Circuits with Transistors

Contents

1 Transistors

Transistors are three terminal semicounductor amplifying device that regulates current or voltage. A small change in the current or voltage at an inner semiconductor layer (which acts as the control electrode) produces a large, rapid change in the current passing through the entire component. The component can thus act as a switch, opening and closing an electronic gate. A transistor is a active device that can amplify, producing an output signal with more power in it than the input signal

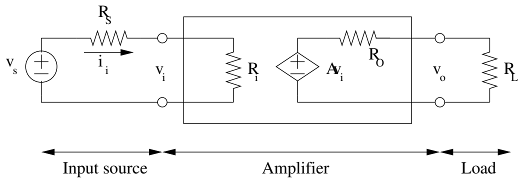


Figure 1: Thevenin's equivalent of an amplifier with signal source connected to input and a load impedance connected to the ouput

There are two kind of transistors, the bipolar transistor (also called the junction transistor), and the field effect transistor (FET).

Invented in 1947 at Bell Labs, transistors have become the key ingredient of all digital circuits, including computers. Prior to the invention of transistors, digital circuits were composed of vacuum tubes, which had many disadvantages: they were much larger, required more energy, dissipated more heat, and were more prone to failures. For a good introduction about vacuum tubes and how to use them visit the web page `http://www.hans-egebo.dk`

2 Amplifiers

An amplifier is a device that takes an input signal and magnifies it by a factor A where $v_{out} = Av_{in}$. These gain is the so called open-loop gain. In order to study how an ideal amplifier looks like, an amplifier has been sketched in figure 1. In this figure the amplifier has been replaced by a Thevenin's equivalent and an input source and output load have been added. In these conditions the "real" amplification factor (A_r) can be expressed as:

$$A_r = \frac{v_o}{v_s} = \frac{i_o R_L}{v_s} = \frac{\frac{Av_i}{R_o R_L}}{v_s} R_L$$

taking into account that the input source equivalent circuit we can state

$$v_i = v_s \frac{R_i}{R_s + R_i}$$

and substituting in the upper expression

$$A_r = A \frac{R_i}{R_s + R_i} \frac{R_L}{R_o + R_L}$$

Looking that expression we can easily sees that the real gain is smaller than the open-loop gain. For an ideal amplifier we can express that:

a) $R_i \to \infty$, so the entire source voltage v_s is developed across R_i. In other words all v_s is placed across the amplifier input and the input source v_s does not have to develop any power ($i_i = 0$ when $R_i = \infty$)

b) $R_o \to 0$ so all the availabe voltage is developed across R_L and none of it is lost internally.

c) $A \to \infty$ for obvious reasons.

d) A should be constant with frequency, that is, amplify all frequencies equally.

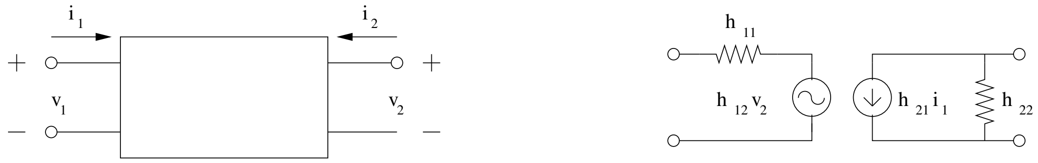


Figure 2: h parameters definition

2.1 h parameters

An amplifier can be seen as a quadrupole. h parameters cames from a direct application of Thevenin theorem to the input dipole and Norton theoreme to the output dipole. See figure 2.

The Kirchoff equations for this model are:

$$v_1 = h_{11}i_1 + h_{12}v_2$$

$$i_2 = h_{21}i_1 + h_{22}v_2$$

If the output is short-circuited $v_2 = 0$ then

$$h_{11} = \frac{v_1}{i_1} = h_i \qquad \text{input impedance}$$
$$h_{21} = \frac{i_2}{i_1} = h_f \qquad \text{current gain}$$

If the input is open $i_1 = 0$

$$h_{12} = \frac{v_1}{v_2} = h_r \qquad \text{inverse voltage gain}$$
$$h_{22} = \frac{i_2}{v_2} = h_o \qquad \text{output admitance}$$

These four last relations gives the meaning of the h parameters. Beware, that the meaning is with the conditions imposed up, that is, output short-circuit (no load) and open input (no input). Typical values of these parameters are:

$$h_{11} = 3.5k\Omega$$
$$h_{12} = 1.3 \times 10^{-4}$$
$$h_{21} = 120$$
$$h_{22} = 8.5\mu S$$

3 Bipolar Junction Transistor (BJT)

A bipolar junction transistor is a device based in three area semiconductor material with two diode junction. There are two types of BJT, the so called npn and pnp transistors, dependig obviously on doping of each area. It is called bipolar because both electrons and holes are involved in its operation. The trhee regions are called $emiter$, $base$ and $collector$. In figure 3 are shown both types of BJT and the majority current flow.

