Overview of Linear & Switching Regulators

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Introduction

Voltage References

Linear Regulators

Switching Regulators

Switched-Capacitor Voltage Converters
Introduction

Goals of the Seminar Series

- Provide an overview of power conversion techniques
  Power supplies are common subsystems in most of our products

- Present follow-up seminars in related areas
  → switching regulator topologies/compensation, simulation

- Offer refresher seminars in fundamental areas
  → mathematical modeling, circuit analysis, control design

http://compass.mot.com/go/powerconversion
Every electronic system needs a source of energy to operate

**Power supplies** provide circuits with ac/dc voltages/currents

**Power management** refers to strategies to generate and control regulated voltages

The regulation/control of energy from source to the consumer is accomplished using **power electronics**
### Types of Power Conversion

<table>
<thead>
<tr>
<th>Type</th>
<th>Process Name</th>
<th>Processor</th>
</tr>
</thead>
<tbody>
<tr>
<td>dc → dc</td>
<td>conversion</td>
<td>converter</td>
</tr>
<tr>
<td>ac → dc</td>
<td>rectification</td>
<td>rectifier</td>
</tr>
<tr>
<td>dc → ac</td>
<td>inversion</td>
<td>inverter</td>
</tr>
<tr>
<td>ac → ac</td>
<td>cycloconversion</td>
<td>cycloconverter</td>
</tr>
</tbody>
</table>

Most of the coverage will be devoted to **dc/dc converters**
# Types of dc/dc Converters

- **Voltage Reference**: $V_{BE}$-based voltage reference circuit
- **Linear Regulator**: Three-terminal circuit with a pass transistor (linear region)
- **Switching Regulator**: Regulator with a switching transistor and inductive storage
- **Switched-Capacitor Converter**: Inductorless voltage converter using capacitive charge transfer
- **Battery Charger**: Specialized converter with voltage/temperature monitoring

All converters except the **battery charger** will be covered.
Example 1: Notebook Computer

**Requirements**
- High performance
- Light weight
- Long battery life
- Fast charging

**Power System**
- Battery: Lithium-ion
- Charger: Switching rectifier
- $\mu$P: Buck converter
- Disk drive: Boost converter
- Display: High-voltage inverter
Example 2: Mobile Phone

**Requirements**
- High performance
- Small size
- Light weight
- Long battery life
- Fast charging
- Low cost

**Power System**
- Battery: Lithium-ion
- Charger: Switching rectifier
- Transmitter: Switching regulator
- Power Management: Linear regulator
- Power Management: Voltage reference
- Display: Regulated charge pump
Introduction to Voltage References

Characteristics

- Voltage reference and regulators have much in common
- Voltage references have great impact on accuracy of analog systems
- Drifting (temp/aging) may be more important than absolute accuracy
- VR must be chosen to account for temp. coefficient and aging
- Noise can also be an issue
- Dynamics (behavior at startup and transient loads)
General types of Voltage References

- **Two-terminal [diodes, Zener diodes]**
  - Flexible polarity
  - Restrictive loading conditions
  - Increased power dissipation with source resistor
  - Non-standard voltages (6.2V)

- **Three-terminal [TL431]**
  - Positive polarity
  - Lower, more stable quiescent current
  - Standard output voltages
  - Relatively high output current
Diode Reference

Simple diode reference

- $V_s$ is the input voltage.
- $I_D$ is the diode current.
- $R_s$ is the series resistor.
- $V_{ref}$ is the output voltage reference.
- $I_L$ is the load current.

