(9)

Output Stages: Classes of Amplifiers

Reference: Neamen, Chapter 8

Learning Outcome

Able to:

- Define the various classes of power amplifiers and determine the maximum power efficiency of each class of amplifier.
- Analyze circuit configuration of:
  - ☐ Class-A operation,
  - ☐ Class-B operation,
  - ☐ Class-AB operation.

9.0) Classes of Amplifiers

- Power amplifiers in the output stage are classified according to the percent (%) of time the output transistors are conducting (turned on):
  - ☐ **Class A:** Output transistor is ***biased*** *at a quiescent current* I_Q and conducts for the ***entire cycle*** *of the input signal.*
  - ☐ **Class B**: Output transistor conducts for only ***one-half*** *of each sine-wave input cycle.*
  - ☐ **Class AB:** Output transistor **biased** *at a small quiescent current* I_Q, and conducts for ***slightly more than half*** *a cycle.*
  - ☐ **Class C:** Output transistors conducts for ***less than half*** *a cycle.*

9.0) Classes of Amplifiers (Cont)

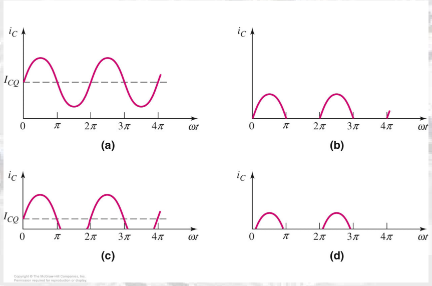


Figure 8.15: Collector current versus time characteristics: (a) class-A amp, (b) class-B amp, (c) class-AB amp, and (d) class-C amp

9.1) Power Dissipation in BJT

9.1.1) Instantaneous power dissipation:

Is given by

$$P_Q = v_{CE} i_C + v_{BE} i_B \quad (8.1)$$

Generally $i_B << i_C$, then

$$P_Q \cong v_{CE} i_C \quad (8.2)$$

9.1.2) Average power:

Is obtained by integrating the instantaneous power dissipation over one cycle of the signal. So,

$$\overline{P}_Q = \frac{1}{T}\int_0^T v_{CE} i_C \, dt \quad (8.3)$$

9.1) Power Dissipation in BJT (Cont)

9.1.3) Power conversion efficiency:

Is defined as

$$\eta = \frac{\overline{P}_L}{\overline{P}_S} \quad (8.12)$$

where $\overline{P}_L$ = average ac power delivered to load.

$\overline{P}_S$ = average power supplied by PSU.

9.2) Class-A Operation (Ref: Sedra pp. 1231-1235)

9.2.1) Circuit diagram

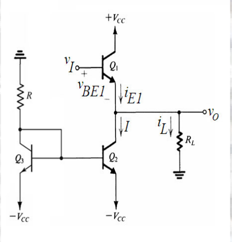
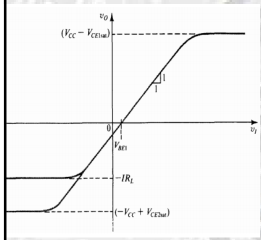


Figure S1

- **Emitter follower circuit, Fig S1** → low output resistance.
- Emitter follower Q_1 is biased with a constant current source I (supplied by transistor Q_2).
- Since $i_{E1} = I + i_L$
  - ❑ **$I \geq$ largest negative load current**
  - ❑ Else Q_1 cuts off, and class-A operation no longer maintained.

9.2) Class-A Operation (Cont)

9.2.2) Transfer Characteristics (TC)



- TC is described by:

$$v_O = v_i - v_{BE1}$$

where v_{BE1} depends on i_{E1} and thus the load current i_L.

$$v_i = V_T \ln\left[\frac{I + \frac{v_O}{R_L}}{I_S}\right] + v_O$$

- Neglecting small changes in v_{BE1} the **linear curve** as shown above is obtained.

9.2) Class-A Operation (Cont)

9.2.2) Transfer Characteristics (Cont)

- **Positive limit** determined by the saturation of Q_1:

$$v_{O\max} = V_{CC} - V_{CE1sat}$$

- **Negative limit** depends on the values of I_Q and R_L:
  - ❑ Q_1 turns off (small R_L): $v_{O\min} = -I\,R_L$
  - ❑ Q_2 saturating (large R_L): $v_{O\min} = -V_{CC} + V_{CE2sat}$
  - ❑ Absolute lowest output voltage is when Q_2 saturating provided that:

$$I \geq \frac{\left|-V_{CC} + V_{CE2sat}\right|}{R_L}$$

9.2) Class-A Operation (Cont)

9.2.3) Signal Waveforms

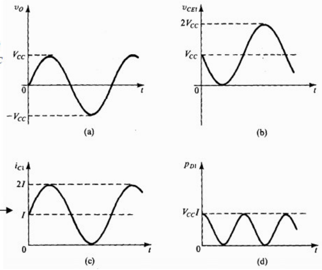
- Assume a **sine-wave input** is applied to the Class A emitter follower circuit.

If bias current I is properly selected, v_O can swing from $-V_{CC}$ to $+V_{CC}$ (neglecting V_{CEsat}).

$v_{CE1} = V_{CC} - v_O$

Collector current of Q_1 waveform assuming that I is selected such that maximum negative load current is V_{CC}/R_L →

Waveform of **instantaneous power dissipation** in Q_1 where $p_{D1} = v_{CE1} i_{C1}$



Maximum signal waveforms in class A output stage of **Figure S1** under the condition $I = V_{CC}/R_L$

9.2) Class-A Operation (Cont)

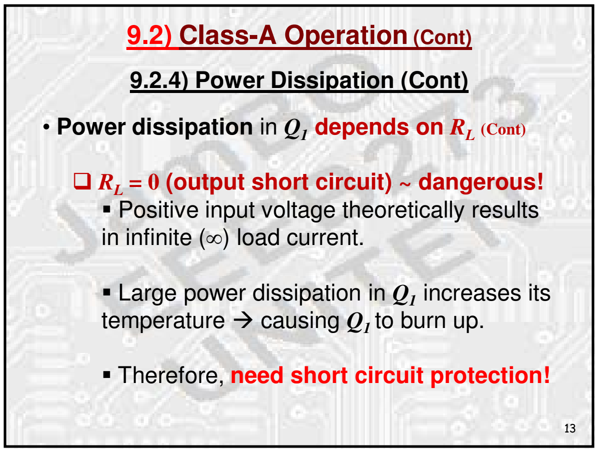
9.2.4) Power Dissipation

- **Maximum instantaneous power dissipation** in the Q_1 is $V_{CC}I$
  - ❑ $V_{CC}I$ = quiescent power dissipation in Q_1
  - ❑ Largest amount of power is dissipated when v_O = **0** (no-input signal).
  - ❑ Q_1 must be able to withstand a continuous power dissipation of $V_{CC}I$ since this condition **(no-input signal) can easily prevail for prolonged periods of time.**

9.2) Class-A Operation (Cont)

9.2.4) Power Dissipation (Cont)

- **Power dissipation** in Q_1 **depends on R_L**
  - ❑ **$R_L = \infty$ (open circuit)**
    - ▪ $I_{C1} = I$ = constant
    - ▪ Instantaneous power dissipation in Q_1 depends on v_O
    - ▪ Max. power dissipation occurs when $v_O = -V_{CC}$
      - ○ $V_{CE1} = 2V_{CC}$ → $p_{D1} = 2V_{CC}I$
      - ○ But condition is not prolonged
    - ▪ Average power dissipation in Q_1 is $V_{CC}I$.



