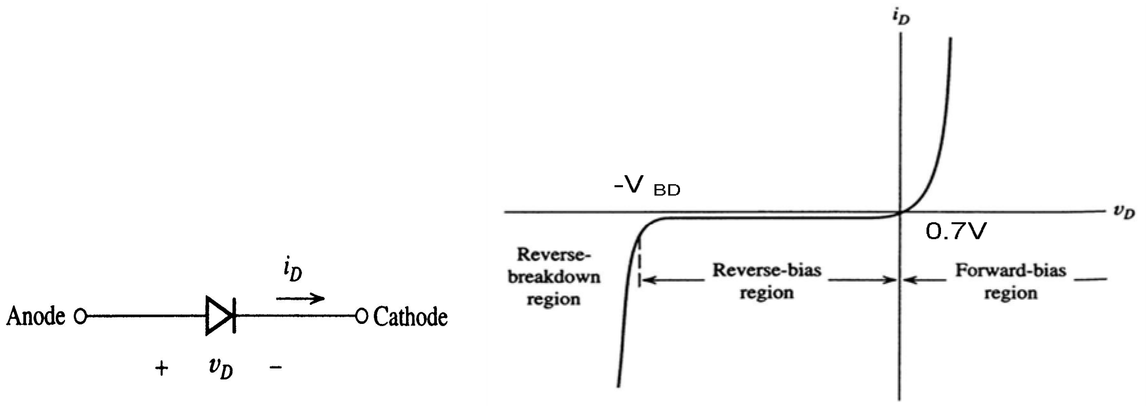
CHAPTER 2: Semiconductor Diodes and their Applications

2.1 Semiconductor Diodes and their Characteristics

A semiconductor diode is simply a pn junction that has two terminals: An **anode** and a **cathode**. The circuit symbol for a diode is shown in Fig.2.1a and the diode volt-ampere characteristic is displayed in Fig. 2.1b.



(a) Circuit symbol (b) Volt-ampere characteristic

Figure 2.1 Semiconductor diode

The v-i characteristic is an exponential function given by:

$$i_d = I_{ss}\left(e^{\frac{qv_D}{\eta KT}} - 1 \right) \tag{2.1}$$

Where:

I_{SS} : Saturation current of the diode

q : Electron charge $(1.602 \times 10^{-19} C)$

T : Temperature in degrees Kelvin;

K : Boltzmann's constant $(= 1.38x10^{-23} J/K)$;

V_T : Thermal voltage (= 26 mV at room temperature).

$$V_T = \frac{KT}{q} = \frac{T}{11{,}600} = 26mV \quad \textit{at room temperature of } 300K$$

η – material scale factor; η is close to 1 for germanium, and in silicon varies over the range $1 < \eta < 2$ at rated current for the diode - emission coefficient (a function of V_D)

As shown in Fig.2.1a, the voltage v_D across the diode is referenced as positive from anode to cathode. Similarly, the diode current i_D is referenced as positive from anode to cathode.

Notice in the characteristics that if the voltage v_D across the diode is positive, relatively large amounts of current flow for small voltages. This condition is called ***forward bias***.

Thus, current flows easily through the diode in the direction of the arrowhead of the circuit symbol (conventional current).
On the other hand for moderately negative values of v_D, the current i_D is very small. This is called the ***reverse-bias*** region, as shown on the diode characteristics.

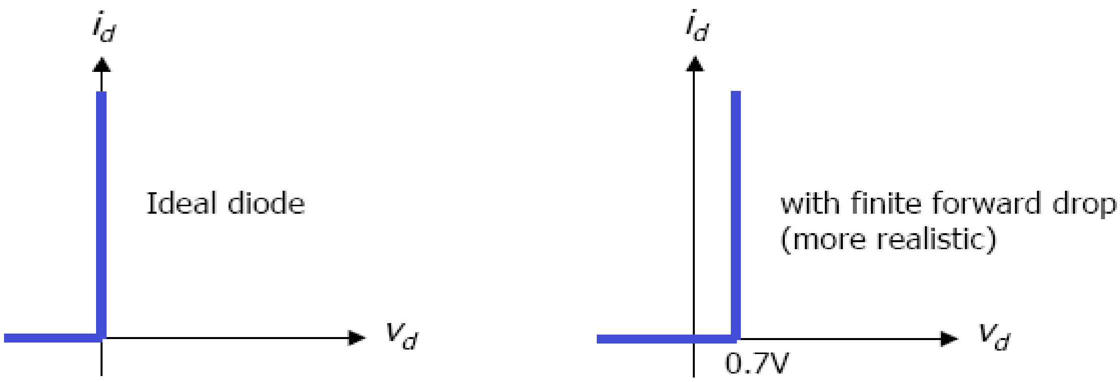
If a sufficiently large reverse-bias voltage is applied to the diode, its operation enters the reverse-breakdown region of the characteristic, and currents of large magnitude flow. Provided that the power dissipated in the diode does not raise its temperature too high, reverse-breakdown operation is not destructive (helpful) to the device. In fact, we will see that diodes are often deliberately operated in the reverse-breakdown region.

2.1.1 Diode Approximation

The above diode equation is a bit complicated and difficult to use for circuit analysis. Electronic engineers deal with this problem by simplifying things and using a model of the diode that suits them.

The Ideal Diode

In Fig.2.1b, the forward current is approximated to zero until the diode voltage reaches the barrier potential. Somewhere in the vicinity of 0.6 to 0.7V, the diode current increases. When the diode voltage is greater than 0.8V, the diode voltage is significant and the graph is almost linear.
Since most of the time we do not need exact solution, we use approximation for diode. And the simplest of this approximation is the ideal diode, in which it conducts in the forward direction (zero resistance = conductor) and not in the reverse direction (infinite resistance = insulator). This is analogous with an ordinary switch which has zero resistance when it is closed and infinite resistance when it is open.



infinite resistance when it is open.

a) Ideal diode b) Second approximation

Fig.2.2. Diode Approximation Curves

Second Approximation

In Fig.2.2b (second approximation), it approximates the diode as if there is no current until the barrier potential, 0.7V. At this point, the diode turns on and after this point, there will only be 0.7V what ever the current is.

In this popular model, we assume that the current is zero for any voltage below V_d but rises when we try to apply a voltage greater than this.

In effect, the diode is viewed as a switch which is open when we apply low or negative voltages but which closes when we apply a voltage equal to or greater than V_d. It means that it is impossible to get a voltage larger than this across the diode, thus it is also called Cut-In or Knee voltage.

Third Approximation

In the third approximation, the diode is approximated as a switch in series with barrier potential of 0.7V and bulk resistance (r_B). During conduction the total voltage across the diode is:

$$V_D = 0.7V + I_D r_B \qquad (2.2)$$

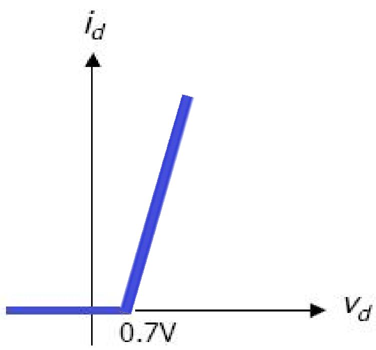


Fig. 2.3 Third Approximation

After silicon diode turns on, the voltage increases linearly with an increase in current. The greater the current, the larger the diode voltage because of the voltage drop across the bulk resistance.

Diode Resistance and Capacitor

A diode may be forward- biased to some dc operating point on the characteristic curve for the device. When a diode is forward biased to a particular operating point called quiescent point (Q), then the effective dc resistance of the diode, R_Q, is simply:

$$R_Q = \frac{V_{DQ}}{I_{DQ}} \qquad (2.3)$$

The value of R_Q will vary depending upon where the Q-point is located on the diode characteristic curve, since the relation between I_{DC} and V_{DC} essentially linear.

If the applied bias varies with time, such as when a sinusoidal bias voltage is superimposed upon the operating point, then a dynamic resistance of the device may be defined.

The dynamic resistance, r_δ of a diode is found by taking the derivative of diode current, I_D with respect to diode voltage V_D, as follows.

$$\frac{1}{r_\delta} = \left.\frac{dI_D}{dV_D}\right|_{I_{DQ}} = \frac{I_{SS}}{\eta V_T} e^{\frac{V_D}{V_T}}$$

When the diode is fully turned on such that the operation is well out on the V-I characteristic curve $I_D = I_{SS} \exp\left(\frac{V_D}{\eta V_T}\right)$ and the above equation reduced to:

$$\frac{1}{r_\delta} = \left.\frac{dI_D}{dV_D}\right|_{I_{DQ}} \approx \frac{I_{DQ}}{\eta V_T}$$

At room temperature, considering for silicon $\eta = 1,\ r_\delta = 0.026V / I_D\ \Omega$ *when* I_D is expressed in amperes. At Q point specified for a diode, the effective dc (static) resistance is $R_Q = \frac{V_{DQ}}{I_{DQ}}$.

On the other hand, the dynamic resistance in response to a small ac superposed upon the operating point is:

$$r_\delta = \frac{\eta V_T}{I_{DQ}} = \frac{0.026}{I_{DQ}}\Omega = \frac{26mV}{I_{DQ}} \quad \textit{at roomtemp} \qquad (2.4)$$

From the equation of dynamic resistance of a diode, we can see that for large value of I_{DQ}, r_δ becomes very small. In such cases, we will only consider the $R_Q = \frac{V_{DQ}}{I_{DQ}}$ value.

Diode capacitances:

There are two types of capacitive effects in a PN - junction

1. Space charge capacitance 2. Diffusion capacitance

Space charge (transition) capacitance (C_T)

This is a capacitance due to bound donor and acceptor ions in the depletion region.

$$C_T = \frac{dQ}{dV} = \frac{\varepsilon A}{d} \qquad \text{------------------- (2.5)}$$

Its effect is reduced in reverse biased diode. This is because the space charge capacitance is indirectly *proportional to the width of the depletion region* and the depletion region gets wider for the reverse bias.