In order to show the transistor effect, the diode polarization should be correct, that is, the emitter-base is in forward bias and the base-collector in reverse bias. In a NPN transistor:

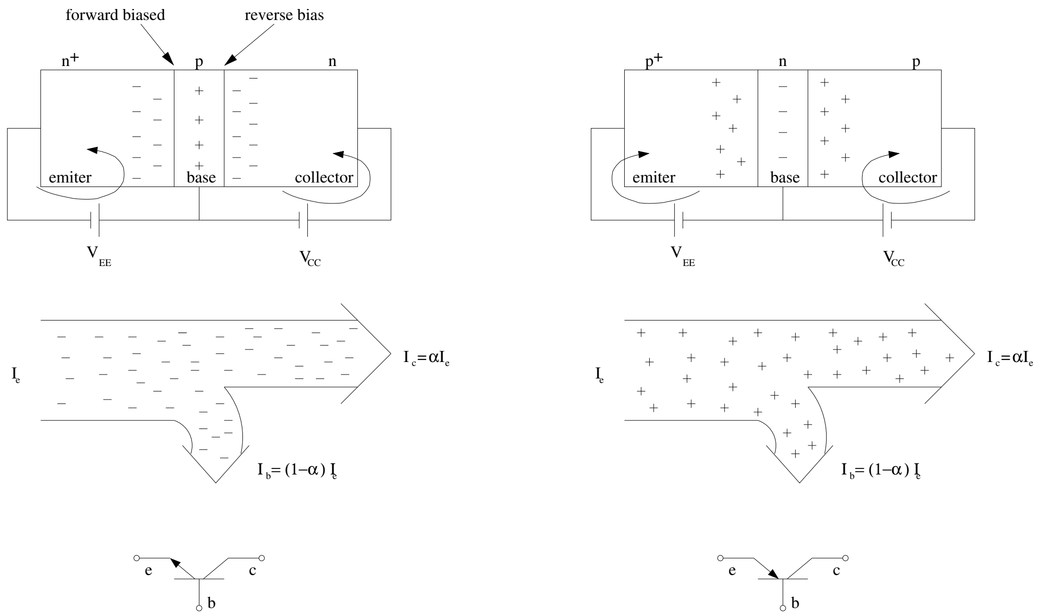


Figure 3:

a) Electrons are majoritary carriers in the emitters, so they can pass with no problems to the base. As the emitter is intended to provide the charge carriers will be heavely doped.

b) The base is slightly doped and made very thin. This allows that the recombination current, that will exit by the base is small and that the diffussion length is longer than the base length and consequently almost all electrons from emitter will pass to the collector

c) Once in the collector, the electrons will exit by the lead.

For PNP transistors the explanation is exactly the same just changing electrons for holes and inversing the currents.

In order to study the transistor we are going to mount the so called common emitter configuration. In figure 4 is shown how this configuration.

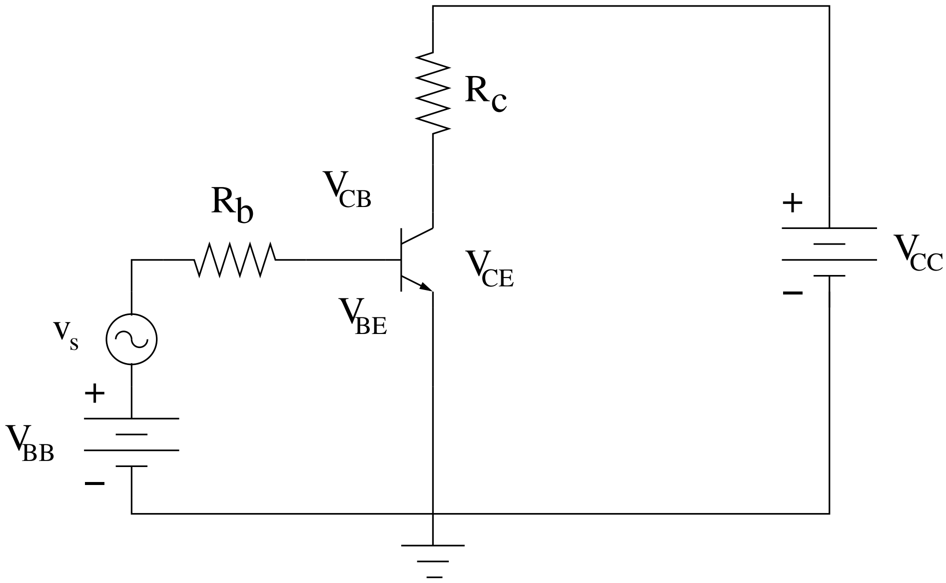
The parameters α_{cc} and β_{cc}, defined for direct current are:

$$\alpha_{cc} = \frac{I_C}{I_E} \sim 0.99$$

$$\beta_{cc} = \frac{I_C}{I_B} \sim 100$$

$$I_E = I_B + I_C \rightarrow \beta_{cc} = \frac{\alpha_{cc}}{1 - \alpha_{cc}}$$

In the right side of the figure 4 have been plotted a family of characterisic courbes of a transistor. For a fixed value of V_{BB}, that fix I_B, we can increase V_{CC} from 0V. For lower values of V_{CC} both diodes are forward bias so V_{CE} will increase accordingly, this region is called saturation. With V_{CC} high enough will enter in the active or linear region, where the base-collector jounction is reverse bias. At this moment I_C becames stable (or almost) and



