Fundamentals of Battery Charger

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Agenda

• Introduction
• Battery Management Solutions Overview
• Battery Basics
• Battery Charging Considerations and Requirements
• Charger Topology
• Switch-mode Charger
• Advanced Charger
• USB On-the-Go (OTG)
• Typical Safety Features
• Complete Charger Systems
• Learn More
Introduction

• **Sam Wong**
  – Systems & Validation Manager, Switching Charger Solutions Product Line

• **Childhood and Education**
  – Born in Hong Kong
  – University of Texas at Austin, B.S., 1996
  – University of Texas at Dallas, M.S., 2002

• **Career Path**
    • MCU, ADC, Phase-Lock Loop, Temperature Sensors
  – Systems Engineer, TI BMS-Gauge (2009-2012)
  – Systems Engineer, Member Group Technical Staff, TI BMS-Charger (2012-2015)
  – Applications Manager, Member Group Technical Staff, TI BMS-Charger (2015-2016)
  – Systems & Validation Manager, Member Group Technical Staff, TI BMS-Charger (2016-now)
Introduction – Objective of Today

• Introduce battery management systems (BMS) and why it’s important
• How multi-disciplines approach (chemistry, analog and power) enable BMS
• How BMS makes our life better
Overview - Battery Management Solutions

Consumer
- Smartphone
- Power Bank
- Sports Cam
- Tablet
- Portable Audio
- MiFi
- Gaming

Wearables
- Fitness
- Smart watch

Industrial
- POS
- Handheld meters
- Drone
- Security
- Medical
- Robotic
- Super cap
- Solar

NB
- Laptop
- Ultrabook

Automotive
- E-Call
- Dash Cam
- Smart Control
- Telematics Car/Fleet Trac
Overview – Battery Management Trends

• **Ever Increasing Battery Capacity**
  – Supports Multi-core CPU for higher performance.
  – Supports long run time

Source: Mediatek http://heliox20.com/
Overview – Fast Charging Trends

Top Chinese Smartphones Charging Time

- 0 to 60%: 10 min
- 25 min
- 38 min
- 15 min
- 33 min
- 60%
Overview – Battery Management Trends

Samsung Galaxy Note 7 Batteries Reportedly Catch Fire

SEUL, South Korea — Almost $7 billion was wiped off smartphone giant Samsung Electronics Co Ltd's market value Thursday after it delayed shipments of its Galaxy Note 7 amid reports of exploding batteries.

Faults with the new flagship device could be a major blow to the South Korean firm. Samsung was counting on the Galaxy Note 7 to maintain momentum against Apple's new iPhones — which are expected to be unveiled next week.

"This is some major buzz-kill for Samsung, especially given all of the hard-earned excitement that products like the Note 7 have been garnering lately," IDC analyst Bryan Ma said. "The
Overview - Requirements of Battery Management Solutions

Safety
- No fire
- Maintain battery cycle life

Charging
- Charge from empty to full
- Fast charge
- Universal charging

Discharging (Gauging)
- Long run time
- Accurate capacity measurements

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Overview - Battery Management Components

**System Host**

- **PMIC Multi-Rail**

**DC/DC Converter(s)**

- **System Rails**

**Pack+**

- **Chemical Fuse**

**Pack-**

- **Sense Resistor**

**Li-Ion Battery Pack**

**Charger IC**

- **1-4 Cells**
- **Host Controlled SMBus or Stand Alone**

**Fuel Gauge IC**

- **Protection**
- **Over/Under Voltage Gauging**
- **Temp Sensing Charge Control Authentication**

**AFE IC**

- **Analog Interface**
- **Over Current Cell Balancing**

**Secondary Safety Over Voltage Protection IC (Optional)**

**PMIC**

- **SPI or I2C**

- **3 V / 5V**

**DC+**

- **AC Adapter**

**DC-**

- **DC/DC Converter(s)**
  - **3 V / 5V**

- **System Host**

- **Focus**

- **Li-Ion Battery Pack**

- **Support Components**

- **SPI or I2C**

- **CLK**

- **DATA**

- **Temp**

- **V_{CELL1}, V_{CELL2}**

- **Sense Resistor**
Battery Basics - 18650 Battery Cell

18650 Cell

Cell Capacity (mAh)

Xiaomi 16,000mAh Power Bank
Battery Basics - Battery Configuration - xSxP

Assume: 1100mAh each battery

1S3P
1100mAh x 3 = 3300mAh
3300mAh x 3.8V = 12.6Wh

2S3P
1100mAh x 3 = 3300mAh
3300mAh x 7.6V = 25.2Wh
Battery Basics - Why is Li-Ion popular?

• Li-Ion is more expensive, and requires more sophisticated pack management compared to other battery types… why has is become so widespread?

