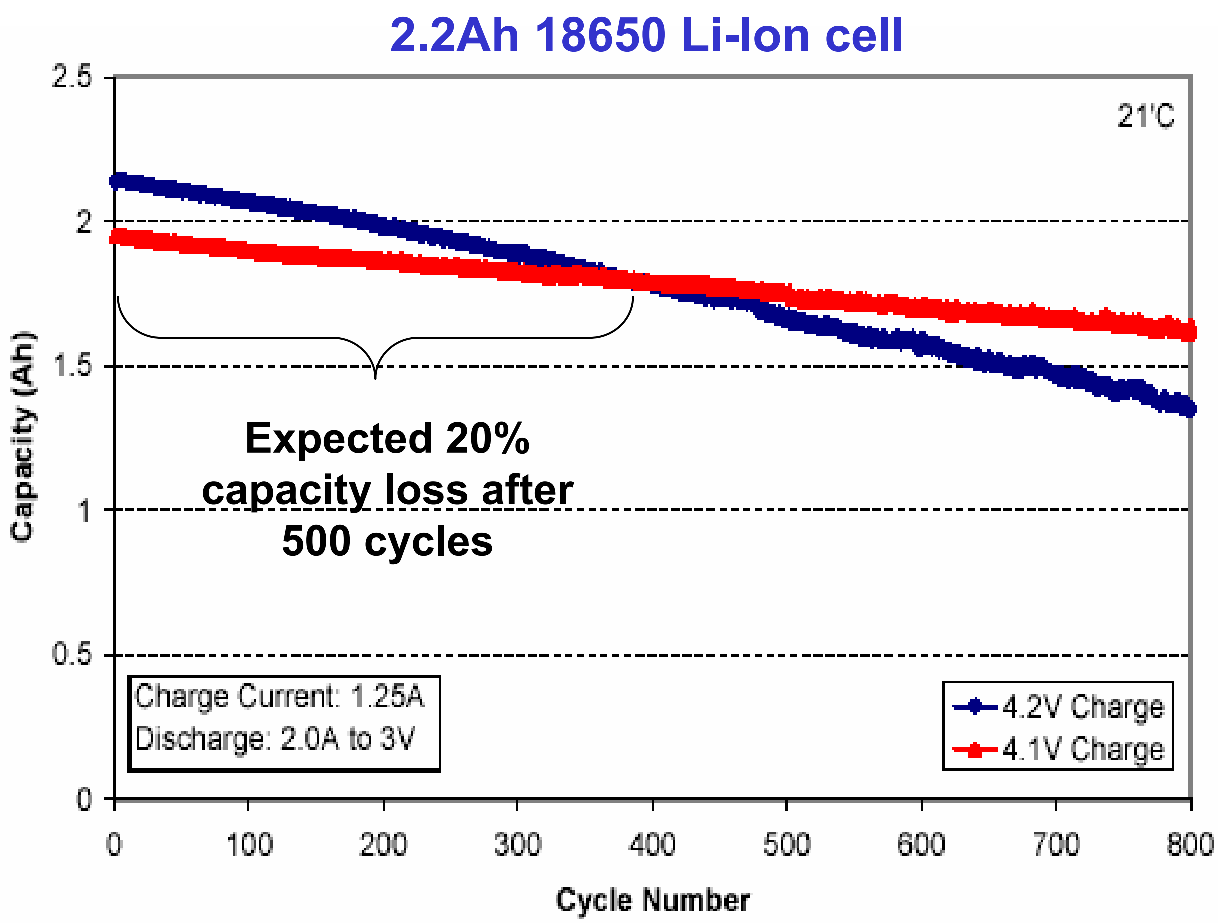
Voltage Relaxation and State of Charge Error





- Any algorithms which either make impedance correction or directly correlate voltage under load with SOC are subject to relaxation error
- Error depends on particular voltage at the moment of estimation
- Maximal error reaches 15%, average error 5%
- Difference in SOC prediction based on voltages measured during relaxation and excitation states reaches 30%
- In discharge state, impedance and relaxation error are about 10 times larger, proportionally increasing error in SOC estimation

