Power Management

Introduction

Courtesy of Dr. Sanchez-Sinencio’s Group
Today

• What is power management?
• Big players
• Market
• Types of converters
• Pros and cons
• Specifications
• Selection of converters
Power Management

Motivation

- Portable consumer electronics
- Alternative energy systems
- LED lighting
- IoT
- Automotive

Global power management IC market size and forecast, 2012 – 2019 (USD billion)

Annual power management IC market revenue ($B USD)

(Source: Power Integrated Circuit - Quarterly Update Q1-2017 report, June 2017, Yole Développement)

Compound Annual Growth Rate: 3.6% from 2016 to 2022

Power management

- Power management broadly refers to the generation and control of regulated voltages required to operate an electronic system.
- Distributed power supply systems require localized regulators at the PC board level.
- Power requirements:
  - Low noise
  - Increased efficiency
- Two methods:
  - Linear regulators
  - Switching regulators
Power management

Applications

- Battery Charger
- Fuel Gauge
- Flyback Controller
- PFC Controller
- 3V ~ 4.2V Battery
- 12V Consumer Adapter
- 24/48V Industrial Supply
- AC line
- Low-noise LDO
- DC/DC Boost, Power Switch
- DC/DC Buck-boost
- DC/DC Buck
- DDR Terminator
- Audio Amplifier
- DC LED Driver
- AC LED Driver
- 3V Wireless Module
- 5V USB Port
- 3.3V Sensor
- 1V System on Chip
- 1.8V/0.9V DDR Memory
- 8Ω Speaker
- LED backlight LCD Panel
- LED Lamp 13V/0.8A

Key players

- Texas Instruments, Inc.
- Alpha and Omega Semiconductor
- Analog Devices
- STMicroelectronics
- Mitsubishi Electric
- Renesas Electronics Corporation
- Dialog Semiconductor PLC
- Linear Technology Corporation
- Maxim Integrated
- ON Semiconductor, Rohm Co., Ltd.
- Samsung Semiconductor
- Semtech Corporation
Power management

Distributed power supply system

Data acquisition board
Power management

Why is Power management necessary?
• Increasing chip functionality and complexity will overrun energy budget
• Need for improved efficiency
• For portable applications
  – Use low power, low cost SoC
• Single battery operation
  – Low voltage circuits
• Battery life extension
  – Efficient regulators/converters
  – Standby mode operation
Power management

Trends

• Move towards lower supply voltages
• Power management is the often misguided attempt to operate the analog and digital circuitry on the same supply
• Reducing supply voltage results in lower power dissipation, reduced dynamic range of signal
• Adoption of unipolar supplies (eliminating negative supply)
Power management

Why convert and regulate?

• Need to convert to appropriate voltage circuit needs
• Need to regulate to ensure proper circuit operation/performance
  – If there is an increase/decrease in the amount of current that is drawn, the output voltage should not fall/rise - **Load regulation**
  – If there is a change in the input voltage of our power supply the output voltage should not change - **Line regulation**
• There are other desirable characteristics such as: transient response, efficiency, EMI, cost, size
Power management

Types of converters

• Linear regulators
  – Work by operating a transistor in the linear region (i.e. like a variable resistor), sensing the output voltage (Vout) and automatically changing this variable resistor value such that Vout remains constant
  – Pros: Cheap, simple, small size
  – Cons: Inefficient, low current applications, limited input/output ranges

• Switching regulators
  – Convert a given supply voltage with a known voltage range to virtually any desired output voltage
  – Switching converter delivers power to the load in bursts from the source.
  – Pros: efficient, wide operating range
  – Cons: EMI, inductor usage-board size increased, increased cost

• Switched capacitor voltage converters
  – Uses capacitors for transfer of energy
  – Pros: can be integrated, small size
  – Cons: inefficient, regulation needed
Selection/Design of Power management devices

Terminologies

- **Input-Output voltage relation**: Based on the input output voltage relation, different converter types should be used. If $V_{out}$ is less than $V_{in}$, a step-down (BUCK) converter is used. If $V_{out}$ is greater than $V_{in}$, a step-up (BOOST) converter is used. If both cases are required, a BUCKBOOST converter is used. If $V_{out}$ and $V_{in}$ have different polarity, an inverting converter is used.

- **DC line regulation**: Change in output voltage for a change in input voltage. This measurement is made under conditions of low power dissipation.

- **DC load regulation**: Change in output voltage for a static change in output/load current.

- **Efficiency**: Power efficiency is defined as the percentage of the input power that is delivered to the output. Ideally, switching converters can approach 100%.

- **Input voltage (Vin) range**: The input voltage range determines the maximum and minimum allowable input supply for the converter. Input supplies higher than the maximum allowable input can damage the converter.