Diffusion Capacitance (C_D)

This is due to the accumulation of minority charge carriers at the edges of the depletion region. Because the accumulation of minority carriers at each side of the depletion region is very large for forward biased and it is almost zero for reverse biased, diffusion capacitance is magnified in forward biased.

$$C_D = \frac{dQ}{dV} \quad ; \quad Q = i\tau$$
$$= \frac{d(i\tau)}{dV} = \tau\frac{di}{dV} = \tau g \quad where - g = conductance = \frac{1}{R}$$
$$C_D = \tau g = \tau\left(\frac{I_S + I}{\eta V_T}\right) \tag{2.6}$$

From the above expression in the forward bias case, the current $\boldsymbol{I_F}$ is large and hence the diffusion capacitance becomes very large. But in the reverse bias condition, since the current $\boldsymbol{I_R}$ is very small, the diffusion capacitance is very small. And remember the diffusion capacitance is always greater than the space charge capacitance ($C_D > C_T$).

Peak Inverse Voltage (PIV) ***(Avalanche and Zener Breakdown)***

Peak Inverse Voltage is the maximum reverse voltage that a diode can sustain without being driven it to the irreversible breakdown region. It is known that as the reverse- bias voltage is increased, the internal electric field in the diode also increases. This accelerates minority carriers to collide with the crystal lattice structure. The collision generates additional hole-electron pair. Thus additional charges are generated in an avalanche manner. There results a rapidly increase reverse in the diode, which is the cause to heat up and finally destroys the diode. Thus to keep the diode for safe operation, the reverse voltage must not be exceeded. Manufacturers always list peak inverse voltage (PIV) ratings for semiconductor diodes.

There are diodes called avalanche diodes and zener diodes in which the breakdown phenomenon is reversible, although eventually excessive reverse bias destroys the diode. With ordinary diodes however, the term avalanche break down implies irreversible damage to the diode.
In avalanche diodes, avalanche effect is self limiting that is, as the diode heats up, lattice vibration increases, which reduces the mean-free path distance for the field-accelerated charges.

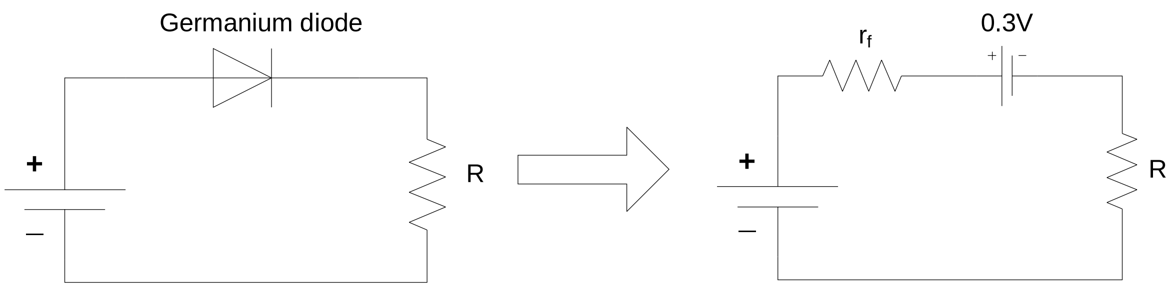
Zener breakdown occurs in specially doped diodes, which are characterized by a sudden rise in current at a particular value of reverse voltage. The underlying process is tunnelling, as opposed to an avalanche phenomenon. The reverse voltage at which the diode current suddenly increases is called the zener breakdown voltage. The zener voltage is essentially constant over a moderate range of current values. Consequently, zener diodes may be used as voltage regulating devices. In this mode of operation, the voltage across an electric load may be held essentially constant, although the load current can vary.

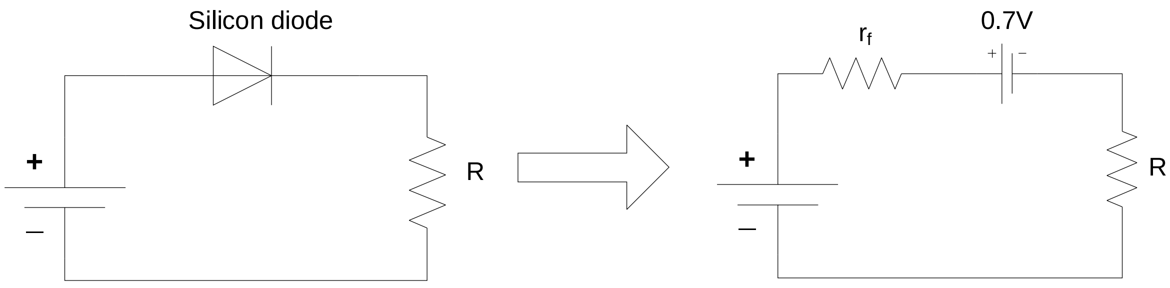
2.2. Analysis of Diode Circuits

Diodes as a Circuit Element

In this section we will investigate current and voltage relationships in circuits that contain diodes and to analyse the circuit containing diodes by replacing the diode with simple equivalent circuit element. The circuit element used to replace the diode depends on the voltage and current levels of the circuit we are analysing.

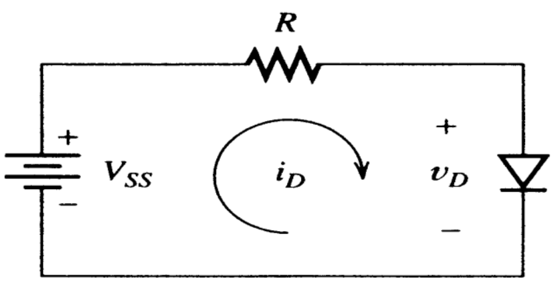
For example consider the following circuits.





Where: $r_f = \dfrac{\eta V_T}{I + I_{SS}}$

Load Line Analysis



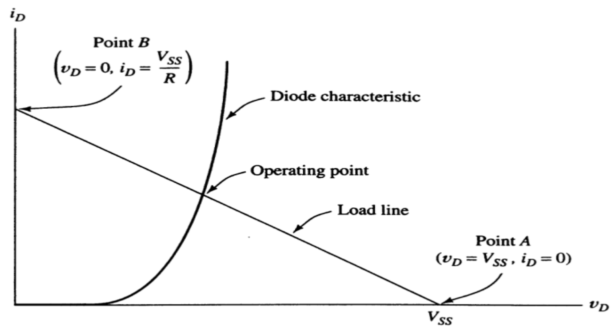


Fig.2.4. (a) Circuit for load line analysis (b) Load line analysis for the circuit of Fig.2.4 a

Applying Kirchhof's voltage law, we can write a load line equation as:

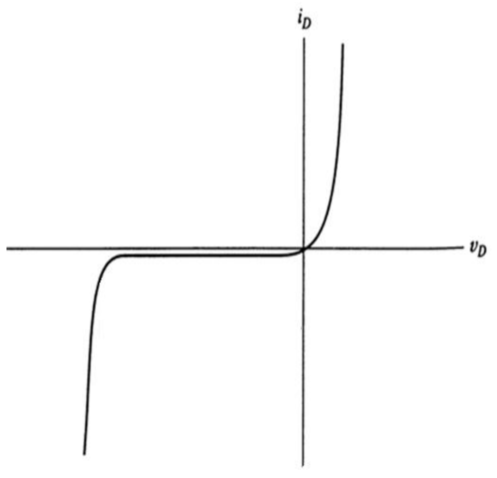
$$Vss = Ri_D + v_D \qquad (2.7)$$

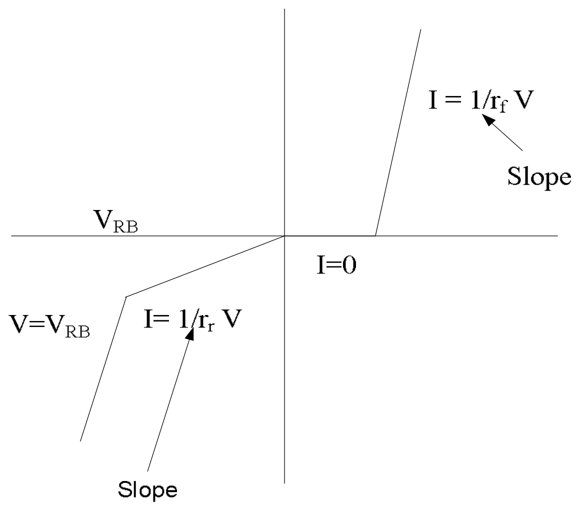
We assume that the values of Vss and R are known and that we wish to find i_D and v_D. Thus, equation (2.7) has two unknowns and another relationship between i_D and v_D is needed to find a solution. The needed relationship is available in graphical form in Fig.2.4b, which shows the volt-ampere characteristic of the diode.

We can obtain the solution by plotting equation (2.7) on the same set of axes used for the diode characteristic. Because this equation is linear, it plots as a straight line that can be drawn if two points satisfying the equation are located. A simple method for locating these points is to assume that i_D = 0. Then equation (2.7) yields $v_D = V_{ss}$. This pair of values is shown as point A in Fig.2.4b. A second point results if we assume that v_D = 0, in which case the equation yields $i_D = \frac{V_{SS}}{R}$. This pair of values is shown as point B in Fig.2.4b.

Then, connecting points A and B results in the plot which is called the **Load Line**. The operating point is the intersection of the load line and the diode characteristic. The operating point represents the simultaneous solution of equation (2.7) and the diode characteristic.

Piecewise Linear Model: This model is simply a model that approximates the graph of $I = I_{SS}\left(e^{\frac{V_D}{\eta V_T}} - 1\right)$ of V-I characteristic in to somewhat linear.





Then by passing the load line equation through each piece, we can determine the variables.

2.3 Types of Diodes

Zener Diode

A **Zener diode** is a type of diode that permits current to flow in the forward direction like a normal diode, but also in the reverse direction if the voltage is larger than the rated breakdown voltage or "Zener voltage".

A conventional solid-state diode will not let current flow if reverse-biased below its reverse breakdown voltage. By exceeding the breakdown voltage, a conventional diode is destroyed in the breakdown due to excess current which brings about overheating. The process is however reversible, if the device is operated within limitation. In case of forward bias (in the direction of the arrow), the diode exhibits a voltage drop of roughly 0.6 volt for a typical silicon diode. The voltage drop depends on the type of the diode.

A **Zener diode** exhibits almost the same properties, except the device is especially designed so as to have a greatly reduced breakdown voltage, the so-called **Zener voltage**.

