Republic of Iraq

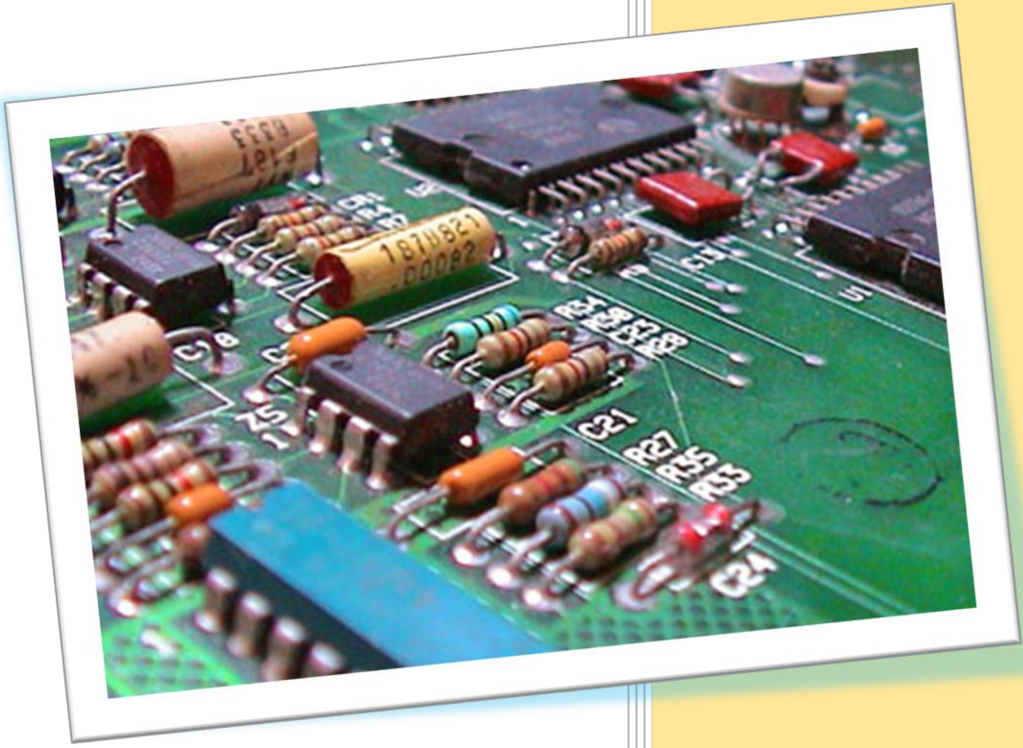
Ministry of Higher Education & Scientific Research

Northern Technical University

Technical College of Kirkuk

Electronic & Control Dept.

Electronic Devices



Preparing by

Assist Lec. : Kaesar Sabah

Discrete Semiconductor devices:

Diodes: are two-terminal devices that allow current in only one direction

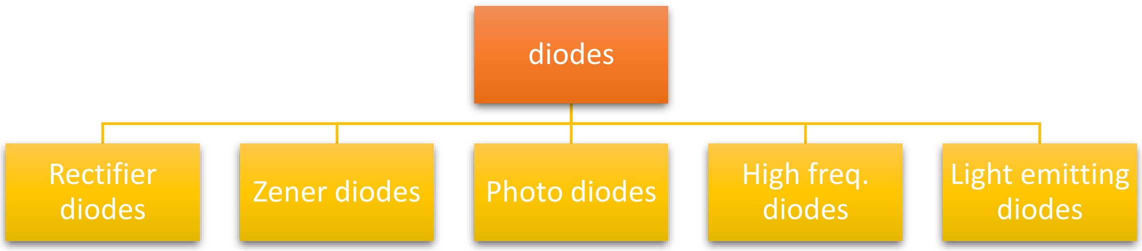
Classification Diodes:

1- According to type of semiconductor material

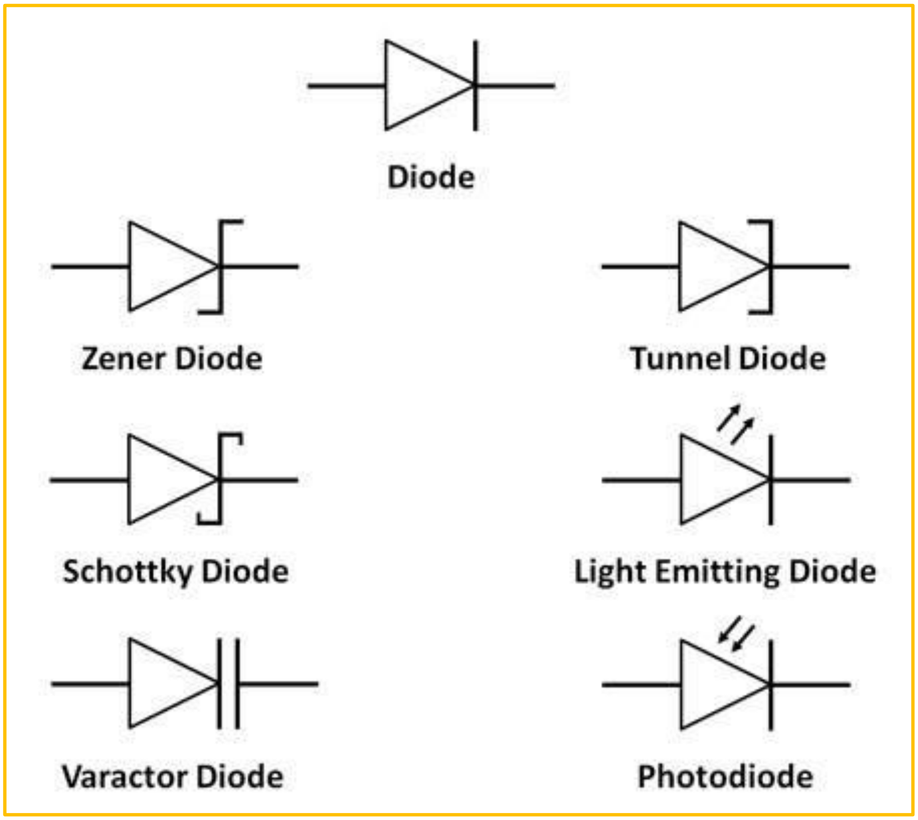
a) Germanium diodes.

b) Silicon diodes

2- According to intended application or particular

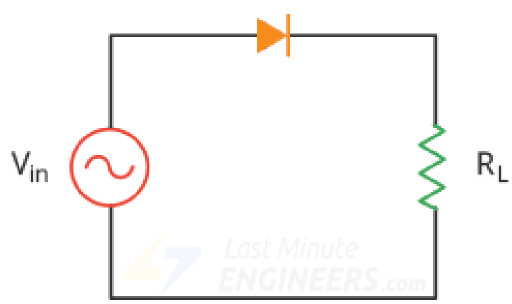


Schematic symbols for several common diodes

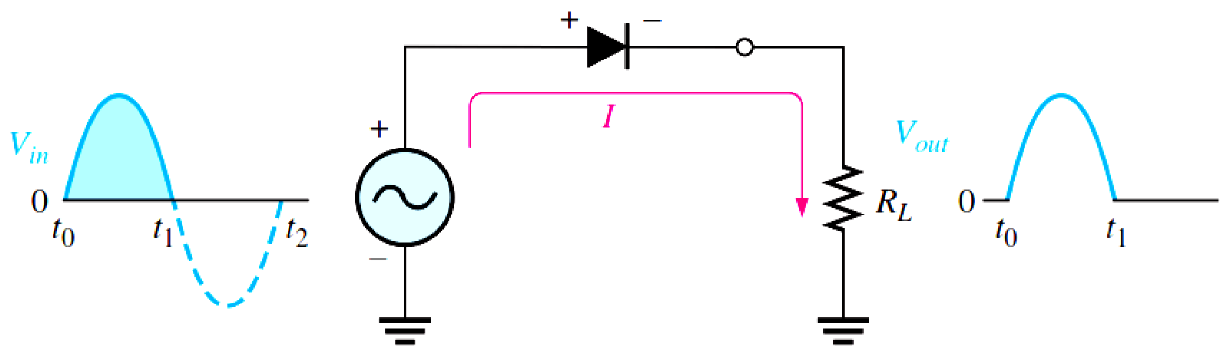


Rectifier diodes

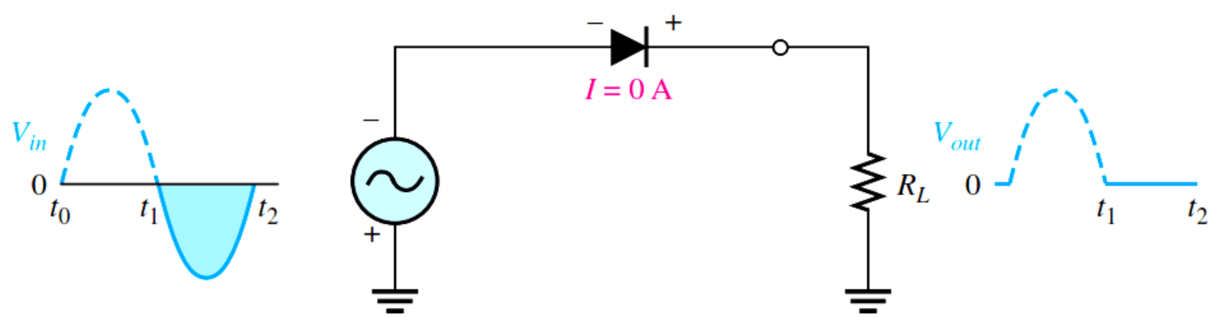
Rectification: is the process of converting (AC) to pulsating (DC). An (AC) source is connected to a load resistance RL through diode shown below



When the sinusoidal input voltage (Vin) goes positive, the diode is forward-biased and conducts current through the load resistor, as shown below. The current produces an output voltage across the load RL, which has the same shape as the positive half-cycle of the input voltage.

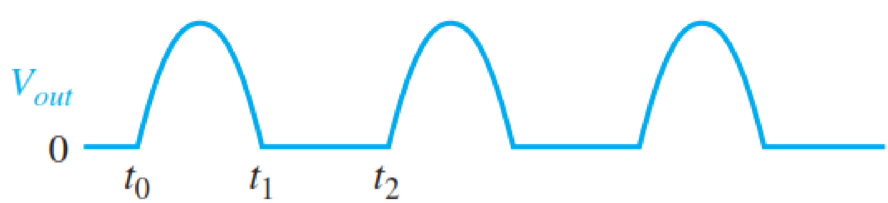


When the input voltage goes negative during the second half of its cycle, the diode is reverse-biased. There is no current, so the voltage across the load resistor is 0 V, as shown in Figure below.



During the positive alternation of the AC input voltage, the output voltage looks like the positive half of the input voltage. The current path is through ground back to the source. During the negative alternation of the input voltage, the current is 0, so the output voltage is also 0.

The net result is that only the positive half-cycles of the ac input voltage appear across the load. Since the output does not change polarity, it is a pulsating dc voltage output as shown in figure below.

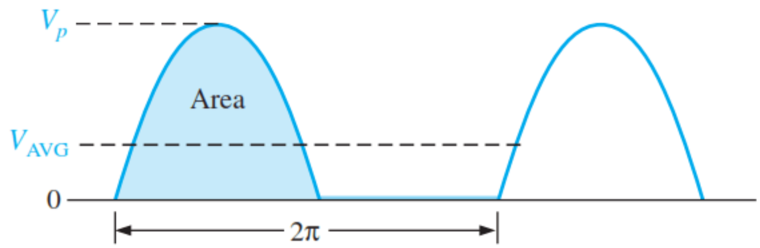


half-wave output voltage for three input cycles

Average Value of the Half-Wave Output Voltage

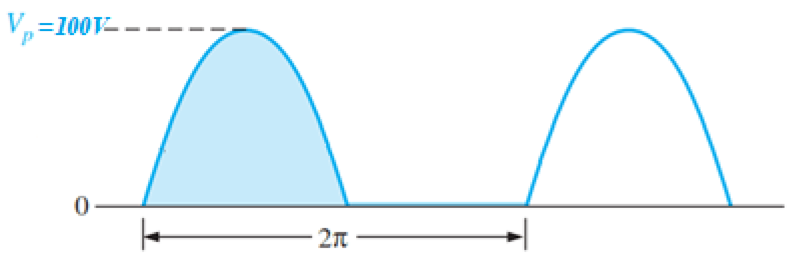
The average value of the half-wave rectified output voltage is the value you would measure on a dc voltmeter. Mathematically, it is determined by finding the area under the curve over a full cycle, as shown in Figure, This equation shows that V_{AVG} is

$$V_{AVG} = \frac{V_p}{\pi}$$



Average value of the half-wave rectified signal.

Ex: For the following fig. What is the average (dc) Value of the half wave rectifier voltage wave form?



$$V_{avg} = \frac{V_p}{\pi} = \frac{100}{3.14} = 31.84$$

Effect of the Barrier Potential on the Half-Wave Rectifier Output

When the practical diode model is used with the barrier potential of 0.7 V taken into account, this is what happens. During the positive half-cycle, the input voltage must overcome the barrier potential before the diode becomes forward-biased. This results in a half-wave output with a peak value that is 0.7 V less than the peak value of the input. The expression for the peak output voltage is

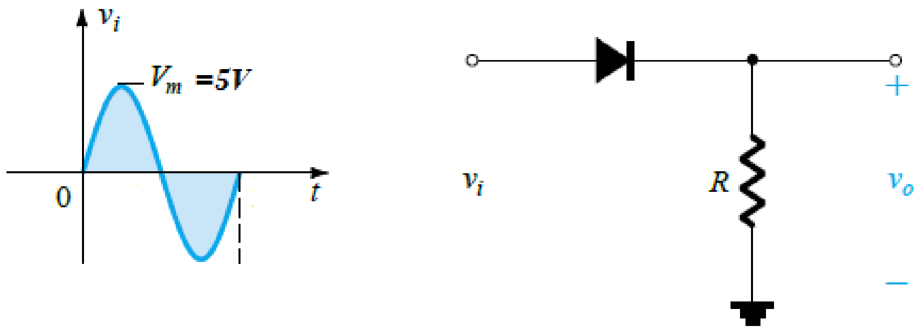
$V_{p(out)} = V_{p(in)}$ → For ideal diode

$V_{p(out)} = V_{p(in)} - V_B$ → When barrier potential of VB taken into account

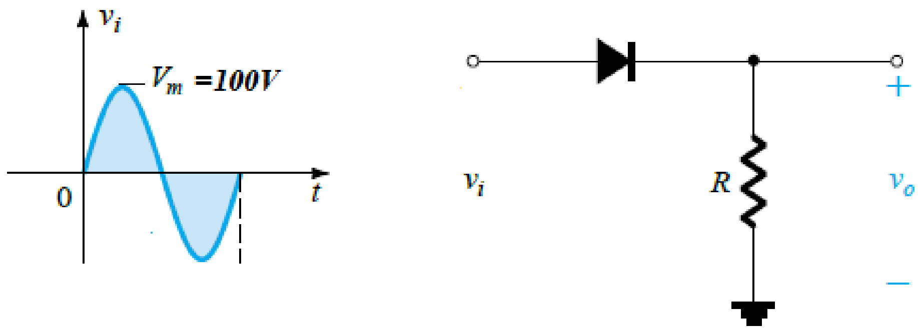
$\therefore \quad V_{p(out)} = V_{p(in)} - 0.7$ → For Si diode

$V_{p(out)} = V_{p(in)} - 0.3$ → For Ge diode

Ex: Determine the output value of each silicon rectifier circuit for the indicated input voltage.



A



B

Each diode is Si and barrier potential should be included.

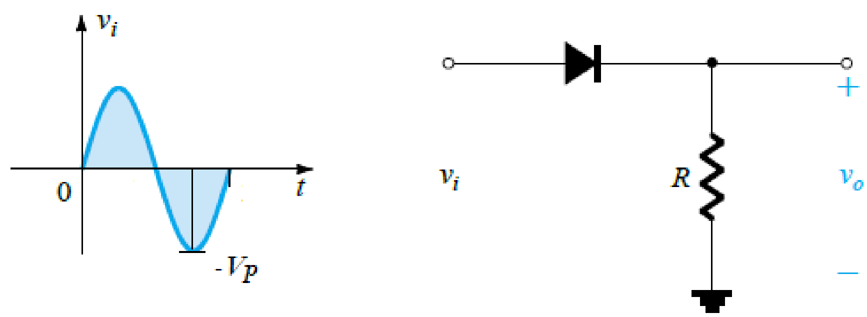
The peak output value of case A circuit is $V_{p(out)} = V_{p(in)} - V_B = 5 - 0.7 = 4.3V$

The peak output value of case B circuit is $V_{p(out)} = V_{p(in)} - V_B = 100 - 0.7 = 99.3V$

Peak Inverse Voltage (PIV)

Definition: The maximum value of the reverse voltage that a PN junction or diode can withstand without damaging itself is known as its **Peak Inverse Voltage.** This rating of Peak Inverse Voltage (PIV) is given and described in the datasheet provided by the manufacturer.

However, if the voltage coming across the junction at reverse biased condition increases beyond this specified value, the junction will get damaged.



A diode is used as a rectifier as shown in the figure above Therefore, care should be taken that during the negative half cycle, the peak value of AC voltage should not be more than the rated value of the Peak Inverse Voltage of the diode.

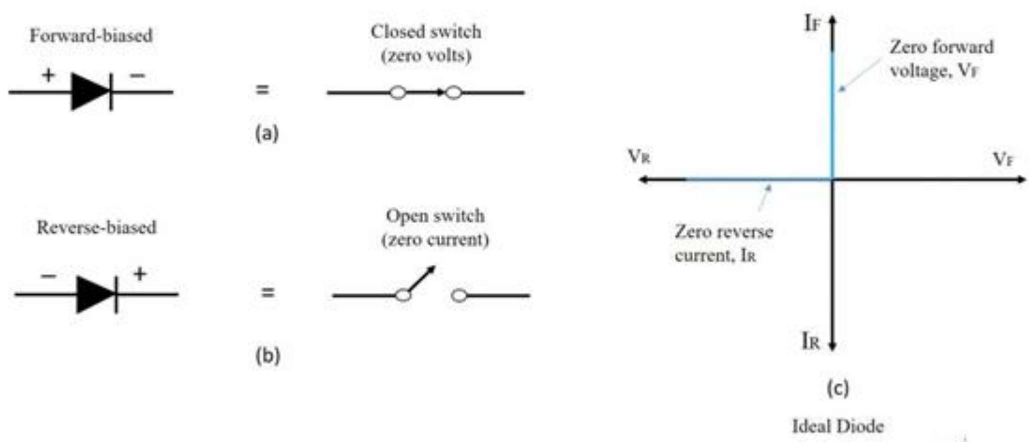
$$V_{PIV(out)} = -V_{p(in)}$$

Diode Approximation

Diode approximation is a mathematical method used to approximate the nonlinear behavior of real diodes to enable calculations and circuit analysis. There are three different approximations used to analyze the diode circuits.

First (ideal) Diode Approximation

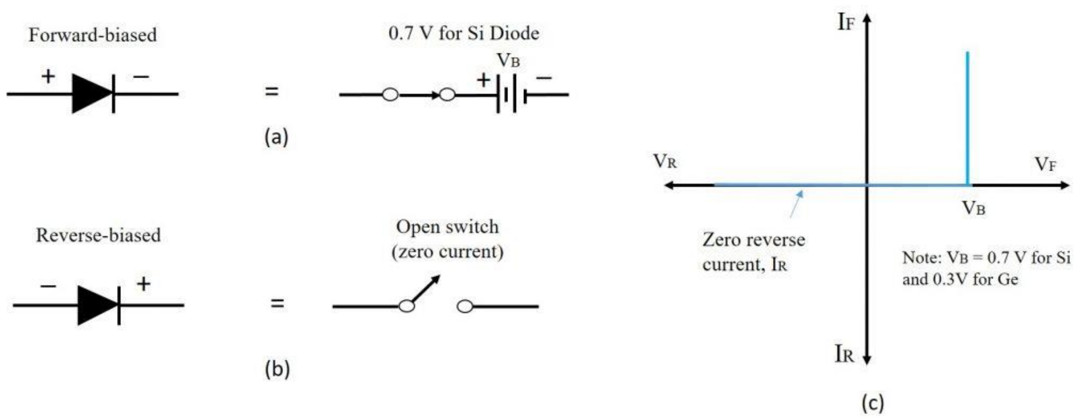
In the first approximation method, the diode is considered as a forward-biased diode and as a closed switch with zero voltage drop. It is not apt to use in real-life circumstances but used only for general approximations where preciseness is not required.



First-approximation

Second Diode Approximation

In the second approximation, the diode is considered as a forward-biased diode in series with a battery to turn on the device. For a silicon diode to turn on, it needs 0.7V. A voltage of 0.7V or greater is fed to turn on the forward-biased diode. The diode turns off if the voltage is less than 0.7V.

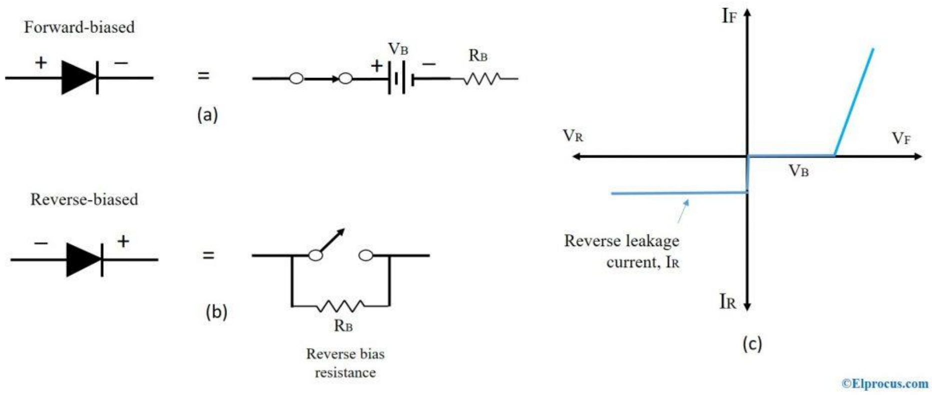


Second-approximation

Third Diode Approximation

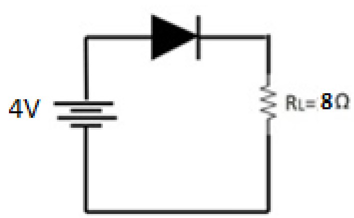
The third approximation of a diode includes voltage across the diode and voltage across bulk resistance, RB. The bulk resistance is low, such as less than 1 ohm and always less than 10 ohms. The bulk resistance, RB corresponds to the resistance of p and n materials. This resistance changes based on the amount of forwarding voltage and the current flowing through the diode at any given time.

The voltage drop across the diode is calculated using the formula



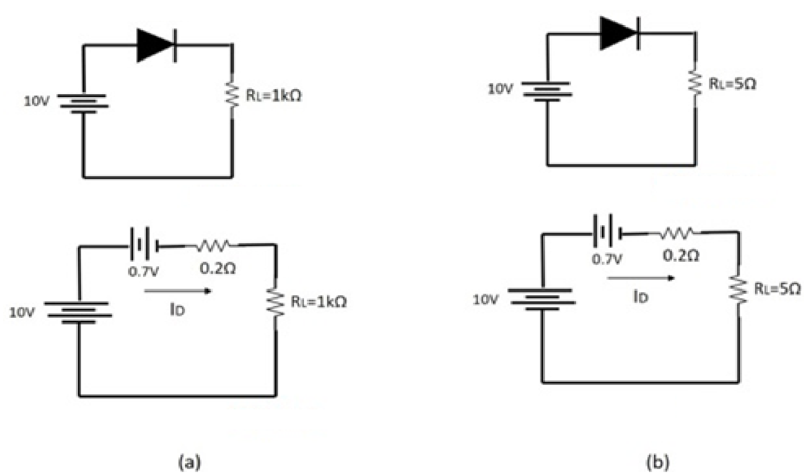
Third-approximation

Ex: For the circuit below use the second approximation of diode to find the current flowing through the diode.



$$I_D = (V_s - V_D)/R = (4-0.7)/8 = 0.41A$$

Ex: For the following circuits, calculate the current flowing through the diode. Using the third approximation method of diode



Circuits-using-third-method

For fig (a)

Adding 1kΩ resistor with bulk resistor 0.2Ω doesn't make any difference in current flowing

ID = 9.3/1000.2= 0.0093 A

If we don't count 0.2Ω, then

ID = 9.3/1000=0.0093 A

For fig (b)

For load resistance of 5Ω, ignoring bulk resistance of 0.2Ω brings a difference in current flow.

Therefore, bulk resistance has to be considered and the correct value of current is 1.7885 A.

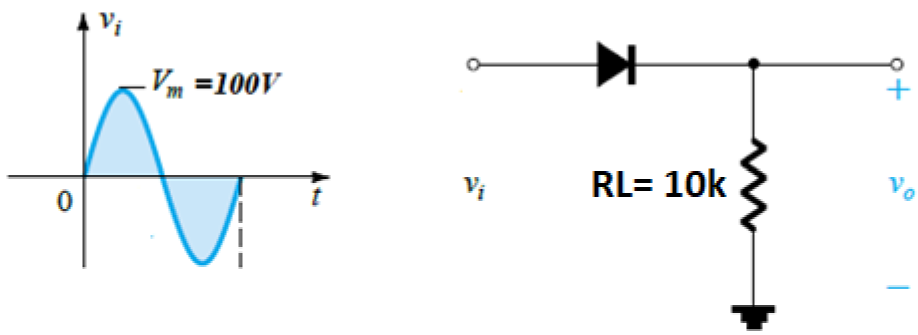
ID=9.3/5.2=1.75885 A

If we don't count 0.2Ω, then

ID=9.3/5=1.86 A

If the load resistance is small, the bulk resistance is taken into effect. However, if the load resistance is very high (ranging to several kilo-ohms), then bulk resistance has no effect on the current.

Ex: For the circuit below use (First (ideal), second and third Diode Approximation if r_B=20Ω) to find the output waveform voltage and I_{peak} and PIV.



First (ideal) Approximation.

$$V_{p(out)} = V_{in}$$

$$I_{peak} = \frac{V_{p(out)}}{RL} = \frac{100}{10k\Omega} = 10mA$$

$$V_{PIV(out)} = -V_{p(in)} = -100V$$

Second Diode Approximation

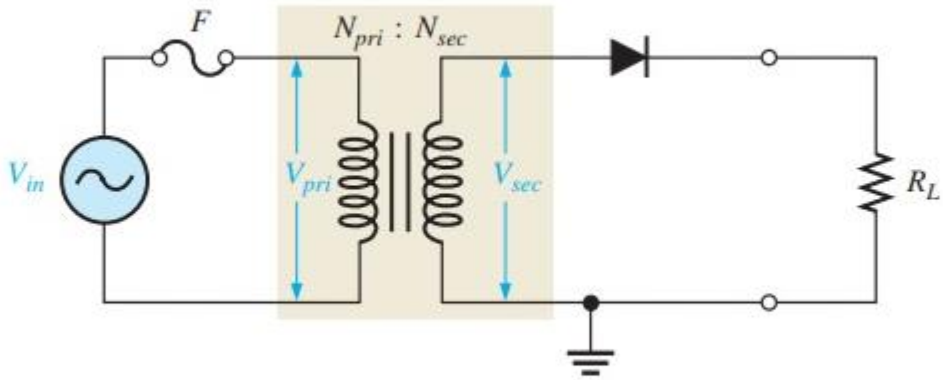
$$V_{p(out)} = V_{in} - V_B = 100 - 0.7 = 99.3V$$

$$I_{peak} = \frac{V_{p(out)}}{RL} = \frac{99.3}{10k\Omega} = 9.93mA$$

Third Diode Approximation

$$I_{peak} = \frac{V_{p(out)}}{RL} = \frac{V_{in} - V_B}{RL + r_B} = \frac{99.3}{10000 + 20} = 9.91mA$$

Half Wave Rectifier with Transformer Coupling



In the above figure, you can see the transfer coupled with the rectifier circuit.
There are 2 advantages of a transformer with a rectifier circuit

1- We can vary the value of voltage according to circuit requirement.
2- The transformer provides protection to the rectifier circuit from the input source.

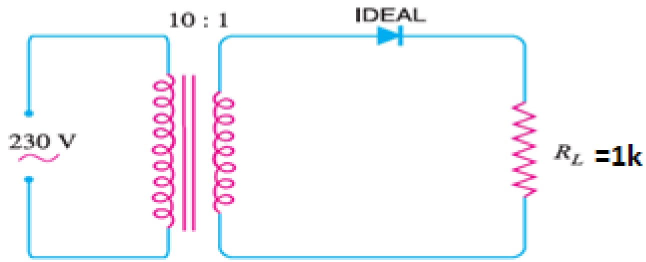
The relation between turn ration and voltage value at the transformer windings is shown below.

$$V_{sec} = \eta V_{pri}$$

$$\eta = \frac{N_{sec}}{N_{pri}}$$

If $\eta > 1 \rightarrow V_{sec} > V_{pri}$ (Step up Transformer)
If $\eta < 1 \rightarrow V_{sec} < V_{pri}$(Step down Transformer)
If $\eta = 1 \rightarrow V_{sec} = V_{pri}$

Ex: an AC supply of 230 V is applied to a half-wave rectifier circuit through a transformer of turn ratio 10: 1.
Find (i) the output average voltage (Vdc) and current (ii) the peak inverse voltage.
Assume the diode to be ideal.



$V_{p(pri)} = (\sqrt{2}) \times Vr.m.s \;\rightarrow\; V_{p(pri)} = (\sqrt{2}) \times 230 = 325.3V$

$V_{p(\sec)} = \eta V_{p(pri)} = 325.3 \times \dfrac{1}{10} = 32.53V$

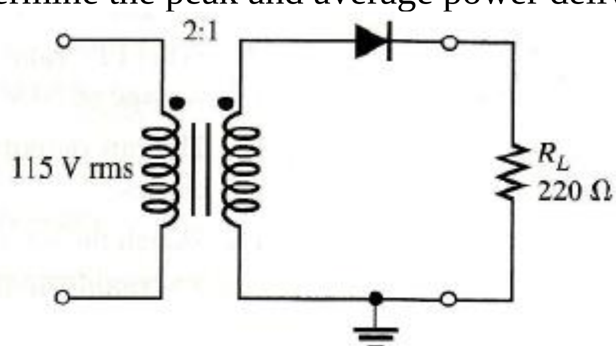
$i)\ V_{avg} = \dfrac{V_p}{\pi} = \dfrac{32.53}{3.14} = 10.36V$

$I_{avg} = I_{dc} = \dfrac{V_{avg}}{RL} = \dfrac{10.36}{1000} = 10.36\, mA$

(ii) During the negative half-cycle of AC supply, the diode is reverse biased and hence conducts no current. Therefore, the maximum secondary voltage appears across the diode.

$$\therefore V_{PIV(out)} = -32.53$$

Ex: For the following circuit determine the peak and average power delivered to RL.



$V_{pri} = (\sqrt{2}) \times Vr.m.s \;\rightarrow\; V_{pri} = (\sqrt{2}) \times 115 = 162.63V$

$V_{p(sec)} = \eta V_{pri} = 162.63 \times \dfrac{1}{2} = 81.3V$

$$V_{avg(sec)} = \frac{V_{p(sec)}}{\pi} = \frac{81.3}{3.14} = 25.9V$$

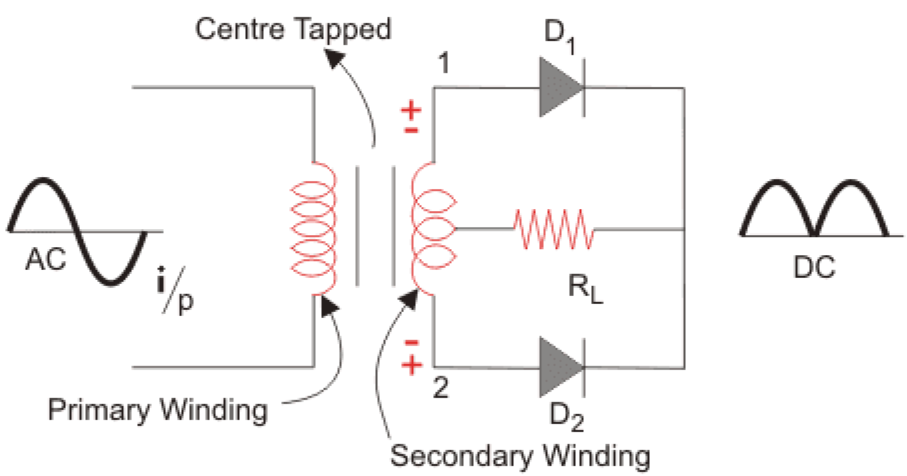
$$P_{l(p)} = \frac{(V_{p(sec)} - 0.7)^2}{RL} = \frac{(80.6)^2}{220} = 29.5W$$

$$P_{l(avg)} = \frac{\left(V_{avg(sec)}\right)^2}{RL} = \frac{(25.9)^2}{220} = 3.05W$$

Full Wave Rectifier

We can further classify **full wave rectifiers** into

- Centre-tapped Full Wave Rectifier
- Full Wave Bridge Rectifier



Centre Tapped Full Wave Rectifier

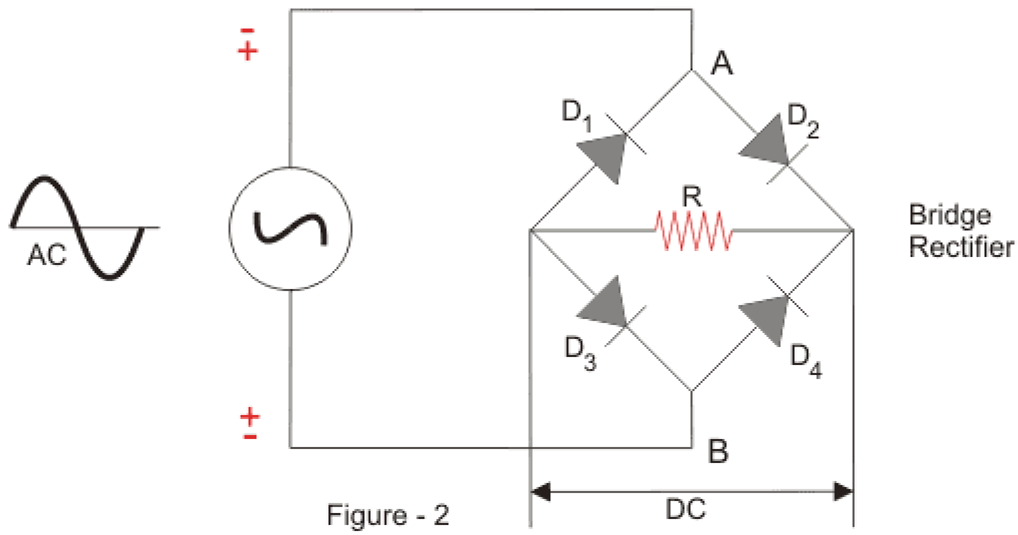
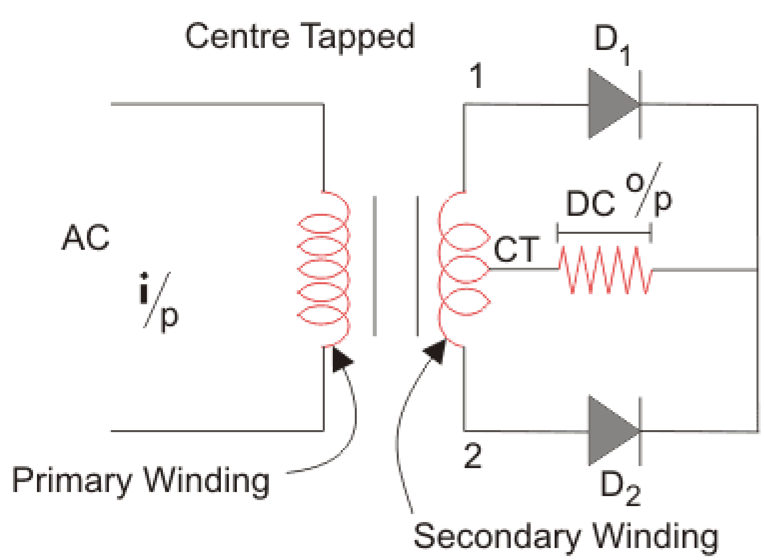


Figure - 2

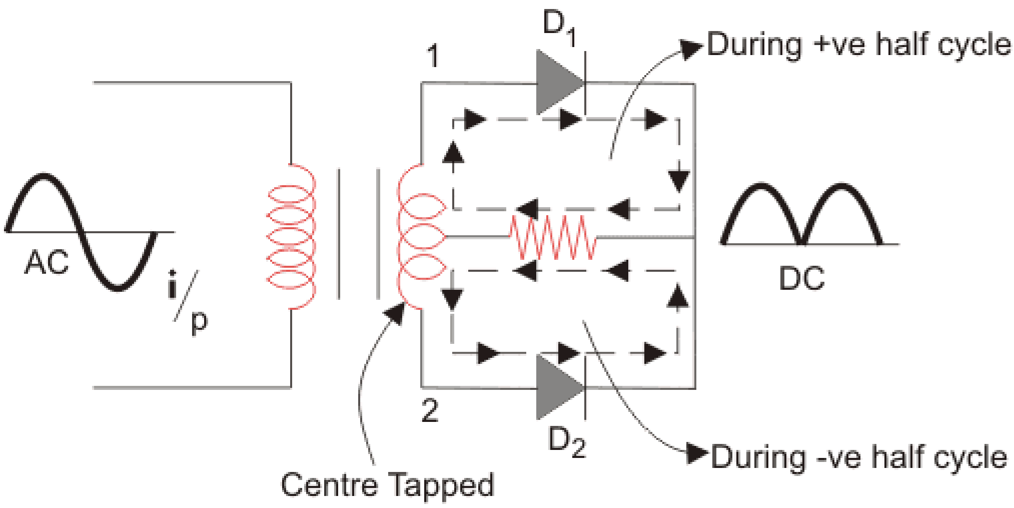
Centre-tapped Full Wave Rectifier

A center-tapped full wave rectifier system consists of:

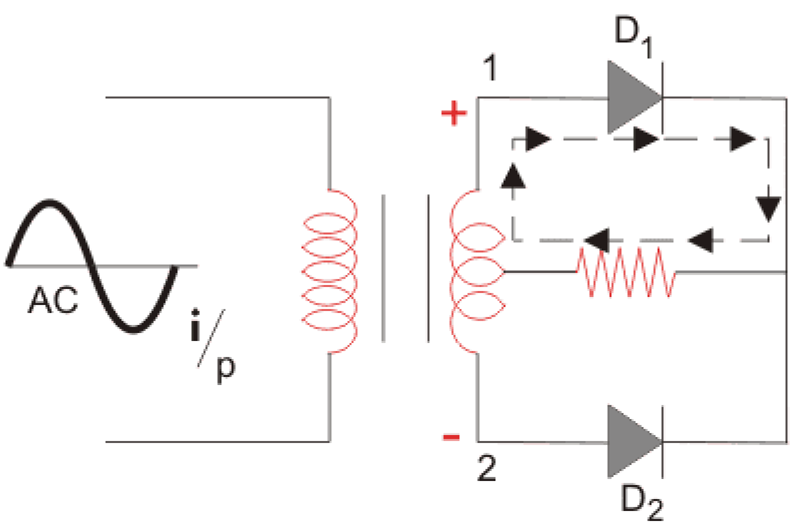
1. Centre-tapped Transformer
2. Two Diodes
3. Resistive Load



Working of Centre-tapped Full Wave Rectifier

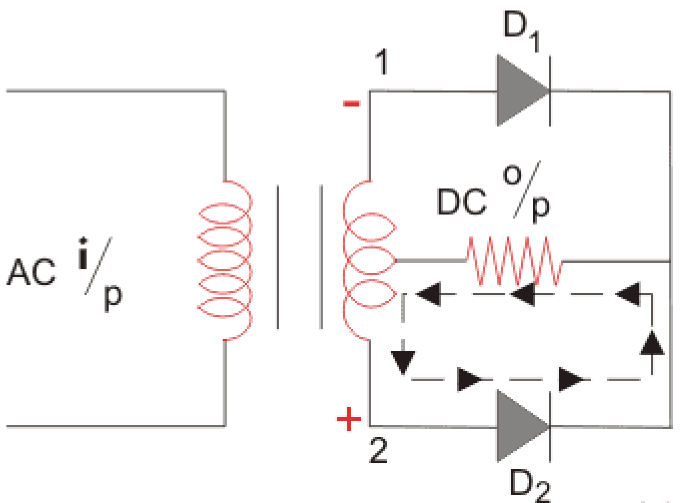


We apply an AC voltage to the input transformer. During the positive half-cycle of the AC voltage, terminal 1 will be positive, center-tap will be at zero potential and terminal 2 will be negative potential. This will lead to forward bias in diode D_1 and cause current to flow through it. During this time, diode D_2 is in reverse bias and will block current through it.



During +ve Cycle

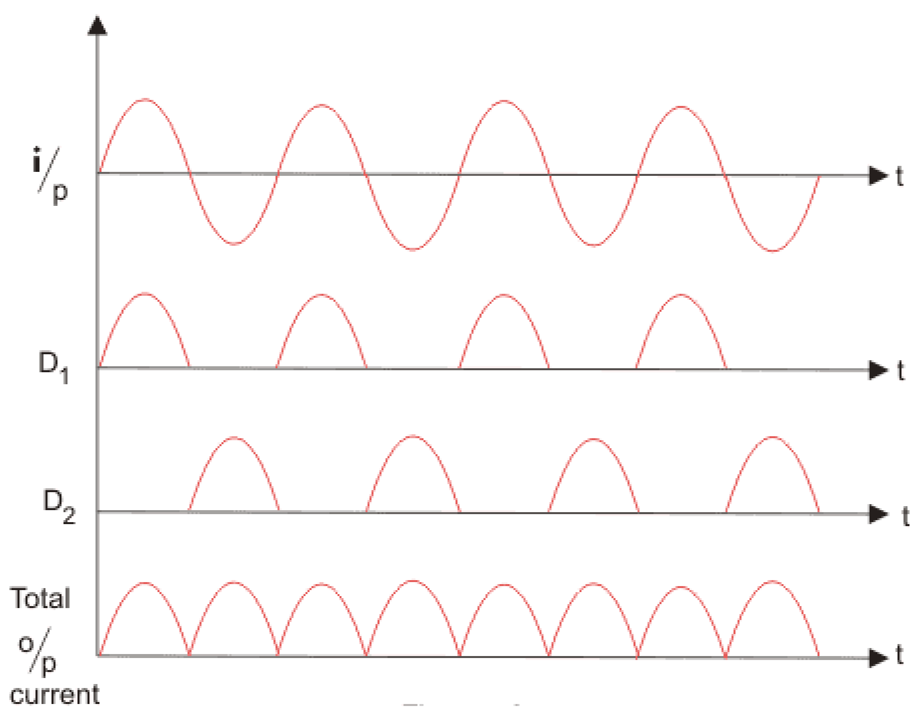
During the negative half-cycle of the input AC voltage, terminal 2 will become positive with relative to terminal 2 and center-tap. This will lead to forward bias in diode D_2 and cause current to flow through it. During this time, diode D_1 is in reverse bias and will block current through it.



During -ve half Cycle

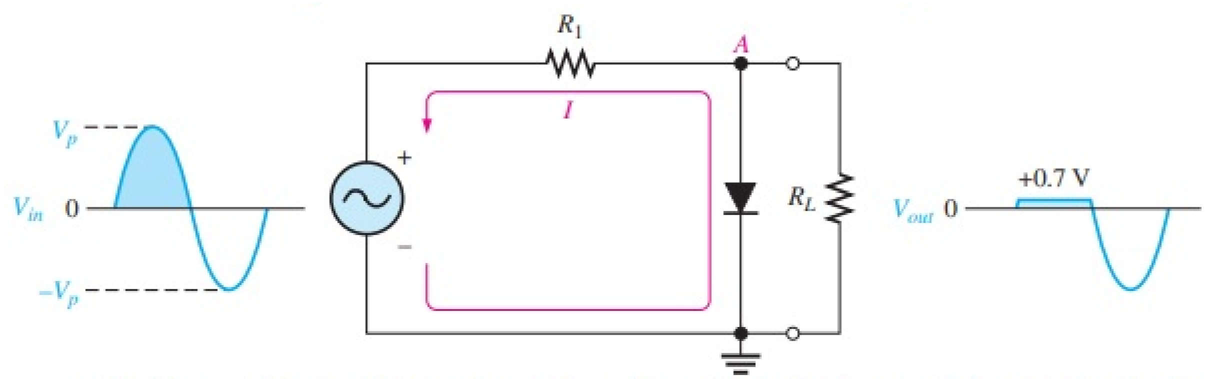
During the positive cycle, diode D_1 conducts and during negative cycle diode D_2 conducts. As a result, both half-cycles are allowed to pass through. The average output DC voltage here is almost twice of the DC output voltage of a half-wave rectifier.

Output Waveforms



Diode Limiters Circuits

Diode limiters are also known as **clipper circuits** that used to clip some portion of the signal. In the below figure, we can see a diode is connected in an input ac signal as the positive portion of input signal comes across the diode it becomes in forward biased condition.



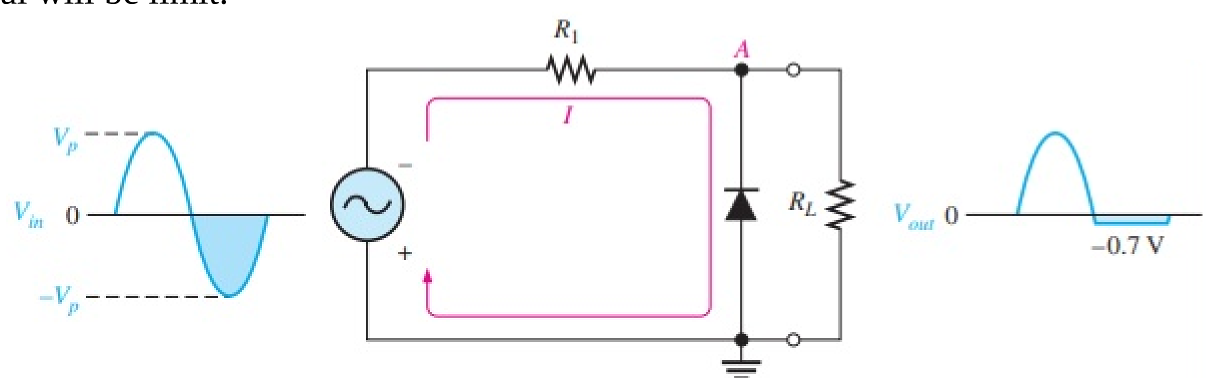
In the above circuit the positive signal is limited to +0.7 volts as it set to that value. When the input signal goes towards a negative signal diode is now in reverse biased condition and operates as an open circuit. The output voltage of this circuitry can be calculated by using the voltage divider rule.

$$V_{out} = \left(\frac{R_L}{R_1 + R_L}\right) V_{in}$$

If the RL >>R1 then the input voltage will be equal to an output voltage.

$$V_{out} = V_{in}$$

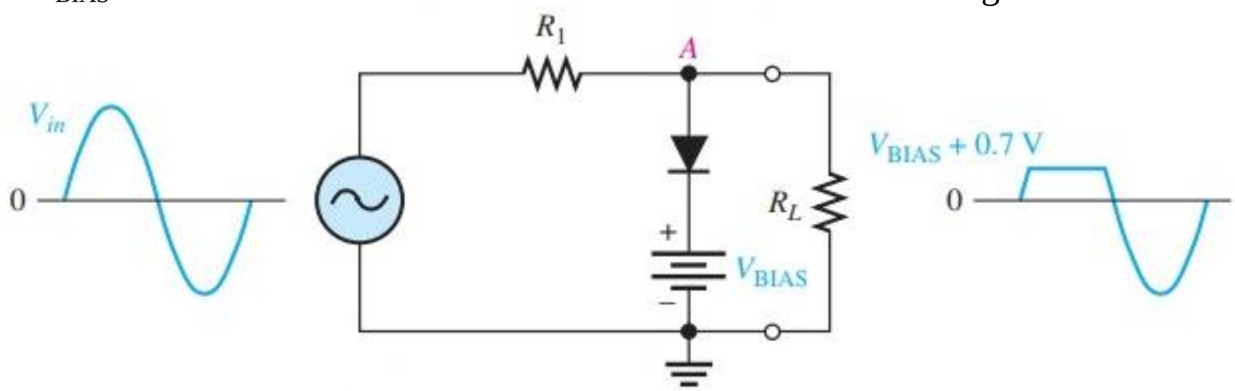
If we vary the direction of the diode as shown in figure below the negative portion of input signal will be limit.



In this state, a diode is forward biased during a negative cycle of a signal and -0.7 volts will be drop across the diode. When the voltage value is larger than the -o.7 volts and a diode is not in a forward-biased condition voltage value across the load resistor is equal to the input supply.

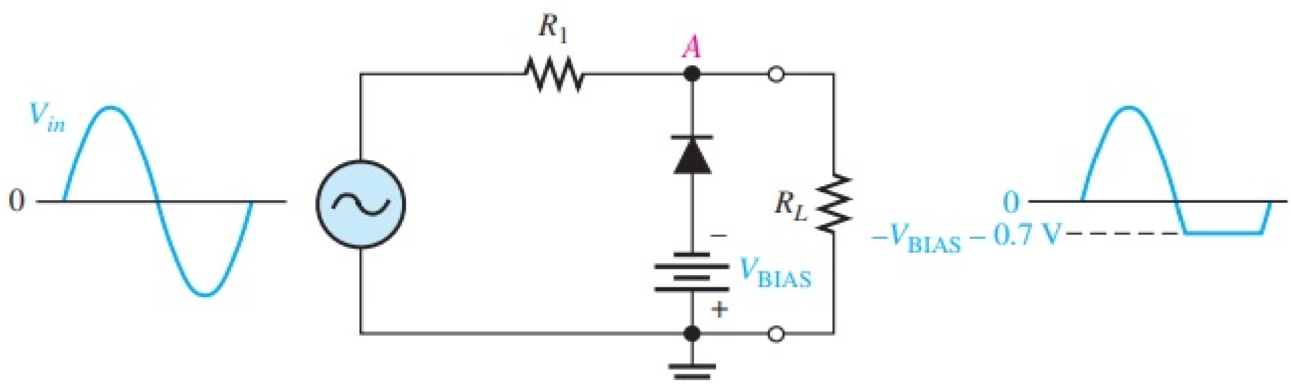
Biased Limiters

In some conditions, we required voltage above the 0.7 volts or -0.7 volts in these case biased limiter circuits are used. The limited voltage can be adjusted by using a bias voltage. This V_{BIAS} is connected in series with the diode as shown in below figure.



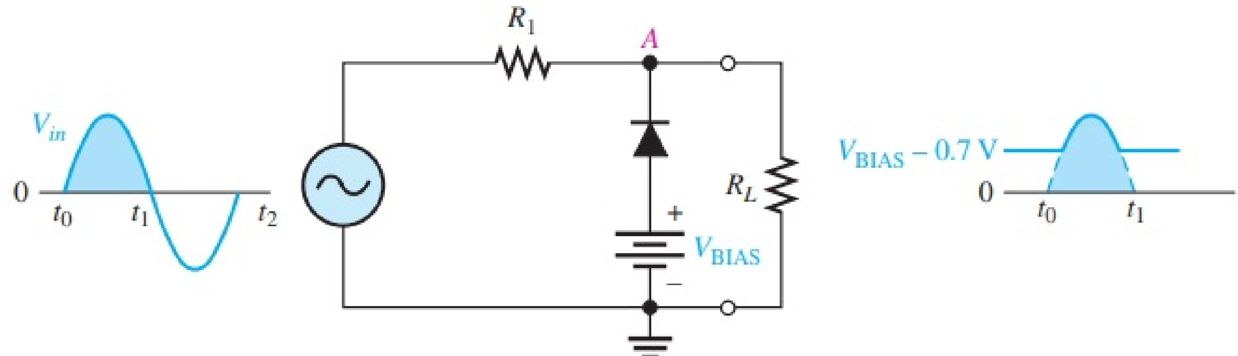
The voltage should be equal to the $V_{BIAS} + 0.7$ before it operates in forward bias. The V_{BIAS} are voltage that will fulfill our requirement after adding in 0.7 volts.
After conducting diode all voltage at the input of diode will limit to the $V_{BIAS} + 0.7$ and the value of voltage above this voltage will be clipped off or limited.

If we require to limit the negative portion of the input signal then the connection arrangements of diode and battery should be according to given below figure**.**

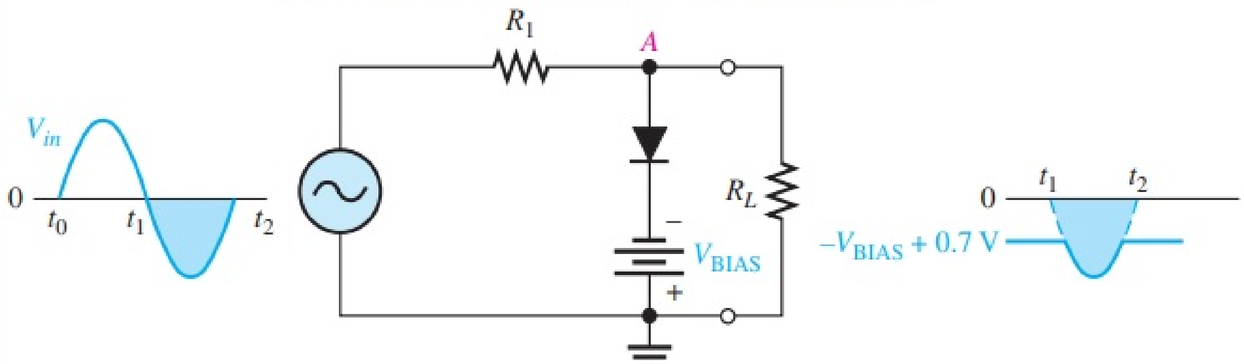


In this case, the voltage at point 'A' will be should go below to the -VBIAS – 0.7 to make diode forward biased and limit the signal.

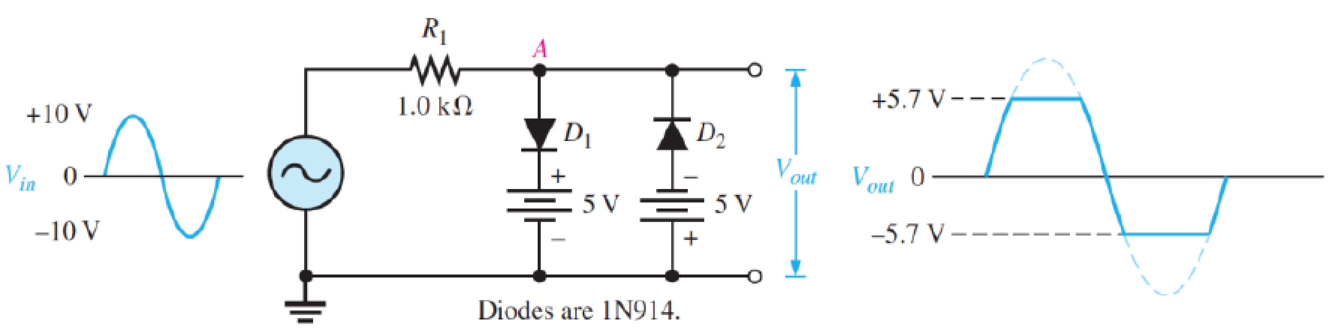
If you change the direction of the diode than a positive limiter will provide an improvement in its function and will limit the input signal to level as shown in the below figure.



The negative limiter can also be modified and limit the input voltage below -VBIAS + 0.7 V shown in the below figure.



In the circuit below combining a positive limiter with a negative limiter.



When the voltage at point A reaches +5.7V, diode D1 conducts and limits the waveform to 5.7V. Diode d2 does not conduct until the voltage reaches -5.7.

Therefore, positive voltages above +5.7V and negative voltages below -5.7V are clipped off.

Diode Clamper Circuits

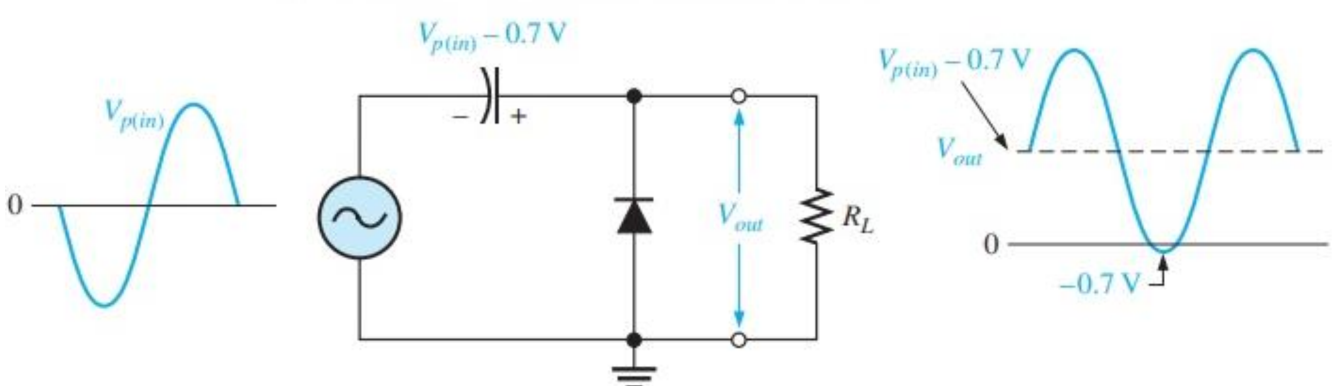
The **clamper** circuits are also known as dc resistors. The main function of these circuits is to add Negative Clamper Circuits some dc level into the input ac signal.

There are 3 main categories of clamper circuits that are listed here.

1- Positive Clamper Circuits
2- Negative Clamper Circuits
3- Biased Clamper Circuits

Positive Clamper Circuits

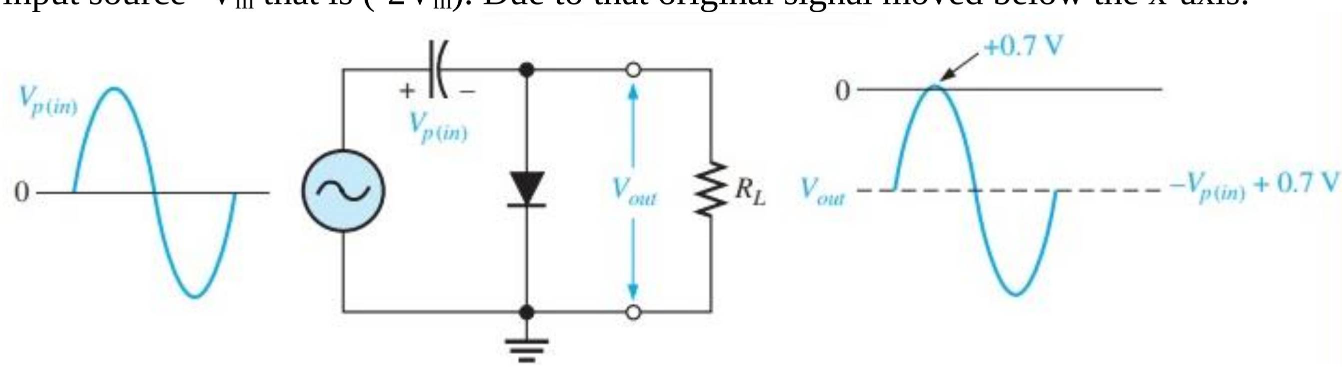
In the below figure the circuit arrangements of positive clamper circuits. This circuit consists of a voltage source V_i capacitor C, diode and load resistance. The diode is linked with the load resistor RL in parallel combination. Due to this arrangement, positive clamper circuits will allow to pass input waveform when a diode is in reversed biased condition and stops input signal to flow when diode is in forward biased condition. When a negative cycle of input waveform comes across the diode it is in forward biased condition and it allows current to flow through the load resistance. Due to this current capacitor get charged to the V_m that is the peak value of input waveform. The charging polarity of capacitor is opposite to signal polarity across a diode. After reaching the extreme point $-V_m$ the capacitor retains the stored charged remains till that point diode is in forward biased condition. When positive half of the input signal passes through the diode it is in reverse biased condition and no current flow through the diode. Due to that, zero current across diode input signal flows towards the load resistance. During a positive cycle, a diode is not in an operating condition so the capacitor releases its stored charge. So the voltage across the load resistance will the addition of voltage across the capacitor V_m due to the charge store and voltage provided by the input source V_m. ($V_o = V_m + V_m = 2V_m$). The polarity of these 2 voltages is also similar. As a consequence, the signal moved to upward that happens in positive clamper circuits.



Negative Clamper Circuits

If we vary the diode position then the negative dc voltage is added with the input signal to generate output similar to shown in the below figure and this type of circuit arrangement is called **negative clamper.**

When a positive cycle is passed through the circuitry the diode is in forward biasing condition due to that zero signal exits across the load resistance. Due forward biasing of diode current passes through the load resistance. Due to this current capacitor gets charged to the extreme value of input signal with the opposite polarity ($-V_m$) and this charge remains till that point diode is in forward biased condition. When a negative cycle comes across circuit diode is in reverse biasing condition so signal exits across load resistance. Due to reverse biasing current does not flows through the diode. So the current coming from the input source moves towards the load resistance. During the negative half, a diode is in a non-operating state and the charge stored on diode will disappear. So the voltage across the load resistance will be an addition of voltage across a capacitor $-V_m$ and voltage due to input source $-V_m$ that is ($-2V_m$). Due to that original signal moved below the x-axis.

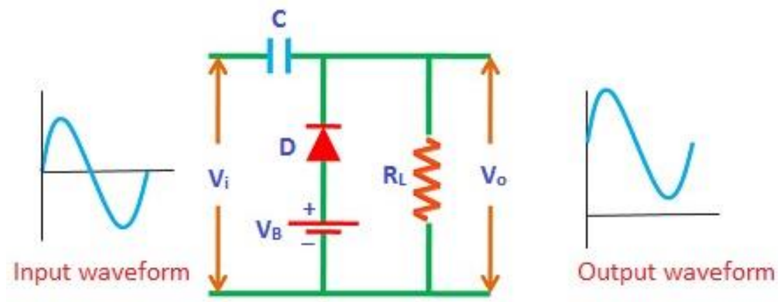


Diode Biased Clamper

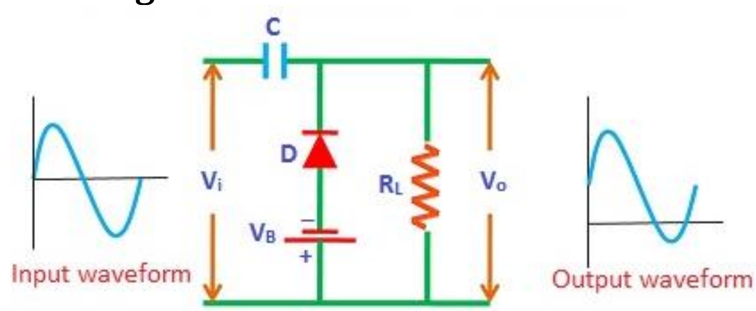
In certain circuits, there is a need of an additional shift in DC level of the input signal. For these purposes, **diode biased clampers** are used. The operation of biased clampers is alike to the unbiased clamper circuits that we have discussed above with the detailed. The difference between biased and unbiased circuits is that in biased circuits additional DC source is used for DC element.

Positive Clamper with Positive Biased

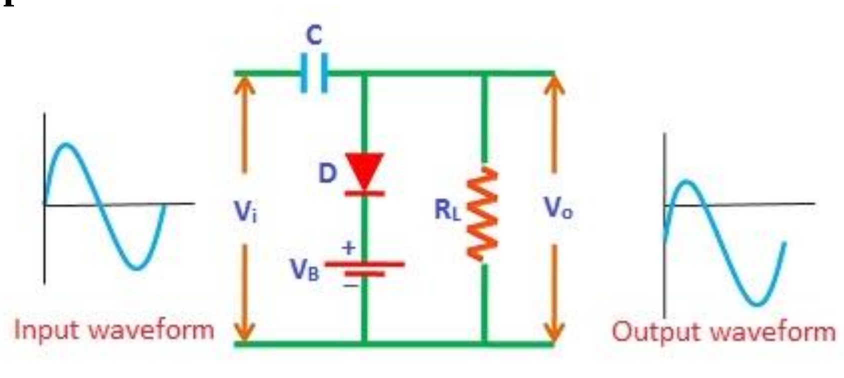
The biased clamper called positive clamper with positive biased if it has positive biasing in the circuitry. The circuitry has a dc source or dc supply, load resistance, capacitor, and diode.



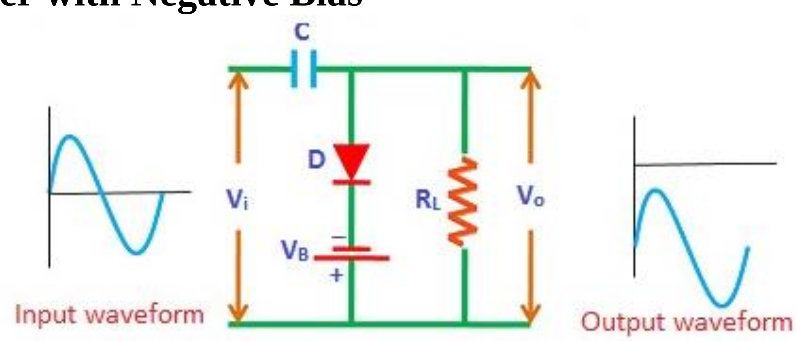
Positive Clamper with Negative Bias



Negative Clamper with Positive Bias



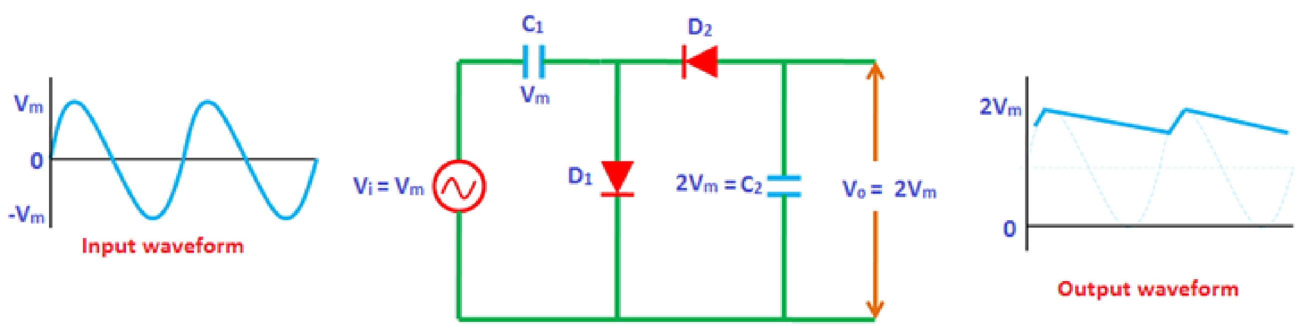
Negative Clamper with Negative Bias



Voltage doubler
Half-wave voltage doubler

A half-wave voltage doubler is a voltage multiplier circuit whose output voltage amplitude is twice that of the input voltage amplitude. During positive half cycle:

The circuit diagram of the half-wave voltage doubler is shown in the below figure. During the positive half cycle, diode D_1 is forward biased. So it allows electric current through it. This current will flows to the capacitor C_1 and charges it to the peak value of input voltage I.e. V_m. However, current does not flow to the capacitor C_2 because the diode D_2 is reverse biased. So the diode D_2 blocks the electric current flowing towards the capacitor C_2. Therefore, during the positive half cycle, capacitor C_1 is charged whereas capacitor C_2 is uncharged.



Half-wave voltage doubler

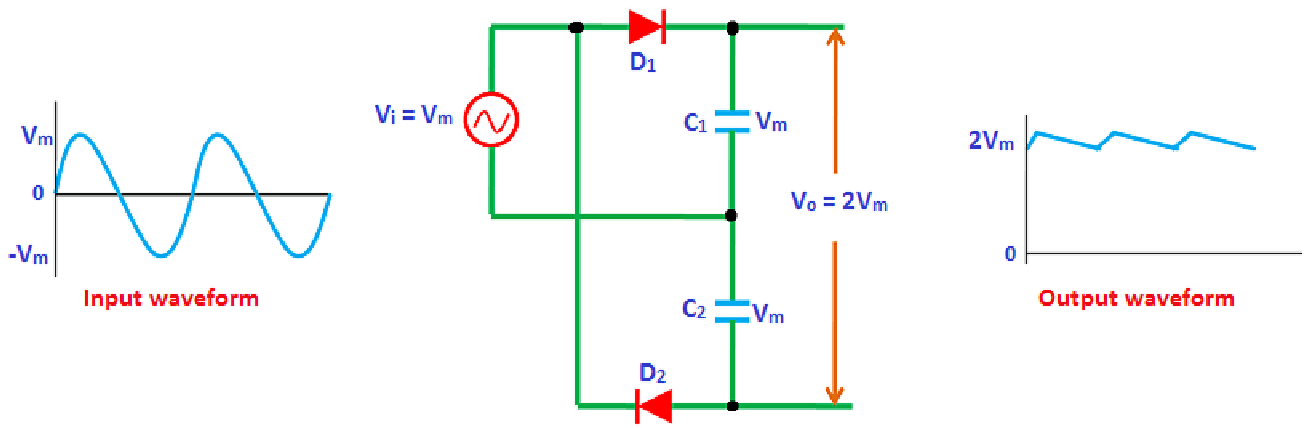
During the negative half cycle, diode D_1 is reverse biased. So the diode D_1 will not allow electric current through it. Therefore, during the negative half cycle, the capacitor C_1 will not be charged. However, the charge (V_m) stored in the capacitor C_1 is discharged (released). The diode D_2 is forward biased during the negative half cycle. So the diode D_2 allows electric current through it. This current will flows to the capacitor C_2 and charges it. The capacitor C_2 charges to a value $2V_m$ because the input voltage V_m and capacitor C_1 voltage V_m is added to the capacitor C_2. Hence, during the negative half cycle, the capacitor C_2 is charged by both input supply voltage V_m and capacitor C_1 voltage V_m. Therefore, the capacitor C_2 is charged to $2V_m$.

If a load is connected to the circuit at the output side, the charge ($2V_m$) stored in the capacitor C_2 is discharged and flows to the output.

Full-wave voltage doubler

The full-wave voltage doubler consists of two diodes, two capacitors, and input AC voltage source.

During the positive half cycle of the input AC signal, diode D_1 is forward biased. So the diode D_1 allows electric current through it. This current will flows to the capacitor C_1 and charges it to the peak value of input voltage V_m. Diode D_2 is reverse biased during the positive half cycle. So the diode D_2 does not allow electric current through it. Therefore, the capacitor C_2 is uncharged.



Full-wave voltage doubler

During the negative half cycle of the input AC signal, the diode D_2 is forward biased. So the diode D_2 allows electric current through it. This current will flows to the capacitor C_2 and charges it to the peak value of the input voltage V_m. Diode D_1 is reverse biased during the negative half cycle. So the diode D_1 does not allow electric current through it.

Thus, the capacitor C_1 and capacitor C_2 are charged during alternate half cycles. The output voltage is taken across the two series connected capacitors C_1 and C_2.

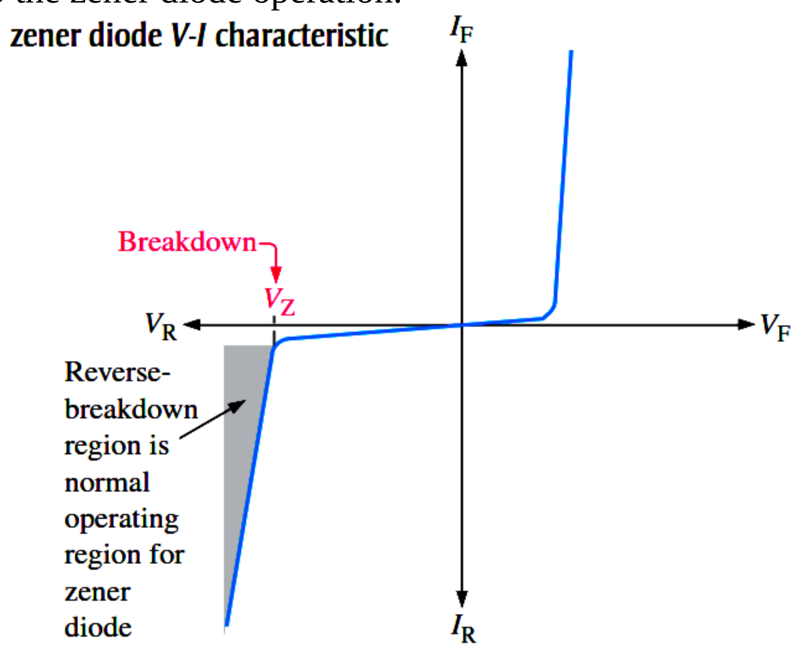
If no load is connected, the output voltage is equal to the sum of capacitor C_1 voltage and capacitor C_2 voltage. $C_1 + C_2 = V_m + V_m = 2V_m$. When a load is connected to the output terminals, the output voltage V_o will be somewhat less than $2V_m$.

Special-Purpose Diodes

The Zener Diode

A major application for Zener diodes is as a type of voltage regulator for providing stable reference voltages for use in power supplies, voltmeters, and other instruments. The symbol for a zener diode is shown in Figure below. A zener diode is a silicon *pn* junction device that is designed for operation in the reverse-breakdown region. When a diode reaches reverse breakdown, its voltage remains almost constant even though the current changes drastically, and this is key to the zener diode operation.

Zener Diode Symbol

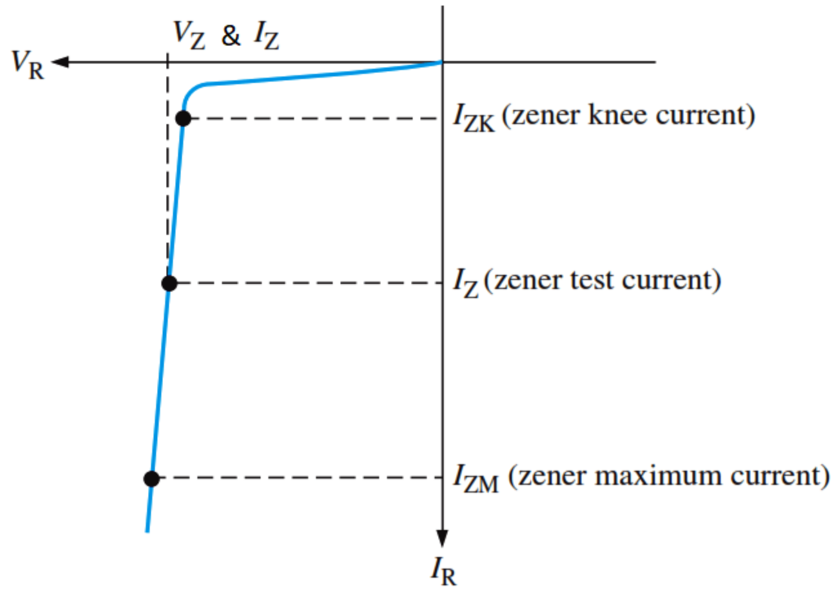


There are two types of reverse break down which happen in reverse bias.

1- **Avalanche break down: happens when the Vz >5V and the doping level is low.**
2- **Zener break down: happens when the Vz < 5V and the doping level is high.**

Both types, however, are called **zener diodes**. Zeners are available with breakdown voltages from less than 1V to more than 250V.

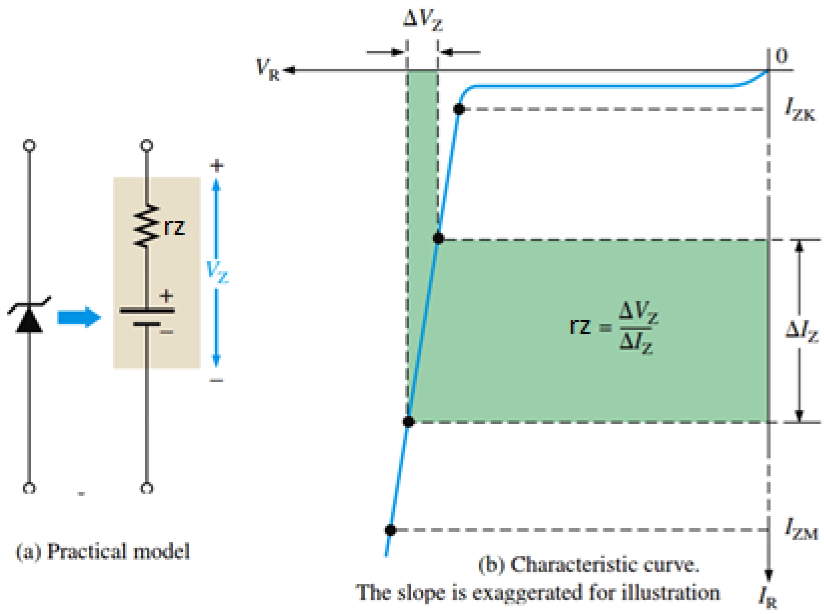
As the reverse voltage (V_R) increases, the reverse current (I_R) remains extremely small up to the knee of the curve. Reverse current is also called zener current (I_z). At knee point the breakdown effect begins, the internal zener resistance (Z_Z) begins to decrease. The reverse current increase rapidly. The zener breakdown (V_Z) voltage remains nearly constant.



Reverse characteristic of a zener diode. V_Z is usually specified at a value of the zener current known as the test current.

The zener impedance, r_Z, is the ratio of a change in voltage in the breakdown region to the corresponding change in current:

$$rz = \frac{\Delta Vz}{\Delta Iz}$$



(a) Practical model

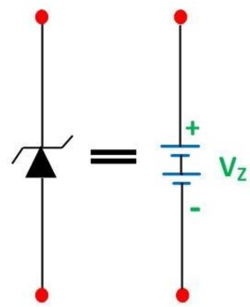
(b) Characteristic curve.
The slope is exaggerated for illustration

Example 1: What is the zener impedance if the zener diode voltage changes from 4.79 V to 4.94 V when the current changes from 5.00 mA to 10.0 mA? **Answer: 30Ω**

Equivalent Circuit of a Zener Diode

Ideal Zener Diode

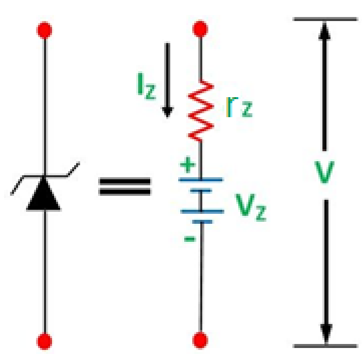
The equivalent circuit diagram is shown below:



In a circuit, an ideal Zener diode can be replaced by a voltage source V_z, when the Zener diode is operating in the breakdown region.

Actual Zener Diode

The figure below shows that the Zener diode has some resistance R_z connected in series with the battery of voltage V_z**.**



The voltage across the Zener diode will be:
$V = Vz + Izrz$

Ex: A (6.8V) zener diode has a resistance (5Ω), what the actual voltage across its terminals when the current is (20mA)

$$V = Vz + Izrz = 6.8 + 20 * 10^{-3} * 5 = 6.9V$$

Temperature Coefficient:

The temperature coefficient specifies the percent change in Zener voltage for each degree Celsius change in temperature. The formula for calculating the change in Zener voltage for a given junction temperature change, for a specified temperature coefficient, is

$$\Delta Vz = Vz \times Tc \times \Delta T$$

Where

Vz : is the nominal Zener voltage at the reference temperature of 25 °C.

Tc : is the temperature coefficient.

ΔT: is the change in temperature from the reference temperature.

A positive TC means that the Zener voltage increases with an increase in temperature.
A negative TC means that the Zener voltage decreases with an increase in temperature.

Ex: An 8.2V zener diode (8.2V at 25°C) has a positive temperature coefficient of 0.05%/°C. What is the zener voltage at 60°C?

Solution:

$\Delta Vz = Vz \times Tc \times \Delta T$

(8.2V)(0.05%/°C)(60°C - 25°C) = (8.2V)(0.0005/°C)(60°C - 25°C)= 144mV.

Zener voltage at 60°C= $\Delta Vz + Vz$=0.144+8.2=8.344

Zener power dissipation

The zener power dissipation is accounted by this equation:

$P_z = V_z I_z$

For max $I_z \rightarrow P_{zmax} = V_z I_{zmax}$

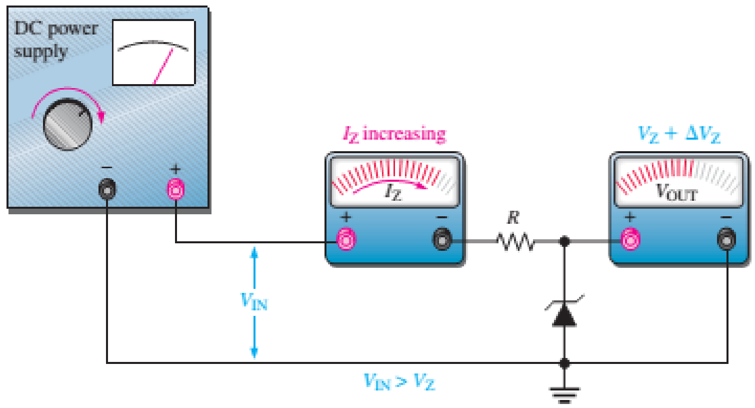
For min $I_z \rightarrow P_{zmin} = V_z I_{zk}$

EX: determine the maximum power dissipation of a zener diode has $V_z = 20V$ and I_z changes at (2mA to 20mA).

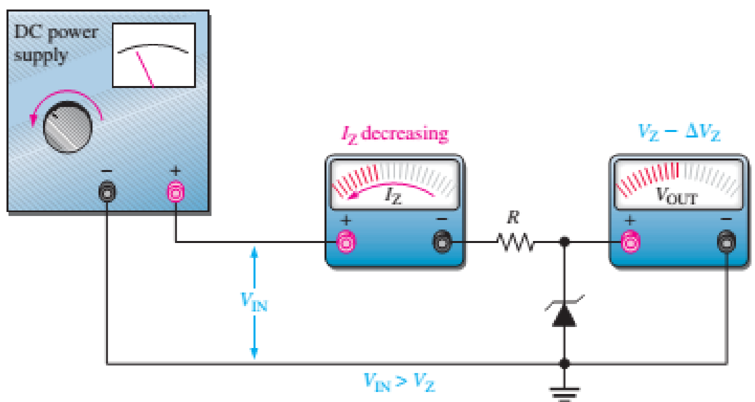
$P_{zmax} = V_z I_{zmax} = 20 * 20 = 400mW$

Output voltage regulation with a varying input voltage

The zener diode can be used as a type of voltage regulator for providing stable reference voltages as in Figure below. The ability to keep reverse voltage constant across its terminal is the key feature of the zener diode. It maintains constant voltage over a range of reverse current values. A **minimum reverse current I_{ZK}** must be maintained in order to keep diode in regulation mode. Voltage decreases drastically if the current is reduced below the knee of the curve. Above I_{ZM}, max current, the zener may get damaged permanently.



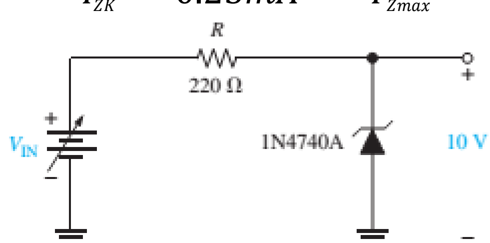
(a) As the input voltage increases, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).



(b) As the input voltage decreases, the output voltage remains nearly constant ($I_{ZK} < I_Z < I_{ZM}$).

To illustrate regulation, let us use the ideal model of the 1N4740A zener diode (ignoring the zener resistance) in the circuit of the following Figure.

• Ideal model of IN4047A • $I_{ZK} = 0.25mA$ •$P_{Zmax} = 1W$ • VZ = 10V



For the minimum zener current, the voltage across the 220Ω resistor is

$V_R = I_{ZK} R = (0.25\, mA)(220\Omega) = 55mV,$

Since

$V_{IN} = V_R + V_Z = 55mV + 10V = 10.055V$,

For the maximum zener current, the voltage across the 220Ω resistor is

$$I_{zmax} = \frac{P_{zmax}}{V_z} = \frac{1}{10} = 100\ mA$$

$V_R = I_{Zmax} R = (100\ mA)(220\Omega) = 22mV$

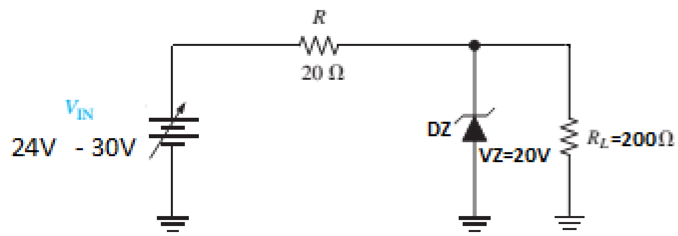
Therefore,

$V_{IN(\max)} = V_R + V_Z = 22mV + 10V = 32V$,

This shows that this zener diode can ideally regulate an input voltage from 10.055 to 32V and maintain an approximate 10V output.

EX: Voltage regulation as shown in fig below determine:

1- I_{ZK} , I_{Zmax}
2- Maximum power dissipation for the resistance R P_{Rmax} and for the zener P_{Zmax}



$$I_L = \frac{V_Z}{R_L} = \frac{20V}{200\Omega} = 0.1A$$

The total voltage for the resistance R

$$V_{in} - V_R = V_Z \quad \rightarrow I_t = \frac{V_{in} - V_Z}{R}$$

$$I_{t\ min} = \frac{V_{in\ min} - V_Z}{R} = \frac{24 - 20}{20} = 0.2A$$

$$I_{t\ max} = \frac{V_{in\ max} - V_Z}{R} = \frac{30 - 20}{20} = 0.5A$$

$$I_t = I_z + I_L \rightarrow I_z = I_t - I_L$$

$$I_{zk} = I_{tmin} - I_L = 0.2 - 0.1 = 0.1A$$

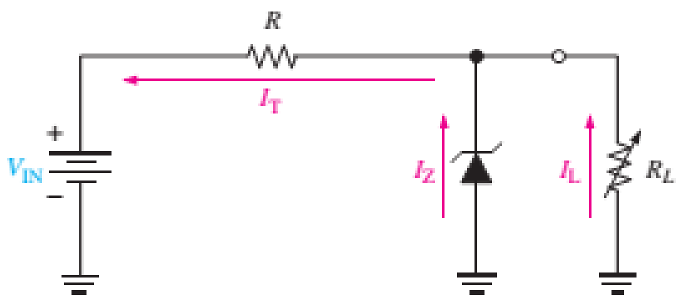
$$I_{zmax} = I_{tmax} - I_L = 0.5 - 0.1 = 0.4A$$

$$P_{Rmax} = (I_{tmax})^2 * R = 0.25 * 20 = 5W$$

$$P_{Zmax} = I_{Zmax} * V_Z = 0.4 * 20 = 8W$$

Voltage regulation with a varying load

Figure below shows a zener voltage regulator with a variable load resistor across the terminals. The zener diode maintains a nearly constant voltage across R_L as long as the zener current is greater than I_{ZK} and less than I_{ZM}.



When $R_L=\infty$ (open circuit)

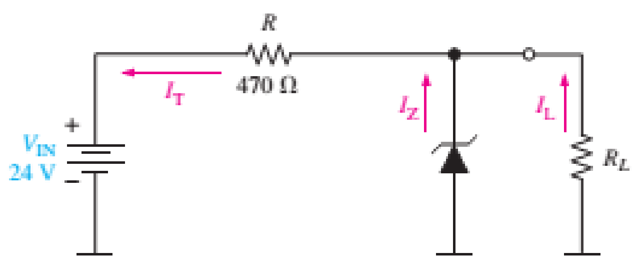
Load current I_L is zero and all of the current pass through zener diode.

When R_L is connected, current is divided between zener diode and R_L.

The total current through R remains constant as long as the zener is regulating.

As R_L decreases, I_L increase and I_Z decreases. The zener continues to regulate the voltage until I_Z reaches its minimum value. Now, the load current is maximum, and a full-load condition exists.

Ex: Determine the minimum and the maximum load currents for which the zener diode in Figure below will maintain regulation. What is the minimum value of R_L that can be used? V_Z=12V, I_{ZK}=1mA, and I_{ZM} =50mA. Assume an ideal zener diode where r_Z=0Ω and V_Z remains a constant 12V over the range of current values.



When $I_L = 0\ ,(R_L = \infty)\ , I_Z = I_{Zmax} = I_T$

$$I_{Zmax} = I_T = \frac{V_{in} - V_Z}{R} = \frac{24 - 12}{470} = 25.5mA$$

This value is less than 50mA, R_L can be removed without disturbing regulation.
$I_{L(\min)} = 0$

$I_{L(\max)}$ Occurs when I_Z is minimum $(I_Z = I_{ZK})$

$I_{L(max)} = I_T - I_{ZK} = 25.5mA - 1mA = 24.5mA$

Minimum value of R_L is

$$R_{Lmin} = \frac{V_Z}{I_{Lmax}} = \frac{12}{24.5} = 490\Omega$$

Percent Regulation

- Line regulation : specifies how much change occurs in the output voltage for a given change in the input voltage

$$Line\ Regulation = \frac{\Delta V_{out}}{\Delta V_{in}} * 100\%$$

- Load regulation : specifies how much change occurs in the output voltage over a certain range of load current value

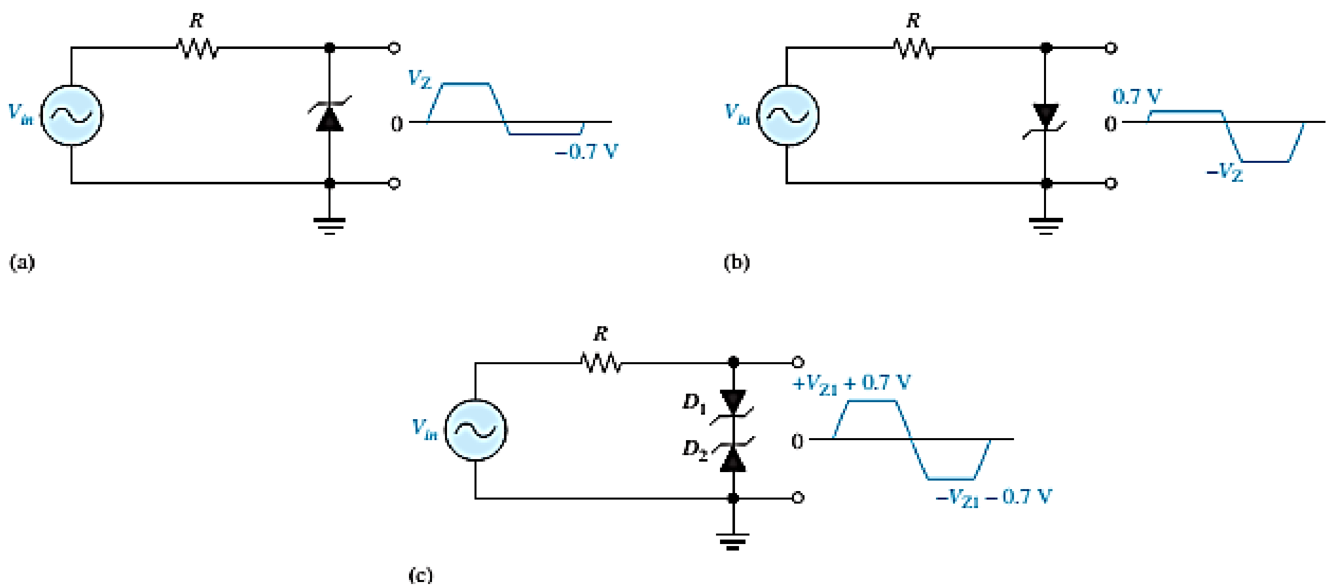
$$Load\ regulation = \frac{V_{NL} - V_{FL}}{V_{FL}} * 100\%$$

Ex: a certain regulation has no load output voltage 12 volts and full load output voltage 10 volts. Determine the percent load regulation

$$Load\ regulation = \frac{V_{NL} - V_{FL}}{V_{FL}} * 100\% = \frac{12 - 10}{10} * 100\% = 20\%$$

Zener Limiter

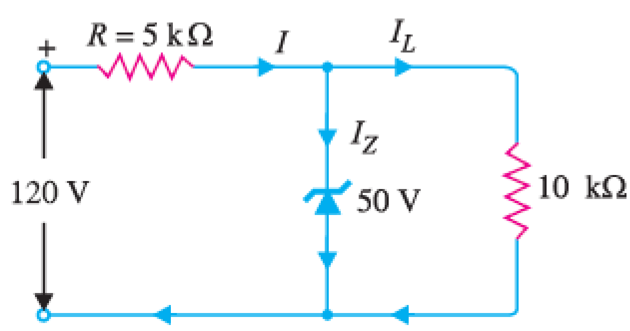
Zener diodes can be used as limiters. Figure below shows three basic ways the limiting action of a zener diode can be used. During the negative alternation, the zener acts as a forward-biased diode and limits the negative voltage to-0.7V as in part (A). When the zener is turned around, as in part (b), the negative peak is limited by zener action and the positive voltage is limited to +0.7V. Two back-to-back zeners limit both peaks to the zener voltage ± 0.7V as shown in part (c).



Basic zener limiting action with a sinusoidal input voltage.

Additional examples

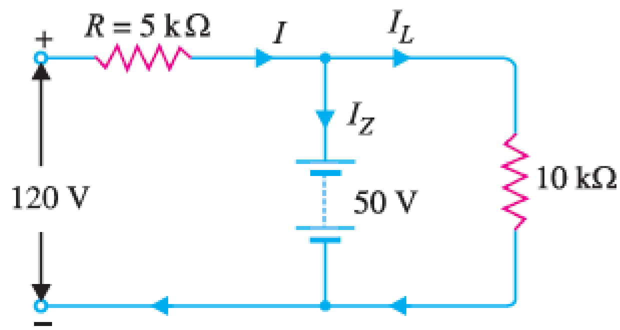
1) For the circuit shown in Fig below find: (i) V_{out} (ii) V_R (iii) I_Z.



If you remove the zener diode, the voltage V across the open-circuit is given by:

$$V = \frac{V_{IN} R_L}{R + R_L} = \frac{10 \times 120}{5 + 10} = 80V$$

Since voltage across zener diode is greater than VZ (= 50 V), the zener is in the "on" state. It can,
therefore, be represented by a battery of 50 V as shown in Fig below.



(i)

Output voltage $= V_Z = \mathbf{50\ V}$

(ii)

Voltage drop across R $=$ Input voltage $- V_Z = 120 - 50 = \mathbf{70\ V}$

(iii)

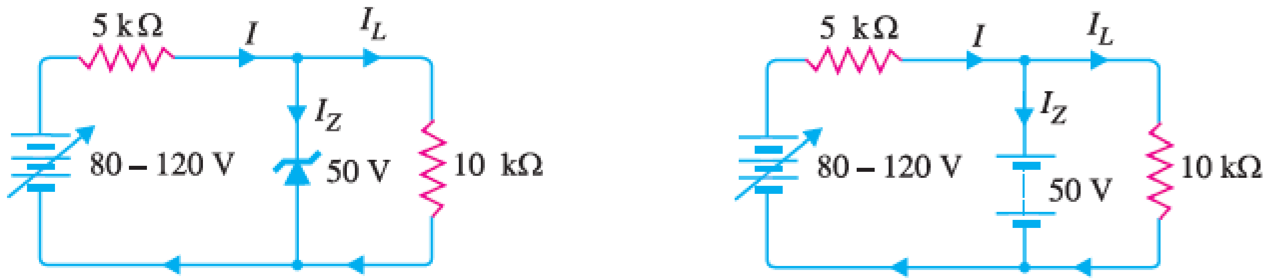
Load current, $I_L = V_Z/R_L = 50\text{ V}/10\text{ k}\Omega = 5\text{ mA}$

Current through R, $I = \frac{70\text{ V}}{5\text{ k}\Omega} = 14\text{ mA}$

Applying Kirchhoff's first law, $I = I_L + I_Z$

$\therefore$ Zener current, $I_Z = I - I_L = 14 - 5 = \mathbf{9\ mA}$

2) For the circuit shown in Fig. below part A find the maximum and minimum values of zener diode current.



A B

The first step is to determine the state of the zener diode. It is easy to see that for the given range of voltages (80 − 120 V), the voltage across the zener is greater than VZ (= 50 V). Hence the zener diode will be in the "on" state for this range of applied voltages. Consequently, it can be replaced by a battery of 50 V as shown in Fig. part B.

Maximum zener current: The zener will conduct maximum current when the input voltage is maximum i.e. 120 V. Under such conditions :

$$\text{Voltage across 5 k}\Omega = 120 - 50 = 70\text{ V}$$

$$\text{Current through 5 k}\Omega,\ I = \frac{70\text{ V}}{5\text{ k}\Omega} = 14\text{ mA}$$

$$\text{Load current, } I_L = \frac{50\text{ V}}{10\text{ k}\Omega} = 5\text{ mA}$$

$$\text{Applying Kirchhoff's first law, } I = I_L + I_Z$$

$$\therefore \quad \text{Zener current, } I_Z = I - I_L = 14 - 5 = \mathbf{9\text{ mA}}$$

Minimum Zener current: The zener will conduct minimum current when the input voltage is minimum 80 V. Under such conditions, we have,

$$\text{Voltage across 5 k}\Omega = 80 - 50 = 30\text{ V}$$

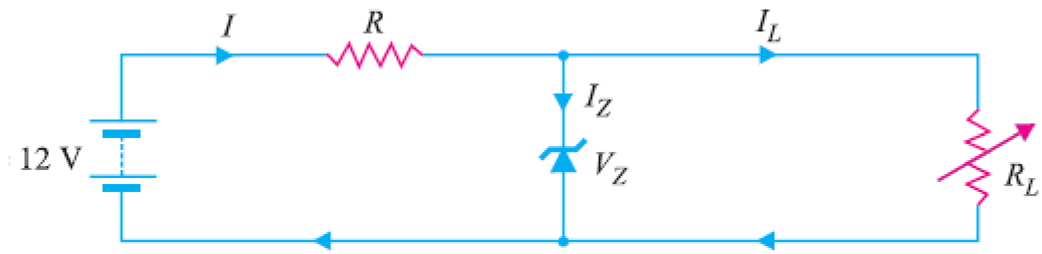
$$\text{Current through 5 k}\Omega,\ I = \frac{30\text{ V}}{5\text{ k}\Omega} = 6\text{ mA}$$

$$\text{Load current, } I_L = 5\text{ mA}$$

$$\therefore \quad \text{Zener current, } I_Z = I - I_L = 6 - 5 = \mathbf{1\text{ mA}}$$

3) A 7.2 V zener is used in the circuit shown in Fig. below and the load current is to vary from 12 to 100 mA. Find the value of R to maintain a voltage of 7.2 V across

the load. The input voltage is constant at 12V and the minimum zener current is 10 mA.



$V_i = 12V \quad ; \quad V_z = 7.2V$

$$R = \frac{V_i - V_o}{I_z + I_L}$$

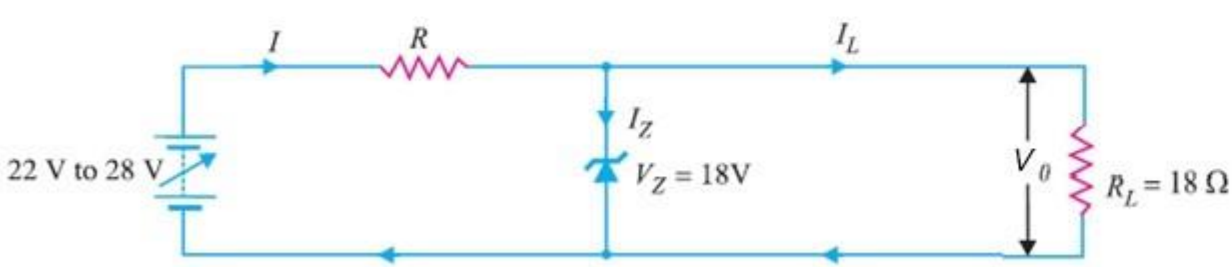
The voltage across R is to remain constant at 12 − 7.2 = 4.8 V as the load current changes from 12 to 100 mA. The minimum zener current will occur when the load current is maximum.

$$\therefore \; R = \frac{V_i - V_o}{(I_z)_{min} + (I_L)_{max}} = \frac{12V - 7.2V}{(10 + 100)mA} = \frac{4.8V}{110mA} = 43.5\Omega$$

If R = 43.5 Ω is inserted in the circuit, the output voltage will remain constant over the regulating range. As the load current IL decreases, the zener current IZ will increase to such a value that IZ + IL = 110 mA.

Note that if load resistance is open-circuited, then IL = 0 and zener current becomes 110 mA.

4) The zener diode shown in Fig. below has VZ = 18 V. The voltage across the load stays at 18 V as long as IZ is maintained between 200 mA and 2 A. Find the value of series resistance R so that V_0 remains 18 V while input voltage Vi is free to vary between 22 V to 28V.

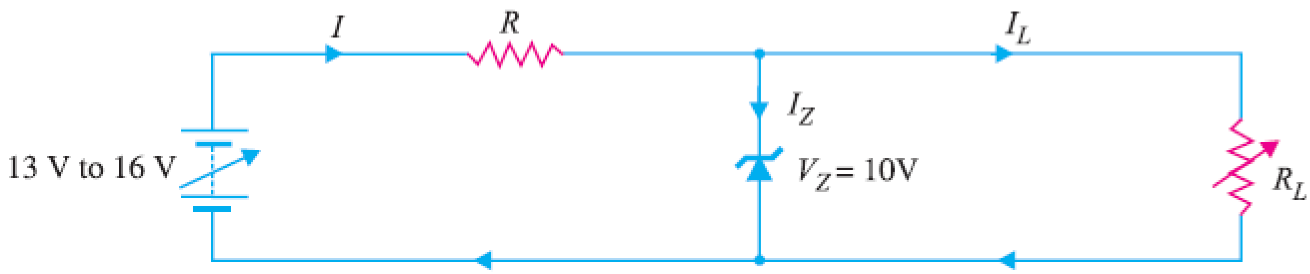


The zener current will be minimum (200 mA) when the input voltage is minimum (22 V).

The load current stays at constant value $I_L = \frac{V_Z}{R_L} = \frac{18V}{18\Omega} = 1A = 1000mA$

$$\therefore\ R = \frac{V_i - V_o}{(I_z)_{min} + (I_L)_{max}} = \frac{22V - 18V}{(200 + 1000)mA} = \frac{4V}{1200mA} = 3.33\Omega$$

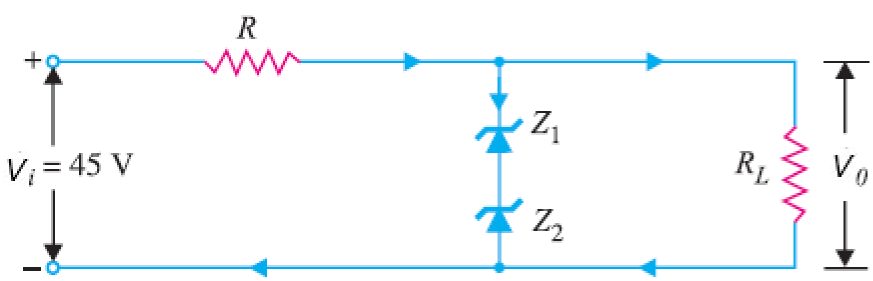
5) A 10-V zener diode is used to regulate the voltage across a variable load resistor. The input voltage varies between 13 V and 16 V and the load current varies between 10 mA and 85 mA. The minimum zener current is 15 mA. Calculate the value of series resistance R.



The zener will conduct minimum current (15 mA) when input voltage is minimum (13 V).

$$\therefore\ R = \frac{V_i - V_o}{(I_z)_{min} + (I_L)_{max}} = \frac{13V - 10V}{(15 + 85)mA} = \frac{3V}{100mA} = 30\Omega$$

6) The circuit in Fig. below uses two zener diodes, each rated at 15 V, 200 mA. If the circuit is connected to a 45-volt unregulated supply, determine :(i) The regulated output voltage (ii) The value of series resistance R.



When the desired regulated output voltage is higher than the rated voltage of the zener, two or more zeners are connected in series. However, in such circuits, care must be taken to select those zeners that have the same current rating.

Current rating of each zener, $I_Z = 200$ mA

Voltage rating of each zener, $V_Z = 15$ V

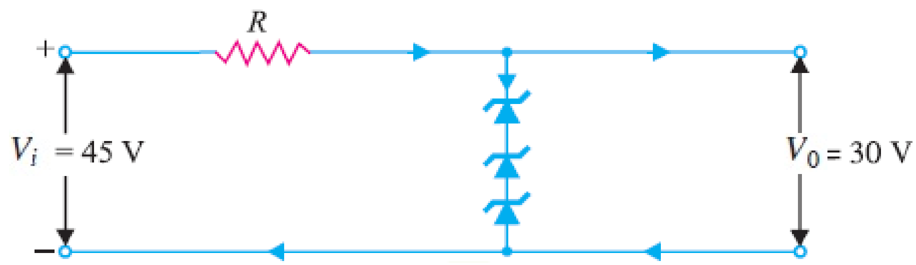
Input voltage, $V_i = 45$ V

(*i*) Regulated output voltage, $V_0 = 15 + 15 = \mathbf{30\ V}$

(*ii*) Series resistance, $R = \dfrac{V_i - V_0}{I_Z} = \dfrac{45 - 30}{200 \text{ mA}} = \dfrac{15 \text{ V}}{200 \text{ mA}} = \mathbf{75\ \Omega}$

7) What value of series resistance is required when three 10-watt, 10-volt, 1000 mA zener diodes are connected in series to obtain a 30-volt regulated output from a 45 volt d.c. power source?

the desired circuit. The worst case is at no load because then zeners carry the maximum current.



Voltage rating of each zener, $V_Z = 10$V

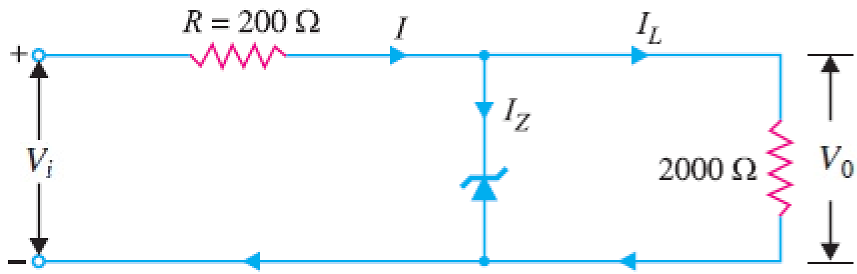
Current rating of each zener, $I_Z = 1000$mA

Input unregulated voltage, $V_i = 45$V

Regulated output voltage, $V_0 = 10 + 10 + 10 = 30$ V

$\therefore$ Voltage across $R = \dfrac{V_i - V_0}{I_Z} = \dfrac{15 \text{ V}}{1000 \text{ mA}} = \mathbf{15\ \Omega}$

8) What range of input voltage will the zener circuit shown in Fig. below maintain 30 V across 2000 Ω load, assuming that series resistance R = 200 Ω and zener current rating is 25 mA ?



The minimum input voltage required will be when IZ = 0. Under this condition,

$$I_L = I = \frac{30\text{ V}}{2000\ \Omega} = 15\text{ mA}$$

∴ Minimum input voltage $= 30 + IR = 30 + 15\text{ mA} \times 200\ \Omega$

$= 30 + 3 = \mathbf{33\ V}$

The maximum input voltage required will be when $I_Z = 25$ mA. Under this condition,

$$I = I_L + I_Z = 15 + 25 = 40\text{ mA}$$

∴ Max. input voltage $= 30 + IR$

$= 30 + 40\text{ mA} \times 200\ \Omega$

$= 30 + 8 = \mathbf{38\ V}$

Therefore, the input voltage range over which the circuit will maintain 30 V across the load is **33 V to 38 V.**