# Electronics Engineering

# Analog Circuits

Comprehensive Theory

*with* Solved Examples and Practice Questions

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# Analog Circuits

## Introduction to Analog Circuits

After studying the basic electronic devices and their characteristics, now we shall deal with more complex analog circuits, of which amplifiers is a very significant category. We shall start our analysis with applications of diode, a very fundamental component, in various circuit configurations such as clipper, clamper, regulator etc. Further, we shall proceed to applications of BJT and FET, particularly as an amplifier.

The other complex analog circuits, including circuits that form operational amplifiers, are also part of this book. These circuits are composed of fundamental configurations, such as differential amplifier, constant-current source, active load, and output stage, all of which have been discussed in detail.

The major emphasis throughout the book is on developing the reader's understanding for analyzing and designing various fundamental circuits, which are always an integral part of various competitive examinations. Throughout the book, a very sequential and comprehensive approach has been used, so that a beginner can also utilize the book in very efficient manner.

# Prelude to Analog Circuits

## Electronics

Electronics is defined as the science of motion of charges in a gas, vacuum, or semiconductor. Note that the charge motion in a metal is excluded from this definition.

This definition was used early in the 20th century to separate the field of electrical engineering, which dealt with motors, generators, and wire communications, from the new field of electronic engineering, which at that time dealt with the vacuum tubes.

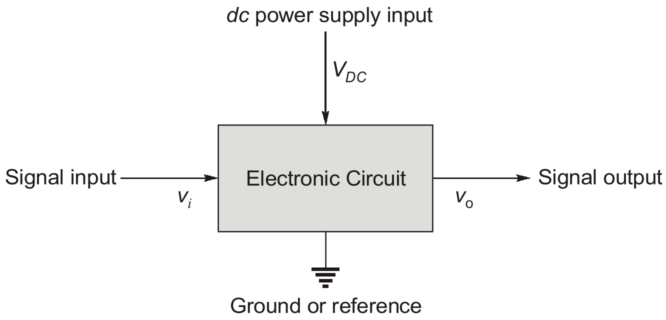
## Microelectronics

Microelectronics refers to the integrated-circuit (IC) technology that is capable of producing circuits which contain millions of components in a small piece of silicon (known as a silicon chip) whose area is on the order of 100 $mm^2$.

## Electronic Circuits

A circuit which consists of at least one electronic device (e.g. amplifier, rectifier, oscillator etc.) is known as an electronic circuit.

In most of the electronic circuits there are two inputs. One input is from power supply which provides dc voltages and currents to establish proper biasing for transistors. The second input is a signal that can be amplified by the circuit. Although the output signal can be larger than the input signal but the output power can never exceed the dc input power. Therefore, the magnitude of dc power supply is one limitation to the output signal response.



## Discrete and Integrated Circuits

Discrete electronic circuits contain discrete components, such as resistors, capacitors and transistors whereas an integrated circuit consists of a single crystal chip of silicon containing both active and passive elements and their interconnections. Such circuits are produced by the same processes used to fabricate individual transistors and diodes.

## Analog and Digital Signals

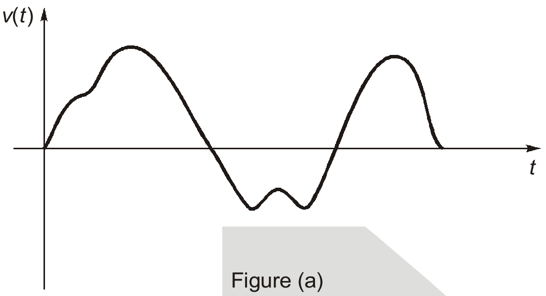


Figure (a)

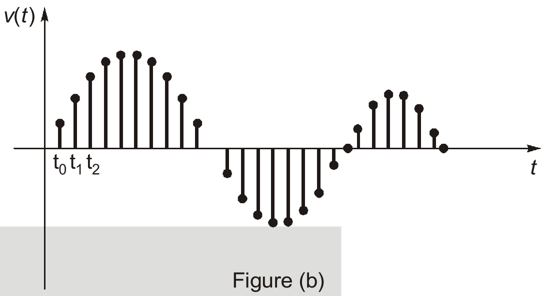


Figure (b)

The voltage signal shown graphically in Fig. (a) is called an ***analog signal***. The name derives from the fact that such a signal is analogous to the physical signal that it represents. The magnitude of an analog signal can take on any value; that is, the amplitude of an analog signal exhibits a continuous variation over its range of activity. Electronic circuits that process such signals are known as ***analog circuits***.

An alternative form of signal representation is that of a sequence of numbers shown in Fig. (b), each number representing the signal magnitude at an instant of time. The resulting signal is called a ***discrete signal***. When discrete signal is quantized in magnitude it becomes a ***digital signal***. Electronic circuits that process digital signals are called ***digital circuits***.

### Advantages of Analog Circuits

- Majority of signals in the "real world" are analog; so these signals can be directly processed in analog circuits whereas digital processing requires analog to digital and digital to analog conversion.
- Analog circuits can be designed to operate even at higher power levels.

### Advantages of Digital Circuits

- In digital circuits effect of noise is less.
- Digital circuits are easier to design.
- Digital circuits can be programmed.
- Digital data can be stored.

