UNIT 2

Solid-State Electronics

There are many semiconductor-based solid-state switches such as diodes, thyristors, transistors and integrated circuits. As name implies, a semiconductor is neither a good conductor of electrical current nor an insulator. Under certain circumstances, the resistive properties of a semiconductor can be varied between those of a conductor and those of an insulator. In general, the resistance of semiconductor materials such as silicon, germanium, etc. decreases as temperature increases, and ultimately a point is reached when they become conductors as the temperature rises. Pure silicon and germanium are poor conductors and are of little use. To overcome this, a process called doping is utilized. The process of doping is adding elements such as arsenic, phosphorous, antimony, indium, boron, etc. to silicon and germanium to improve their conductivity.

Three types of doped semiconductors are commonly used in the semiconductor industry based on the nature of the impurity as follows:

1. N-type: This negative-type semiconductor has impurities of the elements with five valence electrons, for example arsenic, phosphorous or antimony. The electrons in the impurities (doping element) are very easily freed and become conduction electrons. The impurities contribute to the conduction electrons which act as dominant current carriers and are known as donors since there are more conduction band electrons. The valence band holes act as minority carriers (Figure 3.1). Note that the term N-type implies an excess of electrons in the material after covalent bonds are formed between the semiconductor material and the donor.

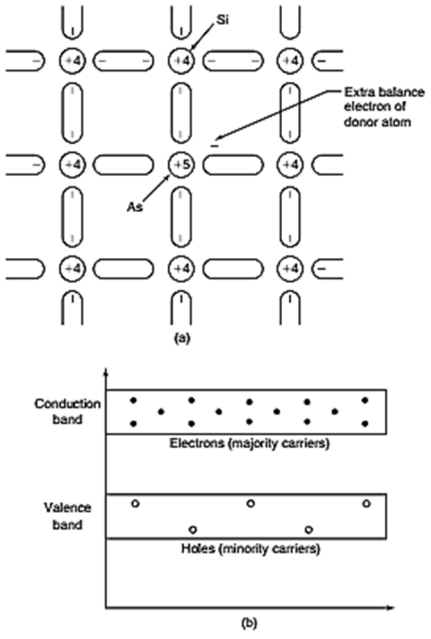


Figure 3.1 | N-type semiconductor: (a) N-type material and (b) energy diagram.

2. P-type: This has, as the doping material, elements with three valence electrons like indium, boron, gallium and aluminum. These semiconductors are commonly known as receptors. The existence of covalent bonding structure is due to the use of trivalent element. The P-type material is shown to have an excess of holes in the valence band as depicted in Figure 3.2. There are many valence band holes than conduction band electrons, therefore holes are the majority carriers.

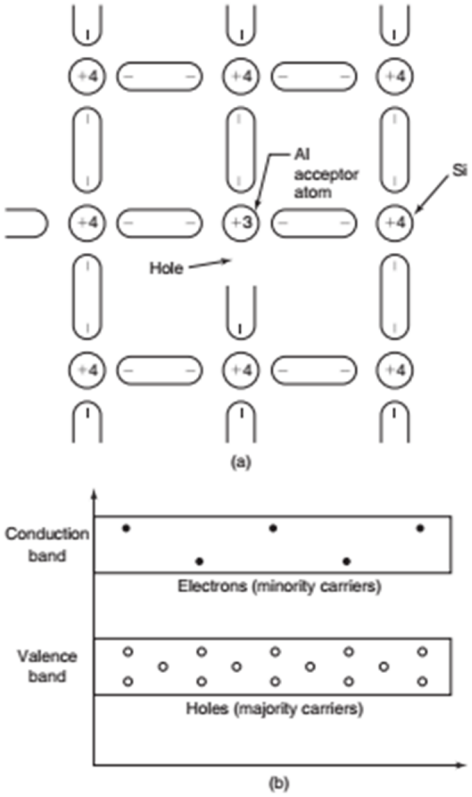


Figure 3.2 | P-type semiconductor: (a) P-type material and (b) energy diagram.

3. PN junction: There is little use of either N-type or P-type materials in isolation and hence the PN junction is constructed by joining the two different types of materials at a junction as shown in Figure 3.3. Note that there is an overlap of conduction and valence bands of the material and consequently results in diffusion of free electrons from the N-type material to the P-type material. The diffusion across the junction leaves one positively charged bond in the N-type material and one negatively charged bond in the P-type material. Subsequently, the N-type material will lose conduction band electron and P-type material will lose valence band hole. At this point, both bonds have been depleted of charge carriers and the junction ends up having a layer called the depletion layer. The difference in charges on two sides of the junction is called barrier potential.

