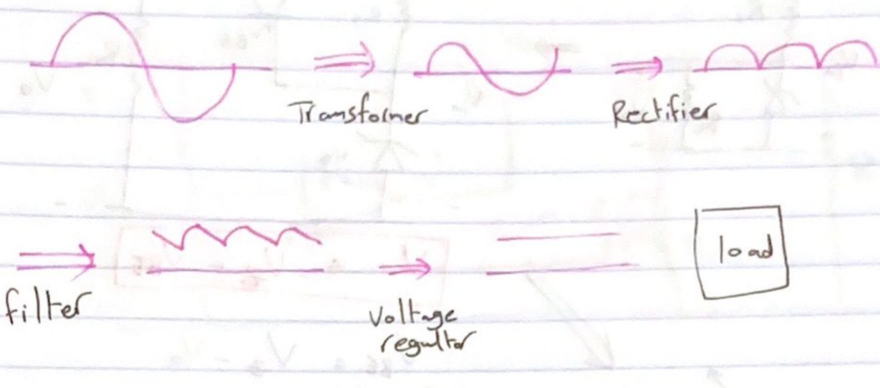
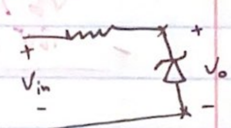
T11: Voltage Regulator

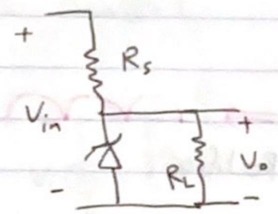


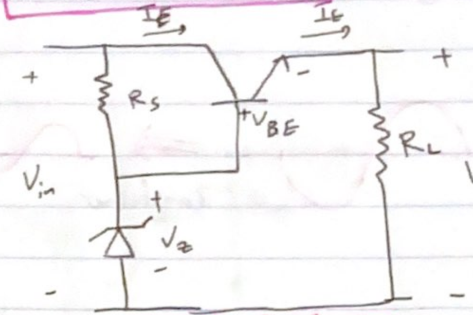
VR

- high power applications — Switching VR ✗
- Linear VR — used for low power apps
  - Series
    - IC VR
      - Fixed output ✓
        - +ve ✓
        - -ve ✓
      - Adjustable output ✓
    - Discrete ✓
      - Transistor series VR
      - opAmp series VR
      - opAmp series with current limit
  - Shunt ✗

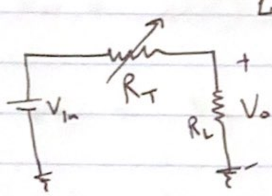


1) Transistor series VR





$$\boxed{V_o = V_Z - V_{BE}}$$



$$V_{BE} = V_Z - V_o$$

↳ control signal

$$\Rightarrow I_C = I_S \left[e^{\frac{V_{BE}}{nV_T}} - 1 \right]$$

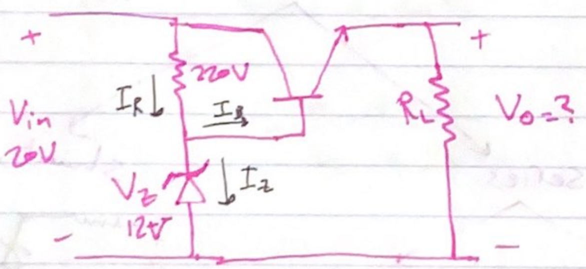
· If $V_o \downarrow$ $(V_{BE} = V_Z - V_o) \uparrow$

when $V_{BE} \uparrow$ $I_B \uparrow$ $I_C \uparrow$ $I_E \uparrow$

$\Rightarrow V_o \uparrow$

$$V_o = \frac{R_L}{R_T + R_L} \cdot V_{in}$$

ex

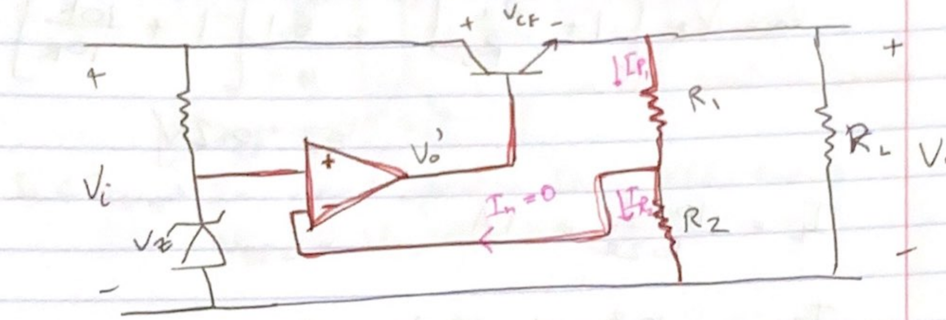


$$V_o = V_Z - V_{BE}$$
$$\cong 12 - 0.7$$

$$\boxed{V_o = 11.3V}$$

$$I_B = I_R + I_Z$$
$$I_B \ll I_Z$$
$$\Rightarrow I_Z = I_R = \frac{20 - 12}{220}$$
$$= 36\,mA$$

2) opAmp series VR



$$V_i = V_o + V_{CE}$$

$$V_o' = A_d V_d$$

$$V_o' = A_d \left[\underset{V_+}{V_Z} - \frac{R_2}{R_2+R_1} \underset{V_-}{V_o} \right]$$

If $V_o \downarrow$, $V_o' \uparrow$, $V_{be}' \uparrow$, $I_E \uparrow$, $V_o \uparrow$

$V_{CE} \gg V_{CE(sat)}$

↳ at least 2V

$V_{CE} = V_{in} - V_o > 2V$

$\boxed{V_{in} > V_o + 2}$ ***

$I_{R_1} = I_{R_2} = I$

in mA's

negative feedback $\Rightarrow$ $V+ = V-$

$V+ = V_Z$

$V- = V_{R2} = V_o \frac{R_2}{R_1+R_2}$

$\Longrightarrow V_Z = V_o \frac{R_2}{R_1+R_2}$

$\boxed{V_o = V_Z \left[1 + \frac{R_1}{R_2} \right]}$ **

1) $V_Z < V_o$

2) $V_{in} > V_o + 2$

ex slide 7

$$V_o = V_Z\left[1 + \frac{R_2}{R_3}\right] = 5.1\left[1 + \frac{10k}{10k}\right]$$

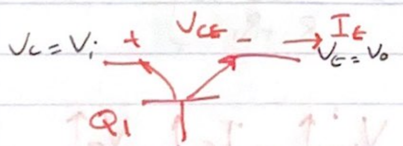
$$= 10.2V$$

$$I_L = \frac{10.2V}{10.2\Omega} = 1A$$

$$I_{R2} = \frac{10.2}{20k} \cong 0.5mA$$

$$I_E = 1.005A$$

Power rating of BJT



$$P_{Q1} = V_{CE} \cdot I_E$$
$$= (V_{in} - V_o)\, I_E$$
$$= (15 - 10.2)(1.005)$$
$$= 4.824 \text{ watt}$$

lost $\rightarrow$ heat

use a 5 watt BJT

use a 5 watt BJT

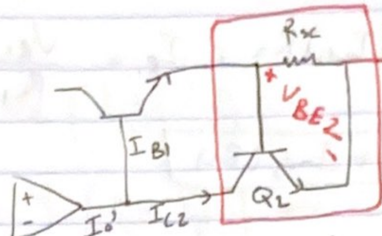
$$I_L = \frac{10.2}{5.1} = 2A$$

$$R_L = 5.1\Omega$$

$$P_{Q1} = (15 - 10.2) \times 2A$$
$$= 9.6 \text{ watt}$$

in this case BJT will be damaged

3) opAmp series VR with current limit



$\boxed{R_{sc}, Q_2}$

— to protect

— to limit $I_{L(max)}$

1) $I_L < I_{L(max)}$ * In normal operation Q_2 is off since

$$V_{BE2} = V_{Rsc} < 0.7V$$

2) $I_L = I_{L(max)}$ $V_{BE} = V_{RSC} = I_{L(max)} \cdot R_{SC} = 0.7$

3) when $I > I_{L(max)}$

$$I_o' = I_{B1} + I_{C2}$$

· for $I_{C2} = 0 \Rightarrow I_o' = I_{B1}$ Q_2 off

2) Q_2 ON $\Rightarrow \downarrow I_{B1} = I_o' - I_{C2}\uparrow$

$\downarrow I_{E1} \Rightarrow \downarrow I_L \leq I_{L(max)}$

$$V_o = \cancel{\left(1 + \frac{R_2}{R_1}\right) V_Z}$$ $\Rightarrow$ not valid in current limit mode

$$\boxed{V_o = I_{L(max)} R_L}$$

⟹ IC Voltage Regulator

- IC VR
  - Adjustable (*317*)
    - always $\boxed{V_{REF} = 1.25}$
  - fixed output
    - negative output 79XX
    - positive output 78XX

