RAJALAKSHMI ENGINEERING COLLEGE

DEPARTMENT OF ECE

ANALOG CIRCUITS I

UNIT I

DESIGN FORMULAS

Equations

$$r_e = \frac{26\text{ mV}}{I_E}$$

Hybrid parameters:

$$h_{ie} = \beta r_e, \quad h_{fe} = \beta_{ac}, \quad h_{ib} = r_e, \quad h_{fb} = -\alpha \cong -1$$

CE fixed bias:

$$Z_i \cong \beta r_e, \quad Z_o \cong R_C$$

$$A_v = -\frac{R_C}{r_e}, \quad A_i = -A_v\frac{Z_i}{R_C} \cong \beta$$

Voltage-divider bias:

$$Z_i = R_1\|R_2\|\beta r_e, \quad Z_o \cong R_C$$

$$A_v = -\frac{R_C}{r_e}, \quad A_i = -A_v\frac{Z_i}{R_C} \cong \beta$$

CE emitter-bias:

$$Z_i \cong R_B\|\beta R_E, \quad Z_o \cong R_C$$

$$A_v \cong -\frac{R_C}{R_E}, \quad A_i \cong \frac{\beta R_B}{R_B + \beta R_E}$$

Emitter-follower:

$$Z_i \cong R_B\|\beta R_E, \quad Z_o \cong r_e$$

$$A_v \cong 1, \quad A_i = -A_v\frac{Z_i}{R_E}$$

Common-base:

$$Z_i \cong R_E\|r_e, \quad Z_o \cong R_C$$

$$A_v \cong \frac{R_C}{r_e}, \quad A_i \cong -1$$

Collector feedback:

$$Z_i \cong \frac{r_e}{\dfrac{1}{\beta} + \dfrac{R_C}{R_F}}, \quad Z_o \cong R_C\|R_F$$

$$A_v = -\frac{R_C}{r_e}, \quad A_i \cong \frac{R_F}{R_C}$$

Collector dc feedback:

$$Z_i \cong R_{F_1}\|\beta r_e, \quad Z_o \cong R_C\|R_{F_2}$$

$$A_v = -\frac{R_{F_2}\|R_C}{r_e}, \quad A_i = -A_v\frac{Z_i}{R_C}$$

Cascode connection:

$$A_v = A_{v_1}A_{v_2}$$

Darlington connection (with R_E):

$$\beta_D = \beta_1\beta_2,$$

$$Z_i = R_B\|(\beta_1\beta_2 R_E), \quad A_i = \frac{\beta_1\beta_2 R_B}{(R_B + \beta_1\beta_2 R_E)}$$

$$Z_o = \frac{r_{e_1}}{\beta_2} + r_{e_2} \quad A_v = \frac{V_o}{V_i} \approx 1$$

Darlington connection (without R_E):

$$Z_i = R_1\|R_2\|\beta_1(r_{e_1} + \beta_1\beta_2 r_{e_2}) \quad A_i = \frac{\beta_1\beta_2(R_1\|R_2)}{R_1\|R_2 + Z_i'}$$

where $Z_i' = \beta_1(r_{e_1} + \beta_2 r_{e_2})$

$$Z_o \cong R_C\|r_{o_2} \quad A_v = \frac{V_o}{V_i} = \frac{\beta_1\beta_2 R_C}{Z_i'}$$

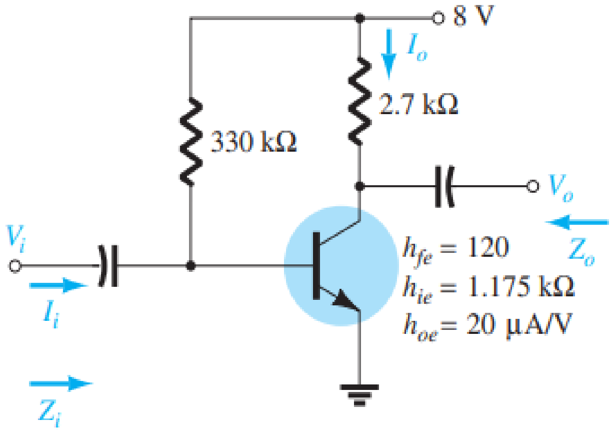
Feedback pair:

$$Z_i = R_B\|\beta_1\beta_2 R_C \quad A_i = \frac{-\beta_1\beta_2 R_B}{R_B + \beta_1\beta_2 R_C}$$

$$Z_o \approx \frac{r_{e_1}}{\beta_2} \quad A_v \cong 1$$

SOLVED DESIGN PROBLEMS IN UNIT I

1. **Design a audio amplifier using common emitter configuration and determine the following :**
   a. Z_i.
   b. Z_o.
   c. A_v.
   d. A_i.