Characteristics

- Current-driven forward-biased diode
- Junction drop $\approx$ independent of $V_s$
- Strong tempco of $\approx -2\text{mV/°C}$
- Sensitive to loading
- Inflexible output voltages ($n \times 600\text{mV}$)
- Polarity is reversible
- Load current $<<$ drive current
Zener Reference

**Zener reference**

- $V_s$
- $R_s$
- $V_{ref}$
- $D_1$
- $D_2$
- $I_D$
- $I_L$

**Characteristics**

- $D_1$ avalanche $\approx 5-8V$ with $+$tempco
- Forward biased $D_2$ has $-$tempco
- Net tempco is $\approx 100$ppm/$^\circ$C
- Limited loading
- Must be driven by a source $> 6V$
- Noisy due to zener breakdown
- 1N821–1N829 temp. comp. zener
Simplified bandgap reference (LM109/LM113)

\[ V_s \]

\[ I_z \]

\[ R_1 \quad 600\Omega \]

\[ R_2 \quad 6k\Omega \]

\[ R_3 \quad 600\Omega \]

\[ Q_1 \]

\[ Q_2 \]

\[ Q_3 \]

\[ V_{BE} \]

\[ \Delta V_{BE} \]

\[ \Delta V_{BE} \]

\[ V_{ref} \]
Bandgap Reference

\( \Delta V_{BE} \)

- Different emitter current densities \((J_1 \approx 10J_2)\) produce \( \Delta V_{BE} \)
- \( \Delta V_{BE} = \frac{kT}{q} \ln \frac{J_1}{J_2} = 0.0002T \) (at \( T = T_0 = 300^\circ K \), \( \Delta V_{BE} = 60mV \))

\( V_{BE} \)

- \( V_{BE} = \frac{kT}{q} \ln \frac{i_E}{I_s} \) but \( I_s \) is a strong function of temperature
- \( V_{BE} \approx V_{g0}(1 - \frac{T}{T_0}) + V_{BE0}(\frac{T}{T_0}) = 1.2(1 - \frac{T}{T_0}) + 0.6(\frac{T}{T_0}) \)

\( V_{ref} \)

- \( V_{ref} = \frac{R_2}{R_3} \Delta V_{BE} + V_{BE} \approx 1.2V \) (see plots)
- \( V_{ref} \) varies \(< 0.5\% \) from \(-55^\circ C\) to \(+125^\circ C\) (see LM113 graph)
\[ V_{BE} = 1.2\left(1 - \frac{T}{T_0}\right) + 0.6\left(\frac{T}{T_0}\right) \]

\[ \frac{R_2}{R_3} \Delta V_{BE} = 0.6 + 0.002(T - T_0) \]
Three-terminal reference

**TL431-based reference**

\[ V_{out} = (1 + \frac{R_1}{R_2}) V_{ref} \]

- \( R_1, R_2 \) should be precision resistors
- \( R_s \) is chosen to make \( I_D \geq 1\text{mA} \) at \( V_{s,\text{min}} \)
- Reference voltage is \( 2.495 \pm 0.055\text{V} \)
- Typically used as \( V_{ref} \) for linear regulators
Choose $R_1 = R_2$ to make $V_{out} = 5$V
Select $R_s$ to make $TL431$ cathode current $\geq 1$mA
Choose transistor $Q$ to handle $I_{out}$
Outline

1. Introduction
2. Voltage References
3. Linear Regulators
4. Switching Regulators
5. Switched-Capacitor Voltage Converters
Introduction to Linear Regulators

- Three-terminal devices – input, output, common (ground)
- Linear regulators may be classified by their series (pass) transistor
  - Series element may consist of bipolar of field-effect transistors
- Bipolar outputs → Darlington NPN, PNP, NPN-PNP
- Majority of regulators use bipolars (FET-based regulators $)
- Series transistor structure determines $V_{\text{dropout}}$, $I_{\text{bias}}$, $I_q$, $P_{\text{diss}}$
- Frequency compensation and protection circuitry also important

$V_{\text{dropout}}$  minimum input-output voltage difference to stay in regulation

$I_{\text{bias}}$  bias current for the pass transistor

$I_q$  regulator quiescent current of which $I_{\text{bias}}$ is one component

$P_{\text{diss}}$  regulator power dissipation
NPN Regulator

Characteristics
- NPN Darlington pass
- PNP driver
- Used in 78xx series
- $I_{bias} \approx I_{load}/\beta^3$
- Smallest chip area
- Small comp. capacitor
- Least expensive
- $V_{do} = 2V_{BE} + V_{sat} \approx 2.0V$
- No reverse battery protection
PNP Low Dropout (LDO) Regulator