7805 → 5V

7815 ⇒ 15V

$V_{in} \geq V_o + 2$

$V_o = V_{R1} + V_{R2}$

$= I_{R_1} R_1 + (I_{R_1} + I_{adj}) R_2$; $I_{R_1} = \frac{V_{R1}}{R_1} = \frac{V_{REF}}{R_1} = \frac{1.25}{R_1}$

$\boxed{V_o = I_{R_1} (R_1 + R_2) + I_{adj} (R_2)}$

for $R_2 = 0$

$V_o = I_{R_1} \cdot R_1 = \frac{V_{REF}}{R_1} \cdot R_1 = V_{REF} = 1.25$

for $R_2 \neq 0$

$V_o =$

ex $R_1 = 220\Omega$, $R_2 = 5k\Omega$ potentiometer $\left(\begin{matrix} R_{2(min)} = 5 \\ R_{2(max)} = 0 \end{matrix} \right)$

$I_{adj} = 50 \mu A$

- Find $V_{o(min)}$ and $V_{o(max)}$
- Find range of V_{in} ?

$V_o = I_{REF} (R_1 + R_2) + I_{adj} R_2$

$I_{R1} = I_{REF} = \frac{1.25}{220} = 5.68mA$

$I_{adj} = 50 \mu A$

1) $V_o \Big|_{R_2 = 5k} = V_{o(max)} = 5.68m (220 + 5k) + 50\mu (5k)$

$= 29.91 \text{ V} \rightarrow V_{in(max)} = 29.91 + 2$

2) $V_o \Big|_{R_2 = 0} = V_{o(min)} = 1.25 \text{ V} = I_{REF} \cdot R_1 = \frac{V_{REF}}{R_1} R_1$

$= V_{REF} = 1.25$

$\Rightarrow V_{in(min)} = 1.25 + 2$

ex slide 10

1) $V_o = V_Z\left[1 + \frac{R_1}{R_2}\right]$

$12 = 4\left[1 + \frac{R_1}{R_2}\right] \Rightarrow \frac{R_1}{R_2} = 2$

I_{R_1} must be small $\Rightarrow$ R_1, R_2 must be in 100's of ohms or $k\Omega$'s

~~$R_1 = 2\Omega$~~
~~$R_2 = 1\Omega$~~

$I_{R_1} = I_{R_2} = \frac{12}{3} = \underline{4A}$ ×

$$\boxed{\begin{array}{l}\text{let } R_1 = 20\,k\Omega \\ \therefore R_2 = 10\,k\Omega\end{array}}$$

* $R_3 = ?$

$I_Z \geq I_{Z(min)}$; $I_Z = I_R = \frac{V_{in} - V_Z}{R_3} \geq 2mA$

$R_3 \leq \frac{V_{in} - V_Z}{2m} = \frac{20 - 12}{2m}$

8 موجود بالمعطيات $? \leq R_3 \leq 8\,k\Omega$

$\boxed{R_3 = 8\,k\Omega}$

2) $I_{L(max)} = 1A$

$R_{sc} = ?$

$V_{BE} = 0.7 \Leftarrow$ default value if another value is not given

$V_{BE} = V_{R_{SC}} = I_L R_{sc}$

$R_{SC} = \frac{V_{BE}}{I_{L(max)}} = \frac{0.7}{1A} = \boxed{0.7\Omega}$

3) $V_o \Rightarrow R_L = 100\Omega$, $R_L = 8\Omega$

$V_o = 12$, $R_L = 100\Omega \Rightarrow I_L = \frac{12}{100} = 0.12A < I_{L(max)}$

$\Rightarrow V_o = 12V$

$V_o = 12$, $R_L = 8\Omega \Rightarrow I_L = \frac{12}{8} = 1.5A > I_{L(max)}$

$V_o = I_{L(max)} * R_L = 1A * 8\Omega = 8V$

$\hookrightarrow V_o \neq V_z\left(1 + \frac{R_1}{R_2}\right) \Leftarrow$ since the current limit circuit starts working

