Lecture 2: Voltage References/Regulators

ECEN 457(ESS): Op-Amps and Applications
Analog & Mixed-Signal Center
Texas A&M University
Agenda

• Last lecture
  – Motivation
  – Important Definitions

• Today
  – Voltage References
    • Bandgap Voltage Reference
  – Voltage Regulators
    • Shunt Regulator
    • Linear Regulators
Voltage References

- Thermal stability is very important in voltage references
  - IC components are strongly influenced by temperature
- Silicon pn junction, which forms the basis for diodes and BJTs.
  - Its forward-bias voltage $V_D$ and current $I_D$ are related:

$$V_D = V_T \ln\left(\frac{I_D}{I_S}\right)$$

where $V_T$ is the thermal voltage and $I_S$ is the saturation voltage.

- Their expressions are:

$$V_T = kT / q \quad I_s = BT^3 \exp\left(-\frac{V_{G0}}{V_T}\right)$$

where $k = 1.381 \times 10^{-23}$ is Boltzmann’s constant, $q = 1.602 \times 10^{-19}$ C is the electron charge, $T$ is the absolute temperature, $B$ is a proportionality constant, and $V_{G0} = 1.205$ V is the bandgap voltage for silicon.

- The TC of the thermal voltage is:

$$TC(V_T) = k/q = 0.0862 mV / C$$

- The TC of the junction voltage $V_D$ at a given bias $I_D$ is $TC(V_D) = \frac{\partial V_D}{\partial T}$

$$TC(V_D) = \frac{\partial V_T}{\partial T} \ln\left(\frac{I_D}{I_s}\right) + V_T \frac{\partial \ln\left(\frac{I_D}{I_s}\right)}{\partial T} = V_D^T / T - V_T^T \left(3\ln T - \frac{V_{G0}}{V_T}\right)$$

$$TC(V_D) = -\left(\frac{V_{G0} - V_D}{T} - \frac{3k}{q}\right)$$

Assuming $V_D = 650 mV$ at 25°C, we get $TC(V_D) \approx -2.1 mV/°C$. 
Bandgap Voltage Reference

- **Advantage:**
  - Low voltage ($V_{DD} < 5V$)

- Based on the idea of adding the voltage drop $V_{BE}$ of a base emitter junction, which has negative TC, to a voltage $KV_T$ proportional to the thermal voltage $V_T$, which has a positive TC.

\[
V_{BG} = K \cdot V_T + V_{BE}
\]

\[
TC(V_{BG}) = K \cdot TC(V_T) + TC(V_{BE})
\]

So \( TC(V_{BG}) = 0 \)

Thus, we need \[
K = -\frac{TC(V_{BE})}{TC(V_T)}
\]

\[
K = -\frac{V_{G0} - V_{BE}}{V_T} + 3
\]

\[
V_{BG} = \left[ \left( \frac{V_{G0} - V_{BE}}{V_T} \right) + 3 \right] \cdot V_T + V_{BE} = V_{G0} + 3V_T
\]

At 25°C we have $V_{BG} = 1.205V + 3 \times 25.7mV = 1.282V$!
Bandgap Voltage Reference (Brokaw)

- Based on two BJTs of different emitter areas.
- The emitter area of $Q_1$ is $n$ times as large as the emitter area $A_E$ of $Q_2$.
- Thus, the saturation currents satisfy $I_{s1}/I_{s2} = n$.

$$I_{c1} = \frac{V_{BE2} - V_{BE1}}{R_3} = V_T \left[ \ln \left( \frac{I_{c2}/I_{s2}}{I_{c1}/I_{s1}} \right) - \ln \left( \frac{I_{c2}/I_{s2}}{I_{c1}/I_{s1}} \right) \right] = \frac{V_T \ln \left( \frac{I_{c2}I_{s1}}{I_{c1}I_{s2}} \right) - V_T \ln (n)}{R_3}$$

$$V_{BG} = V_{BE2} + (I_{c1} + I_{c2}) \cdot R_4 = V_{BE2} + 2 \cdot I_{c1} \cdot R_4 = V_{BE2} + \left[ 2 \frac{R_4}{R_3} \ln (n) \right] \cdot V_T$$

$$V_{BG} = V_{BE2} + k \cdot V_T$$

where $$k = 2 \frac{R_4}{R_3} \ln (n)$$

$$V_{REF} = (1 + R_2/R_1)V_{BG}$$
To function as a regulator, the diode must operate well within the breakdown region under all possible line and load regulation. In particular, $I_Z$ must never be allowed to drop below some safety value $I_Z(\text{min})$. 
Shunt Voltage Regulator (Load Regulation)

\[ V_o = \frac{151.98}{151.98 + 470} \times 15V = 3.66V \]

At this point the circuit is a voltage divider!
Design Approach

1) \( V_{Z0} = V_z - r_z I_z \)

2) \( R_s \left( I_{z(\text{min})} + I_{o(\text{max})} \right) \leq V_{I(\text{min})} - V_{Z0} - r_z I_{z(\text{min})} \)

3) \( I_{Z(\text{min})} \approx \frac{I_{o(\text{max})}}{4} \)

Compromise between the need to ensure proper worst-case operation and avoid excessive power wastage.

