CHAPTER 3 DIODES

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3.1 Ideal Diode

Ideal diode characteristics
- An diode is a two-terminal device:
  - **Anode**: the positive terminal
  - **Cathode**: the negative terminal
- Forward biased → turned on → short
- Reverse biased → turned off → open

Circuit applications

\[
Y = A + B + C \\
Y = A \cdot B \cdot C
\]
3.2 Terminal Characteristics of Junction Diodes

I-V characteristics of junction diodes

- Diode current: \( i = I_s (e^{v/nV_T} - 1) \)
  - \( I_s \) (saturation current): proportional to diode area
  - \( n \) (ideality factor): between 1 and 2
  - \( V_T \) (thermal voltage) \( \approx 25 \text{ mV} \) at room temperature

- The forward-bias region, determined by \( v > 0 \)
- The reverse-bias region, determined by \( v < 0 \)
- The breakdown region, determined by \( v < -V_{ZK} \)

Forward-bias region

- The simplified forward-bias I-V relationship:
  - For a given forward voltage: \( i \approx I_s e^{v/nV_T} \)
  - For a given forward current: \( v \approx nV_T \ln(I/I_s) \)

- Due to the exponential I-V relationship
  - \( i \approx 0 \) for \( v < 0.5\text{V} \) (cut-in voltage)
  - Fully conduction for \( 0.6\text{V} < v < 0.8\text{V} \) \( \rightarrow V_{on} = 0.7\text{V} \)

Temperature dependence

- \( I_s \) doubles for every \( 5^{\circ}\text{C} \) rise in temperature
- Voltage decreases \( 2\text{mV/}^{\circ}\text{C} \) for a given current
- Current increases with temperature for a given voltage
Reverse-bias region

- Reverse current: \( i \approx -I_s \)
- Ideally, the reverse current is independent of reverse bias
- In reality, reverse current is larger than \( I_s \) and also increases somewhat with the reverse bias
- Temperature dependence: reverse current doubles for every 10°C rise in temperature

Breakdown region

- The knee of the I-V curve is specified as breakdown voltage \( V_{ZK} \) for Zener breakdown mechanism
- In breakdown region, the reverse current increases rapidly with a small increase in the reverse bias
- Normally, the reverse current is specified by external circuitry to assure the power dissipation within a safe range (non-destructive operation)
3.3 Modeling the Diode Forward Characteristics

Circuit analysis

- Determine the diode current $I_D$ and voltage $V_D$ for circuit analysis
- The equation required for the analysis:
  - $I_D = I_S \exp(V_D/nV_T) \to$ diode I-V characteristics
  - $I_D = (V_{DD} - V_D)/R \to$ Kirchhoff loop equation
- Need to solve non-linear equations

Graphical analysis

- Plot the two equations in the same I-V coordination
- The straight line is known as load line
- The intersect is the solution for $I_D$ and $V_D$

Iterative analysis

- Set initial value $V_D = V_o$
- Use $I_D = (V_{DD} - V_D)/R$ to obtain $I_I$
- Use $V_D = nV_T \ln (I_D/I_S)$ to obtain $V_2$
- Repeat until it converges ($I_3, V_4, I_5, V_6...$)
- Iterations are needed to solve the nonlinear circuit
The need for rapid analysis

- Rapid analysis using simplified models for initial design
- Accurate analysis (iterative analysis or computer program) for final design
- Rapid analysis (I): ideal-diode model
  - The most simplified model used when supply voltage is much higher than the diode voltage
  - Diode on: $v_D = 0$ V and $i > 0$
  - Diode off: $i = 0$ and $v_D < 0$ V
  - Equivalent circuit model as an ideal diode
- Rapid analysis (II): constant-voltage-drop model
  - The most widely used model in initial design and analysis phases
  - Diode on: $v_D = 0.7$ V and $i > 0$
  - Diode off: $i = 0$ and $v_D < 0.7$ V
  - Equivalent circuit model as an ideal diode with a 0.7-V voltage source

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Small-signal approximation

- The diode is operated at a dc bias point and a small ac signal is superimposed on the dc quantities:
  \[ v_D(t) = V_D + v_d(t) \]
  \[ i_D(t) = I_S e^{v_D/nV_T} = I_S e^{(V_D + v_d)/nV_T} = I_S e^{v_D/nV_T} e^{v_d/nV_T} = I_D e^{v_d/nV_T} \]

- Under small-signal condition: \( v_d / nV_T \ll 1 \)
  \[ i_D(t) \approx I_D \left(1 + \frac{v_d}{nV_T}\right) = I_D + \frac{I_D}{nV_T} v_d = I_D + i_d \]
  - \( I_D \) associates with \( V_D \to \) dc operating point \( Q \)
  - \( i_d \) associates with \( v_d \to \) small signal response

- The diode exhibits linear I-V characteristics under small-signal conditions (\( v_d \leq 10mV \))

- Diode small-signal resistance and conductance at operating point
  \[ i_d = \frac{I_D}{nV_T} v_d = g_d v_d = \frac{v_d}{r_d} \]
  \[ g_d = \frac{I_D}{nV_T} = \left[\frac{\partial i_D}{\partial V_D}\right]_{i_0 = I_D} \]
  \[ r_d = \frac{nV_T}{I_D} = \frac{1}{\left[\frac{\partial i_D}{\partial V_D}\right]_{i_0 = I_D}} \]

The diode small-signal model

- Choose proper dc analysis technique or model to obtain the operation point \( Q \)
- The small-signal model is determined once \( Q \) is provided
- The small-signal model is used for circuit analysis when the diode is operating around \( Q \)
**Circuit analysis techniques for total quantities (AC+DC)**

- Eliminate all the time varying signals (ac voltage and current sources) for operation point analysis
- Use rapid analysis or accurate analysis to obtain dc voltage and current at operating point $Q$
- Determine the parameters of small-signal models from $Q$
- Replace the devices with small-signal models and eliminate all the dc sources
- Circuit analysis under small-signal approximation
- The complete response of the circuit is obtained by superposition of the dc and ac components

**Voltage regulator by diode forward drop**

- A regulator is to provide a constant dc voltage regardless changes in load and power-supply voltage
- The forward-voltage drop remains almost constant at 0.7 V within a wide current range
- Multiple diodes in series to achieve the required voltage drop
- Better regulation can be provided for higher bias current and smaller $r_d$

![Voltage regulator diagram](image-url)
3.4 Operation in the Reverse Breakdown Region – Zener Diodes

Symbol and circuit model for the Zener diode

- In breakdown region, a reverse bias \((V_Z)\) beyond the knee voltage \((V_{ZK})\) leads to a large reverse current \((I_Z)\).
- The diode in breakdown region is given by \(V_Z = V_{Z0} + r_z I_Z\)
  - The breakdown diode is modeled by a voltage source \(V_{Z0}\) in series with an incremental resistance \(r_z\)
  - Incremental voltage versus current: \(\Delta V = r_z \Delta I\)
  - The simplified model is only valid for \(I_Z > I_{ZK}\) (knee current)
  - Equivalent \(r_z\) increases as \(I_Z\) decreases

- Diode types:
  - Diode: only forward and reverse regions are considered
  - Zener diode: forward, reverse and breakdown regions

\[\text{Diagram showing diode symbols and circuit model.}\]
Design of the Zener shunt regulator

Output voltage of the regulator:

\[ V_o = \frac{R}{R + r_z} V_{z_0} + \frac{r_z}{R + r_z} V^+ - \frac{R r_z}{R + r_z} I_L \]

- **Line regulation:**
  \[ \frac{\Delta V_o}{\Delta V^+} = - \frac{r_z}{R + r_z} \]

- **Load regulation:**
  \[ \frac{\Delta V_o}{\Delta I_L} = - \frac{R r_z}{R + r_z} \]