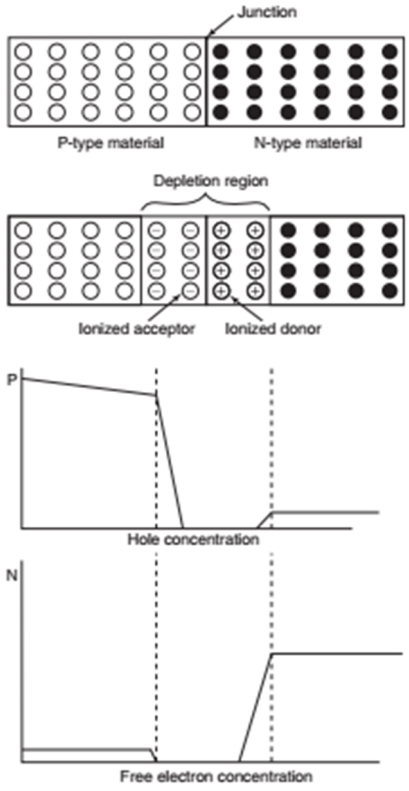


Figure 3.3 | PN junction.

3.2 PN Junction Diode

A diode is a two-electrode device and often acts as a one-way conductor. The basic type of diode is the PN junction diode. The construction and symbol of PN junction diode is shown in Figure 3.4. The positive P-end connection is called anode and the negative N-end connection is called cathode. Some electrons in the N-material near the junction are attracted to the holes in the P-material, thus leaving holes in the N-material. Therefore a potential difference exists across the layers due to diffusion of charges and hence, the material will conduct in one direction but not in the opposite direction. We can control the width of depletion layer to control the resistance of the PN junction and thus, the amount of current passing through the device by applying a potential to the junction. This can be achieved in the following two ways.



Figure 3.4 | Semiconductor diodes: (a) Construction and (b) symbol.

1. Forward biasing: Here the applied voltage causes the N-type material to be more negative than the P-type material and potential is used to reduce the resistance of a PN junction. Figure 3.5(a) shows a diode connected in the forward-biased condition. The diode is connected in such a way that the cathode has a more negative voltage applied to it with respect to the anode. The applied voltage opposes the contact potential and closes the depletion layer. Here the rapid rise in current only occurs when the potential difference exceeds the threshold value.

2. Reverse biasing: A PN junction is reverse-biased when the applied voltage causes the N-type material to be more positive than the P-type material. The connection for reverse biasing the PN junction is given in Figure 3.5(b). The effect is to widen the depletion layer and the junction current is reduced to almost zero. The diode blocks the current and the potential barrier increases [Figure 3.5(b)].

Figure 3.6 shows a typical operating curve for a basic diode. Note that if the voltage across the diode is positive, relatively large amount of current flow occurs for small voltages. This is a forward-biased condition. Therefore, in the forward direction, the diode has a very small resistance and can be ignored. On the other hand, in the reverse-biased region, for moderate values of negative voltage, the current is very small. However, a large current will flow for a sufficiently large reverse-bias voltage applied to the diode and the diode enters the reverse breakdown region. Therefore, in the reverse direction, the diode conducts very little, up to a critical

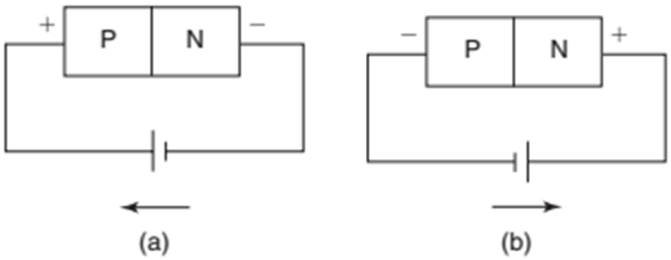


Figure 3.5 | PN diode: (a) Forward-biased and (b) reverse-biased.

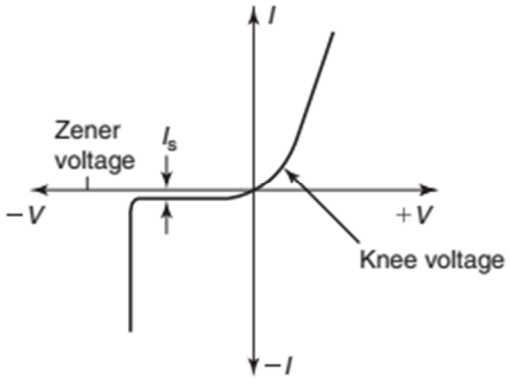


Figure 3.6 | Current–voltage relationship for a PN semiconductor diode.

3.3 Bipolar Junction Transistor (BJT)

The term transistor stands for transfer resistor. Transistors are used primarily as amplifying devices that can transfer current from a low-resistance circuit to a high-resistance circuit. One major type of transistor is the bipolar transistor, a three-terminal component that consists of two PN diodes connected together with one common section as shown in Figure 3.12. Three terminals are called the emitter, the collector and the base. The emitter and the collector are made up of same semiconductor materials, while the base is made up of another type of semiconductor material. There are two configurations: PNP and NPN transistors.