9.2) Class-A Operation (Cont)

9.2.4) Power Dissipation (Cont)

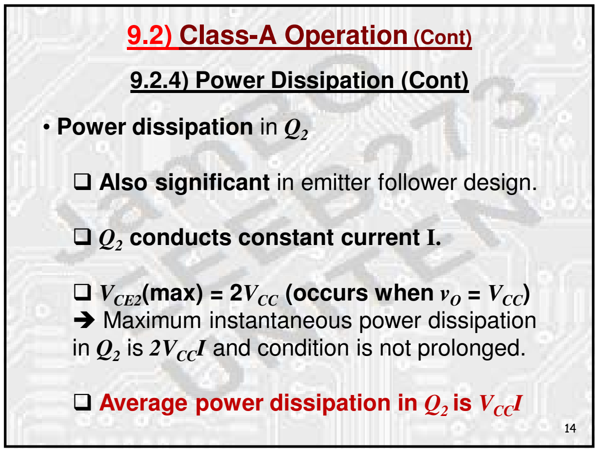
- **Power dissipation** in Q_1 **depends on R_L** (Cont)

❑ **R_L = 0 (output short circuit) ~ dangerous!**

▪ Positive input voltage theoretically results in infinite (∞) load current.

▪ Large power dissipation in Q_1 increases its temperature → causing Q_1 to burn up.

▪ Therefore, **need short circuit protection!**



9.2) Class-A Operation (Cont)

9.2.4) Power Dissipation (Cont)

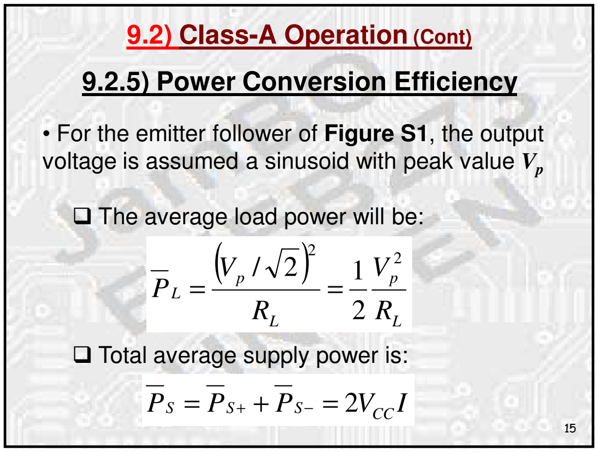
- **Power dissipation** in Q_2

❑ **Also significant** in emitter follower design.

❑ **Q_2 conducts constant current I.**

❑ **V_{CE2}(max) = 2V_{CC} (occurs when v_O = V_{CC})**
➔ Maximum instantaneous power dissipation in Q_2 is $2V_{CC}I$ and condition is not prolonged.

❑ **Average power dissipation in Q_2 is $V_{CC}I$**



9.2) Class-A Operation (Cont)

9.2.5) Power Conversion Efficiency

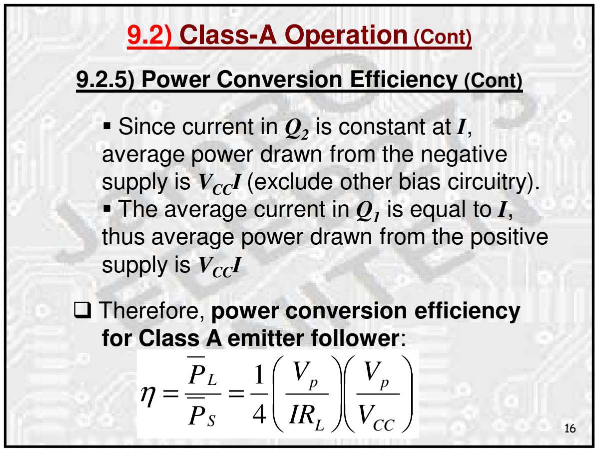
- For the emitter follower of **Figure S1**, the output voltage is assumed a sinusoid with peak value V_p

❑ The average load power will be:

$$\overline{P}_L = \frac{\left(V_p/\sqrt{2}\right)^2}{R_L} = \frac{1}{2}\frac{V_p^2}{R_L}$$

❑ Total average supply power is:

$$\overline{P}_S = \overline{P}_{S+} + \overline{P}_{S-} = 2V_{CC}I$$



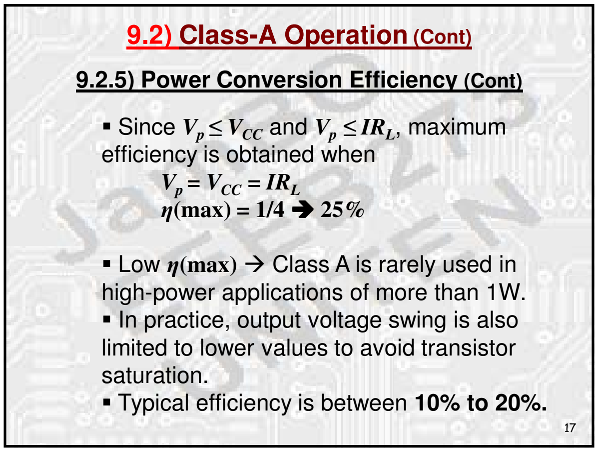
9.2) Class-A Operation (Cont)

9.2.5) Power Conversion Efficiency (Cont)

▪ Since current in Q_2 is constant at I, average power drawn from the negative supply is $V_{CC}I$ (exclude other bias circuitry).
▪ The average current in Q_1 is equal to I, thus average power drawn from the positive supply is $V_{CC}I$

❑ Therefore, **power conversion efficiency for Class A emitter follower**:

$$\eta = \frac{\overline{P}_L}{\overline{P}_S} = \frac{1}{4}\left(\frac{V_p}{IR_L}\right)\left(\frac{V_p}{V_{CC}}\right)$$



9.2) Class-A Operation (Cont)

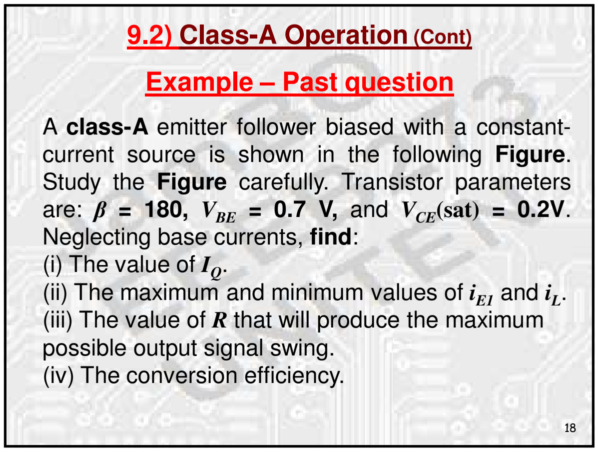
9.2.5) Power Conversion Efficiency (Cont)