• 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
Typical Anode and Cathode Materials used for Li-Ion Cells

- All the above cells are considered “Li-ion”
- In addition to the different voltage ranges shown, they will 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
- The charge control (algorithm) needs to be tuned to the specific type of cell being used

<table>
<thead>
<tr>
<th>Cathode Material (LI+)</th>
<th>Li-CoO₂</th>
<th>Li-Mn₂O₄</th>
<th>Li-FePO₄</th>
<th>Li-NMC</th>
<th>Li-NCA</th>
<th>Li-CoO₂-NMC</th>
<th>Li-MnO₂-NMC</th>
<th>Li-CoO₂</th>
<th>Li-CoO₂</th>
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</thead>
<tbody>
<tr>
<td>Anode Material</td>
<td>Graphite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vₘₐₓ</td>
<td>4.20</td>
<td>4.20</td>
<td>3.60</td>
<td>4.20</td>
<td>4.20</td>
<td>4.35</td>
<td>4.20</td>
<td>4.20</td>
<td>2.70</td>
</tr>
<tr>
<td>Vₘᵢᵈ</td>
<td>3.60</td>
<td>3.80</td>
<td>3.30</td>
<td>3.65</td>
<td>3.60</td>
<td>3.70</td>
<td>3.75</td>
<td>3.75</td>
<td>2.20</td>
</tr>
<tr>
<td>Vₘᵳᵡ</td>
<td>3.00</td>
<td>2.50</td>
<td>2.00</td>
<td>2.50</td>
<td>2.50</td>
<td>3.00</td>
<td>2.00</td>
<td>2.50</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Battery Basics - Variations of “Li-Ion” Batteries
Battery Model - Battery Equivalent Circuit

- Battery is equivalent to a huge cap + parasitic resistor (over simplified)

![Diagram showing battery model]

- Constant Current
- Capacitor Voltage
- 4.2V
- 3.0V
Battery Model - Battery Equivalent Circuit

- Battery is equivalent to a huge cap + parasitic resistor (over simplified)

\[ C \cdot \Delta V = I \cdot \Delta t \ (mAh) \]

- For a given battery, higher charging current (mA) can reduce the charging time (h)
Battery Model - Battery C-rate

• Expressing current relative to nominal battery capacity
• If nominal capacity is 1100mAh
  – 1C discharge rate means discharge of a fully charged battery in 1 hour when $I_{\text{discharge}} = 1100$ mAh
Battery Model - Li-ion Battery Resistance Profile

Impedance is strongly dependent on Temperature, State of Charge (SOC) and Aging

DOD=1-SOC (State of Charge)
SOC=1 (Full charged battery)
SOC=0 (Full discharged battery)
Battery Basics - Effect of battery impedance on run-time

Battery Voltage (V)

4.2
3.9
3.6
3.3
3.0
2.7
2.4

OCV (no load)

I \cdot R

Low impedance cell (loaded)

High impedance cell (loaded)

End of Dsg

Battery Capacity
Battery Charging - Charging System Considerations

- **Battery**
  - Battery chemistry, number of cells... 1s2p, 1s3p, 3s1p, etc.
  - Charge current, battery voltage, and charger profile

- **System**
  - Input voltage, adapter current, system voltage, board size and thickness
Battery Charging - “Ideal” Li-Ion CC-CV Charge Curve

Charge Characteristics
Measurement temperature: 20°C
Charge: CC-CV: 2.1A-4.2V (3hrs.cut)

Cell voltage
“CC”
“CV”
capacity
current

Charge time (min.)

Cell voltage (V)
0 30 60 90 120 150 180
2.0 2.5 3.0 3.5 4.0 4.5

Current (mA)
0 500 1000 1500 2000 2500

Capacity (mAh)
0 500 1000 1500 2000 2500

UR18650F

Texas Instruments
Battery Charging

• Constant Current (CC) and Constant Voltage (CV) required
• CV requires more time than discharge
Battery Charging - “Li-Ion needs high accuracy charge control

- 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 LiCoO₂,” Journal of Power Sources 111 (2002) 130-136
Battery Charging - Charging System

• **Charging system functions:**
  - Regulate battery inputs: constant voltage and constant current
  - Safety of charging
  - Status of charging
Charger Topology

Linear Charger

Switch-mode Charger
Charger Topology – Linear Power Conversion

Conduction Loss Dominates

\[ P_{\text{LOSS}} = (V_{\text{IN}} - V_{\text{OUT}}) \times I_{\text{CHG}} \]

Efficiency can only be 50-90%
Charger Topology – Switch-mode Power Conversion

Conduction Loss Dominates

\[ P_{\text{LOSS}} = P_{\text{LOSS}_Q2} + P_{\text{LOSS}_Q3} \]

\[ P_{\text{LOSS}_Q2} = I_{\text{CHG}}^2 \times R_{\text{DS}_Q2} \times D \]

\[ P_{\text{LOSS}_Q3} = I_{\text{CHG}}^2 \times R_{\text{DS}_Q3} \times (1-D) \]

Where Duty Cycle \( D = \frac{V_{\text{OUT}}}{V_{\text{IN}}} \)

Efficiency can be 85-95%
Charging Topology - 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 ~ 1A and higher should use switching charger… or, if you need to maximize charge rate from a current-limited USB port
# Charging Topology - LDO vs Switch-mode