NPN transistor has N-type emitter and collector terminals and a P-type base. The PNP transistor has P-type emitter and collector terminals and an N-type base. Figure 3.13 shows the construction of BJT with symbols. Note that the arrow always points in the direction of the hole flow (current), or from the P-type to N-type sections, no matter whether the P-type section is the emitter or the base. Operating Principles There are two junctions in the BJT. One is the interface at which the emitter and base are joined and is called base–emitter junction. The other one is the interface where base and collector meet, known as collector–emitter junction.

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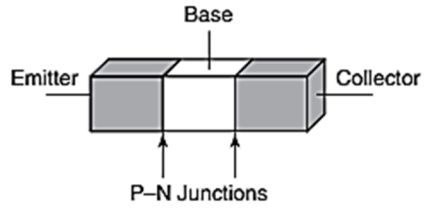


Figure 3.12 | Bipolar junction transistor.

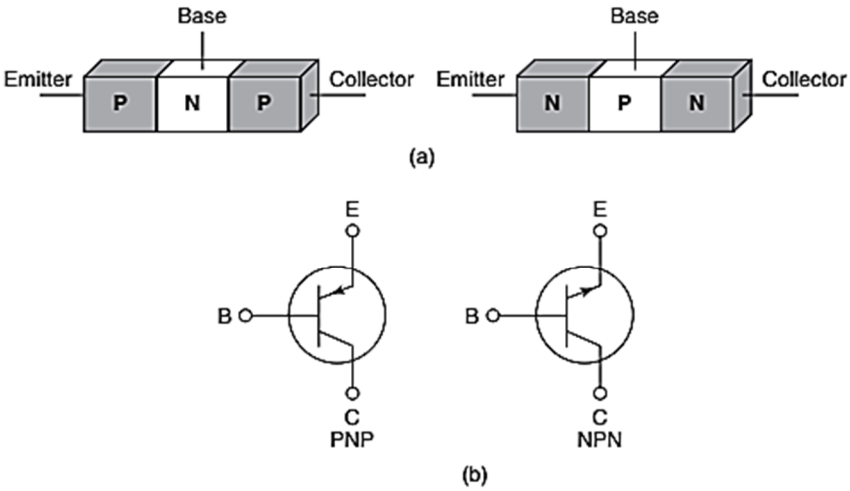


Figure 3.13 | Bipolar transistor: (a) Construction and (b) symbols.

NPN Transistor

An NPN transistor with voltage sources connected is represented in Figure 3.14 and consists of a layer of P-doped semiconductor (the base) between two N-doped layers. A small current entering the base in common emitter (CE) mode is amplified in the collector output. The arrow in the NPN transistor symbol is on the emitter leg and points in the direction of the conventional current flow when the device is in forward active mode. Note that the emitter terminal is common to both voltage sources. There are three operating regions for the transistors:

1. Cut-off region: Here both base–emitter and collector–emitter junctions are reverse-biased. With the larger depletion layers, only small amount of reverse current passes from the emitter to the collector.

2. Active region: Here the base–emitter junction is forward-biased and the collector–base junction is reverse-biased. BJTs operate in the active region as amplifiers. To make the transistor conduct appreciable current (of the order of 1 mA) from collector to emitter, base–emitter voltage (V_{BE})must be above a threshold voltage value that is large enough to overcome the barrier potential of the junction. This applied voltage causes the lower PN junction to "turn on" allowing a flow of electrons from the emitter into the base.

3. Saturation region: When both junctions are forward-biased, the transistor is said to be operating in the saturation region. Here the collector current reaches its maximum value as determined by the collector supply voltage and the value of the load resistance or impedance.

PNP Transistor

A PNP transistor with voltage sources connected is represented in Figure 3.15. The majority carriers in the emitter P-type material are holes.The base–emitter junction is forward-biased and the base–collector junction is reverse-biased. Note that the polarities of voltage applied to the PNP device must be opposite to those applied to NPN devices, and hence the current flow. PNP transistors cause a lot of holes to cross from the emitter region to the base region, as the base is slightly doped with N-type impurity. Large proportions of the holes in the base region cross the base–collector junction into collector region, thereby creating the collector current.

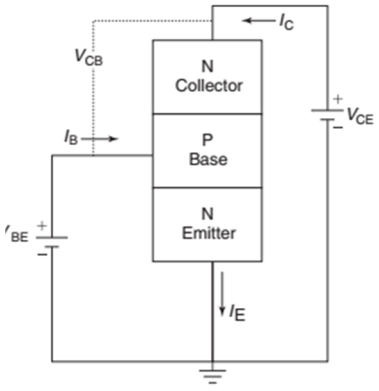


Figure 3.14 | NPN transistor.