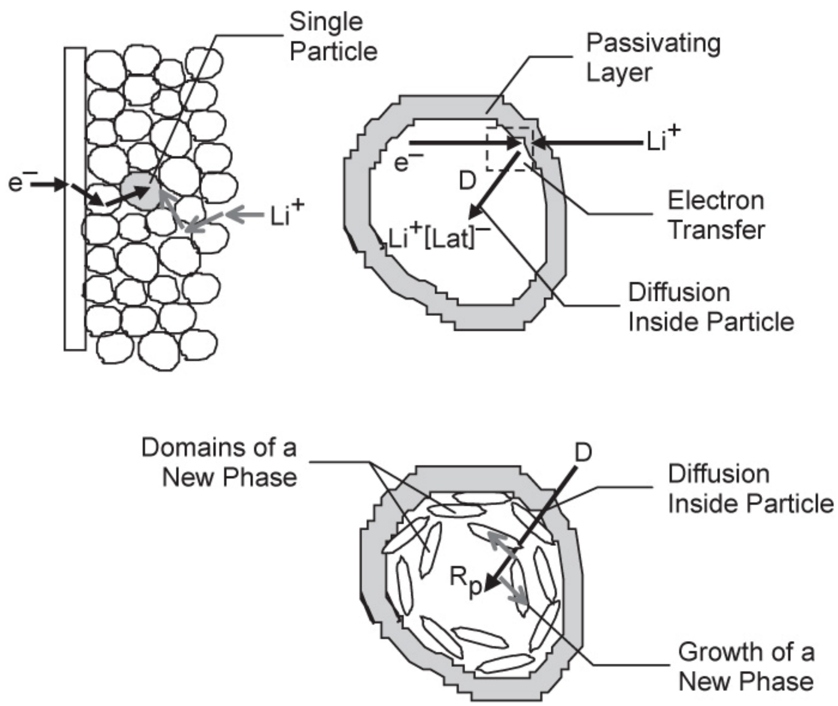
Charge voltage impacts cycle life & run time



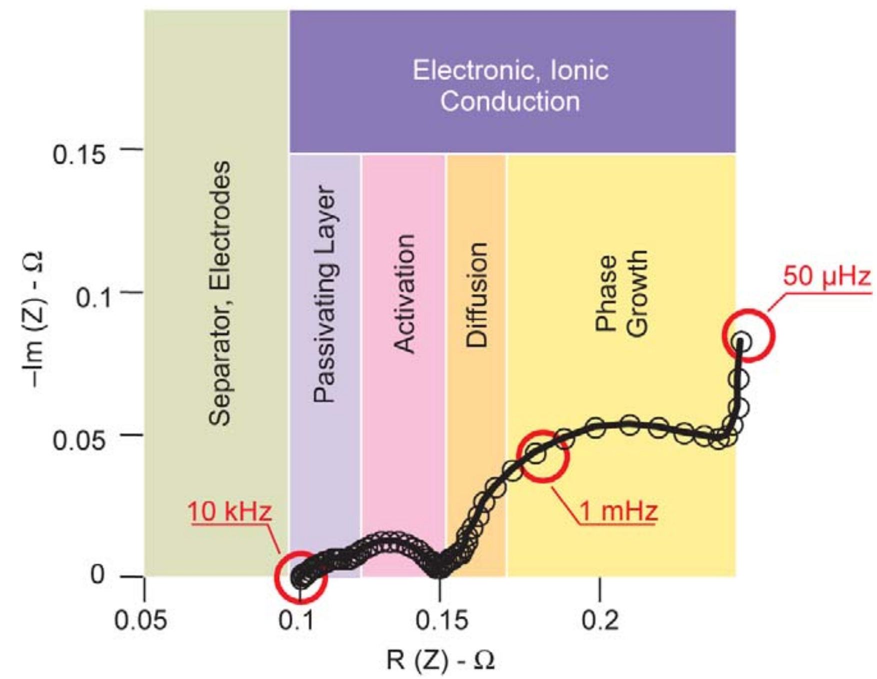
Additional 20% capacity loss at 800 cycles with 4.2V charge

Battery – Under the Hood

Kinetic Steps in Li-Ion Battery

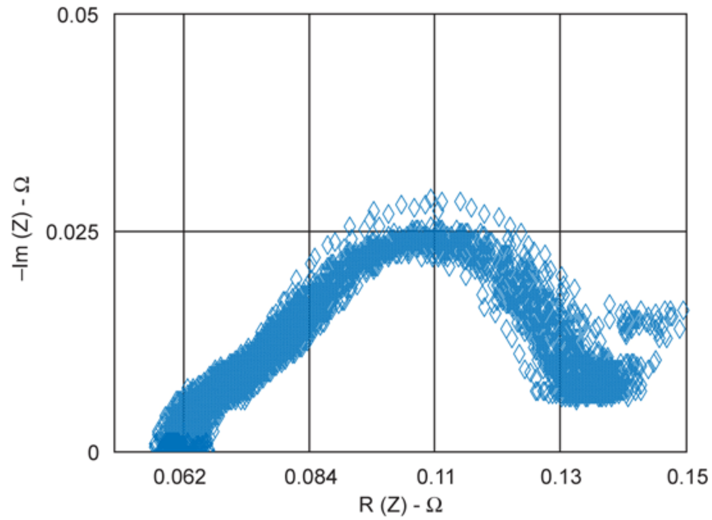


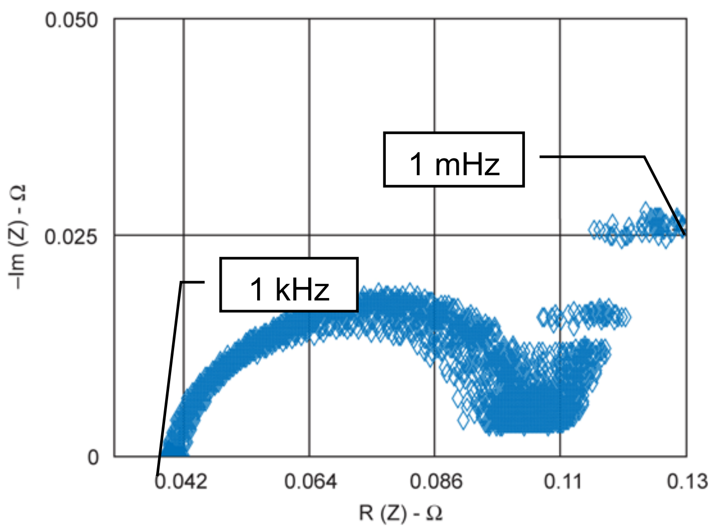
Corresponding Impedance Spectrum



*E. Barsoukov et al., J. New Materials for Electrochem. Sys., 3, (2000) 301

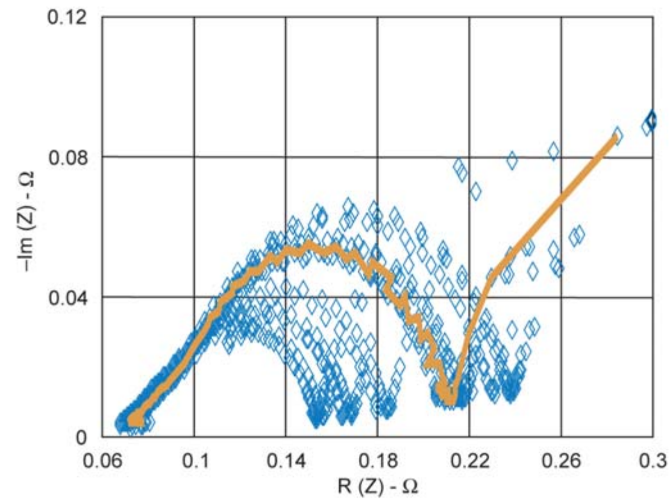
Effect of Impedance Differences of New Cells