- Line and load regulation should be minimized
- For \( r_z \ll R \), line regulation can be minimized by choosing small \( r_z \)
- Load regulation can be minimized by choosing small \( r_z \) and large \( R \)
- There is an upper limit on the value of \( R \) to ensure sufficiently high current \( I_Z \) (\( r_z \) increases if \( I_Z \) is too low)
- \( R \) should be selected from
  \[ R = \frac{V_{S_{\text{min}}} - V_{z_0} - r_z I_{Z_{\text{min}}}}{I_{Z_{\text{min}}} + I_{L_{\text{max}}}} \]

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3.5 Rectifier Circuits

Block diagram of a dc power supply

- DC power supply
  - Generate a dc voltage from ac power sources
  - The ac input is a low-frequency **large-signal** voltage

- Power transformer
  - Step the line voltage down to required value and provides electric isolation

- Diode rectifier
  - Converts the input sinusoidal to a **unipolar output**
  - Can be divided to **half-wave** and **full-wave rectifiers**

- Filter
  - Reduces the magnitude variation for the rectifier output
  - Equivalent to time-average operation of the input waveform

- Voltage Regulator
  - Further stabilizes the output to obtain a constant dc voltage
  - Can be implemented by Zener diode circuits
The half-wave rectifier

- Voltage transfer curve:
  \[ v_s < V_{D0} \rightarrow v_o = 0 \]
  \[ v_s \geq V_{D0} \rightarrow v_o = v_s - V_{D0} \]

- Rectifier diode specifications:
  - Current-handling capability: the largest current the diode is expected to conduct
  - **Peak inverse voltage** (PIV): the largest reverse voltage the diode can stand without breakdown
  - PIV = \( V_s \) (input voltage swing) and the diode breakdown voltage is selected at least 50% higher

\[ V_s < V_{D0} \rightarrow v_o = 0 \]
\[ V_s \geq V_{D0} \rightarrow v_o = V_s - V_{D0} \]
The full-wave rectifier (center-tapped transformer)

- Voltage transfer curve:
  \[ |v_S| < V_{D0} \Rightarrow v_O = 0 \]
  \[ v_S \geq V_{D0} \Rightarrow v_O = v_S - V_{D0} \]
  \[ v_S \leq -V_{D0} \Rightarrow v_O = -v_S - V_{D0} \]

- Transformer secondary winding is center-tapped
- Peak inverse voltage (PIV) = \(2V_S - V_{D0}\)
- Rectified output waveform for both positive and negative cycles
Full-wave rectifier (Bridge rectifier)

- Voltage transfer curve:
  \[|v_s| < 2V_{D_0} \rightarrow v_o = 0\]
  \[v_s \geq 2V_{D_0} \rightarrow v_o = v_s - 2V_{D_0}\]
  \[v_s \leq -2V_{D_0} \rightarrow v_o = -v_s - 2V_{D_0}\]

- Does not require a center-tapped transformer
- Higher turn-on voltage \(2V_{D_0}\)
- Peak inverse voltage (PIV) = \(V_s - V_{D_0}\)
- Most popular rectifier circuit configuration

\[v_o \rightarrow v_s\]

\[\text{Slope } \approx -1 \rightarrow \text{Slope } \approx 1\]

\[V_s, -v_s, v_o, 2V_D\]

\[R\]
Rectifier with a filter capacitor – the peak rectifier

- Output unloaded case:

- Output loaded case:

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**Precision half-wave rectifier – the superdiode**

- Superdiode is composed of an op amp and a diode.
- Superdiode works as an ideal diode with zero turn-on voltage.
  - Positive input voltage:
    - Diode turns on
    - Closed-loop op amp with virtual short at input
    - Output voltage follows input voltage
  - Negative input voltage:
    - Diode turns off
    - Op amp in open loop
    - Output voltage is 0 V
- Rectifier with superdiode can demonstrate better efficiency.
3.6 Limiting and Clamping Circuits

Limiter circuits

- For input in a certain range, the limiter acts as a linear circuit.
- For input exceeds the threshold, the output voltage swing is limited.
- Classification:
  - Based on transfer characteristics: hard limiter and soft limiter
  - Based on the polarity: single limiter and double limiter
- A variety of limiting circuits by diodes:

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Clamped capacitor or DC restorer

- Output unloaded case:

- Output loaded case: