【Outline】

3.1 The Ideal Diode
3.2 Terminal Characteristics of Junction Diodes
3.3 Modeling the Diode Forward Characteristic
3.4 Operation in the Reverse Breakdown Region — Zener Diodes
3.5 Rectifier Circuits
3.6 Limiting and Clamping Circuits
3.7 Special Diode Types
3.1 The Ideal Diode

(a) diode circuit symbol

Anode \[ i \] \[ + \] \[ v \] \[ − \]
Cathode

(b) \( i-v \) characteristic

----- Reverse bias \[ \rightarrow \] Forward bias -----

\( i \)
\[ + \] \[ v \] \[ − \]

\( v < 0 \implies i = 0 \)

(c) equivalent circuit in the reverse direction

\( i \)
\[ + \] \[ v \] \[ − \]

\( i > 0 \implies v = 0 \)

(d) equivalent circuit in the forward direction.
The two modes of operation of ideal diodes and the use of an external circuit.

(a) the forward current

(b) the reverse voltage
(a) Input waveform.

(b) Rectifier circuit.

(c) Equivalent circuit when \( v_i \geq 0 \).

(d) Equivalent circuit when \( v_i \leq 0 \).

(e) Output waveform.
Example 3.1  Fig.3.4(a), shows a circuit for charging a 12-V battery. If $v_s$ is sinusoid with 24-V peak amplitude, (a) Find the fraction of each cycle during which the diode conducts. (b) Also find the peak value of the diode current and (c) the maximum reverse-bias voltage that appears across the diode.

Method 1:

(a) $24 \sin \alpha = 12 \Rightarrow \alpha = 30^\circ$

$2\theta = 180^\circ - 2\alpha = 120^\circ$
Method 2:

(a) $24 \cos \theta = 12 \Rightarrow \theta = 60^\circ$

Conduction angle $= 2\theta = 120^\circ$

(b) $I_{D(\text{max})} = \frac{24 - 12}{100} = 0.12\text{A}$

(c) The maximum reverse voltage across the diode:

$V_{D(\text{max})} = 24 + 12 = 36\text{V}$
3.1.3 Another Application: Diode Logic Gates

(a) OR gate

(b) AND gate

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Example 3.2  Assuming the diode to be ideal, Find the values of $I$ and $V$ in the circuit of Fig. (a) and (b)

Sol:
Assume that both diodes are conducting

$V_B = 0$ and $V = 0$

$I_{D_2} = \frac{(10 - 0)V}{10k\Omega} = 1mA$

Writting a node equation at B (K.C.L)

$I + 1 = \frac{0 - (-10)}{5} \Rightarrow I = 1mA$

Results in $I = 1mA$,
Thus $D_1$ is conducting as originally assumed
and the find result is $I = 1mA$ and $V = 0V$
Our assumption is not correct, we start again assuming that $D_1$ is OFF and $D_2$ is ON.

The current $I_{D_2}$ is given by $I_{D_2} = \frac{10 - (-10)}{15} = 1.33\text{mA}$

$V_B = -10 + 10 \cdot 1.33 = 3.3\text{V}$

Thus $D_1$ is reverse biased as assumed $\therefore I = 0\text{A}$ and $V = 3.3\text{V}$
3.2 Terminal Characteristics junction diode

Figure 3.8 The diode $i-\nu$ relationship with some scales expanded and others compressed in order to reveal details.
3.2.1 The Forward-bias region

\[ i = I_s \left( e^{\frac{v}{nV_T}} - 1 \right) \]  \hspace{1cm} (3.1)

(a) \( I_s \) is saturation current, another name for \( I_s \) is the scale current.

(b) \( I_s \) is a constant for a given diode at a given temperature.

(c) \( I_s \) is directly proportional to the across-sectional area of the diode.