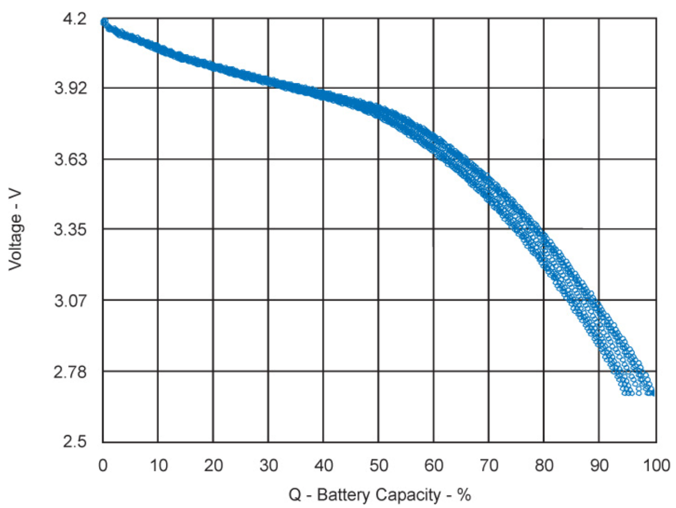




- New cells made by same manufacturer (even in the same batch), and in same state of charge, have significant impedance differences
- Common industry impedance measurement at 1 kHz gives false feeling of security by being similar for different cells. However, only low-frequency impedance reflects DC performance
- 50 cells reviewed for 2 different manufacturers showed low-frequency (1 mHz) impedance variation ±15%
- At 1C rate discharge, this difference amounts to about 40-mV difference, which results in maximum SOC error of ±15% as shown in previous slide

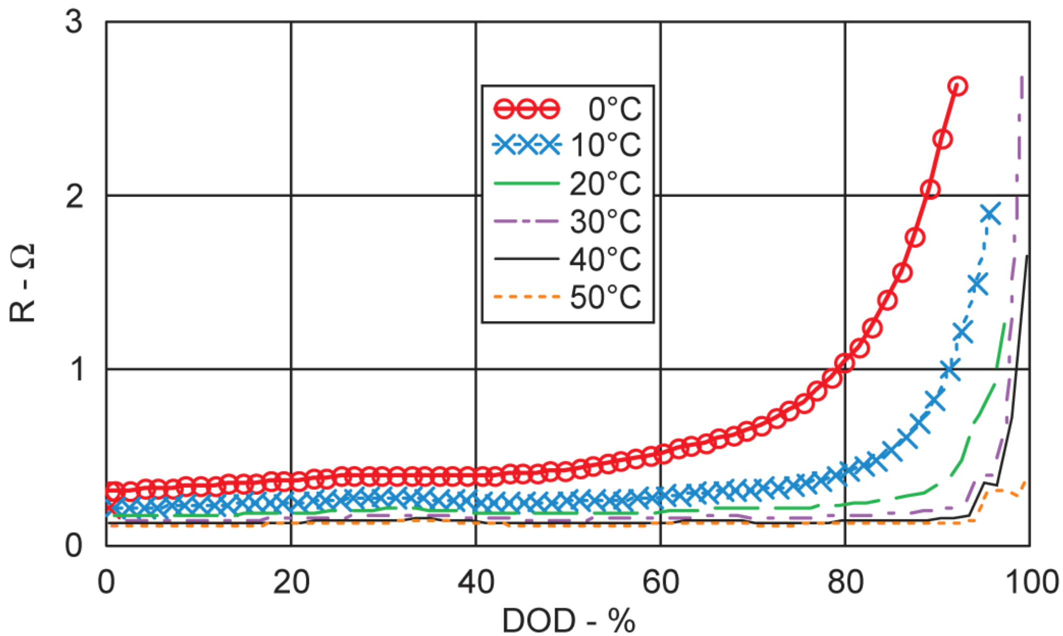
Voltage Error Due to Impedance Change During Aging





- Increase of battery impedance with aging is much faster than the decrease of capacity
- At 70 cycles, impedance typically doubles compared to original
- This change of impedance results in voltage-drop error of 75 mV at 1C rate in fully charged state, and much bigger one in discharged state
- Impedance increase widely depends on usage conditions such as temperature. Therefore, estimation of aging by cycle counting has limited precision