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# CHAPTER 01

# Diode Circuits

## 1.1 Introduction

The simplest and most fundamental non-linear circuit element is a diode. Just like a resistor, the diode has two terminals; but unlike the resistor which has a linear (straight-line) relationship between the current flowing through it and the voltage appearing across it, the diode has non-linear i-v characteristics. The analysis of non-linear electronic circuits is not as straight-forward as the analysis of linear electric circuits. However, there are electronic functions that can be implemented only by non-linear circuits. Examples include the generation of dc voltages from sinusoidal voltages and the implementation of logic functions.

## 1.2 Diode Circuits : DC Analysis and Models

Mathematical relationships, or ***models***, that describes the current-voltage characteristics of electrical elements allow us to analyze and design circuits without having to fabricate and test them in the laboratory. An example is Ohm's law, which describes the properties of a resistor. In this section, we will develop the dc analysis and modelling techniques of diode circuits.

To begin to understand diode circuits, consider an ***ideal diode***. It is a two terminal device having the circuit symbol of Fig. 1.1 (a) and the i-v characteristics shown in Fig.1.1 (b).

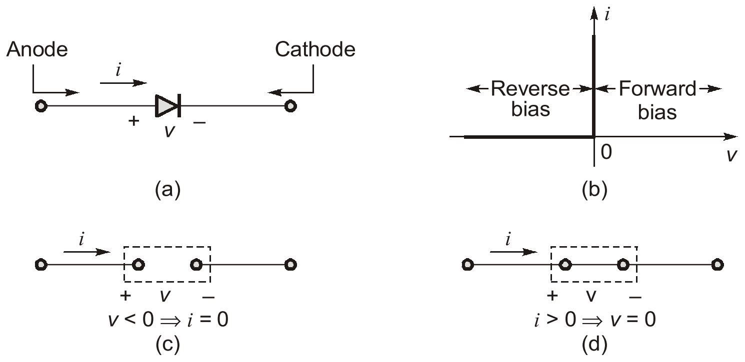


***Figure-1.1:*** *Ideal diode and its characteristics*

The terminal characteristics of the ideal diode can be interpreted to follows:

- If a negative voltage is applied to the diode, no current flows and the diode behaves as an ***open circuit*** [as shown in Fig. 1.1 (c)]. Diodes operated in this mode are said to be ***reverse biased***.
- On the other hand, if a positive current is applied to the ideal diode, zero voltage drop appears across the diode. In other words the ideal diode behaves as a ***short circuit*** in the forward direction [as shown in Fig. 1.1 (d)]. Diodes operated in this mode are said to be ***forward biased***

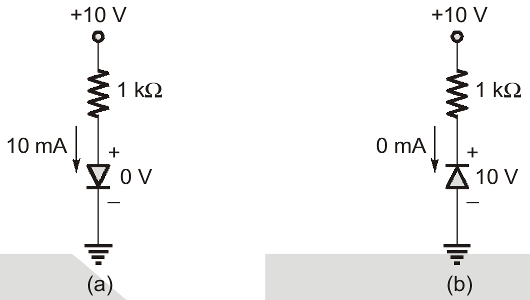


***Figure-1.2 :*** *The two modes of operation of ideal diodes and the use of external circuit to limit (a) the forward current and (b) the reverse voltage*

From the above description it should be noted that the external circuit must be designed to limit the forward current through a conducting diode, and the reverse voltage across a cut-off diode to predetermined values. Fig. (1.2) shows two diode circuits that illustrate this point. In the circuit of Fig. 1.2 (a) the diode is obviously conducting. Thus its voltage drop will be zero, and the current through it will be determined by the +10 V supply and the 1 kΩ resistor as 10 mA. The diode in the circuit of 1.2 (b) is obviously cut-off, and thus its current will be zero which in turn means that the entire 10 V supply will appear as reverse bias across the diode.

### 1.2.1 Load-Line Analysis

The circuit of Fig. (1.3) is the simplest of diode configurations. Solving the circuit of Fig. (1.3) is all about finding the current and voltage levels that will satisfy both the characteristics of the diode and the chosen network parameters at the same time.

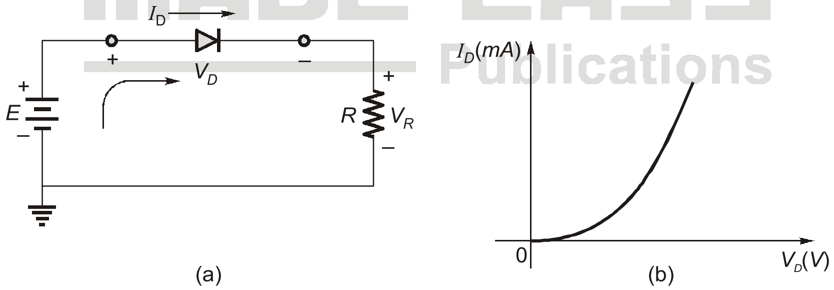


***Figure-1.3 :*** *Series diode configuration (a) Circuit (b) Characteristics*

In Fig. (1.4) the diode characteristics are placed on the same set of axis as a straight line defined by the parameters of the network. The straight line is called a ***load line*** because the intersection of the vertical axis is defined by the applied load *R*. The analysis to follow is therefore called ***load-line analysis***. The intersection of the two curves will define the solution for the network and define the current and the voltage levels for the network.

