Outline

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- Class A Output Stage
- Class B Output Stage
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Classification Of Output Stages

Class A Stage

The class A stage is biased at a current $I_C$ greater than the amplitude of the signal current, $I_c$.

The transistor in a class A stage conducts for the entire cycle of the input signal; that is, the conduction angle is $360^\circ$. 
Class B Stage

The class B stage is biased at zero dc current. The transistor in a class B stage conducts for only half of the cycle of the input sine wave, resulting in a conduction angle of 180°.

Class AB Stage

An intermediate class between A and B, named class AB, involves biasing the transistor at a nonzero dc current much smaller than the peak current of the sine-wave signal. The transistor in a class AB stage conducts for a interval slightly greater than half a cycle. The resulting conduction angle is greater than 180° but much less than 360°.
Class C Stage

The transistor in a class C stage conducts for an interval shorter than that of a half cycle; that is, the conduction angle is less than 180°.

Class C amplifiers are usually employed for radio-frequency (RF) power amplification (required, for example, in mobile phones and TV transmitters).

Class A Output Stage
Transfer Characteristic

Because of its low output resistance, the emitter follower is the most popular class A output stage.

An emitter follower ($Q_1$) biased with a constant current $I$ supplied by transistor $Q_2$:

- Since $i_{E1} = I + i_L$, the bias current $I$ must be greater than the largest negative load current; otherwise, $Q_1$ cuts off and class A operation will no longer be maintained.

- The transfer characteristic of the emitter follower:
  \[ v_O = v_I - v_{BE1} \]
  where $v_{BE1}$ depends on the emitter current $i_{E1}$ and thus on the load current $i_L$.

Transfer characteristic of the emitter follower:

- The linear characteristic is obtained by neglecting the change in $v_{BE1}$ with $i_L$.

- The maximum positive output is determined by the saturation of $Q_1$:
  \[ v_{O_{max}} = V_C - V_{CE1_{sat}} \]

- In the negative direction, the limit of the linear region is determined either by $Q_1$ turning off or by $Q_2$ saturating, depending on the values of $I$ and $R_L$.

  1. $Q_1$ turning off: $v_{O_{min}} = -IR_L$
  2. $Q_2$ saturating: $v_{O_{min}} = -V_C + V_{CE2_{sat}}$ (the absolutely lowest output voltage)
Biasing current:
The bias current $I$ is greater than the magnitude of the corresponding load current. ($I \geq i_L$)

$$I \geq \frac{V_{CC} + V_{CE2sat}}{R_L}$$

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Signal Waveforms

(Neglect $v_{CE_{sat}}$) Consider that maximum signal waveforms are under the condition $I = V_{CC}/R_L$.

(a) $v_{CE1} = V_{CC} - v_O$

(b) $i_{c1}$

(c) The instantaneous power dissipation in $Q_1$:

$$P_{DI} = v_{CE1}i_{c1}$$
**Power Dissipation**

- Maximum instantaneous power dissipation in \( Q_1 = V_{CC}I \) (\( v_O = 0 \)).
- The power dissipation in \( Q_1 \) depends on the value of \( R_L \).
  - If \( R_L = \infty \), then
    - \( i_{c1} = I \), constant.
    - The maximum power dissipation will occur when \( v_O = -V_{CC} \).
      \[ P_{D1} = 2V_{CC}I. \]
    - The average power dissipation in \( Q_1 \) is \( V_{CC}I \).
  - If \( R_L = 0 \), then
    - A very large current may flow through \( Q_1 \). It raises the junction temperature beyond the specified maximum, causing \( Q_1 \) to burn up.
    - Need short-circuit protection.

- The maximum instantaneous power dissipation in \( Q_2 \) is \( 2V_{CC}I \) when \( v_O = V_{CC} \). A more significant quantity for design purpose is the average power dissipation in \( Q_2 \), which is \( V_{CC}I \).