<table>
<thead>
<tr>
<th>Linear</th>
<th>Switch-mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Thermal performance depends on $V_{OUT} - V_{IN}$</td>
<td>• Good thermal performance across wider $V_{OUT} - V_{IN}$ range</td>
</tr>
<tr>
<td>• Lower charging current</td>
<td>• High charging current</td>
</tr>
<tr>
<td>• No EMI concern</td>
<td>• Proper layout needed for best EMI performance</td>
</tr>
<tr>
<td>• Simple</td>
<td>• High efficiency</td>
</tr>
<tr>
<td>• Lower cost</td>
<td>• High cost</td>
</tr>
</tbody>
</table>

**Linear**

- +
- $V_{IN}$

**Linear Charger**

```
+ V_IN
- Battery
```

**Switch-mode**

```
V_IN
```

**System**

```
Battery
```

**Switch Charger**
Switch-mode Charger – Basic Waveform
Switch-mode Charger – Basic DC/DC

- Single voltage or current loop
- Dynamic response
- Single source and load

Diagram shows a basic DC/DC converter setup with key components labeled:
- Compensation
- EAO
- PWM
- Driver
- Vin
- S
- Vo
- V_ref
- I_ref

Graphs show:
- Output Voltage
- Output Current
- Time
Switch-mode Charger – Basic Charger

- **Battery charger:**
  - Constant voltage and constant current loops
  - High accuracy of voltage regulation (0.5% Charger vs 5% DCDC)
  - Battery can be a *load* or a *source*
Q: How to handle different input sources?

- Different Input sources with *known* current capability
  - OEM adaptor
  - USB port

- **Input Current DPM**
  - Limit the input current with the system load as high priority

**Benefit:**
Maximize the utilization of adaptor capability *without* overloading
Q: How to handle third party adaptors?

- Different Input sources with *unknown* current capability
  - Non-OEM adaptors
  - Traveler adaptor

- Input Voltage DPM (VINDPM)
  - Limit the input voltage with the system load as high priority

**Benefit:**
Maximize the utilization of adaptor capability **with** limited overloading
Advanced Charger – Thermal Regulation

• 32ºC rise with high charge current

• 12ºC rise with low charge current

• How to prevent system from over-heat
Advanced Charger - Thermal Regulation Loop

Q: What to do if the device is too hot?

- Thermal regulation
  - Better customer experience
  - Safe charging
  - Continuous charging current

![Diagram of Advanced Charger - Thermal Regulation Loop](image)
• Charge current can be automatically adjusted to maintain a pre-determined max die temperature.
Advanced Charger – BATFET Power-path Management

Q: How to power up system when battery voltage is low?

- Plug in adaptor and no response
- Bad user experience
Advanced Charger – BATFET Power-path Management

- Add a switch to separate the system and battery
- **When battery voltage is low (< 3.6V)**
  - Buck regulates to Vout (3.6V)
  - Linear regulates BATFET to provide charge current
- **When battery voltage is high (> 3.6V)**
  - Fully enable BATFET
  - Buck regulates to Vbat

![Diagram of Advanced Charger with BATFET Power-path Management](image)
USB On-The-Go – What is OTG

- Allow devices to communicate with each other
- USB Host can provide **power** to accessories

**Power** accessories such as USB sticks, mice, keyboards

**Charge** accessories such as wearable or phones

Power accessories such as USB sticks, mice, keyboards

Charge accessories such as wearable or phones
USB On-the-Go: OTG Implementation

- Charge runs in buck converter during charging mode.
- In USB On-the-Go Mode (OTG) the buck converter is reversed to run as boost converter to provide OTG power.

**Highlights:**
- Minimal additional loop control
- Re-use loop control analog
- Re-use power components.
Typical Safety Features

**ACOV**: Input Overvoltage Protection

**Charge time protection**: Precharge + fast chg safety timer

**OTG OCP**: OTG output current limit

**Cycle-by-Cycle OCP**: Over current protection for charging and OTG

**SYSOVP**: System Overvoltage Protection

**BATOC**: Battery over current discharge protection

**BATOV**: Protection from Overcharge

**BAT temp protection**: Thermistor Monitoring for Battery overtemp / undertemp

*Host*

**Input 3.9V-14V**

**Thermal protection**: Thermal regulations or shutdown for device overtemp

*Destructive tests are performed on all chargers family to ensure “No Smoke”*
Complete Charger System (Multi-Disciplines Engineering)

- Battery Chemistry
- Power Electronics
  - Switch-mode converter
  - Linear regulator
- Analog
  - Loop Controls
- Digital
  - State-machines
- Regulatory
  - Understand of safety requirements
Learn More - Battery Power Management for Portable Devices

- Battery Chemistry Characteristics
- Battery Charging Techniques
- Battery Safety and Protection
- Cell-Balancing
- Battery Fuel Gauging
- System Battery Power Management Solutions

Available at:
- Amazon.com
- Artechhouse.com
Summary

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Thanks You !!