(d) \( I_s \) For "small-signal" diode intended for low-power application,
\[ I_s \] is on the order of \( 10^{-15} \) A

(e) \( I_s \) a very strong function of temperature. As a rule of thumb,
\[ I_s \] doubles in value for every 5°C rise in temperature.
$V_T$: Thermal voltage

$$V_T = \frac{K \cdot T}{q} \quad (3.2)$$

where $K =$ Boltzmann's constant $= 1.38 \times 10^{-23}$ Joules/Kelvin

$T =$ The absolute temperature in Kelvin $= 273 +$ temperature °C

$q =$ The magnitude of electronic charge $= 1.60 \times 10^{-19}$ Coulomb

At room temperature($20^\circ$C), $V_T \cong 25.2$mV.

At room temperature($27^\circ$C), $V_T \cong 26$mV.

$n : 1 \leftrightarrow 2$, Depending on the material and the physical structure of the diode.
If the voltage is \( V_n \), the diode current \( I \) thus

\[
i \approx I_s e^{V_n/\eta V_T} \Rightarrow V = nV_T \ln \frac{i}{I_s}
\]

If the voltage is \( v_1 (v_2) \), the diode current \( I_1 (I_2) \)

thus \( i_1 \approx I_s e^{v_1/\eta V_T} \) and \( i_2 \approx I_s e^{v_2/\eta V_T} \)

\[
\frac{i_2}{i_1} = e^{(v_2-v_1)/\eta V_T}
\]

\[
v_2 - v_1 = nV_T \ln \frac{i_2}{i_1} = 2.3nV_T \log \frac{i_2}{i_1}
\]

(3.5)

This equation simply states that for a decade changes in current,
the diode voltage drop changes by \( 2.3nV_T \approx 60 \text{mV} \), for \( n = 1 \)
**Example:** Design the circuit in below Figure to provide an output voltage of 2.4V. Assume that diode available have 0.7V drop at 1mA and that $\Delta V = 0.1V$/decade changes in current.

**Sol:**

Refer Fig.a to obtain $v_o = 2.4V$

each diode must have a voltage drop of 0.8V thus

\[
v_2 - v_1 = 2.3nV_T \log \frac{i_2}{i_1}
\]

\[
0.1 = 2.3 \cdot 2.25 \cdot 10^{-3} \cdot \log \frac{i_2}{i_1} = 0.1 \log \frac{i_2}{i_1}
\]

\[
i_2 = 10i_1 = 10mA
\]

The value of $R$ is determined from

\[
R = \frac{(10 - 2.4)V}{10mA} = 760\Omega
\]
Figure 3.9 Illustrating the temperature dependence of the diode forward characteristic. At a constant current, the voltage drop decreases by approximately 2 mV for every 1°C increase in temperature.
Example 3.3: A silicon diode said to be a 1-mA device displays a forward voltage of 0.7V at a current of 1mA. Evaluate the junction scaling constant $I_s$ in the event that $n$ is either 1 or 2, what scaling constants would apply for a 1-A diode of the same manufacture that conducts 1A at 0.7V

Since $i \approx I_s e^{v/nV_T} \Rightarrow I_s = i \cdot e^{-(v/nV_T)}$

for the 1–mA diode.

If $n = 1$ $I_s = 1 \times 10^{-3} \times e^{-700/25} = 6.9 \times 10^{-16}$ A

If $n = 2$ $I_s = 1 \times 10^{-3} \times e^{-700/50} = 8.3 \times 10^{-10}$ A

The diode conducting 1A at 0.7V corresponds to 1000 1mA in parallel with a total junction area 1000 times greater. Thus it is also 1000 times greater being 1pA and 1µA, respectively for $n = 1$ and $n = 2$. 
3.2.2 The Reverse-Bias Region

If $\nu$ is negative and a few times large then $V_T$ (25mV) in magnitude the diode current becomes

$$i \approx -I_s \quad \text{(Saturation current)}$$

$I_s$: It doubles for every $10^\circ$C rise in temperature

$$I_{s_2} = I_{s_1} \cdot 2^{(T_2-T_1/10)}$$

3.2.3 The Breakdown Region

$$\nu < -V_{ZK} \begin{cases} 
Z: \text{Zener} \\
K: \text{Knee} 
\end{cases}$$

In the breakdown region the reverse current increase rapidly with the associated increase in voltage drop very small.
3.3 Modeling the diode forward characteristic