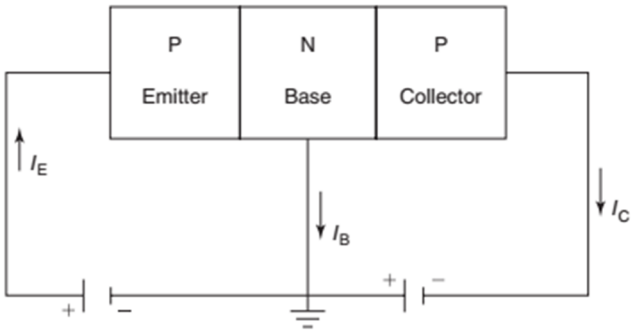


Figure 3.15 | PNP transistor.

Common Configurations

In a transistor circuit, the common central section is referred to as the base and the other two terminals are called the emitter and the collector. Normally one terminal will be used as the input terminal, the other as the output terminal. The third terminal is common to input and output. Based on input, output and common terminal connection in the transistor circuit, three possible connection schemes for the transistor are shown in Figure 3.16.

1. Common base (CB) configuration scheme: In this emitter is the input terminal, collector is the output terminal and base is the common terminal.

2. Common emitter (CE) configuration scheme: Here base is the input terminal, collector is the output terminal and emitter is the common terminal.

3. Common collector (CC) configuration scheme: Here base is the input terminal, emitter is the output terminal and collector is the common terminal.

3.4 Field-Effect Transistor (FET)

An FET is a three-terminal device such as the BJT, but operates by a different principle. FETs are voltage controlled devices and are unipolar because conduction in the FET is the result of only one dominant charge carrier. The three terminals are called the source, the drain and the gate. The voltage applied to the gate controls the current flowing in the source–drain channel. No current flows through the gate electrode, thus the gate is essentially insulated from the source–drain channel. Because no current flows through the gate, the input impedance of the FET is extremely large (in the range of 1010–1015). The large input impedance of the FETs makes them an excellent choice for amplifier inputs. There are two types of FETs:

1. Junction field-effect transistor (JFET).

2. Metal oxide semiconductor field-effect transistor (MOSFET).

JFET

The construction of and symbols used for JFET are shown in Figure 3.25. There are two types of JFETs based on semiconductors used, N -channel and P-channel. In the JFET, the gate-channel contact is a reverse-biased PN junction. The gate-channel junction of the JFET must always be reverse-biased otherwise it may behave as a diode. All JFETs are depletion mode devices – they are ON when the gate bias is zero ($V_{GS} = 0$).

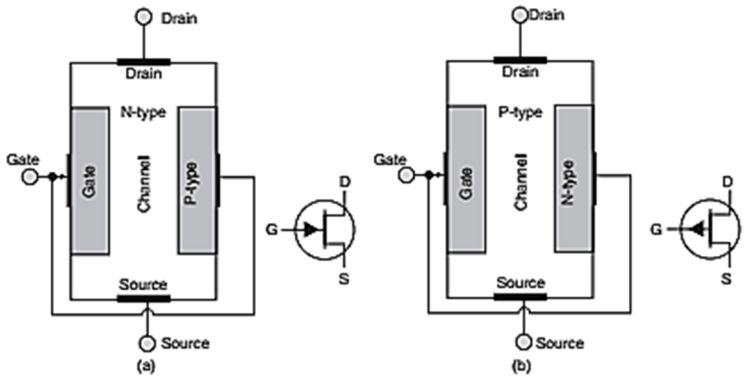


Figure 3.25 | JFET: (a) N-channel JFET and (b) P-channel JFET.

The difference is the arrow head on the gate lead. The arrow head points inward on the N-channel and points outward on the P-channel. The operation of both is identical with the exception that polarities of the voltages are reversed. N-channel JFET is normally used with positive voltage supply, while P-channel JFET is used with negative voltage supply.

Drain–source voltage (V_{DS}) causes the conduction through JFET. If the drain voltage is increased from zero, the cross-sectional area of the channel will be reduced. This will result in increase in the width of the gate. The resistance of the wider gate with narrower channel will be greater and this will be controlled by applying reverse bias to the gate–source junction (V_{GS}). This reverse-biases the gate–source junction, causing depletion layer to form that prevents the current flow. If the area of the channel decreases then the drain current will decrease. Note that as VGS increases, ID decreases.

Other method to control depletion layer is to change VGS and keeping the value of VDS constant. The size of depletion layer can be increased by reverse biasing the junction between the gate and source. These facts are reflected in the characteristic curves.

The general characteristic of an FET is shown in Figure 3.26 and there are three regions of JFET operations. Note that, for given value of gate voltage, an increase in drain–source voltage from zero initially gives a linear rise in the drain current.

Regions of JFET Operation The three regions of JFET are as follows.

1. Cut-off region:The transistor is OFF. There is no conduction between the drain and the source when the gate–source voltage is greater than the cut-off voltage. The value of V_{GS} that causes ID to drop to approximately zero is called the cut-off voltage.
2. Active region (also called the saturation region): The transistor is ON. The drain current is controlled by the gate–source voltage (V_{GS})and is relatively insensitive to V_{DS}. In this region the transistor can act as an amplifier. This region is called constant current region as ID will remain constant for a constant value of V_{GS} for a range of values of V_{DS} between pinch-off and cut-off voltages.

