BASIC ELECTRONICS

Module 2

P-N Junction Diode

By

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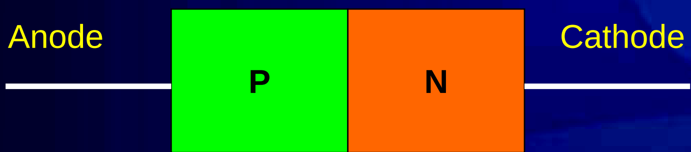
Syllabus

- P-N Junction characteristics
- Diode equation
- Diode as rectifier
- Half wave rectifier
- Full wave and Bridge rectifiers
- Capacitor filter
- Zener diode characteristics
- Zener as voltage regulator

P-N Junction Diode

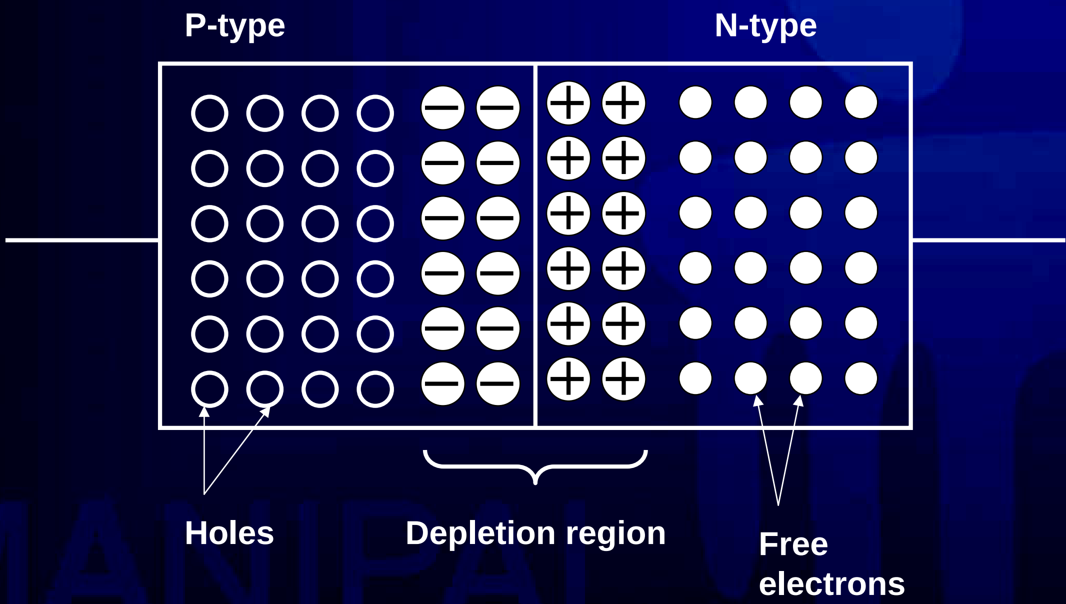
- P-N Junction diode is a 2-terminal, 2-layer, single-junction semiconductor device made out of a single block of silicon or germanium, with one side doped with acceptor (p-type) impurity and the other side with donor (n-type) impurity
- Very important device with numerous applications like
  - Switch, Rectifier, Regulator, Voltage multiplier, Clipping, Clamping, etc.

P-N Junction Diode



- The two terminals are called Anode and Cathode
- At the instant the two materials are “joined”, electrons and holes near the junction cross over and combine with each other
- Holes cross from P-side to N-side
- Free electrons cross from N-side to P-side
- At P-side of junction, negative ions are formed
- At N-side of junction, positive ions are formed

P-N Junction Diode

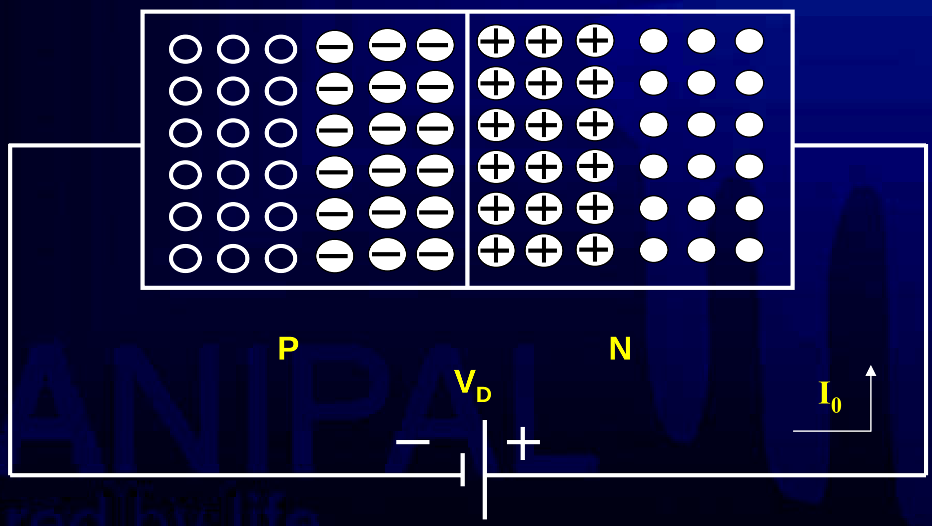


P-N Junction Diode

- Depletion region is the region having no free carriers
- Further movement of electrons and holes across the junction stops due to formation of depletion region
- Depletion region acts as barrier opposing further diffusion of charge carriers. So diffusion stops within no time
- Current through the diode under no-bias condition is zero
- Bias
  - Application of external voltage across the two terminals of the device

Reverse bias

- Positive of battery connected to n-type material (cathode)
- Negative of battery connected to p-type material (anode)

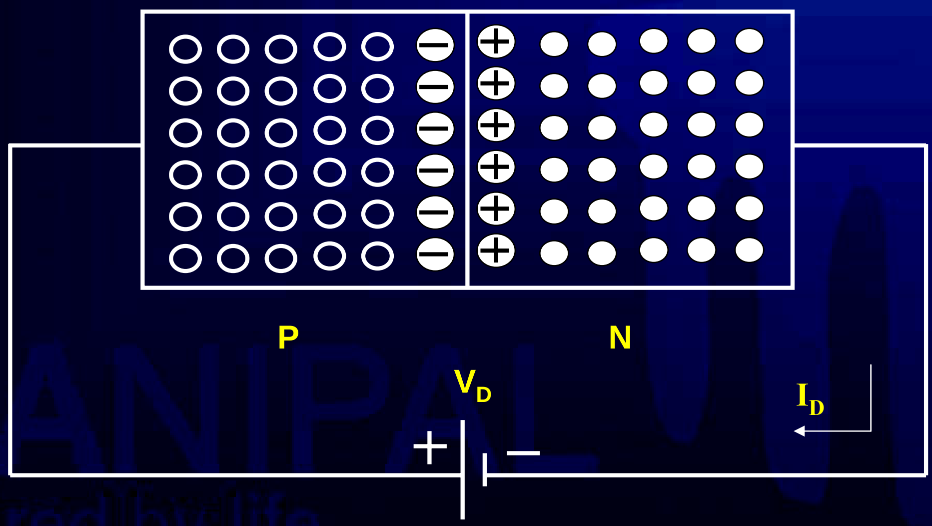


Reverse bias

- Free electrons in n-region are drawn towards positive of battery, Holes in p-region are drawn towards negative of battery
- Depletion region widens, barrier increases for the flow of majority carriers
- Majority charge carrier flow reduces to zero
- Minority charge carriers generated thermally can cross the junction – results in a current called "reverse saturation current" I_o
- I_o is in micro or nano amperes or less
- I_o does not increase "significantly" with increase in the reverse bias voltage

Forward bias

- Positive of battery connected to p-type (anode)
- Negative of battery connected to n-type (cathode)



Forward bias

- Electrons in n-type are forced to recombine with positive ions near the boundary, similarly holes in p-type are forced to recombine with negative ions
- Depletion region width reduces
- An electron in n-region “sees” a reduced barrier at the junction and strong attraction for positive potential
- As forward bias is increased, depletion region narrows down and finally disappears – leads to exponential rise in current
- Forward current is measured in milli amperes

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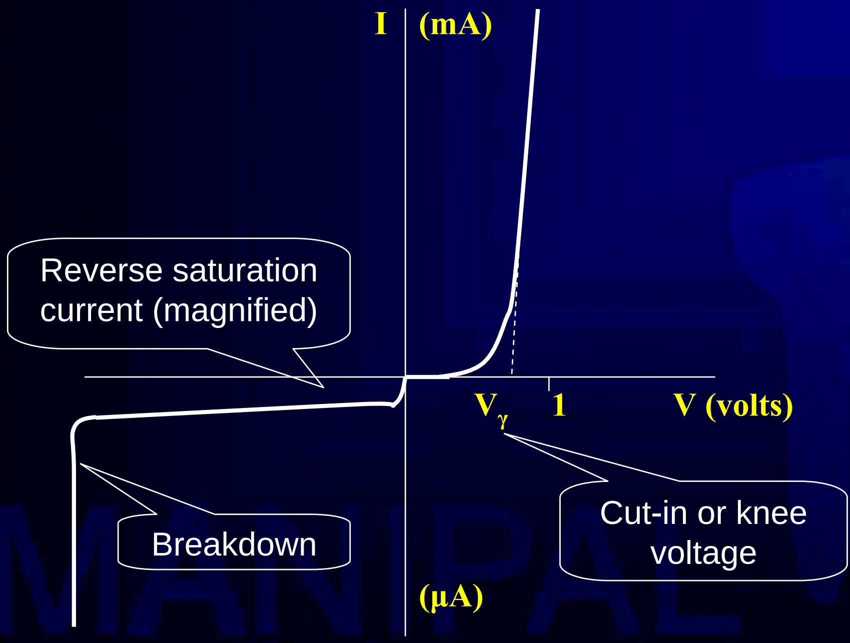
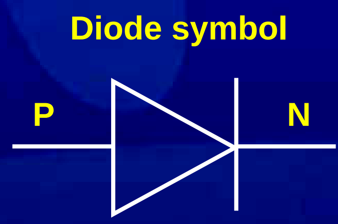
Diode characteristics

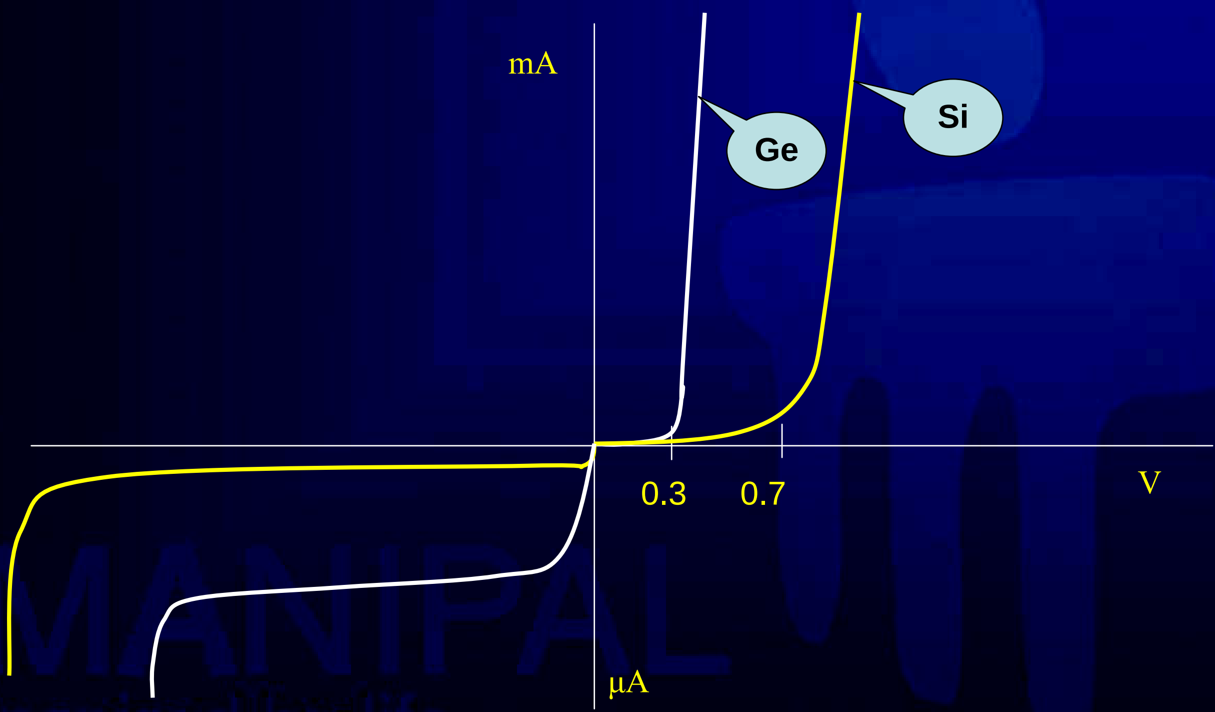




Vγ is 0.2 ~ 0.3 for Ge

0.6 ~ 0.7 for Si

Silicon vs. Germanium



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Diode current equation

$$I_D = I_o(e^{V_D/\eta V_T} - 1)$$
$$= I_o e^{V_D/\eta V_T} - I_o$$

- I_D is diode current
- I_o is reverse saturation current
- V_D is voltage across diode
- V_T is thermal voltage = T / 11600
- η is a constant = 1 for Ge and 2 for Si

Diode current equation

- For positive values of V_D (forward bias), the first term grows quickly and overpowers the second term. So,

$$I_D \approx I_o e^{V_D/\eta V_T}$$

- For large negative values of V_D (reverse bias), the first term drops much below the second term. So,

$$I_D \approx -I_o$$

Tutorials

1. A germanium diode has reverse saturation current of 0.19μA. Assuming η =1, find the current in the diode when it is forward biased with 0.3 V at 27°C. (Ans: 19.5mA)
2. The forward current in a Si diode is 15 mA at 27°C. If reverse saturation current is 0.24nA, what is the forward bias voltage? (Ans: 0.93V)
3. A silicon diode is reverse biased with 5V at room temperature. If reverse sat current is 60 pA, what is the diode current?
4. A germanium diode carries a current of 10mA when it is forward biased with 0.2V at 27°C. (a) Find reverse sat current. (b) Find the bias voltage required to get a current of 100mA. (Ans: 4.42μA, 0.259V)

Diode resistances

- Two types of resistances are defined for a diode :
- **Static or DC resistance:**
  - It is simply the ratio of diode voltage and diode current

$$R_D = \frac{V_D}{I_D}$$

  - The dc resistance at the knee and below will be greater than the resistance at the linear section of characteristics
  - The dc resistance in the reverse bias region will naturally be quite high

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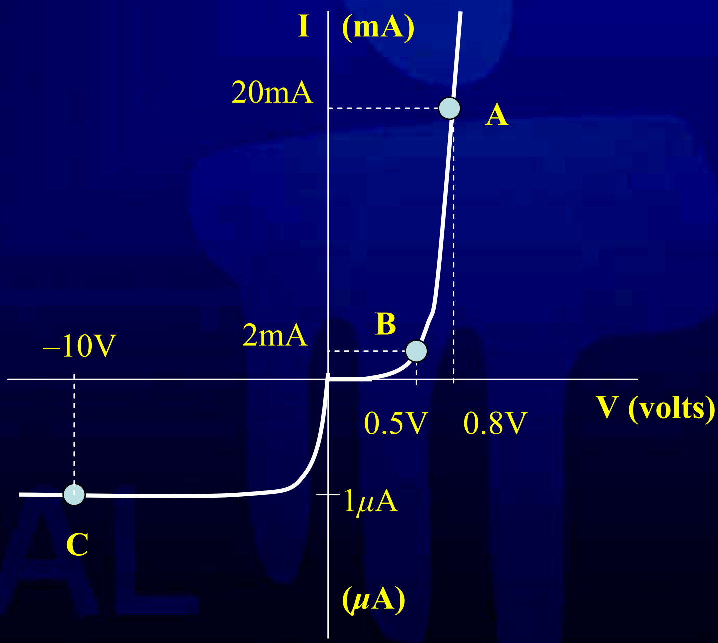
Diode resistances

- Determine the dc resistances at the three different operating points shown



Ans:

- A: 40 Ω
  B: 250 Ω
  C: 10 MΩ

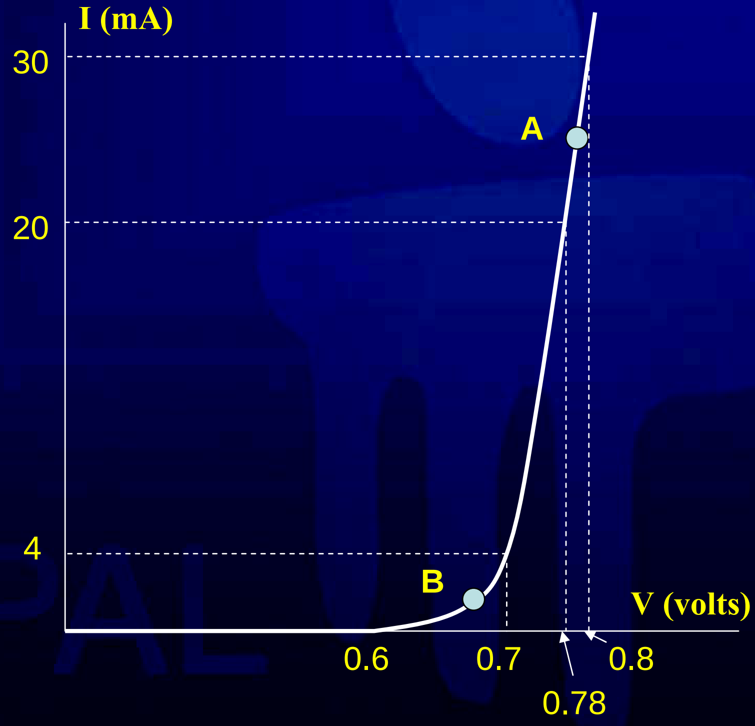
Diode resistances

- **Dynamic or AC resistance**
  - Often sinusoidal voltages are applied to diode
  - So the instantaneous operating point moves up and down in the characteristic curve
  - So DC resistance is not a suitable parameter
  - Instead, AC resistance is used
  - It is the change in the diode voltage divided by the corresponding change in the diode current, where the change is as small as possible

$$r_d = \frac{\Delta V_D}{\Delta I_D}$$

Diode resistances

- Determine the AC resistances at operating points A and B



- Ans:
  A: 2 Ω
  B: 25 Ω

Diode resistances

- AC resistance is nothing but reciprocal of the slope of the tangent line drawn at that point
- Derivative of a function at a point is equal to the slope of the tangent line at that point

$$\frac{d}{dV_D}(I_D) = \frac{d}{dV_D}\left[I_o e^{V_D/\eta V_T} - I_o\right]$$

$$\frac{dI_D}{dV_D} = \frac{I_D + I_o}{\eta V_T}$$

$$r_d = \frac{\Delta V_D}{\Delta I_D} = \frac{dV_D}{dI_D} = \frac{\eta V_T}{I_D + I_o} \approx \frac{\eta V_T}{I_D}$$

Diode resistances

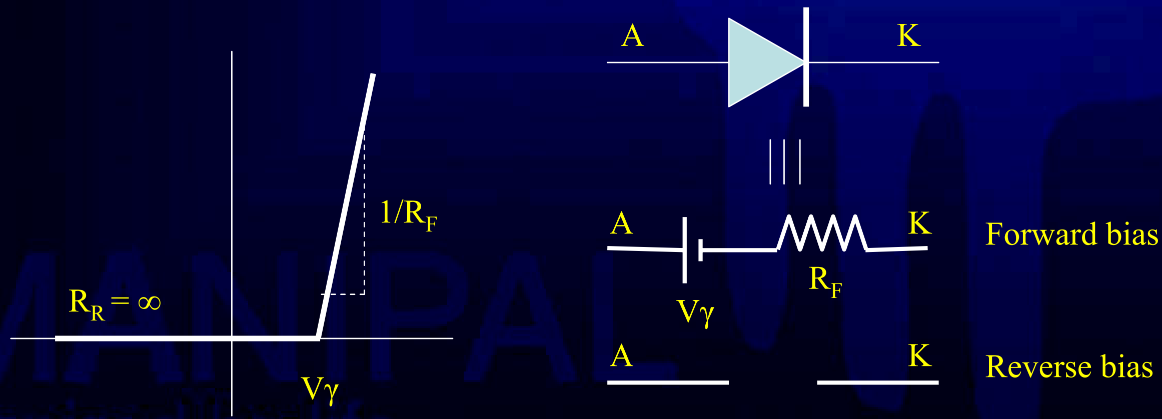
- Dynamic resistance can be found using previous equation, no need of characteristic curve
- Dynamic resistance in reverse region is very high, since slope of characteristic curve is almost zero
- The resistance calculated using equation does not include the resistance due to the metal contact (usually less than 0.1 Ω)

- *Problem:*

1. Find the static and dynamic resistances of a germanium diode with 0.2 V forward bias applied, if reverse sat current is 1μA and temperature is 30^{o}C (Ans: 94.79Ω, 12.38Ω)

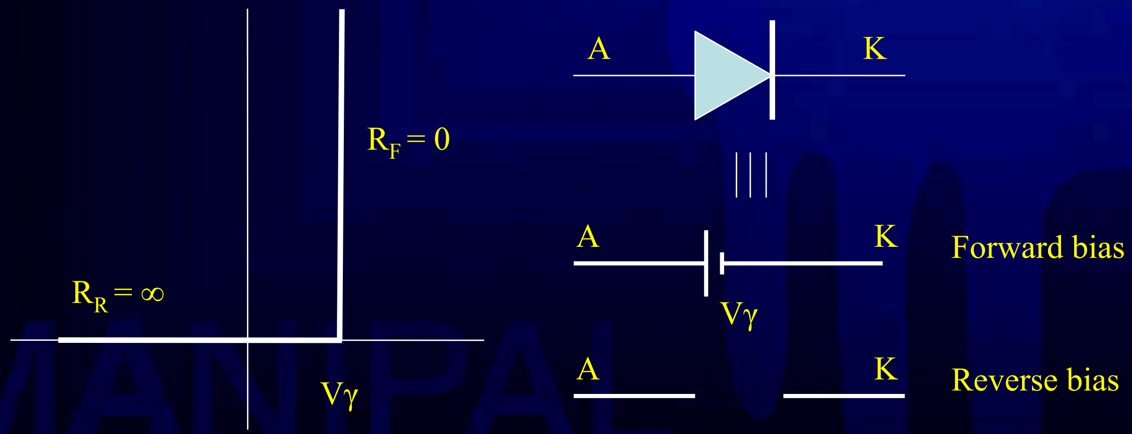
Diode Equivalent Circuit

- Diode is often replaced by its equivalent circuit during circuit analysis and design
- Equivalent circuit is obtained by replacing the characteristic curve by straight-line segments



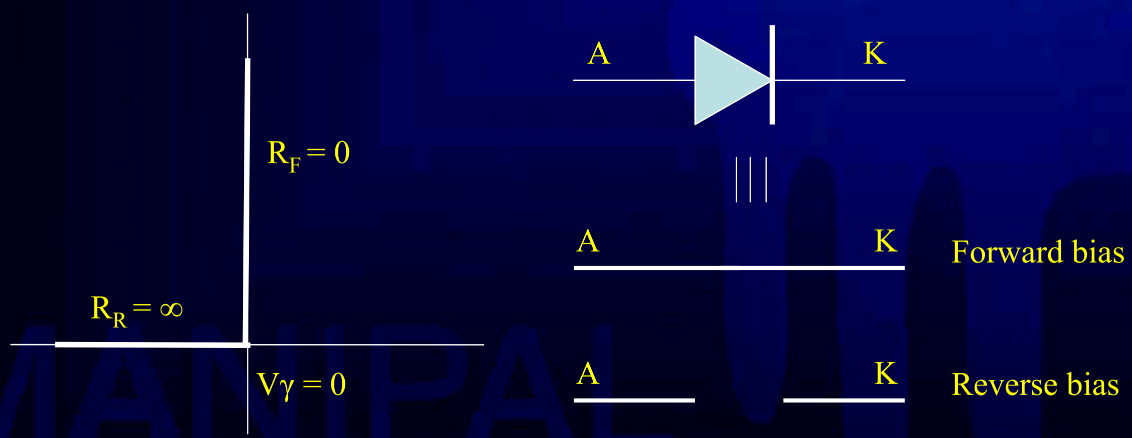
Diode Equivalent Circuit

- As further approximation, we can neglect the slope of the characteristic i.e., $R_F = 0$



Diode Equivalent Circuit

- As third approximation, even the cut-in voltage can be neglected (Ideal diode)



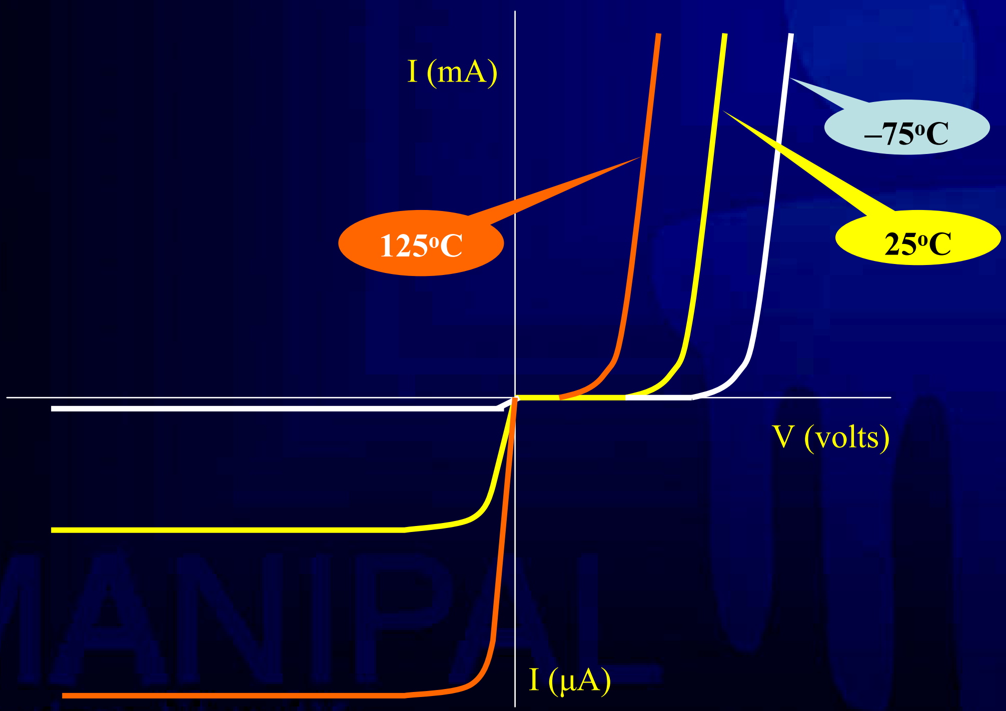
Temperature dependence of diode characteristics

- Reverse saturation current approximately doubles for every 10 degree rise in temperature

$$I_{o2} = I_{o1} 2^{(T_2 - T_1)/10}$$

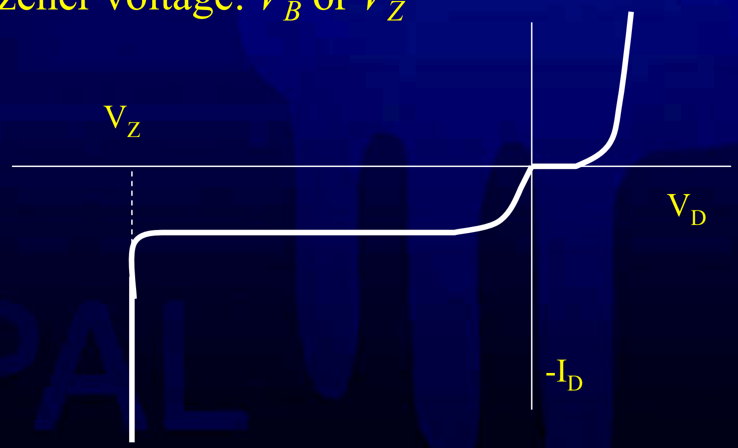
- Where, I_{o1} is reverse sat current at temperature T_1 and
  I_{02} is reverse sat current at temperature T_2
- Cut-in voltage decreases with increase in temperature

Temperature dependence of diode characteristics



Breakdown region

- When a diode is applied with too much reverse bias, the current increases sharply. This is called diode breakdown
- The reverse voltage at which breakdown occurs is called breakdown voltage or zener voltage: V_B or V_Z



Breakdown region

- Two breakdown mechanisms:
  - As reverse bias voltage increases, velocity of minority charge carriers increases
  - As the charge carriers speed up towards respective terminals, they collide with other valence electrons
  - If kinetic energy of speeding electrons are sufficiently high, they release additional carriers through collisions
  - Additional carriers thus released also speed up and collide with other valence electrons
  - The process multiplies, and is called Avalanche breakdown
  - Generally occurs in lightly doped diodes

Breakdown region

- Zener breakdown:
  - Occurs in heavily doped diodes
  - Since charge concentration is high, width of depletion region is narrow
  - So, high electric filed is generated within the depletion region
  - High electric field disrupts the bonding forces and generates carriers
- Normally, at lower reverse bias voltages, zener mechanism is prominent, and at higher reverse voltages, avalanche breakdown is prominent
- Maximum reverse voltage that can be applied before entering breakdown region is called Peak Inverse Voltage (PIV)

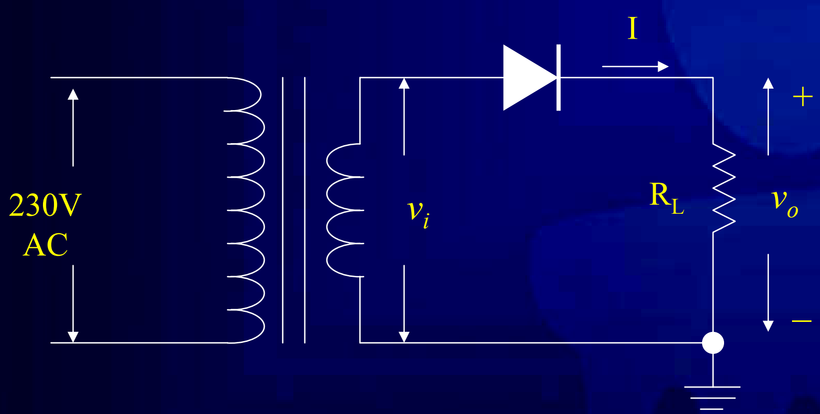
Tutorials

- A Ge diode has reverse sat current 3µA at 40^{o}C. Calculate the reverse sat current when the temperature rises to 125^{o}C
  (Ans: 1.09 mA)
- Calculate the factor by which reverse saturation current of silicon diode is multiplied when the temperature increases from 25 to 100^{O}C. (Ans: 181)
- A Si diode has reverse sat current 12 nA at 20^{o}C. (a) Find the diode current when it is forward biased by 0.65 V. (b) Find the diode current when the temperature rises to 100^{o}C.
  (Ans: 4.65mA, 75.89mA)

Rectifiers

- Rectifier is a circuit that converts alternating current (AC) to direct current (DC)
- Diode is the primary element used in rectifiers
- Two types of rectifiers are: Half wave rectifier
  Full wave rectifier
- Half wave rectifier –
  - Only half of the input cycle (positive or negative) is rectified
- Full wave rectifier –
  - Both positive and negative half cycles are rectified
  - Again two types exist – Full wave center-tapped transformer and
    Full wave bridge rectifier

Half wave rectifier



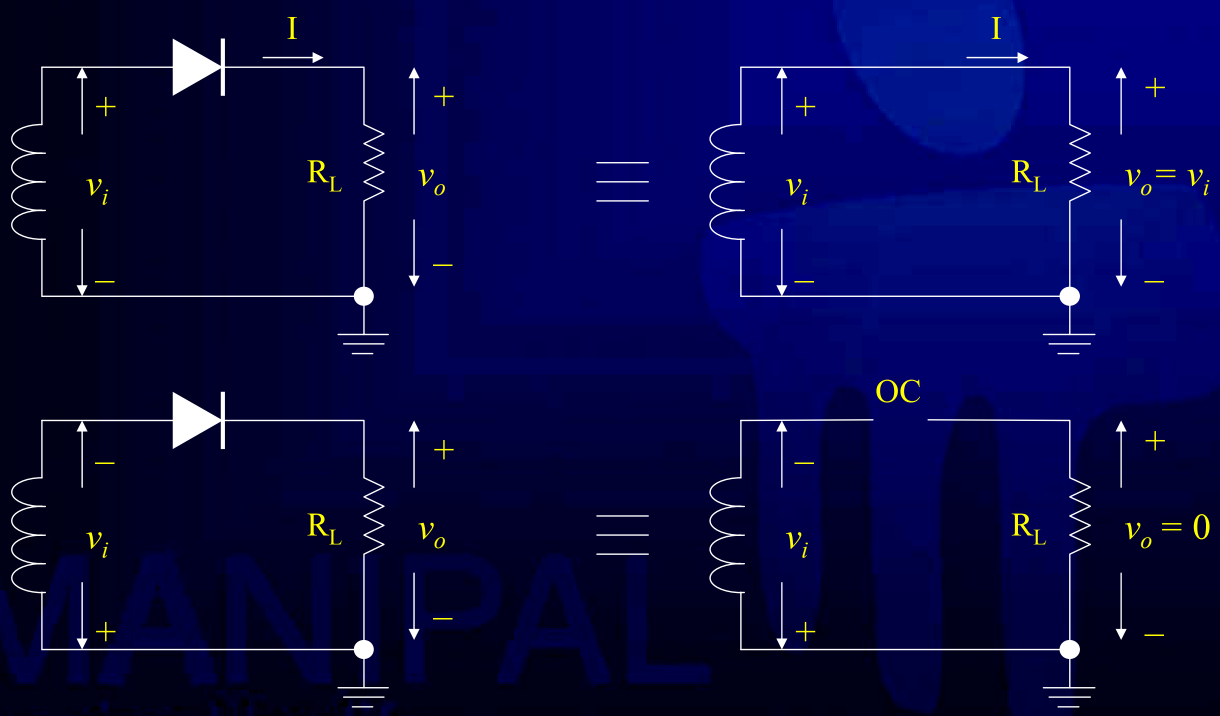
- 230V ac is stepped down using transformer

  $v_i = V_m sin(\omega t)$ is instantaneous voltage at the input of rectifier

  V_m is peak value of input voltage

  ωt is angular frequency in radians

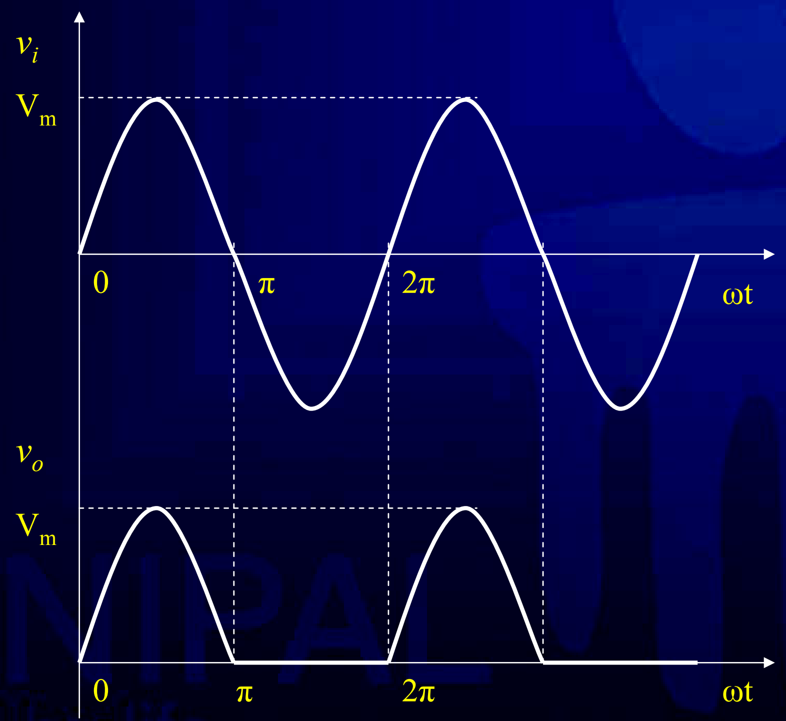
Half wave rectifier



Half wave rectifier

- During positive half cycle, diode is forward biased – short circuit equivalent (neglecting $V\gamma$ and R_F)
- Current flows through the load, hence output $v_o = v_i$
- During negative half cycle, diode is reverse biased – open circuit equivalent (neglecting R_R)
- Current does not flow, hence $v_o = 0$
- Since the current through load flows only during half cycle, circuit is called half wave rectifier
- Output current is not pure DC, but it flows in only one direction through the load

Half wave rectifier



Half wave rectifier

- Current waveform is similar to voltage waveform
  i.e., during positive half cycle, $i = I_m sin(\omega t)$
  where I_m is peak value of current

$$I_m = \frac{V_m - V_\gamma}{R_L + R_F} \approx \frac{V_m}{R_L}$$

  During negative half cycle, $i = 0$
- Average value of current for pure AC is zero
- Average value of load current in half wave rectifier is:

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i\, d(\omega t) = \frac{1}{2\pi}\int_0^{\pi} I_m \sin(\omega t)\, d(\omega t) = \frac{-I_m}{2\pi}\left[\cos(\omega t)\right]_0^{\pi} = \frac{I_m}{\pi}$$

which is non-zero

Half wave rectifier

- Average output voltage is $V_{dc} = I_{dc} R_L$
- RMS value of load current in half wave rectifier is:

$$I_{rms} = \left[\frac{1}{2\pi} \int_0^{2\pi} i^2 \, d(\omega t) \right]^{1/2}$$

$$I_{rms}^2 = \frac{1}{2\pi} \int_0^{\pi} I_m^2 \sin^2(\omega t) d(\omega t) \quad = \frac{I_m^2}{2\pi} \int_0^{\pi} \left(\frac{1 - \cos(2\omega t)}{2} \right) d(\omega t) \quad = \frac{I_m^2}{4}$$

$$I_{rms} = \frac{I_m}{2}$$

- RMS output voltage is $V_{rms} = I_{rms} R_L$

Half wave rectifier

- Form factor is ratio of V_{rms} to V_{dc} $= \frac{I_{rms}}{I_{dc}} = \frac{I_m/2}{I_m/\pi} = \pi/2 = 1.57$

- Another parameter of interest in rectifiers is Ripple factor
- Ripple factor is: $\gamma = \frac{\text{rms value of ac component of current}}{\text{dc value of current}}$

$$\gamma = \frac{\sqrt{I_{rms}^2 - I_{dc}^2}}{I_{dc}} \quad = \sqrt{\left(\frac{I_{rms}}{I_{dc}} \right)^2 - 1} \quad = \sqrt{\left(\frac{I_m/2}{I_m/\pi} \right)^2 - 1} \quad = 1.21$$

- So ripple factor in half wave rectifier is 1.21, independent of load current and input voltage

Half wave rectifier

- Another parameter of interest is efficiency of rectifier:

$$\eta = \frac{\text{dc power delivered to the load}}{\text{ac power supplied by the secondary of transformer}} = \frac{P_{dc}}{P_{ac}}$$

$$P_{dc} = I_{dc}^2 R_L = \frac{I_m^2}{\pi^2} R_L \qquad P_{ac} = I_{ac}^2 (R_L + R_F) = \frac{I_m^2}{4}(R_L + R_F)$$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{4/\pi^2}{1 + \frac{R_F}{R_L}} = \frac{0.406}{1 + \frac{R_F}{R_L}}$$

- So, efficiency of half wave rectifier is around 40.6% only

Half wave rectifier

- Yet another factor of interest is Transformer Utilization Factor (TUF) $TUF = \frac{P_{dc}}{P_{ac(\text{rated})}}$

  where $P_{ac(rated)}$ is the product of rated rms voltage of secondary and actual current flowing in secondary winding

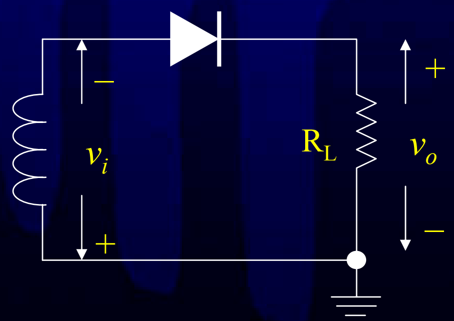
$$TUF = \frac{I_{dc}^2 R_L}{(V_m/\sqrt{2})(I_{rms})} = \frac{(I_m/\pi)^2 R_L}{(V_m/\sqrt{2})(I_m/2)}$$

where $I_m = \frac{V_m}{R_L + R_F}$

- Hence $TUF = \frac{2\sqrt{2}/\pi^2}{1 + \frac{R_F}{R_L}}$ ≈ 0.287

Half wave rectifier

- Note that during negative half cycle, when the diode is reverse biased, the reverse voltage appearing across the diode is v_i
- The peak value of this reverse voltage is V_m
- So, for the rectifier to work properly (without the diode going to breakdown), we have to use a diode with breakdown voltage more than V_m
- i.e., PIV rating of diode should be $\geq V_m$



Half wave rectifier

- Advantages of HWR
  - Single diode used
  - Simple circuit
  - PIV rating is V_m
- Disadvantages of HWR
  - High ripple factor
  - Low efficiency
  - Low TUF

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Half wave rectifier

Problem

1. A sinusoidal voltage of peak value 10V and frequency 50Hz is applied to half wave rectifier. If the load resistance is 800Ω and diode forward resistance is 8Ω, calculate
   a) Peak value of load current
   b) Average load current
   c) Rms load current
   d) Average output voltage
   e) Rms output voltage
   f) Efficiency
   g) Ripple factor

Half wave rectifier

2. An AC voltage of 230V, 50Hz is applied to transformer having turns ratio 10:1. The secondary of transformer is connected to half wave rectifier. The diode has cut-in voltage 0.6V and forward resistance 10Ω. Determine average and rms values of output current and voltage. What should be the PIV rating of the diode?

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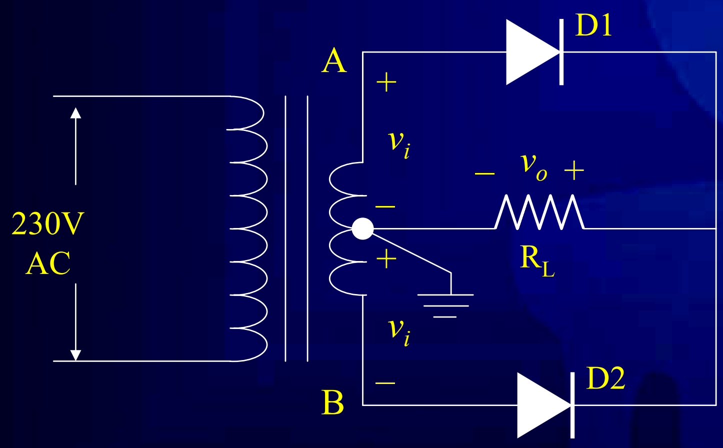
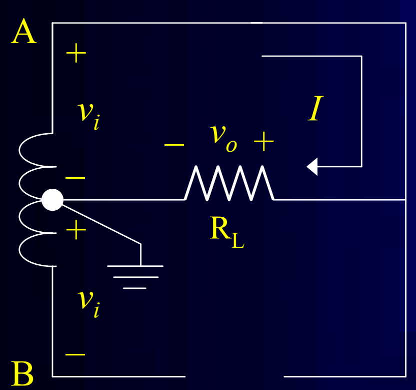
Full wave Rectifier



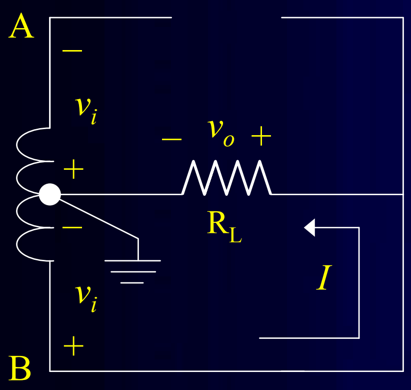
- Centre-tapped transformer is used
- When the centre-tap is grounded, the voltage above and below centre-tap have opposite polarities

Full wave Rectifier



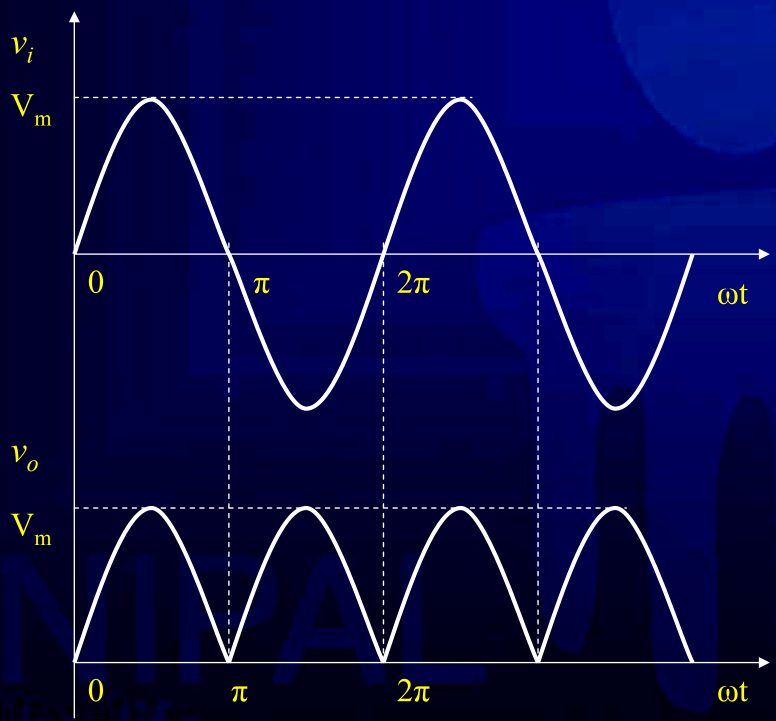
- During positive cycle:
  - Point A is positive w.r.t. ground, so diode D1 is forward biased – short circuit equivalent
  - Point B is negative w.r.t. ground, so diode D2 is reverse biased – open circuit equivalent
- So current flows through load resistance in the direction from right to left
- Load voltage is positive w.r.t. ground $\quad v_o \approx v_i$

Full wave Rectifier



- During negative half cycle:
  - Point A is negative w.r.t. ground, so diode D1 is reverse biased – open circuit equivalent
  - Point B is positive w.r.t. ground, so diode D2 is forward biased – short circuit equivalent
- So, current flows through load resistance again in the direction from right to left
- Load voltage is positive w.r.t. ground $v_o \approx v_i$

Full wave Rectifier



Full wave Rectifier

- During either positive or negative half cycles, only one diode is conducting while the other is not.
- So, peak value of load current is: $I_m = \dfrac{V_m - V_\gamma}{R_L + R_F} \approx \dfrac{V_m}{R_L}$
- Average or dc value of load current is:

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} i\, d(\omega t) \qquad = \frac{2I_m}{\pi}$$

- Average or dc output voltage is: $V_{dc} = I_{dc} R_L$

Full wave Rectifier

- RMS or ac load current is: $I_{rms} = \left[\dfrac{1}{\pi}\displaystyle\int_0^{\pi} i^2\, d(\omega t)\right]^{1/2} \qquad = \dfrac{I_m}{\sqrt{2}}$
- RMS output voltage is $V_{rms} = I_{rms} R_L$
- Ripple factor is: $\gamma = \dfrac{\sqrt{I_{rms}^2 - I_{dc}^2}}{I_{dc}} \qquad = 0.48$
- Efficiency is: $\eta = \dfrac{P_{dc}}{P_{ac}} \qquad = \dfrac{0.81}{1 + \dfrac{R_F}{R_L}}$

Full wave Rectifier

- Transformer utilization factor is

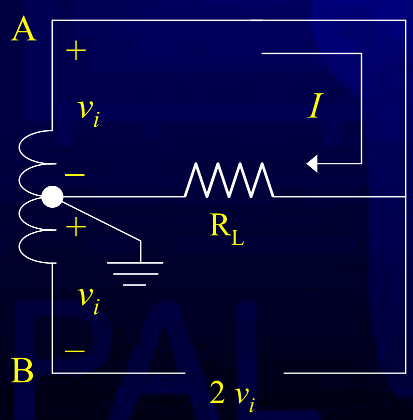
$$TUF = \frac{I_{dc}^2 R_L}{\left(V_m/\sqrt{2}\right)\left(I_{rms}\right)} = \frac{\left(2I_m/\pi\right)^2 R_L}{\left(V_m/\sqrt{2}\right)\left(I_m/\sqrt{2}\right)} \quad = ?$$

- Form factor is:

$$= \frac{I_{rms}}{I_{dc}} = \frac{I_m/\sqrt{2}}{2I_m/\pi} = ?$$

Full wave Rectifier

- Voltage appearing across reverse biased diode is $2v_i$
- So, PIV rating of diode required is > $2V_m$



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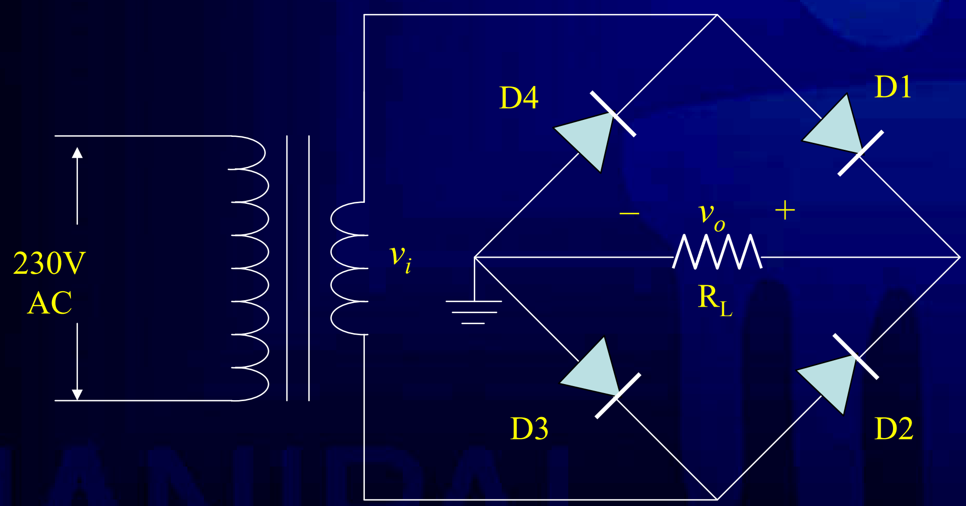
Full wave Rectifier

Problem

- A sinusoidal voltage 20 sin(2π 50t) is applied to full wave rectifier. If the load resistance is 1000Ω and diode forward resistance is 10Ω, calculate
  - Peak value of load current
  - Average load current
  - Rms load current
  - Average output voltage
  - Rms output voltage
  - Efficiency
  - Ripple factor

Full wave Bridge Rectifier



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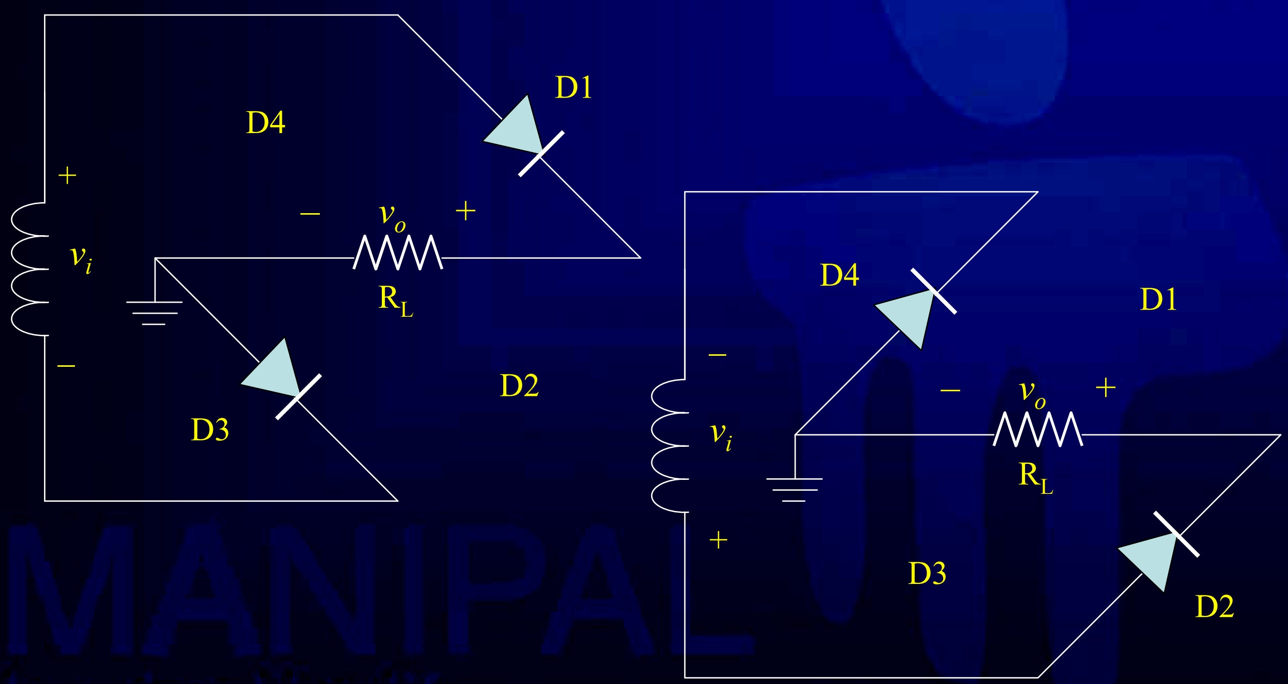
Full wave Bridge Rectifier



Full wave Bridge Rectifier

- During positive (negative) half cycle
  - diodes D_1 and D_3 are forward (reverse) biased and diodes D_2 and D_4 are reverse (forward) biased
  - Current flows through diode D1 (D2), R_L and D3 (D4)
  - Neglecting the voltage drops across the two diodes, output voltage is $v_o = v_i$
- During entire cycle, current through load flows in one direction only
- Hence output voltage is dc, but it has ripples
- Output waveform is same as that of full-wave centre-tap

Full wave Bridge Rectifier

- At any point of time, two diodes are conducting, and remaining two are not conducting
- So, peak value of load current is: $I_m = \frac{V_m - 2V_\gamma}{R_L + 2R_F} \approx \frac{V_m}{R_L}$
- Since output waveform is same as earlier,

$$I_{dc} = \frac{1}{\pi}\int_0^\pi i\, d(\omega t) \quad = \frac{2I_m}{\pi}$$

- Average output voltage is $V_{dc} = I_{dc} R_L$

Full wave Bridge Rectifier

- RMS load current is: $I_{rms} = \left[\frac{1}{\pi}\int_0^\pi i^2\, d(\omega t)\right]^{1/2} \quad = \frac{I_m}{\sqrt{2}}$
- RMS output voltage is $V_{rms} = I_{rms} R_L$
- Ripple factor is $\gamma = \frac{\sqrt{I_{rms}^2 - I_{dc}^2}}{I_{dc}} \quad = 0.48$
- Efficiency is $\eta = \frac{P_{dc}}{P_{ac}} \quad = \frac{0.81}{1 + \frac{2R_F}{R_L}}$

