Lecture 2: Voltage References/Regulators

ECEN 457(ESS): Op-Amps and Applications
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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 VD and current ID are related:

$$V_D = V_T \ln\left(I_D / I_S\right)$$

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

- Their expressions are:

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

where k = $1.381\text{x}10^{-23}$ is Boltzmann's constant, q = $1.602\text{x}10^{-19}$ 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:

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

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

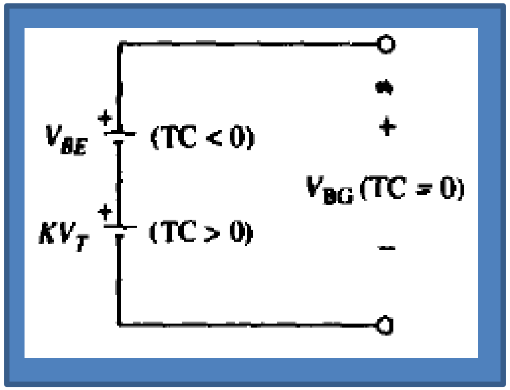
$$TC(V_D) = \frac{\partial V_T}{\partial T} \ln\left(I_D/I_s\right) + V_T \frac{\partial \ln\left(I_D/I_s\right)}{\partial T} = V_D \big/ T - V_T \frac{\partial\left(3\ln T - V_{G0}/V_T\right)}{\partial T}$$

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

Assuming V_D = 650mV at 25C, we get TC(V_D) ≅ -2.1mV/°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.


Bandgap voltage reference

$$V_{BG} = K \cdot V_T + V_{BE}$$

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

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

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

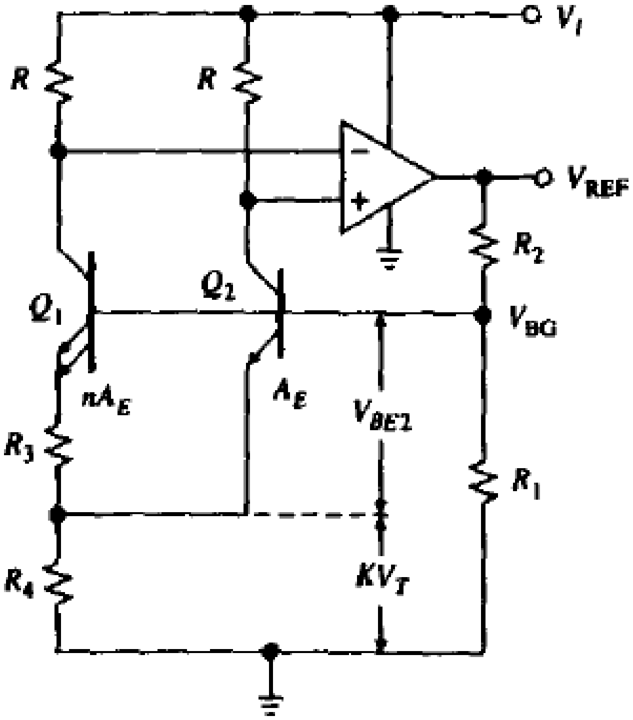
$$K = -\frac{V_{G0} - V_{BE}}{V_T} + 3$$

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

At 25°C we have V_{BG}= 1.205V + 3 x 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 $I_{s1}/I_{s2} = n$.