Impedance Dependent on Temperature and Depth of Discharge (DOD)



- Limiting impedance is strongly dependent on temperature in both value and profile shape
- Pulse-relaxation profiles are acquired at different temperatures to provide temperature dependence database

Effect of aging on voltage correlation based fuel-gauging

- Impedance increase with aging introduces significant error in both IR correction or SOC(V,I,T) table based methods
- Some existing algorithms relay on correlation between R increase and number of cycles.
- However, this correlation is vague because R increase depends on usage conditions (such as temperature, recharge frequency, storage time) more then on number of cycles.

Voltage integration based fuel-gauging

Advantages

- Learning can occur without full discharge
- No correction for self-discharge needed

Disadvantages

- I· R correction introduces significant error because of relaxation effects and variations of R from cell to cell, so accuracy is generally lower then in integration methods
- Common noisy operation environments results in SOC value fluctuations
- Significant data collection for SOC(I,V,T) database is needed for every new battery model

The POWER Behind Your Designs

How to improve handling of battery aging?

- Combine advantages of voltage and current based methods
- Use voltage based method where no load is applied to battery, to determine starting SOC and no-load capacity degradation
- Use current integration based method when under load
- Update impedance at every cycle using voltage and current information
- Calculate remaining run-time at given average load using both open circuit voltage and impedance information.

TI Innovation: Impedance Tracking

- Impedance Track Technology is a TI-patented technique for accurate battery gauge implementation

- <u>bq20z80-based fuel gauge system has been ramped to production in 2005</u>

(12) **United States Patent**
Barsoukov et al.

(10) **Patent No.: US 6,789,026 B2**
(45) **Date of Patent: Sep. 7, 2004**

(54) **CIRCUIT AND METHOD FOR MONITORING BATTERY STATE OF CHARGE**

(75) Inventors: **Evgenij Barsoukov**, Dallas, TX (US); **Dan R. Poole**, Austin, TX (US); **David L. Freeman**, McKinley, TX (US)

(73) Assignee: **Texas Instruments Incorporated**, Dallas, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/428,689**

(22) Filed: **May 2, 2003**

(65) **Prior Publication Data**

US 2004/0128086 A1 Jul. 1, 2004

Related U.S. Application Data

(60) Provisional application No. 60/437,313, filed on Dec. 29, 2002.

(51) **Int. Cl.**[7] **G01R 31/36**
(52) **U.S. Cl.** **702/63**; 320/104; 320/132; 324/427; 324/428
(58) **Field of Search** 702/63–67, 71; 320/104, 107, 134; 324/426, 427

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,357,203 A	* 10/1994	Landau et al.	....	324/427
5,691,078 A	11/1997	Kozaki et al.	....	429/92
5,949,217 A	9/1999	Okada et al.	....	320/132
6,061,639 A	5/2000	Wistrand	....	702/63
6,107,779 A	8/2000	Hara et al.	....	320/132
6,404,163 B1	* 6/2002	Kapsokavathis et al.	....	320/104

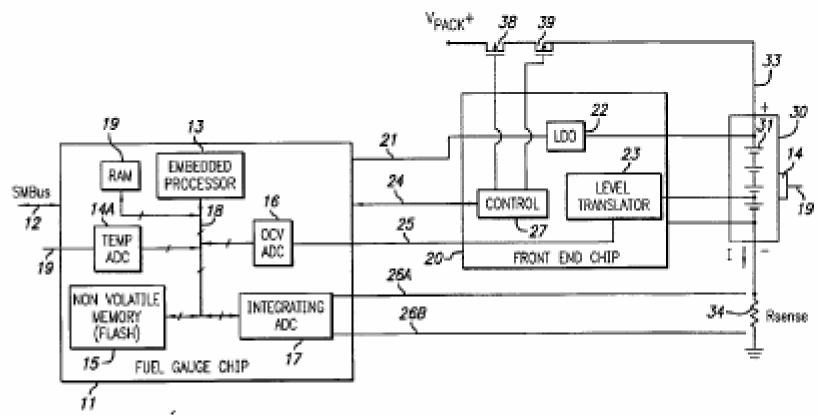
* cited by examiner

Primary Examiner—John Barlow
Assistant Examiner—John Le
(74) *Attorney, Agent, or Firm*—W. Daniel Swayze, Jr.; W. James Brady; Frederick J. Telecky, Jr.

