Last time: Full Wave Rectifiers

Example: Available: 60Hz / 120V RMS
Need: Need \( [4.95 \div 5.00] \) V DC
\( R_{load} \approx 1\kOmega \)

Bridge

Center tap

Input: \( V(t) = V_0 \cdot \sin(\omega t) \)
\( V_0 = 120 \cdot \sqrt{2} \approx 170 \text{ V} \)
\( \omega = 2\pi \cdot f \); \( T = \frac{1}{f} = \frac{1}{60\text{Hz}} \approx 17\text{ ms} \)
**BRIDGE RECTIFIER**

\[
V_L^{\text{MAX}} = 5V = V_S^{\text{MAX}} - 2 \cdot V_{D0}
\]

Assume \(V_{D0} \approx 0.8V\)

\[\Rightarrow V_S^{\text{MAX}} = 5V + 1.6V = 6.6V\]

\[\Rightarrow \frac{N_2}{N_1} = \frac{6.6V}{170V} \Rightarrow N_2 \approx \frac{N_1}{26}\]

\[V_r = \frac{T/2}{\tau} \cdot V_L^{\text{MAX}} \Rightarrow \text{NEED} \quad \frac{V_r}{V_L^{\text{MAX}}} = \frac{50mV}{5V} = 0.01 = 1\%\]

\[\Rightarrow \tau = \frac{T/2}{0.01} = 50 \cdot T = 0.85s \Rightarrow C \approx \frac{0.85s}{100\%} \approx 8.5\text{ mF}\]

\[\Delta t \approx \frac{T}{2u} \sqrt{\frac{2V_r}{V_L^{\text{MAX}}}} = \frac{17ms}{6.28} \cdot \sqrt{0.02} \approx 0.38\text{ ms} \ll T \text{ INDEED}\]

\[I_D^{\text{MAX}} \approx \left(\frac{50mV \cdot 8.5\text{ mF}}{0.38\text{ ms}} + \frac{5}{100}\right) \approx (1.12\text{ A} + 50\text{ mA}) = 1.17\text{ A}\]
Center Tap Rectifier

\[ V_L^{\text{MAX}} = 5 \text{V like before, but } V_L = V_S - V_{DO} \]

\[ \Rightarrow V_S^{\text{MAX}} = 5.8 \text{V} \Rightarrow \frac{N_{21}}{N_1} = \frac{5.8}{170} \Rightarrow N_{21} \approx \frac{N_1}{29} \text{ a bit less} \]

**BUT** \[ N_{22} = N_{21} \Rightarrow \text{bigger transformer} \]

\[ P \cdot V = 2 \cdot V_S^{\text{MAX}} - V_{DO} = 10.8 \text{V} (\text{almost twice bigger than for bridge}) \]

\[ C, \Delta t \& I_D^{\text{MAX}} - \text{sane} \]
Note on diode current when cap is being charged.

\[ I_D = I_c + I_L \quad ; \quad I_c = C \frac{dV_c}{dt} \]

We estimated before diode current:

\[ I_D^{\text{MAX}} = I_L + I_c^{\text{AVERAGE}} \]

in fact \( I_c \) takes max at the start of charge process

\[ I_c^{\text{MAX}} \approx 2 \cdot I_c^{\text{AVERAGE}} \]

Hence \( I_D \) in fact is twice higher than \( I_D^{\text{MAX}} \) from our estimation.
Half wave rectifier circuit

Square wave input

\[ V_{in} \]

\[ V_D \]

\[ R_L \]

\[ V_L \]

\[ I_D \]

Simplified diode model

\[ R_S = 0, \quad I_S = 0 \]

\[ |V_{in}| < V_B, \quad V_{TO} = 0.7V \]

For diode with no parasitic capacitance and no charge accumulation effect we would obtain:

\[ V(t) \]

\[ V_D \]

\[ V_I \]

\[ V_L \]

\[ V_{o-I \pi V} \]

* Spectrum of square wave signal contains many frequencies besides \( f_0 = 1/T \).

For 50% duty \(-V_o \) to \(+V_o\) square wave:

\[ V_{in}(t) = \frac{4 \cdot V_{in}}{\pi} \left( \sin(2 \cdot \pi \cdot f_0) + \frac{\sin(6 \cdot \pi \cdot f_0)}{3} + \ldots \right) \]
Half wave rectifier circuit

Square wave input

Real diodes have depletion and diffusion capacitances so the transient response will be complicated.

Simplified diode model

\[ R_s = 0, \quad I_s = 0 \]
\[ |V_{in}| < V_B, \quad V_{TO} = 0.7V \]

* Spectrum of square wave signal contains many frequencies besides \( f_0 = 1/T \).

Diode "keeps" forward bias after input is switched

Diode recovery time. Determined by how fast the caps can be discharged.
Pn-junction diode recovery time

Under forward bias the excess minority carriers are injected. Hence, the excess carrier concentrations are present on both sides of pn-junctions. We call it—"charge accumulation" and characterize it by so called diffusion capacitance.

Accumulated charges cannot disappear immediately after bias is changed, hence diode would appear to keep forward bias $V_{D0}$ for some time after bias is changed.

$$I_{TRAN} \approx \frac{0.7V}{R}$$

$$\tau_s = \frac{Q_{\text{Stored}}}{I_{TRAN}}$$

Discharge of junction depletion capacitance

Transition time $\tau_{TR}$

Recovery time

$$\tau_{REC} = \tau_s + \tau_{TR}$$
Pn-junction diode recovery time

Consider the case when voltage changes from positive to negative

\[ I = \frac{V_0 - 0.7V}{R} \]

\[ I_{\text{TRAN}} = \frac{-V_0 - 0.7V}{R} \]

Large negative current spike but recovery time is decreased as compared to positive-to-zero transition case since now the same stored charge is being removed by larger current.
Voltage Amplifiers

1. Single Ended

\[ A_v = \frac{V_{out}}{V_{in}} \]  
Voltage Gain

2. Linear Amp.

\[ A_v \text{ does not depend on value of } V_{in} \]  
(Can depend on freq.)

\[ V_- \text{ & } V_+ \text{ - power supplies} \]

Input Signal Power: \[ P_{in} = V_{in} \cdot I_{in} \]

Output Signal Power: \[ P_{out} = V_{out} \cdot I_{out} \]

Power Taken from Power Supplies: \[ P_{dc} = (V_+ I_+ + V_- I_-) \]

\[ P_{out} = \left[ P_{in} + P_{dc} \right] - P_{dissipated} \]

Amp. Efficiency: \[ \eta = \frac{P_{out}}{P_{dc}} \cdot 100\% \]  
*Pin often negligible*
Gains of Amp.

Power Gain: \( A_p = \frac{P_{out}}{P_{in}} = \frac{V_{out}}{V_{in}} \cdot \frac{I_{out}}{I_{in}} \), \( \frac{W}{W} \)

Voltage Gain: \( A_v = \frac{V_{out}}{V_{in}} \), \( \frac{V}{V} \)

Current Gain: \( A_i = \frac{I_{out}}{I_{in}} \), \( \frac{A}{A} \)

dB Scale:
- \( A_v, \text{dB} = 20 \cdot \log |A_v| \)
- \( A_i, \text{dB} = 20 \cdot \log |A_i| \)
- \( A_p, \text{dB} = 10 \cdot \log |A_p| \)

② \( A_v = 100 \frac{V}{V} \Rightarrow A_v, \text{dB} = 20 \log 100 = 20 \log 10^2 = 40 \text{ dB} \)

\( A_v = 0.1 \frac{V}{V} \Rightarrow A_v, \text{dB} = 20 \log 10^{-1} = -20 \text{ dB} \)
Note on Power Supplies

Model of DC Power Supply with Limited Power:

\[ P_{\text{MAX}} = V_{\text{OC}} \cdot I_{\text{SC}} = \frac{V_s^2}{R_s} \]

Open Circuit Voltage

Short Circuit Current

Thevenin Form

Equivalent

Norton
Thevenin (Norton) equivalents of any circuit.

SUPERPOSITION

\[ I_{L1} = 0 \]
\[ I_{L2} = I_L \]

\[ V_{EQ} = V_{OC} \quad \text{and} \quad R_{EQ} = \text{equivalent impedance} \]
\[ V_{\text{Eq}} = V_{\text{oc}} = V_s \frac{X_{C_2}}{R_s + X_{C_1} + X_{C_2}} \]

\[ Z_{\text{Eq}} = (R_s + X_{C_1}) \parallel X_{C_2} \]

\[ X_{C_1} = \frac{1}{j\omega C_1} \quad ; \quad X_{C_2} = \frac{1}{j\omega C_2} \]

* Norton \quad I_{\text{Eq}} = \frac{V_{\text{Eq}}}{Z_{\text{Eq}}} \]
Voltage Transfer Characteristics

Linear amp when
\[-\frac{V_0}{A_v} < V_{in} < \frac{V_+}{A_v}\]

\[\text{Vo} \cdot \cos(\omega t) \quad \leftrightarrow \quad A_v \cdot \text{Vo} \cdot \cos(\omega t)\]

增加振幅

- In general, \(A_v(\omega)\) & phase can be shifted
- For now - consider low frequencies
Bias of Amplifier

What if

\[ V_{in} \rightarrow V_{out} \]

Here

\[ V_{in} \rightarrow \begin{cases} V_{out} \neq A \cdot V_{in} \text{ at output} \end{cases} \]

Output is not linear function of input

But

\[ \Delta V_{in} \rightarrow V_{out} + \]

\[ V_{DC} \]

\[ V_{out} = V_{bias} + \Delta V_{out} \]

\[ \frac{\Delta V_{out}}{\Delta V_{in}} = A_{V} - \text{linear again!} \]
EQUIVALENT CIRCUIT OF LINEAR AMP.

**Signal Source**

\[ V_L = V_{\text{bias}} + \frac{V_L}{V_s} = A_v \text{ Differential Voltage Gain} \]

Bias determines gain & allowed signal swing

For signals:
- DC voltage = zero signal voltage
- DC current = zero signal current

**Input Impedance**

\[ S \]

\[ V_{\text{in}} \]

\[ R_{\text{in}} \]

**Output Impedance**

\[ R_{\text{out}} \]

\[ A_v = \text{open circuit voltage gain} \]

\[ V_L = A_v \cdot V_{\text{in}} \cdot \frac{R_L}{R_{\text{out}} + R_L} = \frac{V_s}{R_s + R_{\text{in}}} \cdot A_v \cdot \frac{R_L}{R_{\text{out}} + R_L} \]
**Net Voltage Gain** 
(From Signal to Load)

1. **In General** $Z$, not $R$.

\[
G_V(\omega) = \frac{V_L}{V_S} = \frac{Z_{\text{in}}}{Z_S + Z_{\text{in}}} \cdot A_{\text{vo}}(\omega) \cdot \frac{Z_L}{Z_{\text{out}} + Z_L}
\]

[Can be $< A_{\text{vo}}$!]

2. **Often** all freq-dependence is inside $Z(\omega)$, not $A_{\text{vo}}$.

3. **Back to $R$** for voltage amp $R_S \ll (R_{\text{in}} \& R_L) > R_{\text{out}}$

4. **Voltage Buffer**

\[
V_{\text{in}} \rightarrow 0 \quad R_{\text{in}} \rightarrow \infty \quad R_{\text{out}} \rightarrow \infty
\]

\[V_{L} = A_{\text{vo}} \cdot V_S\]
EXAMPLE

\[ \mathcal{V}_s \]

\[ \mathcal{V}_{\text{in}} - \frac{R_{\text{in}}}{C_{\text{in}}} \]

\[ \mathcal{V}_{\text{out}} \]

\[ \mathcal{V}_{L} \]

\[ R_{\text{out}} \]

\[ A_{\text{vo}} \cdot \mathcal{V}_{\text{in}} \]

\[ R_L \]

\[ \mathcal{V}_{\text{in}}(\omega) = \mathcal{V}_{\text{s}}(\omega) \]

\[ G_V(\omega) = \frac{\mathcal{V}_L(\omega)}{\mathcal{V}_{\text{in}}(\omega)} = \left[ \frac{\mathcal{V}_L(\omega)}{\mathcal{V}_{\text{in}}(\omega)} \right] \cdot \frac{\mathcal{V}_{\text{in}}(\omega)}{\mathcal{V}_{\text{s}}(\omega)} = \left[ \frac{R_L}{R_{\text{out}} + R_L} \right] \cdot A_{\text{vo}} \cdot \frac{\mathcal{V}_{\text{in}}(\omega)}{\mathcal{V}_{\text{s}}(\omega)} \]

\[ \frac{\mathcal{V}_{\text{in}}(\omega)}{\mathcal{V}_{\text{s}}(\omega)} = ? \]
RC low pass filter

\[ T(\omega) = \frac{V_{out}}{V_{in}} = \frac{X_c}{R + X_c} = \frac{1}{j\omega C} = \frac{1}{1 + j\omega RC} = |T|e^{j\phi_T} \]

\[ \tau = RC \quad \omega = 2\pi f \]

Magnitude response

Phase response

20 \log_{10} |T|, dB

\[ f_{3dB} = \frac{1}{2\pi \tau} \]

20 dB/dec

Delay
\[ G_V(t) = \left[ \frac{R_L}{R_{out} + R_L} \cdot A_{vo} \right] \cdot \frac{V_{in}(t)}{V_s(t)} \]

\[ \frac{V_{in}}{V_s} = \frac{V_{eq}}{V_s} \cdot \frac{V_{in}}{V_{eq}} = \frac{R_{in}}{R_s + R_{in}} \cdot \frac{1}{1 + j\omega \tau} \]

\[ \tau = C_{in} \cdot \frac{R_s \cdot R_{in}}{R_s + R_{in}} \]

\[ G_V(t) = \left[ \frac{R_{in}}{R_s + R_{in}} \cdot A_{vo} - \frac{R_L}{R_{out} + R_L} \right] \cdot \frac{1}{1 + j2\pi f \cdot \left[ C_{in} \frac{R_s \cdot R_{in}}{R_s + R_{in}} \right]} \]

**Voltage Gain at DC**

\[ |G_V|_{dB} \]

\[ G_{DC} \]

\[ f_H = \frac{(R_s + R_{in})}{2\pi C_{in}(R_s \cdot R_{in})} \]

\[ G_V(t) = \frac{G_{DC}}{1 + \frac{j\omega}{f_H}} \approx \frac{G_{DC}}{\frac{j\omega}{f_H}} \]

\[ \Rightarrow G_V(t) \cdot f \approx G_{DC} \cdot f_H \]

**Gain-Bandwidth Product**