**Power Conversion Efficiency**

- Power-conversion efficiency
  \[ \eta \equiv \frac{\text{Signal power delivered to load } (P_L)}{\text{dc power supplied to output circuit } (P_S)} \times 100\% \]
- Average load power
  \[ P_L = \frac{1}{2} \frac{V_O^2}{R_L} \]
- Total average supply power:
  \[ P_S = 2V_{CC}I \]
  - Since the current in \( Q_2 \) is constant (I), the power drawn from the negative supply is \( V_{CC}I \).
  - The average current in \( Q_1 \) is equal to \( I \), and thus the average power drawn from the positive supply is \( V_{CC}I \).
  - Thus, the total average supply power is \( P_S = 2V_{CC}I \).
Determine power-conversion efficiency of the class A output stage:

\[
\eta = \frac{1}{4} \frac{\hat{V}_O^2}{IR_r V_{CC}} = \frac{1}{4} \left( \frac{\hat{V}_O}{IR_L} \right) \left( \frac{\hat{V}_O}{V_{CC}} \right)
\]

- Small signal, i.e., \( \hat{V}_O \) is small,
  - \( \eta \to 0 \).
  - Static power consumption \( 2V_{CC}I \) even no excitation.
- Since \( \hat{V}_O \leq V_{CC} \) and \( \hat{V}_O \leq IR_L \), maximum efficiency is obtained when \( \hat{V}_O = V_{CC} = IR_L \). \( \therefore \eta_{max} = 25\% \)
- In practice the output voltage is limited to lower values in order to avoid transistor saturation and associated nonlinear distortion.
  - The efficiency achieved is usually in the 10% to 20% range.
- Class A operation is a poor choice for power amplification.

Class B Output Stage
Output Stages

- Ideal output stages
  - Supply external load current
  - Low output impedance
  - Large output swing \( \approx V_{CC} - V_{EE} \) (ideally)

- Commonly used complementary emitter follower
  - Each transistor is on for only half the time.

Circuit Operation

Class B output stage consists of a complementary pair of transistors connected in such a way that both conduct simultaneously.

1. \( v_t = 0 \), \( \Rightarrow Q_P \) and \( Q_N \) are cut off and \( v_O = 0 \).
2. \( v_t > 0.5V \), \( \Rightarrow Q_P \) is cut off; \( Q_N \) turns on and acts as an emitter follower.
   \[ u_O = v_t - v_{BEN} \]
   and \( Q_N \) supplies the load current.
3. \( v_t < -0.5V \), \( \Rightarrow Q_N \) is cut off; \( Q_P \) conducts and operates as an emitter follower.
   \[ u_O = v_t + v_{EBP} \]
   and \( Q_P \) supplies the load current.

Operation in push-pull fashion:

- The transistors in class B stage are biased at zero current and conduct only when the input signal is present.
- \( Q_N \) pushes (sources) current into the load when \( v_t \) is positive, and \( Q_P \) pulls (sinks) current from the load when \( v_t \) is negative.
Transfer Characteristic

There exists a range of $v_I$ centered around zero where both transistors are cut off and $v_O$ is zero. This dead band results in the **crossover distortion**.

Illustrating how the dead band in the class B transfer characteristic results in crossover distortion.

The effect of crossover distortion will be pronounced when the amplitude of the input signal is small. Crossover distortion in audio power amplifiers gives rise to unpleasant sounds.
Power Conversion Efficiency

We neglect the crossover distortion and consider the case of an output sinusoid of peak amplitude $V_o$.