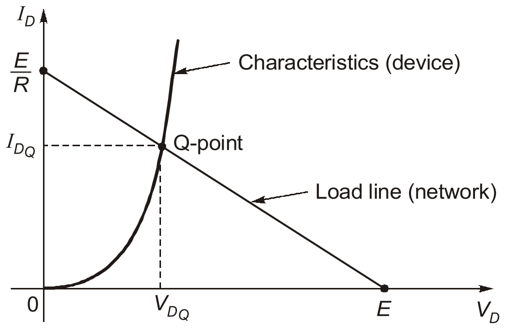


***Figure-1.4:*** *Drawing the load line and finding the point of operation*

- The intersection of the load line on the characteristics of Fig. (1.4) can be determined by applying Kirchhoff's voltage law in the clockwise direction, which results in

$$E - V_D - V_R = 0$$

$$\text{or} \quad E = V_D + I_D R \qquad \text{...(1.1)}$$

- The two variables of the equation (1.1), $V_D$ and $I_D$, are the same as the diode axis variables of Fig. (1.4). This similarity permits plotting equation (1.1) on the same characteristics of Fig. (1.4).
- Set, $V_D = 0$ V in equation (1.1)

$$E = 0\text{ V} + I_D R$$

$$\therefore \quad I_D = \frac{E}{R}\bigg|_{V_D = 0\text{ V}} \qquad \text{...(1.2)}$$

Equation (1.2) gives the magnitude of $I_D$ on the vertical axis.

- Set, $I_D = 0$ A in equation (1.1)

$$E = V_D + (0\text{ A})\,R$$

$$\Rightarrow \quad E = V_D$$

$$\therefore \quad V_D = E\big|_{I_D = 0\text{ A}} \qquad \text{...(1.3)}$$

Equation (1.3) gives the magnitude of $V_D$ on the horizontal axis.

- A straight line drawn between the two points will define the load line as depicted in Fig. (1.4). Change the level of $R$ (the load) and the intersection on the vertical axis will change. The result will be change in the slope of the load line and different point of intersection between the load line and the device characteristics.
- We now have a load line defined by the network and a characteristic curve defined by the device. The point of intersection between the two is the point of operation for this circuit.
- By simply drawing a line down to the horizontal axis, we can determine the diode voltage $V_{D_Q}$, whereas a horizontal line from the point of intersection to the vertical axis will provide the level of $I_{D_Q}$. The point of operation is usually called the ***quiescent point*** (abbreviated "***Q-point***") to reflect its "still, unmoving" qualities as defined by a dc network.
- The solution obtained at the intersection of the two curves is the same as would be obtained by a simultaneous mathematical solution of

$$I_D = \frac{E}{R} - \frac{V_D}{R} \qquad \text{[Derived from equation 1.1]}$$

$$\text{and} \quad I_D = I_0\left(e^{V_D/\eta V_T} - 1\right) \qquad \text{[Diode equation]}$$

### 1.2.2 Series Diode Configuration

The approximate models will now be used to investigate a number of series diode configurations with dc inputs. This will establish a foundation in diode analysis that will carry over into the sections and chapters to follow. The procedure described can, in fact, be applied to networks with any number of diodes in variety of configurations.

- For each configuration the state of each diode must first be determined. Which diodes are "*on*" and which are "*off*"? Once determined, the appropriate equivalent can be substituted and the remaining parameters of the network determined.
- For the conduction region the only difference between the silicon diode and the ideal diode is the vertical shift in the characteristics, which is accounted for in the equivalent model by a dc supply of 0.7 V opposing the direction of forward current through the device. For voltages less than 0.7 V for a silicon diode and 0 V for the ideal diode the resistance is so high compared to the other elements of the network that its equivalent is the open circuit.
- ***In general, a diode is in the "on" state if the current established by the applied sources is such that its direction matches that of the arrow in the diode symbol, and $V_D \geq 0$ V for ideal diode, $V_D \geq 0.3$ V for germanium diode, $V_D \geq 0.7$ V for silicon diode, and $V_D \geq 1.2$ V for gallium arsenide diode.***

The series circuit of Fig. (1.5) will be used to demonstrate the approach described in the above paragraphs.

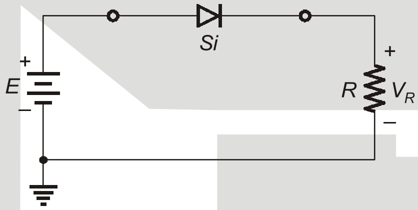
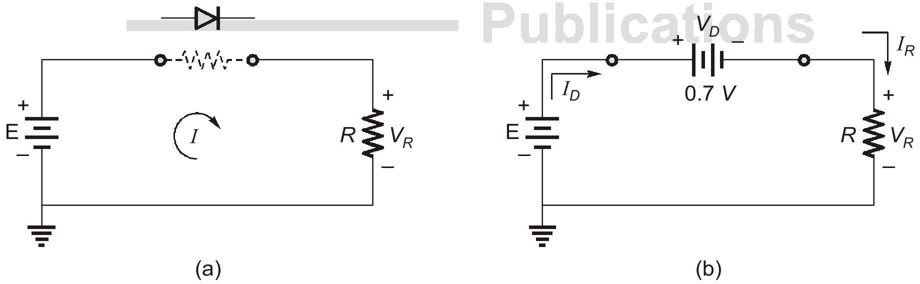


***Figure-1.5:*** *Series diode configuration*

The state of the diode is first determined by mentally replacing the diode with a resistive element as shown in Fig. 1.6 (a). The resulting direction of $I$ is a match with the arrow in the diode symbol, and since $E > V_\gamma$ (cut-in voltage of diode), the diode is in the "on" state. The network is redrawn as shown in Fig. 1.6 (b) with the appropriate equivalent model for the forward biased silicon diode.