Full wave Bridge Rectifier

- Important point to note is the PIV rating of diode
- During either of half cycles, voltage across reverse biased diode is v_i, neglecting the voltage drop across conducting diodes
- So, PIV rating of diode is > V_m

  which is half that of full-wave centre-tap rectifier

Full wave Bridge Rectifier

- Advantages and disadvantages of bridge rectifier, compared to centre-tap full wave rectifier:

Advantages:

1. PIV rating is V_m
2. Centre-tap transformer is not required

Disadvantages:

1. Four diodes are used

Full wave Bridge Rectifier

- Problems:

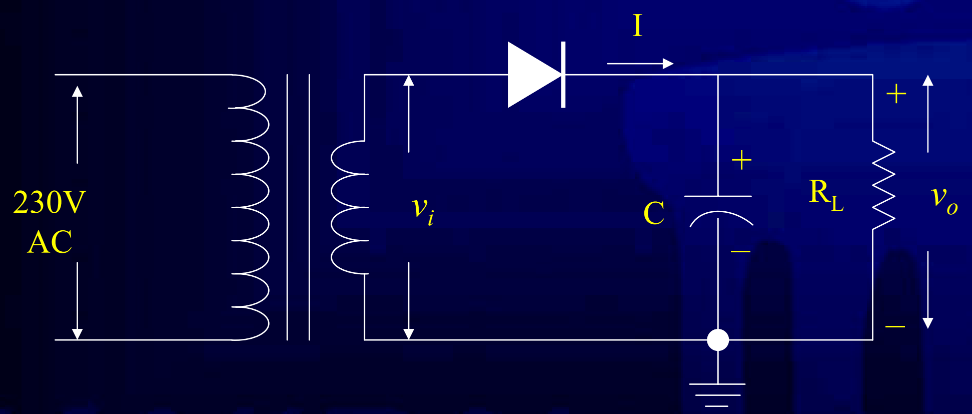
1. Primary voltage is 120V, 60Hz. Turns ratio is 5:1. This transformer supplies to bridge rectifier employing 4 identical diodes with forward voltage drops 0.6V and forward resistance 15Ω. The load resistance is 1kΩ. Calculate average and rms load voltage, efficiency, ripple factor, PIV rating and frequency of output waveform.
2. If the secondary winding of above transformer has resistance of 5Ω, then repeat the above calculations with 500Ω load

Capacitor filter

- Most electronic equipments require constant DC power supply voltage
- Outputs of both HWR and FWR are not constant, but pulsating DC
- We have smoothen the output of rectifier by passing it through a circuit called Filter
- There are many filters – one is capacitor filter
- Capacitor filter:
  - A capacitor of suitable value is connected in parallel with the load resistance

Capacitor filter

- Fig shows HWR with capacitor filter



- Capacitor is connected across R_L with polarity as shown

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Capacitor filter

- Assume capacitor is initially uncharged
- During first quarter cycle (0 to $\pi/2$)
  - capacitor charges up to V_m
- During second quarter cycle ($\pi/2$ to π)
  - Since the capacitor retains charge, the cap voltage is now more than input voltage
  - So diode is reverse biased
  - Capacitor supplies the current to the load and in the process, slowly loses charge (discharges) through R_L
- During third and fourth quarter cycles, the same repeats

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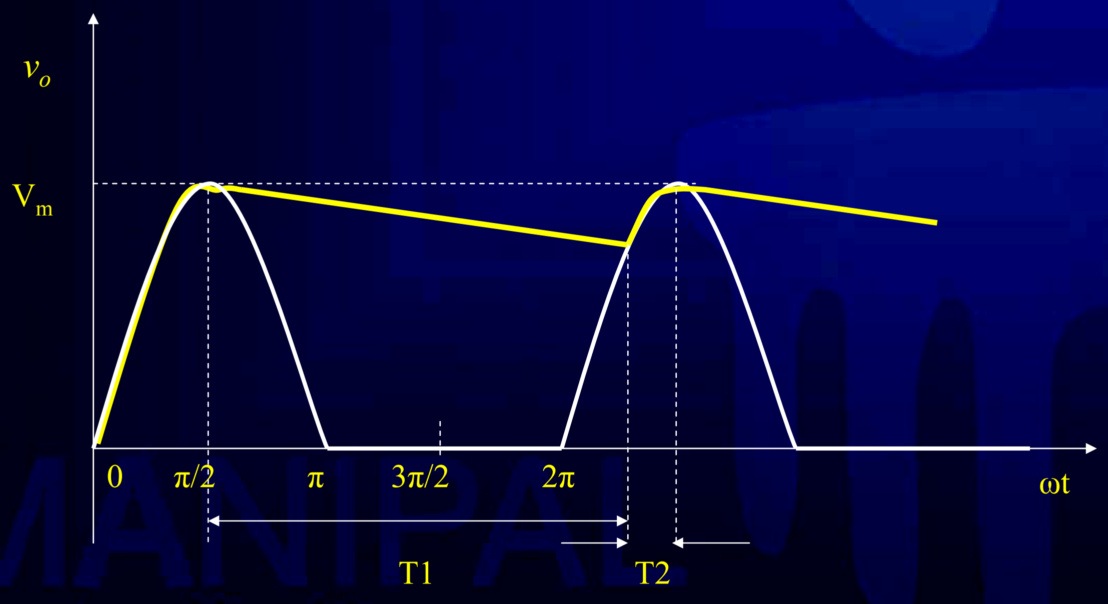
Capacitor filter

- During fifth quarter cycle
  - Input voltage begins to rise
  - When input voltage just exceeds cap voltage, then diode starts conducting
  - Cap again charges up to V_m
- During subsequent cycles, process repeats

Capacitor filter

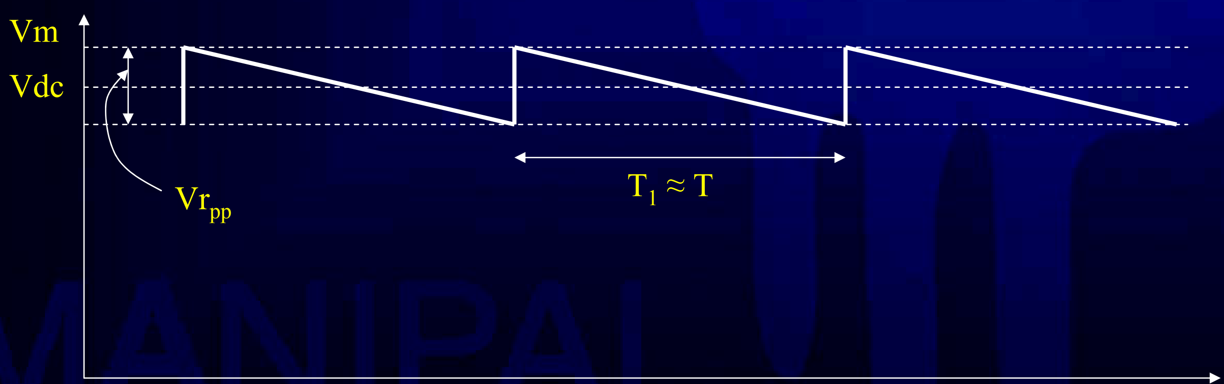


Capacitor filter

- T1 is discharging time; T2 is charging time
- The rate of capacitor discharge depends on the product $R_L C$
- If $R_L C$ is small, then capacitor loses more charge; If $R_L C$ is large, then capacitor loses less charge during same time
- Large value of $R_L C$ is preferred to get smoother waveform

Capacitor filter

- Since charging time is much less than discharging time, we can ignore it ($T_2 << T_1$). Also, the smooth output waveform can be approximated as below (saw tooth):



Capacitor filter

- Let I_{dc} be the average capacitor discharge current
- Charge lost by the capacitor during T_1 is: $Q_{\text{discharge}} = I_{dc}.T_1$
- This charge is replaced during T_2, and voltage rises by Vr_{pp} $\quad Q_{\text{charge}} = Vr_{pp}.C$
- Since charge lost = charge gained,

$Q_{\text{discharge}} = Q_{\text{charge}}$ or $I_{dc}.T_1 = Vr_{pp}.C$

- Since $T_1 \approx T = 1/f$, $\quad Vr_{pp} = \dfrac{I_{dc}T}{C} = \dfrac{V_{dc}}{fCR_L}$ ------(1)

Capacitor filter

- RMS value of saw tooth waveform is given by: $Vr_{rms} = \dfrac{Vr_{pp}}{2\sqrt{3}}$

or $Vr_{pp} = 2\sqrt{3}\,Vr_{rms}$ -----(2)

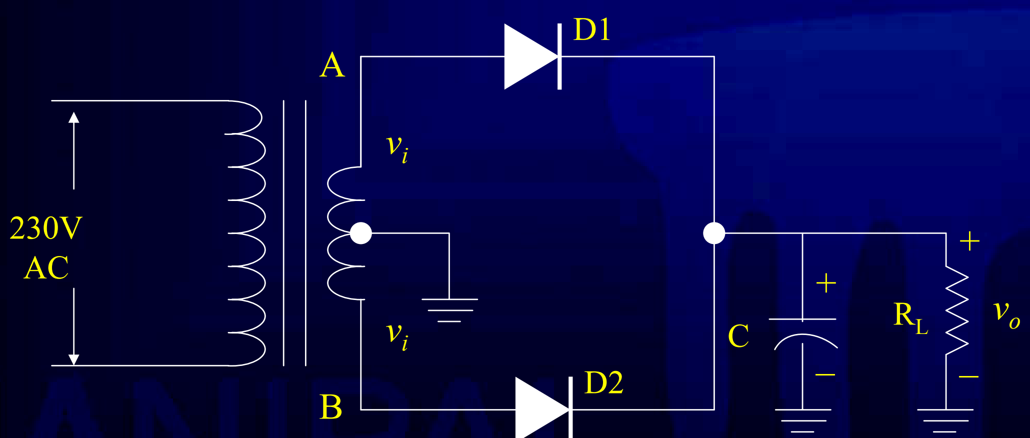
- Substituting (2) in (1), we get $2\sqrt{3}\,Vr_{rms} = \dfrac{V_{dc}}{fCR_L}$
- Ripple factor is given by: $\gamma = \dfrac{Vr_{rms}}{V_{dc}} = \dfrac{1}{2\sqrt{3}\,fCR_L}$
- If the product CR_L is large, then ripple factor is small

Capacitor filter

- From waveform, we get: $V_{dc} = V_m - \frac{Vr_{pp}}{2}$
- Using (1), we get: $V_{dc} = V_m - \frac{V_{dc}}{2fCR_L}$
- Hence dc output voltage is: $V_{dc} = \frac{2f\,CR_L}{1+2f\,CR_L} V_m$

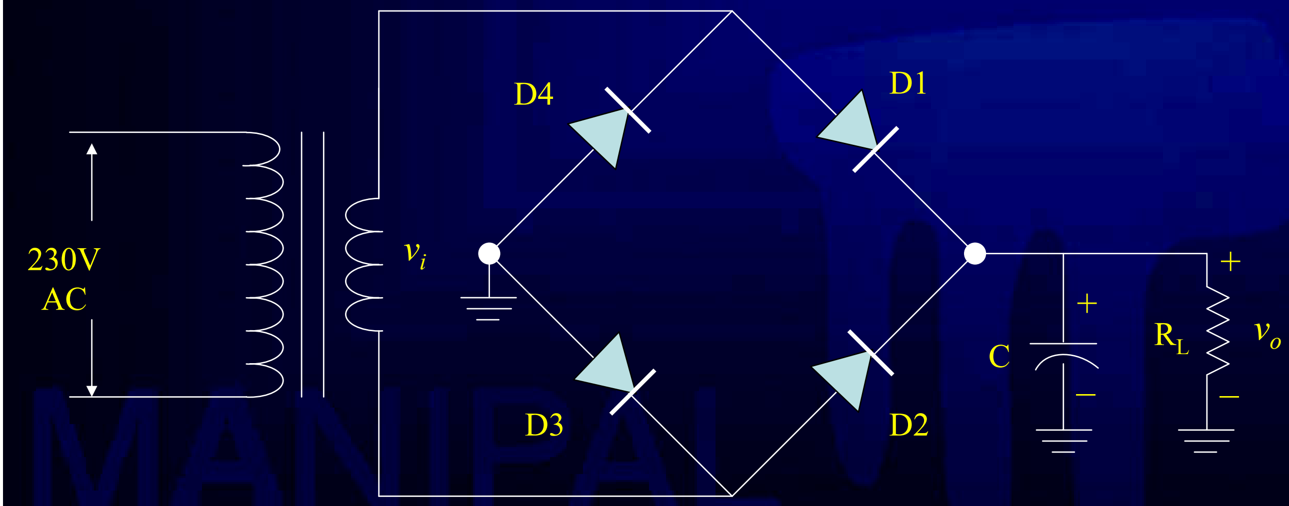
Capacitor filter

- Full wave rectifier with cap filter



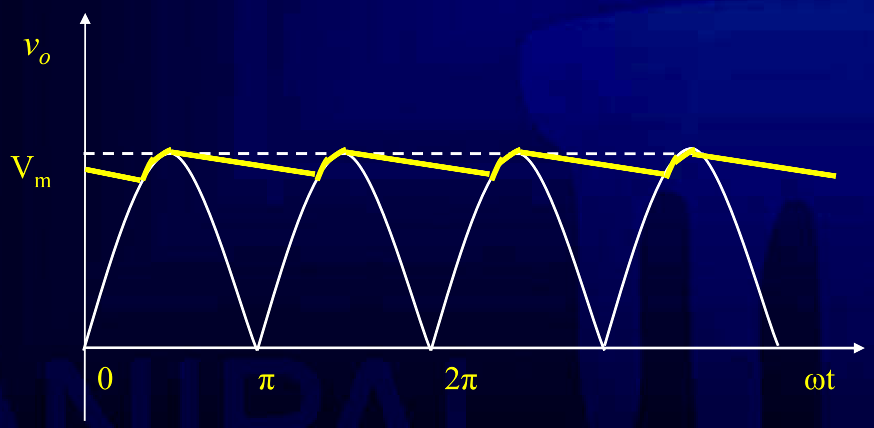
Capacitor filter

- Full wave bridge rectifier with cap filter



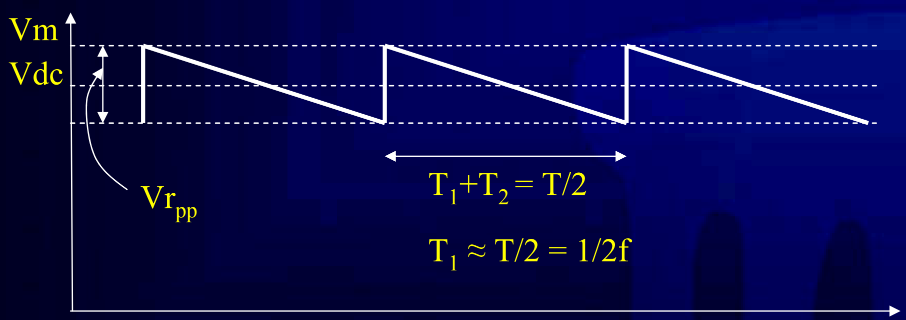
Capacitor filter

- Output waveform with filter (yellow)



Capacitor filter

- Saw tooth approximation



- Peak-to-peak ripple voltage is (from equation 1 of HWR)

$$Vr_{pp} = \frac{I_{dc}T_1}{C} \qquad = \frac{V_{dc}}{2\,f\,CR_L}$$

Capacitor filter

- Ripple factor equation becomes: $\gamma = \dfrac{1}{4\sqrt{3}\,fCR_L}$

- Average output voltage is: $V_{dc} = \dfrac{4\,f\,CR_L}{1+4\,f\,CR_L}V_m$

Capacitor filter

- Problems

1. (a) A half wave rectifier with capacitor filter is supplied from transformer having peak secondary voltage 20V and freq 50Hz. The load resistance is 560Ω and capacitor used is 1000μF. Calculate ripple factor and dc output voltage.

   (b) Repeat for full wave rectifier

   (Ans for part a: 0.0103, 19.65V)

2. (a) A half wave rectifier with capacitor filter has to supply an average voltage of 30V to 900Ω load. Calculate the rms input voltage and value of capacitor needed to get ripple factor of 0.05, assuming f = 50Hz.

   (b) Repeat for full wave rectifier (Ans for part a: 23V, 128.3μF)

Capacitor filter

3. (a) A half wave rectifier is fed from a transformer having turns ratio 6:1. The primary voltage is 110V at 60Hz. It is decided to have ripple factor less than 0.03 and dc load current of 500mA. Find the value of capacitor needed.

   (b) Repeat for full wave bridge rectifier

   (Ans for part a: 3.25 mF)

4. A load is to be supplied 10mA current at 5V dc, with ripple not more than 0.2%. Calculate the value of cap needed for the full wave bridge rectifier. Also, if the primary voltage of transformer is 220V at 50Hz, calculate the turns ratio needed. (Ans: 2.89mF, 62)

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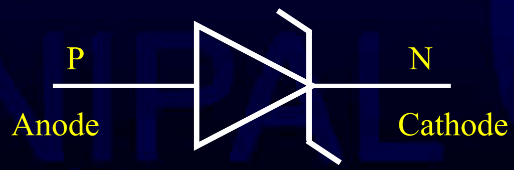
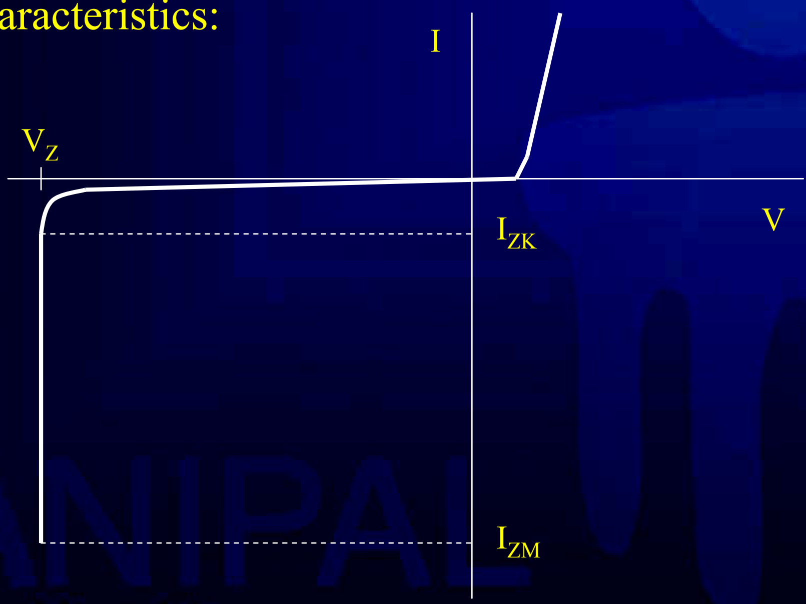
Zener Diode characteristics

- Zener diode is heavily doped P-N junction diode
- Optimized to operate in reverse breakdown region
- Each zener diode has specific breakdown voltage (V_Z). Value of V_Z depends on doping level (inversely proportional)
- Zener diodes are available with V_Z ranging from 1.8V to 200V, power ratings from 250mW to 50W
- Symbol of zener diode:



Zener Diode characteristics

- V-I characteristics:

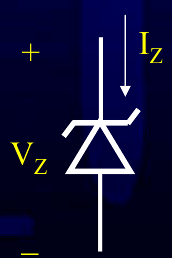


Zener Diode characteristics

- V-I characteristics:
  - When zener diode is forward biased, it acts like ordinary diode – i.e., until certain voltage $V\gamma$ is reached, current is zero, then afterwards, current rises exponentially
  - When zener diode is reverse biased, until the breakdown voltage is reached, current is zero or negligible
  - When reverse voltage equals zener voltage, current rises exponentially in reverse direction
  - After the breakdown has occurred, voltage across zener diode remains almost constant at V_Z, only the current increases with the increase in applied reverse bias.

Zener Diode characteristics

- I_{ZK} or I_{Zmin} – Minimum current necessary to maintain breakdown
- I_{ZM} or I_{ZMax} – Maximum current that can be safely passed through the zener diode
- P_{ZM} or P_{ZMax} – Maximum power dissipation across zener diode
- $P_{ZM} = V_Z.I_{ZM}$
- Zener diode is always connected such that it is reverse biased, and it is in zener breakdown region



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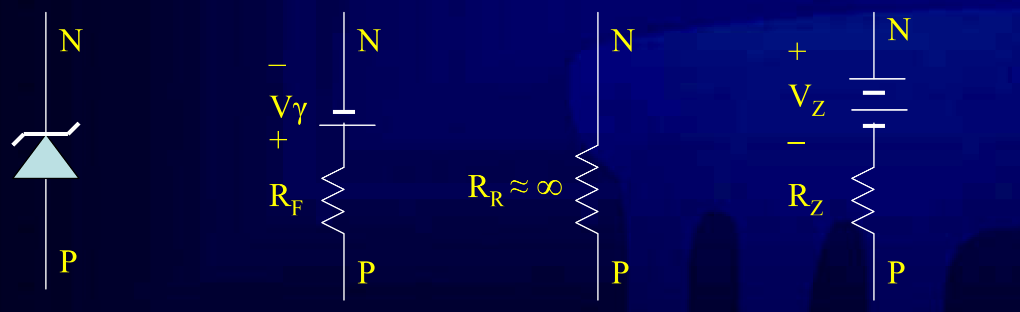
Zener Diode characteristics

- Equivalent circuits of zener diode

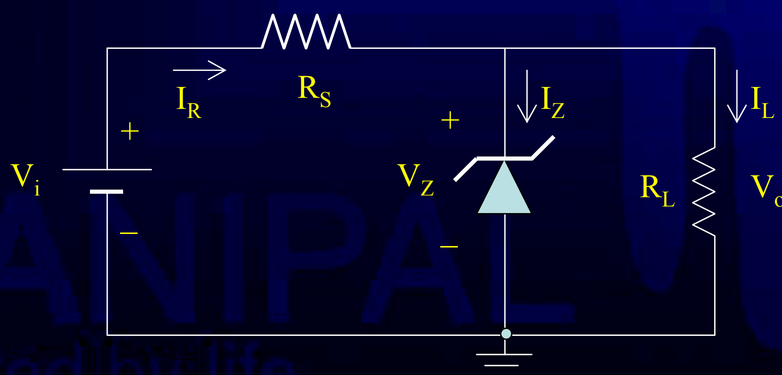


Forward Reverse Breakdown

- Note: R_Z is usually very small, can be neglected

Zener diode circuits

- Analysis of networks employing zener diodes is similar to analysis of ordinary diodes
- First, the state of the diode (on, off or breakdown) must be determined, followed by substitution of correct model
- Fig shows simple circuit employing zener diode



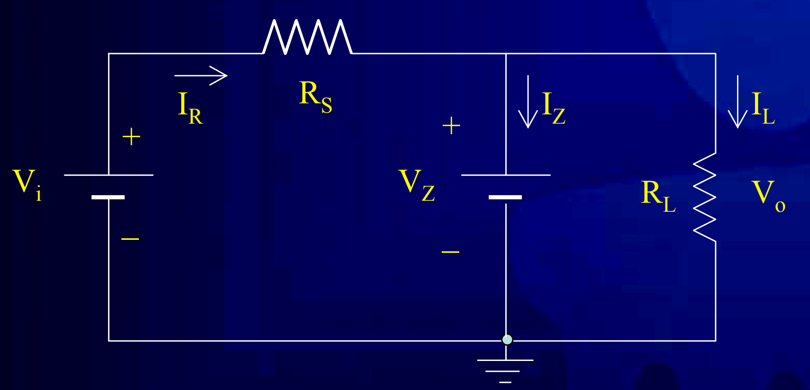
Zener diode circuits

- Step 1:
  - Remove the zener diode from the circuit, and calculate the voltage V across the resulting open circuit

$$V = \frac{V_i R_L}{R_S + R_L}$$

  - If $V \geq V_Z$, the zener is ON, appropriate equivalent model substituted
  - If $V < V_Z$, the zener is Off, and open circuit equivalent substituted
- Step 2:
  - Substitute the appropriate equivalent model and solve for the desired unknown
  - Suppose that we get $V > V_Z$, then zener is in breakdown region, and equivalent model is V_Z (neglecting R_Z)

Zener diode circuits



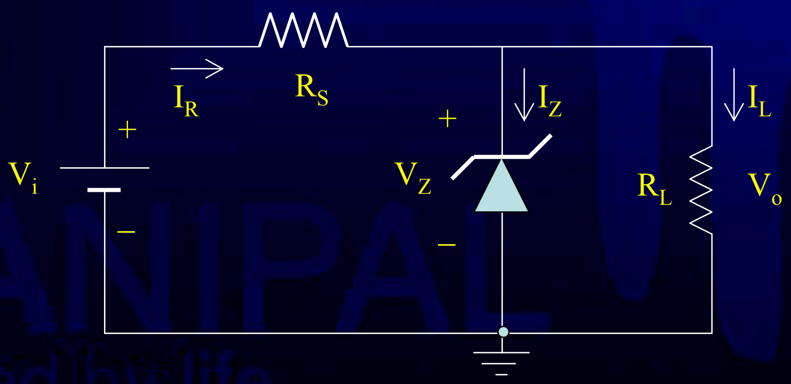
$I_Z = I_R - I_L$ where,

$$I_R = \frac{V_i - V_Z}{R_S} \qquad I_L = \frac{V_o}{R_L} \qquad V_o = V_Z$$

Zener diode circuits

- Example:

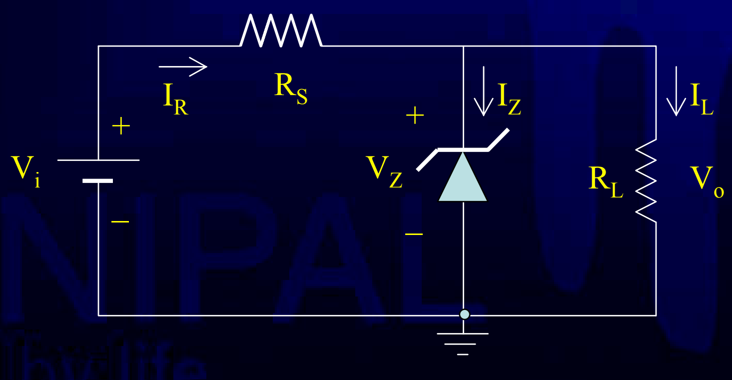
1. For the zener network, V_i= 16 V, R_S= 1 K, V_Z= 10 V and R_L= 3 K. Determine V_o, I_Z and P_Z (Ans: 10 V, 2.67 mA, 26.7 mW)
2. Repeat with R_L= 1.2 K (Ans: 8.73 V, 0, 0)



Application of zener

- Most important application of zener is in providing constant voltage to the load (voltage regulation)

1. In the circuit shown below, R_S= 220Ω, V_Z= 20V, P_{ZM}= 1.2W, I_{ZK}= 1mA and R_L=1.2K. Determine the range of values of V_i that will maintain zener in "on" state



Application of zener

- Minimum zener current required to maintain zener in ON state is I_{ZK}
  Load current is I_L (constant) = V_Z/R_L
  So, $I_{R\min} = I_{ZK} + I_L$
- We have $I_R = \dfrac{V_i - V_Z}{R_S}$ $\qquad I_{R\ \min} = \dfrac{V_{i\min} - V_Z}{R_S}$

$$V_{i\min} = I_{R\min} R_S + V_Z$$

- Maximum zener current allowed is $I_{ZM} = P_{ZM} / V_Z$
  So, $I_{R\,Max} = I_{ZM} + I_L$

$$V_{i\mathrm{Max}} = I_{R\max} R_S + V_Z$$

Application of zener

2. In a zener network, $R_S = 120\Omega$, $R_L = 250\Omega$ and $V_Z = 5V$. Find the minimum and maximum current flowing through zener when input varies from 9V to 15V.
   (Ans: 13.33mA, 63.33mA)
3. A 5V zener is used to regulate the voltage across 500Ω load when the input is 12V±3V. Determine the range of values for R_S given that I_{ZK} = 1mA and I_{ZM} = 500mA
   (Ans: 19.6Ω, 363.6Ω)

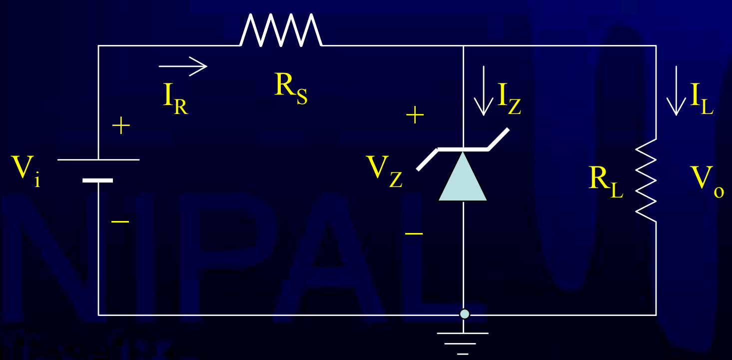
(Note: If I_{ZK} is not given in question, take 0 mA)

- Problems discussed so far come under "Line regulation"

Application of zener

- Load regulation

1. For the zener network shown, $R_S = 10\Omega$, $V_Z = 10V$, $V_i = 25V$. Find the minimum and maximum current through zener when R_L is varied between 10Ω and 100Ω



Application of zener

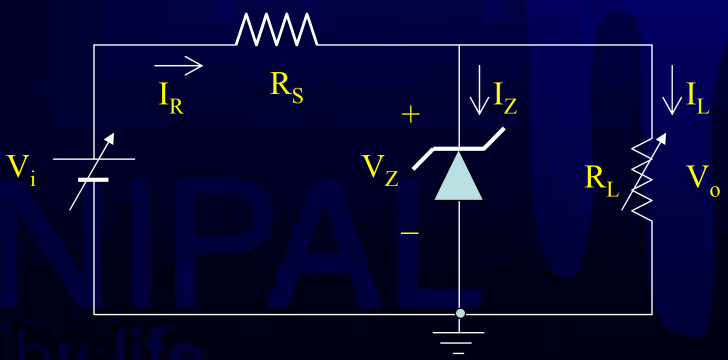
2. For a zener network, $R_S = 470\Omega$, $V_Z = 12V$ and $V_i = 25V$. Find the minimum and maximum values of R_L so that zener diode remains in ON state, given that $I_{ZK} = 2$ mA and $P_{ZM} = 10$ W

3. Design a zener voltage regulator for output voltage 15V, $R_{L(min)} = 100\Omega$, R_L (max) $= \infty$ and $V_i = 20V$. Given that zener has $I_{ZK} = 1mA$ and $I_{ZM} = 1A$.

Application of zener

- Combined line and load regulation

1. For the zener voltage regulator circuit shown below, input voltage is 15V±20%, $R_S = 110\Omega$, $V_Z = 5.6V$. Find the minimum and maximum currents through zener when the load resistance is varied between 100Ω and 1000Ω.



Application of zener

$$I_{L\max} = \frac{V_Z}{R_{L\min}} = \frac{5.6}{100} = 56\,mA \qquad I_{L\min} = \frac{V_Z}{R_{L\max}} = \frac{5.6}{1000} = 5.6\,mA$$

$$I_{R\min} = \frac{V_{i\min} - V_Z}{R_S} = \frac{12 - 5.6}{110} = 58.18\,mA$$

$$I_{R\max} = \frac{V_{i\max} - V_Z}{R_S} = \frac{18 - 5.6}{110} = 112.73\,mA$$

$$I_{Z\min} = I_{R\min} - I_{L\max} = 58.18 - 56 = 2.18\,mA$$

$$I_{Z\max} = I_{R\max} - I_{L\min} = 112.73 - 5.6 = 107.13\,mA$$

Application of zener

2. A zener voltage regulator uses 12V zener diode with I_{ZK} of 10mA and I_{ZM} of 10A. If the series resistance is 10Ω and input voltage is 30V ± 20%, find the min and max load resistance that can be connected at the output.

(Ans: 10.08 Ω to ∞)

3. Find the range of values of R_S that can be used with zener regulator, given that V_i is 25V ± 5V, V_Z is 10V, I_{ZK} = 5mA, I_{ZM} = 1A, $R_{L\,min}$ = 100Ω and $R_{L\,max}$ = 5K

Hint: $R_S \geq \dfrac{V_{in(max)} - V_Z}{I_{zmax} + I_{Lmin}}$ $\quad R_S \leq \dfrac{V_{in(min)} - V_Z}{I_{zmin} + I_{Lmax}}$

End of module 2