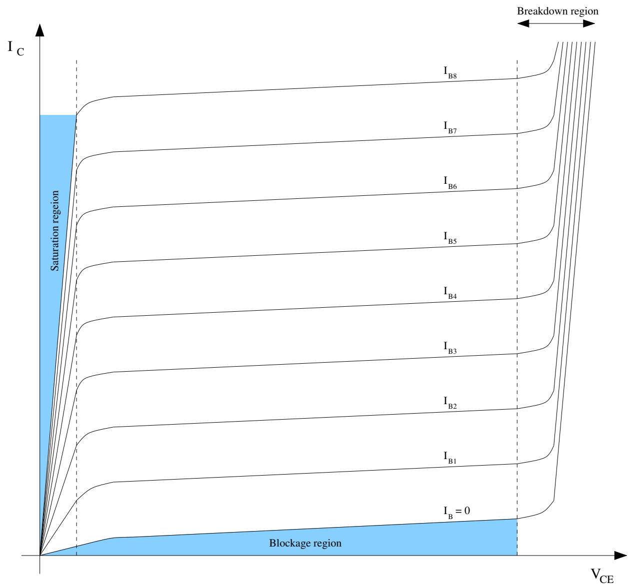


Figure 4: Transistor charactersitic curves $I_{B1} < I_{B2} < I_{B3}$,etc

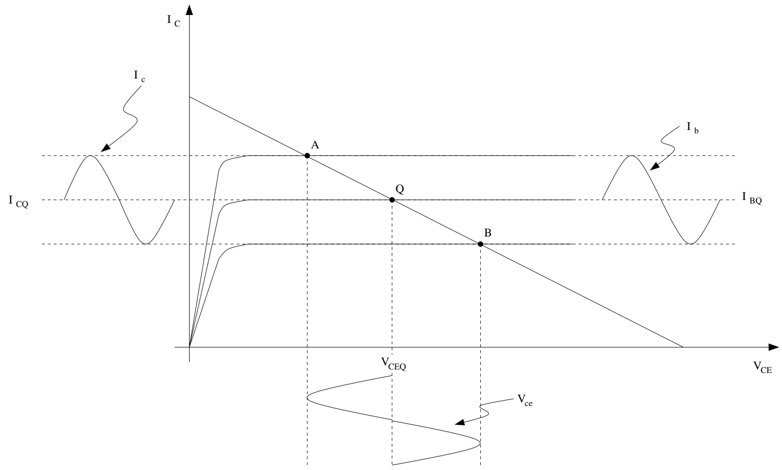


Figure 5: Q point. Variations induced in collector current I_C and V_{CE} by a variation of the base current I_B

does not change with V_{CE}. In fact, I_C increas just a bit due to the larger depletion region in the base-collector junction. So in this region the value of I_C is controlled by I_B in such a way that $I_C = \beta_{CC} I_B$. With V_{CE} large enough the base-collector junction breakdown increasing I_C quickly. Note that if $I_B = 0$ then $I_C = 0$ so the transistor does not conduct. In this situation thetransistor is in the so called blockage state.

Applying directly Kirchoff's laws to the circuit we can find directly in the output circuit that the summation of voltages around the loop gives

$$V_{CC} - I_C R_C - V_{CE} = 0$$

$$I_C = \frac{V_{CC}}{R_C} - \frac{1}{R_C} V_{CE}$$

this is the equation of a straight line, known as load line. Superimposing the load line on the output characteristics in effect gives us a graphical solution to two simultaneous equations: one equation, belonging to the transistor, non-linear equation given by the family of $I_C - VCE$ graphs, and the other the load line. The intersection points show the possible values that may exist in the circuit. In absence of the any input signal, $v_s = 0$, the operational point is called Q-point. In case of an input signal provoques the variation of the V_{CE} value, modifiyng consequently the operational point. In figure 5 is shown how the operational point moves in the transistor characteristic-plot.

3.1 BJT as a switch

One of main utilities of BJT are as electronic switches. If the transistor is in blockage, then the transistor can be seen as an open circuit. On the other hand, if the transistor is in saturation, then the transistor can be seen as a closed circuit.

3.2 Small signal BJT amplifiers

We can found three types of small signal BJT amplifier configurations as shown in figure 7:

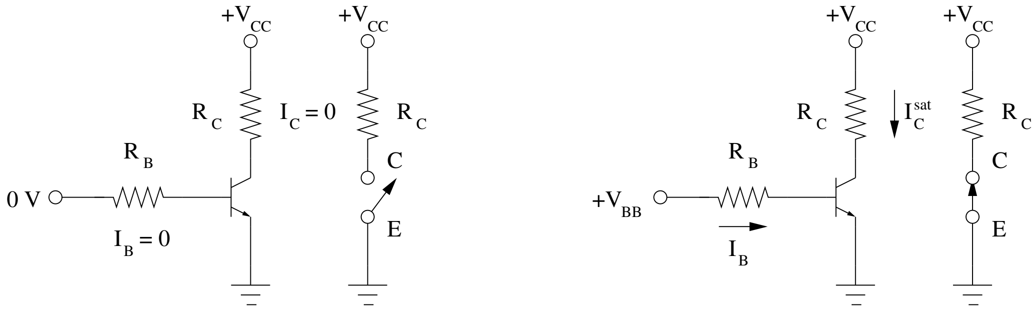


Figure 6: Transistor view as an electronic switch

- Common Emitter. From AC point of view the emitter is connected to the ground. Input signal is in the base and output in the collector
- Common Collector. From AC point of view the collector is connected to the ground. Input signal is in base and output in the emitter.
- Common base. From AC point of view the base is connected to the ground. Input signal is in the emitter and output in the collector.