- **Average load power** $P_L = \frac{1}{2} \frac{V_o^2}{R_L}$

- **Total supply power**
  1. The peak amplitude of current draw from supply: $\frac{V_o}{R_L}$
  2. The average current draw from supply: $\frac{V_o}{\pi R_L}$

  The average power drawn from each of the two power supplies:
  
  \[ P_{S+} = P_{S-} = \frac{1}{\pi} \frac{V_o}{R_L} V_{CC} \]

  The total supply power
  
  \[ P_S = \frac{2}{\pi} \frac{V_o}{R_L} V_{CC} \]

- **Efficiency**
  
  \[ \eta = \frac{\pi}{4} \frac{V_o}{V_{CC}} \] (14.15)

  \[ \eta_{max} = \frac{\pi}{4} = 78.5\% \text{ when } V_o = V_{CC} - V_{CE\text{sat}} \approx V_{CC} \]

- **Maximum average power available** $P_{L\text{max}} = \frac{1}{2} \frac{V_{CC}^2}{R_L}$

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Power Dissipation

Unlike the class A stage, which dissipates maximum power under quiescent conditions ($v_o = 0$), the quiescent power dissipation of the class B stage is zero.

- **Average power dissipation**
  
  \[ P_D = P_S - P_L = \frac{2}{\pi} \frac{V_o}{R_L} V_{CC} - \frac{1}{2} \frac{V_o^2}{R_L} \]

- **Maximum average power dissipation** $\left( \frac{\partial P_D}{\partial V_o} = 0 \right)$
  
  \[ P_{D\text{max}} = \frac{2V_{CC}^2}{\pi^2 R_L} \text{ when } \frac{\partial P_D}{\partial V_o} \bigg|_{P_{D\text{max}}} = \frac{2}{\pi} V_{CC} \]

  \[ \therefore P_{D\text{max}} = P_{DP\text{max}} = \frac{V_{CC}^2}{\pi^2 R_L} \]

  By Eq. (14.15), at the point of max. power dissipation the efficient $\eta = 50\%$.

- **Average load power** $P_L = \frac{1}{2} \frac{V_o^2}{R_L}$
Power dissipation of the class B output stage versus amplitude of the output sinusoid.

Increasing \( V_o \) beyond \( 2V_{CC}/\pi \) decreases the power dissipated in the class B stage while increasing the load power.

The price paid is an increase in nonlinear distortion as a result of approaching the saturation region of operation of \( Q_P \) and \( Q_N \). Transistor saturation flattens the peaks of the output sine waveform.

- This type of distortion cannot be significantly reduced by the application of negative feedback.
- The transistor saturation should be avoided in applications requiring low THD.

**Example 9.1 Class B output stage design**

The class B output stage deliver an average power of 20W to an 8-\( \Omega \) load. Select the power supply such that \( V_{CC} \) is about 5V greater than the peak output voltage. This avoids transistor saturation and the associated nonlinear distortion, and allows for including short-circuit protection circuitry. Determine the supply voltage required, the peak current drawn from each supply, the total supply power, and the power-conversion efficiency. Also determine the maximum power that each transistor must be able to dissipate safely.

**Solution**

1. Determine \( V_{CC} \):  \( P_L = \frac{1}{2} V_o^2 / R_L \) \( \Rightarrow \ V_o = \sqrt{2P_L R_L} = \sqrt{2 \times 20 \times 8} = 18V \)
2. The peak current drawn from each supply  \( I_o = \frac{V_o}{R_L} = \frac{17.9}{8} = 2.24A \)
3. The average power drawn from each supply  \( P_{S+} = P_{S-} = \frac{1}{\pi} V_o V_{CC} = \frac{1}{\pi} \times 2.24 \times 23 = 16.4W \)
4. Total supply power \( = P_{S+} + P_{S-} = 32.8W \)
5. The power-conversion efficiency  \( \eta = \frac{P_L}{P_S} = \frac{20}{32.8} = 61\% \)
6. The maximum power dissipated in each transistor  \( P_{DN\text{max}} = P_{DP\text{max}} = \frac{V_{CC}^2}{\pi^2 R_L} = \frac{(23)^2}{\pi^2 \times 8} = 6.7W \)
Distortion in the Class B Push-Pull Stage

- Harmonic distortion
  - For matched devices $Q_N$ & $Q_P$
  - $i_N$ and $i_P$ are identical except shifted in phase by $180^\circ$

$$i_N = I_c + B_0 + B_1 \cos \omega t + B_2 \cos 2\omega t + B_3 \cos 3\omega t + \cdots$$

$$i_P(\omega t) = i_N(\omega t + \pi)$$

$$i_p = I_c + B_0 - B_1 \cos \omega t + B_2 \cos 2\omega t - B_3 \cos 3\omega t + \cdots$$

$$i_L = i_N - i_p = 2(B_1 \cos \omega t + B_3 \cos 3\omega t + \cdots)$$

Even-order harmonic distortions have been eliminated.
If $I-V$s of $Q_N$ & $Q_P$ are not identical, then even-order harmonic is expected.

- Crossover distortion: has been discussed before.

Reducing Crossover Distortion

Class B circuit with an op amp connected in a negative-feedback loop to reduce crossover distortion

- The $\pm 0.7V$ dead band is reduced to $\pm 0.7/A_0$ volts, where $A_0$ is the dc gain of the op amp.
- Slew-rate limiting of the op amp.
Single-Supply Operation

Class B output stage operated with a single power supply

Class AB Output Stage
Class AB Output Stage

- Crossover distortion can be virtually eliminated by biasing the complementary output transistors at a small, non-zero current.
- A bias voltage $V_{BB}$ is applied between the bases of $Q_N$ and $Q_P$, giving rise to a bias current

$$i_N = i_P = I_Q = I_S e^{V_{bb}/2V_T}$$

(Assuming matched devices)

Circuit Operation

1. $V_{BEN} + V_{EBP} = V_{BB} \Rightarrow V_T \ln \left( \frac{i_N}{I_S} \right) + V_T \ln \left( \frac{i_P}{I_S} \right) = 2V_T \ln \left( \frac{i_Q}{I_S} \right) \Rightarrow i_N i_P = i_Q^2$

As $i_N$ increases, $i_P$ decreases by the same ratio while the product remains constant.

2. $i_N = i_P + i_L \Rightarrow i_N^2 - i_L i_N - i_Q^2 = 0$
Output resistance

Determine the small-signal output resistance of the class AB circuit

\[ R_{out} = r_{eN} \parallel r_{eP} \]

where \( r_{eN} \) and \( r_{eP} \) are the small-signal emitter resistances of \( Q_N \) and \( Q_P \), respectively.

\[ r_{eN} = \frac{V_T}{i_N} \quad \text{and} \quad r_{eP} = \frac{V_T}{i_P} \]

\[ \Rightarrow R_{out} = \frac{V_T}{i_N} \parallel \frac{V_T}{i_P} = \frac{V_T}{i_P + i_N} \]

Biasing The Class AB Circuit
Biasing Using Diodes

Class AB output stage utilizing diodes for biasing. If the junction area of the output devices, $Q_N$ and $Q_P$, is $n$ times that of the biasing devices $D_1$ and $D_2$, a quiescent current $I_Q = nI_{bias}$ flows in the output devices.

![Image of a circuit diagram]

**Example 14.2  Class AB output stage design**

$V_{CC} = 15V$, $R_L = 100\Omega$, and the output is sinusoidal with a maximum amplitude of 10V. Let $Q_N$ and $Q_P$ be matched with $I_S = 10^{-13}A$ and $\beta = 50$. Assume the biasing diodes have one-third the junction area of the output devices. Find the value of $I_{bias}$ that guarantees a minimum of 1mA through the diode at all times. Determine the quiescent current and the quiescent power dissipation in the output transistors (i.e., at $v_O = 0$). Also find $V_{BB}$ for $v_O = 0$, $+10V$, and $-10V$.