Solution:

a. $Z_i = R_B \| h_{ie} = 330\,\text{k}\Omega \| 1.175\,\text{k}\Omega$

$\cong h_{ie} = \mathbf{1.171\,k\Omega}$

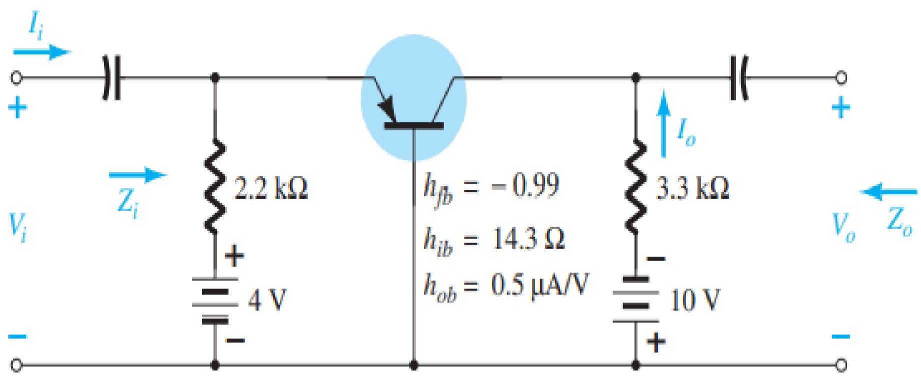
b. $r_o = \dfrac{1}{h_{oe}} = \dfrac{1}{20\,\mu\text{A/V}} = 50\,\text{k}\Omega$

$Z_o = \dfrac{1}{h_{oe}} \| R_C = 50\,\text{k}\Omega \| 2.7\,\text{k}\Omega = \mathbf{2.56\,k\Omega} \cong R_C$

c. $A_v = -\dfrac{h_{fe}(R_C \| 1/h_{oe})}{h_{ie}} = -\dfrac{(120)(2.7\,\text{k}\Omega \| 50\,\text{k}\Omega)}{1.171\,\text{k}\Omega} = \mathbf{-262.34}$

d. $A_i \cong h_{fe} = \mathbf{120}$

2. **Design a audio amplifier using common gate configuration and determine the following :**
   a. Z_i.
   b. Z_o.
   c. A_v.
   d. A_i.



Solution:

a. $Z_i = R_E \| h_{ib} = 2.2\,\mathrm{k\Omega} \| 14.3\ \Omega = \mathbf{14.21\ \Omega} \cong h_{ib}$

b. $r_o = \dfrac{1}{h_{ob}} = \dfrac{1}{0.5\ \mu\mathrm{A/V}} = \mathbf{2\ M\Omega}$

$$Z_o = \frac{1}{h_{ob}} \| R_C \cong R_C = \mathbf{3.3\ k\Omega}$$

c. $A_v = -\dfrac{h_{fb} R_C}{h_{ib}} = -\dfrac{(-0.99)(3.3\,\mathrm{k\Omega})}{14.21} = \mathbf{229.91}$

d. $A_i \cong h_{fb} = \mathbf{-1}$

UNIT II

DESIGN FORMULAS

Equations

JFET:

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$I_D = I_{DSS}\big|_{V_{GS}=0\,\mathrm{V}}, \quad I_D = 0\,\mathrm{mA}\big|_{V_{GS}=V_P}, \quad I_D = \frac{I_{DSS}}{4}\bigg|_{V_{GS}=V_P/2}, \quad V_{GS} \cong 0.3V_P\big|_{I_D=I_{DSS}/2}$$

$$V_{GS} = V_P\left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right)$$

$$P_D = V_{DS} I_D$$

$$r_d = \frac{r_o}{(1 - V_{GS}/V_P)^2}$$

MOSFET (enhancement):

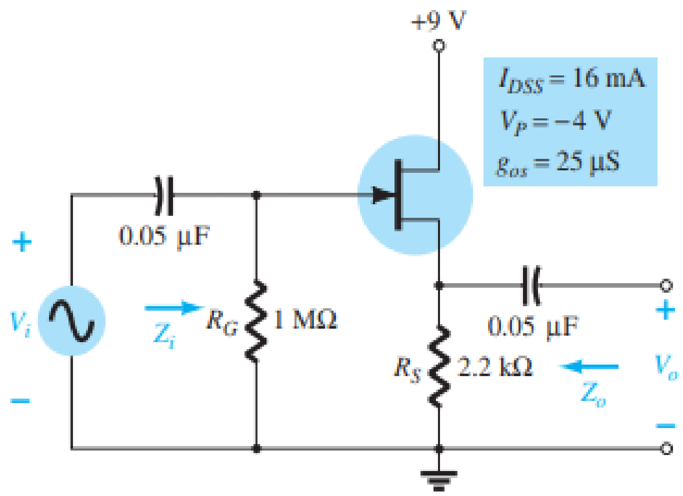
$$I_D = k(V_{GS} - V_T)^2$$

$$k = \frac{I_{D(\mathrm{on})}}{(V_{GS(\mathrm{on})} - V_T)^2}$$

SOLVED DESIGN PROBLEMS IN UNIT II

3. EXAMPLE 8.10 A dc analysis of the source-follower network of Fig. 8.32 results in VGSQ = -2.86 V and IDQ = 4.56 mA.

a. Determine g_m.
b. Find r_d.
c. Determine Z_i.
d. Calculate Z_o with and without r_d. Compare results.
e. Determine A_v with and without r_d. Compare results.



Solution:

a. $g_{m0} = \dfrac{2I_{DSS}}{|V_P|} = \dfrac{2(16\text{ mA})}{4\text{ V}} = 8\text{ mS}$

$$g_m = g_{m0}\left(1 - \frac{V_{GS_Q}}{V_P}\right) = 8\text{ mS}\left(1 - \frac{(-2.86\text{ V})}{(-4\text{ V})}\right) = \mathbf{2.28\text{ mS}}$$

b. $r_d = \dfrac{1}{g_{os}} = \dfrac{1}{25\ \mu\text{S}} = \mathbf{40\text{ k}\Omega}$

c. $Z_i = R_G = \mathbf{1\text{ M}\Omega}$

d. With r_d,

$$\begin{aligned} Z_o = r_d \| R_S \| 1/g_m &= 40\text{ k}\Omega \| 2.2\text{ k}\Omega \| 1/2.28\text{ mS} \\ &= 40\text{ k}\Omega \| 2.2\text{ k}\Omega \| 438.6\ \Omega \\ &= \mathbf{362.52\ \Omega} \end{aligned}$$

which shows that Z_o is often relatively small and determined primarily by $1/g_m$.
Without r_d,

$$Z_o = R_S \| 1/g_m = 2.2\text{ k}\Omega \| 438.6\ \Omega = \mathbf{365.69\ \Omega}$$

which shows that r_d typically has little effect on Z_o.

e. With r_d,

$$\begin{aligned} A_v &= \frac{g_m(r_d \| R_S)}{1 + g_m(r_d \| R_S)} = \frac{(2.28\text{ mS})(40\text{ k}\Omega \| 2.2\text{ k}\Omega)}{1 + (2.28\text{ mS})(40\text{ k}\Omega \| 2.2\text{ k}\Omega)} \\ &= \frac{(2.28\text{ mS})(2.09\text{ k}\Omega)}{1 + (2.28\text{ mS})(2.09\text{ k}\Omega)} = \frac{4.77}{1 + 4.77} = \mathbf{0.83} \end{aligned}$$

which is less than 1, as predicted above.