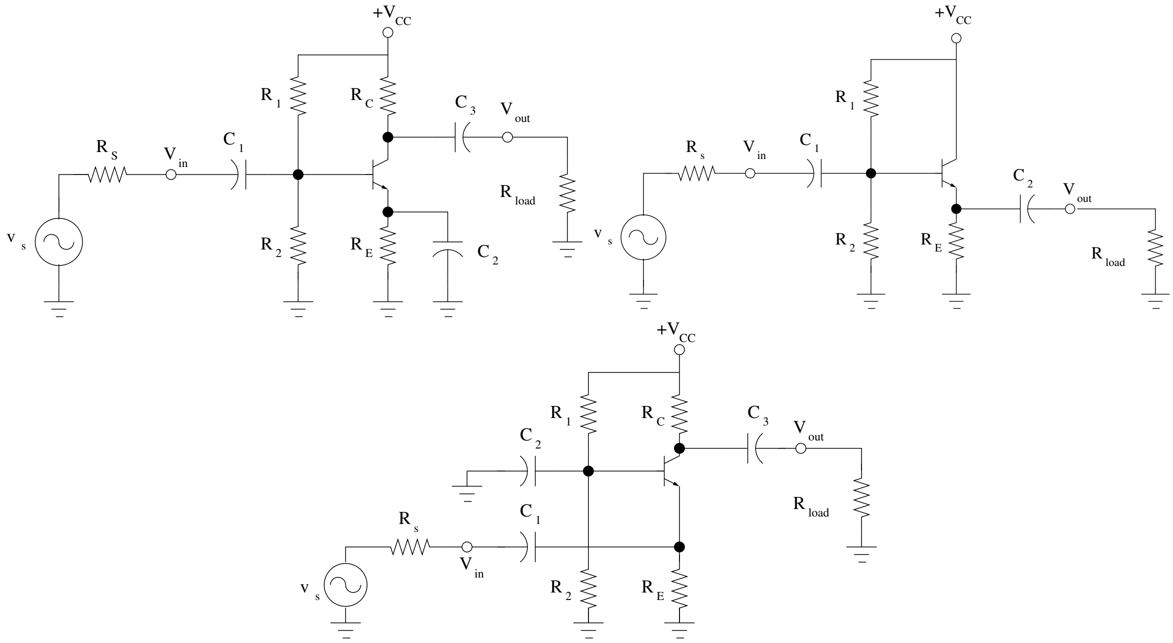


Figure 7: The three amplifier configurations. On the left the common emitter amplifier, in the center the common collector amplifier and on the left the common base amplifier

In figure 8 are shown the definition of h parameters for these three configurations. In table 1 are shown the ratios for the three configurations.

Common Emmiter	Common Base	Common Collector
$h_{ie} = V_b/I_b$	$h_{ib} = V_e/I_b$	$h_{ic} = V_b/I_b$
$h_{re} = V_b/V_c$	$h_{rb} = V_e/V_c$	$h_{rc} = V_b/V_e$
$h_{fe} = I_c/I_b$	$h_{fb} = I_c/I_b$	$h_{fc} = I_e/I_b$
$h_{oe} = I_c/V_c$	$h_{ob} = I_c/V_c$	$h_{oc} = I_e/V_e$

Table 1: h parameters ratios for the three amplifier configurations

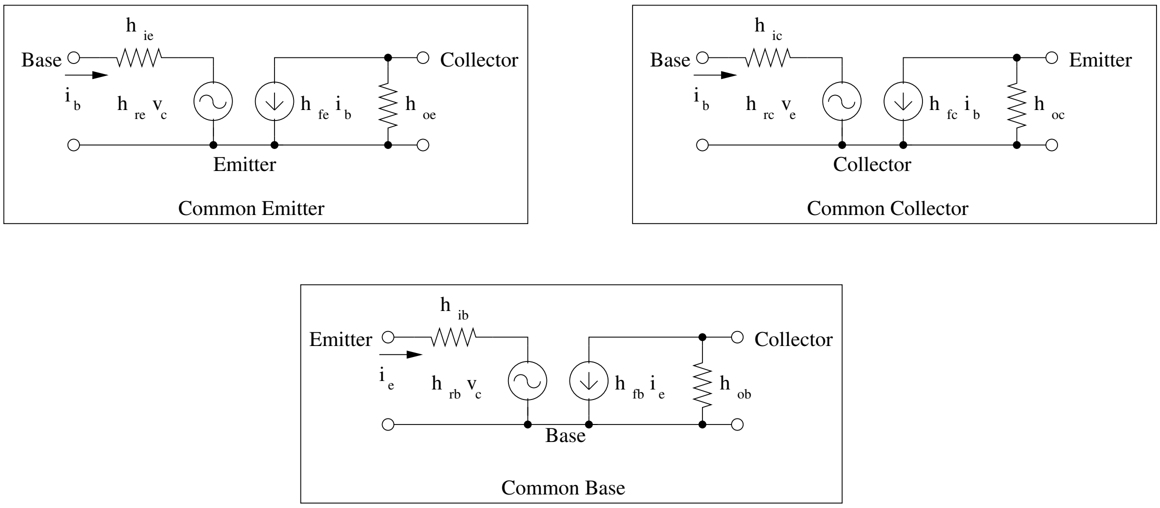


Figure 8: h parameters definition

3.2.1 r parameters

It is much more easy to work with resistances than with h-parameters. This is why has been defined a second set of parameters, called r-parameters. Their definitions are:

α_{ca}	Alpha AC (I_c/I_e)
β_{ca}	Alpha AC (I_c/I_b)
r'_e	AC resistance at emitter
r'_b	AC resistance at base
r'_c	AC resistance at collector

The relationship between both set of parameters is

$$\alpha_{ca} = h_{fb}$$

$$\beta_{ca} = h_{fe}$$

$$r'_e = \frac{h_{re}}{h_{oe}} \simeq \frac{25mV}{I_E}$$

$$r'_c = \frac{h_{re}+1}{h_{oe}}$$

$$r'_b = h_{ie} - \frac{h_{re}}{h_{oe}}(1+h_{fe})$$

3.2.2 Common Emitter Amplifier

- The input is at base and the output is at collector
- There is a phase inversion between input and output
- C_1 and C_3 are coupling capacitors for input and output signals
- C_2 is the so called derivation capacitor allows the maximum gain at the setup.
- The reactance of all capacitors should be negligable at operational frequency.
- Emitter is connected to ground from AC point of view.

Direct current relations

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

$$V_E = V_B - V_{BE}$$

$$I_E = \frac{V_E}{R_E}$$

$$V_C = V_{CC} - I_C R_C$$

Alternative current relations

$$r'_e = \frac{25mV}{I_E}$$

$$R_{in} = \beta_{ca} r'_e$$
$$R_{out} \simeq R_C$$
$$A_v = \frac{R_C}{r'_e}$$
$$A'_v = \frac{V_b}{V_{out}} A_v$$
$$A_i = \frac{I_C}{I_{inp}}$$
$$A_p = A'_v A_i$$

3.2.3 Common Collector Amplifier

- Input is at base and output at the emitter.
- There is no phase inversion between input and output
- Input resistance is high and output resistance is low
- Maximal gain in voltage is 1.
- The collector is connected to ground from the AC point of view.
- The capacitor reactance must be negligable at the operating frequency

Direct current relations

$$V_B = \left(\frac{R_2 || \beta_{CC} R_E}{R_1 + R_2 || \beta_{CC} R_E} \right) V_{CC}$$
$$V_E = V_B - V_{BE}$$
$$I_E = \frac{V_E}{R_E}$$
$$V_C = V_{CC}$$

Alternative current relations

$$r'_e = \frac{25mV}{I_E}$$
$$R_e = R_E || R_{charge}$$
$$R_{in} = \beta_{ca}(r'_e + R_e)$$
$$R_{out} = \left(\frac{R_s}{\beta_{ca}} \right) || R_E$$
$$A_v = \frac{R_e}{r'_e + R_e}$$
$$A_i = \frac{I_e}{I_{inp}}$$
$$A_p = A_i$$

3.2.4 Common Base Amplifier

- Input is at emitter and output at collector
- There is no phase inversion between input and output
- Input resistance is low and output resistance is high
- Maximal current gain is 1.
- Base is connected to AC ground

Direct current relations

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

$$V_E = V_B - V_{BE}$$

$$I_E = \frac{V_E}{R_E}$$

$$V_C = V_{CC} - I_C R_C$$

Alternative current relations

$$r'_e = \frac{25mV}{I_E}$$

$$R_{in} \simeq r'_e$$

$$R_{out} \simeq R_C$$

$$R_c = R_C || R_{charge}$$

$$A_v \simeq \frac{R_c}{r'_e}$$

$$A_i \simeq 1$$

$$A_p \simeq A_v$$

4 Field Effect Transistors (FET)

4.1 Small signal FET amplifiers

5 Power amplifiers

Up to now we have studied single stage amplifiers, but a practical amplifier consists of several stages which are cascaded to produce a gain high enough in order to drive a signal. Typically input signals (from a microphone, a radio station or a particle detector), are on the order of μV, whereas usable signals should be in the volt range. Once the signal is in this range, it can be considered inmune from interference by noise or other disturbing signals.

Firsts stages of the amplifier are voltage gain amplifiers as the ones we have seen previously coupled either directly or via a capacitor or a transformer. Usually the last stage of an amplifier is a power amplifier. This section does not contribute to voltage gain, it is basically a current amplifier. Another way of looking at it is that the voltage section is a signal amplifier with no significant power an its output. It is the task of the power amplifier to produce substantial power at the output, which it does by amplifying the currents. Power amplifiers should be feed by large noise-free voltage signals.

There are four different power amplifiers, called of class A, class B, class AB and class C. This classification is determined by the percentage of input cycle that the amplifier works in the linear region.

5.1 Class A power amplifiers

A class A amplifier is an amplifier polorized in such a way that it works in the linear region for the whole cycle (360^o). In this mode the transistor never enters in the blockage or saturation region so the output signal is an amplified copy of the input one. A class A amplifier is equal as any of the small signal amplifier presented before. As an example we will use a common emitter amplifier in the same configuration as in figure 7.

As we are dealing with big signals the optimal operational Q-point is the one that is centered in the load line. In case of asymmetry the output signal will be limited by the closest point of blockage or saturation. The condition needed to center the Q-point in the case of an common emitter amplifier is:

$$V_{CEQ} = I_{CQ} R_c$$

5.1.1 Voltage and power gain

Voltage and power gain are the same as in small signal amplifiers,

$$A_v = \frac{R_c}{r'_e}$$

$$A_i = \beta_{CC}$$

the only difference is that the formule $r'_e \sim 25mV/I_E$ is not longer valid because the big oscillations of the signals almost covers the transconductance curve I_C vs V_{BE}, as is shown in figure 9. As $r'_e = \Delta V_{BE}/\Delta I_C$ the value is bigger in the lower part of the curve than in the upper part. This behaviour can produce some distorsions due to the different gain. The only way to reduce this distorsion is to work in the most linear region.

5.1.2 Power gain

The gain in power is:

$$A_p = A_i A_v = \beta_{CC} A_v = \beta_{CC} \left(\frac{R_C}{r'_e} \right)$$

5.1.3 Efficiency

Efficiency (η) is given by the ratio of AC signal power to DC power supplied.

$$\eta = \frac{P_{AC}}{P_{DC}} = \frac{0.5}{2} = 0.25$$

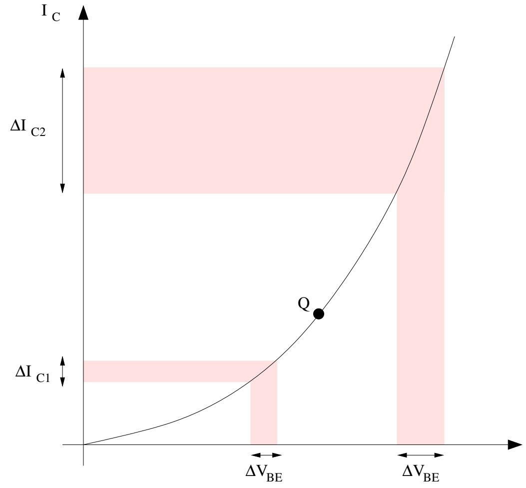


Figure 9: Variation of r'_e over the transconductance curve

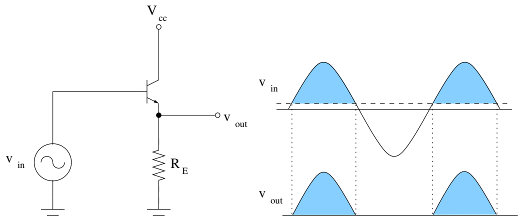


Figure 10: Class B amplifier in common collector

where

$$P_{AC} = \frac{1}{\sqrt{2}} V_{CEQ} \frac{1}{\sqrt{2}} I_{CQ} = 0.5 V_{CEQ} I_{CQ}$$
$$P_{CC} = 2 V_{CEQ} I_{CQ}$$

5.2 Class B and class AB power amplifiers

A class B power amplifier is an amplifier in which the transistor is polarized at the blockage point, in such a way that will operate in the linear region only half of the cycle (180^o). The advantage of this kind of setups is that the efficiency is bigger than in a class A amplifier, on the other hand, if we need to amplify the whole cycle we need to build a set up with two transistors in the so called push-pull amplifier.

In figure 10 is shown how it works a class B common collector a mplifier. As it has been said the operational Q-point is at blockage, so while the signal is in the positive region the transistor will be in the linear reagion, but once the signal is lower enough to make $V_{BE} < 0.7V$ then the transistor is in blockage and will not conduct. Due to this the output signal is not a copy of the input signal.

In order to amplify the whole cycle, we have to build the push-pull setup, composed by two follower emitters, once made with a npn and the oter with a pnp. In figure 11 is shown the principle of this setup. The principle is the same as explained before for the npn. The pnp will have the same behaviour but when the signals polarities changed. As it has been said

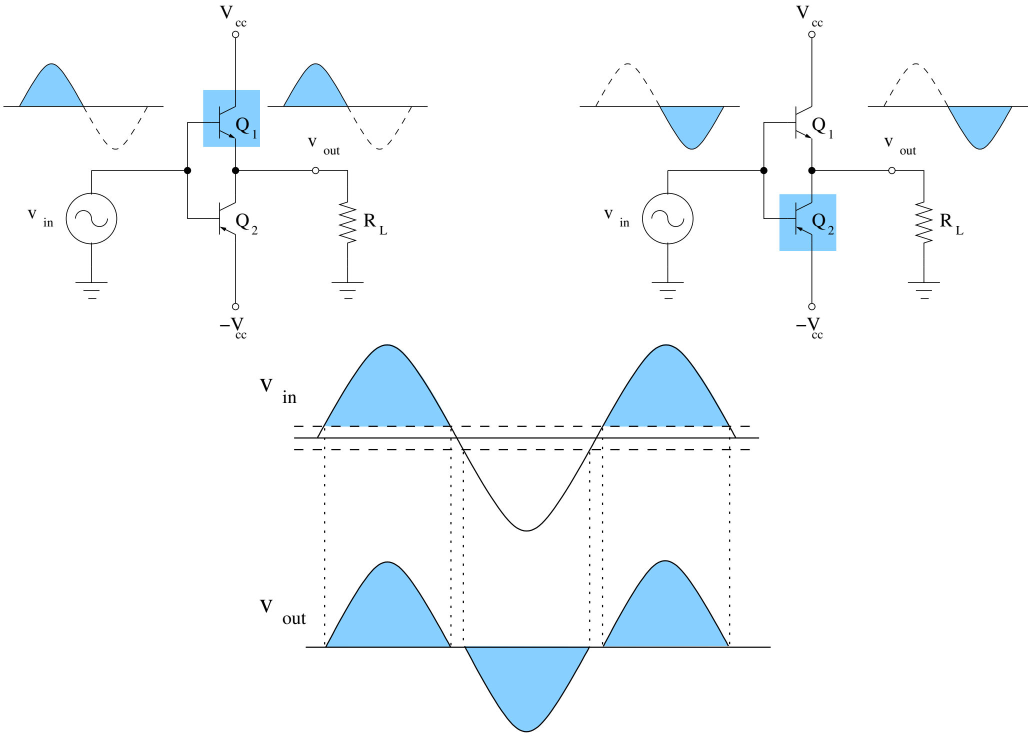


Figure 11: In the upper plot is shown how a class push-pull works. In the lower plot is shown the distorsion in the push-pull amplifier. The transistors onlye are propoerly polarized in the shadowed regions.

around a base polarisation region around 0V none of the transistors will conduct, because both base-emitter junctions will not be properly polarized, what produces a gap in the output, known as crossover distorsion. In order to avoid this gap, both transistors should be slightly polarized before the blocakge point. This variation is called as class AB amplifier. In the case of the push-pull setup this polarization can be done either by a resistor divider or with a couple of diodes. This last configuration is prefered because its behaviour with the temperature is much stable. In figure 12 are shown both setups.

5.2.1 Efficiency

$$\eta = \frac{P_{AC}}{P_{DC}} = 0.25\pi = 0.79$$

where

$$P_{AC} = \frac{1}{\sqrt{2}} V_{CEQ} \frac{1}{\sqrt{2}} I_{CQ} = 0.5 V_{CC} I_C^{sat}$$

For each transistor, output is a half-wave signal, so the current mean value is

$$P_{CC} = \frac{V_{CC} I_C^{sat}}{\pi}$$

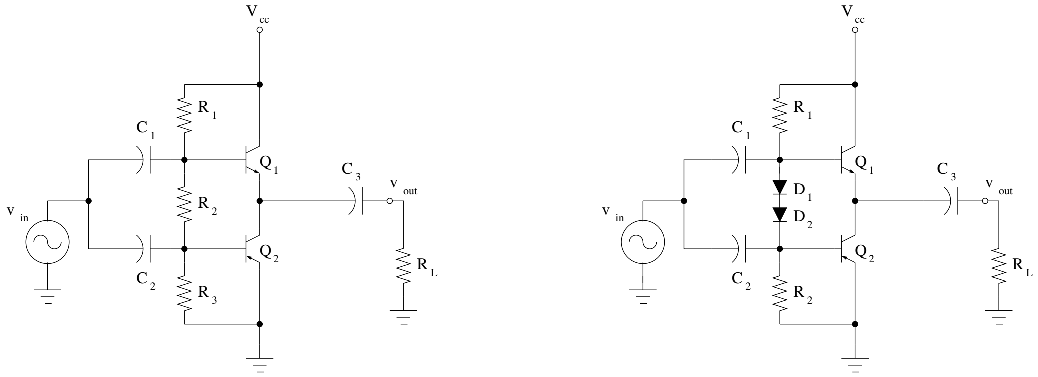


Figure 12: Push-pull polarization in class AB in order to avoid the crossover distorsion

5.3 Class C power amplifiers

Class C amplifiers are polarized in order to allow conduction in less that half cycle. The efficiency is much higher that the rest of power amplifiers, but the wave form is severely distorted. They are used usually for radio frequency resonance amplifiers.

6 Differential amplifier

Is a configuration used to amplify the difference voltage between two input signals. In the ideal case the output is enterely independent of the individual signals levels (only difference matters). When both inputs change levels togethers that's a common-mode input change. A differential change is called normal-mode.

With discrete components one can imagine four configurations, show in figure 13, regarding the number of input and outputs possibles.

The output tension in all cases can be expressed in the form:

$$v_o = A_{diff}(v_1 - v_2)$$

The input that is in phase with the output (v_1) is called non-inverting input, while the other (v_2), that has opposite phase with the output is called inverting output. The gain A_{diff} will change for each configuration. This gain is called differential gain.

6.1 Two inputs and two ouputs

This amplifier is sketched in figure 13-a . This is the most general differential amplifier. The output is taken between both collectors. Ideally the circuit is symetric, that is both transistors and resistors are identical everywhere. In this case, if $v_1 = v_2$ the output will be 0. The gain is calculated as:

$$A_{diff} = \frac{R_C}{(R_1 + R_E + r'_e)}$$

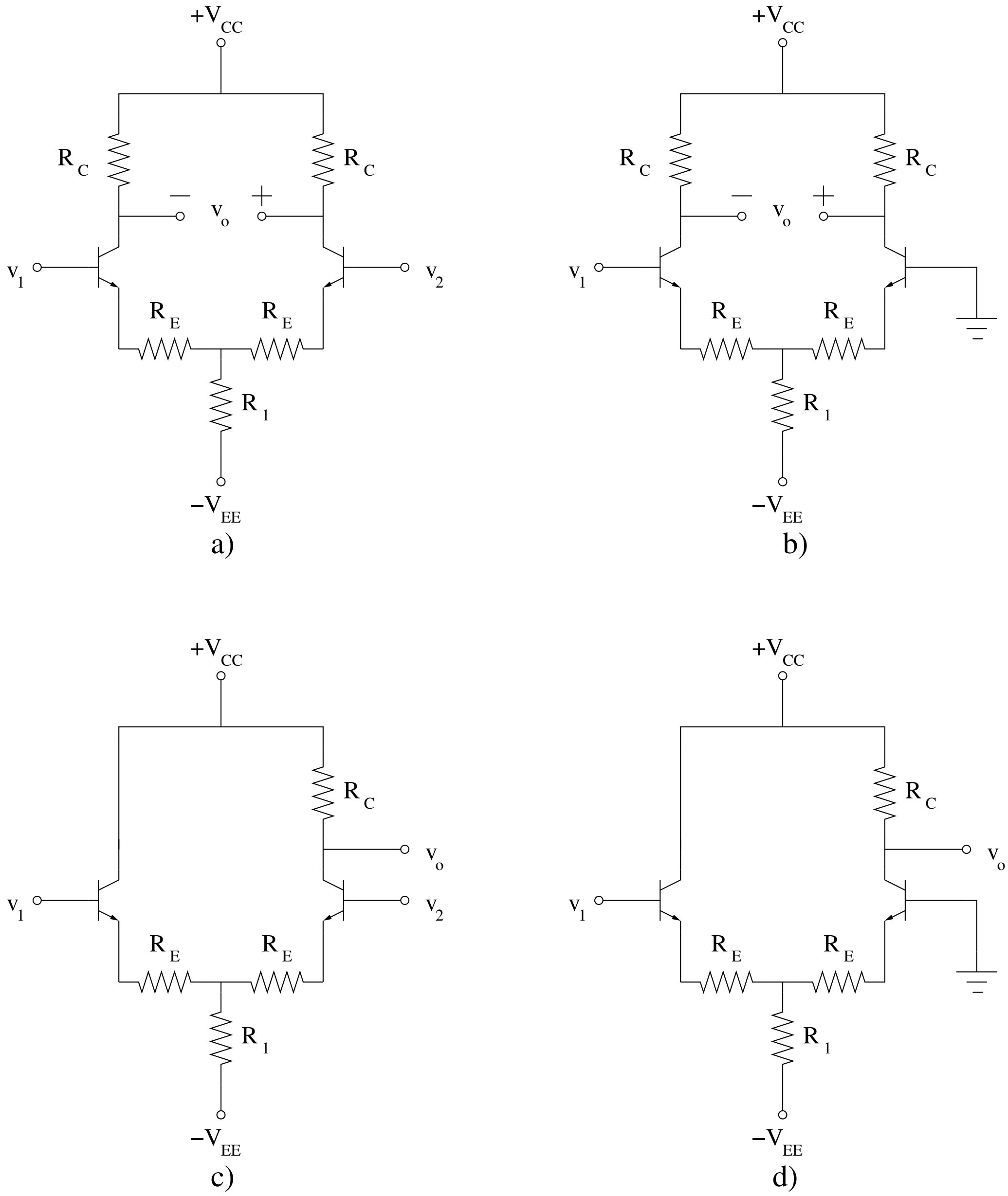


Figure 13: Differential amplifiers: a) Two inputs, two outputs. b) One input, two outputs. c) Two inputs, one output. d) One input, one output

6.2 One input and two ouputs

In case that one of the inputs it is not used, this should be connected to the ground. This amplifier is sketched in figure 13-b. The gain is also $A_{diff} = R_C/(R_1 + R_E + r'_e)$.

The applications of two outputs differential amplifiers are quite rare because they need a floating charge, that should be connected between both collectors, while usual charges has one end connected to the ground.

6.3 Two inputs and one ouputs

This amplifier, sketched in figure 13-c is by far the most useful. Please note that the amplifier is not symetric anymore, and the non-inverting input is clearly defined. Usually one people talk about operational amplifier is talking about this configuration. The gain is calculated as:

$$A_{diff} = \frac{R_C}{2(R_E + r'_e)}$$

. The factor 2 cames from the fact that there is only one R_C. The input impedance (for any of both inputs) is:

$$r_i = 2\beta r'_e$$

.

The common mode input gain is expressed as:

$$A_{CM} = -\frac{R_C}{2R_1 + R_E + r'_e}$$

An important parameter is the so called Common Mode Rejection Ratio (CMRR), that express, usually in db, the ratio of responso of normal mode signal to the response for a common-mode signal of the same amplitude. CMRR is defined then as:

$$CMRR = \frac{A_{diff}}{A_{CM}} = \frac{2R_1 + R_E + r'_e}{2(R_E + r'_e)}$$

For usual configurations $R_1 >> R_E + r'_e$ so

$$CMRR \simeq \frac{R_1}{R_E + r'_e}$$

The discussion about differential amplifiers in “Principes d’Electronique” by P. Malvino is excellent.

6.4 One input and one ouput

Sketched in figure 13-d. One of the inputs is not used so it is connected to ground. The gain is $A_{diff} = R_C/2(R_E + r'_e)$.

7 Darlington and Sziklai connections