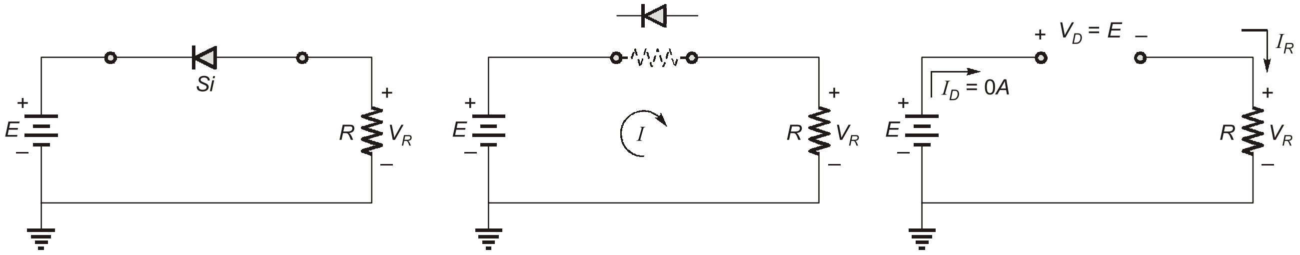


(a) (b)

***Figure-1.6:*** *Series diode circuit analysis in forward bias*

Following are the resulting voltage and current levels:

$$\boxed{\begin{aligned} V_D &= V_\gamma \\ V_R &= E - V_\gamma \\ I_D &= I_R = \frac{V_R}{R} \end{aligned}} \qquad \text{...(1.4)}$$



(a) (b) (c)

**Figure-1.7:** *Series diode circuit analysis in reverse bias*

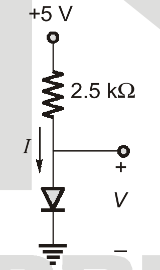
In Fig. 1.7 (a) the diode of Fig. (1.5) has been reversed. Mentally replacing the diode with a resistive element as shown in Fig. 1.7 (b) will reveal that the resulting current direction does not match the arrow in the diode symbol. The diode is in the "off" state, resulting in the equivalent circuit of Fig. 1.7 (c). Due to the open circuit, the diode current is 0 A and the voltage across the resistor R is the following:

$$V_R = I_R R = I_D R = (0\text{ A})\ R = 0\text{ V}$$

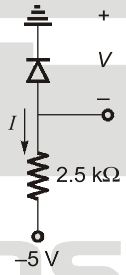
The fact that $V_R = 0$ V will establish $E$ volts across the open circuit defined by Kirchhoff's voltage law. Always keep in mind that under any circumstances dc, ac instantaneous values, pulses, and so on—***Kirchhoff's voltage law must be satisfied!***

**Example-1.1** [Single Branch Diode Circuits]

Assuming the diodes to be ideal, find the values of $I$ and $V$ in the circuits shown below:



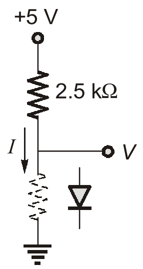
(a)



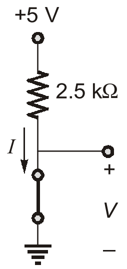
(b)

***Solution:***

In Fig. (a) replacing the diode with a resistive element as shown below in *Fig. (i)*:



*(i)*



*(ii)*

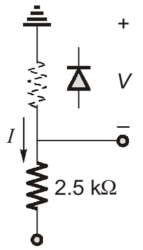
The resulting direction of $I$ is a match with the arrow in the diode symbol, the diode is in the "on" state. Now the network can be redrawn as shown in *Fig. (ii)*.

The resulting voltage and current levels are the following:

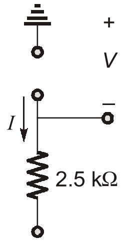
$$V = 0\text{ V} \qquad \text{[as diode is ideal so } V_\gamma = 0\text{ V]}$$

and $$I = \frac{5-0}{2.5\,k} = 2\text{ mA}$$

In Fig. (b) replacing the diode with a resistive element as shown below in ***Fig. (iii)***:



*(iii)*



*(iv)*

Fig. (iii) reveals that the resulting direction of current $I$ does not match the arrow in the diode symbol. The diode is in the "off" state resulting in the equivalent circuit as shown in ***Fig. (iv)***:

Resulting current and voltage can be calculated as below:

$$I = 0\text{ A} \qquad \text{[Since diode is open circuit]}$$

Now applying KVL in the circuit

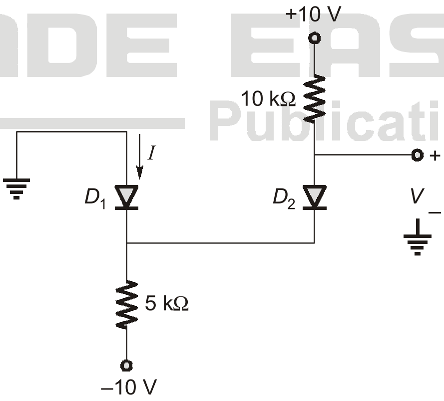
$$V + 2.5\,I - 5 = 0$$

$$\Rightarrow \quad V + 2.5 \times 0 - 5 = 0$$

$$\Rightarrow \quad V = 5\text{ V}$$

**Example-1.2** [Multiple Branch Diode Circuit]

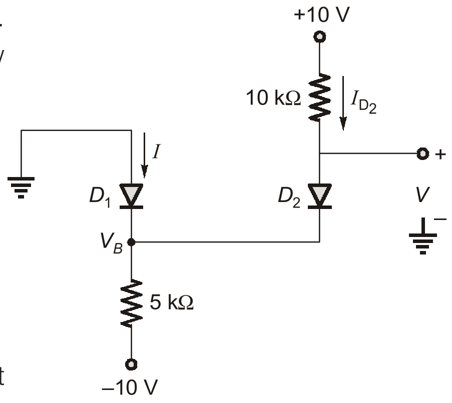
Assuming diodes to be ideal, find the values of $I$ and $V$ in the following circuit:



***Solution:***

**NOTE**

In such type of circuits it might not be obvious at first sight whether none, one, or both diodes are conducting. In such cases, we make a plausible assumption, proceed with the analysis, and check whether we end up with a consistent solution.



For this circuit, we shall assume that both diodes are conducting. It follows that $V_B = 0$ and $V = 0$. The current through $D_2$ can now be determined from

$$I_{D_2} = \frac{10-0}{10\text{k}} = 1\text{mA}$$

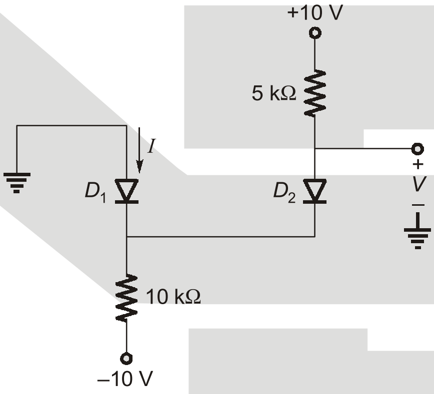
Writing a node equation at B,

$$I + 1\text{ mA} = \frac{0-(-10)}{5\text{k}}$$

$$\Rightarrow \qquad I = +1\text{ mA}$$

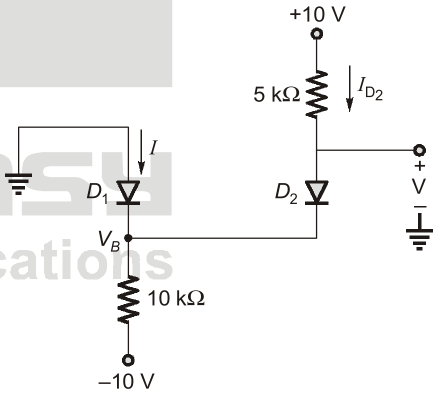
Thus $D_1$ is conducting as originally assumed and the final result is $I =$ **1 mA** and $V =$ **0 V**.

**Example-1.3** Assuming diodes to be ideal, find the values of $I$ and $V$ in the following circuit:



**Solution:**

If we assume that both diodes are conducting then $V_B = 0$ V and $V = 0$ V. The current in $D_2$ is obtained from



$$I_{D_2} = \frac{10-0}{5\text{k}} = 2\text{ mA}$$

The node equation at $B$ is $$I + 2\text{ mA} = \frac{0-(-10)}{10\text{ k}}$$

$$\Rightarrow \qquad I = -1\text{ mA}$$

$I = -1$ mA, is not possible as $I$ does not match with arrow direction of the diode $D_1$ so our original assumption is not correct. We start again, assuming that $D_1$ is off and $D_2$ is on. The current $I_{D_2}$ is given by

$$I_{D_2} = \frac{10-(-10)}{10\text{ k}+5\text{ k}} = 1.33\text{ mA}$$

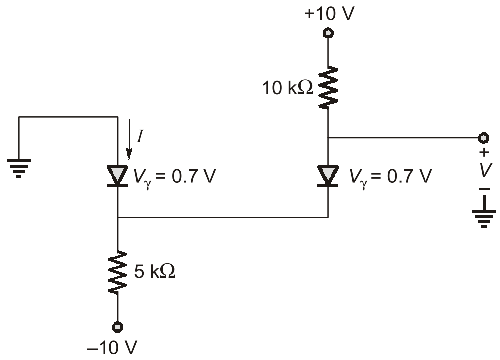
and the voltage at node $B$ is

$$V_B = -10 + 10\text{ k} \times 1.33\text{ mA} = +3.3\text{ V}$$

Thus $D_1$ is reverse biased as assumed, and the final result is $I =$ **0 A** and $V =$ **3.3 V**.

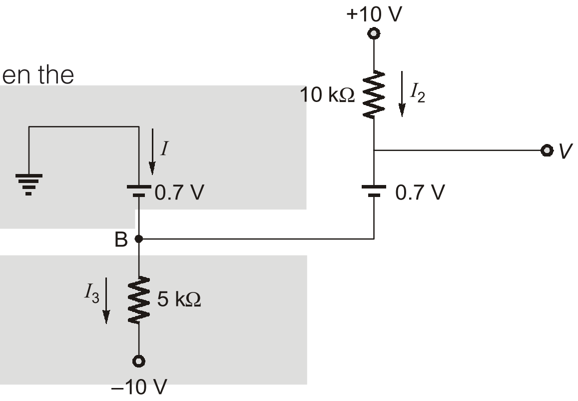
**Example-1.4** [Practical diode circuit]

Find $I$ and $V$ for the circuit shown below:



**Solution:**

We shall assume that $D_1$ and $D_2$ are forward bias then the equivalent circuit can be redrawn as shown below:



So, voltage at node $B$ is

$$V_B = -0.7\text{ V}$$

and
$$V = 0.7 + V_B$$
$$= 0.7 - 0.7 = 0\text{ V}$$

Hence, $I_2$ can be calculated as

$$I_2 = \frac{10-0}{10\text{ k}} = 1\text{ mA}$$

Now applying KCL at node $B$

$$I_3 = \frac{0.7-(-10)}{5\text{ k}\Omega} = 1.86\text{ mA}$$

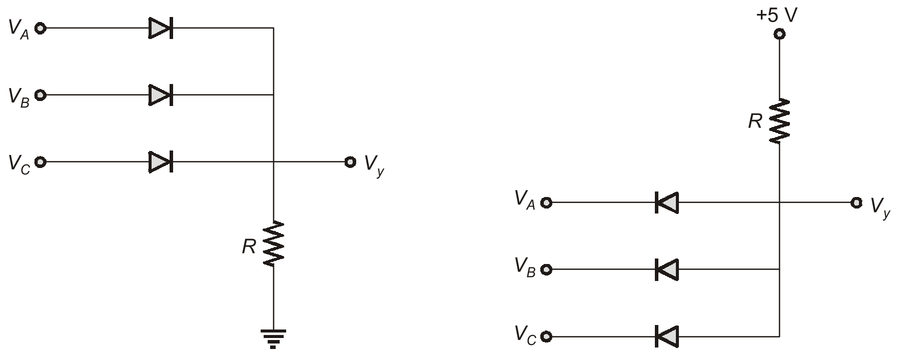
$$I = I_3 - I_2 = 1.86\text{ mA} - 1\text{ mA}$$

$\Rightarrow$
$$I = 0.86\text{ mA}$$

Thus $D_1$ is conducting as originally assumed and the final result is $I$ = 0.86 mA and $V$ = 0 V.

## 1.3 Diode Logic Gates

Diodes together with resistors can be used to implement digital logic functions. Fig. (1.8) shows two diode logic gates.



(a) (b)

**Figure-1.8 :** *Diode logic gates (a) OR gate (b) AND gate*

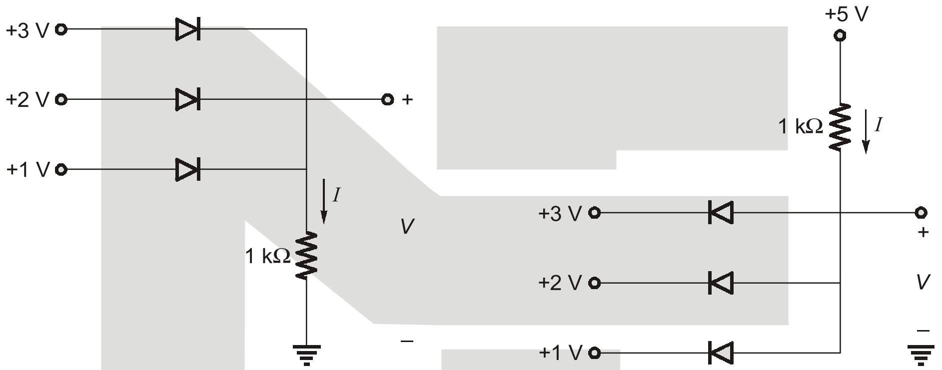
To understand the functioning of these circuits consider a positive-logic system in which voltage values close to 0 V correspond to logic 0 (or low) and voltage values close to +5 V correspond to logic 1 (or high). The circuit in Fig. 1.8 (a) has three inputs $V_A$, $V_B$ and $V_C$. It is easy to see that diodes connected to +5 V inputs will conduct, thus clamping the output $V_y$ to a value equal to +5 V. This positive voltage at the output will keep the diodes whose inputs are low (around 0 V) cut-off . Thus the output will be high if one or more of the inputs are high. The circuit therefore implements the ***logic OR function***, which in Boolean notation is expressed as

$$Y = A + B + C \qquad \text{...(1.5)}$$

Similarly, we can show that using the same logic system mentioned above, the circuit of Fig. 1.8 (b) implements the ***logic AND function***,