Characteristics

- PNP pass
- NPN or EA direct drive
- \( V_{do} = V_{sat} \approx 600\text{mV} \)
- Inherent reverse battery protection
- \( I_{bias} \approx \frac{I_{load}}{\beta_{pnp}} \)
- Large chip area
- Large comp. capacitor
- More expensive

PNP (LDO) Regulator

\[ V_{in} \quad \begin{array}{c} \text{PNP pass} \\ \text{NPN or EA direct drive} \\ V_{do} = V_{sat} \approx 600\text{mV} \\ \text{Inherent reverse battery protection} \\ I_{bias} \approx \frac{I_{load}}{\beta_{pnp}} \\ \text{Large chip area} \\ \text{Large comp. capacitor} \\ \text{More expensive} \end{array} \]
Composite (Quasi-LDO) Regulator

Composite Regulator

\[ V_{in} \rightarrow \text{Error Amp} \rightarrow V_{out} \]

\[ I_{bias} \downarrow \rightarrow V_{ref} \]

\[ R_1 \rightarrow R_2 \rightarrow GND \]

Characteristics

- NPN pass
- PNP driver
- \( V_{do} = V_{BE} + V_{sat} \approx 1.3V \)
- \( I_{bias} \approx I_{load}/\beta^2 \)
- Compromise between NPN and PNP
- Larger chip area than NPN
- Large comp. capacitor
- No reverse battery protection
<table>
<thead>
<tr>
<th>Topology</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPN</td>
<td>smallest die size</td>
<td>large dropout voltage</td>
</tr>
<tr>
<td></td>
<td>fastest transient response</td>
<td>no rev. batt. protection</td>
</tr>
<tr>
<td></td>
<td>smallest comp. capacitor</td>
<td></td>
</tr>
<tr>
<td>PNP</td>
<td>low dropout voltage</td>
<td>high quiescent current</td>
</tr>
<tr>
<td></td>
<td>rev. battery protection</td>
<td>large comp. capacitor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>large die size</td>
</tr>
<tr>
<td>NPN/PNP</td>
<td>moderate dropout voltage</td>
<td>large comp. capacitor</td>
</tr>
<tr>
<td></td>
<td>lower $I_q$ than PNP</td>
<td>no rev. battery protection</td>
</tr>
</tbody>
</table>

Linear Regulator Performance Comparison

\[
P_{\text{diss}} = (V_{\text{in}} - V_{\text{out}})I_{\text{load}} + V_{\text{in}}I_{\text{q}}
\]

Power Dissipation

Linear Regulators for \( V_{\text{out}} = 5V \) and \( I_{\text{load}} = 100\text{mA} \) at 25°C

<table>
<thead>
<tr>
<th>Topology</th>
<th>Part</th>
<th>( V_{\text{do}} )</th>
<th>( I_{\text{q}} )</th>
<th>( P_{\text{diss}} ) at ( V_{\text{in}} = 12V )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPN</td>
<td>LM109</td>
<td>1.60V</td>
<td>5.15mA</td>
<td>(700+62) mW</td>
</tr>
<tr>
<td>PNP</td>
<td>CS8129</td>
<td>0.37V</td>
<td>45.0mA</td>
<td>(700+540)mW</td>
</tr>
<tr>
<td>NPN/PNP</td>
<td>CS8121</td>
<td>0.95V</td>
<td>2.50mA</td>
<td>(700+30) mW</td>
</tr>
</tbody>
</table>

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Switching converters are often referred to as switchers.
Conversion based on inductive storage and lowpass filtering.
Basic topology has one switch, diode, inductor and capacitor.
Input current ripple must not get on supply line (input capacitance).
Output voltage ripple depends on L, C and switching frequency.
Theoretical efficiency is 100% (elements in box are lossless).
Advantages/Disadvantages