▪ Since $V_p \le V_{CC}$ and $V_p \le IR_L$, maximum efficiency is obtained when

$V_p = V_{CC} = IR_L$

η(max) = 1/4 ➔ 25%

▪ Low η(max) → Class A is rarely used in high-power applications of more than 1W.
▪ In practice, output voltage swing is also limited to lower values to avoid transistor saturation.
▪ Typical efficiency is between **10% to 20%.**



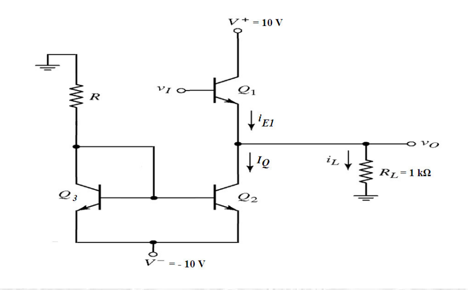
9.2) Class-A Operation (Cont)

Example – Past question

A **class-A** emitter follower biased with a constant-current source is shown in the following **Figure**. Study the **Figure** carefully. Transistor parameters are: β = 180, V_{BE} = 0.7 V, and V_{CE}(sat) = 0.2V. Neglecting base currents, **find**:
(i) The value of I_Q.
(ii) The maximum and minimum values of i_{E1} and i_L.
(iii) The value of R that will produce the maximum possible output signal swing.
(iv) The conversion efficiency.

9.2) Class-A Operation (Cont)

Example – Past question (Cont)



9.2) Class-A Operation (Cont)

Example – Past question (Cont)

(i) $v_O(\max) = V^+ - V_{CE}(\text{sat}) = 10 - 0.2 = 9.8$ V
$I_Q = i_L(\max) = v_O(\max) / R_L = 9.8 / 1\text{k} = 9.8$ mA

(ii) $i_{E1}(\max) = 2\,I_Q = 19.6$ mA
$i_{E1}(\min) = 0$

$i_L(\max) = I_Q = 9.8$ mA
$i_L(\min) = -I_Q = -9.8$ mA

(iii) $R = (0 - V_{BE} - (-10)) / I_Q = 9.3 / 9.8\text{m} = 949\ \Omega$

9.2) Class-A Operation (Cont)

Example – Past question (Cont)

(iv)

$$\overline{P}_L = \frac{1}{2}\left(i_L(\max)\right)^2 R_L = \frac{1}{2}(9.8\text{m})^2(1\text{k})$$

$$\Rightarrow \overline{P}_L = 48.02\text{mW}$$

$$\overline{P}_S = I_Q(V^+ - V^-) + I_Q(0 - V^-)$$

$$\Rightarrow \overline{P}_S = 9.8\text{m}(20) + 9.8\text{m}(10) = 294\text{mW}$$

$$\eta = \frac{\overline{P}_L}{\overline{P}_S} = \frac{48.02\text{m}}{294\text{m}} = 16.3\%$$

9.2) Class-A Operation (Cont)

Exercises

Exercise 1
For the emitter follower in **Fig S1**, $V_{CC} = 15$V, V_{CEsat}=0.2V, V_{BE}=0.7V and constant, and β is very high. Find the value of R that will establish a bias current sufficiently large to allow the largest possible output swing for R_L=1kΩ. Determine the resulting output signal swing and the minimum and maximum emitter currents.
(Answer: R = 0.97 kΩ, $-14.8\text{ V} \le v_O \le 14.8$ V, $0 \le i_{E1} \le 29.6$ mA)

Exercise 2
For the emitter follower in Exercise 1, in which $I_Q = 14.8$ mA, consider the case in which v_o is limited to the range -10 V to +10 V. Let Q_1 have $v_{BE} = 0.6$V at $i_C = 1$ mA, and assume $\alpha \approx 1$. Find v_{In} corresponding to v_O = -10V, 0V, and +10V.
(Answer: -9.63 V, 0.64 V, 10.68 V)

9.2) Class-A Operation (Cont)

Exercises (Cont)

Exercise 3 - Power Dissipation
Consider the emitter follower in **Fig S1**, with $V_{CC} = 10$V, I_Q=100mA and R_L=100Ω. Find the power dissipated in Q_1 and Q_2 under quiescent conditions ($v_O = 0$). For a sinusoidal output voltage of maximum possible amplitude (neglecting V_{CEsat}), find the average power dissipation in Q_1 and Q_2. Also find the load power.
(Answer: 1 W, 1 W, 0.5 W, 1 W, 0.5 W)

Exercise 4 – Conversion Efficiency
For the emitter follower of **Fig S1**, let $V_{CC} = 10$V, $I_Q = 100$ mA, and R_L=100Ω. If the output voltage is an 8-V-peak sinusoid, find the following:
(a) Power delivered to the load
(b) The average power drawn from the supplies
(c) The power conversion efficiency
Ignore the loss in Q_3 and R.
(Answer: 0.32 W, 2 W, 16%)

9.3) Class-B Operation

9.3.1) Idealized Class-B Output Stage

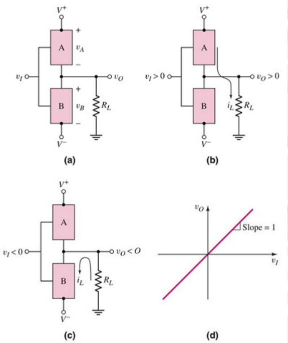


Figure 8.18: Idealized complementary pair of electronic devices

Fig (a): v_I = **0**, both devices off, ➔ $v_O = 0$

Fig (b): $v_I > 0$, device A turns on, supply current to load.

Fig (c): $v_I < 0$, device B turns on, sink current from load.

Fig (d): Voltage transfer characteristics ➔ **Unity** voltage gain.

9.3) Class-B Operation (Cont)

9.3.2) Approximate Class-B Circuit

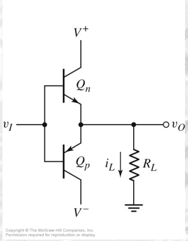


Figure 8.19: Basic complementary BJT push-pull output stage.

- $v_I = 0$, both Q_n & Q_p cut-off, $v_O = 0$
- Assume V_{BE}(on)=0.6V

→ v_O **remains 0** as long as **$-0.6V \le v_I \le +0.6V$**

9.3) Class-B Operation (Cont)

9.3.2) Approximate Class-B Circuit (Cont)

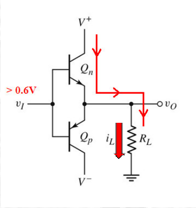


Figure 8.19: Basic complementary BJT push-pull output stage.

- **$v_I > +0.6V$, Q_n turns on** and operates as emitter follower

❑ I_L is **positive**, **supplied thru Q_n**

❑ B-E junction of Q_p **is reverse-biased**

9.3) Class-B Operation (Cont)

9.3.2) Approximate Class-B Circuit (Cont)

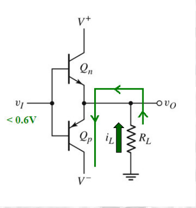


Figure 8.19: Basic complementary BJT push-pull output stage.

