Output Stages

- Power amplifier classification
- Class A amplifier circuits
- Class A Power conversion efficiency
- Class B amplifier circuits
- Class B Power conversion efficiency
- Class AB amplifier circuits
- Class AB Power conversion efficiency
Output Stage Functions

- Provide amplifier with low output resistance
- Handle large signals with low THD
- Deliver power to the load efficiently
- Output stages are classified according to the $i_C$ waveform due to input $v_I$ waveform
Amplifier Classifications

**Class A amplifier** – amplifier BJT conducts for entire $v_I$ cycle. For all $v_I$:

$$v_I + V_B \geq 0.7 \, V \quad \text{where} \quad V_B > max\left(v_I\right) + 0.7 \, V$$

Transistor cut off ($i_C = 0$) if:

$$v_I + V_B < 0.7 \, V$$

NOTE: when $v_I = 0$, $i_C = I_C$
Amplifier Classifications - cont.

**Class B – Amplifier**
BJT conducts positive-half of $v_I$ cycle.

Amp BJT conducts for all $v_I$ s.t.:

$$V_B = 0 \text{ V} \Rightarrow v_I \geq 0.7 \text{ V}$$

Transistor cut off ($i_C = 0$) if:

$$v_I + V_B < 0.7 \text{ V}$$

**NOTE:**
1. when $v_I < 0.7 \text{ V}$, $i_C = 0$
2. a 2$^{\text{nd}}$ class B BJT is needed to conduct for the negative $v_I$ cycle.
Class AB – Amplifier BJT conducts for positive $v_I$ swing + part of negative $v_I$ swing s.t.:

$$v_I + V_B \geq 0.7 \, V \quad \text{where} \quad 0 < V_B < max(v_I) + 0.7 \, V$$

Conducts for: $v_I \geq 0.7 - V_B$

Cut-off for rest of negative $v_I$ swing:

Transistor cut-off ($i_C = 0$) if:

$$v_I + V_B < 0.7 \, V$$

NOTE:
1. when $v_I = 0$, $i_C = I_C$
2. a 2\textsuperscript{nd} class AB BJT is needed to conduct for interval slightly larger than the negative $v_I$ cycle.
Class A Power Amplifier Design

Used as op amp output stage and some audio output power amps.

Basic considerations for low (audio) frequency operation.
   1. Power usually delivered to a low impedance load.
   2. Signal usually has little, preferably no dc content.
   3. May have low frequency content, as low as 20 Hz.

Emitter follower circuit has best power transfer efficiency, since its output impedance is low. As a bonus, its input impedance is relatively high.

Principal advantage – lower distortion than Class B & AB.
Principal disadvantage – lower power efficiency than Class B & AB.
Current Biased Class A Emitter Follower

A current mirror establishes the bias current.

\[ i_L = i_{E1} - I \]

To operate reliably,
1. \( Q_1 \) and \( Q_2 \) must be forward active.
2. Current Mirror \( Q_3 \) and \( Q_2 \) need to be matched as well as possible and be at the same ambient temperature.
Class A Amplifier Analysis

Consider the case when \( v_I \geq v_{BE1} = 0.7 \text{ V} \) (pos. swing of \( v_I \)):

- If \( v_{CE1} < V_{CE1-sat} \Rightarrow Q_1 \text{ sat.} \)
  
  For \( Q_1 \neq \text{sat.} \): \( v_{CE1} > V_{CE1-sat} \)
  
  \[
  v_{CE1} = V_{CC} - v_O > V_{CE1-sat} \\
  -v_O > -V_{CC} + V_{CE1-sat} \\
  v_O < V_{CC} - V_{CE1-sat} \Rightarrow v_{O-max} = V_{CC} - V_{CE1-sat}
  
  Max values: \( Q_1 \neq \text{sat.} \)
  
  \[
  v_O < v_{O-max} = V_{CC} - V_{CE1-sat} \\
  v_I < v_{I-max} = V_{CC} - V_{CE1-sat} + 0.7 \text{ V}
  
\]
Class A Amplifier Analysis - cont.

Consider the case where \( v_I < 0.7 \) V (neg. swing of \( v_I \)):

\[
\begin{align*}
v_{CE1} &= V_{CC} - v_O \\
i_L &= i_{E1} - I \\
v_O &= v_I - 0.7V = i_L R_L \\
v_{CE2} &= v_O + V_{CC} \\
i_E1 &= i_L - I
\end{align*}
\]

if \( v_{CE2} < V_{CE2-sat} \) => \( Q_2 \) sat.

\[
\begin{align*}
v_{CE2} &= v_O + V_{CC} > V_{CE2-sat} \\
\Rightarrow v_O &= -V_{CC} + V_{CE2-sat} \\
v_I &= -V_{CC} + V_{CE2-sat} + 0.7
\end{align*}
\]