(57) **ABSTRACT**

A processor (**13**) operates to determine amount of charge presently stored in a battery by determining that the battery is in a zero-current relaxed condition. Circuitry (**16**,**23**) including a first ADC (**16**) measures an open circuit voltage (OCV) of the battery prior to a period of time during which flow of current through the battery is not negligible. A program executed by the processor correlates the measured open circuit voltage (OCV**0**) with a corresponding value of the variable and selects the corresponding value as a value of the variable.

38 Claims, 4 Drawing Sheets



How does Impedance Track work?

- Combines voltage measurements with coulomb counting
  - SOC calculated from OCV (C/50) as a starting point: OCV occurs during periods of system inactivity (%FULL) – consistent among supplies with same anode and cathode materials
  - Coulomb counting used to calculate capacity (DELTA)
  - Discharge capacity (FCC) updated as a function of SOC(start), SOC(end), and current integration
  - Real-time impedance measurement (Impedance Track) corrects FCC for impedance changes (aging, long storage, wear-out)

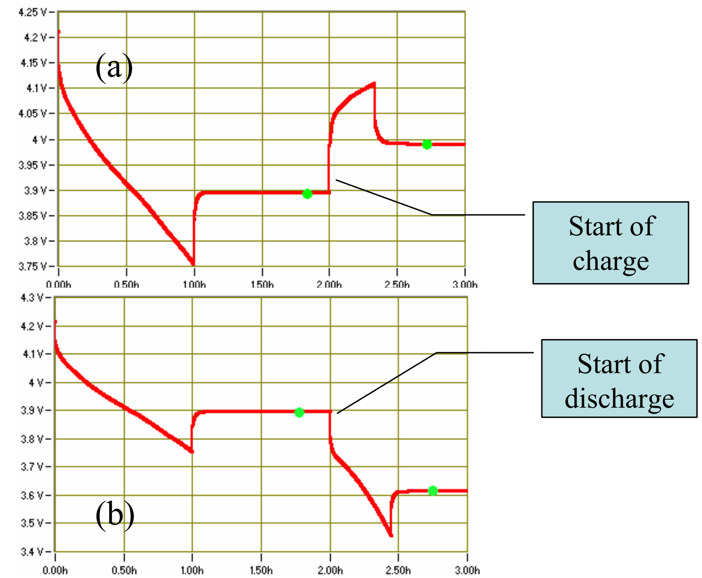
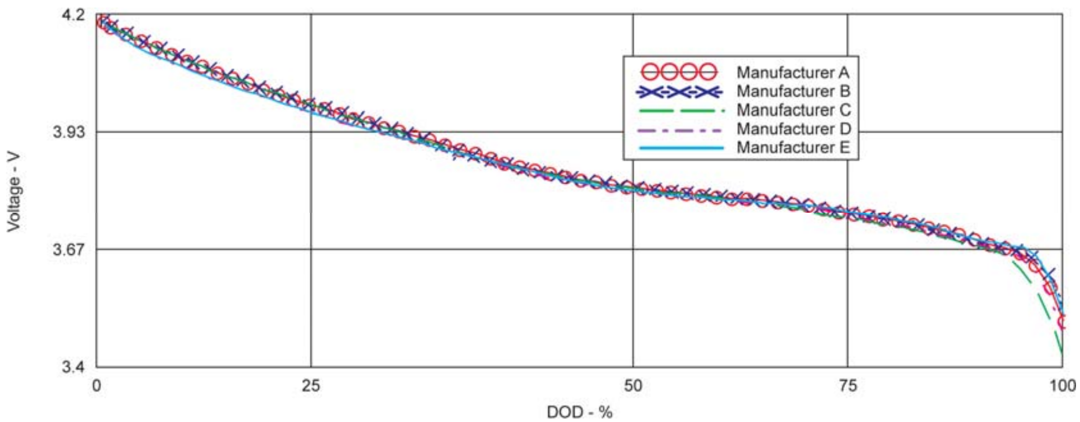