- **$v_I < -0.6V$, Q_p turns on** and operates as emitter follower

❑ **Q_p sinks I_L**, which is **negative**

❑ B-E junction of Q_n **is reverse-biased**

9.3) Class-B Operation (Cont)

9.3.2) Approximate Class-B Circuit

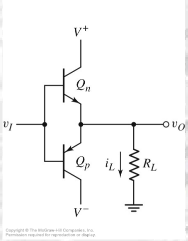


Figure 8.19: Basic complementary BJT push-pull output stage.

➔ **Complementary push-pull output stage:**

❑ **Q_n conducts during positive ½ cycle.**

❑ **Q_p conducts during negative ½ cycle.**

❑ **Q_n & Q_p do not conduct both at the same time.**

9.3) Class-B Operation (Cont)

9.3.3) Transfer Characteristics

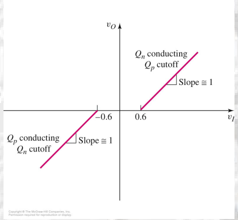


Figure 8.20: Voltage transfer characteristics of basic complementary push-pull output stage.

- **Voltage gain** of emitter follower **≈ 1**.
- Each transistor actually **conducts for slightly less than half** the input voltage cycle.
- **Dead band**: range of input voltage where v_O **is zero** → **Where both transistors are cut-off**.

9.3) Class-B Operation (Cont)

9.3.4) Crossover Distortion

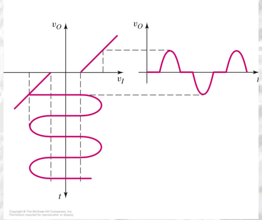


Figure 8.21: Crossover distortion of basic complementary push-pull output stage.

- **Dead band** produces a **crossover distortion**, **Figure 8.21**.
- Crossover distortion can be virtually eliminated by **biasing both transistors with a small quiescent collector current when v_I is zero** (**class-AB output stage ~~ next topic!**).

9.3) Class-B Operation (Cont)

9.3.5) Idealized Power Efficiency

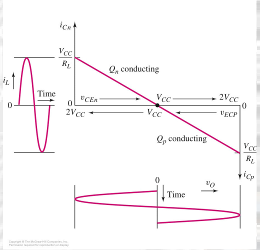


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Figure 8.22: Effective load line of class-B output stage.

- **Figure 8.22** shows the effective dc load line for ideal Class B output stage (Fig 8.18), i.e. V_{BE}(on)=0 V.

- The Q-point is at zero collector current, or at cutoff for both transistors. The quiescent power dissipation is then zero since $p_Q = v_{CE} i_C$

9.3.5) Idealized Power Efficiency (Cont)

9.3.5.1) Average Power Dissipation

- **Output voltage** for the idealized class-B output stage:

$$v_O = V_p \sin \omega t \qquad (8.16)$$

where **maximum** possible value of V_p is V_{CC}

- **The instantaneous power dissipation in Q_n** is

$$p_{Qn} = v_{CEn} i_{Cn} \qquad (8.17)$$

where the collector current is

$i_{Cn} = (V_p / R_L) \sin \omega t$ for $0 \le \omega t \le \pi$,

and $i_{Cn} = 0$ for $\pi \le \omega t \le 2\pi$

9.3.5) Idealized Power Efficiency (Cont)

9.3.5.1) Average Power Dissipation (Cont)

- From **Figure 8.22**, C-E voltage can be written as:

$$v_{CEn} = V_{CC} - V_p \sin \omega t \qquad (8.19)$$

- Therefore, **the total instantaneous power dissipation in Q_n** is

$p_{Qn} = (V_{CC} - V_p \sin\omega t)(V_p/R_L)\sin\omega t$ for $0 \le \omega t \le \pi$,

and $p_{Qn} = 0$ for $\pi \le \omega t \le 2\pi$

- **The average power dissipation** is therefore

$$\overline{P}_{Qn} = \frac{V_{CC}V_p}{\pi R_L} - \frac{V_p^2}{4R_L} \qquad (8.21)$$

9.3.5) Idealized Power Efficiency (Cont)

9.3.5.1) Average Power Dissipation (Cont)

- The average power dissipation **in Q_p** is exactly the **same as that for Q_n** **because of symmetry**.
- A plot of the average power dissipation in each transistor as a function of V_p is shown in **Fig 8.23**

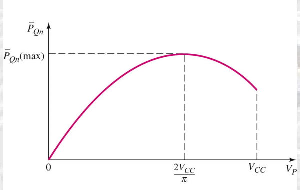

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Figure 8.23: Average power dissipation in each transistor versus peak output voltage for class-B output stage.

9.3.5) Idealized Power Efficiency (Cont)

9.3.5.1) Average Power Dissipation (Cont)

- The power dissipation first increases with increasing output voltage, reaches a maximum at $V_p = 2V_{CC}/\pi$, and finally decreases with increasing V_p.

- **The maximum average power dissipation** is given by

$$\overline{P}_{Qn}(\max) = \frac{V_{CC}^2}{\pi^2 R_L} \qquad (8.22)$$

which occurs when

$$V_p\Big|_{\overline{P}_{Qn}(\max)} = \frac{2V_{CC}}{\pi} \qquad (8.23)$$

9.3.5) Idealized Power Efficiency (Cont)

9.3.5.2) Power Conversion Efficiency (η)

- **The average power** delivered to the load is

$$\overline{P}_L = \frac{1}{2}\frac{V_p^2}{R_L} \qquad (8.24)$$

- Since the average current supplied by each PS is

$$V_p / (\pi R_L)$$

→ **The average power supplied** by each PS source is therefore

$$\overline{P}_{S+} = \overline{P}_{S-} = V_{CC}\left(\frac{V_p}{\pi R_L}\right) \qquad (8.25)$$

9.3.5) Idealized Power Efficiency (Cont)

9.3.5.2) Power Conversion Efficiency (η) (Cont)

→ **The total average power supplied** by the two sources is

$$\overline{P}_S = 2V_{CC}\left(\frac{V_p}{\pi R_L}\right) \qquad (8.26)$$

- **The conversion efficiency** (from 8.12) is then

$$\eta = \frac{\frac{1}{2}\frac{V_p^2}{R_L}}{2V_{CC}\left(\frac{V_p}{\pi R_L}\right)} = \frac{\pi}{4}\frac{V_p}{V_{CC}} \qquad (8.27)$$

9.3.5) Idealized Power Efficiency (Cont)

9.3.5.2) Power Conversion Efficiency (η) (Cont)

- **The maximum possible efficiency** occurs when $V_{CC}=V_p$ is

$$\eta(\max) = \frac{\pi}{4} \Rightarrow 78.5\% \qquad (8.28)$$

➔This maximum efficiency value is **substantially larger than of standard class-A amplifier**.

- From (8.24), **maximum possible average power** that can be delivered to the load is

$$\overline{P}_L(\max) = \frac{1}{2}\frac{V_{CC}^2}{R_L} \qquad (8.29)$$

9.3.5) Idealized Power Efficiency (Cont)

9.3.5.2) Power Conversion Efficiency (η) (Cont)

- **Practically**, the conversion efficiency obtained is **less than the 78.5%** due to other circuit losses, and because $V_p < V_{CC}$ to avoid transistor saturation.

- **Conversion efficiency at maximum transistor power dissipation** (i.e. $V_p = 2\, V_{cc}/\pi$) is

$$\eta = \frac{\pi}{4V_{CC}}.V_p = \left(\frac{\pi}{4V_{CC}}\right).\left(\frac{2V_{CC}}{\pi}\right) = \frac{1}{2} \Rightarrow 50\%$$

9.3.5) Idealized Power Efficiency (Cont)

9.3.5.2) Power Conversion Efficiency (η) (Cont)

Example – Past question

An idealized class B output stage is to deliver 35 W of average power to a 25Ω load for a symmetrical input sine wave. The maximum output voltage is required to be 80% of the power supply voltage.

- Find the power supply voltage.
- With that power supply voltage, calculate the value of the power conversion efficiency η.

9.3.5) Idealized Power Efficiency (Cont)

9.3.5.2) Power Conversion Efficiency (η) (Cont)

Example – Past question (Cont)

$P_L{}^*$ = 35 W, R_L = 25Ω
$P_L{}^*$ = (1/2)($V^2{}_P/R_L$) → 35=(1/2)($V^2{}_P$/25)
V_P = 41.83 V = 0.8 V_{CC}
$V_{CC} = V_P$ / 0.8 = 52.3 V

$P_S{}^*$ = (2 V_{CC})($V_P/\pi R_L$) = (2x52.3)(41.83/π(25))
→ $P_S{}^*$ = 55.7 W
$\eta = P_L{}^*/\, P_S{}^*$ = 35/55.7 = **0.628 or 62.8%**

9.4) Class-AB Operation

9.4.1) Circuit diagram

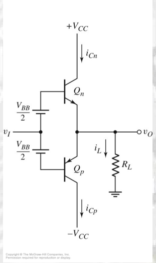

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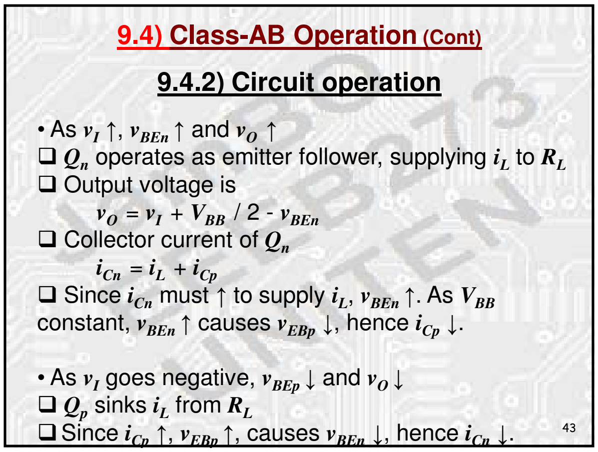
Figure 8.24: Bipolar class-AB output stage

- Crossover distortion can be virtually eliminated **by applying a small quiescent bias on each output transistor**, for a zero input signal. This creates a **class-AB output stage** as shown in **Figure 8.24**.
- If Q_n **&** Q_p are matched: For $v_I = 0$,
  $V_{BEn} = V_{EBp} = V_{BB}/2,$
  and $v_O = 0$
- Quiescent collector current
  $I_{CQ} = i_{Cn} = i_{Cp} = I_S \exp(V_{BB}/2V_T)$



9.4) Class-AB Operation (Cont)

9.4.2) Circuit operation

- As v_I ↑, v_{BEn} ↑ and v_O ↑

❑ Q_n operates as emitter follower, supplying i_L to R_L

❑ Output voltage is

$$v_O = v_I + V_{BB} / 2 - v_{BEn}$$

❑ Collector current of Q_n

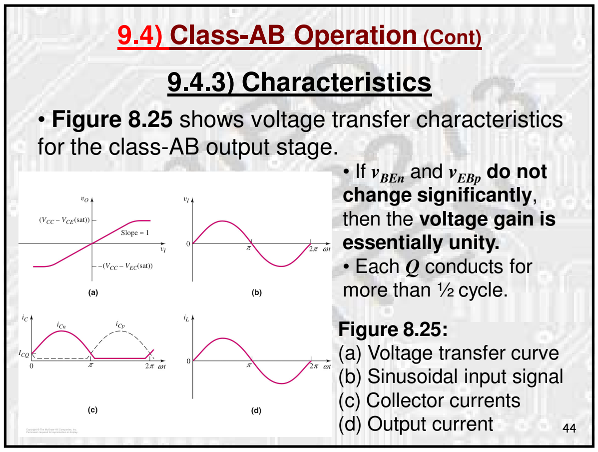
$$i_{Cn} = i_L + i_{Cp}$$

❑ Since i_{Cn} must ↑ to supply i_L, v_{BEn} ↑. As V_{BB} constant, v_{BEn} ↑ causes v_{EBp} ↓, hence i_{Cp} ↓.

- As v_I goes negative, v_{BEp} ↓ and v_O ↓

❑ Q_p sinks i_L from R_L

❑ Since i_{Cp} ↑, v_{EBp} ↑, causes v_{BEn} ↓, hence i_{Cn} ↓.



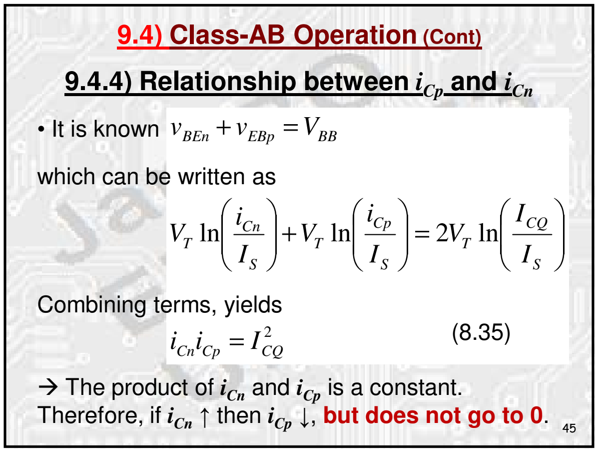
9.4) Class-AB Operation (Cont)

9.4.3) Characteristics

- **Figure 8.25** shows voltage transfer characteristics for the class-AB output stage.

- If v_{BEn} and v_{EBp} **do not change significantly**, then the **voltage gain is essentially unity.**
- Each Q conducts for more than ½ cycle.

Figure 8.25:
(a) Voltage transfer curve
(b) Sinusoidal input signal
(c) Collector currents
(d) Output current



9.4) Class-AB Operation (Cont)

9.4.4) Relationship between i_{Cp} and i_{Cn}

- It is known $v_{BEn} + v_{EBp} = V_{BB}$

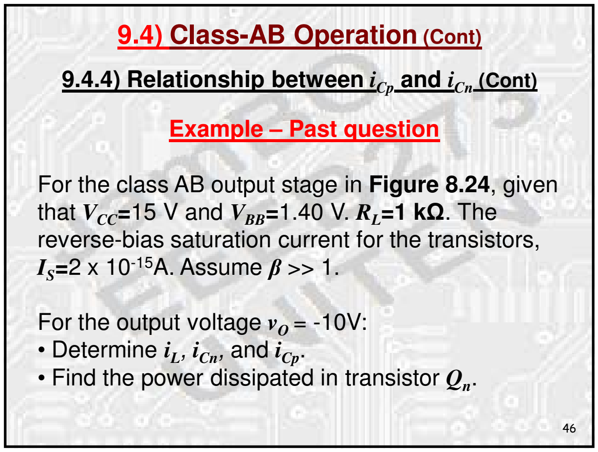
which can be written as

$$V_T \ln\left(\frac{i_{Cn}}{I_S}\right) + V_T \ln\left(\frac{i_{Cp}}{I_S}\right) = 2V_T \ln\left(\frac{I_{CQ}}{I_S}\right)$$

Combining terms, yields

$$i_{Cn} i_{Cp} = I_{CQ}^2 \qquad (8.35)$$

→ The product of i_{Cn} and i_{Cp} is a constant. Therefore, if i_{Cn} ↑ then i_{Cp} ↓, **but does not go to 0**.



9.4) Class-AB Operation (Cont)

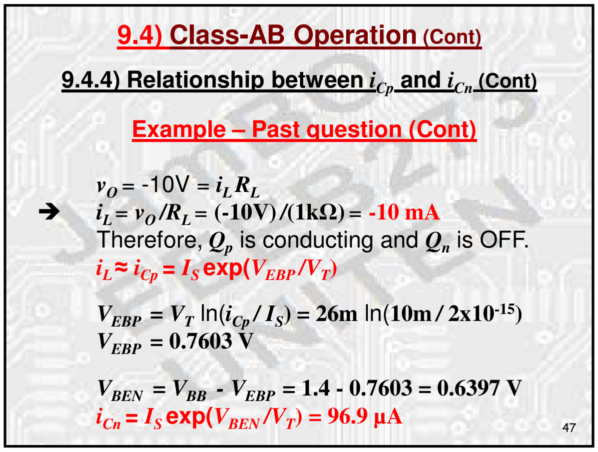
9.4.4) Relationship between i_{Cp} and i_{Cn} (Cont)

Example – Past question

For the class AB output stage in **Figure 8.24**, given that V_{CC}=15 V and V_{BB}=1.40 V. R_L=1 kΩ. The reverse-bias saturation current for the transistors, I_S=2 x 10^{-15}A. Assume $\beta >> 1$.

For the output voltage v_O = -10V:

- Determine i_L, i_{Cn}, and i_{Cp}.
- Find the power dissipated in transistor Q_n.



9.4) Class-AB Operation (Cont)

9.4.4) Relationship between i_{Cp} and i_{Cn} (Cont)

Example – Past question (Cont)

v_O = -10V = $i_L R_L$

➔ $i_L = v_O / R_L$ = (-10V)/(1kΩ) = **-10 mA**

Therefore, Q_p is conducting and Q_n is OFF.

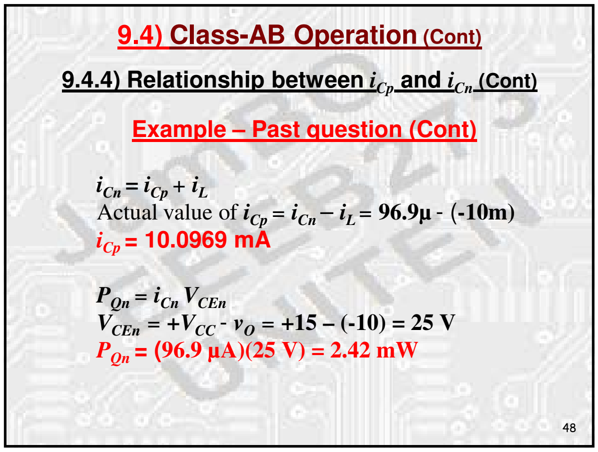
$i_L \approx i_{Cp} = I_S \exp(V_{EBP}/V_T)$

$V_{EBP} = V_T \ln(i_{Cp}/I_S)$ = 26m ln(10m / 2x10^{-15})

V_{EBP} = 0.7603 V

$V_{BEN} = V_{BB} - V_{EBP}$ = 1.4 - 0.7603 = 0.6397 V

$i_{Cn} = I_S \exp(V_{BEN}/V_T)$ = 96.9 µA



9.4) Class-AB Operation (Cont)

9.4.4) Relationship between i_{Cp} and i_{Cn} (Cont)

Example – Past question (Cont)

$i_{Cn} = i_{Cp} + i_L$

Actual value of $i_{Cp} = i_{Cn} - i_L$ = 96.9µ - (-10m)

i_{Cp} = 10.0969 mA

$P_{Qn} = i_{Cn} V_{CEn}$

$V_{CEn} = +V_{CC} - v_O$ = +15 – (-10) = 25 V

P_{Qn} = (96.9 µA)(25 V) = 2.42 mW

9.4) Class-AB Operation (Cont)

Example 2 – Past question

For the class AB output stage in **Figure 8.24**, given that V_{CC}=12 V and V_{BB}=1.20 V. R_L=100 Ω. The reverse-bias saturation current for the transistors, I_S=4 x 10^{-13}A. Assume β >> 1.

9.4) Class-AB Operation (Cont)

Example 2 – Past question (Cont)

i. For the case of the input voltage $v_I = 0$, calculate the quiescent collector currents, i_{Cn} and i_{Cp}, and the power dissipated in transistors Q_p and Q_n.

ii. What is the maximum amplitude of the output voltage, v_O, and the corresponding maximum power that can be delivered to the load?

iii. For the case of v_O =-4 sin ωt V, determine i_L, i_{Cn}, i_{Cp}, and v_I.

9.4) Class-AB Operation (Cont)

Example 2 – Past question (Cont)

i.

$$i_{Cn} = i_{Cp} = I_S e^{\frac{V_{BB}}{2V_T}}$$

$$i_{Cn} = (4x10^{-13})(e^{\left[\frac{1.2}{(2)(0.026)}\right]}) = 4.210mA$$

$$P_{Qn} = P_{Qp} = v_{CE} i_C$$

$$v_{CE} = 12V$$

$$P_Q = (12)(4.210m) = 50.52mW$$

9.4) Class-AB Operation (Cont)

Example 2 – Past question (Cont)

ii.

$$v_{O(\max)} = 12V$$

$$P_{L(\max)} = \frac{1}{2}\frac{V_p^2}{R_L} = (0.5)\left(\frac{12^2}{100}\right) = 0.72W$$

9.4) Class-AB Operation (Cont)

Example 2 – Past question (Cont)

iii.

At v_O = -4 V peak, the load current flows into Q_p,

thus $i_{Cp} \cong i_L = \frac{v_O}{R_L} = \frac{-4\sin\omega t}{100} = -40\sin\omega t$ mA

$i_{Cn} = 0$

$$v_I = v_O - v_{EBp} + \frac{V_{BB}}{2}$$

$$v_{EBp} = V_T \ln\left[\frac{i_{Cp}}{Is}\right] = (0.026)\ln\left[\frac{40m}{4x10^{-13}}\right] = 0.6585V$$

$$v_I = -4 - 0.6585 + \frac{1.2}{2} = -4.0585$$

v_I = -4.0585 sin ωt V

9.4) Class-AB Operation (Cont)

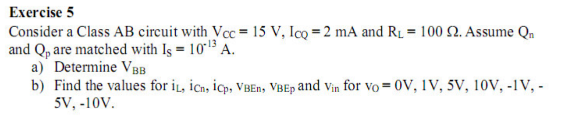
9.4.5) Comparison between class-AB and class-B

- In class-AB, quiescent collector current I_{CQ} exists even for a zero input signal. Hence:
  - ❑ The average power supplied by each source and the average power dissipated in each transistor are ***larger*** than class-B
  - ❑ The η will be ***less*** than an idealized class-B
  - ❑ The required power handling capability of Qs in class-AB will be ***slightly larger*** than class-B. Since I_{CQ} is usually small compared to I_p, the increase in power dissipation is not great.

9.4) Class-AB Operation (Cont)

9.4.5) Comparison between class-AB and class-B (Cont)

- However, the advantage of **eliminating crossover distortion** greatly overweighs the disadvantage of reduced η and increased power dissipation.



Exercise 5

Consider a Class AB circuit with $V_{CC} = 15$ V, $I_{CQ} = 2$ mA and $R_L = 100\ \Omega$. Assume Q_n and Q_p are matched with $I_S = 10^{-13}$ A.

a) Determine V_{BB}

b) Find the values for i_L, i_{Cn}, i_{Cp}, v_{BEn}, v_{BEp} and v_{in} for v_O = 0V, 1V, 5V, 10V, -1V, -5V, -10V.

9.4.6) Biasing of Class-AB

9.4.6.1) With Diode Biasing

- **Figure 8.31** shows the V_{BB} voltage established by voltage drops across diodes D_1 and D_2.

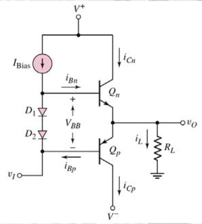


Figure 8.31: Quiescent bias established by diodes

- A constant current I_{Bias} establishes the required voltage across D_1 and D_2 (pair of diodes or diode-connected transistors)
- Since D_1 and D_2 may not be matched to Q_n and Q_p, hence I_{CQ} may not be equal to I_{Bias}

9.4.6) Biasing of Class-AB (Cont)

9.4.6.1) With Diode Biasing (Cont)

- **Problem: V_{BB} is not constant**
  - ☐ As v_I ↑, v_O ↑ so i_{Cn} ↑, hence i_{Bn}↑
  - ☐ i_{Bn}↑ is supplied by I_{Bias}, the current through D_1 and D_2 ↓, hence V_{BB} ↓ slightly
  - ☐ Since V_{BB} does not remain constant in this circuit, previous relationship for collector currents $i_{Cn}i_{Cp} = (I_{CQ})^2$ is not precisely valid for this situation

9.4.6) Biasing of Class-AB (Cont)

9.4.6.1) With Diode Biasing (Cont)

Design Example 8.9

Objective: Design the class-AB output stage in Figure 8.31 to meet specific design criteria.

Assume I_{SD} **= 3 x 10^{-14} A** for D_1 and D_2, I_{SQ} **= 10^{-13}** for Q_n and Q_p, and $\beta_n = \beta_p$ **= 75**. Let R_L **= 8 Ω**. The average power delivered to the load is to be **5 W**. The peak output voltage is to be no more than 80 percent of V_{CC}, and the minimum value of diode current I_D is to be no less than **5 mA**.

9.4.6) Biasing of Class-AB (Cont)

9.4.6.1) With Diode Biasing (Cont)

Design Example 8.9 (Cont)

$P_L^* = (1/2)(V^2_P/R_L)$

$V_P = \text{sqrt}[2\ R_L\ P_L^*] = \text{sqrt}[2(8)(5)] = 8.94$ V

The supply voltage must then be

$V_{CC} = V_P / 0.8 = 8.94/0.8 = 11.2$ V

At this peak output voltage, the emitter current of Q_n is approximately equal to the load current, or

$i_{En} \approx i_L(\text{max}) = V_P(\text{max})/\ R_L = 8.94/8 = 1.12$ A

and the base current is

$i_{Bn} = i_{En}\ /\ (1+\beta_n) = 1.12/76 = 14.7$ mA

9.4.6) Biasing of Class-AB (Cont)

9.4.6.1) With Diode Biasing (Cont)

Design Example 8.9 (Cont)

For a minimum I_D = 5 mA, we can choose I_{Bias} = 20 mA. For a zero input signal, neglecting base currents, we find that

$V_{BB} = 2V_T\ \ln(I_D\ /\ I_{SD})$

$= 2(0.026)\ \ln(20\text{x}10^{-3}/3\text{x}10^{-14}) = \mathbf{1.416V}$

The quiescent collector currents are then

$I_{CQ} = I_{SQ}\ \exp(V_{BB}\ /\ 2\ V_T)$

$= 10^{-13}\ \exp(1.416/2(0.026)) = \mathbf{67.0\ mA}$

9.4.6) Biasing of Class-AB (Cont)

9.4.6.1) With Diode Biasing (Cont)

Design Example 8.9 (Cont)

For v_O = 8.94 V and I_L = 1.12 A, the base current is i_{Bn} = 14.7 mA, and

$$i_D = i_{Bias} - i_{Bn} = 5.3 \text{ mA}$$

The new value of V_{BB} is then

$$V_{BB} = 2V_T \ln(I_D / I_{SD}) = 2(0.026)\ln(5.3\text{x}10^{-3}/3\text{x}10^{-14}) = \mathbf{1.347V}$$

9.4.6) Biasing of Class-AB (Cont)

9.4.6.1) With Diode Biasing (Cont)

Design Example 8.9 (Cont)

The B-E voltage of Q_n is

$$v_{BEn} = V_T \ln(i_{Cn} / I_{SQ}) = (0.026) \ln(1.12/10^{-13}) = \mathbf{0.781V}$$

The E-B voltage of Q_p is then

$$v_{EBp} = V_{BB} - v_{BEn} = 1.347\text{-}0.781 = \mathbf{0.566V}$$

and

$$i_{Cp} = I_{SQ} \exp(v_{EBp} / V_T) = 10^{-13} \exp(0.566/0.026) = \mathbf{0.285 \text{ mA}}$$

9.4.6) Biasing of Class-AB (Cont)

9.4.6.2) Using the V_{BE} Multiplier

- **Figure 8.32** shows voltage V_{BB} established by Q_1, R_1 and R_2, biased by constant-current source I_{Bias}

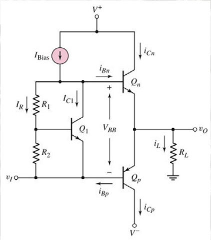


Figure 8.32: Class-AB with V_{BE} Multiplier bias circuit

- Neglecting the base current in Q_1, then

$$I_R = V_{BE1} / R_2 \qquad (8.48)$$

and voltage V_{BB} is

$$V_{BB} = I_R (R_1 + R_2) = V_{BE1} (1 + R_1 / R_2)$$

➔ V_{BB} is a multiplication of V_{BE1}, circuit is **V_{BE} Multiplier**

9.4.6) Biasing of Class-AB (Cont)

9.4.6.2) Using the V_{BE} Multiplier (Cont)

- A fraction of I_{Bias} flows through Q_1, so that

$$V_{BE1} = V_T \ln (I_{C1} / I_S) \qquad (8.50)$$

- Also, can neglect i_{Bn} and i_{Bp} because i_{Cn} and i_{Cp} are normally small. Current I_{Bias} divides between I_R and I_{C1}, satisfying both Equations (8.48) and (8.50).

