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Semiconductor Diodes.

Introduction:

Semiconductor is a chemical Element in which the conductivity lies between conductor and insulator, Hence the movement of electrons (Current Conduction) can be controlled easily by means of an external voltage (Biasing).

Two types of Semiconductors
1. Intrinsic Semiconductor (Pure Semiconductor) and
2. Extrinsic Semiconductor (Impure semiconductor/Added impurity)

Extrinsic semiconductor is further classified into two types
a. P-Type Extrinsic Semiconductor (Doping Trivalent element) and
b. N-Type Extrinsic Semiconductor (Doping Pentavalent element).

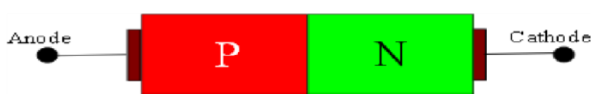
The holes are majority charge carriers and electrons are minority charge carriers in P-Type and electrons are majority and holes are minority charge carriers in case of N-Type Semiconductor.

P-N Junction(Semiconductor Diode/ Diode):

Construction: +

Starting with a piece of intrinsic semiconductor and divide it into two halves, one half is doped with any tri-valent element such as Boron, Aluminum etc., to form P-Type semiconductor, in which the holes are majority charge carriers and electrons are minority charge carriers. Other half is doped with any penta-valent element such as phosphorus, arsenic etc., to form N-Type Semiconductor, in which the electrons are majority charge carriers and holes are minority charge carriers.

The Junction or a line dividing the P-Type and N-Type is called P-N Junction. Metallic contact is connected to P-Type and N-Type material to get terminals for the device called Electrodes such as Anode and Cathode, this device is called P-N Junction Diode or Semiconductor diode or simply Diode as shown in figure(1).



Figure(1): P-N Junction Diode/Diode

Working:

The working principle can be studied in three different operations or Biasing arrangements as follows.

Case (1): Zero Biasing.

Without any external supply and at normal room temperature, at the time of contact with P-Type and N-Type material, it has a tendency to move or diffusing the electrons from N side and occupies holes from the P side. Similarly holes in the P side attract electrons in the N side. This results forming a thin layer near the P-N Junction due to loosing electrons near the junction from the N side and holes near the junction from the P side. This layer or region is called depletion layer and it acts as an intrinsic semiconductor as shown in figure (2).

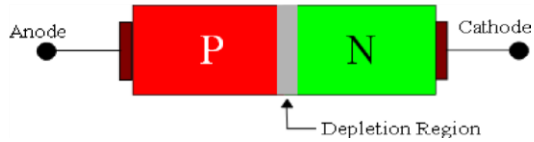


Figure (2): P-N Junction Diode/Diode with depletion layer/region.

Case (2): Reverse Biasing.

External supply with Positive terminal of the battery is connected to the cathode and negative terminal of the battery is connected to the anode is called Reverse biasing.

With this biasing the negative terminal of the battery sucks out or attracts the holes from P-Type material and positive terminal of the battery sucks out or attract electrons from N-Type material, this results wider depletion region and the resistance is very high, and the current that flows through the device only due to minority charge carriers as shown in figure (3).

The magnitude of current under reverse biasing is in terms of nano amperes for silicon diodes.

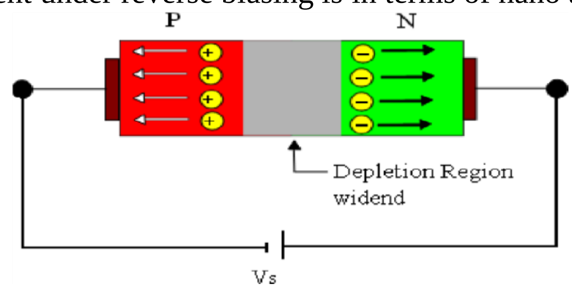


Figure (3): P-N Junction Diode is under Reverse Biasing.

Case (3): Forward Biasing.

External Supply with Positive terminal of the battery is connected to the anode and negative terminal of the battery is connected to the cathode is called forward biasing.

With this biasing the negative terminal of the battery pushes or pumps more electrons to the N-Type material and positive terminal of the battery pushes or pumps more holes to the P- Type material. By go on increasing the biasing voltage the width of the depletion region decreases, Resistance decreases and the current flowing through the device is increases(not proportional to voltage). If the Biasing voltage V_S is greater than or equal to V_γ (Thresold Voltage) the depletion layer completely vanishes and easily current will flow as shown in figure (4).The cut in voltage or threshold voltage (V_γ) for silicon diodes is 0.7 V and for Germanium diodes is 0.3V.

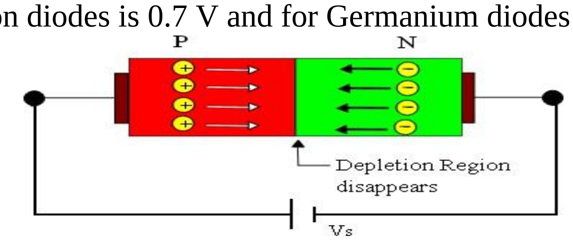


Figure (4): P-N Junction Diode is under Forward Biasing.

V-I Characteristics:

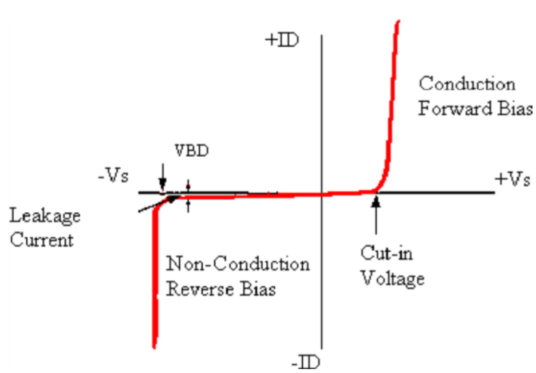


Figure (5): V-I Characteristics of P-N Junction Diode.

Figure (5) shows the V-I Characteristics of P-N Junction diode, V_S is the biasing voltage, I_D is the Diode Current and V_{BD} is the Break down voltage. The leakage current flows through the device under reverse biasing due to minority charge carriers. Under forward biasing and biasing voltage is greater than or equal to the threshold voltage, the device then acts as a conducting material.

Diode Characteristic Parameters:

1. Reverse Resistance (R_r):

The ratio of Reverse biasing voltage to the reverse current is called Reverse resistance of the PN Junction Diode.

i.e., $R_r = \frac{V_R}{I_o}$; where, V_R is the Biasing voltage under reverse biasing, called as reverse voltage and I_o is the reverse leakage current.

2. Forward Resistance (R_f):

The ratio of Forward biasing voltage to the Forward current is called Forward resistance of the PN Junction Diode.

i.e., $R_r = \frac{V_F}{I_F}$; where, V_F is the Biasing voltage under Forward biasing, called as Forward voltage and I_D is the Forward Current.

Diode Current Equation:

The diode current equation is given by,

$$I_D = I_O(e^{\frac{V_F}{\eta V_T}} - 1)$$

Where,

I_D is the diode current,

I_O is the reverse saturation or leakage current,

V_F is the applied forward voltage, η is a constant 1 for Ge and 2 for Si and

$$V_T = \frac{kT}{q};$$

V_T is the volt equivalent temperature (Thermal Voltage) is given by, Where, k is the boltzmann's constant, T is the temperature in Kelvin and q is the charge of an electron.

$$k = 1.38064852 \times 10^{-23} J/K$$

$$q = 1.6x10^{-19} Coloumbs$$

At room Temperature, i.e., at 300°K,

$$V_T = 25.85mV \approx 26mV$$

Or

$$V_T = \frac{T}{11600}$$

Equivalent Circuit of diode:

1. DC Equivalent Circuit.

The DC equivalent circuit of a diode under reverse biasing is an open circuit or Reverse Resistance R_r(typically in terms of MΩ) shown in figure (6a), and under forward biasing as shown in figure (6). Where R_f is the forward resistance of the diode, V_{ON} is the voltage drop across the diode under Conduction State (V_{ON}=0.7V for Silicon diodes and V_{ON}=0.3V for Germanium Diodes).

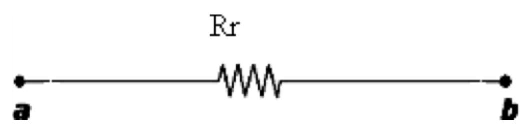


Figure (6a): Diode DC Equivalent Circuit under reverse biasing.

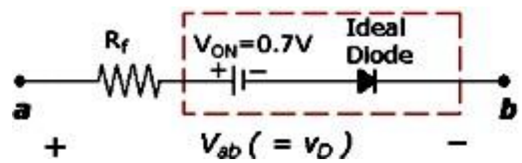


Figure (6b): Diode DC Equivalent Circuit under forward biasing.

2. AC Equivalent Circuit.

The AC equivalent circuit of a diode under reverse biasing and for forward biasing is the parallel connection of a Resistor and a Capacitor as shown in figure (7a) and figure (7b) respectively.

Under reverse biasing the depletion layer width increases and acts as a parallel plate capacitor with dielectric, hence the diode will be considered as a capacitor called Transition Capacitance/ Junction Capacitance/ Space charge Capacitance.

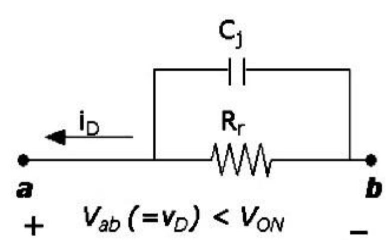


Figure (7a): AC Equivalent circuit under Reverse Biasing.

Under forward biasing the rate of change of charge carriers increases with respect to the applied forward voltage, hence the diode under forward biasing acts as a capacitor called diffusion Capacitance.

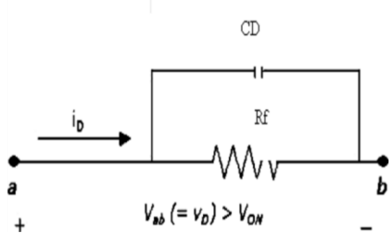


Figure (7b): AC equivalent Circuit under forward biasing.

Effect of Temperature on Diodes:

The number of charge carriers will vary depending on the temperature. i.e., if temperature increases the number of charge carriers also increases and due to this the conduction current (ID) also increases. The relation between current, voltage and temperature is as follows.

- The reverse saturation current doubles for every 10oC rise in Temperature.

i.e., $I'_O = I_O \, x \, 2^{\left(\frac{t_2 - t_1}{10}\right)}$; where,

I_O' is the reverse saturation current at temperature t_2 and I_O is the reverse saturation current at temperature t_1.

- The forward voltage drop across the diode reduces 2.56mV for every 1°C rise in temperature.

i.e., $V_F' = V_F - 2.56m(t_2 - t_1)$.

Where,

V_F' is the voltage drop across the diode at t2 and
V_F is the voltage drop across the diode at t1

Rectifiers:

Rectifiers are the electronics circuits that convert AC quantity into to DC quantity. This can be achieved by using unidirectional conduction devices like diode.

Depending on the conduction angle the rectifier circuits are classified into two types, they are,

1. Half wave Rectifier and
2. Full wave Rectifier.

The Full wave Rectifiers are further classified (based on number of diodes using) into two types, they are,

a. Center Tap Transformer (Two Diodes) full wave rectifier and
b. Bridge Type (Four Diodes) full wave rectifier.

1. Half wave Rectifier:

The half rectifier is an electronic circuit, which converts AC quantity into pulsating DC, by using a single diode with conduction angle only 180° that is only half cycle.

Circuit Diagram:

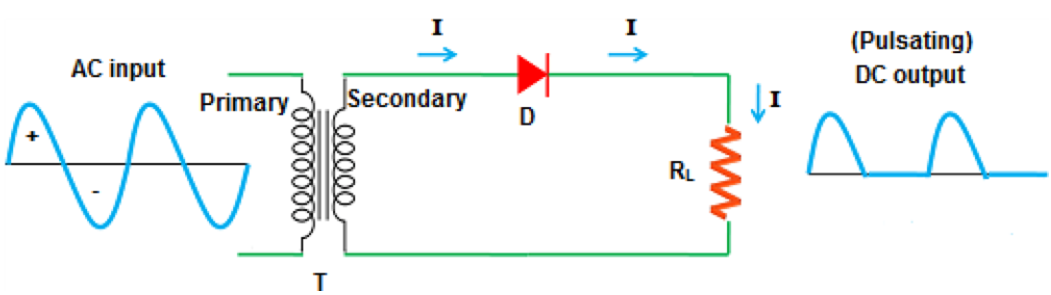


Figure (8): Half wave Rectifier circuit.

Figure (8) shows the circuit diagram of a half wave rectifier, where D is a diode (Assume Diode is ideal), R_L is the load resistor, input is an AC signal and output is the Pulsating DC Signal.

Explanation:

During every Positive half cycle diode D conducts and acts as a short circuit, hence the current flows through the Load resistor and is proportional to the input voltage according to Ohm's law, therefore the voltage across R_L is same as input signal.

i.e., $V_o = V_i$

During every negative half cycle diode D does not conducts and acts as an open circuit and no current flows through the load element, hence the voltage across R_L is zero.

i.e., $V_o = 0$

Waveforms:

Figure (9) shows the waveforms of an half wave rectifier circuit, and it can be observed that the output is only half cycle for every complete cycle input and also pulsating DC (Ripples/ some AC Components also present), i.e., not a pure DC.

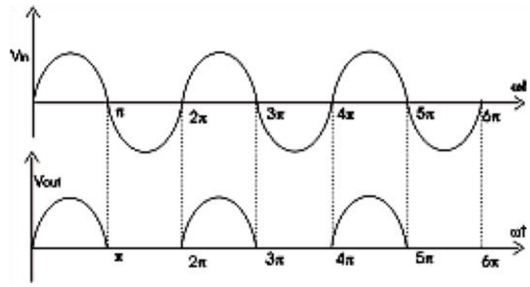


Figure (9): Input and Output Waveforms of a Half wave Rectifier circuit.

Mathematical expressions:

The output of half wave rectifier circuit is irregular in nature and hence, need to analyze the circuit for average DC and AC voltage or current along with the efficiency and ripple factor. Transformer voltage and current is given by,

$v(t) = v_m sin\omega t.$

$i(t) = i_m sin\omega t$

Therefore

1. Average DC Voltage.

$$V_{dc} = \frac{1}{T}\int_0^T v(t)d\omega t.$$

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} v_m sin\omega t\, d\omega t.$$

$$V_{dc} = \frac{1}{2\pi}\int_0^{\pi} v_m sin\omega t\, d\omega t + \frac{1}{2\pi}\int_{\pi}^{2\pi} v_m sin\omega t\, d\omega t\,.$$

$$V_{dc} = \frac{1}{2\pi}\int_0^{\pi} v_m sin\omega t\, d\omega t + \frac{1}{2\pi}\int_{\pi}^{2\pi} 0\, d\omega t\,.$$

$$V_{dc} = \frac{v_m}{2\pi}[-cos\omega t]_0^{\pi}$$

$$V_{dc} = \frac{v_m}{2\pi} x2$$

$$V_{dc} = \frac{v_m}{\pi}$$

2. Average DC Current.

$$I_{dc} = \frac{1}{T}\int_0^T I(t)d\omega t.$$

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i_m sin\omega t \, d\omega t.$$

$$I_{dc} = \frac{1}{2\pi}\int_0^{\pi} i_m sin\omega t \, d\omega t + \frac{1}{2\pi}\int_{\pi}^{2\pi} i_m sin\omega t \, d\omega t.$$

$$I_{dc} = \frac{1}{2\pi}\int_0^{\pi} i_m sin\omega t \, d\omega t + \frac{1}{2\pi}\int_{\pi}^{2\pi} 0 \, d\omega t.$$

$$I_{dc} = \frac{i_m}{2\pi}[-cos\omega t]_0^{\pi}$$

$$I_{dc} = \frac{i_m}{2\pi} x2$$

$$I_{dc} = \frac{i_m}{\pi}$$

Or

$$I_{dc} = \frac{V_{dc}}{R_L}$$

3. Root Mean Square value of the output voltage.

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^{T} v^2(t) d\omega t}.$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} (v_m sin\omega t)^2 \, d\omega t}.$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} v_m^2 sin^2 \omega t \, d\omega t}.$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} v_m^2(1 - cos\, 2\omega t)/2 \, d\omega t}.$$

$$V_{rms} = \frac{v_m}{2}$$

4. Root mean square value of the output current.

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^{T} i^2(t) d\omega t}.$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}} \; 2\pi$$

$$1 \qquad \int_0 (i_m \sin \omega t)^2 \, d\omega t.$$

$$I_{rms} = \sqrt{\frac{\;}{2\pi}\int_0^{2\pi} i_m^2 \sin^2 \omega t \, d\omega t.}$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} i_m^2(1 - \cos 2\omega t)/2 \ d\omega t}.$$

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

Or

$$I_{rms} = \frac{V_{rms}}{R_L}$$

5. Ripple factor.

Ripple factor is the ratio of rms value of the ac component to the dc value of the component.

$$ripple\ factor\ (\gamma) = \frac{Vr_{rms}}{V_{dc}}$$

$$\gamma = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}}$$

$$\gamma = \frac{\sqrt{\left(\frac{V_m}{2}\right)^2 - \left(\frac{V_m}{\pi}\right)^2}}{\frac{V_m}{\pi}}$$

$$\gamma = 1.2114.$$

6. Efficiency.

It is the ratio of dc output power present in the output to the ac power input.

$$\eta = \frac{P_{dc}}{P_{ac}} x100$$

$$\eta = \frac{\frac{V_{dc}^2}{R_L}}{\frac{V_{rms}^2}{R_L}} x100$$

$$\eta = 0.406x100$$

$$\eta = 40.6\%.$$

7. Peak Inverse Voltage.

The maximum voltage applied across the diode under reverse biasing, in other words maximum reverse voltage, which occurs at the peak of the input signal when the diode is reverse biased is called Peak Inverse Voltage or Peak Reverse Voltage.

The Maximum reverse voltage applied across the diode is V_m.

i.e., $PIV = V_m$

Note: The above expressions holds good only for the ideal diode (R_f=0 and V_{ON}=0) and ideal transformer (R_s=0).

Case (i): For a diode with R_f.

$$I_m = \frac{V_m}{R_f + R_L} \qquad I_{DC} = \frac{I_m}{\pi}$$

$$V_{DC} = I_{DC} X R_L$$

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

$$V_{rms} = I_{rms} X R_L$$

$$\gamma = \frac{\sqrt{I_{rms}^2 - I_{DC}^2}}{I_{DC}}$$

$$\%\eta = \frac{I_{DC}^2 R_L}{I_{rms}^2 (R_f + R_L)} x100$$

Case (ii): For a diode with R_f and Transformer with Rs

$$I_m = \frac{V_m}{R_f + R_s + R_L}$$

$$I_{DC} = \frac{I_m}{\pi}$$

$$V_{DC} = I_{DC} X R_L$$

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

$$V_{rms} = I_{rms} X R_L$$

$$\gamma = \frac{\sqrt{I_{rms}^2 - I_{DC}^2}}{I_{DC}}$$

$$\%\eta = \frac{I_{DC}^2 R_L}{I_{rms}^2 (R_f + R_s + R_L)} x100$$

Rectifier with C Filter:

From the above discussion it was observed that the output of the rectifier is not a pure dc. i.e., some ac components (ripples) also present, to remove the ripples we need to connect a filter. Filter can be capacitor or inductor, in the following context the capacitor filter will be discussed.

Filter is an electronic circuit which converts pulsating dc into pure dc.

The property of the capacitor is that it allows the ac component (High frequency component and low resistance) and blocks the dc component (low frequency component and high resistance).

Figure (10), shows the circuit diagram of an half-wave rectifier with capacitor filter, i.e., a capacitor is connected across the load resistor R_L. When AC voltage is applied, during the positive half cycle, the diode D is forward biased and allows electric current through it and capacitor starts charging instantly to its maximum level. During negative half cycle diode does not conducts and no current flow through the capacitor and hence starts discharging slowly. The discharging time constant is given by,

$$\boldsymbol{T_d = CR_L}$$

Note: If C or R_L or both increases the discharging time also increases and we will get pure dc. For very high Td the capacitor never discharges and it acts as a voltage source of value is equal to load voltage.

As we already know that, the capacitor provides high resistive path to dc components (low- frequency signal) and low resistive path to ac components (high-frequency signal).

Electric current always prefers to flow through a low resistance path. So when the electric current reaches the filter, the dc components experience a high resistance from the capacitor and ac components experience a low resistance from the capacitor.

The dc component does not like to flow through the capacitor (high resistance path). So they find an alternative path (low resistance path) and flows to the load resistor (RL) through that path shown in figure (11).

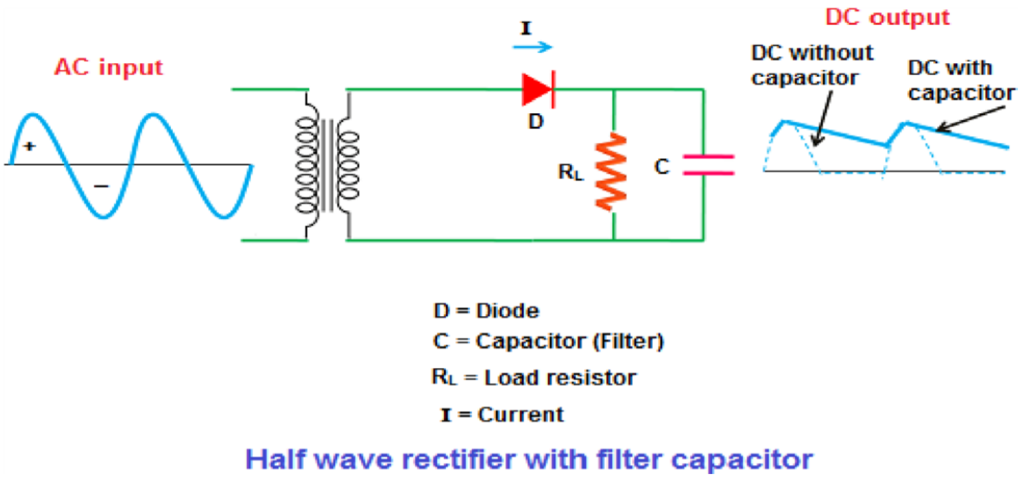


Figure (10): Half wave Rectifier circuit with Capacitor Filter.

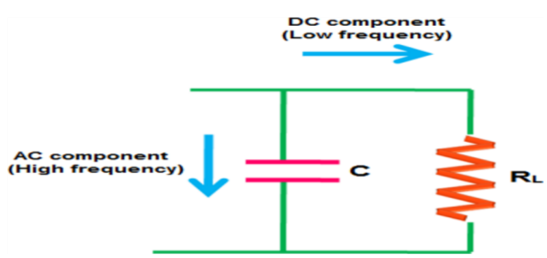


Figure (11): Working of Capacitor filter.

Electric current always prefers to flow through a low resistance path. So the AC components will flow through the capacitor whereas the DC components are blocked by the capacitor. Therefore, they find an alternate path and reach the output load resistor R_L. The flow of AC components through the capacitor is nothing but the charging of a capacitor.

Waveforms:

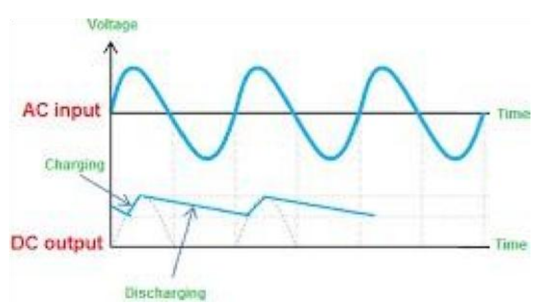


Figure (12): waveform of a Half wave Rectifier with C-filter.

Figure (12) shows the waveform of a half-wave rectifier filtered output. If discharging time increases then the output become pure dc.

The Ripple factor of a filtered output signal is given by

$$\gamma = \frac{1}{2\sqrt{3} f R_L C}$$

Advantage:

- Simple and easy to construct. PIV is only V_m.

Disadvantages:

- Conducts only half cycle, due to this more power will be wasted.
- More ripples occur in the output.

2. Full wave Rectifier using Center tap transformer:

A full wave rectifier is a type of rectifier which converts both half cycles of the AC signal into pulsating DC signal. ***Circuit Diagram:***

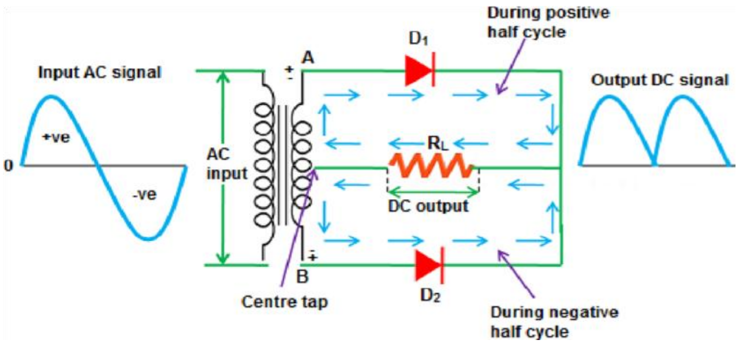


Figure (13): Full-wave Rectifier circuit.

As shown in the figure (13), the full wave rectifier converts both positive and negative half cycles of the input AC signal into output pulsating DC signal.

Note: The center tapped transformer shown in figure (14), works almost similar to a normal transformer. Like a normal transformer, the center tapped transformer also increases or reduces the AC voltage. However, a center tapped transformer has another important feature. That is the secondary winding of the center tapped transformer divides the input AC current or AC signal (V_P) into two parts.

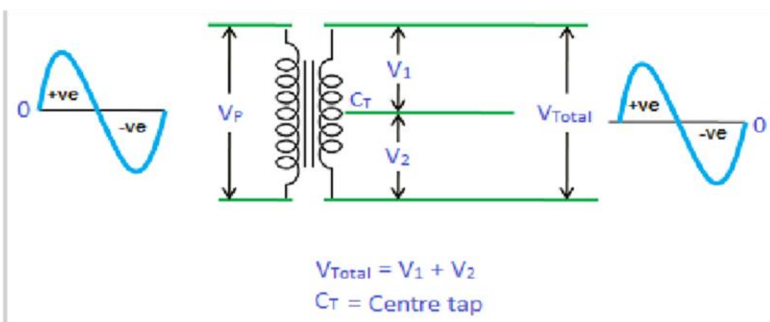


Figure (14): Working of Center Tapped Transformer.

The upper part of the secondary winding produces a positive voltage V_1 and the lower part of the secondary winding produces a negative voltage V_2. When we combine these two voltages at output load, we get a complete AC signal.

i.e. $\boldsymbol{V_{Total} = V_1 + V_2}$

The voltages V_1 and V_2 are equal in magnitude but opposite in direction. That is the voltages (V_1 and V_2) produced by the upper part and lower part of the secondary winding are 180 degrees out of phase with each other. However, by using a full wave rectifier with center tapped transformer, we can produce the voltages that are in phase with each other. In simple words, by using a full wave rectifier with center tapped transformer, we can produce a current that flows only in single direction.

The AC source is connected to the primary winding of the center tapped transformer. A center tap (additional wire) connected at the exact middle of the the secondary winding divides the input voltage into two parts.

The upper part of the secondary winding is connected to the diode D_1 and the lower part of the secondary winding is connected to the diode D_2. Both diode D_1 and diode D_2 are connected to a common load R_L with the help of a center tap transformer. The center tap is generally considered as the ground point or the zero voltage reference point.

Explanation:

The center tapped full wave rectifier uses a center tapped transformer and two diodes to convert the input AC voltage into output DC voltage.

When input AC voltage is applied, the secondary winding of the center tapped transformer divides this input AC voltage into two parts: positive and negative.

During every positive half cycle of the input AC signal, terminal A become positive, terminal B become negative and center tap is grounded (zero volts). The positive terminal A is connected to the p-side of the diode D_1 and the negative terminal B is connected to the n-side of the diode D_1. So the diode D_1 is forward biased during the positive half cycle and allows electric current through it.

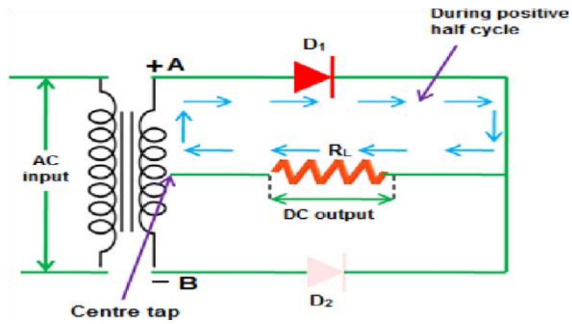


Figure (15): Full-wave rectifier circuit during every positive half cycle.

On the other hand, the negative terminal B is connected to the p-side of the diode D_2 and the positive terminal A is connected to the n-side of the diode D_2. So the diode D_2 is reverse biased during every positive half cycle and does not allow electric current through it.

The diode D_1 supplies DC current to the load R_L. The DC current produced at the load R_L will return to the secondary winding through a center tap.

$$\text{i.e., } \boldsymbol{V_o = V_i}$$

During the positive half cycle, current flows only in the upper part of the circuit while the lower part of the circuit carry no current to the load because the diode D_2 is reverse biased. Thus, during the positive half cycle of the input AC signal, only diode D_1 allows electric current while diode D_2 does not allow electric current as shown in figure (15).

During every negative half cycle of the input AC signal, terminal A become negative, terminal B become positive and center tap is grounded (zero volts). The negative terminal A is connected to the p-side of the diode D_1 and the positive terminal B is connected to the n-side of the diode D_1. So the diode D_1 is reverse biased during the negative half cycle and does not allow electric current through it.

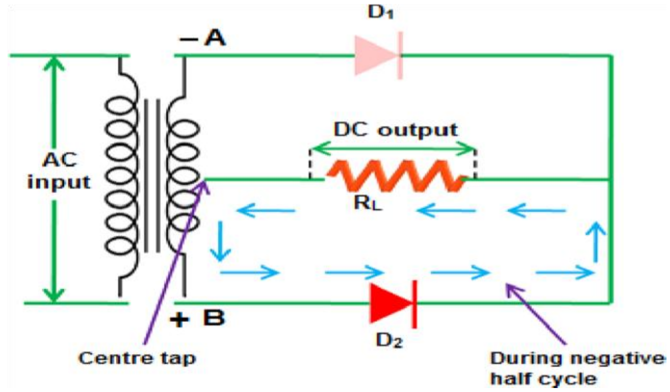


Figure (16): Full-Wave Rectifier during every negative half cycle.

On the other hand, the positive terminal B is connected to the p-side of the diode D_2 and the negative terminal A is connected to the n-side of the diode D_2. So the diode D_2 is forward biased during the negative half cycle and allows electric current through it.

The diode D_2 supplies DC current to the load R_L. The DC current produced at the load R_L will return to the secondary winding through a center tap as shown in figure (16).

During the negative half cycle, current flows only in the lower part of the circuit while the upper part of the circuit carry no current to the load because the diode D_1 is reverse biased. Thus, during the negative half cycle of the input AC signal, only diode D_2 allows electric current while diode D_1 does not allow electric current.

Thus, the diode D_1 allows electric current during the positive half cycle and diode D_2 allows electric current during the negative half cycle of the input AC signal. As a result, both half cycles (positive and negative) of the input AC signal are allowed. So the output DC voltage is almost equal to the input AC voltage as shown in figure (17).

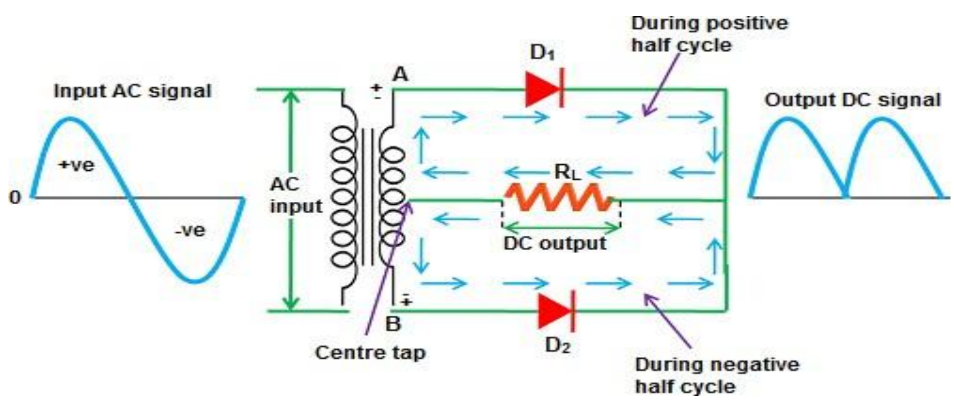


Figure (17): Full-wave rectifier with total output.

The diodes D_1 and D_2 are commonly connected to the load R_L. So the load current is the sum of individual diode currents.

We know that a diode allows electric current in only one direction. From the figure (17), we can see that both the diodes D_1 and D_2 are allowing current in the same direction.

We know that a current that flows in only single direction is called a direct current. So the resultant current at the output (load) is a direct current (DC). However, the direct current appeared at the output is not a pure direct current but a pulsating direct current.

The value of the pulsating direct current changes with respect to time. This is due to the ripples in the output signal. These ripples can be reduced by using filters such as capacitor and inductor.

The average output DC voltage across the load resistor is double that of the single half wave rectifier circuit.

Waveforms:

The output waveforms of the full wave rectifier is shown in figure (18).

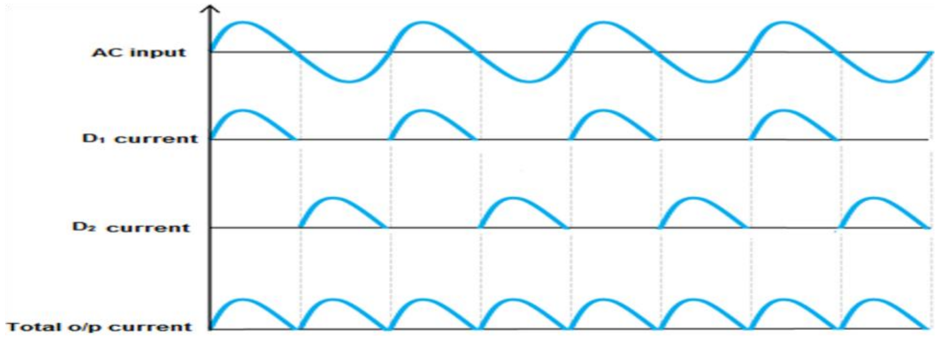


Figure (18): waveforms of full wave rectifier.

The first waveform represents an input AC signal. The second waveform and third waveform represents the DC signals or DC current produced by diode D_1 and diode D_2. The last waveform represents the total output DC current produced by diodes $D_1$and D_2. From the above waveforms, we can conclude that the output current produced at the load resistor is not a pure DC but a pulsating DC.

Mathematical Expressions:

The output of half wave rectifier circuit is irregular in nature and output would be equal to the average voltage or current.

Transformer voltage and current is given by,

$$v(t) = v_m sin\omega t.$$

$$i(t) = i_m sin\omega t$$

Therefore

1. Average or DC Voltage.

$$V_{dc} or\, V_{avg} = \frac{1}{T}\int_0^T v(t) d\omega t.$$

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} v_m sin\omega t\ d\omega t.$$

$$V_{dc} = \frac{1}{2\pi}\int_0^{\pi} v_m sin\omega t\ d\omega t + \frac{1}{2\pi}\int_{\pi}^{2\pi} v_m sin\omega\omega t\ dt\,.$$

$$V_{dc} = \frac{1}{2\pi}\int_0^{\pi} v_m sin\omega t\ d\omega t + \frac{1}{2\pi}\int_{\pi}^{2\pi} v_m sin\omega t\ \ d\omega t\,.$$

Component Between π to 2π is same as the 0 to π component.

Therefore,

$$V_{dc} = 2x\frac{1}{2\pi}\int_0^{\pi} v_m sin\omega t\ d\omega t.$$

$$V_{dc} = 2x\frac{v_m}{2\pi}[-cos\omega t]_0^{\pi}$$

$$V_{dc} = 2x\frac{v_m}{2\pi}x2$$

$$V_{dc} = \frac{2v_m}{\pi}$$

2. Average or DC Current.

$$I_{dc} or\ I_{avg} = \frac{1}{T}\int_0^T I(t)d\omega t.$$

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i_m sin\omega t\ d\omega t.$$

$$I_{dc} = \frac{1}{2\pi}\int_0^{\pi} i_m sin\omega t\ d\omega t + \frac{1}{2\pi}\int_{\pi}^{2\pi} i_m sin\omega t\ d\omega t\ .$$

$$I_{dc} = 2x\frac{1}{2\pi}\int_0^{\pi} i_m sin\omega t\ d\omega t$$

$$I_{dc} = 2x\frac{i_m}{2\pi}[-cos\omega t]_0^{\pi}$$

$$I_{dc} = 2x\frac{i_m}{2\pi}x2$$

$$I_{dc} = \frac{2i_m}{\pi}$$

Or

$$I_{dc} = \frac{V_{dc}}{R_L}$$

3. <u>Root Mean Square value of the output voltage.</u>

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)d\omega t}.$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} (v_m sin\omega t)^2\ d\omega t}.$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} v_m^2 sin^2\omega t\, d\omega t}.$$

$$V_{rms} = \sqrt{2x\ \frac{1}{2\pi}\int_0^{\pi} v_m^2(1 - cos\,2\omega t)/2\ \ d\omega t}.$$

$$V_{rms} = \frac{v_m}{\sqrt{2}}$$

4. <u>Root mean square value of the output current.</u>

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)\,d\omega t} \; .$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} (i_m sin\omega t)^2 \; d\omega t} \; .$$

$$I_{rms} = \sqrt{2x\frac{1}{2\pi}\int_0^{\pi} i_m^2 sin^2\,\omega t\, d\omega t}.$$

$$I_{rms} = \sqrt{2x\frac{1}{2\pi}\int_0^{2\pi} i_m^2 (1 - cos\,2\omega t)/2 \;\; d\omega t}.$$

$$I_{rms} = \frac{i_m}{\sqrt{2}}$$

Or

–

$$I_{rms} = \frac{V_{rms}}{R_L}$$

5. Ripple factor.

Ripple factor is the ratio of rms value of the ac component to the dc value of the component.

$$\textbf{ripple factor } (\gamma) = \frac{Vr_{rms}}{V_{dc}}$$

$$\gamma = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}}$$

$$\gamma = \frac{\sqrt{\left(\frac{V_m}{\sqrt{2}}\right)^2 - \left(\frac{2V_m}{\pi}\right)^2}}{\frac{2V_m}{\pi}}$$

$$\gamma = 0.48.$$

6. Efficiency.

It is the ratio of dc output power present in the output to the ac power input.

$$\eta = \frac{P_{dc}}{P_{rms}} x100$$

$$\eta = \frac{\frac{V_{dc}^2}{R_L}}{\frac{V_{rms}^2}{R_L}} x100$$

$$\eta = 0.812x100$$

$$\eta = 81.2\%.$$

7. Peak Inverse Voltage.

The maximum voltage applied across the diode under reverse biasing, in other words maximum reverse voltage, which occurs at the peak of the input signal when the diode is reverse biased is called Peak Inverse Voltage or Peak Reverse Voltage.

The Maximum reverse voltage applied across the diode is $2V_m$.

i.e., $\boldsymbol{PIV = 2V_m}$

Note: The above expressions holds good only for the ideal diode (R_f=0 and V_{ON}=0) and ideal transformer (R_s=0).

Case (i): For a diode with R_f.

$$I_m = \frac{V_m}{R_f + R_L}$$

$$I_{DC} = \frac{2I_m}{\pi}$$

$$V_{DC} = I_{DC} X\ R_L$$

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

$$V_{rms} = I_{rms} X\ R_L$$

$$\gamma = \frac{\sqrt{I_{rms}^2 - I_{DC}^2}}{I_{DC}}$$

$$\%\eta = \frac{I_{DC}^2 R_L}{I_{rms}^2 (R_f + R_L)} x100$$

Case (ii): For a diode with R_f and Transformer with Rs

$$I_m = \frac{V_m}{R_f + R_s + R_L}$$

$$I_{DC} = \frac{2I_m}{\pi}$$

$$V_{DC} = I_{DC} X R_L$$

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

$$V_{rms} = I_{rms} X R_L$$

$$\gamma = \frac{\sqrt{I_{rms}^2 - I_{DC}^2}}{I_{DC}}$$

$$\%\eta = \frac{I_{DC}^2 R_L}{I_{rms}^2 (R_f + R_s + R_L)} x100$$

Full-wave Rectifier with C Filter:

The filter is an electronic device that converts the pulsating Direct Current into pure Direct Current.

In the circuit diagram, the capacitor C is placed across the load resistor R_L.

Note: The working of the full-wave rectifier with filter is almost similar to that of the half wave rectifier with filter. The only difference is that in the half wave rectifier only one half cycles (either positive or negative) of the input AC current will charge the capacitor but the remaining half cycle will not charge the capacitor. But in full wave rectifier, both positive and negative half cycles of the input AC current will charge the capacitor.

The main duty of the capacitor filter is to short the ripples to the ground and blocks the pure DC (DC components), so that it flows through the alternate path and reaches output load resistor R_L.

Figure (19) shows the circuit diagram of a full-wave rectifier with Capacitor filter, when input AC voltage is applied, during the positive half cycle, the diode D_1 is forward biased and allows electric current whereas the diode D_2 is reverse biased and blocks electric current. On the other hand, during the negative half cycle the diode D_2 is forward biased (allows electric current) and the diode D_1 is reverse biased (blocks electric current).

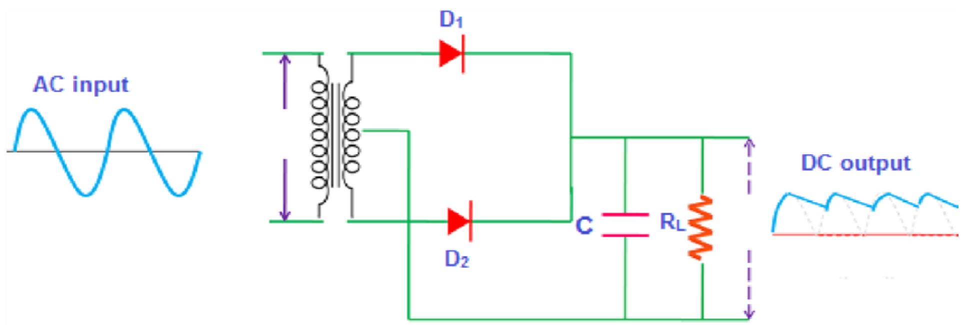


Figure (19): Full-wave Rectifier circuit with Capacitor filter.

During the positive half cycle, the diode (D_1) current reaches the filter and charges the capacitor. However, the charging of the capacitor happens only when the applied AC voltage is greater than the capacitor voltage.

Initially, the capacitor is uncharged. That means no voltage exists between the plates of the capacitor. So when the voltage is turned on, the charging of the capacitor happens immediately.

During this conduction period, the capacitor charges to the maximum value of the input supply voltage. The capacitor stores a maximum charge exactly at the quarter positive half cycle in the waveform. At this point, the supply voltage is equal to the capacitor voltage.

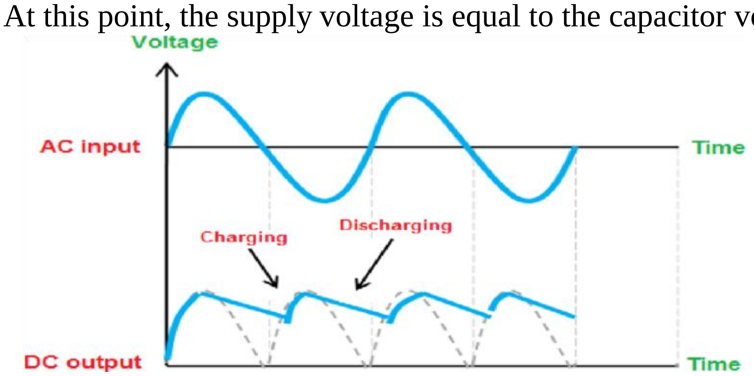


Figure (20): Full-wave Rectifier filtered output.

When the AC voltage starts decreasing and becomes less than the capacitor voltage, then the capacitor starts slowly discharging as shown in figure (20).

The discharging of the capacitor is very slow as compared to the charging of the capacitor. So the capacitor does not get enough time to completely discharge. Before the complete discharge of the capacitor happens, the charging again takes place. So only half or more than half of the capacitor charge get discharged.

When the input AC supply voltage reaches the negative half cycle, the diode D_1 is reverse biased (blocks electric current) whereas the diode D_2 is forward biased (allows electric current). During the negative half cycle, the diode (D_2) current reaches the filter and charges the capacitor. However, the charging of the capacitor happens only when the applied AC voltage is greater than the capacitor voltage.

The capacitor is not completely uncharged, so the charging of the capacitor does not happen immediately. When the supply voltage becomes greater than the capacitor voltage, the capacitor again starts charging.

In both positive and negative half cycles, the current flows in the same direction across the load resistor R_L. So we get either complete positive half cycles or negative half cycles. In our case, they are complete positive half cycles.

The Ripple factor of a filtered output signal is given by

$$\gamma = \frac{1}{4\sqrt{3} f R_L C}$$

Advantages:

- Conducts both the half cycles. Efficiency is improved
- Ripples factor is reduced.

Disadvantages:

- Center tapped transformer more expensive and bulky.
- PIV is 2Vm.

3. Bridge type Full wave Rectifies:

The Bridge Type Full-wave rectifier is an electronic circuit, which converts AC quantity into pulsating DC, by using the four diodes with conduction angle only 360^{o} that is complete cycle.

Circuit Diagram:

The Circuit diagram of a bridge rectifier is shown in figure (21). The bridge rectifier is made up of four diodes namely D_1, D_2, D_3, D_4 and load resistor R_L. The four diodes are connected in a closed loop (Bridge) configuration to efficiently convert the Alternating Current (AC) into Direct Current (DC).

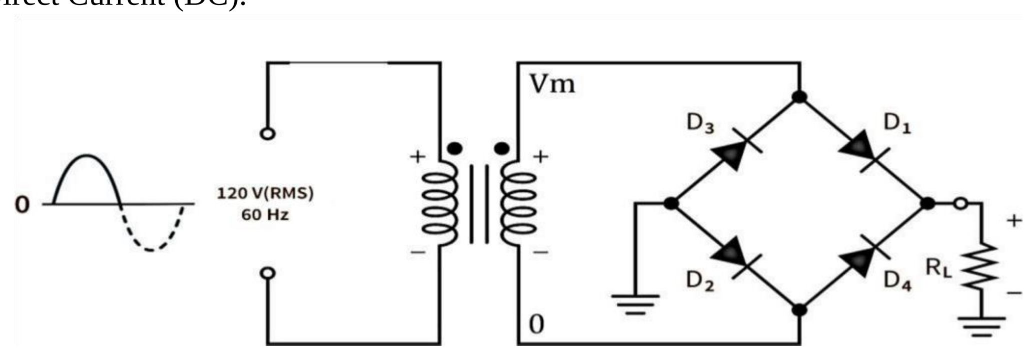


Figure (21): Full-wave Bridge Rectifier Circuit diagram.

Explanation:

The input AC signal is applied across two terminals A and B and the output DC signal is obtained across the load resistor R_L which is connected between the terminals C and D.

The four diodes D_1, D_2, D_3, D_4 are arranged in series with only two diodes allowing electric current during each half cycle. For example, diodes D_1 and D_2 are considered as one pair which allows electric current during the positive half cycle whereas diodes D_3 and D_4 are considered as another pair which allows electric current during the negative half cycle of the input AC signal.

When input AC signal is applied across the bridge rectifier, during the positive half cycle diodes D_1 and D_2 are forward biased and allows electric current while the diodes D_3 and D_4 are reverse biased and blocks electric current. On the other hand, during the negative half cycle diodes D_3 and D_4 are forward biased and allow electric current while diodes D_1 and D_2 are reverse biased and blocks electric current.

During the positive half cycle, the terminal A becomes positive while the terminal B becomes negative. This causes the diodes D_1 and D_2 forward biased and at the same time, it causes the diodes

D_3 and D_4 reverse biased.

The current flow direction during the positive half cycle is shown in the figure (22) (i.e. A to D to C to B).

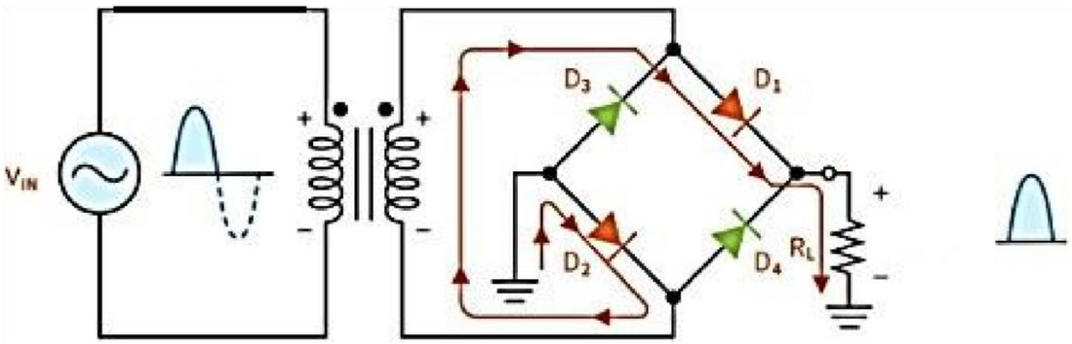


Figure (22): Bridge Rectifier during every positive half cycle.

During the negative half cycle, the terminal B becomes positive while the terminal A becomes negative. This causes the diodes D_3 and D_4 forward biased and at the same time, it causes the diodes

D_1 and D_2reverse biased.

The current flow direction during negative half cycle is shown in figure (23) (I.e. B to D to C to A).

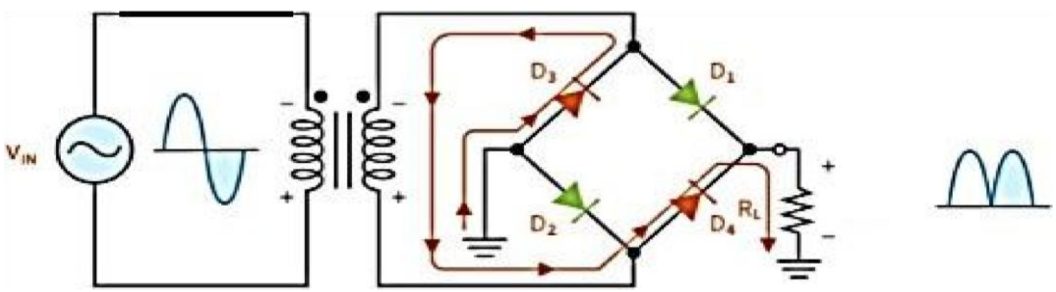


Figure (23): Bridge Rectifier during every negative half cycle.

From the two figures (22 and 23), we can observe that the direction of current flow across load resistor R_L is same during the positive half cycle and negative half cycle. Therefore, the polarity of the output DC signal is same for both positive and negative half cycles. The output DC signal polarity may be either completely positive or negative. In our case, it is completely positive. If the direction of diodes is reversed then we get a complete negative DC voltage.

Thus, a bridge rectifier allows electric current during both positive and negative half cycles of the input AC signal.

The output waveforms of the bridge rectifier is shown in figure (24).

Waveforms:

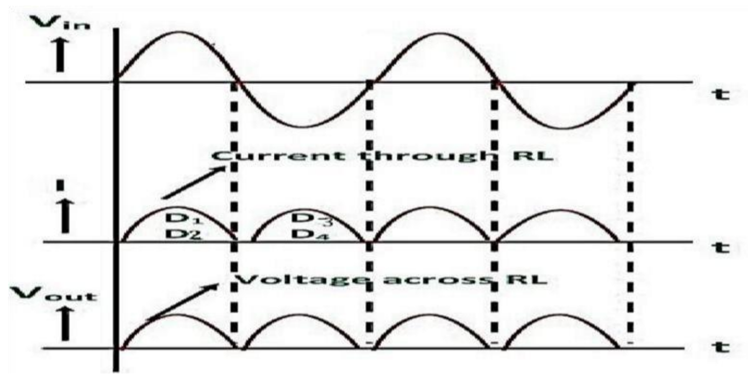


Figure (24): Bridge Rectifier waveforms.

Mathematical Expressions:

Same as Full wave Rectifier except PIV.

PIV of Bridge type full wave rectifier is only Vm.

i.e., $\boldsymbol{PIV = V_m}$

Note: The above expressions holds good only for the ideal diode (R_f=0 and V_{ON}=0) and ideal transformer (R_s=0).

Case (i): For a diode with R_f.

$$I_m = \frac{V_m}{2R_f + R_L}$$

$$I_{DC} = \frac{2I_m}{\pi}$$

$$V_{DC} = I_{DC} X R_L$$

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

$$V_{rms} = I_{rms} X R_L$$

$$\gamma = \frac{\sqrt{I_{rms}^2 - I_{DC}^2}}{I_{DC}}$$

$$\%\eta = \frac{I_{DC}^2 R_L}{I_{rms}^2 (2R_f + R_L)} x100$$

Case (ii): For a diode with R_f and Transformer with Rs

$$I_m = \frac{V_m}{2R_f + R_s + R_L}$$

$$I_{DC} = \frac{2I_m}{\pi}$$

$$V_{DC} = I_{DC} X R_L$$

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

$$V_{rms} = I_{rms} X R_L$$

$$\gamma = \frac{\sqrt{I_{rms}^2 - I_{DC}^2}}{I_{DC}}$$

$$\%\eta = \frac{I_{DC}^2 R_L}{I_{rms}^2 (2R_f + R_s + R_L)} x100$$

Bridge Rectifier with C Filter:

Same as Full wave Rectifier with C Filter.

Advantages:

- Center tapped Transformer is not necessary hence circuit becomes simple and cheap.
- PIV is only Vm.

Disadvantages:

- Requires four diodes.

Choke Filter:

Choke filter is a circuit consists of an inductor connected in series with load and capacitor connected across the load. The choke filter is also called L-section filter as shown in figure (25).

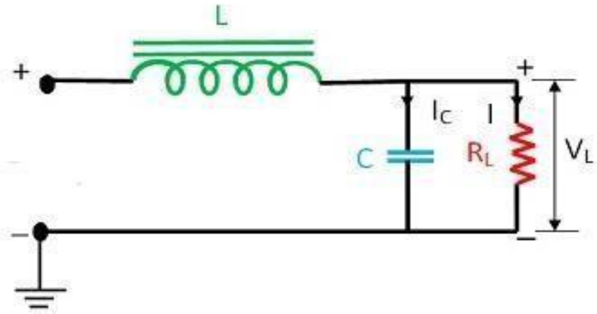


Figure (25): Choke Filter.

The choke filter is used to remove the ripples present in the rectified output. The Pulsating DC signal pass through the inductor or choke will blocks ac and allows dc and further the ripples i.e., some of the residual ripples will get bypassed through the capacitor (capacitor blocks dc and allows ac). Hence from the choke filtered output is pure dc. The Ripple factor of a filtered output signal is given by

$$\gamma = \frac{1.19}{LC}$$

Significance of Choke filters:

The series inductor filter decreases the current, and shunt capacitor filter increases the current.

Zener Diode:

The reverse current through the normal diode is in terms of microamperes and it is almost constant until the reverse voltage is less than break down voltage, if the reverse voltage is greater than or equal to the break down voltage the junction breaks and high current will flow through the device and more power will be dissipated then the device may be destroyed or damaged.

If we limit the current through the device by means of connecting a resistor in series with the device, the power dissipation reduces and the device may not be destroyed even under breakdown region. By using this principle the special type of diode is designed by Clearance Zener called as Zener diode.

There are two types of breakdown occurs in Zener diode depending on the break down voltage levels.

i) Zener Break down:

This type of breakdown occurs in the device if the breakdown voltage is less than or equal to 6V(typically), this strong electric field at the junction becomes very large and breaks the covalent bonds to release free electrons, due to this very high current will flow through the device. This mechanism or process is called ionization by Electric field.

ii) Avalanche Breakdown:

This type of breakdown occurs in the device if the breakdown voltage is greater than 6V (Typically), this high potential forces minority charge carriers to move quickly means kinetic energy increases, due to this the minority charge carriers collide with atoms to break covalent bonds which increase the free electrons and hence the current increases sharply. This process or mechanism is called, Impact Ionization or Ionization by collision. In this mechanism, the free electrons increase in multiples and hence called avalanche breakdown.

VI Characteristics of Zener Diode:

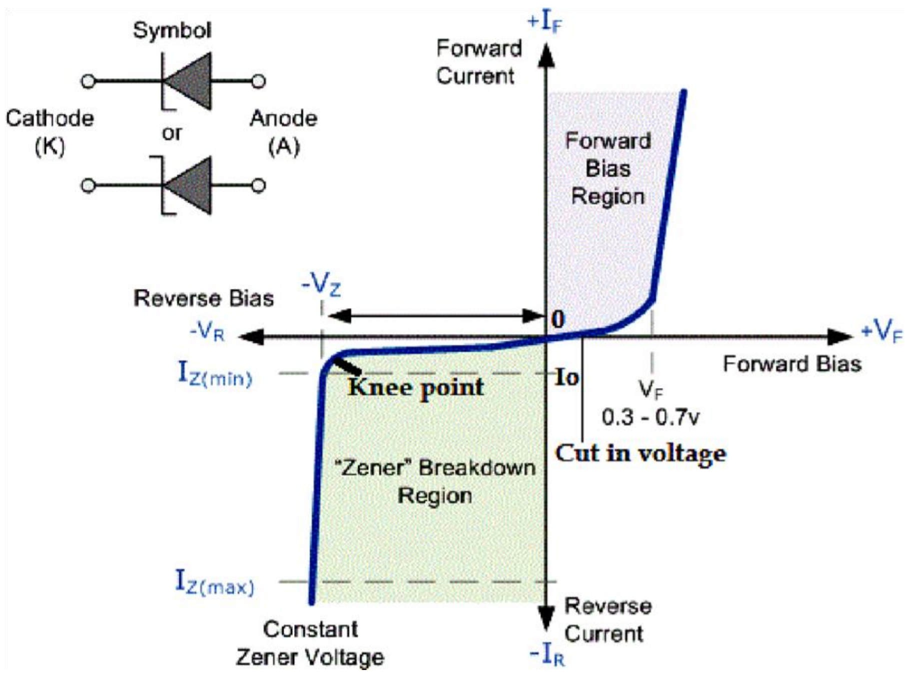


Figure (26): VI Characteristics of Zener Diode.

Zener Diode Voltage Regulator:

Zener diode provides constant voltage if the Zener Current is between I_{Zmin} to I_{Zmax} under reverse biasing, this feature of Zener diode will be utilized to design a voltage regulator.

Voltage regulator is a system which produces the constant voltage irrespective of variations in line (Input) and load.

Figure (27) shows the circuit diagram of a Zener Diode Voltage Regulator. Where, R is the Series Resistor used to limit or control the sharp current flowing through the Zener diode under breakdown condition, R_L is the Load resistance, V_i is the unregulated power supply, I_Z is the current through the Zener diode, I_L is the load current, V_R is the voltage drop across series resistor. V_Z is the Zener Voltage, V_o is the voltage across the load resistor called output voltage and I is the input current.

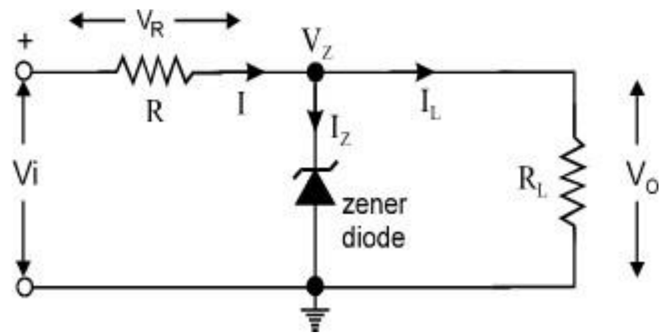


Figure (27): Zener Diode Voltage Regulator Circuit.

From the above figure, the input unregulated power supply V_i, Positive terminal is connected to the cathode terminal and negative terminal is connected to the anode terminal, hence the Zener diode is operating in the reverse biasing mode.

And the above circuit provides a constant voltage even by varying the input voltage and varying load, i.e., provides regulation for both line and load.

Case(i): Line Regulation; Variable input and constant load:

If the input voltage V_i is less than the Zener Voltage V_Z (Zener Break Down Voltage), the output voltage is same as the input voltage Vi, because the Zener diode is in off state, if the input voltage is greater than the Zener voltage V_Z, the diode in ON state and hence it acts as a voltage source of V_Z Volts.

If V_i increases, the input current I also increases, and I_Z increases to maintain I_L constant, but I_Z should be between I_{Zmin} to I_{Zmax}.

If V_i decreases, the input current I also decreases, and I_Z decreases to maintain I_L constant, but I_Z should be between I_{Zmin} to I_{Zmax}.

Therefore the voltage across the load resistor constant and is given by

$$V_o=V_Z$$

Case(ii): Load Regulation; Fixed input and variable load:

If R_L increases, I_L decreases and to keep input current I constant I_Z increases, but I_Z should be between I_{Zmin} to I_{Zmax}.

If R_L decreases, I_L increases and to keep input current I constant I_Z decreases, but I_Z should be between I_{Zmin} to I_{Zmax}.

Therefore the voltage across the load resistor constant and is given by

$$V_o=V_Z$$

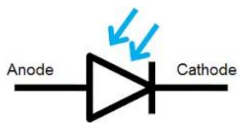
Special types of diodes

The PN junctions with additional features are called special types of diodes, which have special form of PN junction compared to normal diodes. Most of the special diodes converts one form of energy into another form, few of them are discussed in the following section.

1. Photodiodes:

Photo diodes are special type of diode or special form of PN junction, which conducts or produces current when the junction is exposed to light radiation under reverse biasing condition. I.e., photo diodes converts light radiation into electrical energy. If the radiation increases, the current produced by the device also increases.

Circuit symbol and realistic view of photodiode:



The pair of inward arrow indicates that, the device starts conducting, when the device receives light radiation.

Internal structure with biasing arrangement:

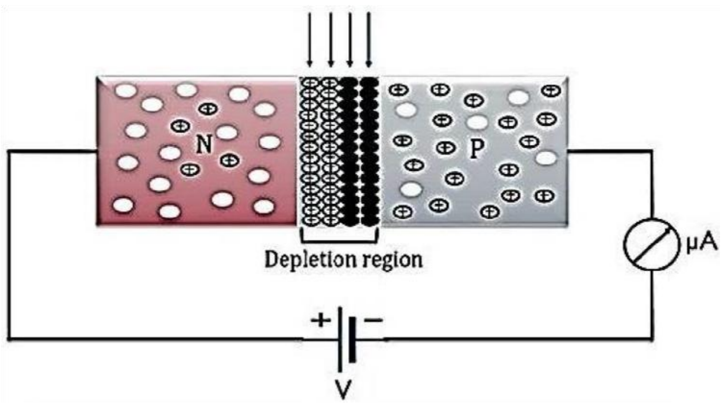


Figure shows the internal structure of the photodiode, these types of diodes are surrounded by a glass surface to allow the radiation into the junction. V is the voltage supply for biasing the device in reverse biasing mode. Ammeter connected in series with the device to read the current produced by the device. Photo diodes will work in two modes

i) Photovoltaic (Solar cells) : Under un-biasing condition, when the junction exposed to radiation, the device will produces current is called photovoltaic mode of operation of photodiode. Example: Solar cells.

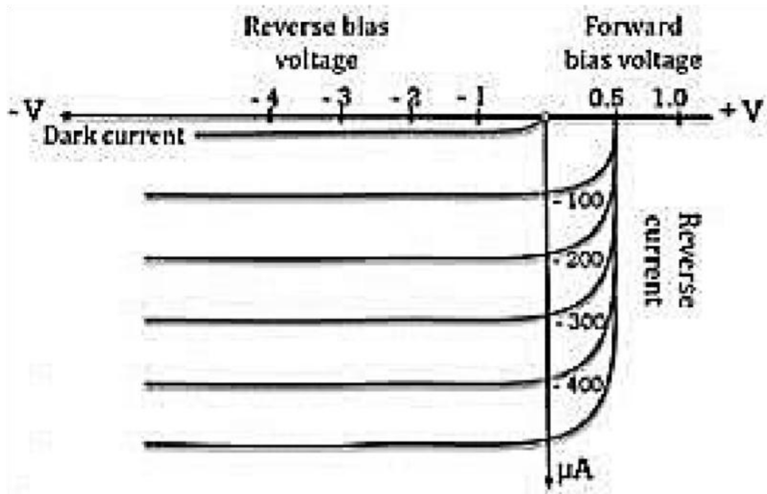
ii) Photoconductive (Photo diode): The device is under reverse biasing and the junction exposed to radiation, produces current. This mode of operation is called photoconductive mode.

Working principle:

Under reverse biasing the depletion region increases and immobile ions accumulates near the junction on both sides, which acts as a barrier and avoids further movement of charge carriers from one region to another region. When the junction is exposed to light radiation, the junction takes sufficient energy to break the covalent bonds. The covalent bonds breaks and generates free electrons, due to the movement of these free electrons, current will be flowing through the device.

VI Characteristics:

Figure shows the VI characteristics of a photodiode, which is a plot of reverse voltage vs current through the device with constant and different light intensities. If the device under reverse biasing and does not exposed to radiation, only small current will flow through the device due to minority charge carriers, this current is called dark current. If the light intensity increases, the current through the device increases.



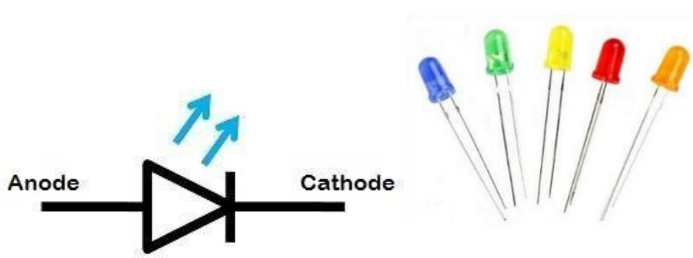
Applications:

- Theft detection
- Automatic door opening and closing
- Obstacle detection

2. Light emitting diode (LED):

Light emitting diode is a special type of diode or special form of PN junction, which converts electrical energy into light energy under forward biasing. The reverse bias operation of LEDs is avoided due to very low breakdown voltage.

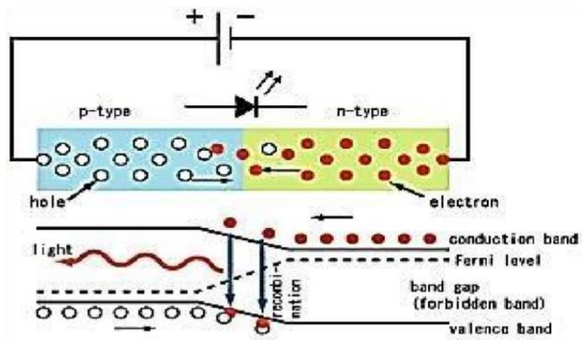
Circuit symbol and realistic view of LED:



The pair of outward arrows, indicates when the device conducts, which emits visible light.

Internal structure with biasing arrangement and working:

Figure, shows the internal structure and biasing arrangement of light emitting diode, these types of diodes are surrounded by a transparent plastic hard epoxy hemisphere cell to protect the device from the external shock and to emit the visible light in different colors.



V is the voltage supply for biasing the device in forward biasing mode. Energy gap must be greater than 1.8eV in order to emit the visible light. The device needs some energy to move the free electrons from valence band to conduction band and during the recombination, electrons releases approximately same amount of energy, if the released energy in the form of photon. Energy of photon is the product of plank's constant and frequency of radiated electromagnetic wave.

$$\text{i.e.,} E_g = hf --- (1)$$

$$w.k.t., f = \frac{c}{\lambda} --- (2)$$

Where, c is the velocity of light and λ is the wavelength of electromagnetic wave.

From the equations (1) and (2), we get,

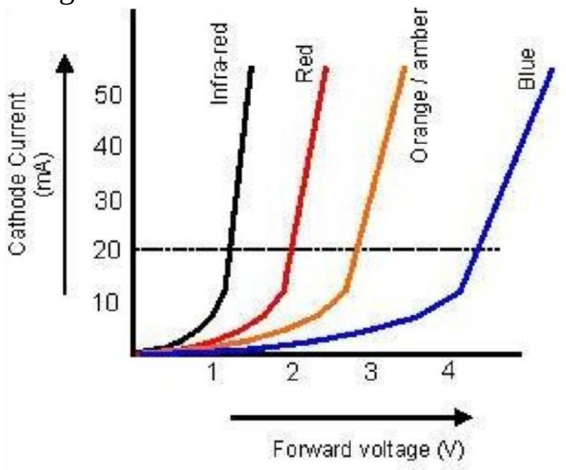
$$E_g \,\alpha \frac{1}{\lambda} --- (3)$$

i.e., energy of a photon is directly proportional to frequency and inversely proportional to wavelength, if the energy gap increases, LEDs emit electromagnetic waves of different wavelength(different colors).

If the energy gap is less than 1.8eV, electrons releases energy in the form of infra-red radiation, which is not visible to human eyes. If the energy gap is greater than or equal to 1.8eV, during the recombination process, which releases energy in the form of light, which are visible to human eye. Ge and Si are not suitable elements to produce visible light signals, so compounded semiconductor materials like gallium arsenide, gallium phosphide, gallium nitride, gallium arsenide phosphide etc…are used to develop light emitting diodes. The cut-in voltage of LEDs ranges from 1.2V to 4V.

VI Characteristics:

Figure shows the VI characteristics of an LED, which is a plot of forward voltage vs current through the device.



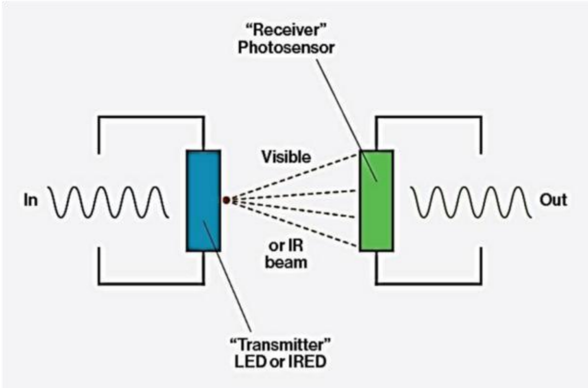
Applications:

- Traffic signal lamps
- Medical devices
- Camera flash lights etc.

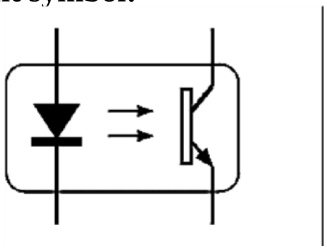
3. Photocoupler:

Also called as optocoupler or optoisolator, acts as an interface between two different circuits with different voltage levels. These devices supplies electrical isolation between input and output source.

Photocouplers are composed of two semiconductor devices, namely light emitting diode and photo-transistor. The photocouplers receives electrical signal as an input from the source and emits light, photo-transistor receives the light signal and converts back into electrical signal. Figure shows the working principle of optocouplers.



Circuit symbol:

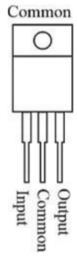


Applications:

- Switching the DC circuits
- PC communication
- AC power control
- Microprocessor input/output switching etc.
-

4. Voltage Regulators (78XX series)

78XX series regulators are linear voltage regulators, which provide stabilized output voltage from a potentially unstable power supply source. These regulators comes in IC package and these are most commonly used voltage regulators to provide a stable output.



Voltage Regulators 78xx Family Models

Model	V_{OUT} Typical

7805	5
7806	6
7808	8
7809	9
7810	10
7812	12
7815	15
7818	18
7824	24

Advantages:

- Very easy to use - just select the required 78XX series regulator and place it in circuit for it to work.
- Very few additional electronic components are required - using the basic circuit only capacitors are required for the input and output.
- Low cost - these linear voltage regulators can be obtained for a very low cost.

NOTE: 79XX series voltage regulators are similar to 78XX series regulators, but 79XX series regulators provides negative voltage.

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