$$Y = A \cdot B \cdot C \qquad \text{...(1.6)}$$

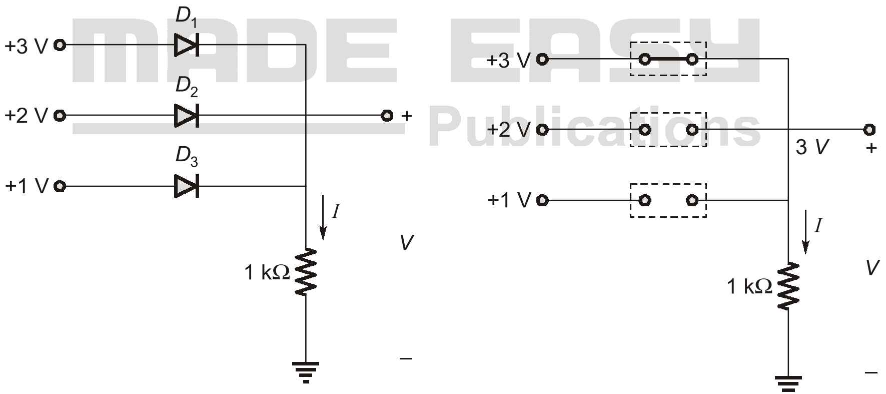
***Example*-1.5** Find the values of $I$ and $V$ in the circuits shown below:



(a) (b)

***Solution:***

- Redrawing the circuit in Fig. (a) as in ***Fig. (i)***.



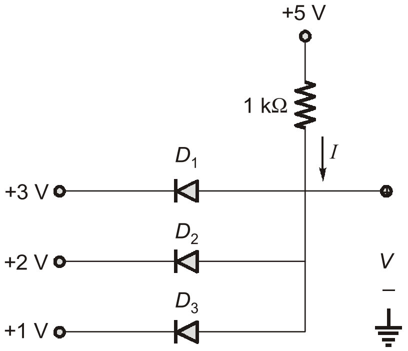
***(i)*** ***(ii)***

If we assume that diode $D_1$ is ON, then it will make off to diodes $D_2$ and $D_3$ as shown in ***Fig. (ii)***:

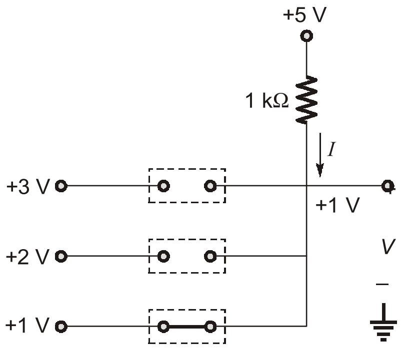
Hence, $V = 3\text{ V}$

and $I = \dfrac{3\text{ V}}{1\text{k}\Omega} = 3\text{ mA}$

Redrawing the circuit in Fig. (b) as in ***Fig. (iii)***.



*(iii)*



*(iv)*

If we assume that either of diodes $D_1$ or $D_2$ are "on" then $D_3$ will also become forward bias; as a result at node $V$ simultaneously more than one voltages will try to exist which is violation of Kirchoff's law. So our assumption is wrong.

Now if we assume that diode $D_3$ is "on" then diodes $D_2$ and $D_1$ are reverse biased and will remain "off" as shown ***Fig. (iv)***:

So, $$V = 1\text{ V}$$

and $$I = \frac{5-1}{1\text{k}} = 4\text{ mA}$$

**Remember**

From above example we conclude that in OR logic design, highest voltage will be present as output [+3 V is the output from the inputs of +1 V, +2 V and +3 V]. Similarly in AND logic design, lowest of all the input voltages will be present as output [+1 V is the output from the inputs of +3, +2 and +1 V].

## 1.4 Diode : The Small Signal Model

There are applications in which a diode is biased to operate at a point on the forward *i-v* characteristics and a small ac signal is superimposed on DC quantities. For this situation, we first have to determine the DC operating point ($V_D$ and $I_D$). Then, for small signal operation around the DC bias point, the diode is best modelled by a resistance equal to the inverse of the slope of the tangent to the exponential i-v characteristics at the bias point.

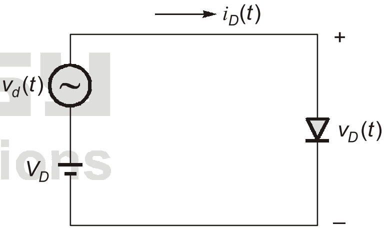


***Figure-1.9:*** *Development of the diode small-signal model*

The diode equation is

$$I_D = I_0(e^{V_D/\eta V_T} - 1)$$

$$I_D \simeq I_0\, e^{V_D/\eta V_T} \quad \text{where, } I_D = \text{DC bias current} \qquad \text{...(1.7)}$$

The total instantaneous diode voltage is

$$v_D(t) = V_D + v_d(t)$$

Correspondingly, the total instantaneous diode current is

$$i_D(t) = I_0\, e^{v_D(t)/\eta V_T}$$

$$\Rightarrow \qquad i_D(t) = I_0\, e^{(V_D + v_d(t))/\eta V_T}$$

$$\Rightarrow \qquad i_D(t) = I_0\, e^{V_D/\eta V_T} \cdot e^{v_d(t)/\eta V_T}$$

$$\Rightarrow \qquad i_D(t) = I_D \cdot e^{v_d(t)/\eta V_T} \qquad \text{[using equation 1.7]} \qquad \ldots(1.8)$$