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

9.4.6) Biasing of Class-AB (Cont)

9.4.6.2) Using the V_{BE} Multiplier (Cont)

- **Advantage of V_{BE} Multiplier:**
  - ❑ **Design flexibility** as **the multiplication factor** is controlled by adjusting R_1 and R_2
  - ❑ V_{BB} is **more constant**
    - As v_I ↑, v_O ↑ so i_{Cn} ↑, hence i_{Bn}↑
    - Now I_{C1} ↓, however the **logarithmic dependence** of V_{BE1} on I_{C1} means V_{BE1} and **V_{BB} remains constant**

Larger circuits

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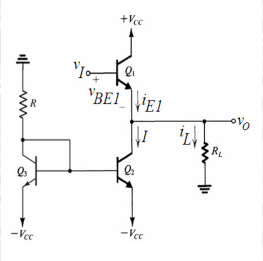
9.2) Class-A Operation (Ref: Sedra pp. 1231-1235)

Circuit diagram **Transfer Characteristics**



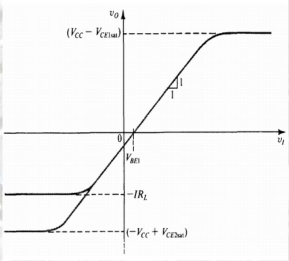


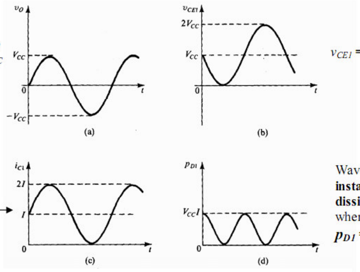
Figure S1

9.2) Class-A Operation (Cont)

9.2.3) Signal Waveforms

- Assume a **sine-wave input** is applied to the Class A emitter follower circuit.

If bias current I is properly selected, v_O can swing from $-V_{CC}$ to $+V_{CC}$ (neglecting V_{CEsat}).



$v_{CE1} = V_{CC} - v_O$

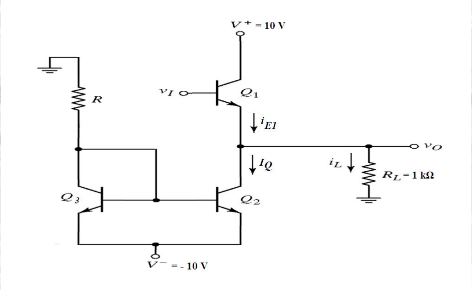
Collector current of Q_1 waveform assuming that I is selected such that maximum negative load current is V_{CC}/R_L

Waveform of **instantaneous power dissipation** in Q_1 where $p_{D1} = v_{CE1}i_{C1}$

Maximum signal waveforms in class A output stage of **Figure S1** under the condition $I = V_{CC}/R_L$

9.2) Class-A Operation (Cont)

Example (Cont)



9.3) Class-B Operation

9.3.1) Idealized Class-B Output Stage

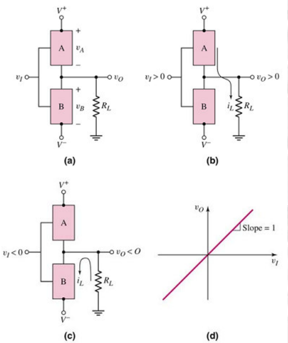


Figure 8.18: Idealized complementary pair of electronic devices

Fig (a): $v_I = 0$, both devices off, ➔ $v_O = 0$

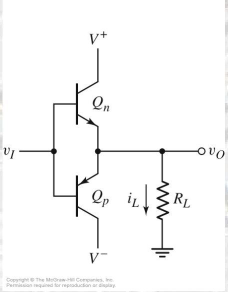
Fig (b): $v_I > 0$, device A turns on, supply current to load

Fig (c): $v_I < 0$, device B turns on, sink current from load

Fig (d): Voltage transfer characteristics ➔ **Unity** voltage gain

9.3) Class-B Operation (Cont)

9.3.2) Approximate Class-B Circuit



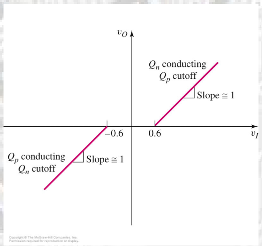
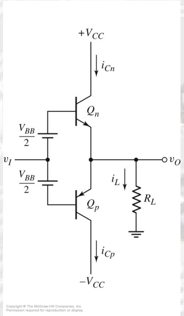


Figure 8.20: Voltage transfer characteristics

Figure 8.19: Basic Class-B circuit

9.4) Class-AB Operation



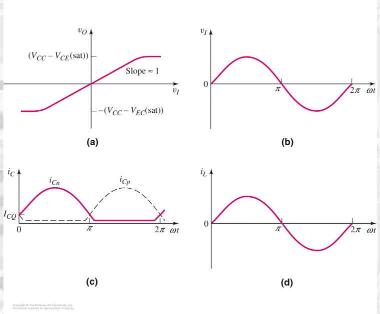
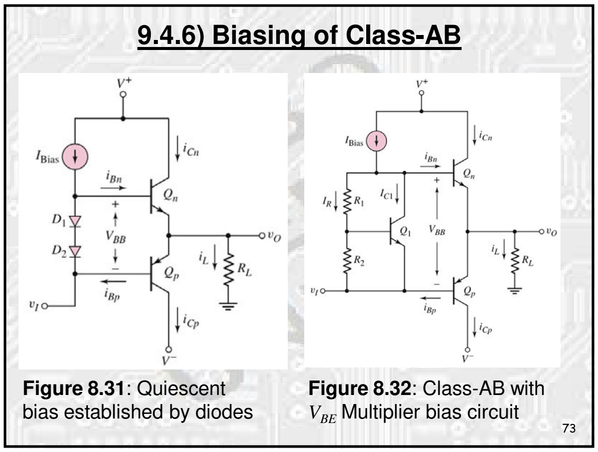


Figure 8.24: Bipolar class-AB output stage

Figure 8.25: (a) Voltage transfer curve (b) Sinusoidal input signal (c) Collector currents (d) Output current



9.4.6) Biasing of Class-AB

Figure 8.31: Quiescent bias established by diodes

Figure 8.32: Class-AB with V_{BE} Multiplier bias circuit

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