Electronics II
Lecture 3(c): Transistor Bias Circuits

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Voltage-Divider Bias

- A method of biasing a transistor for linear operation using a single-source resistive voltage divider.

- Earlier, a separate dc source, $V_{\text{BB}}$, was used to bias the base-emitter junction because it could be varied independently of $V_{\text{CC}}$.

& it helped to illustrate transistor operation.

- More practical bias method: use $V_{\text{CC}}$ as the single bias source.

- A dc bias voltage at the base of the transistor can be developed by a resistive voltage divider that consists of $R_1 \& R_2$. $V_{\text{CC}}$: the dc collector supply voltage

- 2 current paths are between point A & ground;
  (1) through $R_2$, and (2) through the base-emitter junction of the transistor & $R_E$

- Generally, voltage-divider bias circuits are designed so that the base current is much smaller than the current ($I_2$) through $R_2$.

For this case, the voltage-divider circuit is very straightforward to analyze because the loading effect of the base current can be ignored.
Voltage-Divider Bias

**Stiff voltage divider:** A voltage divider in which the *base current is small compared to the current in $R_2$* (the base voltage is relatively independent of different transistors & temperature effects).

*Ideally,* a voltage-divider circuit is **stiff**; where transistor does **not appear as a significant load**.

To determine if the divider is stiff or not, then need to **examine the dc input resistance looking in at the base**.

![Voltage Divider Circuit Diagram]

Stiff:

$$V_B = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC}$$

$$R_{IN(BASE)} \gg 10R_2$$

Not stiff:

$$V_B = \left(\frac{R_2 \parallel R_{IN(BASE)}}{R_1 + R_2 \parallel R_{IN(BASE)}}\right) V_{CC}$$

$$R_{IN(BASE)} < 10R_2$$
Loading-Effect of Voltage-Divider Bias

(1) DC Input Resistance at the Transistor Base

(2) Stability of Voltage-Divider Bias

(3) Voltage-Divider Biased PNP Transistor
DC Input Resistance at the Transistor Base

- The dc input resistance of the transistor is proportional to $\beta_{DC}$, thus it will change for different transistors.

- When a transistor is operating in its linear region, the emitter current is $\beta_{DC}I_B$.

- When the emitter resistor is viewed from the base circuit, the resistor appears to be larger than its actual value by a factor of is $\beta_{DC}$ because of the current gain in the transistor. Thus,

$$R_{IN(BASE)} = \frac{DCV_B}{I_E}$$

- This is the effective load on the voltage divider illustrated in earlier Figure.
DC Input Resistance at the Transistor Base

- We can estimate the loading effect by comparing $R_{IN(BASE)}$ to the resistor $R_2$ in the voltage divider.

- As long as $R_{IN(BASE)}$ is at least 10x larger than $R_2$, the loading effect will be 10% or less & the voltage divider is stiff.

- If $R_{IN(BASE)}$ is less than 10x $R_2$, it should be combined in parallel with $R_2$. 
Stability of Voltage-Divider Bias

- Thevenin’s theorem is applied when analyze a voltage-divider biased transistor circuit for **base current loading effects**.

- 1st, get an equivalent base-emitter circuit for this circuit using Thevenin’s theorem.

- Looking out from the base terminal, the bias circuit can be redrawn as shown in this figure.

- Apply Thevenin’s theorem to the circuit left of point A, with \( V_{CC} \) replaced by a short to ground & the transistor disconnected from the circuit.

- The voltage at point A with respect to ground is,

\[
V_{TH} = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC}
\]

- and the resistance is,

\[
R_{TH} = \frac{R_1 R_2}{R_1 + R_2}
\]
Stability of Voltage-Divider Bias

- The Thevenin equivalent of the bias circuit, connected to the transistor base, is as shown in the grey box in the figure.

- Applying Kirchhoff’s voltage law around the equivalent base-emitter loop gives,
  \[ V_{TH} - V_{RTH} - V_{BE} - V_{RE} = 0 \]

- Substituting, using Ohm’s law, & solving for \( V_{TH} \),
  \[ V_{TH} = I_B R_{TH} + V_{BE} + I_E R_E \]

- Substituting \( I_E / \beta_{DC} \) for \( I_B \),
  \[ V_{TH} = I_E (R_E + R_{TH}/\beta_{DC}) + V_{BE} \]
Stability of Voltage-Divider Bias

- Solving for $I_E$, 
  
  \[ I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}} \]

- If $R_{TH}/\beta_{DC}$ is small compared to $R_E$, the result is the same as for unloaded voltage divider.

- Reason of why a voltage-divider bias is widely used;
  - Reasonably good bias stability is achieved with a single supply voltage.
Stability of Voltage-Divider Bias

The **unloaded voltage divider** approximation for $V_B$ gives reasonable results. A more exact solution is to Thevenize the input circuit.

\[
\begin{align*}
V_{TH} &= V_B(\text{no load}) \\
&= 4.62 \text{ V} \\
R_{TH} &= R_1 || R_2 = \\
&= 8.31 \text{ k}\Omega \\
\end{align*}
\]

The Thevenin input circuit can be drawn:

\[
\begin{align*}
\beta_{DC} &= 200 \\
\end{align*}
\]
Now write KVL around the base emitter circuit and solve for $I_E$.

\[ V_{TH} = I_B R_{TH} + V_{BE} + I_E R_E \]

\[ I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH} / \beta_{DC}} \]

Substituting and solving,

\[ I_E = \frac{4.62 \text{ V} - 0.7 \text{ V}}{680 \Omega + 8.31 \text{ k}\Omega / 200} = 5.43 \text{ mA} \]

and

\[ V_E = I_E R_E = (5.43 \text{ mA})(0.68 \text{ k}\Omega) = 3.69 \text{ V} \]
Voltage-Divider Biased PNP Transistor

- pnp transistor requires bias polarities opposite to the npn.
- This can be accomplished by using a negative collector supply voltage: (a), or with a positive emitter supply voltage (b). 3rd figure is same as (b), only that it is drawn upside down.

![Diagrams showing pnp transistor biasing methods](image_url)
Voltage-Divider Biased PNP Transistor

- Analysis procedure is the same as for an npn transistor circuit.

- For a stiff voltage divider (ignoring loading effects),

  \[ V_B \approx \frac{R_1}{R_1 + R_2} V_{EE} \quad V_E = V_B + V_{BE} \]

- By Ohm’s law,

  \[ I_E = \frac{V_{EE} - V_E}{R_E} \quad V_C = I_C R_C \]

- Thus,

  \[ V_{EC} = V_E - V_C \]
Voltage-Divider Biased PNP Transistor

Determine \( I_E \) for the pnp circuit. Assume a stiff voltage divider (no loading effect).

**Example:**

**Solution:**

\[
V_B = \left( \frac{R_1}{R_1 + R_2} \right) V_{EE} \\
= \left( \frac{27 \text{ k}\Omega}{27 \text{ k}\Omega + 12 \text{ k}\Omega} \right) (+15.0 \text{ V}) = 10.4 \text{ V} \\
V_E = V_B + V_{BE} = 10.4 \text{ V} + 0.7 \text{ V} = 11.1 \text{ V} \\
I_E = \frac{V_{EE} - V_E}{R_E} = \frac{15.0 \text{ V} - 11.1 \text{ V}}{680 \Omega} = 5.74 \text{ mA}
\]
EMITTER BIAS

Provides excellent bias stability in spite of changes in $\beta$ or temperature.

Use both a positive & a negative supply voltage.

In an npn circuit, the small base current causes the base voltage to be slightly below ground.

The emitter voltage is one diode drop less than this.
EMITTER BIAS

The combination of this small drop across $R_B$ & $V_{BE}$ forces the emitter to be at approximately -1 V.