3.3.1 The Exponential Model.

Assuming that

\[
\begin{aligned}
V_{DD} &> 0.5V \\
I_D &> I_s
\end{aligned}
\]

\[\Rightarrow I_D = I_s e^{V_D/nV_T} \quad (3.6)\]

The other equation that governs circuit operation is obtained by writing a
loop equation by KVL, resulting in

\[I_D = \frac{V_{DD} - V_D}{R} \quad (3.7)\]
3.3.2 Graphical Analysis Using the Exponential Model.

Figure 3.11 Graphical analysis of the circuit in Fig. 3.10 using the exponential diode model.
3.3.3 Iterative analysis using the exponential model

**Example 3.4** determine the current $I_D$ and the diode voltage $V_D$ for the circuit in Fig.3.10 with $V_{DD} = 5V$ and $R = 1k\Omega$, assume that the diode has a current of 1mA at voltage of 0.7V and that its voltage drop changes by 0.1V for every decade change in current.

**Sol:** We assume that $V_D = 0.7V$, $I_D = 1mA$

$$I_D = \frac{V_{DD} - V_D}{R} = \frac{(5 - 0.7)V}{1k\Omega} = 4.3mA$$

$$V_2 - V_1 = 2.3 \cdot n \cdot V_T \cdot \log \frac{I_2}{I_1}$$

$$V_2 = V_1 + 0.1 \cdot \log \frac{I_2}{I_1} (n = 2, 2.3 \cdot n \cdot V_T \approx 0.1V)$$

$$V_2 = 0.7 + 0.1 \cdot \log \frac{4.3mA}{1mA} = 0.763V$$

The first iteration are $I_D = 4.3mA$, $V_D = 0.763V$
We assume that $V_D = 0.763\,\text{V}$, $I_D = 4.3\,\text{mA}$

\[
I_D = \frac{V_{DD} - V_D}{R} = \frac{(5 - 0.763)\,\text{V}}{1\,\text{k}\Omega} = 4.237\,\text{mA}
\]

\[
V_2 = 0.763 + 0.1 \cdot \log \frac{4.237\,\text{mA}}{4.3\,\text{mA}} = 0.762\,\text{V}
\]

The second iteration are $I_D = 4.237\,\text{mA}$, $V_D = 0.762\,\text{V}$

We assume that $V_D = 0.762\,\text{V}$, $I_D = 4.237\,\text{mA}$

\[
I_D = \frac{V_{DD} - V_D}{R} = \frac{(5 - 0.762)\,\text{V}}{1\,\text{k}\Omega} = 4.238\,\text{mA}
\]

\[
V_2 = 0.762 + 0.1 \cdot \log \frac{4.238\,\text{mA}}{4.237\,\text{mA}} = 0.762\,\text{V}
\]

Because $I_D$ did not change by much stop here and the solution is $I_D = 4.237\,\text{mA}$ and $V_D = 0.762\,\text{V}$
3.3.5 The Constant-Voltage-Drop Model. (Rapid analysis)

\[ i_D (\text{mA}) \]

\[ V_D = 0.7V \]
\[ \begin{align*}
  i_D &= 0, & v_D \leq 0.7V \\
  i_D &= (v_D - 0.7V)/R, & v_D \geq 0.7V
\end{align*} \]
The constant-voltage-drop model of the diode forward characteristics and its equivalent-circuit representation.

\[ V_D = 0.7 \text{V} \]
Example: Repeat the problem in example 3.4, utilizing the constant-voltage-drop model whose parameters are given in Fig 3.12. Find $I_D$ and $V_D$.

Sol:

\[ I_D = \frac{V_{DD} - V_D}{R} = \frac{(5 - 0.7)V}{1k\Omega} = 4.3\text{mA} \]

\[ V_D = V_D = 0.7\text{V} \]
3.3.7 The Diode Small-Signal Model.

\[ i_D = I_S e^{v_D/nV_T} \quad (3.8) \]

\[ v_D(t) = V_D + v_d(t) \quad (3.9) \]
\[ i_D(t) = I_s e^{v_D(t)/nV_T} = I_s e^{[V_D+v_d(t)]/nV_T} \]
\[ = I_s e^{V_D/nV_T} \cdot e^{v_d(t)/nV_T} \]
\[ = I_D \cdot e^{v_d(t)/nV_T} \quad (3.12) \]

If the signal \( v_d(t) \) is kept sufficiently small such that \( \frac{v_d(t)}{nV_T} \ll 1 \)

Thus, the approximate expression

\[ i_D(t) = I_D \cdot \left(1 + \frac{v_d}{nV_T}\right) \quad (3.14) \]

Small-signal approximation
We have
\[ i_D(t) = I_D + \frac{I_D}{nV_T} v_d \]  \hspace{1cm} (3.15)

where
\[ i_d = \frac{I_D}{nV_T} v_d \]  \hspace{1cm} (3.17)

\[ r_d \equiv \frac{v_d}{i_d} = \frac{nV_T}{I_D} \]  \hspace{1cm} (3.18) \hspace{0.5cm} \text{The } r_d \text{ is diode small-signal resistance, and called incremental resistance.}

In Fig.3-13(b), which is equal to the slope of the tangent to the \(i\)-\(v\) curve at the operating point Q is equal to the small-signal conductance.

that is, \[ r_d = \frac{1}{\left[ \frac{\partial i_d}{\partial v_d} \right]_{i_d=I_D}} \]  \hspace{1cm} (3.19)
**Example 3.6:** Consider the circuit shown in Fig 3.15 a string of three diode is used to provide a constant voltage of about 2.1V, we want to calculate the percentage change in this regulated voltage cause by:

(a) 10% change in the power-supply voltage
(b) Connection of a 1kΩ load resistance. Assume \( n=1 \)

![Circuit Diagram]

**Sol:**

with no load

\[
I = \frac{(10 - 2.1)V}{1k\Omega} = 7.9mA
\]

\[
r_d = \frac{nV_T}{I} = \frac{25mV}{7.9mA} = 3.2\Omega
\]

The total incremental resistance

\[
r = 3r_d = 9.6\Omega
\]
(a) \[ \Delta V_o = \pm 1 \frac{r}{r + R} = \pm 1 \frac{0.0096}{0.0096 + 1} = \pm 9.5\text{mV} \]

This implies a change of about \( \pm 3.2\text{mV} \) per diode.

(b) When a load resistance of 1k\(\Omega\) is connected across the diode string, it draws a current of 2.1mA.

\[ \therefore \Delta V_o = -2.1 \times r = -2.1 \times 9.6 = -20\text{mV} \]

this implies that the voltage across each diode decreases by about 6.7mV.
3.4 Operation in the reverse breakdown region - Zener diode

(1) $r_Z$ is the inverse of the slope of the almost-linear $i - v$ curve at point Q

(2) $r_Z$: increase resistance

(3) Typically, $r_Z$ is in the range of a few ohms to a few ten ohms
\[ V_z = V_{zo} + I_z r_z \]  (3.20)
3.4.2 Use of the Zener as a Shunt Regulator

**Example 3.7:** The 6.8V Zener diode in the circuit of Fig.3.19(a) is specified to have $V_Z = 6.8V$ at $I_Z = 5mA$, $r_z = 20\Omega$ and $I_{ZK} = 0.2mA$, the $V^+$ is $10V \pm 1V$. 
(a) Find $V_o$ with no load and with $V^+$ at its nominal value.

Sol: first we must determine the value of $V_{zo}$

$$V_{zo} = V_z - I_z r_z = 6.8 - 5 \cdot 10^{-3} \times 20 = 6.7 \text{V}$$

$$I_z = I = \frac{10-6.7}{0.5+0.02} = 6.35 \text{mA}$$

Thus $V_o = V_z = V_{zo} + I_z r_z = 6.83 \text{V}$

(b) Find change in $V_o$ resulting from the ±1V change in $V^+$.

Sol: $\Delta V_o = \Delta V^+ \frac{r_z}{R + r_z} = \pm 1 \times \frac{20}{500 + 20} = \pm 38.5 \text{mV}$

line regulation $\equiv \Delta V_o / \Delta V_i = \pm 38.5 \text{mV/1V} = \pm 38.5 \text{mV/V}$
(c) Find change in $V_o$ resulting from connecting a load resistance $R_L$ that draws a current $I_L = 1\text{mA}$, and hence find the load regulation $(\Delta V_o / \Delta I_L)$ in mV/mA.

Sol:
\[ \Delta V_o = \Delta I_z \cdot r_z = 20\Omega \times -1\text{mA} = -20\text{mV} \]
load regulation $\equiv \Delta V_o / \Delta I_L = -20\text{mV/mA}$

(d) Find change in $V_o$ when $R_L = 2k\Omega$.

Sol: $R_L = 2k\Omega, I_{RL} \approx \Delta I_z \approx -6.8\text{V}/2k\Omega = -3.4\text{mA}$
\[ \Delta V_o = \Delta I_z \cdot r_z = -20 \times 3.4 = -68\text{mV} \]
(e) Find the value of \( V_o \) when \( R_L = 0.5k \Omega \).

Sol:

\( R_L = 0.5k \Omega \), would draw a \( I_L = 6.8 / 0.5 = 13.6 \text{mA} \). This is impassible. because I supplied through \( R \) is only 6.4 mA, therefore, the zener must be cut-off. Hence \( V_o = V^+ \frac{R_L}{R + R_L} = 5 \text{V} \)

(f) What is the minmum value of \( R_L \) for which the diode still operates region in the breakdown.

Sol:

\( I_z = I_{zk} = 0.2 \text{mA} \Rightarrow V_z = V_{zk} \approx V_{zo} = 6.7 \text{V} \)

\( I(\text{min}) = \frac{9 - 6.7}{0.5} = 4.6 \text{mA} \)

\( I(\text{max}) = (4.6 - 0.2) \text{mA} = 4.4 \text{mA}, \quad : \quad R_L = \frac{6.7}{4.4} = 1.5 \text{k} \Omega \)
3.4.3 Temperature effects, T.C or Temco

(1) $V_Z < 5V, \frac{dV_z}{dT} < 0$. Negative T.C

(2) $V_Z > 5V, \frac{dV_z}{dT} > 0$. Positive T.C

(3) $V_Z = 5V, \frac{dV_z}{dT} = 0$. Zero T.C
3.5 Rectifier Circuits

Figure 3.20  Block diagram of a dc power supply.

(1) The Half-wave rectifier.
(2) The full-wave rectifier
   (a) The center tap  rectifier
   (b) The bridge rectifier
3.5.1 Half-Wave Rectifier.

(a) Half-wave rectifier.  
(b) Equivalent circuit of the half-wave rectifier with the diode replaced with its battery-plus-resistance model.
(c) Transfer characteristic of the rectifier circuit.

\[
\begin{aligned}
\nu_O &= 0, \quad \nu_S < V_{DO} \\
\nu_O &= \frac{R}{R + r_D} (\nu_S - V_{DO}), \quad \nu_S \geq V_{DO}
\end{aligned}
\]