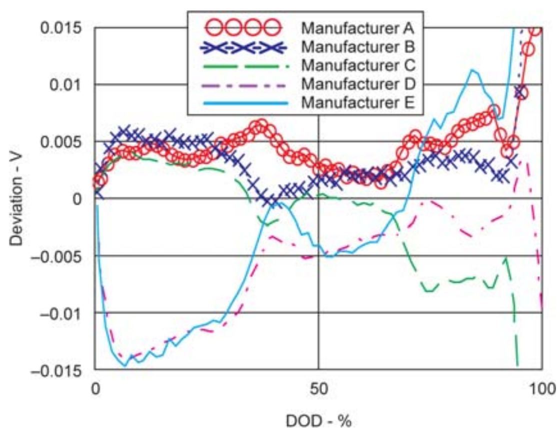
Fig. 9 Determining starting SOC for next active period and final SOC after charging (a) or discharging (b) known amount of charge through battery by OCV measurement after relaxation from previous active period.

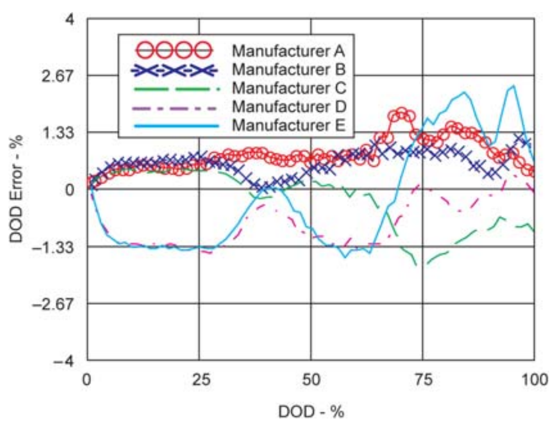
Remaining Capacity = (%FULL * FCC) – DELTA