A Zener diode contains a heavily doped p-n junction allowing electrons to tunnel from the valence band of the p-type material to the conduction band of the n-type material. A reverse biased Zener diode will exhibit a controlled breakdown and let the current flow to keep the voltage across the Zener diode at the Zener voltage. For example, a 3.2-volt Zener diode will exhibit a voltage drop of 3.2 volts if reverse biased. The breakdown voltage can be controlled quite accurately in the doping process.

Another mechanism that produces a similar effect is the avalanche effect as in the avalanche diode. The two types of diode are in fact constructed the same way and both effects are present in diodes of this type. In silicon diodes up to about 5.6 volts, the zener effect is the predominant effect and shows a marked negative temperature coefficient. Above 5.6 volts, the avalanche effect becomes predominant and exhibits a positive temperature coefficient.

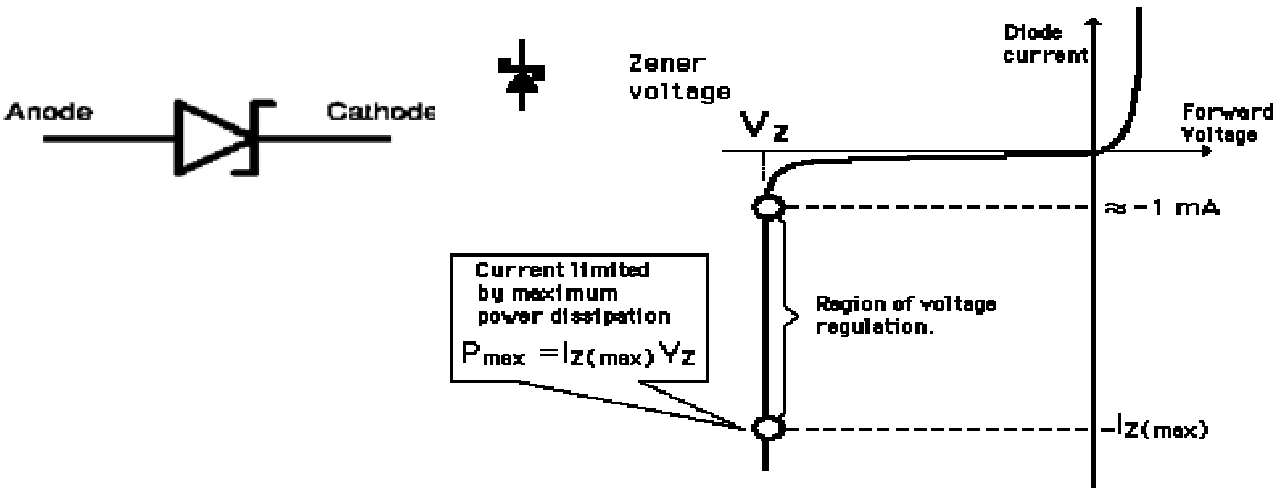


Fig.2.5. Schematic symbol and V-I Characteristics of a Zener diode

The V-I characteristic of a zener diode is shown in Fig.2.5. With the application of sufficient reverse voltage, a p-n junction will experience a rapid avalanche breakdown and conduct current in the reverse direction.

Valence electrons, which break free under the influence of the applied electric field, can be accelerated enough that they can knock loose other electrons and the subsequent collisions quickly become an avalanche.

When this process is taking place, very small changes in voltage can cause very large changes in current. The breakdown process depends upon the applied electric field, so by changing the thickness of the layer to which the voltage is applied, zener diodes can be formed which break down at voltages from about 4 volts to several hundred volts.

Shottky Diodes

These are diodes consisting of a junction called metal semiconductor junction and formed by bringing metal (Aluminium) into moderately doped n-type semiconductor. Aluminium acts as a p-type material (anode), the n-type material is the cathode.

Unlike a normal semiconductor diode Shottky Diodes can be turned off very quickly.

Light Emitting Diode (LED)

When pn-junction is forward biased, free electrons cross the junction and recombines with holes at p-side. These electrons have been in the conduction band and drop to the valence band by recombination. Because they are falling to a lower energy level they emit energy. This released energy may be in the form of heat or light depending on the material used.

For example, silicon and germanium diodes release energy in the form of heat, whereas gallium arsenide (GaAs) and gallium phosphate (GaP) release light energy.

The colour of emitted light is controlled by the doping level.

Reading assignment

Tunnel diode
Step-recovery diode
Varactor diode

2.4. Application of Diode Circuits

Semiconductor diodes find many applications in electronics circuit designing. A major use is as a rectifier in power supplies, to convert ac to dc, in radio frequency receivers; in some instrumentation systems they are used in a similar manner to recover (detect) amplitude modulation super imposed upon a carrier signal. They may be used as polarity sensitive dc conductive devices (often called steering diodes) as such they pass dc of one polarity while blocking dc of the opposite polarity. In clipping, limiting and clamping circuits they are used to shape and alter signal profiles. Zener diodes are used as voltage regulating devices.

Varactor diodes serve as voltage tuned capacitors and find many applications in radio frequency design. Light emitting diodes (LEDs) are used as indicator lights and in displays, while light sensitive photodiodes are used as optical detectors.

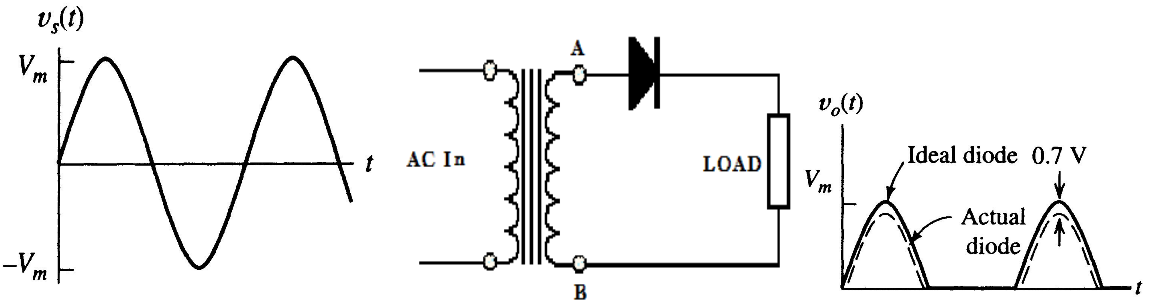
2.4.1. Rectification

Diodes are used as rectifiers in electronic power supplies. Rectification is the process by which time varying voltages are converted to pulsating d.c voltages. DC power supplies are typically produced by rectifying the sinusoidal voltage available from the a.c power mains. The initial rectification process produced sinusoidal voltage pulses, i.e. still the rectified voltage is a time varying signal. To obtain a d.c voltage, the rectified voltage (pulsating d.c voltage) must be processed by a filter. When a very stable and pure d.c voltage is required the rectified and filtered voltage may be further processed using a voltage regulator. Of course, there are different types of circuits of each stage. For example there are many configurations of diodes that produce rectification:

Half wave rectifier: which uses only one diode
Full wave rectifier: that uses two diodes and a centre - tapped transformer
Bridge rectifier: that uses four diodes

Rectification is a process that involves large signal operation of a diode, and it is therefore a non-linear process. The diode turns on and off in response to the applied sinusoidal voltage.

a) Half wave rectifier



a) Input ac voltage b) Circuit c) Rectified output voltage

Fig.2.6. Half wave rectifier circuit and its corresponding waveforms

Principles of Operation

The Fig.2.6b shows the circuit diagram of half wave rectifier. The voltage at point A has the opposite polarity of that at point B. When A is increasing in a positive direction, B is increasing in a negative direction. It is rather like the two ends of a seesaw. During the first half cycle of the waveform shown on the left (Input ac voltage), point A is positive with respect to point B. The diode is forward biased and current flows around the circuit formed by the diode, the transformer winding and the load. Since the current through the load and the voltage across the load are in the same proportions, then the voltage across the load is as shown in the right hand diagram (Fig.2.6c), during the first half cycle. During the second half cycle, point A and the anode are negative while point B and the cathode are positive. The diode is reverse biased and no current flows. This is indicated by the horizontal line in the right hand diagram (Fig.2.6c). The diode conducts only on every other half cycle (during half the cycle). Hence, ***Half Wave Rectification***. The rectified voltage is d.c (it is either positive or negative in value depending on the direction of the diode connection). However, it is not a steady d.c, but pulsating d.c. It needs to be smoothed before it becomes useful.

Peak Inverse Voltage

When the input voltage reaches its maximum value (V_m) during the negative half cycle, the voltage across the diode is also maximum equal to V_m. This maximum voltage across non conducting diode is known as the Peak - Inverse - Voltage. Thus for a half wave rectifier,

$$PIV = V_m$$

Let V_i be the voltage to the primary of the transformer. Thus, Vi is given by

$$Vi = V_m \sin \omega t, V_m >> Vr$$

Where: Vr is the cut-in voltage (barrier potential) of the diode.

