Guide to NPN Amplifier Analysis

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1. Transistor characteristics

A BJT has three operating modes cutoff, active, and saturation. For applications, like amplifiers, where linear characteristics are nice, we want the transistor to stay in the active region. For non-linear applications, like digital logic, the other two regions become more important.

i) Cutoff region

The base-emitter junction is reverse biased. In this case no current is flowing into the base, into the collector, or out of the emitter. This is just as if the transistor was not powered at all.

ii) Active region

The base-emitter junction is forward biased and the base-collector junction is reverse biased. In this region the collector current is proportional to the base current. The following equations dictate the current characteristics of the transistor.

$$I_C = \beta I_B$$
$$I_E = I_B + I_C$$
$$I_E = \alpha I_C$$
$$\alpha = \frac{\beta}{\beta + 1}$$
$$V_{BE} \simeq 0.7\,V$$

iii) Saturation region

The base-emitter junction is forward biased and the base-collector junction is forward biased. In this mode the current into the collector is limited and is no longer proportional to the base current. The collector-emitter voltage should remain about constant.

$$V_{CE} \simeq 0.2\,V$$

2. DC Bias Point Analysis

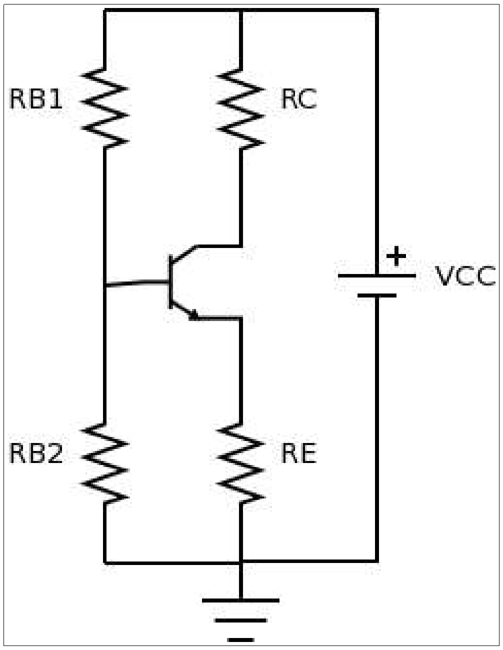


Figure 1-Typical Biasing Network

Figure one shows the typical Beta Stabilized Biasing Network. It allows the transistor to be biased using a single voltage source. The analysis of the DC operating point is straight forward and is shown below.

i) Simplify the circuit
Use a Thevenin equivalent circuit to replace the resistors and source connected to the base.

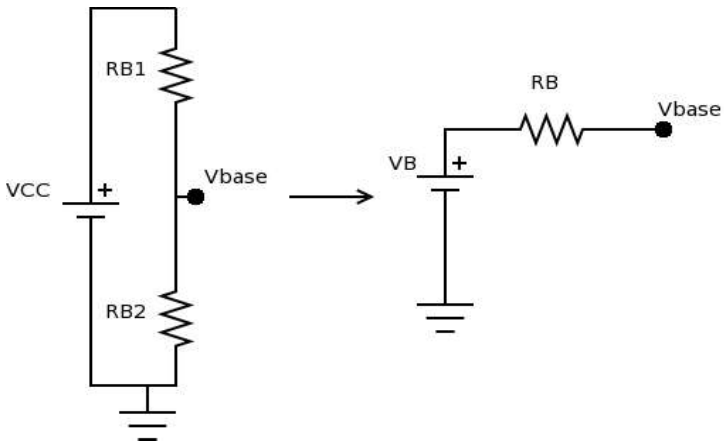


Figure 2-Thevenin Equivalent For Base

This conversion is simple. VBB can be calculated from the voltage divider on the left and RB is simply the equivalent of RB1 and RB2 in parallel.

$$V_{BB} = V_{CC}\frac{R_{B2}}{R_{B1}+R_{B2}}$$
$$R_B = R_{B1} \| R_{B2}$$

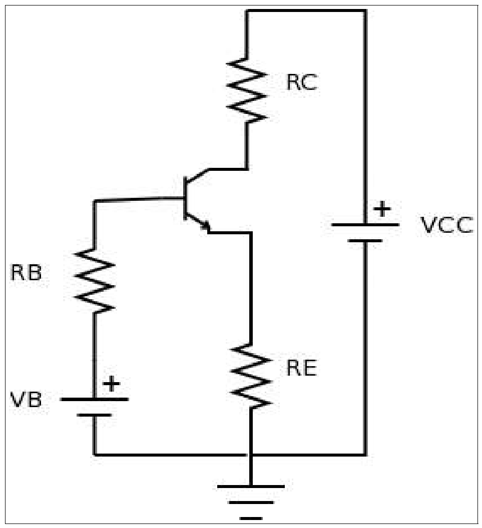


Figure 3-Updated Biasing Network

ii) Calculate IB

Use Kirchhoff's voltage law to solve for IB.

$$V_{BB} - I_B R_B - V_{BE} - I_E R_E$$
$$V_{BB} - V_{BE} = I_B(R_B + (\beta+1)R_E)$$
$$I_B = \frac{V_{BB} - V_{BE}}{R_B + (\beta+1)R_E}$$

iii)Finish the DC Analysis

All of the other parameters should fall into place.

$$I_C = \beta I_B$$
$$I_E = (\beta+1)I_B$$
$$V_B = V_{BB} - I_B R_B$$
$$V_C = V_{CC} - I_C R_C$$
$$V_E = I_E R_E$$

iv)Obtain the small signal parameters

The small signal parameters show us how this circuit will operate when a small signal is applied.

$$r_\pi = \frac{V_T}{I_B}$$
$$r_e = \frac{V_T}{I_E}$$
$$g_m = \frac{I_C}{V_T}$$

3. Small Signal Models

There are two different models that can be used for small signal analysis the 'T' and 'Pi' models. These replace the complicated exponential I-V characteristics of the transistor in the active region with linear relations in the form of resistors and dependent voltage sources. As long as the variation in v_{be} is small, there is little error in the approximation.

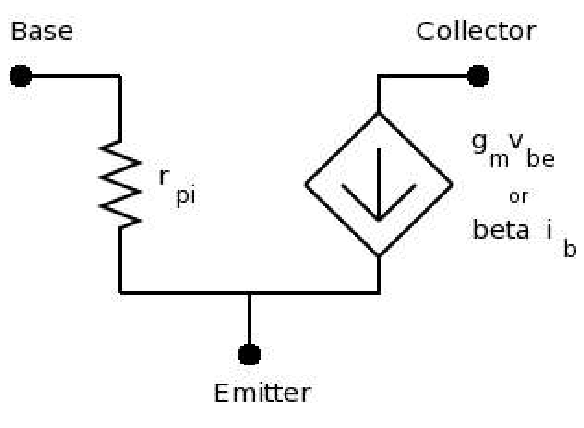


Figure 5-Pi Model

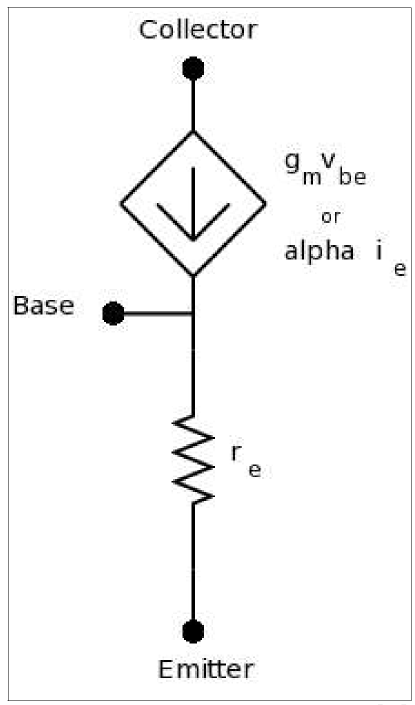


Figure 4-T Model

Note that the relationships between the currents still apply in the small signal model.

4. Small Signal Analysis

We now replace the transistor with the model of your choice, short all capacitors and ground all DC voltage sources. We assume that the capacitors are large enough that they do not affect the time varying part of the signal significantly.

For the following example we will analyze a common emitter amplifier, which has an input at the base, output at the collector, and a capacitor between the emitter and ground.

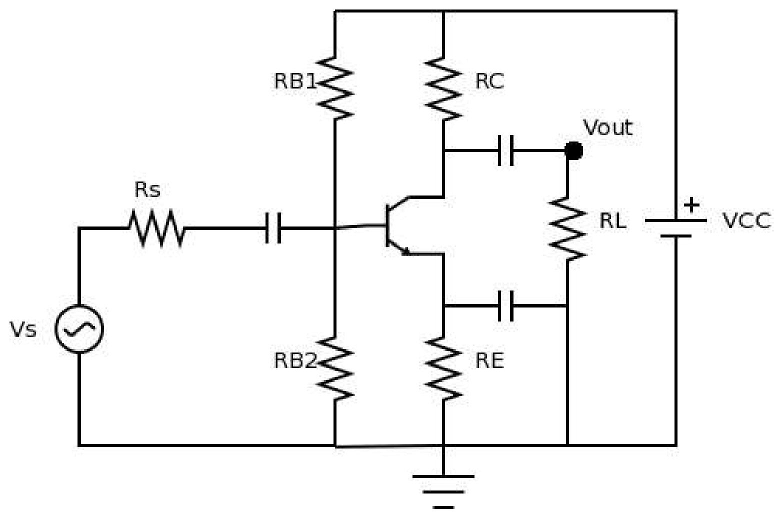
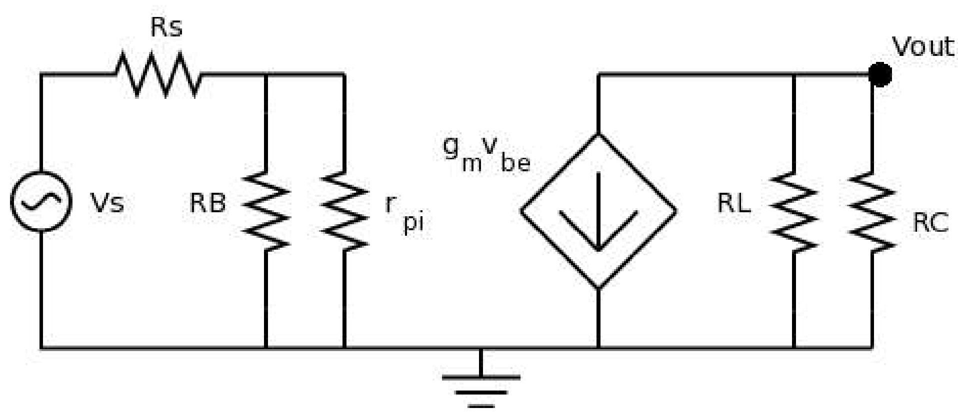


Figure 6-Common Emitter Amplifier

Rs is the output resistance of the previous stage and RL is the input resistance of the next stage. After the DC analysis from section 2 and applying the transforms from section 3 we get the circuit shown below.



This is a trivial circuit to solve for any parameter. Remember that v_{be} is the voltage across r_{π}. To obtain the voltage gain we attempt to find Vout with respect to Vs.

$$i_s = \frac{v_s}{R_s + R_B \| r_\pi}$$

$$v_{be} = i_s (R_B \| r_\pi)$$

$$v_{be} = V_s \frac{R_B \| r_\pi}{R_s + R_B \| r_\pi}$$

$$i_c = g_m v_{be}$$

$$i_c = g_m V_s \frac{R_B \| r_\pi}{R_s + R_B \| r_\pi}$$

$$V_{out} = i_c (R_C \| R_L)$$

$$V_{out} = g_m V_s \frac{(R_B \| r_\pi)(R_C \| R_L)}{R_s + R_B \| r_\pi}$$

$$\frac{V_{out}}{V_s} = g_m \frac{(R_B \| r_\pi)(R_C \| R_L)}{R_s + R_B \| r_\pi}$$

(I haven't had a chance to double check this, but it looks correct.) Notice that in an ideal case, low R_S and high R_L, the final expression collapses to $g_m R_C$. There are circumstances where the capacitor connected to the emitter can be removed to gain more control over the amplifier's characteristics. In this case R_E must be accounted for in the small-signal model. The 'T' model is more useful in this case.

If this were an actual design, you would want to add together your DC and small-signal values for the voltages and make sure that the transistor stays in the active mode and that none of the signals are clipped by the power supply. The value of Vout can not be greater than VCC or lower than 0V.