$$R = \frac{OCV - V(rate)}{I}$$

Comparison of OCV/DOD Profiles for 5 Manufacturers

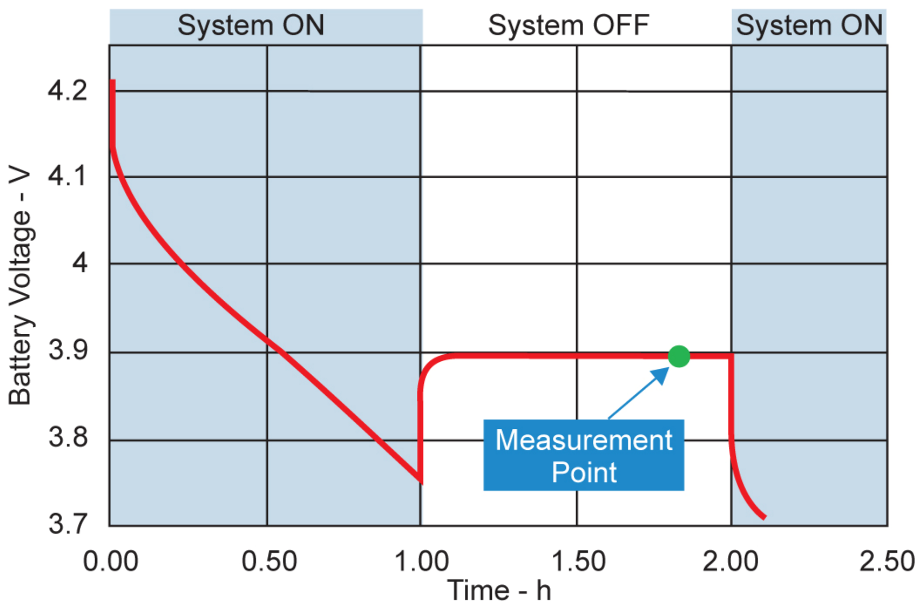






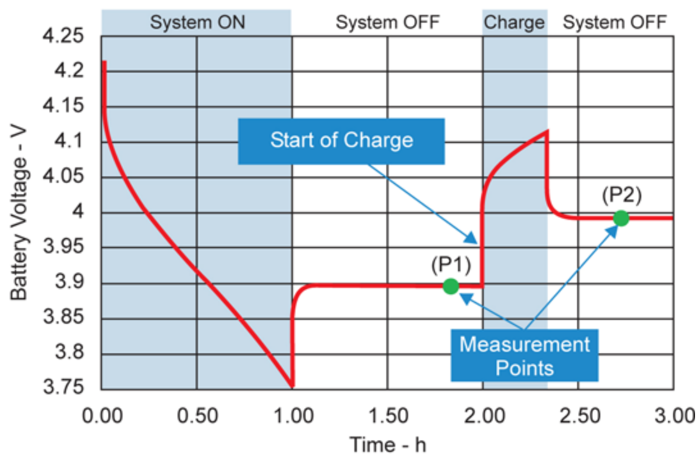
- OCV profiles similar for all tested manufacturers
- Most voltage deviations from average are below 5 mV
- Average DOD prediction error based on average voltage/DOD dependence is below 1.5%
- Same database can be used with batteries produced by different manufacturers as long as base chemistry is same
- Generic database allows significant simplification of fuel-gauge implementation at user side

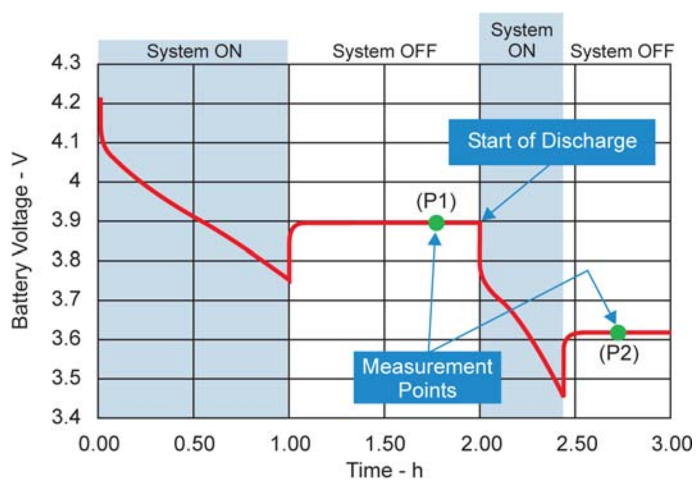
Improved Initial State Estimation Using OCV from Last Wake-up Measurement



- Precision of OCV measurement allows SOC with 0.1% max error
- 1000 seconds is sufficient relaxation time for all tested batteries
- If time between last termination and new start is less then 1000 seconds, previous SOC can be used because self-discharge is negligible
- Therefore, the need for self-discharge estimation is eliminated

Removing the Need of Full Discharge to Account for Capacity Fade





- Problems with full discharge
  - Takes long time, so rarely used if at all. Errors can accumulate between updates and cause erroneous values due to temperature dependence of termination or point load spike
- Solution
  - Full capacity can be detected by comparing SOC before and after exposure to load. SOC is obtained from OCV points (P1) and (P2)
  - Charge passed during exposure is determined by exact coulomb counting
  - Method works for both charge or discharge exposure

Summary – Battery Capacity Monitoring

- **Problems of existing methods**
  - Need for full-discharge removed for capacity correction
  - Difficulty with low-current coulomb counting removed
  - Cumulative uncertainty associated with self-discharge correction removed
  - Correction for change in cell impedance eliminates large errors in run-time estimation in aged cells

- **Improvements with Impedance Track ™ algorithm**
  - Easy implementation on user side: removed the need for user-database collection for most cases
  - Additional flexibility: Automated database collection for new chemistries supported on chip
  - New level of precision due to continuously updated total capacity and resistance