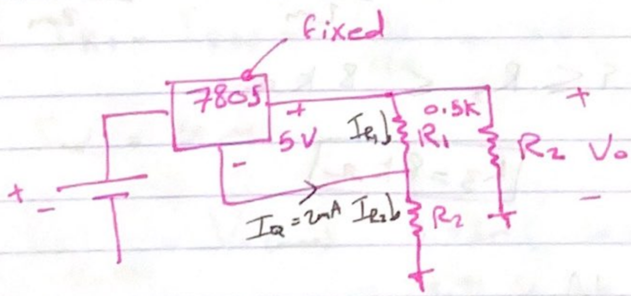
4) $P_{Q_1} = V_{CE(max)} * I_{E(max)}$

$V_{CE(max)} = V_{in(max)} - V_{o(min)} = 25 - 8 = 17V$

$I_{E(max)} = I_{R_1} + I_{L(max)} = \frac{8}{30k} + 1A = 1.000\cancel{4}26A$

$P_{Q_1} = 17 * 1.000\cancel{4}26 = 17.0068\,W$

ex



choose value of R_2 in order to have $V_o = 7.4V$

$V_o = V_{R_1} + V_{R2}$

$\cancel{8}7.4 = 5 + V_{R2}$

$\boxed{V_{R2} = 2.4V}$

$I_{R2} = I_{R_1} + I_Q$

$\frac{5}{0.5k} + 2m = \boxed{12mA = I_{R2}}$

$R_2 = \frac{V_{R2}}{I_{R2}} = \frac{2.4}{12m}$

$\boxed{R_2 = 0.2k\Omega}$

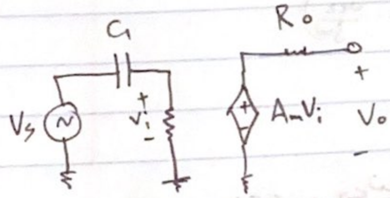
T12: Frequency Response

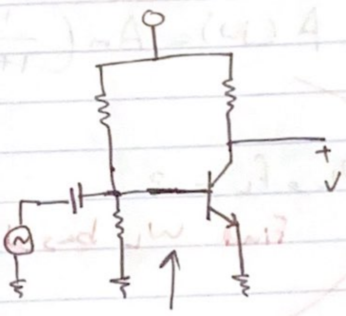
$X \begin{cases} f \text{ or } \omega = 2\pi f \\ \log f, \log \omega \xrightarrow{\text{unit}} [\text{decade}] \end{cases}$

$y \begin{cases} A(j\omega) = \frac{V_o}{V_i} \\ |A(j\omega)| \text{ or } 20 \log |A(j\omega)| \Rightarrow \text{in dB} \end{cases}$

$$f_L, \omega_L = \frac{|A_v(mid)|}{\sqrt{2}}$$

1) consider C_1 only (C_1, C_2 ∈ short, C_{be}, C_{bc} ⇒ open)





$\frac{V_o}{V_s} = ?$

$V_o = A_m V_i$

$A_m = A_v(mid)$

$$V_i = \frac{R_i}{R_i + \frac{1}{j\omega C_1}} V_s \Rightarrow V_o = \frac{A_m . R_i}{R_i + \frac{1}{j\omega C_1}} V_s$$

$$\frac{V_o}{V_s} = \frac{A_m . R_i}{R_i + \frac{1}{j\omega C_1}}$$

$$\Rightarrow |A(j\omega)| = \frac{A_m . R_i}{\sqrt{(R_i)^2 + \left(\frac{1}{\omega C_1}\right)^2}}$$

$$\Rightarrow \quad = \frac{A_m}{\sqrt{1 + \left(\frac{\omega_{c1}}{\omega}\right)^2}} \qquad \omega_{c1} = \frac{1}{R_i C_1}$$

for $\omega = \omega_{c1} \rightarrow 20\log|A(j\omega)| = 20\log A_m - 20\log 0.707$