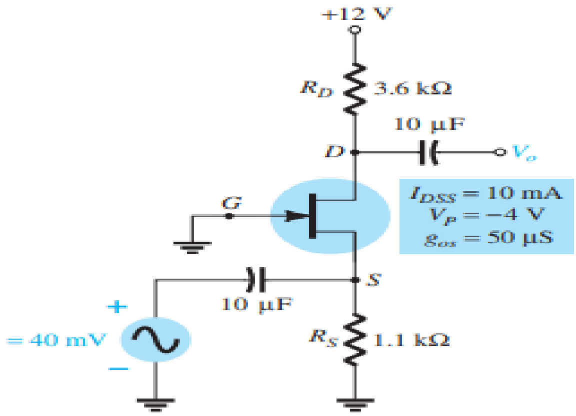
Without r_d,

$$\begin{aligned} A_v &= \frac{g_m R_S}{1 + g_m R_S} = \frac{(2.28\text{ mS})(2.2\text{ k}\Omega)}{1 + (2.28\text{ mS})(2.2\text{ k}\Omega)} \\ &= \frac{5.02}{1 + 5.02} = \mathbf{0.83} \end{aligned}$$

which shows that r_d usually has little effect on the gain of the configuration.

3. **In the common-gate variety, a close examination will reveal that it has all the characteristics of Figure given below. If VGSQ = -2.2 V and IDQ = 2.03 mA:**

a. Determine g_m.
b. Find r_d.
c. Calculate Z_i with and without r_d. Compare results.
d. Find Z_o with and without r_d. Compare results.
e. Determine V_o with and without r_d. Compare results.



Solution:

a. $g_{m0} = \dfrac{2I_{DSS}}{|V_P|} = \dfrac{2(10\text{ mA})}{4\text{ V}} = 5\text{ mS}$

$$g_m = g_{m0}\left(1 - \frac{V_{GS_Q}}{V_P}\right) = 5\text{ mS}\left(1 - \frac{(-2.2\text{ V})}{(-4\text{ V})}\right) = \mathbf{2.25\text{ mS}}$$

b. $r_d = \dfrac{1}{g_{os}} = \dfrac{1}{50\ \mu\text{S}} = \mathbf{20\text{ k}\Omega}$

c. With r_d,

$$Z_i = R_S \| \left[\frac{r_d + R_D}{1 + g_m r_d}\right] = 1.1\text{ k}\Omega \| \left[\frac{20\text{ k}\Omega + 3.6\text{ k}\Omega}{1 + (2.25\text{ mS})(20\text{ k}\Omega)}\right]$$
$$= 1.1\text{ k}\Omega \| 0.51\text{ k}\Omega = \mathbf{0.35\text{ k}\Omega}$$

Without r_d,

$$Z_i = R_S \| 1/g_m = 1.1\text{ k}\Omega \| 1/2.25\text{ ms} = 1.1\text{ k}\Omega \| 0.44\text{ k}\Omega$$
$$= \mathbf{0.31\text{ k}\Omega}$$

Even though the condition $r_d \geq 10R_D$ is not satisfied with $r_d = 20\text{ k}\Omega$ and $10R_D = 36\text{ k}\Omega$, both equations result in essentially the same level of impedance. In this case, $1/g_m$ was the predominant factor.

d. With r_d,

$$Z_o = R_D \| r_d = 3.6\text{ k}\Omega \| 20\text{ k}\Omega = \mathbf{3.05\text{ k}\Omega}$$

Without r_d,

$$Z_o = R_D = \mathbf{3.6\text{ k}\Omega}$$

Again the condition $r_d \geq 10R_D$ is *not* satisfied, but both results are reasonably close. R_D is certainly the predominant factor in this example.

e. With r_d,

$$A_v = \frac{\left[g_m R_D + \dfrac{R_D}{r_d}\right]}{\left[1 + \dfrac{R_D}{r_d}\right]} = \frac{\left[(2.25\text{ mS})(3.6\text{ k}\Omega) + \dfrac{3.6\text{ k}\Omega}{20\text{ k}\Omega}\right]}{\left[1 + \dfrac{3.6\text{ k}\Omega}{20\text{ k}\Omega}\right]}$$

$$= \frac{8.1 + 0.18}{1 + 0.18} = \mathbf{7.02}$$

and $\quad A_v = \dfrac{V_o}{V_i} \Rightarrow V_o = A_v V_i = (7.02)(40\text{ mV}) = \mathbf{280.8\text{ mV}}$

Without r_d,

$$A_v = g_m R_D = (2.25\text{ mS})(3.6\text{ k}\Omega) = \mathbf{8.1}$$

with $\quad V_o = A_v V_i = (8.1)(40\text{ mV}) = \mathbf{324\text{ mV}}$

In this case, the difference is a little more noticeable, but not dramatically so.

5. Design an MOSFET based amplifier using following parameters VGSQ = 0.35 V and IDQ = 7.6 mA.

a. Determine g m and compare to g_{mo}.

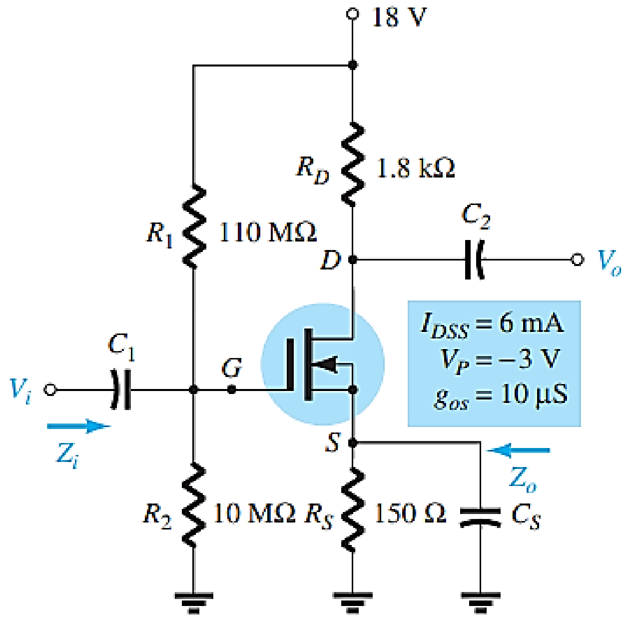
b. Find r_d.

c. Sketch the ac equivalent network for Fig. below.

d. Find Z_i.

e. Calculate Zo.

f. Find Av.



Solution:

a. $g_{m0} = \dfrac{2I_{DSS}}{|V_P|} = \dfrac{2(6\text{ mA})}{3\text{ V}} = 4\text{ mS}$

$$g_m = g_{m0}\left(1 - \frac{V_{GS_Q}}{V_P}\right) = 4\text{ mS}\left(1 - \frac{(+0.35\text{ V})}{(-3\text{ V})}\right) = 4\text{ mS}(1 + 0.117) = \mathbf{4.47\text{ mS}}$$

b. $r_d = \dfrac{1}{y_{os}} = \dfrac{1}{10\ \mu\text{S}} = \mathbf{100\ k\Omega}$

c. See Fig. 8.35. Note the similarities with the network of Fig. 8.23. Equations (8.28) through (8.32) are therefore applicable.

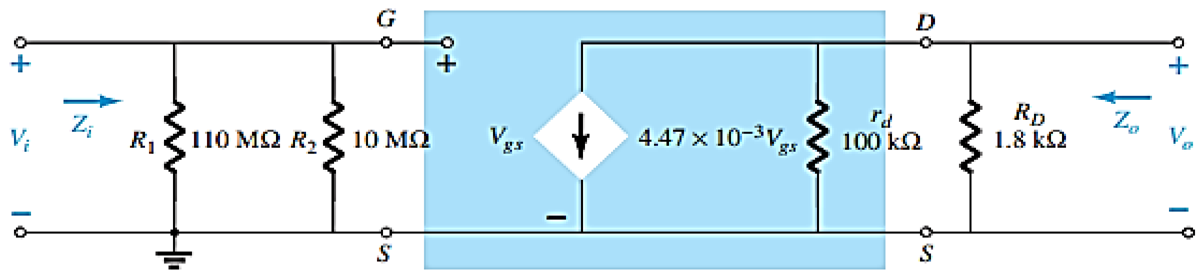


FIG. 8.35
AC equivalent circuit for Fig. 8.34.

d. Eq. (8.28): $Z_i = R_1 \| R_2 = 10\text{ M}\Omega \| 110\text{ M}\Omega = \mathbf{9.17\text{ M}\Omega}$

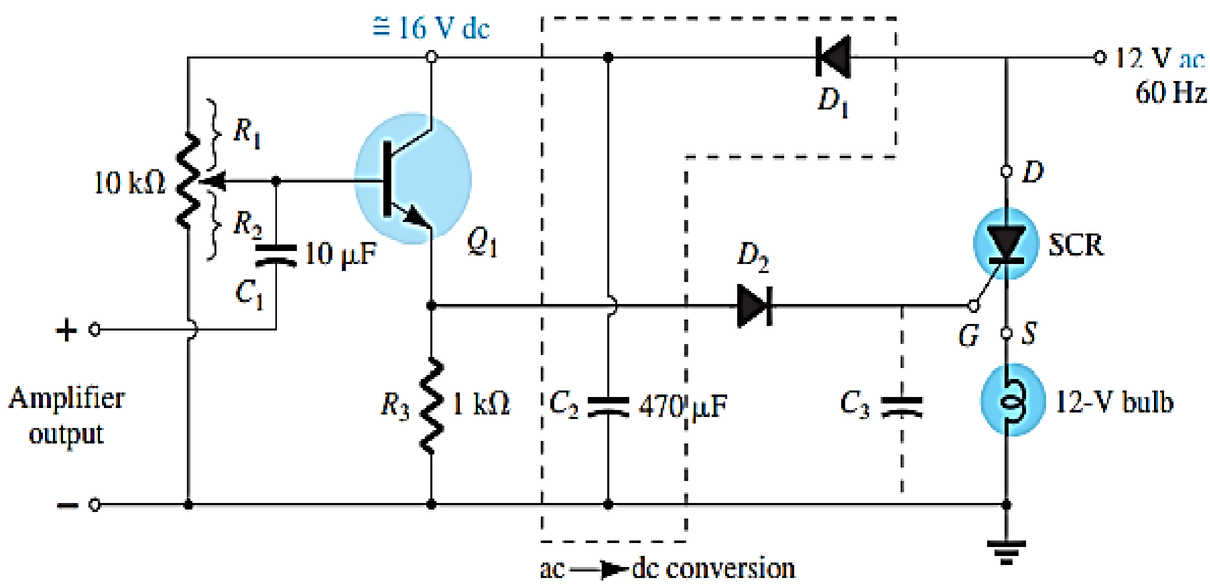
e. Eq. (8.29): $Z_o = r_d \| R_D = 100\text{ k}\Omega \| 1.8\text{ k}\Omega = \mathbf{1.77\text{ k}\Omega} \cong R_D = \mathbf{1.8\text{ k}\Omega}$

f. $r_d \geq 10R_D \rightarrow 100\text{ k}\Omega \geq 18\text{ k}\Omega$

Eq. (8.32): $A_v = -g_m R_D = -(4.47\text{ mS})(1.8\text{ k}\Omega) = \mathbf{8.05}$

Design and working of Sound-Modulated Light Source

The light from the 12-V bulb of figure below will vary at a frequency and an intensity that are sensitive to the applied signal. The applied signal may be the output of an acoustical amplifier, a musical instrument, or even a microphone. Of particular interest is the fact that the applied voltage is 12 V ac rather than the typical dc biasing supply.



The immediate question, in the absence of a dc supply, is how the dc biasing levels for the transistor will be established. In actuality, the dc level is obtained through the use of diode D1 , which rectifies the ac signal, and capacitor C2 , which acts as a power supply filter to generate a dc level across the output branch of the transistor. The peak value of a 12-V rms supply is about 17 V, resulting in a dc level after the capacitive filtering in the neighbourhood of 16 V. If the potentiometer is set so that R1 is about 320, the voltage from base to emitter of the transistor will be about 0.5 V, and the transistor will be in the "off" state. In this state the collector and emitter currents are essentially 0 mA, and the voltage across resistor R3 is approximately 0 V. The voltage at the junction of the collector terminal and the diode is therefore 0 V, resulting in D2 being in the "off" state and 0 V at the gate terminal of the silicon-controlled rectifier (SCR).