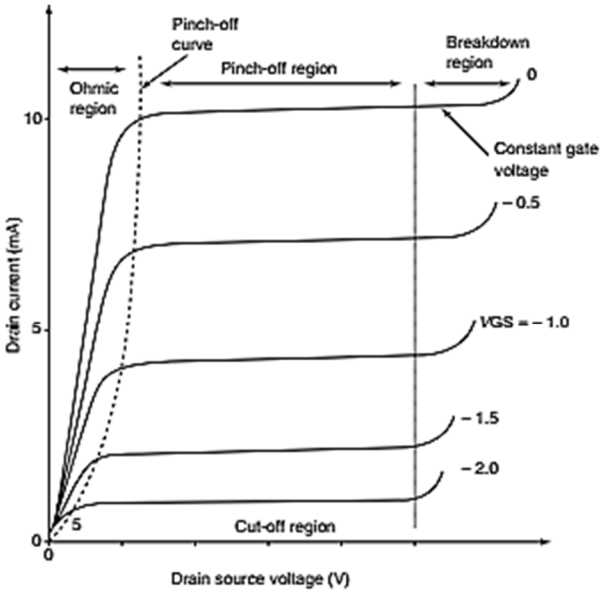


Figure 3.26 | Characteristics of an FET.

3. Ohmic region: The transistor is ON, but behaves as a voltage-controlled resistor. When VDS is less than its value in the active region, the drain current is roughly proportional to the source–drain voltage and is controlled by the gate voltage.

JFET has the following features in relation to tripolar transistors: Applications are similar to that of a transistor but these following features make it more applicable to some specific applications.

1. Very high input impedance.
2. Less operational variation with respect to temperature.
3. Noise problem in communication is minimal.
4. Operating-frequency bandwidth is small.

MOSFET

Alternate means of controlling the resistance of the sources to a drain channel can be achieved by a MOSFET. This is an FET in which the gate is insulated from the conducting channel by a thin layer of silicon oxide. By placing an insulating layer between the gate and the channel, a wider range of control (gate) voltages and further decreases in the gate current (and thus increases the device input resistance) can be obtained. The insulator is typically made of an oxide (such as silicon dioxide,(SiO_2)The substrate is often connected to the source internally. The insulated gate is on the opposite side of the channel from the substrate. The bias voltage on the gate terminal either attracts or repels the majority carriers of the substrate across the PN junction

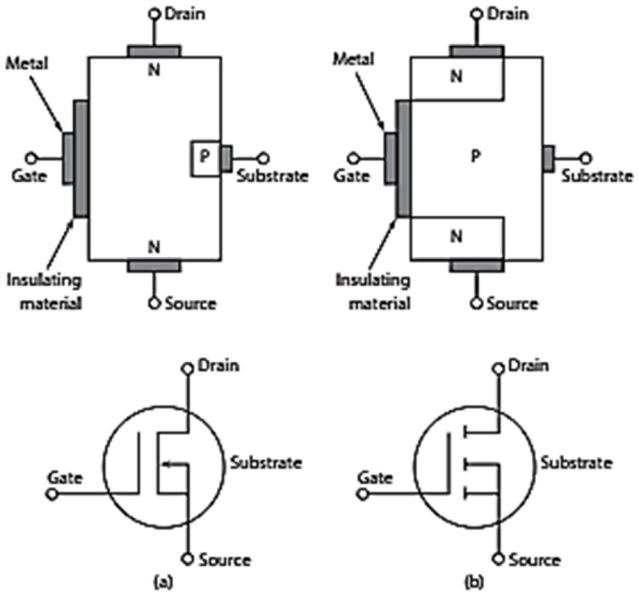


Figure 3.27 | MOSFET construction and symbols: (a) N-channel depletion-type MOSFET and (b) N-channel enhancement-type MOSFET.

with the channel. This narrows (depletes) or widens (enhances) the channel, respectively, as VGS changes polarity. The construction and the symbols for the MOSFET are shown in Figure 3.27, and they are of two types: P-channel type and the N-channel type. For N-channel MOSFETs, positive gate voltages with respect to the substrate and the source (VGS > 0) repel holes from the channel into the substrate, thereby widening the channel and decreasing the channel resistance. Conversely, VGS < 0 causes holes to be attracted from the substrate, thereby narrowing the channel and increasing the channel resistance. The polarities are reversed for P-channel devices. The common abbreviation for an N-channel MOSFET is NMOS, and for a P-channel MOSFET, it is PMOS. There are two modes of operation for MOSFETs as they can both deplete the channel, like the JFET, and also enhance it. The construction of MOSFET devices differs depending on the channel size in the resting state. A depletion mode device (also called a normally ON MOSFET) has a conducting channel in the resting state (when there is no reverse bias across gate to substrate) and this channel gets constricted with reversebiased voltage across the gate and substrate. This device conducts current with no bias applied. When the gate–source junction is reverse-biased as shown in Figure 3.28(a), the biasing voltage depletes the channel and effectively reduces the width of channel, thereby increasing its resistance. This operation is exactly similar to JFET operating state. An enhancement mode device (also normally called an OFF MOSFET) is built without a channel and does not conduct current when VGS = 0; increasing forward bias forms a channel that conducts current.