Min values: \( Q_1 \) and \( Q_2 \) forward-active

\[
\begin{align*}
v_O &= v_{o-min} = \max \{-I R_L, -V_{CC} + V_{CE2-sat}\} \\
v_I &= v_{i-min} = \max \{-I R_L + 0.7V, -V_{CC} + V_{CE2-sat} + 0.7V\}
\end{align*}
\]

NOTE: \( \max \) means least negative
Class A Amplifier VTC – Plot

Bias current $I$ & $R_L$ set limits on negative $v_O = v_{O-min}$ swing

Iff $-IR_L > -(V_{CC} - V_{CE2-sat})$

$v_O > v_{O-min} = -IR_L \Rightarrow$

$R_L < \frac{V_{CC} - V_{CE2-sat}}{I}$

If $-IR_L < -(V_{CC} - V_{CE2-sat})$

$v_O > v_{O-min} = -V_{CC} + V_{CE2-sat} \Rightarrow$

$R_L > \frac{V_{CC} - V_{CE2-sat}}{I}$

$v_O = v_I - 0.7$ where $\max\left\{-IR_L, -(V_{CC} - V_{CE2-sat})\right\} < v_O < V_{CC} - V_{CE1-sat}$
Class A Stage VTC Simulation

\[ I = 120 \text{ mA} \]

\[ IR_L = V_{CC} = 12 \text{ V} \Rightarrow R_L = 100 \Omega \]

\[ V_{EE} = -V_{CC} \]

ideal current source i.e. no \( Q_2 \)

Q1 forward active => no clipping

\[ v_O < v_{O_{-\text{max}}} = V_{CC} - V_{CE1_{-\text{sat}}} = 11.8 \text{ V} \]

Q1 not Sat

\[ v_O > v_{O_{-\text{min}}} = -IR_L = -12 \text{ V} \]

Q1 not Cut-off
Class A Stage VTC Simulation - cont.

\[ I = 120 \text{mA} \quad R_L = 75 \Omega \]

\[ IR_L = 9 \text{V} < V_{CC} - V_{CE1\text{-sat}} \]
Quick Review

Class A Amp VTC

$$v_O = v_I - 0.7 \quad \text{where} \quad \max \left\{ -IR_L, -(V_{CC} - V_{CE2-sat}) \right\} < v_O < V_{CC} - V_{CE1-sat}$$
Example

Let $V_{CE1\text{-sat}} = V_{CE2\text{-sat}} = 0.2 \text{ V}$, $V_{BE1} = V_{BE2} = 0.7 \text{ V}$ and $\beta_1 = \beta_2 = \text{large}$.

1. Determine the value for resistor $R$ that will set the bias current $I$ sufficiently large to allow the largest possible output voltage $v_O$ swing.

2. Determine the resulting output voltage swing and the maximum and minimum $Q_1$ emitter currents.
Example cont.

SOLUTION:

1. For maximum output voltage swing:

\[ IR_L = V_{CC} - V_{CE2\text{-sat}} \]

where \( R_L = 1 \text{k} \Omega \)

\[
\begin{align*}
I &= \frac{V_{CC} - V_{CE\text{sat}}}{R_L} = \frac{15 \text{V} - 0.2 \text{V}}{1 \text{k} \Omega} = 14.8 \text{mA} \\
R &= \frac{V_{CC} - V_{BE}}{I} = \frac{15 \text{V} - 0.7 \text{V}}{14.8 \text{mA}} = 0.97 \text{k} \Omega
\end{align*}
\]
Example - cont.

From Part 1:

\[ I = 14.8 \text{ mA} \]

SOLUTION:

2. Output voltage swing:

\[ V_{o-peak} = I R_L = 14.8 \text{ V} \Rightarrow -14.8 \text{ V} < v_O < 14.8 \text{ V} \]

\[ -14.8 \text{ V} < v_O < 14.8 \text{ V} \Rightarrow -I < i_L < I \]

Max and min \( Q_1 \) emitter currents:

\[ i_{E1} = I + i_L \Rightarrow 0 \text{ mA} < i_{E1} < 2I = 29.6 \text{ mA} \]
Instantaneous and Average Power

The source of power to the amplifier load, $R_L$, comes from the supplies, $V_{CC}$ and $-V_{CC}$. The supplies deliver power, and the load and the transistors absorb it.

