8. POWER AMPLIFIER CIRCUITS

8.1. CLASS-A AMPLIFIERS: 1. DC-COUPLED LOAD

Load Line:
1. $R_{AC} = R_C = R_L$
2. Q-point is placed in the middle so that $\Delta V_{MAX+} = \Delta V_{MAX-} = \Delta V_{MAX}$
Question: How much Signal AC Power \( P_{AC} \) can be delivered to the load?

\[
P_{AC} = \frac{\Delta V_{\text{max}}^2}{2 R_L} \quad \text{for sinusoidal signals}
\]

\[
P_{DC} \approx I_{CQ} \cdot V_{CC}
\]

\[
\eta = \frac{P_{AC}}{P_{DC}} = \frac{\Delta V_{\text{max}}^2}{2 R_L \cdot I_{CQ} \cdot V_{CC}}
\]

**Ideal Case:** \( V_{\text{CESAT}} \to 0 \) and \( V_{EQ} \to 0 \) then \( 2 \cdot \Delta V_{\text{max}} = V_{CC} \)

For Best Swing (undistorted swing) from maximum undistorted swing criteria:

\[
I_{CQ} = \frac{\Delta V_{\text{max}}}{R_{AC}}
\]

Maximum Efficiency Possible:

\[
\eta_{\text{max possible}} = \frac{\Delta V_{\text{max}}^2}{2 R_L \cdot \frac{\Delta V_{\text{max}}}{R_{AC}} \cdot V_{CC}}
\]

Substitute \( V_{CC} = 2 \cdot \Delta V_{\text{max}} \)

\[
\eta_{\text{max possible}} = \frac{\Delta V_{\text{max}}}{2 \left( 2 \cdot \Delta V_{\text{max}} \right)} = 25\%
\]

CLASS A: This says four times DC-Power is needed for each watt of signal power delivered to the load!

Note that for smaller swings (smaller than maximum drives) \( \Delta V < \Delta V_{\text{max}} \). Therefore 25% figure above represents the best collector efficiency possible with this circuit. In most applications (for example, amplifying music) \( \Delta V \ll \Delta V_{\text{max}} \) most of the time. This results in very low average collector efficiencies particularly when operating these amplifiers much below their rated output levels.

### 2. AC-COUPLED LOAD

Efficiency:

\[
\eta = \frac{\Delta V_{\text{max}}^2 / 2 R_L}{I_{CQ} \cdot V_{CC}} \quad \text{sinusoidal swing}
\]

Collector Current:

\[
I_{CQ} = \frac{\Delta V_{\text{max}}}{R_{AC}}
\]

Also from Max Swing Condition:

\[
R_{AC} = R_{C} || R_{L} \quad \text{and,} \quad V_{CC} - V_{EQ} - V_{\text{CESAT}} = \Delta V_{\text{max}} \left( 1 + \frac{R_{C}}{R_{AC}} \right)
\]
Efficiency:

\[ \eta = \frac{\Delta V_{\text{max}}^2 / 2 \, R_L}{\Delta V_{\text{max}} \left[ \Delta V_{\text{max}} \left( 1 + \frac{R_C}{R_{AC}} \right) + V_{\text{EQ}} + V_{\text{CESAT}} \right]} \]

**Ideally**

\( V_{\text{CESAT}} \rightarrow 0 \) and \( V_{\text{EQ}} \rightarrow 0 \)

Then the collector efficiency:

\[ \eta = \frac{R_{AC}}{2 \, R_L \left( 1 + \frac{R_C}{R_{AC}} \right)} = \frac{1}{2 \, \frac{R_L}{R_{AC}} \left( 1 + \frac{R_C}{R_{AC}} \right)} \]

We know that:

\( R_{AC} = R_C \parallel R_L \) and \( \frac{1}{R_{AC}} = \frac{1}{R_L} + \frac{1}{R_C} \)

This gives:

\[ \eta = \frac{1}{2 \left( 1 + \frac{R_L}{R_C} \right) \left( 2 + \frac{R_C}{R_L} \right)} \]

For \( R_L = R_C \) \((\eta)_{AC\text{-coupled}} = \frac{1}{2 \left( 1 + 1 \right) \left( 2 + 1 \right)} = \frac{1}{2 \times 2 \times 3} \approx 8.25\% \)

For \( R_L = R_C / \sqrt{2} \) \((\eta)_{AC\text{-coupled}} = \frac{1}{2 \left( 1 + 1 / \sqrt{2} \right) \left( 2 + \sqrt{2} \right)} \approx 8.58\% \text{ at best} \)

Note that the collector efficiency of a common-emitter with capacitive coupling is much smaller than the 25% figure we obtained with the direct coupled load.

### 3. TRANSFORMER COUPLED LOAD

Circuit Diagram: Same as before except coupling is from an "ideal transformer". It means

1. No dc resistance through its windings,
2. No AC loss \( \Rightarrow V_{\text{primary}} \cdot I_{\text{primary}} = V_{\text{secondary}} \cdot I_{\text{secondary}} \) or \( P_{\text{primary}} = P_{\text{secondary}} \), and
3. \( \frac{V_{\text{secondary}}}{V_{\text{primary}}} = \frac{1}{n} \)}
\[ V_{CEQ} = V_{CC} - V_{EQ} \]

AC Load Line: Q-Point with equal swings  
DC Load Line: Slope = \( R_E^{-1} \) and no \( R_C \)

**Observe that:**  \( (V_{CE})_{MAX} > V_{CC} \)

Application: Ignition circuits that create the spark in the spark plugs of a car.