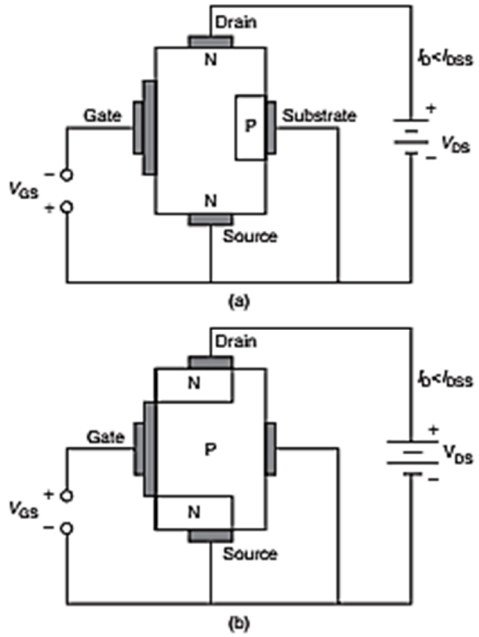


Figure 3.28 | (a) Depletion mode of MOSFET and (b) enhancement mode of MOSFET.

When positive potential is applied to the gate see Figure 3.28(b), VGS is positive and channel is effectively widened to reduce the resistance. ID increases the above the value of ID when the sources source and terminal are shortened together (IDSS). For an enhancement mode NMOS, the operation can be separated into three different modes (Figure 3.29), depending on the voltages at the terminals as depicted in Figure 3.28(b). 1. Cut-off or sub-threshold mode: When VGS is less than the threshold voltage of the device (Vth), the transistor is turned OFF, and there is no conduction between the drain and the source. 2. Linear mode: When VGS > Vth and VDS < (VGS –Vth). In this case the transistor is turned ON and a channel has been created that allows current to flow between the drain and the source. The MOSFET operates like a resistor, controlled by the gate voltage relative to both the source and drain voltages. 3. Saturation mode: When VGS > Vth and VDS > (VGS – Vth). Here, the switch is turned ON and a channel has been created that allows current to flow between the drain and the source. Since the drain voltage is higher than the gate voltage, a portion of the channel is turned OFF. The onset of this region is also known as pinch-off. The drain current is now relatively independent of the drain voltage and the current is controlled by only the gate–source voltage

MOSFET has the following features in comparison with JFET:

1. High input resistance.

2. Higher gain.

3. Greater fragility.

4. Has zero-effect voltage.

5. Easier to fabricate.

6. Drain resistance is less.

7. Operated in both depletion and enhancement modes.

3.5 Thyristors

For switching very large currents and voltages, a power electronic device known as thyristor or silicon controlled rectifier (SCR) is used. A thyristor is a four-layer, unidirectional semiconductor device (Figure 3.30) with three connections. When a small current flows into the gate (G), a larger current is allowed to flow from the anode (A) to the cathode (C). Even when the current into the gate stops, the thyristor continues to allow current to flow from anode to cathode. It latches on. Therefore, only a pulse in the gate circuit would suffice to start conduction in the thyristor and conduction stops when the voltage falls to zero.

The typical characteristics of an SCR are shown in Figure 3.31. When the anode is at a positive potential (anode to cathode voltage, VAK) with respect to the cathode with no voltage applied at the gate, junctions J1 and J3 are forward-biased while junction J2 is reverse-biased. As J2 is reverse-biased, no conduction takes place (OFF state). Now if VAK is increased beyond the breakdown voltage, VBO, of the thyristor, avalanche breakdown of J2 takes place and the thyristor starts conducting (ON state).

If a positive potential VG is applied at the gate terminal with respect to the cathode, the breakdown of the junction J2 occurs at a lower value of VAK. By selecting an appropriate value of VG, the thyristor can be switched into the ON state immediately at any value of VAK.

It should be noted that once avalanche breakdown has occurred, the thyristor continues to conduct, irrespective of the gate voltage, until either (a) the potential VAK is removed or (b) the current through the

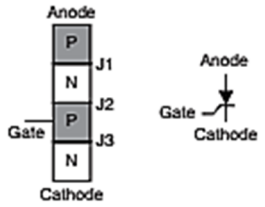


Figure 3.30 | Construction and symbol of SCR.

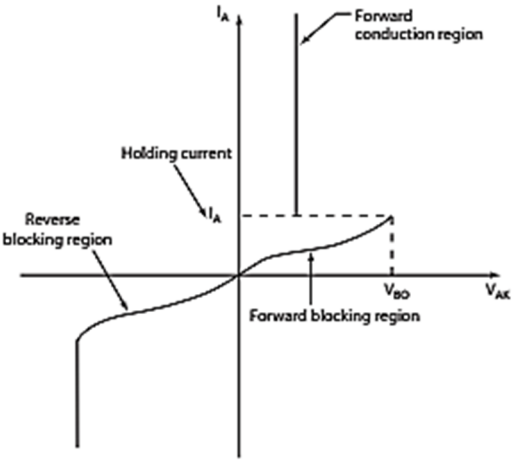


Figure 3.31 | Operating curve for SCR.

device (anode-cathode) is less than the holding current specified. Hence VG can be a voltage pulse. These gate pulses are characterized in terms of gate-trigger voltage (VGT) and gate-trigger current (IGT). Gate-trigger current varies inversely with gate pulse width in such a way that a minimum gate charge is provided to trigger the thyristor.

Some features of SCR are:

1. It acts as a diode and is ON when positive voltage is applied to the gate.

2. SCR will not turn ON when negative voltage is applied to the gate.

3. It fails to conduct current when no voltage is applied to the gate and changes from non-conducting to conducting mode if a voltage is applied to the thyristor.

4. Once SCR is turned ON, it will stay ON under full load even after the positive gate voltage is removed.
5. The thyristor will turn OFF when the current flowing through it is reduced below holding current.

6. The thyristor is used extensively for switching on the supply and as a speed controller for DC motors.

Applications of SCR

1. Control of DC motor: In this simple form, the SCR circuit shown in Figure 3.32 could suffice as a start/stop control circuit for a DC motor, lamp or other practical loads.

2. Overvoltage protection: Another practical use of the SCR in a DC circuit is the over voltage protection. The circuit is known as Crowbar (shown in Figure 3.33) and consists of an SCR placed in parallel with the output of a DC power supply, for the purpose of placing a short circuit route across the output of that supply to prevent excessive voltage from reaching the load in the event of an over voltage.

3. SCR half-wave rectification: By connecting a suitable control circuit to the gate of an SCR, we can "chop" the sine wave of an AC supply at any point to allow for time-proportioned power control to a load. The simple circuit is shown in Figure 3.34. Here, an SCR is positioned in a circuit to control power to a load from an AC source. Being a unidirectional (one-way) device, the SCR delivers half-wave power to the load, in the half-cycle of AC where the supply voltage polarity is positive at the top and negative at the bottom. With no triggering to the gate, and the AC source voltage well below the SCR's breakover voltage rating, the SCR will never turn ON. SCR will be triggered almost immediately at the beginning of every positive half-cycle. We can delay the triggering of the SCR by inserting some resistance into the gate circuit. This will increase the amount of voltage drop required before there is enough gate current to trigger the SCR. Therefore, the half-sine wave can be chopped at any point by delaying triggering of the SCR resulting in time-proportioned power.

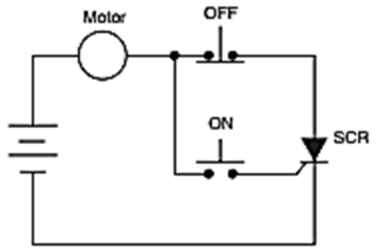


Figure 3.32 | DC motor start/stop control circuit.

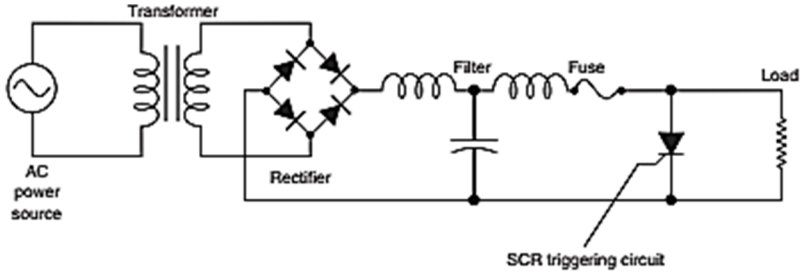


Figure 3.33 | Over voltage protection.

4. Full-wave rectification: An example of full-wave rectification is the controlled SCR bridge rectifier shown in Figure 3.35. In the bridge rectifier circuit, the rectifying SCRs and diodes must conduct in opposite pairs. During the positive half cycle of the supply voltage, SCR1 and diode D2 conduct, but SCR2 and D1 do not conduct. Likewise SCR2 and D1 conduct during the negative half cycle.