Ripple Factor

Ripple factor (r) is a *purity of the output dc voltage* and can be defined as the ratio of the effective (rms) value of ac components voltage (or current) to the dc or the average value components in the output.

$$r = \frac{RMS\, value\, of\ the\, AC\, Component}{DC\, value\, of\ the\, Component}$$

$$r = \frac{Vr_{rms}}{V_{DC}}$$

$$Vr_{rms} = \sqrt{V_{rms}^2 - V_{DC}^2}$$

$$r = \sqrt{\left(\frac{V_{rms}}{V_{DC}}\right)^2 - 1} \qquad (2.8)$$

The average (V_{av}) or the dc output content of the voltage across the load is given by:

$$V_{av} = V_{dc} = \frac{1}{2\pi}\left[\int_0^{\pi} V_m \sin \omega t \, d(\omega t) + \int_{\pi}^{2\pi} 0.d\,(\omega t)\right]$$

$$= \frac{V_m}{2\pi}\left[-\cos \omega t\right]_0^{\pi} = \frac{V_m}{\pi}$$

$$\mathrm{V_{av}} = \mathrm{V_{dc}} = \frac{\mathrm{V_m}}{\pi} \qquad (2.9a)$$

and

$$I_{av} = I_{dc} = \frac{V_{dc}}{R_L} = \frac{V_m}{\pi R_L} = \frac{I_m}{\pi} \qquad (2.9b)$$

Effective (rms) voltage at the load resistance can be calculated as:

$$V_{rms} = \left[\frac{1}{2\pi}\int_0^{\pi} V_m^2 \sin^2 \omega t \, d(\omega t)\right]^{\frac{1}{2}}$$

$$= V_m \left[\frac{1}{4\pi}\int_0^{\pi} (1 - \cos 2\omega t) d(\omega t)\right]^{\frac{1}{2}} = \frac{V_m}{2}$$

$$V_{rms} = \frac{V_m}{2} \qquad (2.10a)$$

$$and \;\; I_{rms} = \frac{I_m}{2} \qquad (2.10b)$$

Thus the ripple factor in the half wave rectifier circuit is;

$$r = \sqrt{\left[\frac{\frac{Vm}{2}}{\frac{Vm}{\pi}}\right]^2 - 1} = 1.21 \qquad So,\; r = 1.21$$

Efficiency (η)

Efficiency (η) of a rectifier is the ability of a rectifier circuit to convert the a.c input power into useful d.c power in the load. It is defined as the ratio of the dc output power (P_{dc}) to the ac input power (P_{ac}) and is, therefore, given by:

$$\eta = \frac{dc\,output\ power}{ac\,input\ power} = \frac{P_{dc}}{P_{ac}} \qquad (2.11)$$

$$= \frac{V_{dc}^2 / R_L}{V_{rms}^2 / R_L} = \frac{\left[Vm/\pi\right]^2}{\left[Vm/2\right]^2} = \frac{4}{\pi^2} = 0.406$$

$$Thus, \eta = 40.6\%$$

Form Factor (F)

$$F=\frac{rms\,values\,of\,\,otput\,voltage}{average\,values\,of\,\,otput\,voltage}=\frac{V_m/2}{V_m/\pi}=\frac{\pi}{2}=1.57 \qquad (2.12)$$

Note! The ripple factor of a rectifier circuit may also be calculated from the form factor as:

$$r=\sqrt{F^2-1} \qquad (2.13)$$

Transformer Utilization Factor (*TUF*)

Transformer Utilization Factor can be used to determine the rating of a transformer secondary and it is defined as:

$$TUF=\frac{dc\ power\ delivered\ the\ load}{ac\ rating\ of\ the\ transformer\ secondary}=\frac{P_{dc}}{P_{ac(rating)}} \qquad (2.14)$$

In half wave rectifier the rated rms voltage of the transformer secondary is: $\frac{V_m}{\sqrt{2}}$

Actually, the rms current flowing through the winding is only: $\frac{I_m}{2}$

$$TUF=\frac{\left(\frac{I_m^2}{\pi^2}R_L\right)}{\left(\frac{V_m}{\sqrt{2}}\frac{I_m}{2}\right)}=\frac{\left(\frac{V_m^2}{\pi^2}\frac{1}{R_L}\right)}{\left(\frac{V_m}{\sqrt{2}}\frac{V_m}{2R_L}\right)}=\frac{2\sqrt{2}}{\pi^2}=0.287 \qquad (2.15)$$

b) Full Wave Rectifier Circuit

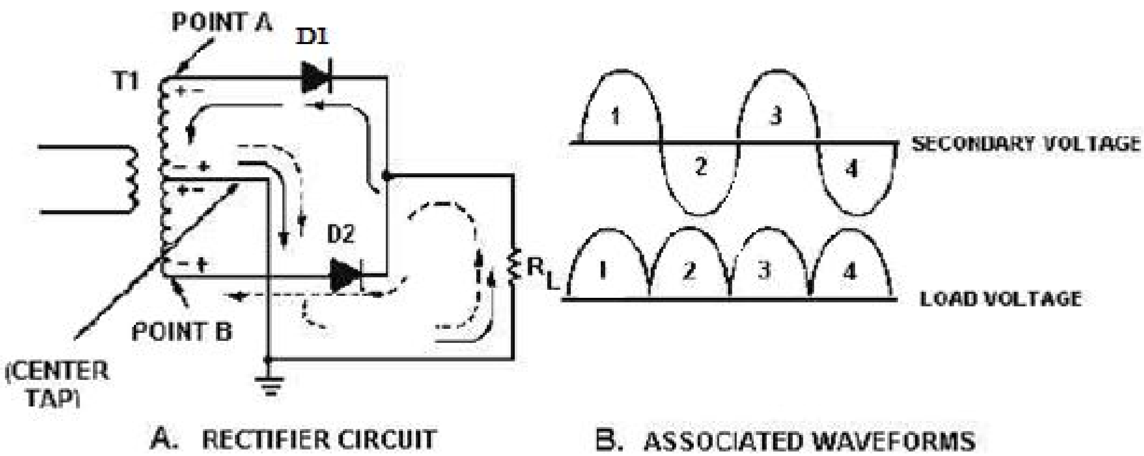


Fig.2.7. Circuit diagram of practical full wave rectifier

Principles of Operation

A practical full-wave rectifier circuit is shown in Fig.2.7. It uses two diodes (D_1, D_2) and a *Centre-tapped transformer* (T_1). When the centre tap is grounded, the voltages at the opposite ends of the secondary windings are 180 degrees out of phase with each other.

Thus, when the voltage at point A is positive with respect to ground, the voltage at point B is negative with respect to ground. Let's examine the operation of the circuit during one complete cycle.

During the first half cycle (indicated by the solid arrows), the anode of D_1 is positive with respect to ground and the anode of D_2 is negative.
The current flows from the ground up through the load resistor (R_L), through diode D_1 to point A. In the transformer, current flows from point A, through the upper winding, and back to ground (centre tap). When D_1 conducts, it acts like a closed switch so that the positive half cycle is felt across the load (R_L).

During the second half cycle (indicated by the dotted lines), the polarity of the applied voltage has reversed. Now the anode of D_2 is positive with respect to ground and the anode of D_1 is negative. Now only D_2 can conduct. Current now flows, as shown, from ground (centre tap), up through the load resistor (R_L), through diode D_2 to point B of T_1. In the transformer, current flows from point B up through the lower windings and back to ground (centre tap).

Notice that the current flows across the load resistor (R_L) in the same direction for both halves of the input cycle.

The average voltage or the dc voltage available across the load resistance is

$$V_{av} = V_{dc} = \frac{1}{\pi}\left[\int_0^{\pi} V_m \sin\omega t \, d(\omega t)\right]$$

$$= \frac{V_m}{\pi}\left[-\cos\omega t\right]_0^{\pi} = \frac{2V_m}{\pi}$$

$$Thus, V_{av} = V_{dc} = \frac{2V_m}{\pi}, \qquad (2.16a)$$

$$and$$

$$I_{av} = I_{dc} = \frac{V_{dc}}{R_L} = \frac{2V_m}{\pi R_L} = \frac{2I_m}{\pi}$$

$$That\ is, I_{av} = I_{dc} = \frac{2I_m}{\pi} \qquad (2.16b)$$

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

The effective (rms) value of the voltage at the load resistance is:

$$V_{rms} = \left[\frac{1}{\pi}\int_0^{\pi} V_m^2 \sin^2 \omega t \, d(\omega t)\right]^{\frac{1}{2}} = V_m\left[\frac{1}{2\pi}\int_0^{\pi}(1-\cos 2\omega t)d(\omega t)\right]^{\frac{1}{2}} = \frac{V_m}{\sqrt{2}}$$

$$So, V_{rms} = \frac{V_m}{\sqrt{2}} \qquad (2.17)$$

The ripple factor of the Full Wave Rectifier circuit can be determined as:

$$r = \sqrt{\left(\frac{V_{rms}/2}{V_{dc}/\pi}\right)^2 - 1} = \sqrt{\left(\frac{\frac{V_m}{\sqrt{2}}}{\frac{2V_m}{\pi}}\right)^2 - 1} = \sqrt{\left(\frac{\pi}{2\sqrt{2}}\right)^2 - 1} = 0.482 \qquad (2.18)$$

$$So, r = 0.482$$

Efficiency

The efficiency of the Full Wave Rectifier circuit can also be determined as:

$$\eta = \frac{dc\,output\ power}{ac\,input\ power} = \frac{P_{dc}}{P_{ac}} = \frac{V_{dc}^2/R_L}{V_{rms}^2/R_L} = \frac{\left[2V_m/\pi\right]^2}{\left[V_m/\sqrt{2}\right]^2} = \frac{8}{\pi^2} = 0.812 \qquad (2.19)$$

$$So, \eta = 81.2\%$$

The maximum efficiency of a Full Wave Rectifier is 81.2% and it is much higher than the efficiency of a Half Wave Rectifier circuit.

Form Factor

Form factor is defined as the ratio of the rms value of the output voltage to the average value of the output voltage.

$$Form\ Factor = \frac{rms\ value\ of\ \ output\ voltage}{average\ value\ of\ \ the\ ouput\ voltage} = \frac{\left(V_m/\sqrt{2}\right)}{\left(2V_m/\pi\right)} = \frac{\pi}{2\sqrt{2}} = 1.11 \qquad (2.20)$$

Peak inverse voltage

The PIV of a Full Wave Rectifier across the non-conducting diode is **2Vm** because the entire secondary voltage appears across this diode.