Caution: The transistor should be able to withstand \( V_{CEMAX} \), i.e., its \( BVCES > V_{CEMAX} \).
For maximum swing:

\[
(\Delta V_{\text{max}})^+ = (\Delta V_{\text{max}})^- = \Delta V_{\text{max}}
\]

For best swing:

\[
I_{\text{CQ}} = \Delta V_{\text{max}} / R_{\text{AC}}
\]

Transformer

\[
V_{\text{prim}} I_{\text{prim}} = V_{\text{sec}} I_{\text{sec}} \quad \Rightarrow \quad \frac{I_{\text{prim}}}{I_{\text{sec}}} = \frac{V_{\text{sec}}}{V_{\text{prim}}} \cdot \frac{1}{n}
\]

The Reflected Impedance

\[
R_{\text{AC}} = \frac{V_{\text{prim}}}{I_{\text{prim}}} = \frac{V_{\text{sec}} \cdot n}{I_{\text{sec}} \cdot \left(\frac{1}{n}\right)} \quad \text{or} \quad R_{\text{AC}} = n^2 \frac{V_{\text{sec}}}{I_{\text{sec}}}
\]

\[
R_{\text{AC}} = n^2 R_L
\]

Max Swing:

\[
\Delta V_{\text{max}} = V_{\text{CEQ}} - V_{\text{CESAT}} = V_{\text{CC}} - V_{\text{EQ}} - V_{\text{CESAT}}
\]

Efficiency:

\[
\eta = \frac{\Delta V_{\text{max}}^2}{2 R_{\text{AC}}} = \frac{\Delta V_{\text{max}}}{2 V_{\text{CC}}} = \frac{V_{\text{CC}} - V_{\text{CESAT}} - V_{\text{EQ}}}{2 V_{\text{CC}}}
\]

at best

\[
\eta = \frac{V_{\text{CC}}}{2 V_{\text{CC}}} = \frac{1}{2}
\]

\[
\eta \leq 50\%
\]

Conclusion: In "Class A Power Amplifiers" the best possible efficiency is 50% and is obtained by employing a transformer coupling at the output. For higher efficiency you have to use a circuit operating in Class B mode. Note that transformer coupling, by effectively reducing \( R_{\text{C}} \), biasing resistance of the circuit to zero, eliminates a major loss of DC power in biasing the transistor, thus, delivers the highest possible collector efficiency among its Class A alternatives.

8.2. CLASS-B AMPLIFIERS

We are assuming that Class-B can also be implemented in a complementary configuration to amplify the other half of the signal and combine them on the load to achieve effectively a "Linear" operation.
No need for $R_E$ since no need for stability: $Q$ is at $ICQ = 0$.

or Complementary Symmetry

$V_{MAX} = V_{CC} - V_{CESAT}$

AC Power: $P_{AC} = \frac{\Delta V_{MAX}^2}{2R_L}$  $\Delta V_{MAX} = V_{CC} - V_{CESAT}$

DC Power: $P_{DC} = \overline{i_C V_{CC}} = \frac{1}{T} \int i_C V_{CC} \, dt$
Assuming sinusoidal waveforms:

\[
\text{Power on one side : } P_{\text{DC}} = \bar{i}.V_{CC} = \frac{1}{\pi} I_{\text{CMAX}} V_{CC}
\]

\[
\text{Power on both sides : } (P_{\text{DC}})_{\text{Both}} = 2 \cdot \frac{1}{\pi} I_{\text{CMAX}} V_{CC}
\]

\[
\text{Max Current : } I_{\text{CMAX}} = \frac{\Delta V_{\text{MAX}}}{R_L}
\]

\[
\text{Efficiency : } \eta = \frac{P_{\text{AC}}}{(P_{\text{DC}})_{\text{Both}}} = \frac{\Delta V_{\text{MAX}}^2 / 2. R_L}{\frac{2}{\pi} (\Delta V_{\text{MAX}} / R_L).V_{CC}}
\]

\[
\eta \Rightarrow \frac{\pi}{4} \approx 78.5\%
\]

\[
\text{Ideally : } \Delta V_{\text{MAX}} \rightarrow V_{CC} \text{ (small } V_{\text{CESAT}}) \quad \text{Then}
\]

This "$\eta$" is the ultimate maximum collector efficiency one can get from a Class-B amplifier that can deliver linear amplification. Most audio amplifiers employ Class-B circuits in their last (i.e. power) stage to benefit from this high efficiency. Note that, unlike the Class-A which draws a constant bias power independent of the signal level, Class-B draws zero battery power when no signal is applied, its power drawn from the battery increases linearly with the output swing.
8.3. AC COUPLED SMALL SIGNAL AMPLIFIERS

ADVANTAGES:
1. Signal and bias are separate. One can concentrate on the bias design w/o worrying about the signal source and the load from dc point.
2. No dc current flows through $R_L$ (or $V_{\text{in}}$ source). Their impedance levels do not interfere with the bias.
3. Stages can be cascaded. Except ac loading of each other. Their design do not have to take dc conditions of their neighbors.

DISADVANTAGES:
1. For dc isolation and stability they depend on the shorting (?) capability of capacitors. 3 capacitors per stage are needed.
   a. At low frequencies the capacitors fail to act like short circuit.
      Therefore, the amplifier is useful above a certain cut-off point (i.e. high pass).
   b. Capacitors are bulky and costly, getting worse as dc is approached,
   c. dc like slowly varying signals cannot be amplified.