Applying superposition principle, we find:

\[
V_{OUT} = \frac{r_z}{R_s + r_z} V_{IN} - \frac{R_s}{R_s + r_z} V_{Z0} - (r_z \parallel R_s) I_{OUT}
\]

\[\text{Line - regulation} = \frac{r_z}{R_s + r_z}\]

\[\text{Load - regulation} = -(r_z \parallel R_s)\]
Example 11.3

A raw voltage $10V \leq V_{\text{IN}} \leq 20V$ is to be stabilized by a 6.8-V,0.5-W,10-Ω Zener diode and is to feed a load with $0 \leq I_{\text{OUT}} \leq 10mA$. (a) Find a suitable value for $R_s$, and estimate the line and load regulation. (b) Estimate the effect of the full-scale changes of $V_{\text{IN}}$ and $I_{\text{OUT}}$ on $V_{\text{OUT}}$.

(a) Let $I_{\text{Z(min)}} \approx \frac{I_{\text{OUT(max)}}}{4} = 2.5mA$

\[ R_s \leq \frac{(10 - 6.43 - 10 \cdot 2.5mA)}{2.5mA + 10mA} = 0.284k\Omega \]

\[ R_s = 270\Omega \]

\[ \text{Line – regulation} = \frac{10}{270 + 10} = 35.7mV / V \]

\[ \text{Load – regulation} = -(10 || 270) = -9.64mV / mA \]

(b) Changing $V_{\text{IN}}$ from 10V to 20V gives: \[ \Delta V_{\text{OUT}} = 35.7mV / V \cdot 10V = 0.357V \]

Changing $I_{\text{OUT}}$ from 0 to 10mA gives: \[ \Delta V_{\text{OUT}} = -9.64mV / mA \cdot 10mA = -0.096V \]
Self-Regulated Voltage Reference

\[ V_o = \left(1 + \frac{R_2}{R_1}\right)V_z \]

Shifts the burden of line and load regulation from the diode to the op amp!

\[ V_0 \text{ is adjustable, for instance, via } R_2. \]

\( R_3 \) can be raised to avoid unnecessary power wastage and self-heating effects.

\begin{align*}
\text{Load - regulation} & \approx -\frac{Z_o}{1 + a\beta} = -\frac{Z_o}{1 + a}\frac{R_1}{(R_1 + R_2)} \\
\Delta V_{os} & = \Delta V_I \left(\frac{1}{PSRR} + \frac{0.5}{CMRR}\right) \qquad \text{Appearing in series with } V_Z.
\end{align*}

\[ \Delta V_o = \Delta V_{os}\left(1 + \frac{R_2}{R_1}\right) \]

where \( a \) and \( Z_o \) are the open-loop gain and impedance of the op amp.

\begin{align*}
\text{Line - regulation} & = \left(1 + \frac{R_2}{R_1}\right)\times\left(\frac{1}{PSRR} + \frac{0.5}{CMRR}\right)
\end{align*}
Self-Regulated Voltage Reference (load regulation)
Basic Series Voltage Regulator

Darlington Pair or series pass element

The regulator can be seen as a non-inverting amplifier with a Darlington current booster!

\[ V_o = \left(1 + \frac{R_2}{R_1}\right)V_{REF} \]

Forward-active region: \( I_C = \beta I_B \)
1) \( V_{BE} = V_{BE(on)} \)
2) \( V_{CE} \geq V_{CE(sat)} \)

Power Transistor (Q₁):
\( \beta = 20 \)
\( V_{BE(on)} \approx 1V \)
\( V_{CE(sat)} \approx 0.5V \)

Typical Transistor (Q₂):
\( \beta = 100 \)
\( V_{BE(on)} \approx 0.7V \)
\( V_{CE(sat)} \approx 0.1V \)
Example 11.9

• Let \( R_B = 510 \Omega \) and \( R_E = 3.3k \Omega \) in the regulator. Assuming a reference voltage of 1.282V and typical BJT parameters, find (a) \( R_2/R_1 \) for \( V_o = 5.0V \), (b) the error amplifier output drive needed to provide, \( I_o = 1A \), (c) the dropout voltage \( V_{DO} \) if the error amplifier saturates at \( V_{OH} = V_I - 0.5V \), and (d) the maximum efficiency attainable for the given \( I_o \)

\[
a) \quad 5 = \left(1 + \frac{R_2}{R_1}\right) \cdot 1.282 \quad \text{gives} \quad \frac{R_2}{R_1} = 2.9.
\]

\[
b) \quad \text{For } I_o = 1A \quad \text{we have } I_{B1} = I_{E1}/(\beta_1 + 1) \approx 1/21 \approx 48mA,
\]
and \( I_{E2} = I_{B1} + V_{BE1(on)}/R_E \approx 48mA. \)

The error amplifier must source: \( I_{OA} = I_{B2} = I_{E2}/(\beta_2 + 1) \approx 48/101 \approx 0.47mA; \)

in addition, :

\[
V_{OA} = V_{BE2(on)} + V_{BE1(on)} + V_{R_B} + V_o \approx 0.51 \times 0.47 + 0.7 + 1 + 5 \approx 7V
\]
Continue Example 11.9...

c) For this circuit to work properly we need \( V_{OA} \leq V_{OH} \) and \( V_{CE} \geq V_{CE(sat)} \) for both BJTs. It is readily seen that these conditions are met if \( V_I \geq 7.5V \).

Hence, \( V_{DO} \geq V_I - V_o = 7.5V - 5.0V = 2.5V \)

d) \( V_I \geq 7.5V, \eta(\%) \leq \left( \frac{5}{7.5} \right) \times 100 \approx 67\% \)