(d) Input and output waveforms, assuming that \(r_D \ll R\).
We assume \( v_S = V_m \sin \alpha \) thus

\[
V_{DC} = \frac{1}{2\pi} \int_0^\pi v_S d\alpha
\]

\[
= \frac{1}{2\pi} \int_0^\pi V_m \sin \alpha d\alpha
\]

\[
= \frac{V_m}{2\pi} \left(-\cos \alpha \right)_0^\pi
\]

\[
= \frac{V_m}{\pi} = 0.318V_m
\]

\[
V_{rms} = \left[ \frac{1}{2\pi} \int_0^\pi v_S^2 d\alpha \right]^{1/2}
\]

\[
V_{rms}^2 = \frac{1}{2\pi} \int_0^\pi V_m^2 \sin^2 \alpha d\alpha
\]

\[
= \frac{V_m^2}{2\pi} \left( \frac{1}{2} - \frac{1}{2} \cos 2\alpha \right)_0^\pi
\]

\[
= \frac{V_m^2}{2\pi} \left( \frac{1}{2} \alpha - \frac{1}{4} \sin 2\alpha \right)_0^\pi
\]

\[
= \frac{V_m^2}{4} \Rightarrow V_{rms} = 0.5V_m
\]

PIV = \( V_m \) (PIV : Peak inverse voltage)

\[
\varphi_i = \sin^{-1} \frac{V_{DO}}{V_m}
\]
3.5.2 The full-wave rectifier

(a) circuit

(b) transfer characteristic assuming a constant-voltage-drop model for the diodes
(c) input and output waveforms.
We assume $v_S = V_m \sin \alpha$ thus

$$V_{DC} = 2 \times \left\{ \frac{1}{2\pi} \int_0^\pi v_S d\alpha \right\}$$

$$= \frac{2}{\pi} \times \int_0^\pi V_m \sin \alpha d\alpha$$

$$= \left. \frac{V_m}{\pi} \right| (-\cos \alpha\big|_0^\pi)$$

$$= \frac{2 \times V_m}{\pi} = 0.636V_m$$

$$V_{rms} = \left[ \frac{2 \times 1}{2\pi} \int_0^\pi v_S^2 d\alpha \right]^{1/2}$$

$$V_{rms}^2 = \frac{2 \times 1}{2\pi} \int_0^\pi V_m^2 \sin^2 \alpha d\alpha$$

$$= \frac{2}{\pi} \times V_m^2 \int_0^\pi \left( \frac{1}{2} - \frac{1}{2} \cos 2\alpha \right) d\alpha$$

$$= \left. \frac{V_m^2}{\pi} \left( \frac{1}{2} \alpha - \frac{1}{4} \sin 2\alpha \right) \right|_0^\pi$$

$$= \frac{V_m^2}{2} \Rightarrow V_{rms} = 0.707V_m$$

$$PIV = 2V_m \text{(PIV : Peak inverse voltage)}$$

$$\varphi_i = \sin^{-1} \frac{V_D}{V_m}$$
3.5.3 The Bridge Rectifier

![Diagram of the bridge rectifier circuit and waveforms](image)

**Figure 3.27** The bridge rectifier: (a) circuit; (b) input and output waveforms.
3.5.4 The Rectifier with a Filter Capacitor-The Peak Detector

A simple circuit used to illustrate the effect of a filter capacitor
We assume that $RC \gg T$ in Fig. 3.29(b)

The load current $i_L = v_o / R$

The diode current $i_D = i_C + i_L = C \frac{dv_L}{dt} + i_L$

(1) Derivative the $V_{r(rms)}$

During the diode cutoff interval $v_o = V_p - V_r$

$V_p - V_r = V_pe^{-T/RC}$

$V_r = V_p \frac{T}{RC} = \frac{V_p}{fRC} \Rightarrow V_{r(rms)} = \frac{V_p}{2\sqrt{3}fRC}$

(2) Derivative the conduction interval $\Delta t$

$V_p \cos(\omega \Delta t) = V_p - V_r$

The angle $\omega \Delta t$ is very small, $\Rightarrow \cos(\omega \Delta t) \approx 1 - \frac{1}{2} (\omega \Delta t)^2$