- **Maximum output current (Iout)**: Maximum output current that the converter can provide while meeting the datasheet parameters.

- **No load current operation**: Several applications need the converter to hold the output voltage stable and provide good performance under a no current load condition.

- **Output voltage noise**: The switching nature of the switching converters results in an output tone with harmonics.

- **Over-current protection**: This feature limits the maximum amount of current that the converter can source.
Selection of Power management devices

Terminologies

- **Power supply rejection ratio (PSRR)** - A measure of how well the converter rejects electrical noise at the input voltage when measured at the output voltage.

- **Quiescent current (Iq)** - Also called ground current, is the current used to operate the converter, and is not delivered to the load. This is measured when the converter is enabled and the output/load current is zero (0).

- **Transient line regulation** - Ability of the converter to maintain a constant output voltage with a transient step at the input.

- **Transient load regulation** - Change in output voltage for a dynamic (step) change in output current.

- **Temperature coefficient** - This describes the output voltage variation with respect to the temperature variation. Usually measured in “parts per million” (ppm).

- **Output voltage ripple amplitude** - This identifies the maximum peak-to-peak ripple amplitude of the output voltage.

- **Soft-start operation** - Guarantees that the output voltage will ramp-up slowly from zero to the required output voltage.
Selection of Power management devices

- Depends a lot on the input and output conditions of the application
- Based on the specific application requirements, different power conversion components could be selected
- Various parameters need to be considered for optimal component choice
- Specific application requirements like efficiency, thermal limits, noise, complexity and cost need to be taken into consideration in order to select an optimal power solution
## Selection of Power management (PM) devices

### Selecting your PM device

<table>
<thead>
<tr>
<th>Condition</th>
<th>Topology</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>When to use</th>
</tr>
</thead>
</table>
| $V_{OUT} < V_{IN}$ | LDO (Linear Regulator) | • Simple  
• Cheap  
• Low noise  
• Fast | • Low efficiency  
• Thermal limit | • Low current  
• Low $V_{IN} \rightarrow V_{OUT}$ ratio  
• Noise sensitive application |
| $V_{OUT} > V_{IN}$ | Boost              | • Good efficiency             | • Switch noise                 | • When $V_{OUT} > V_{IN}$ |
| $V_{OUT} \neq V_{IN}$ (changing $V_{IN}$) | Buck-Boost         | • Good efficiency             | • Switch noise                 | • When $V_{IN}$ can be smaller or larger than $V_{OUT}$  
• i.e.: Battery input |
Low drop-out linear regulator

- **LDO** is suitable for applications which require low noise, low current and low VIN / VOUT ratio
- LDOs regulate the output voltage by controlling the conduction of the pass element in a linear fashion
- Linear regulation provides accurate, noise free output voltage which can quickly respond to load changes on the output
Low drop-out linear regulator

- Linear regulation means that the voltage difference between input and output times the average load current is dissipated in the LDO pass element

\[ P_d = \frac{V_{in} - V_{out}}{I_{load}} \]

- LDO power dissipation exceeds ~0.8W, wise to look for alternatives

\[ V_{out} = V_{ref} \left( 1 + \frac{R_1}{R_2} \right) \]
Low drop-out linear regulator

Selecting or designing LDOs

- Consider the input and output voltage range
- LDO current capability
- Package dissipation capability
- LDO dropout voltage - minimum \( VIN - VOUT \) voltage where the device can regulate
- LDO quiescent current \( I_Q \)
Switching regulators

Analogy

- Imagine that an incandescent light bulb is to be dimmed whereby the switch is on 100% of the time,
- A resistor is placed in series with it and if switched on all the time then when the light is dimmed, energy is wasted in the resistor - (this is like the linear regulator)
- If instead of the resistor, switch is turned off for 50% of the time and then turned on for 50% of the time then light will be dimmed by 50%
- If the rate of switching is slow, (eg. once per second) then the light flickers, but if switching is fast then no flicker seen
- This is the basic principle by which step down switching power supplies work
Buck Converters

• Switch-mode step-down converters which can provide high efficiency and high flexibility at higher VIN / VOUT ratios and higher load current
• Most Buck converters contain an internal high side MOSFET and low side synchronous rectifier MOSFET
• Switches are switched on and off via internal duty-cycle control circuit to regulate the average output voltage
• Switching waveform is filtered via an external LC filter stage
Buck Converters

• MOSFETs are either ON or OFF, very little power dissipated
• Duty-cycle control makes large $\frac{V_{in}}{V_{out}}$ ratios possible
• Internal MOSFETs $R_{\text{ds_on}}$ determines the current handling capabilities of the Buck converter
• MOSFET voltage ratings determine the maximum input voltage
• Switching frequency together with the external LC filter components will determine the ripple voltage on the output
• Higher switching frequency buck converters can use smaller filter components but increased switching loss
• Low power standby modes- use a method called Pulse Skipping Mode (PSM): reduction in switching frequency at light load, thereby increasing light load efficiency
Boost Converters

• Boost converters are used when $V_{\text{OUT}}$ needs to be higher than $V_{\text{IN}}$
• Step-up the input voltage to a higher output voltage
• Accomplished by charging an inductor via an internal MOSFET switch, and discharging the inductor via a rectifier to the load when the MOSFET switch is off
• Transition from inductor charge to discharge will reverse the voltage across the inductor, thereby stepping up the voltage higher than $V_{\text{IN}}$
Boost Converters

• on/off duty-cycle of the MOSFET switch will determine $\frac{V_{out}}{V_{in}}$ boost ratio
• Feedback loop controls the duty-cycle to maintain stable output voltage
• Output capacitor is the buffer element to reduce the output voltage ripple
• Current rating of the MOSFET switch together with step-up ratio will determine the maximum load current
• MOSFET voltage rating will determine the maximum output voltage capability
Buck-Boost converter

Topology 1

- Used in applications where input voltage can vary, either below or above the output voltage (more flexibility)
- Input voltage is positive, and the output voltage is negative
- Switch is on, the inductor current builds up
- Switch is opened, the inductor supplies current to the load through the diode
- Circuit can be modified for a negative input and a positive output by reversing the polarity of the diode
Buck-Boost converter

Topology 2

• Circuit allows both the input and output voltage to be positive

• When the switches are closed, the inductor current builds up.

• When the switches open, the inductor current is supplied to the load through the current path provided by D1 and D2

• Output current capability in Buck mode is higher than in Boost mode, due to step-up requiring higher switch current at the same load conditions when compared to Buck mode

• MOSFET voltage ratings will determine the maximum input and output voltage range

• Fundamental disadvantage to this circuit is that it requires two switches and two diodes
Switched Capacitor converters

• Previous discussed topologies used inductors to transfer energy and perform voltage conversions
• Switched capacitor voltage converters accomplish energy transfer and voltage conversion using capacitors
• Not as efficient as an inductive-based converter
• Small solution size and ruggedness not found in the inductive alternative
• No magnetic elements
• Minimal EMI
• Two most common switched capacitor voltage converters are the voltage inverter and the voltage doubler
Switched Capacitor converters

- C1, is charged to the input voltage during the first half of the switching cycle
- During the second half of the switching cycle, its voltage is inverted and applied to capacitor C2 and the load
- Output voltage is the negative of the input voltage, and the average input current is approximately equal to the output current

- Pump capacitor is placed in series with the input voltage during its discharge cycle, thereby accomplishing the voltage doubling function
- Average input current is approximately twice the average output current

- Switching frequency impacts the size of the external capacitors required, and higher switching frequencies allow the use of smaller capacitors
- Duty cycle ~ 50%- optimal charge transfer efficiency
- Inverter and doubler circuits provide no output voltage regulation
Other power management devices

• LED drivers
  – Regulate for constant output current instead of constant output voltage, because LEDs need to be driven with certain current for specific light output
  – Most high brightness LEDs have a forward voltage between 3 ~ 3.5V
  – Depending on the input voltage and the number of LEDs used in the LED string, the converter can be a buck, boost or buck-boost (for different LED strings)
  – Key parameters for selecting LED drivers are input voltage, LED string voltage and LED string current, single / multi-string LEDs and dimming, whether the LED driver needs to fulfil power factor and THD requirements

• Power switches
  – Used to enable and disable power rails
  – EN pin is used to activate the pass element
  – current limit circuit will open the switch when output current exceeds the current limit threshold

• Battery chargers
  – Provide the correct charge current and voltage for the specific battery cell
## Summary

- Covered power management basics, terminologies, selections

<table>
<thead>
<tr>
<th>Linear</th>
<th>Switching</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Function</strong></td>
<td>Only steps down (buck) so input voltage must be greater than output voltage</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>Low to medium, but actual battery life depends on load current and battery voltage over time. Efficiency is high if difference between input and output voltages is small</td>
</tr>
<tr>
<td><strong>Waste heat</strong></td>
<td>High, if average load and/or input to output voltage difference are high</td>
</tr>
<tr>
<td><strong>Complexity</strong></td>
<td>Low, usually requiring only the regulator and low value bypass capacitors</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>Small to medium in portable designs, but may be larger if heatsinking is needed</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td>Low</td>
</tr>
<tr>
<td><strong>Ripple/Noise</strong></td>
<td>Low; no ripple, low noise, better noise rejection</td>
</tr>
</tbody>
</table>
Next class

• Linear regulators