Now if amplitude of the signal $v_d(t)$ is kept sufficiently small such that

$$\frac{v_d(t)}{\eta V_T} << 1$$

then

$$i_D(t) \simeq I_D\left(1+\frac{v_d(t)}{\eta V_T}\right)$$

$$\Rightarrow \qquad i_D(t) = I_D + \frac{I_D}{\eta V_T} v_d(t) \qquad \ldots(1.9)$$

Thus superimposed on the dc current $I_D$, we have a small signal current component directly proportional to the signal voltage $v_d(t)$. That is,

$$i_D(t) = I_D + i_d(t)$$

$$\therefore \qquad i_d(t) = \frac{I_D}{\eta V_T} v_d(t)$$

$$= g\, v_d(t) \qquad \ldots(1.10)$$

Hence, diode small signal conductance;

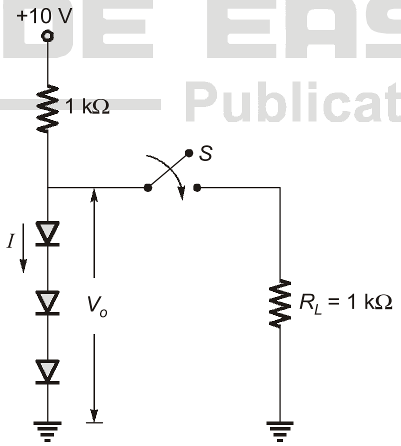
$$\boxed{g = \frac{I_D}{\eta V_T}} \qquad \ldots(1.11)$$

The inverse of this parameter is the diode small signal resistance, or incremental resistance, $r_d$

$$\boxed{r_d = \frac{\eta V_T}{I_D}} \qquad \ldots(1.12)$$

**Note:** Incremental resistance is inversely proportional to the dc bias current.

**Example-1.6** Consider the circuit shown below:



For each diode $\eta$ = 2, $V_\gamma$ = 0.7 V, dc forward resistance of diode is $R_f$ = 0 Ω. Assuming initially when S is open $V_0$ = 2.1 V ; for this condition find the incremental resistance in the circuit.

***Solution*:**

Current through each diode in the given circuit is

$$I = \frac{10 - V_0}{1\text{k}\Omega} = \frac{10 - 2.1}{1\text{k}\Omega} = 7.9 \text{ mA}$$

so incremental resistance of each diode is

$$r_d = \frac{\eta V_T}{I} = \frac{2 \times 25.9 \text{ mV}}{7.9 \text{ mA}}$$

$$\Rightarrow \quad r_d = 6.56 \ \Omega$$

So total incremental resistance of the circuit is

$$= 3\, r_d = 3 \times 6.56 \ \Omega$$

$$= \mathbf{19.68 \ \Omega}$$

## 1.5 DC Power Supply

Electricity is transmitted in ac form as it is less expensive and safer, but most of the electronic circuits require dc power. For this purpose ac to dc conversion is required. A block diagram of such dc power supply is shown in Fig. (1.10).

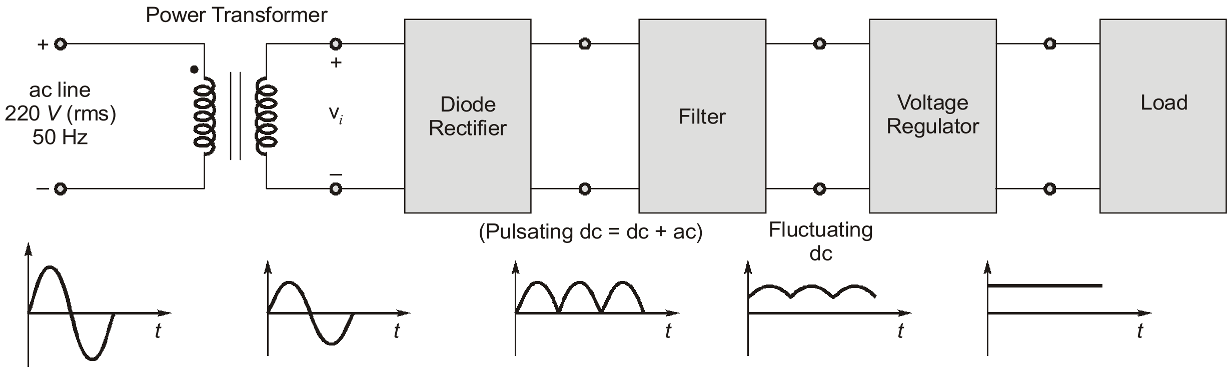


***Figure-1.10:** Block diagram of a dc power supply*

- The first block in a dc power supply is power transformer. By adjusting the turn ratio of primary and secondary [e.g. $N_1/N_2$] of the transformer, the designer can step the line voltage down to the required value to yield particular DC voltage output. For instance, a secondary voltage of 8 V rms may be appropriate for a DC output of 5 V.
- In addition to providing the appropriate sinusoidal amplitude for DC power supply, the power transformer provides electrical isolation between the electronic equipment and the power-line circuit. This isolation minimizes the risk of electric shock to the equipment user.
- Periodic variation of pulsating dc signal indicates presence of ac component and non-zero average value indicates presence of dc component. Hence pulsating dc signal is said to be combination of DC and AC.
- Properties of Pure ac:
  (i) Periodic variation
  (ii) Bidirectional
  (iii) Zero average or zero dc value
  (iv) No harmonic component except fundamental frequency