Transformer Utilization Factor

Transformer Utilization Factor, TUF can be used to determine the rating of a transformer secondary. It is determined by considering the primary and the secondary windings separately and it gives a value of 0.693.

c) <u>Full-Wave Bridge Rectifier</u>

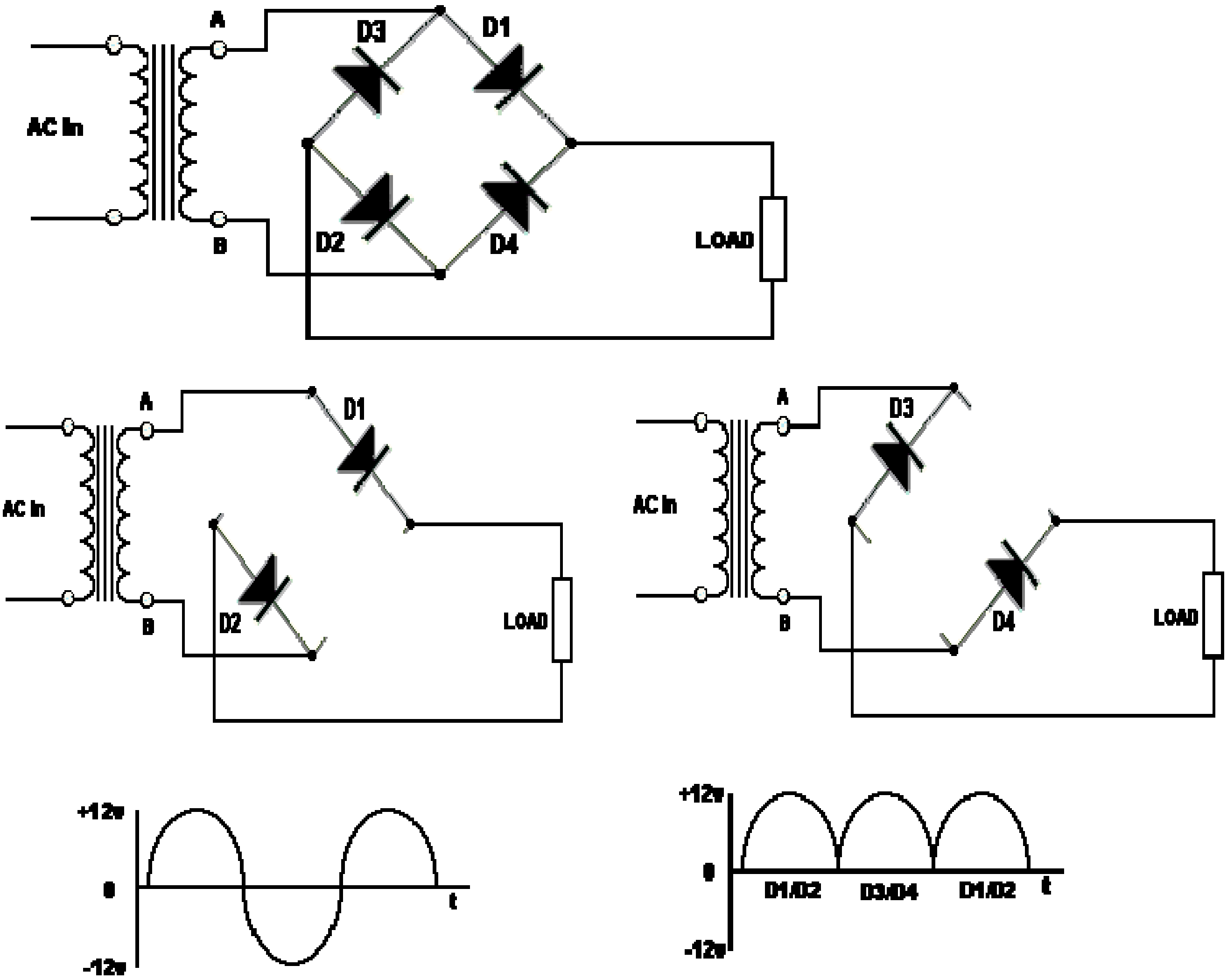


Fig.2.8. Full wave bridge rectifier circuit and its waveforms

Principles of Operation

The voltages at points A and B on the transformer are changing in opposite directions. When A is increasing in a positive direction, B is increasing negatively. It is like the opposite ends of a seesaw. During the first half cycle, A is positive and B is negative. D_1 has positive on its anode, D_2 has negative on its cathode. Both are forward biased. Current flows around the circuit formed by these diodes, the load and the transformer winding, as shown in the second diagram. The current flowing up through the load produces a pulse of voltage across the load as shown in the right hand waveform.

During the next half cycle, A is negative and B is positive. D_4 has positive on its anode, D_3 has negative on its cathode. Both are forward biased. Current flows around the circuit as shown in the bottom diagram, again flowing in the same direction through the load and producing another pulse of voltage.

Since the full cycle is used, this circuit is called a ***Full Wave*** *rectifier.*

The following parameters are the same as the full wave rectifier; they are I_{dc}, V_{dc}, I_{rms}, V_{rms}, *Ripple factor, Efficiency, Form factor, peak facto (TUF).* Its Peak Inverse Voltage (PIV) is V*m*, due to the two conducting diodes are in series.

Bridge rectifier has a number of advantages: low ripple, High efficiency, TUF is higher than centre tapped FWR, less bulky and expensive, PIV is only V*m*, and since TUF is high it can be used for high power applications. And its disadvantage is: Uses four diodes, which reduces voltage by two diode drops for every half cycle.

Filtering Circuits

The voltage that we get by rectification is pulsating DC. In order to get a smooth DC (pure dc), we need to filter out the pulsation. Filtering is removing the ac components of the output voltage to the load. There are different types of filtering circuits:

Half wave capacitor input filter (C filter)

One method of smoothing the rectified output voltage is by placing a large capacitance across the output terminals of the rectifier. The circuit and waveform of the output voltage is shown in Fig.2.9 below.

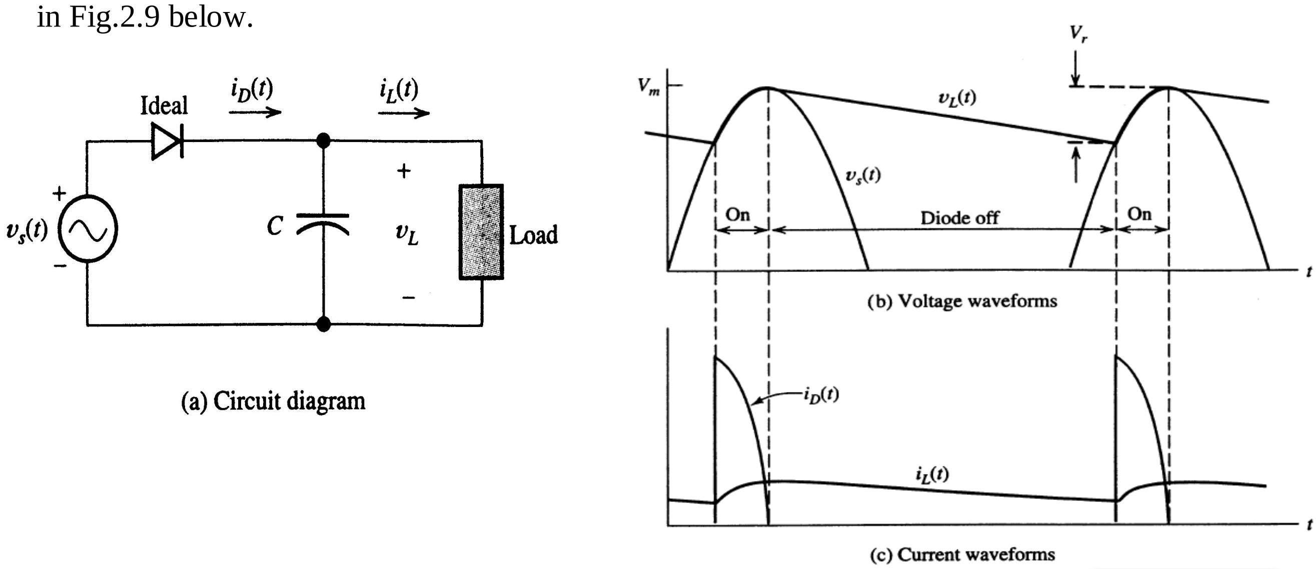


Fig.2.9. Half wave rectifier with smoothing capacitor

When the ac source reaches a positive peak, the capacitor is charged to the peak voltage (assuming ideal diode). Then, when the source voltage drops below the voltage stored on the capacitor, the diode is reverse biased and no current flows through it. The capacitor continues to supply the current to the load, slowly discharging until the next positive peak of the ac input. As shown in the figure, current flows through the diode in pulses that recharge the capacitor.

Because of the charge and discharge cycle, the load voltage contains a small ac component called ripple. Usually it is desirable to minimize ripple, so we choose the largest capacitance value that is practical.

In this case the capacitor discharges for nearly the entire cycle, and the charge removed from the capacitor during one discharge cycle is; $Q = I_L T$

Where: I_L is the average load current (I_{dc}) and T is the period of the AC output voltage. Since the charge removed from the capacitor is the product of the change in voltage and the capacitance, we can also write as, $Q = V_r C$

Where *Vr* is the *peak to peak ripple voltage* and *C* is the capacitance. Equating the right hand sides of the above equations allows as to estimate the filter capacitance needed in a half wave rectifier: $C = \frac{I_L T}{V_r} = \frac{I_L}{V_r f}$ (2.21) *and* $V_r = \frac{I_L}{fC}$ (2.22)

Ripple Factor

The effective (rms) value of the ripple components of almost triangular wave is dependent only on the peak to peak value of the ripple components. Taking the time axis along the V_{dc} curve, the rms value of this triangular a.c component of voltage can be given by:

$$Vrms = \frac{V_{rp-p}}{2\sqrt{3}} \qquad (2.23)$$

Hence the ripple factor is: $r = \frac{V_{rms}}{V_{dc}} = \frac{V_{rp-p}}{2\sqrt{3}\, I_{dc} R_L}$ (2.24)

Substituting the value of V_{rp-p} from Eq. (2.22) into Eq. (2.24) we get;

$$Ripple\ fcror(r) = \frac{1}{2\sqrt{3}\, fC R_L} \qquad (2.25)$$

Output d.c Voltage or Current

The average or the d.c voltage value of the output voltage is almost midway between the peak values (V_m) and the minimum value given by points positive V_{rp} and negative V_{rp} respectively. Thus we get;

$$V_{av} = V_{dc} = V_m - \frac{V_{rp-p}}{2} = V_m - \frac{I_{dc}}{2fC}, Since\ I_{dc} = \frac{V_{dc}}{R_L}, then\ V_{dc} = \frac{V_m}{1 + \frac{1}{2fCR_L}} \qquad (2.26)$$

and $$I_{av} = I_{dc} = I_m - \frac{I_{rp-p}}{2} = \frac{V_m}{R_L + \frac{1}{2fC}} \qquad (2.27)$$

Full wave with capacitor filter

During the positive half cycle, the capacitor charges up to the peak vale of the transformer secondary voltage, V_m and will try to maintain this value as the full wave input drops to zero. Capacitor will discharge through R_L slowly until the transformer secondary voltage again increases to a value greater than the capacitor voltage. The diode conducts for a period, which depends on the capacitor voltage. The diode will conduct when the transformer secondary voltage becomes more than the diode voltage. This is called the cut-in voltage. The diode stops conducting when the transformer voltage becomes less than the diode voltage. This is called cut- out voltage. Referring to the figure below, with slight approximation the ripple voltage can be assumed as triangular. From the cut-in point to the cut-out point, whatever charge the capacitor acquires is equal to the charge the capacitor has lost during the period of non conduction, i.e., from cut-out point to the next cut-in point.