- The maximum current through $Q_N$:
  \[ I_{bias} = \frac{10V}{0.1k \Omega} = 100mA \]
  The maximum base current in $Q_N$ is 2mA.
- To maintain a min. of 1mA through the diodes, we select $I_{bias} = 3mA$.
- A quiescent current of 9mA through $Q_N$ and $Q_P$.
- Quiescent power dissipation
  \[ P_{DQ} = 2 \times 15 \times 9 = 270mW \]
- For $v_O = 0$, $I_{BQ1} = 9/51 = 0.18mA$.
  \[ I_B = I_{DQ1} = 3 \times 0.18 = 2.82mA \]
- Since the diodes have $I_S = 4 \times 10^{-13}$, then
  \[ V_{BB} = 2 \times V_I \ln \frac{I_D}{I_S} = 2 \times 0.025 \times \ln \frac{2.82mA}{I_S} = 1.26V \]
- $v_O = 10V \Rightarrow I_D \approx 1mA \Rightarrow V_{BB} = 1.21V$
- $v_O = -10V \Rightarrow I_D \approx 3mA \Rightarrow V_{BB} = 1.26V$
Biasing using the $V_{BE}$ multiplier

Find $V_{BB}$:

$$I_R = \frac{V_{BE1}}{R_1}$$

$$V_{BB} = I_R (R_1 + R_2) = V_{BE1} \left(1 + \frac{R_2}{R_1}\right)$$

Determine $V_{BE1}$:

$$I_{C1} = I_{bias} - I_R$$

$$V_{BE1} = V_T \ln \left(\frac{I_{C1}}{I_{S1}}\right)$$

A discrete-circuit class AB output stage with a potentiometer used in the $V_{BE}$ multiplier. The potentiometer is adjusted to yield the desired value of quiescent current in $Q_N$ and $Q_P$. 
Variations On The Class AB Configuration

Use of Input Emitter Followers

- High input resistance
- Quiescent current in $Q_3$ and $Q_4$ is equal to that in $Q_1$ and $Q_2$ if $R_L = \infty$ and $R_3 = R_4 \approx 0$.
- $R_3$ and $R_4$ are small and are included to guard against the possibility of thermal runaway due to temperature differences between the input and output – stage transistor.
Use of Compound Devices

The Darlington configuration

1. increase current gain
2. reduce base current drive
3. Equivalent $V_{BE(eq.)} = 2V_{BE}$
4. can be used for both NPN transistors and PNP transistors

The compound-pnp configuration

1. used to improve PNP configuration
2. $Q_1$ is usually a lateral PNP having low $\beta$ ($\approx 5-10$)

A class AB output stage utilizing a Darlington $npn$ and a compound $pnp$. Biasing is obtained using a $V_{BE}$ multiplier.

- Bias is obtained using a $V_{BE}$ multiplier.
- $V_{BE}$ multiplier is required to provide $3V_{BE}$. 
Short-Circuit Protection

A class AB output stage is equipped with protection against the effect of short-circuiting the output while the stage is sourcing current.

1. A large current that flows through $Q_1$ in the event of a short circuit will develop a voltage drop across $R_{E1}$ of sufficient value to turn $Q_5$ on.
2. The collector of $Q_5$ will then conduct most of the current $I_{bias}$, robbing $Q_1$ of its base drive.
3. The current through $Q_1$ will thus be reduced to a safe operating level.

$$i_L \uparrow \Rightarrow V_{RE1} \uparrow \Rightarrow I_{C5} \uparrow \Rightarrow I_{B1} \downarrow \Rightarrow I_{C1} \downarrow$$

Thermal Shutdown

Thermal shutdown circuit

Transistor $Q_2$ is normally off.

1. As the chip temperature rises, a combination of positive temperature coefficient of zener diode $Z_1$ and the negative temperature coefficient of $V_{BE1}$ causes the voltage at the emitter of $Q_1$ to rise.
2. This in turn raises the voltage at the base of $Q_2$ to the point at which $Q_2$ turns on.

$$T \uparrow \Rightarrow V_{Z1} \uparrow, \ V_{BE} \downarrow \Rightarrow V_{R2} \uparrow \Rightarrow I_{C2} \uparrow$$

$Q_2$ absorbs bias current of OPAMP
Homework

- Problem 2, 11, 16, 19, 33