<table>
<thead>
<tr>
<th>Linear</th>
<th>Switch-mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple, inexpensive</td>
<td>Complex, expensive</td>
</tr>
<tr>
<td>Electrically quiet</td>
<td>Electrically noisy</td>
</tr>
<tr>
<td>$V_{in} &gt; V_{out}$</td>
<td>Wide $V_{in}$ range</td>
</tr>
<tr>
<td>Poor efficiency (&lt; 60%)</td>
<td>High efficiency (&gt; 90%)</td>
</tr>
<tr>
<td>Physically large</td>
<td>Compact</td>
</tr>
<tr>
<td>Single output</td>
<td>Multiple outputs</td>
</tr>
</tbody>
</table>
Buck Converter

\[ \frac{V_{out}}{V_{in}} = D \]
Buck Converter – Steady-State Analysis

Buck Converter Circuit Modes

Steady-state operation requires $\langle v_L \rangle = \frac{1}{T_s} \int_0^{T_s} v_L dt = 0$

This is referred to as volt-second balance or flux balance

Mode 1 $\rightarrow v_L = V_{in} - V_{out}$; Mode 2 $\rightarrow v_L = -V_{out}$

$\langle v_L \rangle = \frac{1}{T_s} \left[ (V_{in} - V_{out})DT_s + (-V_{out})(1 - D)T_s \right] = 0 \Rightarrow \frac{V_{out}}{V_{in}} = D$
Boost Converter

\[ \frac{V_{out}}{V_{in}} = \frac{1}{1-D} \]

\[ V_{out} = V_{in} \cdot \frac{D}{1-D} \]

\[ DTS \]

\[ TS \]
Buck/Boost Converter

\[ \frac{V_{out}}{V_{in}} = -\frac{D}{1-D} \]
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Switched-Capacitor Voltage Converters (SCVC)

**Characteristics**
- SCVCs transfer energy and convert voltage without inductors.
- Voltage conversion accomplished by capacitive charge transfer.

**SCVC Inverter**

\[
\begin{align*}
V_{\text{in}} & \quad I_{\text{in}} \quad A \quad B \\
A' & \quad C_1 \quad C_2 \quad \text{load} \quad B' \\
\quad & \quad I_{\text{out}} \quad V_{\text{out}} \approx -V_{\text{in}}
\end{align*}
\]

**Steady-State Operation**
- **AA'**: \( V_{\text{in}} \) applied to \( C_1 \)
- **BB'**: \( V_{\text{in}} \) inverted & applied to \( C_2 \) and load
### Switched-Capacitor Voltage Converters (SCVC)

#### Advantages/Disadvantages

- Elimination of inductor & related design issues
- Low noise, minimal radiated EMI
- Simple implementation (2–3 external capacitors)
- Low cost, low profile, compact design
- Efficiency > 90%
- Optimized for doubling or inverting supply voltage
- Limited current output (typically 150-200mA)
- Basic SCVCs have no output voltage regulation
C_1 charged to V_{in} during 1st half of switching cycle
- During 2nd half, voltage is inverted and applied to C_2 and load
- V_{out} \approx -V_{in}, I_{in} \approx I_{out}
- After startup transient, C_1 provides small amount of charge to output
- Charge transfer depends on I_{load} and f_{sw}
- When C_1 is being charged, C_2 supplies load current \rightarrow voltage droop
- For same voltage droop, smaller caps can be used if f_{sw} is increased
Each SPDT switch can be implemented with 2 SPST switches
SPST switches can be implemented with a bipolar or CMOS process
IC SCVCs contain all the switches, oscillator and control circuits
Pump capacitor \((C_1)\), load capacitor \((C_2)\) are external
Voltage Doubler

Operation if very similar to the inverter
- $C_1$ charged to $V_{in}$ during 1st half of switching cycle
- During 2nd half, $C_1$ is placed in series with $C_2$ and load
- $V_{out} \approx 2V_{in}$, $I_{in} \approx 2I_{out}$
Voltage Doubler Implementation

Voltage Doubler

Implementation of inverter and doubler uses a common structure

- Most ICs allow implementation of either structure
  - (ADM660/ADM8660)
Conclusion

- Reference circuits used in many designs
- Linear regulators utilized when low-noise is important
- Switching regulators are more flexible and efficient
- Charge-pumps usually designed into ICs
- External components (e.g. filtering) are critical to performance
- Frequency response analysis essential in avoiding oscillations
- Modeling/simulation key to avoiding power supply design issues
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