$V_p \left[1 - \frac{1}{2} (\omega \Delta t)^2\right] = V_p - V_r \Rightarrow \omega \Delta t = \sqrt{2V_r / V_p}$ (3.30)

We note that when $V_r \ll V_p$ the conduction angle $\omega \Delta t$ will be small
(3) Determine the average diode current during conduction, \( i_{D_{av}} \)
the charge that the diode supplies to the capacitor
\[
Q_{\text{Supplied}} = i_{C_{(av)}} \cdot \Delta t \tag{a}
\]
the charge that the capacitor loses
\[
Q_{\text{lost}} = C \cdot V_r \tag{b}
\]
The(a) equal to (b) \( \Rightarrow i_{C_{(av)}} = \frac{C \cdot V_r}{\Delta t} \)
Using(3.29a) \( V_r = \frac{V_P}{fRC} \) \( \Rightarrow C = \frac{V_P}{V_r fR} \),
and(3.30) \( \omega \Delta t = \sqrt{2V_r / V_P} \) \( \Rightarrow \Delta t = \frac{\sqrt{2V_r}}{\omega \sqrt{V_P}} \)
we obtain:
\[
i_{C_{(av)}} = \frac{C \cdot V_r}{\Delta t} = \frac{V_P}{\sqrt{2V_r}} \cdot \frac{1}{\sqrt{2V_r} / V_P} = \frac{2\pi \sqrt{V_P}}{2\pi \sqrt{V_P}} \cdot \frac{V_P}{R} = I_L \cdot \pi \cdot \sqrt{2V_P / V_r}
\]
\[
i_{D_{(av)}} = i_{C_{(av)}} + I_L = I_L \left[ 1 + \pi \sqrt{2V_P / V_r} \right] \tag{3.31}
\]
(4) Determine the peak value of the diode current, \( i_{D_{(\text{max})}} \)

\[
i_{D_{(\text{max})}} = C \frac{dv_I}{dt} + i_L
\]

\((t = t_1 = -\Delta t) \Rightarrow C \frac{dv_I}{dt} = C \frac{d}{dt} (V_P \cos(-\omega \Delta t)) = \omega CV_P \sin(\omega \Delta t)\]

\[
= \omega \cdot C \cdot V_P \cdot (\omega \Delta t)
\]

\[\sin(\omega \Delta t)] = \omega \Delta t + \frac{(\omega \Delta t)^3}{3!} + \cdots\]

\[
= 2\pi f \cdot \frac{V_P}{fV_r R} \cdot V_P \cdot \sqrt{\frac{2V_r}{V_P}} = I_L \cdot 2\pi \cdot \sqrt{\frac{2V_P}{V_r}}
\]

\[
i_{D_{(\text{max})}} = i_C + I_L = I_L \left[ 1 + 2\pi \sqrt{\frac{2V_P}{V_r}} \right]
\]

\[(3.32)\]
the full-wave rectifier circuit.

\[ f_r = 2f_i \]

\[ V_P - V_r = V_P e^{\frac{-T/2}{RC}} \]

\[ V_r = V_P \frac{T/2}{RC} = \frac{V_P}{2fRC} \]  \hspace{1cm} (3.33)

\[ V_{r(rms)} = \frac{V_P}{4\sqrt{3}fRC} \]
\[ V_{r(rms)} = \frac{2.4V_P}{RC} \quad (f = 60\text{Hz}, \ R_L = k\Omega, \ C = \mu\text{F}) \]

when the ripple small then 6.5% \( \Rightarrow V_P = V_{DC} \)

\[ V_{r(rms)} = \frac{2.4V_{DC}}{RC} = \frac{2.4I_{DC}}{C} \]

\[ r\% = \frac{V_{r(rms)}}{V_{DC}} = \frac{2.4}{RC} \% \]