Thus, emitter current is,  
\[ I_E = \frac{-V_{EE} - 1}{R_E} \]

Applying the approximation that  
\[ I_C \approx I_E \]

to calculate the collector voltage, thus  
\[ V_C = V_{CC} - I_C R_C \]
EMITTER BIAS

- Approximation that \( V_E \approx -1 \) & the neglect of \( \beta_{DC} \) may **not be accurate enough for design work or detailed analysis**.
- Kirchhoff’s voltage law (KVL) can be applied to develop a more detailed formula for \( I_E \).

- In (a): KVL applied around the base-emitter circuit
- In (b): (a) is redrawn for analysis
- Thus,

\[
V_{EE} + V_{RB} + V_{BE} + V_{RE} = 0
\]

\[
V_{EE} + I_B R_B + V_{BE} + I_E R_E = 0
\]

- Substitute transposing \( V_{EE} \), & \( I_B \approx I_E / \beta_{DC} \)

\[
\left( \frac{I_E}{\beta_{DC}} \right) R_B + I_E R_E + V_{BE} = -V_{EE}
\]
EMITTER BIAS

- Thus,

\[ I_E = \frac{-V_{EE} - V_{BE}}{R_E + R_B/\beta_{DC}} \]

- Voltages with respect to ground are indicated by a single subscript.
- Thus, the emitter voltage with respect to the ground is,

\[ V_E = V_{EE} + I_E R_E \]

- The base voltage with respect to ground is,

\[ V_B = V_E + V_{BE} \]

- The collector with respect to the ground is,

\[ V_C = V_{CC} - I_C R_C \]
This method of biasing is common in switching circuits.

Analysis of this circuit for the linear region shows that it is directly dependent on $\beta_{DC}$.

- Starts with KVL around the base circuit,
  $$V_{CC} - V_{RB} - V_{BE} = 0$$

- Substitutes $I_B R_B$ for $V_{RB}$,
  $$V_{CC} - I_B R_B - V_{BE} = 0$$

- Thus,
  $$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$
BASE BIAS

- When KVL is applied around the collector circuit, we get,
  \[ V_{CC} - I_C R_C - V_{CE} = 0 \]

- Thus,
  \[ V_{CE} = V_{CC} - I_C R_C \]

- Substitute \( I_C = \beta_{DC} I_B \), we get,
  \[ I_C = \beta_{DC} \left( \frac{V_{CC} - V_{BE}}{R_B} \right) \]

Base bias is used in switching circuits because of its simplicity, but not widely used in linear applications because the \( Q \)-point is \( b \) dependent.
BASE BIAS

Base current is derived from the collector supply through a large base resistor.

Example:
What is $I_B$?

Solution:

$$I_B = \frac{V_{CC} - 0.7\,\text{V}}{R_B} = \frac{15\,\text{V} - 0.7\,\text{V}}{560\,\text{k}\Omega} = 25.5\,\text{mA}$$
Q-Point Stability of Base Bias

- Equation

\[ I_C = \beta_{DC} \left( \frac{V_{CC} - V_{BE}}{R_B} \right) \]

shows that \( I_C \) is dependent on \( \beta_{DC} \). Thus, a variation in \( \beta_{DC} \) causes \( I_C \) and, as a result, \( V_{CE} \) to change, thus changing the Q-point of the transistor. Therefore, the base bias circuit is extremely beta-dependent & unpredictable.

- \( \beta_{DC} \) varies with temperature & collector current.

- There is a large spread of \( \beta_{DC} \) values from one transistor to another of the same type due to manufacturing variations.

- Therefore, base bias is rarely used in linear circuits.
Emitter-Feedback Bias

- If an emitter resistor is added to the base-circuit, we get an emitter-feedback bias.

- Help make base bias more predictable with negative feedback, which negates any attempted change in collector current with an opposing change in base voltage.

- If the collector current tries to increase, the emitter voltage increases, causing an increase in base voltage due to $V_B = V_E + V_{BE}$

- This increase in base voltage reduces the voltage across $R_B$, thus reducing the base current & keeping the collector current from increasing.
Emitter-Feedback Bias

- The same scenario happens if the collector current tries to decrease.

- This circuit is better for linear circuits than base bias, but still dependent on $\beta_{DC}$ & is not predictable as voltage-divider bias.

- To calculate $I_E$, write KVL around the base circuit.

  $$-V_{CC} + I_B R_B + V_{BE} + I_E R_E = 0$$

- Substitute $I_E/\beta_{DC}$ for $I_B$, can see that $I_E$ is still dependent on $\beta_{DC}$.

  $$I_E = \frac{V_{CC} - V_{BE}}{R_E + R_B/\beta_{DC}}$$
Collector-Feedback Bias

- The collector voltage provides the bias for the base-emitter junction.
- The negative feedback creates an “offsetting” effect that tends to keep the Q-point stable.
- If $I_C$ tries to increase, it drops more voltage across $R_C$, and thus causing $V_C$ to decrease.
- When $V_C$ decreases, there is a decrease in voltage across $R_B$, which decreases $I_B$.
- The decrease in $I_B$ produces less $I_C$ which, in turn, drops less voltage across $R_C$ & thus offsets the decrease in $V_C$.
- By Ohm’s law, $I_B = \frac{V_C - V_{BE}}{R_B}$
- Assume that $I_C \gg I_B$, thus the collector voltage, $V_C \approx V_{CC} - I_C R_C$
- Also, $I_B = \frac{I_C}{\beta_{DC}}$
- Thus, $\frac{I_C}{\beta_{DC}} = \frac{V_{CC} - I_C R_C - V_{BE}}{R_R}$
- Thus, $I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B / \beta_{DC}}$
- Since the emitter is ground, $V_{CE} = V_C$, then $V_{CE} = V_{CC} - I_C R_C$
Q-Point Stability Over Temperature

- Equation

\[ I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}} \]

shows that \( I_C \) is dependent to some extent on \( \beta_{DC} \) and \( V_{BE} \).

- The dependency can be minimized by making \( R_C \gg R_B/\beta_{DC} \) & \( V_{CE} \gg V_{BE} \).

- The collector-feedback bias is essentially eliminates the \( \beta_{DC} \) & \( V_{BE} \) dependency even if the stated conditions are met.

- \( \beta_{DC} \) varies directly with temperature, & \( V_{BE} \) varies inversely with temperature. As the temperature goes up in a collector-feedback circuit, \( \beta_{DC} \) goes up & \( V_{BE} \) goes down.
Q-Point Stability Over Temperature

- The increase in $\beta_{DC}$ acts to increase $I_C$. The decrease in $V_{BE}$ acts to increase $I_B$ which, in turn also acts to increase $I_C$. As $I_C$ tries to increase, the voltage drop across $R_C$ also tries to increase. This tends to reduce the collector voltage & therefore the voltage across $R_B$, thus reducing $I_B$ & offsetting the attempted increase in $I_C$ & the attempted decrease in $V_C$.

- The result is that the collector-feedback circuit maintains a relatively stable Q-point. The reverse action occurs when the temperature decreases.
Q-Point Stability Over Temperature

Example:

Compare $I_C$ for the case when $b = 100$ with the case when $b = 300$.

Solution:

When $b = 100$,

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + \frac{R_B}{\beta_{DC}}} = \frac{15 \text{ V} - 0.7 \text{ V}}{1.8 \text{ k}\Omega + 330 \text{ k}\Omega/100} = 2.80 \text{ mA}$$

When $b = 300$,

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + \frac{R_B}{\beta_{DC}}} = \frac{15 \text{ V} - 0.7 \text{ V}}{1.8 \text{ k}\Omega + 330 \text{ k}\Omega/300} = 4.93 \text{ mA}$$