$= -3dB$

$\omega = 0.1\,\omega_c \Rightarrow 20\log|A(j\omega)| = -20\,dB \leftarrow$ High pass filter

together

$C_1 \rightarrow \omega_{c1} = \dfrac{1}{C_1 R_{th1}}$

$A(j\omega) = A_m\left(\dfrac{1}{1+\frac{\omega_{c1}}{j\omega}}\right)$

$C_2 \rightarrow \omega_{c2} \rightarrow A_m\left(\dfrac{1}{1+\frac{\omega_{c2}}{j\omega}}\right)$

$$A(j\omega) = A_m\left(\frac{1}{1+\frac{\omega_{c1}}{j\omega}}\right)\left(\frac{1}{1+\frac{\omega_{c2}}{j\omega}}\right)$$

$\omega_L, f_L = ?$

Find ω_L based on $\omega_{c1}, \omega_{c2}, \ldots$

$\rightarrow |A(j\omega_L)| = \dfrac{A_m}{\sqrt{2}}$

$$\omega_L^2 = \frac{\omega_{c1}^2 + \omega_{c2}^2}{2} + \frac{\sqrt{\omega_{c1}^4 + 6\,\omega_{c1}^2\omega_{c2}^2 + \omega_{c2}^4}}{2}$$

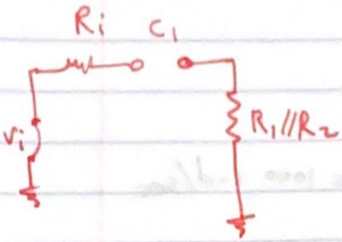
$\boxed{\omega_{c1} < \omega_L < \omega_{c1} + \omega_{c2}}$

الكبيرة ← → sum

$\boxed{\max(\omega's) < \omega_L < \mathrm{sum}(\omega's)}$

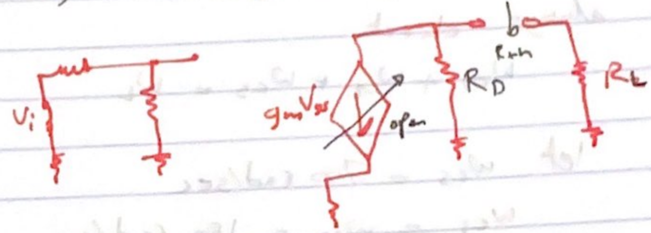
ex slide 13

Action Plan: 1) take C_1 (while C_2, C_s shorted) and Find $w_{c1} = \frac{1}{C_1 R_{th1}}$;



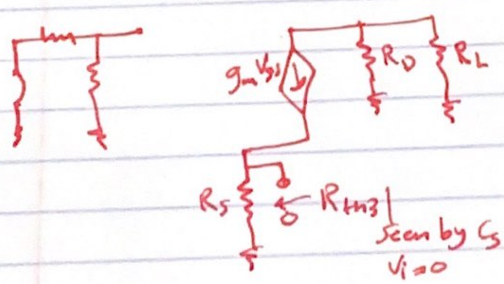
$R_{th1}\Big|_{\substack{\text{seen by } C_1 \\ \& \ V_i = 0}} = (R_1 // R_2) + R_i$

2) take C_2 (while C_1, C_s shorted)



$V_{gs} = 0$, $R_{th2} = R_L + R_D$

3) consider C_s (while C_1, C_2 shorted)



$= R_s \ // \ \frac{1}{g_m}$

$\lim_{r_{ds} \to \infty} \left(\frac{r_{ds} + R_D // R_L}{\mu + 1} \right)$

$w_{c1} = 45.45$ rad/sec

$w_{c2} = 100$ rad/sec

$w_{cs} = 1050$ rad/sec

analysis $\boxed{1050 < w_L < 1195.5}$

* Design of ω_L

$$? \leq \omega_L \leq \omega_{c1} + \omega_{c2} + \omega_{cs}$$

$\omega_{cs} > \omega_{c1}$

$\omega_{cs} > \omega_{c2}$

Design criteria

$\omega_L = 1000$ rad/sec

assume $\omega_{cs} = (0.7 - 0.8)\, \omega_L$

$\omega_{c1} = \omega_{c2} = (0.1 - 0.15)\, \omega_L$

always check

$\omega_{c1} + \omega_{c2} + \omega_{cs} = \omega_L$

let $\omega_{cs} = 700$ rad/sec

$\omega_{c1} = \omega_{c2} = 150$ rad/sec

$\omega_{cs} = \dfrac{1}{C_s R_{ths}}$; $\Rightarrow C_s = ?$