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

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

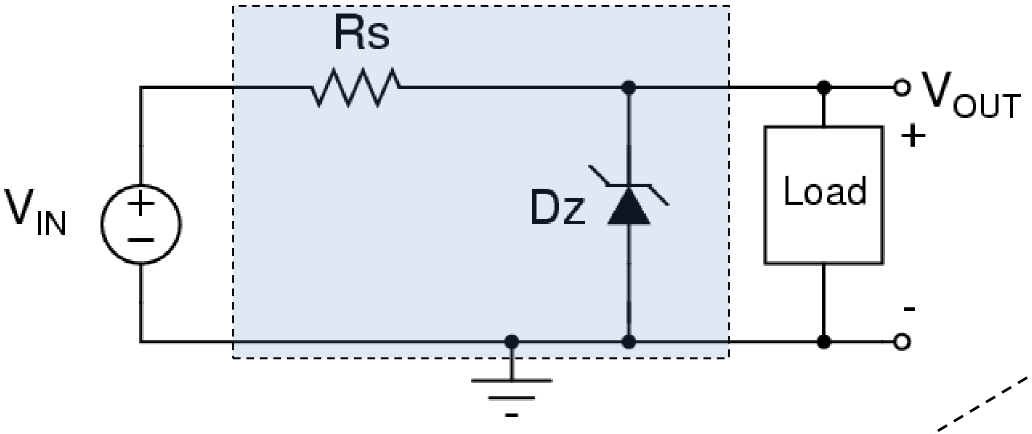
$$V_{BG}=V_{BE2}+k\cdot V_T$$

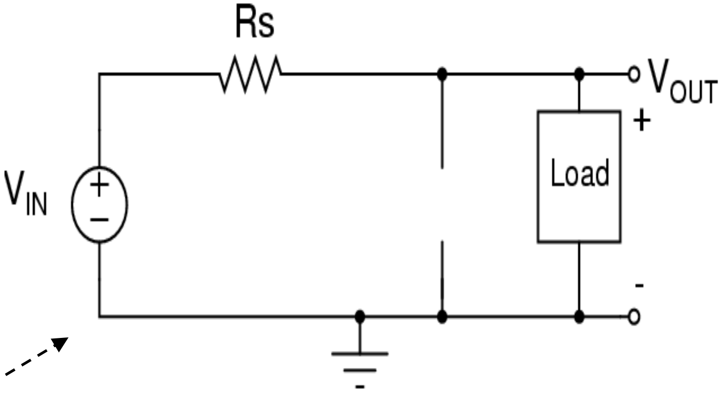
where $$k=2\frac{R_4}{R_3}\ln(n)$$

$$V_{REF}=(1+R_2/R_1)V_{BG}$$

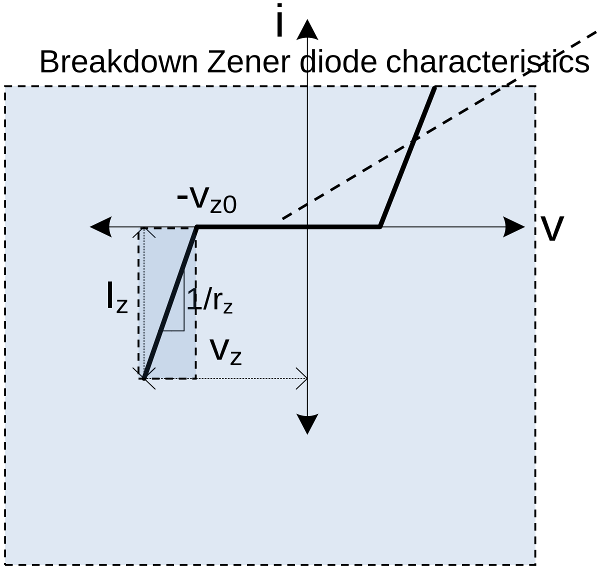
Shunt Voltage Regulator

Shunt regulator