If \( r\% > 6.5\% \)

\[ V_{DC} = V_P - \frac{1}{2}V_r = V_P - \frac{V_P}{4fRC} = \left[1 - \frac{4.17}{RC}\right] \cdot V_P \]

\[ i_{D(\text{av})} = i_{C(\text{av})} + I_L = I_L \left[1 + \pi \sqrt{\frac{V_P}{2V_r}}\right] \quad (3.34) \]

\[ i_{D(\text{max})} = i_C + I_L = I_L \left[1 + 2\pi \sqrt{\frac{V_P}{2V_r}}\right] \quad (3.35) \]
Figure 3.27 The “superdiode” precision half-wave rectifier and its almost-ideal transfer characteristic. Note that when $v_I > 0$ and the diode conducts, the op amp supplies the load current, and the source is conveniently buffered, an added advantage. Not shown are the op-amp power supplies.
3.6 limiting and clamping circuits

3.6.1 limiter circuit.

\[
\frac{L_-}{K} \leq v_I \leq \frac{L_+}{K}
\]

\[v_O = Kv_I\]

In general, \(K > 1\)

In this section, let \(K \leq 1\)

(a) If \(v_I > \frac{L_+}{K}\) (the upper threshold),

the \(v_O\) is limited or clamping to the upper limiting level \(L_+\)

(b) If \(v_I < \frac{L_-}{K}\) (the lower limited threshold),

the \(v_O\) is limited to the lower limiting level \(L_-\).
Hard limiting.

Soft limiting.
Example 3.26 Assuming the diode to be ideal, describe the transfer characteristic of the circuit shown in Figure E3.26.

![Diode Circuit Diagram](image)

**Figure E3.26**

**Sol:**

1. \( v_I \leq -5 \text{V} \),
   
   \( D_1 : \text{conducts, } D_2 : \text{cut-off} \)
   
   \[ v_O = v_I \frac{10}{10+10} - 5 \frac{10}{10+10} = 0.5v_I - 2.5 \]

2. \(-5 \leq v_I \leq 5 \text{V}, \)
   
   both diode are cut-off and
   
   \[ v_O = v_I \]

3. \( v_I \geq 5 \text{V}, \)
   
   \( D_1 : \text{cut-off, } D_2 : \text{conducts} \)
   
   \[ v_O = v_I \frac{10}{10+10} + 5 \frac{10}{10+10} = 0.5v_I + 2.5 \]
\[ v_O = 0.5v_I + 2.5 \]

\[ v_O = 0.5v_I - 2.5 \]
Example: Assuming the diode to be ideal, describe the transfer characteristic of the circuit shown in Fig. a. $0 < v_i \leq 150V$

![Circuit Diagram]

(1) For $0 < V_i \leq 25V$, both diodes are cut-off

$v_O = 25V$

(2) For $25V < V_i < 137.5V$,

$D_1$ conducts and $D_2$ cut-off

$v_O = V_A = \frac{2}{3}v_i + \frac{25}{3}(V)$

(3) For $137.5V < V_i < 150V$,

both diodes are conducts

$v_O = 100V$

Sol:

For $V_A \geq 100V$, both diodes are conducts

$v_i \cdot \frac{2}{3} + \frac{25}{3} = 100 \Rightarrow v_i = 137.5V$
The graph shows the relationship between $v_o$ and $v_i$ with the equation:

$$v_o = \frac{2}{3} v_i + \frac{25}{3}$$

The graph indicates that for $v_i = 25V$, $v_o = 25V$, and for $v_i = 137.5V$, $v_o = 100V$. The gradient of the line is determined by the coefficient of $v_i$, which is $\frac{2}{3}$. The constant term is $\frac{25}{3}$. The diagram visually represents the linear relationship between the input and output voltages.
3.6.2 The Clamped Capacitor or DC Restorer

Figure 3.32 The clamped capacitor or dc restorer with a square-wave input and no load.
Figure 3.33  The clamped capacitor with a load resistance $R$. 
3.6.3 Voltage Doubler

Figure 3.34 Voltage doubler: (a) circuit; (b) waveform of the voltage across $D_1$. 
Thanks For Your Attention!

Q&A