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

\[
Y = A + B + C \quad Y = A \cdot B \cdot C
\]
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) \( \approx 25 \) 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 \( v < 0.5V \) (cut-in voltage)
  - Fully conduction for \( 0.6V < v < 0.8V \) \( \Rightarrow V_{on} = 0.7V \)

**Temperature dependence**

- \( I_s \) doubles for every 5°C rise in temperature
- Voltage decreases 2mV/°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 $10^\circ C$ 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:
  - $I_D = I_S \exp(V_D/nVT)$ → doide I-V characteristics
  - $I_D = (V_{DD} - V_D)/R$ → 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 $V_D = V_0$
- Use $I_D = (V_{DD} - V_D)/R$ to obtain $I_1$
- Use $V_D = nVT \ln(I_D/I_S)$ 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: $v_D = 0 \text{ V}$ and $i > 0$
  - Diode off: $i = 0$ and $v_D < 0 \text{ V}$
  - 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: $v_D = 0.7 \text{ V}$ and $i > 0$
  - Diode off: $i = 0$ and $v_D < 0.7 \text{ V}$
  - Equivalent circuit model as an ideal diode with a 0.7-V voltage source
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: \( v_d / nV_T \ll 1 \)
  \[ i_D(t) \approx I_D (1 + \frac{v_d}{nV_T}) = I_D + \frac{I_D}{nV_T} v_d = I_D + i_d \]
  - \( I_D \) associates with \( V_D \rightarrow \) dc operating point \( Q \)
  - \( i_d \) associates with \( v_d \rightarrow \) small signal response

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

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

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 \( r_d \)

Example 3.5 (Textbook)
Example 3.6 (Textbook)
Exercise 3.14 (Textbook)
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

\[ \Delta V = \Delta I r_z \]
Design of the Zener shunt regulator

- Output voltage of the regulator:
  \[ V_o = \frac{R}{R + r_z} V_{z0} + \frac{r_z}{R + r_z} V^+ - \frac{R r_z}{R + r_z} I_L \]

  ■ 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 
  \[ R = \frac{V_{Z_{\text{min}}} - V_{Z0} - r_z I_{Z_{\text{min}}}}{I_{L_{\text{max}}} + I_{Z_{\text{min}}}} \]

Example 3.7 (Textbook)
Exercise 3.16 (Textbook)
Exercise 3.17 (Textbook)
Exercise 3.18 (Textbook)
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

  ![Block diagram of a dc power supply](image)

- **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

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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
The full-wave rectifier (center-tapped transformer)

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

- 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:
  - $|v_s| < 2V_{D0} \rightarrow v_o = 0$
  - $v_s \geq 2V_{D0} \rightarrow v_o = v_s - 2V_{D0}$
  - $v_s \leq -2V_{D0} \rightarrow v_o = -v_s - 2V_{D0}$
- Does not require a center-tapped transformer
- Higher turn-on voltage ($2V_{D0}$)
- Peak inverse voltage (PIV) = $V_s - V_{D0}$
- Most popular rectifier circuit configuration

Exercise 3.19 (Textbook)
Exercise 3.20 (Textbook)
Exercise 3.21 (Textbook)
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 a 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 demonstrates 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: