Chapter 5  Bipolar Amplifiers

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Bipolar Amplifiers

- In an ideal voltage amplifier, the input impedance is infinite and the output impedance zero.
- But in reality, input or output impedances depart from their ideal values.
The figure above shows the techniques of measuring input and output impedances.

When calculating input/output impedance, small-signal analysis is assumed.

When calculating I/O impedances at a port, we usually ground one terminal while applying the test source to the other terminal of interest.

With Early effect, the impedance seen at the collector is equal to the intrinsic output impedance of the transistor (if emitter is grounded).
The impedance seen at the emitter of a transistor is approximately equal to one over its transconductance (if the base is grounded).

**Three Master Rules of Transistor Impedances**

- Rule #1: looking into the base, the impedance is $r_{\pi}$ if emitter is (ac) grounded.
- Rule #2: looking into the collector, the impedance is $r_o$ if emitter is (ac) grounded.
- Rule #3: looking into the emitter, the impedance is $1/g_m$ if base is (ac) grounded and Early effect is neglected.

**Biasing of BJT**

- Transistors and circuits must be biased because (1) transistors must operate in the active region, (2) their small-signal parameters depend on the bias conditions.

**DC Analysis vs. Small-Signal Analysis**

- First, DC analysis is performed to determine operating point and obtain small-signal parameters.
- Second, sources are set to zero and small-signal model is used.
Notation Simplification

- Hereafter, the battery that supplies power to the circuit is replaced by a horizontal bar labeled $V_{cc}$, and input signal is simplified as one node called $V_{in}$.

Example of Bad Biasing

- The microphone is connected to the amplifier in an attempt to amplify the small output signal of the microphone.
- Unfortunately, there’s no DC bias current running through the transistor to set the transconductance.

Another Example of Bad Biasing

- The base of the amplifier is connected to $V_{cc}$, trying to establish a DC bias.
- Unfortunately, the output signal produced by the microphone is shorted to the power supply.

Biasing with Base Resistor

- Assuming a constant value for $V_{BE}$, one can solve for both $I_B$ and $I_C$ and determine the terminal voltages of the transistor.
- However, bias point is sensitive to $\beta$ variations.
**Improved Biasing: Resistive Divider**

- Using resistor divider to set $V_{BE}$, it is possible to produce an $I_C$ that is relatively independent of $\beta$ if base current is small.

$$V_X = \frac{R_2}{R_1 + R_2} V_{CC}$$

$$I_C = I_S \exp\left(\frac{V_{CC}}{V_T}\right)$$

**Accounting for Base Current**

- With proper ratio of $R_1$ and $R_2$, $I_C$ can be insensitive to $\beta$; however, its exponential dependence on resistor deviations makes it less useful.

$$I_C = I_S \exp\left(\frac{V_{Th} - I_B R_{Th}}{V_T}\right)$$

**Emitter Degeneration Biasing**

- The presence of $R_E$ helps to absorb the error in $V_X$ so $V_{BE}$ stays relatively constant.
- This bias technique is less sensitive to $\beta$ ($I_1 >> I_B$) and $V_{BE}$ variations.

**Design Procedure**

- Choose an $I_C$ to provide the necessary small signal parameters, $g_m$, $r_\pi$, etc.
- Considering the variations of $R_1$, $R_2$, and $V_{BE}$, choose a value for $V_{RE}$.
- With $V_{RE}$ chosen, and $V_{BE}$ calculated, $V_X$ can be determined.
- Select $R_1$ and $R_2$ to provide $V_X$. 
**Self-Biasing Technique**

- This bias technique utilizes the collector voltage to provide the necessary $V_x$ and $I_B$.
- One important characteristic of this technique is that collector has a higher potential than the base, thus guaranteeing active operation of the transistor.

**Self-Biasing Design Guidelines**

1. $R_C >> \frac{R_B}{\beta}$
2. $\Delta V_{BE} << V_{CC} - V_{BE}$

(1) provides insensitivity to $\beta$.
(2) provides insensitivity to variation in $V_{BE}$.

**Summary of Biasing Techniques**

- Same principles that apply to NPN biasing also apply to PNP biasing with only polarity modifications.
Possible Bipolar Amplifier Topologies

- Three possible ways to apply an input to an amplifier and three possible ways to sense its output.
- However, in reality only three of six input/output combinations are useful.

Study of Common-Emitter Topology

- Analysis of CE Core
  - Inclusion of Early Effect
- Emitter Degeneration
  - Inclusion of Early Effect
- CE Stage with Biasing

Common-Emitter Topology

- Input Applied to Base
- Output Sensed at Collector

Small Signal of CE Amplifier

\[ A_v = \frac{V_{out}}{V_{in}} \]

\[ -\frac{V_{out}}{R_C} = g_m v_\pi = g_m V_{in} \]

\[ A_v = -g_m R_C \]
Limitation on CE Voltage Gain

Since $g_m$ can be written as $I_C/V_T$, the CE voltage gain can be written as the ratio of $V_{RC}$ and $V_T$.

$V_{RC}$ is the potential difference between $V_{CC}$ and $V_{CE}$, and $V_{CE}$ cannot go below $V_{BE}$ in order for the transistor to be in active region.

Tradeoff between Voltage Gain and Headroom

$|A_v| = \frac{I_C R_C}{V_T}$

$|A_v| = \frac{V_{RC}}{V_T}$

$|A_v| < \frac{V_{CC} - V_{BE}}{V_T}$

I/O Impedances of CE Stage

When measuring output impedance, the input port has to be grounded so that $V_{in} = 0$.

CE Stage Trade-offs
Inclusion of Early Effect

Early effect will lower the gain of the CE amplifier, as it appears in parallel with RC.

\[ A_v = -g_m (R_C \parallel r_O) \]

\[ R_{out} = R_C \parallel r_O \]

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Intrinsic Gain

As \( R_C \) goes to infinity, the voltage gain reaches the product of \( g_m \) and \( r_O \), which represents the maximum voltage gain the amplifier can have.

- The intrinsic gain is independent of the bias current.

\[ A_v = -g_m r_O \]

\[ |A_v| = \frac{V_A}{V_T} \]

Current Gain

Another parameter of the amplifier is the current gain, which is defined as the ratio of current delivered to the load to the current flowing into the input.

- For a CE stage, it is equal to \( \beta \).

\[ A_I = \frac{i_{out}}{i_{in}} \]

\[ A_I|_{CE} = \beta \]

Emitter Degeneration

- By inserting a resistor in series with the emitter, we “degenerate” the CE stage.

- This topology will decrease the gain of the amplifier but improve other aspects, such as linearity, and input impedance.
**Small-Signal Model**

- Interestingly, this gain is equal to the total load resistance to ground divided by $1/g_m$ plus the total resistance placed in series with the emitter.

$$A_v = -\frac{g_m R_C}{1 + g_m R_E}$$

$$A_v = -\frac{R_C}{\frac{1}{g_m} + R_E}$$

**Emitter Degeneration Example I**

- The input impedance of Q$_2$ can be combined in parallel with $R_E$ to yield an equivalent impedance that degenerates Q$_1$.

$$A_v = -\frac{R_C}{\frac{1}{g_m} + R_E \parallel r_{\pi 2}}$$

**Emitter Degeneration Example II**

- In this example, the input impedance of Q$_2$ can be combined in parallel with $R_C$ to yield an equivalent collector impedance to ground.

$$A_v = -\frac{R_C \parallel r_{\pi 2}}{\frac{1}{g_m} + R_E}$$

**Input Impedance of Degenerated CE Stage**

- With emitter degeneration, the input impedance is increased from $r_\pi$ to $r_\pi + (\beta+1)R_E$, a desirable effect.

$$V_A = \infty$$

$$v_X = r_\pi i_X + R_E (1 + \beta)i_X$$

$$R_{in} = \frac{v_X}{i_X} = r_\pi + (\beta+1)R_E$$
Output Impedance of Degenerated CE Stage

Emitter degeneration does not alter the output impedance in this case. (More on this later.)

Example: Design CE Stage with Degeneration as a Black Box

- If $g_m R_E$ is much greater than unity, $G_m$ is more linear.