Instantaneous power absorbed by resistor $R_L$:

$$p_a(t) = v_{ab}(t)i_{ab}(t) = i_{ab}^2(t) R_L = v_{ab}^2(t)/R_L$$

Instantaneous power delivered by battery $V_{CC}$:

$$p_d(t) = v_{ab}(t)i_{ba}(t) = V_{CC}I$$

Average power: $i_{ab} = I_{ab-peak} \sin(\omega t)$ for period $T$

$$P_{ab\text{ av}} = \frac{1}{T} \int_{0}^{T} i_{ab}^2(t) R_L dt = I_{ab-\text{rms}}^2 R_L = \frac{I_{ab-\text{peak}}^2}{2} R_L = \frac{V_{ab-\text{peak}}^2}{2 R_L}$$

$$P_{D\text{ av}} = V_{CC} I$$
Emitter Follower Power Relationships

I. Average power delivered by the batteries:

For the current mirror transistor side:

\[ P_{-VCC} = V_{CC} I \]

For the amplifier transistor side:

\[ P_{+VCC} = \frac{1}{T} \int_{0}^{T} V_{CC} i_{C1} \, dt \quad \text{where} \quad i_{C1} = I + \hat{I}_c \sin(\omega t) \]

\[ P_{+VCC} = V_{CC} I \left( 1 + \frac{\hat{I}_c}{I} \sin(\omega t) \right) dt = V_{CC} I \]

Total delivered power:

\[ P_D = P_{D\text{av}} = P_{-VCC} + P_{+VCC} = 2V_{CC} I \]

II. Average power to the load:

\[ V_O = V_{o-\text{peak}} \sin(\omega t) \]

\[ P_{L\text{av}} = \frac{V_{o-\text{rms}}^2}{R_L} = \frac{(V_{o-\text{peak}} \sqrt{2})^2}{R_L} = \frac{V_{o-\text{peak}}^2}{2R_L} \]
Class A Power Conversion Efficiency

Using the power delivered to transistors from the batteries $P_{Dav}$ and the power delivered to the load $P_{Lav}$:

$$P_{Dav} = 2V_{CC}I \quad \text{and} \quad P_{Lav} = \frac{V_{o-peak}^2}{2R_L}$$

Note:
1. Average currents and $P_{Dav}$ from the power supply do not change with the signal level $V_{o-peak}$.
2. $P_{Lav}$ increases with the square of the signal level $V_{o-peak}$.

\[
\eta = \frac{P_{Lav}}{P_{Dav}} = \frac{V_{o-peak}^2 / 2R_L}{2V_{CC}I} = \frac{V_{o-peak}^2}{4V_{CC}IR_L} = \frac{1}{4} \frac{V_{o-peak}^2}{IR_L} = \frac{1}{4} \frac{V_{o-peak} V_{o-peak}}{V_{CC}}
\]
**Power Conversion Efficiency**

\[
\eta = \frac{1}{4} \frac{V_{o-peak}^2}{I R_L V_{CC}} = \frac{1}{4} \frac{V_{o-peak}}{I R_L} \frac{V_{o-peak}}{V_{CC}}
\]

Since \( V_{o-peak} < V_{CC} \) and \( V_{o-peak} < I R_L \):

Maximum power conversion efficiency is realized when \( V_{o-peak} = V_{CC} = I R_L \) ignoring the \( V_{CE1-sat} \) and \( V_{CE2-sat} \)

Hence:

\[
\eta_{max} = \frac{1}{4} \frac{V_{CC}}{V_{CC}} \frac{V_{CC}}{V_{CC}} = \frac{1}{4} \quad \text{or 25}\% 
\]
Class A Power Efficiency Simulation

\[ V_{o-peak} = V_{i-peak} - 0.7 \]
\[ V_{o-peak} = 12 - 0.7 = 11.3 \text{V} < V_{CC} - V_{CE-sat} = I \cdot R_L \]

\[ P_{Lav} = 692.36 \text{mW} \]
\[ P_{Dav} = 1.33 \text{W} + 1.44 \text{W} = 2.77 \text{W} \]

\[ \eta = \frac{P_{Lav}}{P_{Dav}} = \frac{0.69 \text{W}}{2.77 \text{W}} = 0.249 \approx 0.25 \]
Class A Power Simulation - cont.

\[ V_{o-peak} = V_{i-peak} - 0.7 \]
\[ V_{o-peak} = 6 - 0.7 = 5.3 \ V < V_{CC} - V_{CE-sat} = I_R L \]

\[ P_{Lav} = 182.28 \ mW \]
\[ P_{Dav} = 1.33 \ W + 1.44 \ W = 2.77 \ W \]

\[ \eta = \frac{P_{Lav}}{P_{Dav}} = \frac{0.18 \ W}{2.77 \ W} = 0.065 < 0.25 \]

\[ R_L = 98 \ \Omega \]
Conclusions

1. The class A amplifier provides the most “nearly linear” amplification of its input, but this comes at a price: The best power conversion efficiency that can be obtained is 25%.

2. That is 75% of the power supplied by the sources is dissipated in the transistors. This is a waste of power, and it leads to a potentially serious heating problems with the transistors. All of this constant battery power is dissipated in the transistors even when no signal is applied – zero percent efficiency!

Next we will consider a much more efficient amplifier configuration – the class B amplifier.