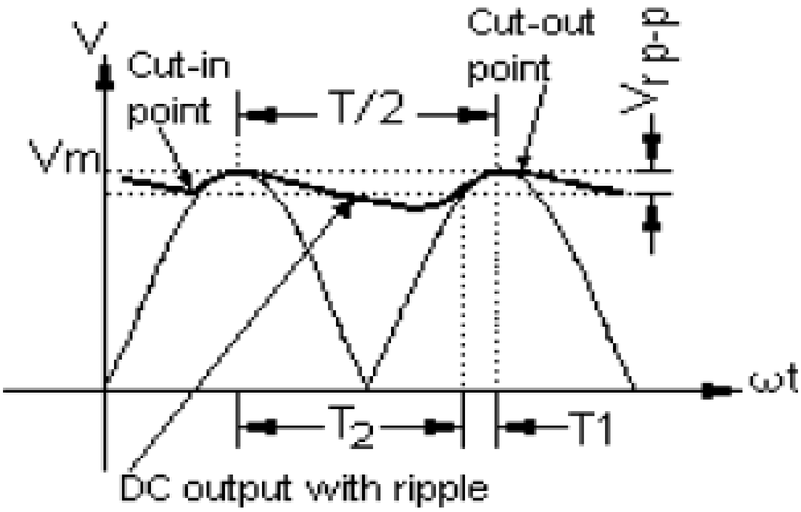


Fig.2.10. Full wave rectifier waveform with smoothing capacitor

When we observe the waveform in Fig.2.10, the *charge the capacitor has acquired* = *Vr x C.* The *charge it has lost* = I_{dc} + T_2. Assuming these charge values are equal, *Vr x C*= I_{dc} + T_2. If the value of the capacitor is fairly large, or the value of the load resistance is very large, then it can be assumed that the time T_2 is equal to half the periodic time of the waveform. Thus,

$$T_2 = \frac{T}{2} = \frac{1}{2f}, \quad then \quad V_r = \frac{I_{dc}}{2fC}$$

From the above assumptions, the ripple waveform will be *triangular* and its *rms* value is given by

$$V_{rms} = \frac{V_r}{2\sqrt{3}} = \frac{I_{dc}}{2\sqrt{3}fC} \; Since, I_{dc} = \frac{V_{dc}}{R_L}, then, V_{rms} = \frac{V_{dc}}{4\sqrt{3}fCR_L} \qquad (2.28)$$

$$and\ the\ ripple\ factor, r = \frac{V_{rms}}{V_{dc}} = \frac{1}{4\sqrt{3}fCR_L} \qquad (2.29)$$

The ripple factor may be decreased by increasing C or R_L (both) with a resulting increase in the d.c output voltage. The d.c output voltage can be determined by the following equation:

$$V_{dc} = \mathrm{V_m} - \frac{V_r}{2} = V_m - \frac{I_{dc}}{4fC} \;, Since\, I_{dc} = \frac{V_{dc}}{R_L}, then\ V_{dc} = \frac{V_m}{1 + \frac{1}{4fCR_L}} \; (2.30a) \; and\ I_{dc} = \frac{V_m}{R_L + \frac{1}{4fC}} \; (2.30b)$$

2.5. Voltage Regulator

Zener Diode Voltage Regulators

Sometimes a circuit that produces constant output voltage while operating from a variable supply voltage is needed. Circuits which perform such operation are called voltage regulators.

Zener Voltage Regulator:

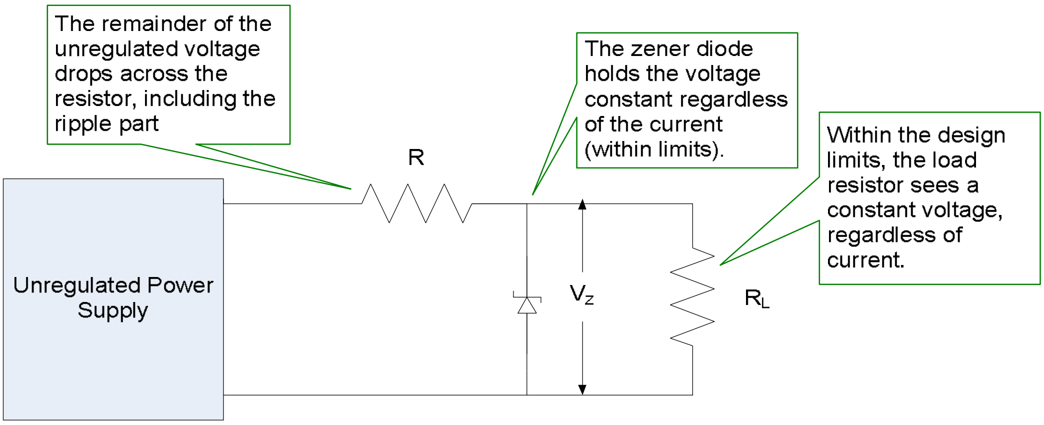


Fig.2.11. Zener Voltage Regulator System

Zener diodes are widely used to regulate the voltage across a circuit. When connected in parallel with a variable voltage source so that it is reverse biased, a zener diode conducts when the voltage reaches the diode's reverse breakdown voltage. From that point it keeps the voltage at that value.

In the circuit shown, resistor R provides the voltage drop between input and output.
The value of R must satisfy two conditions:

- R must be small enough that the current through D keeps D in reverse breakdown.
  If insufficient current flows through D, then output will be unregulated, and could rise as high. When calculating R, allowance must be made for any current flowing through the external load, not shown in this diagram, connected across the output.

- R must be large enough that the current through D does not destroy the device.
  If the current through D is I_D, a breakdown voltage V_B and its maximum power dissipation $P_{\max}$, then, $I_D V_B < P_{\max}$.

A zener diode used in this way is known as a *shunt voltage regulator*, and voltage regulator being a class of circuit that produces a stable voltage across any load.

Consider the following circuit for the voltage regulator

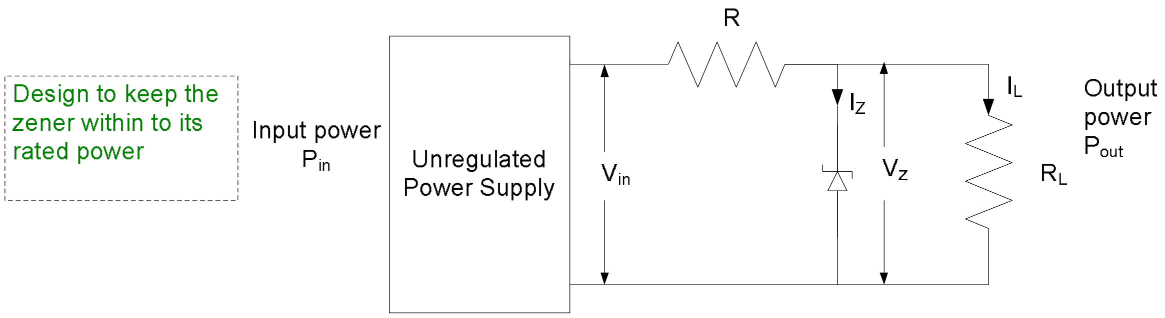


Fig.2.12. A Simple Zener Voltage Regulator Circuit

The circuit has to maintain constant voltage across a load resistor R_L. The circuit holds the voltage across the load R_L almost equal to the voltage across zener V_Z even after the input V_{in} and load resistor R_L undergo changes. If the unregulated dc voltage Vin rises, the current through R (Rs) increases. This extra current is directed to the zener diode instead of flowing through the load. The zener diode voltage is virtually unaffected by the increase in this current and load voltage which is same as the diode voltage V_Z remains constant. If the load requires more current when R_L is decreased, the zener diode can supply the extra current without affecting the load voltage.

Let Is be the current through the resister Rs, we can write as;

$I_S = I_Z + I_L$ *or* $I_S = \dfrac{V_{in} - V_Z}{R_S}$. The power dissipated in the zener diode is, $P_Z = I_Z V_Z$.

In the voltage regulation case, the selection of Rs is very important. Thus we have

$R_S = \dfrac{V_{in} - V_Z}{I_S} = \dfrac{V_{in} - V_Z}{I_Z + I_L}$. For ***Line Regulation***, R_L is constant and causes $I = \dfrac{V_Z}{R_L}$ is also constant while V_{in} varies between its $V_{in(min)}$ to its $V_{in(max)}$. For ***Load Regulation***, V_{in} is constant and R_L varies between R_{Lmin} and R_{Lmax} and load current is given by:

$I_{L\min} = \dfrac{V_Z}{R_{L\max}}$ *and* $I_{L\max} = \dfrac{V_Z}{R_{L\min}}$. When $V_{in} = V_{in\min}$, and I_L is constant then

$I_{\min} = \dfrac{V_{in\min} - V_Z}{R_S} = I_{Z\min} + I_L$. Similarly when $V_{in} = V_{in\max}$, we have, $I_{\max} = \dfrac{V_{in\max} - V_Z}{R_S} = I_{Z\max} + I_L$

The selected Rs must be small enough to permit minimum zener current to ensure that the zener diode is in its breakdown region. That is Rs must be small enough to ensure that minimum current $I_{Z\min}$ flows under worst condition. This is when V_{in} falls to its smallest possible value $V_{in\min}$ and I_L is its largest possible value $I_{L\max}$ (***Load Regulation***). At the same time Rs must be selected large enough to ensure that the current through the zener diode should not exceed the maximum zener current $I_{Z\max}$ so that power dissipation in the zener diode will not exceed Pz. That is the condition when V_{in} rises to the value of $V_{in\max}$ and load current I_L to its minimum $I_{L\min}$. So, we can write

$$R_S \le \frac{V_{in\min} - V_Z}{I_{Z\min} + I_{L\max}} \quad and \quad R_S \ge \frac{V_{in\max} - V_Z}{I_{Z\max} + I_{L\min}}$$

2.6. Power Supply Systens

Most electronic equipment requires d.c voltages for its operation. These can be provided by batteries or by internal power supplies that convert alternating current as available at the home electric outlet, into regulated d.c voltages. Thus, a power supply system may be defined as ***an electronic circuit which converts an a.c input of 50/60 Hz line power to a d.c output voltage***. A power supply circuit is one of the most important diode circuits.