Capacitor at Emitter

- At DC the capacitor is open and the current source biases the amplifier.
- For AC signals, the capacitor is short and the amplifier is degenerated by $R_E$.

Degenerated CE Stage with Base Resistance

$$V_A = \infty$$
$$\frac{v_{out}}{v_{in}} = \frac{V_A}{V_{in}}$$
$$v_{out} = -\frac{\beta R_C}{\beta + 1}$$
$$A_v \approx \frac{1}{g_m + \frac{R_E}{\beta + 1}} + \frac{R_S}{\beta + 1}$$
Input/Output Impedances

- $V_{in} = \infty$
- $R_{in1} = r_\pi + (\beta + 1)R_E$
- $R_{in2} = R_B + r_\pi + (\beta + 1)R_E$
- $R_{out} = R_C$

- $R_{in1}$ is more important in practice as $R_B$ is often the output impedance of the previous stage.

Emitter Degeneration Example III

- $A_v = \frac{- (R_C \parallel R_r)}{1 + R_2 + \frac{R_B}{\beta + 1}}$
- $R_{in} = r_\pi + (\beta + 1)R_2$
- $R_{out} = R_C \parallel R_1$

Output Impedance of Degenerated Stage with Finite $V_A$

- Emitter degeneration boosts the output impedance by a factor of $1 + g_m (R_E \parallel r_\pi)$.
- This improves the gain of the amplifier and makes the circuit a better current source.

Two Special Cases

1. $R_E >> r_\pi$
   - $R_{out} \approx r_O (1 + g_m r_\pi) \approx \beta r_O$

2. $R_E << r_\pi$
   - $R_{out} \approx (1 + g_m R_E) r_O$
Analysis by Inspection

This seemingly complicated circuit can be greatly simplified by first recognizing that the capacitor creates an AC short to ground, and gradually transforming the circuit to a known topology.

\[
R_{\text{out}} = R_i \parallel R_{\text{ser}} \Rightarrow R_{\text{ser}} = [1 + g_m (R_2 \parallel r_o)] r_o \Rightarrow R_{\text{out}} = R_i \parallel [1 + g_m (R_2 \parallel r_o)] r_o
\]

Example: Degeneration by Another Transistor

Called a “cascode”, the circuit offers many advantages that are described later in the book.

\[
R_{\text{out}} = [1 + g_m (r_o2 \parallel r_o1)] r_o1
\]

Bad Input Connection

Since the microphone has a very low resistance that connects from the base of Q1 to ground, it attenuates the base voltage and renders Q1 without a bias current.

Use of Coupling Capacitor

Capacitor isolates the bias network from the microphone at DC but shorts the microphone to the amplifier at higher frequencies.
**DC and AC Analysis**

A coupling capacitor is open for DC calculations and shorted for AC calculations.

\[ A_v = -g_m (R_C \parallel r_O) \]
\[ R_{in} = r_\pi \parallel R_B \]
\[ R_{out} = R_C \parallel r_O \]

**Bad Output Connection**

Since the speaker has an inductor, connecting it directly to the amplifier would short the collector at DC and therefore push the transistor into deep saturation.

**Still No Gain!!!**

In this example, the AC coupling indeed allows correct biasing. However, due to the speaker's small input impedance, the overall gain drops considerably.

\[ A_v = -g_m (R_C \parallel r_O) \]
\[ R_{in} = r_\pi \parallel R_1 \parallel R_2 \]
\[ R_{out} = R_C \parallel r_O \]
CE Stage with Robust Biasing

\[ A_v = \frac{-R_C}{1 + g_m R_E} \]

\[ R_{in} = [r_\pi + (\beta + 1)R_E]||R_1||R_2 \]

\[ R_{out} = R_C \]

Removal of Degeneration for Signals at AC

- Capacitor shorts out RE at higher frequencies and removes degeneration.

Complete CE Stage

\[ A_v = -g_m R_C \]

\[ R_{in} = r_\pi || R_1 || R_2 \]

\[ R_{out} = R_C \]

Summary of CE Concepts