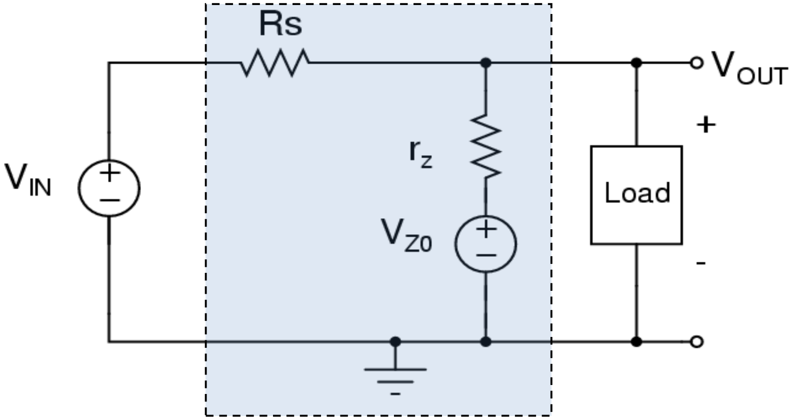




Breakdown Zener diode characteristics

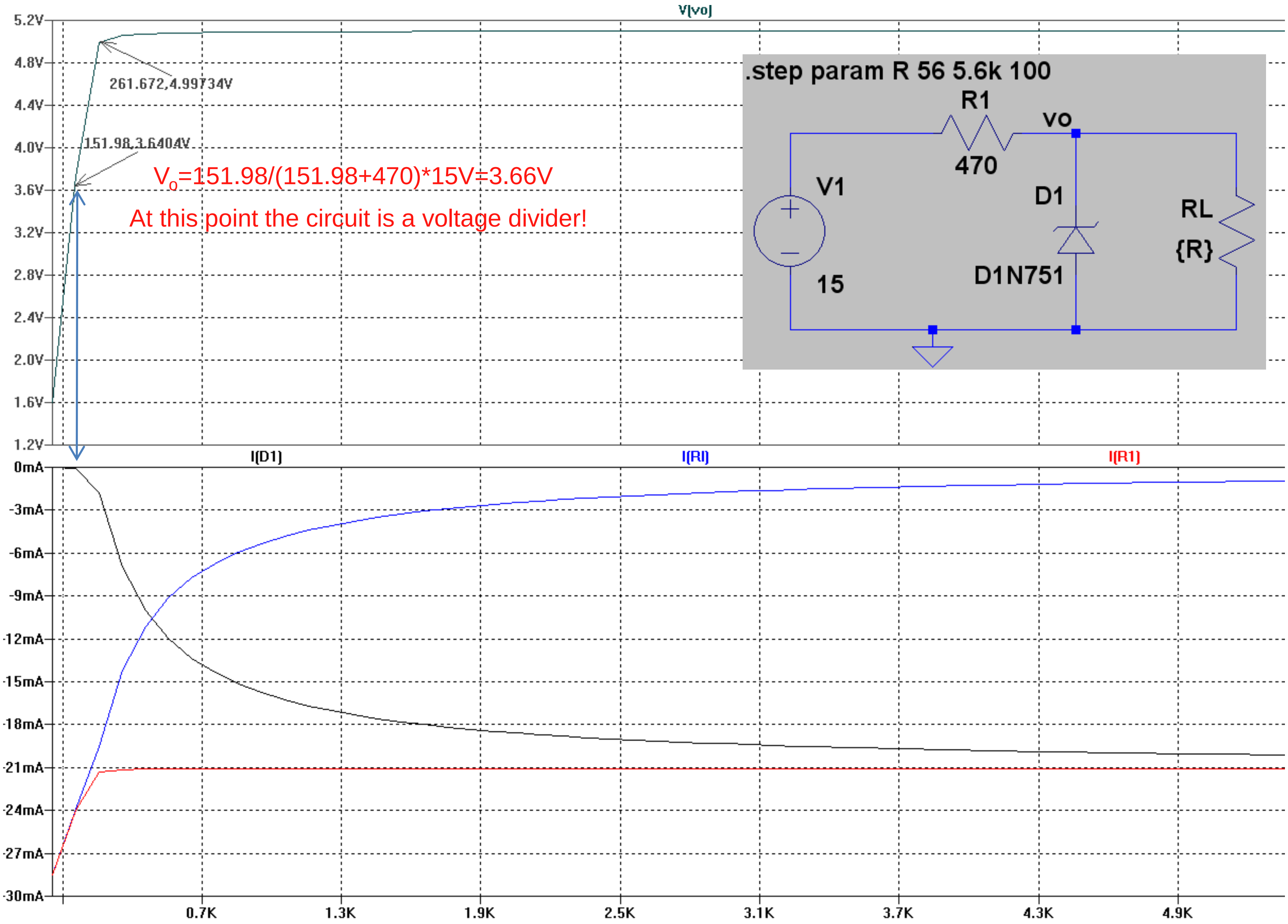


Equivalent circuit of the shunt regulator



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 $I_{z(min)}$.

Shunt Voltage Regulator (Load Regulation)



V_o=151.98/(151.98+470)*15V=3.66V

At this point the circuit is a voltage divider!

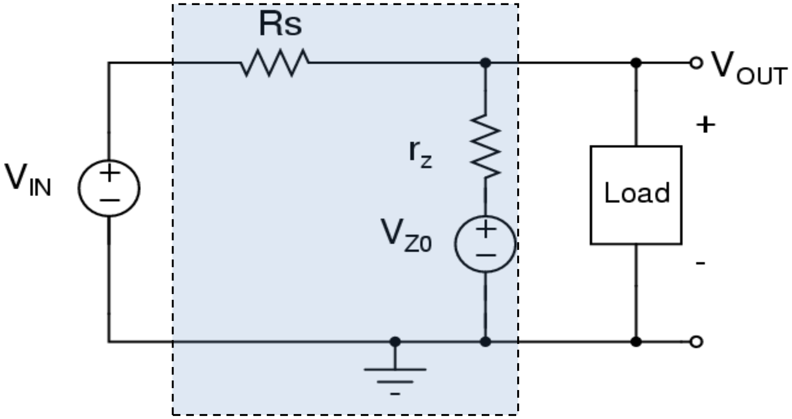
Design Approach

1) $V_{Z0} = V_Z - r_z I_z$

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

3) $I_{Z(\min)} \cong \dfrac{I_{o(\max)}}{4}$

Equivalent circuit of the shunt regulator



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

Applying superposition principle, we find:

$$V_{OUT} = \frac{r_z}{R_s + r_z} V_{IN} - \frac{R_s}{R_s + r_z} V_{Z0} - \left(r_z \parallel R_s\right) I_{OUT}$$

$$Line - regulation = \frac{r_z}{R_s + r_z}$$

$$Load - regulation = -\left(r_z \parallel R_s\right)$$

Example 11.3

- A raw voltage 10V ≤ V_{IN} ≤ 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 ≤ I_{OUT} ≤ 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_{IN} and I_{OUT} on V_{OUT}.

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

$$R_s \le (10 - 6.43 - 10 \cdot 2.5mA)/(2.5mA + 10mA) = 0.284k\Omega$$

$$R_s = 270\Omega$$

$$Line - regulation = \frac{10}{270 + 10} = 35.7mV/V$$

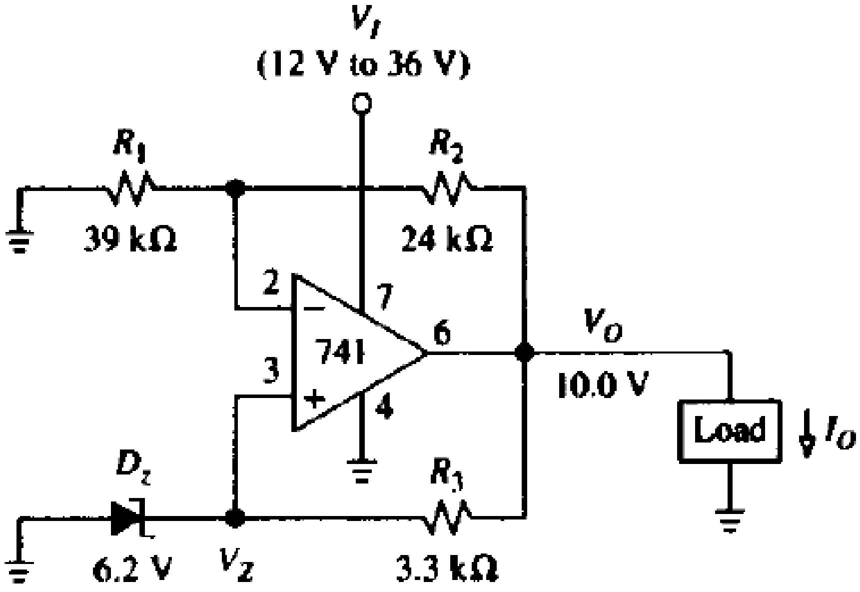
$$Load - regulation = -(10 \parallel 270) = -9.64mV/mA$$

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

Changing I_{OUT} from 0 to 10mA gives: $\Delta V_{OUT} = -9.64mV/mA \cdot 10mA = -0.096V$

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!

Vo is adjustable, for instance, via R_2.

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

$$Load-regulation \cong -\frac{z_o}{1+a\beta} = -\frac{z_o}{1+a\,{R_1}/{(R_1+R_2)}}$$

where a and z_o are the open-loop gain and impedance of the op amp.

$$\Delta V_{os} = \Delta V_I\left(\frac{1}{PSRR}+\frac{0.5}{CMRR}\right)$$

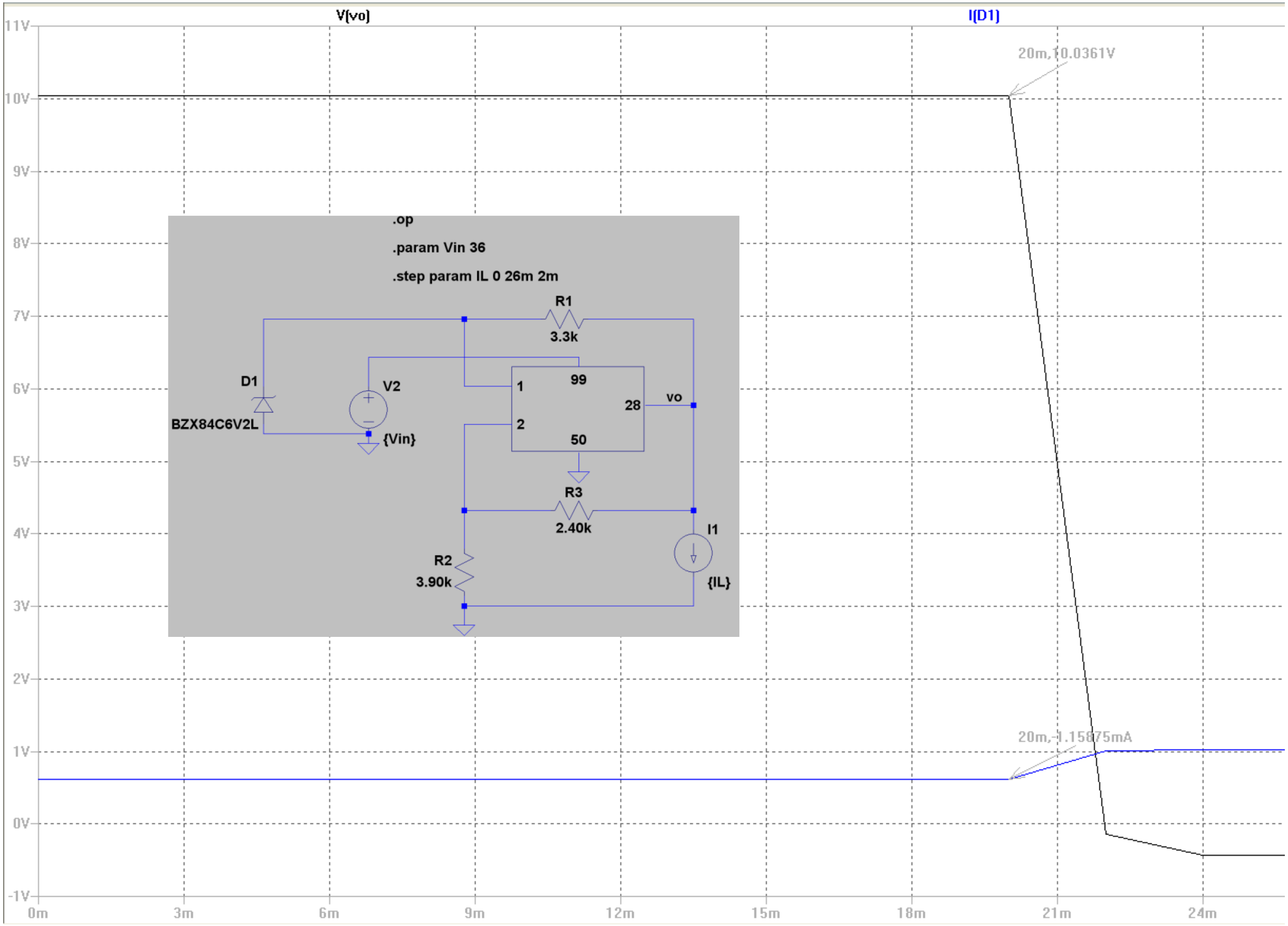
Appearing in series with V_Z.

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

⇒

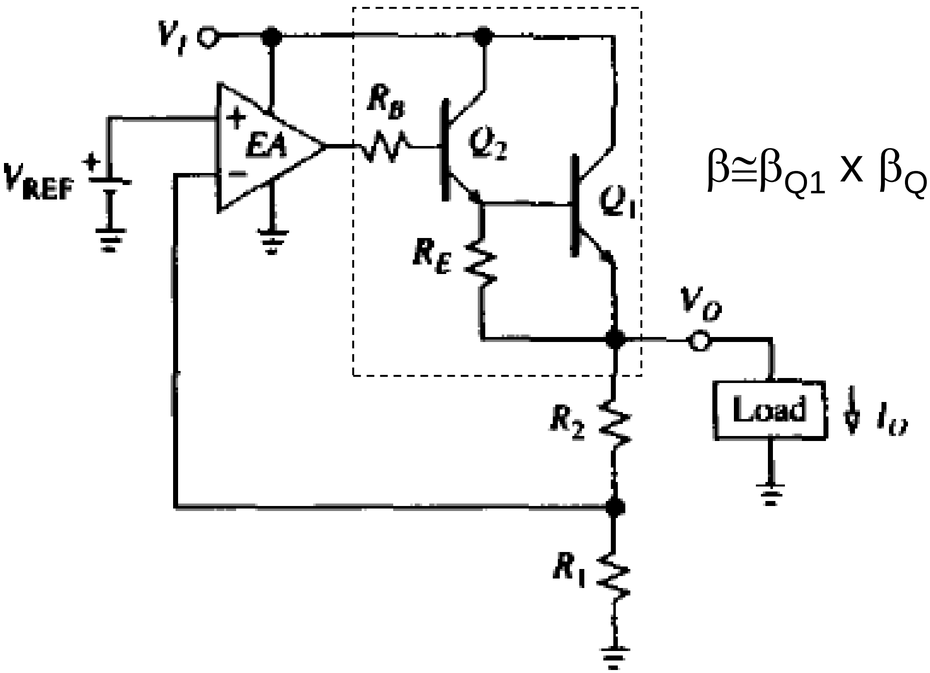
$$Line-regulation = \left(1+\frac{R_2}{R_1}\right)\times\left(\frac{1}{PSRR}+\frac{0.5}{CMRR}\right)$$

Self-Regulated Voltage Reference (load regulation)



```
.op
.param Vin 36
.step param IL 0 26m 2m
```

Basic Series Voltage Regulator



Darlington Pair or series pass element

$\beta \cong \beta_{Q1} \times \beta_{Q2}$

Forward-active region: $I_C = \beta I_B$

1) $V_{BE} = V_{BE(on)}$

2) $V_{CE} \geq V_{CE(sat)}$

Power Transistor (Q_1):
$\beta = 20$
$V_{BE(on)} \approx 1V$
$V_{CE}(sat) \approx 0.5V$

Typical Transistor (Q_2):
$\beta = 100$
$V_{BE(on)} \approx 0.7V$
$V_{CE}(sat) \approx 0.1V$

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

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

Example 11.9

- Let R_B = 510Ω and R_E=3.3kΩ 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) $5=\left(1+\frac{R_2}{R_1}\right)\cdot 1.282$ gives $\frac{R_2}{R_1}=2.9.$

b) For $I_o=1A$ we have $I_{B1}=I_{E1}/(\beta_1+1)\cong 1/21\cong 48mA,$

and $I_{E2}=I_{B1}+V_{BE1(on)}/R_E\cong 48mA.$

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

in addition, :

$$V_{OA}=V_{BE2(on)}+V_{BE1(on)}+V_{R_B}+V_o\cong 0.51\times 0.47+0.7+1+5\cong 7V$$

Continue Example 11.9…

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

Hence, $V_{DO} \ge V_I - V_o = 7.5V - 5.0V = 2.5V$

d) $V_I \ge 7.5V, \eta(\%) \le \left(5/7.5\right) \times 100 \cong 67\%$