The first element in an internal d.c power supply is a transformer, which steps up or steps down the input voltage to a level suitable for the operation of the equipment. The transformer is then followed by a rectifier.

Fluctuations and ripples superimposed on the rectified DC voltage can be filtered out by a filter. Finally to get more precise control over voltage levels and ripples can be achieved by a voltage regulator. This whole process can be shown by the following block diagram.

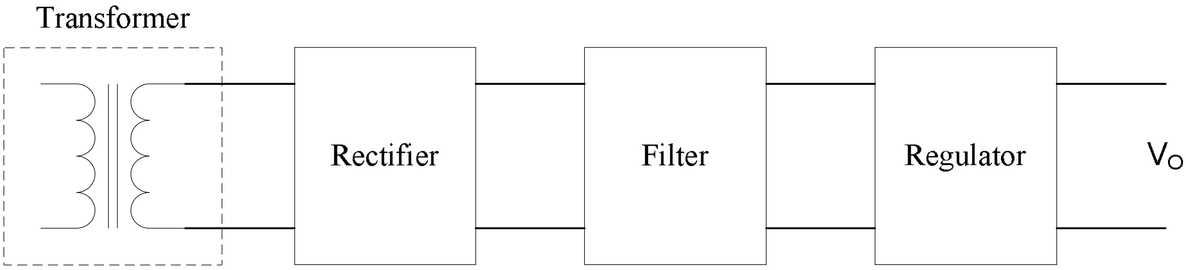
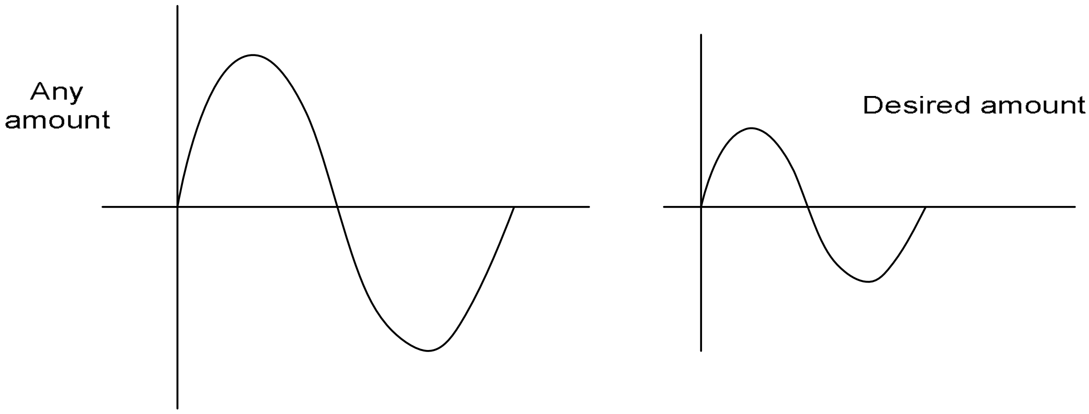


Fig.2.13 DC Power Supply System

Function of each part

a) Transformer

This block (the transformer) levels the amplitude to the desired amount, steps up and steps down as well as it isolates the whole electronic elements from the line voltage.



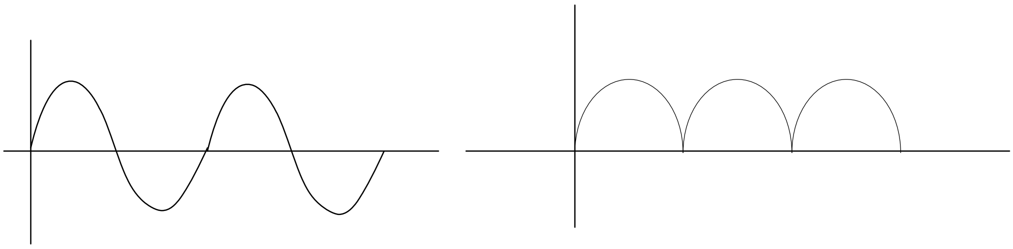
We know that the line voltage from the outlet is given by

$$V_{rms}^2 = V_{dc}^2 + V_{ac}^2$$

Rectifier

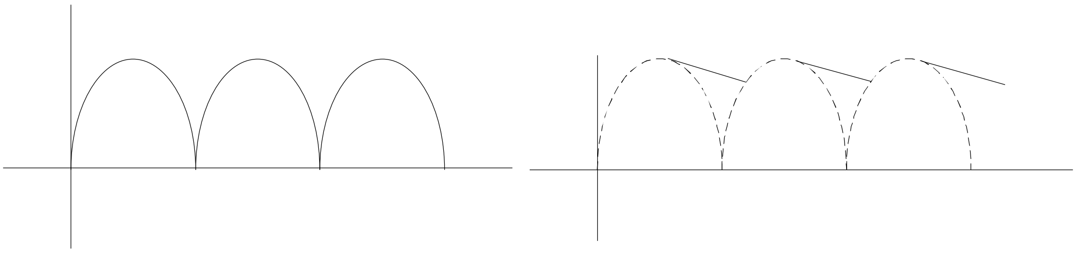
The second block is the rectifier which changes a.c into pulsating d.c. Here the rectification result is not pure d.c. It has got some a.c components and some d.c components, as it is shown in the following figure and equation for full wave rectifier:

$$V_{rms}^2 = V_{dc}^2 + V_{ac}^2$$
$$V_{ac} = \sqrt{V_{rms}^2 - V_{dc}^2}$$



Filter

The third block reduces the ripple (a.c) components of the rectified output and thus smoothes, the output d.c voltage.



$$V_{dc} = V_m - \frac{V_r}{2}$$

Voltage Regulator

The last block, the regulator, reduces the ripple component of the output of the filter and stabilizes the output voltage against the variation of source and load. Thus it provides relatively a constant output d.c voltage to the load despite a change in input voltage (V_{in}) and load current (I_L).

2.7. Wave Shaping Circuits

A wide variety of wave-shaping circuits are useful in electronic systems. These circuits transform one waveform into another. Wave-shaping circuits are employed in function generators used to generate electrical test signals.

Once an oscillator generates a sinusoidal waveform, for instance, by use of integrators it can be converted to a square waveform. Then, moreover, the square waveform is passed through a carefully designed wave shaping circuit to produce a triangular waveform. That is, all other important waveforms are available for use.

Numerous examples of wave-shaping circuits can be found in transmitters & receivers for TV or radar and in other electronic systems.

2.7.1. Clipper Circuits

Diodes can be used to form clipper circuits, in which a portion of an input signal waveform is clipped off. For example, the three equivalent circuits in Fig 2.14 clip off any part of the input waveform above 6V or less than -9V. If the input voltage is between -9 & 6V, all of the diodes in each circuit are off and no current flows. Then there is no drop across the resistor R, & the output voltage V_O is equal to the input voltage V_{in}. The output waveform resulting from a 15V peak-to- peak sinusoidal input is shown in Fig. 2.14D.

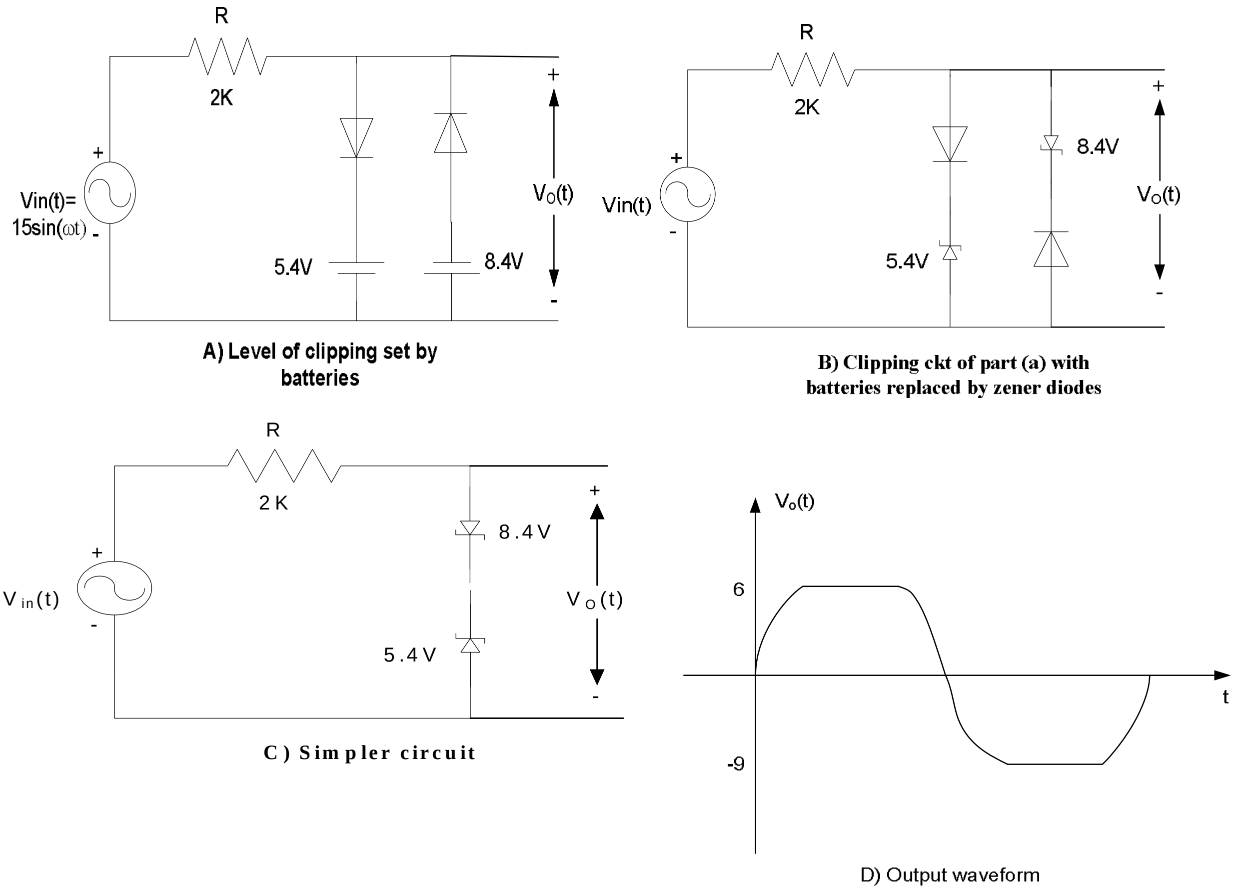


Fig.2.14. Clipper circuits and the output waveform

The resistance value of R is selected to be large enough so that the forward diode current is with in reasonable bounds, but small enough so that the reverse diode current results in a negligible voltage drop.

2.7.2. Clamper Circuits

Another diode wave shaping circuit is the clamper circuit, which is used to add a d.c component to an a.c input waveform that the positive (or negative) peaks are forced to take a specified value. In other words, the peaks of the waveform are "clamped" to a specified voltage value. Examples of clamper circuits are shown in Fig.2.15 with their waveform output for $V_{in}(t) = 5\sin(\omega t)$.

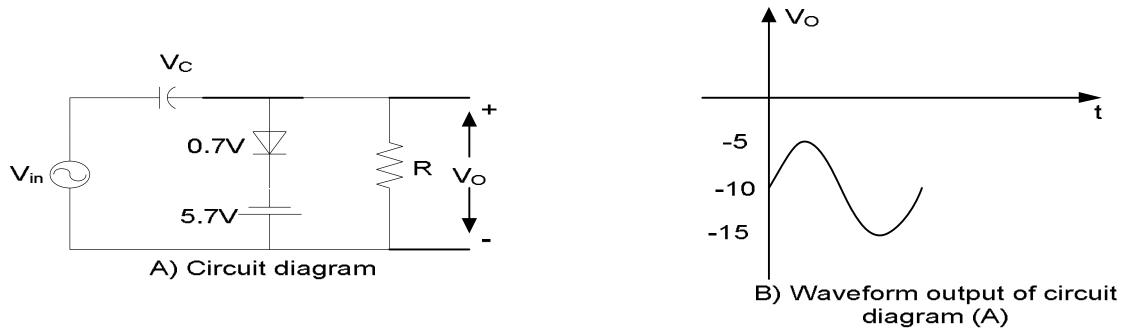


Fig.2.15. Clamper Circuit

The capacitor is a large value, so it discharges only very slowly, and we can consider the voltage across the capacitor to be constant. Because the capacitor is large, it has very small impedance for the a.c input signal. Thus, the output voltage of the circuit is given by

$$Vo(t) = V_{in}(t) - V_c$$

Of course, we can change the voltage to which the circuit clamps by changing the battery voltage. Reversing the direction of the diode causes the negative peak to be clamped instead of the positive peak. Further more, it is often more convenient to use zener diodes rather than batteries. A circuit including these features is shown in Fig 2.16.

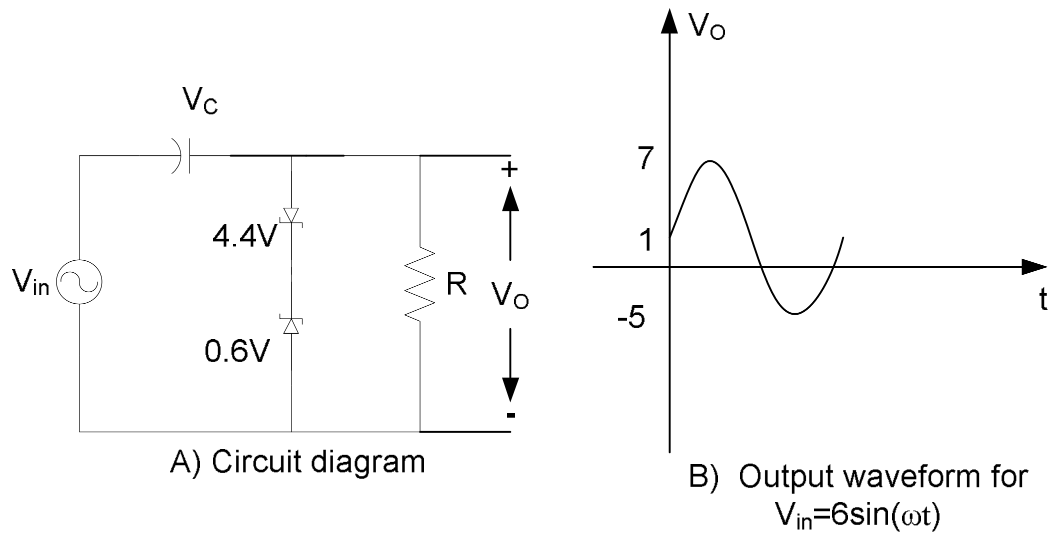


Fig.2.16. Clamper circuit-batteries replaced by zener diode

Electronic signals often lose their d.c levels during signal transmission or storage. For example, d.c levels are lost during radio transmission, and a TV broadcast signal must have its d.c level restored in the radio & TV receivers. It is also impossible to send d.c signals through the recording and play back heads for cassette tape recorders or compact disc players. DC restoration may be required if these devices are used to store digital data.

2.8. Voltage Multiplier Circuits

Voltage-multiplier circuits are employed to maintain a relatively low transformer peak voltage while stepping up the peak output voltage to two, three, four, or more times the peak rectified voltages. These power supplies are used for high voltage, low current devices like cathode - ray tubes (CRT) of the picture tubes in TV receivers, oscilloscopes and computer displays or monitors

2.8.1. Voltage Doubler

The network of Fig.2.17 is a half-wave voltage doubler. During the positive voltage half-cycle across the transformer, secondary diode D_1 conducts (and diode D_2 is cut off), charging capacitor C_1 up to the peak rectified voltage (V_m). Diode D_1 is ideally a short during this half-cycle, and the input voltage charges capacitor C_1 to V_m with the polarity shown in Fig. 2.18a

$$V_{C1} = V_m$$

During the negative half-cycle of the secondary voltage, diode D_1 is cut off and diode D_2 conducts charging capacitor C_2. At the same time C_1 discharges. Since diode D_2 acts as a short during the negative half-cycle (and diode D_1 is open), we can sum the voltages around the outside loop (see Fig. 2.18b): as

$$V_{dc} = V_{C2} = V_{C1} + V_m = 2V_m$$

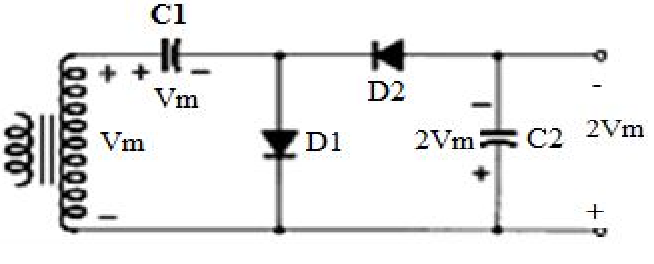


Fig.2.17. Half wave voltage doubler

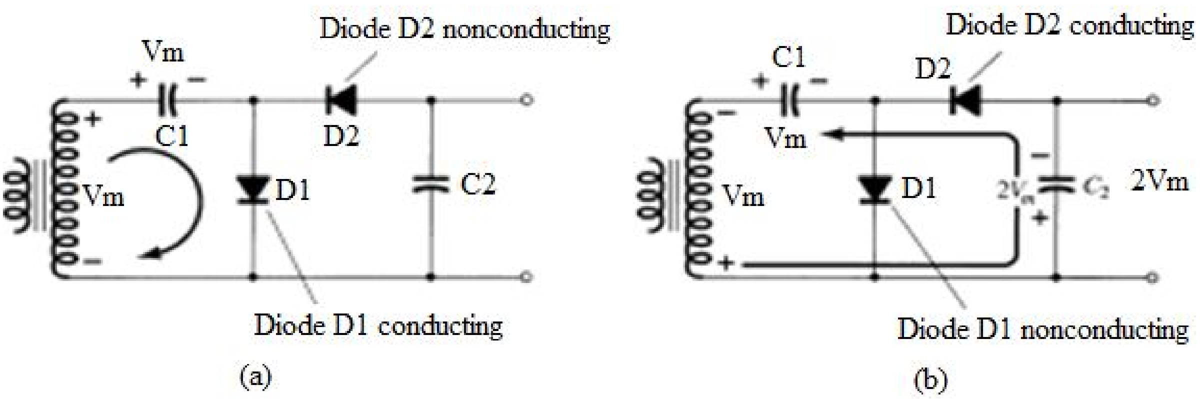


Fig.2.18. Voltage Doubler operation, showing each half-cycle of operation: (a) positive half-cycle; (b) negative half cycle.

2.8.2. <u>Voltage Tripler and Voltage Quadrupler</u>

Voltage Tripler

Basically, it is a half-wave doubler and an extra (additional) half-wave peak rectifier connected in series.

Fig. 2.19. Voltage Triplre Circuit

The first two peak rectifiers (D_1 and D_2) act like a doubler. At the peak of the negative half cycle, D_3 is forward biased. This charges C_3 to $\mathbf{2V_{\mathit{m}} = Vc_2}$.

The triple output voltage appears across C_1 and C_3. The load resistance is connected across the triple output. As long as the time constant is long (R_L large enough), the output voltage equals approximately $\mathbf{3V_{\mathit{m}}}$.

Voltage Quadrupler

Basically, a voltage quadrupler is two half-wave doublers whose output capacitors are connected in series (four peak rectifiers in cascade).

Fig. 2.20. Voltage Quadrupler Circuit

The first 3 peak rectifiers (D_1, D_2 & D_3) are a Tripler, and the fourth makes the overall circuit a quadrupler. The first capacitor (C_1) charges to $V_{inp} = V_m$, all other charge to $2_{vinp} = 2V_m$. The quadrupler output is taken across the series connection of C_2 and C_4. As usual, a large load resistance (long time constant) is needed to have an output voltage of approximately $4_{vinp} = 4V_m$. or $V_{dc}= V_{C2} +V_{C4} = 4V_m$)