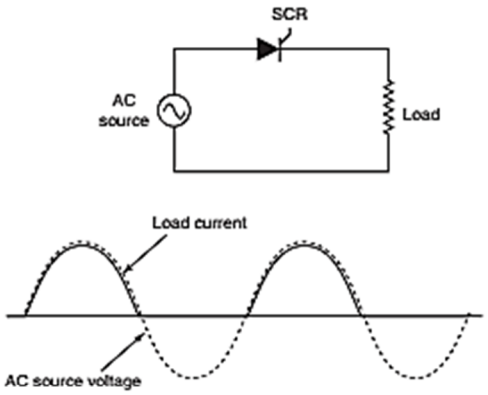


Figure 3.34 | Half-wave rectification.

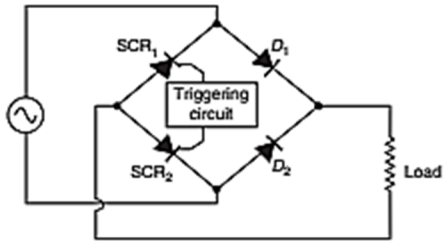


Figure 3.35 | Full-wave rectification.

3.6 Diode AC Switch (DIAC) and Triode AC Switch (TRIAC)

DIAC

A DIAC is a four-layered device whose top and bottom layers contain both N- and P-materials. The construction and symbol of DIAC is shown in Figure 3.36. The terms anode and cathode no longer apply, so the connections are simply named main terminal 1 (MT1) and main terminal 2 (MT2). Each terminal can serve as either anode or cathode, according to the polarity of the applied voltage.The DIAC, like the four-layer diode, remains non-conducting until its breakover voltage is reached, at which point it turns ON fully and remains ON until the applied voltage or circuit current is reduced

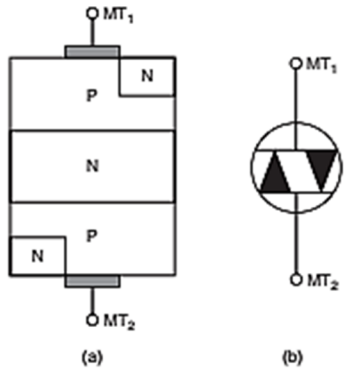


Figure 3.36 | DIAC: (a) Construction and (b) symbol.

below the holding values at which conduction can be maintained. Note that MT1 is positive with respect to MT2 during the positive half-cycle, whereas in the negative half-cycle, MT2 is positive with respect to MT1.

TRIAC

TRIAC is a bidirectional device that can be used to give a controlled AC output and is essentially a two-way SCR with one gate. If two SCRs are joined in back-to-back parallel fashion, we have a new device known as the TRIAC. The TRIAC construction and symbol are shown in Figure 3.37.

TRIACs are usually used in simple, low-power applications like household dimmer switches. Note that the conduction is blocked in either direction until a gate pulse of any polarity is applied when the device goes to a low-impedance state. Conduction continues until the current falls below a holding current. Figure 3.38 shows an AC circuit using a TRIAC and the output wave form from the circuit.

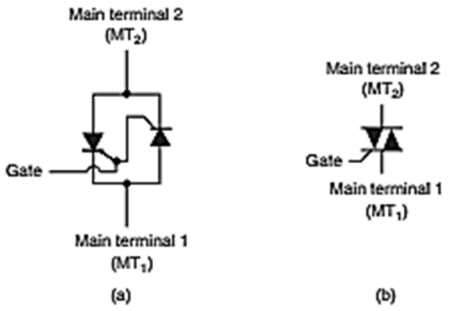


Figure 3.37 | (a) TRIAC equivalent circuit and (b) TRIAC schematic symbol.

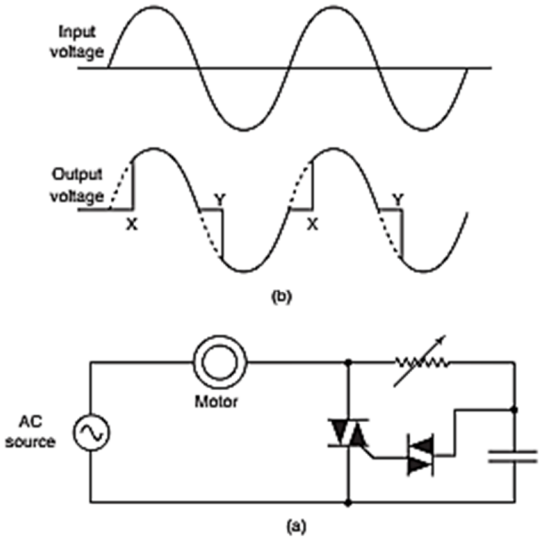


Figure 3.38 | (a) TRIAC with AC circuit and (b) output waveforms.

3.7 Light-Emitting Diodes and Optical Isolation Light-Emitting Diodes (LEDs)

When current flows through a forward-biased PN junction [Figure 3.39(a)], free electron cross the N-side and recombine with holes on the P-side. If the free electron in the conduction band recombines with a hole in valence band, then it releases energy as it falls into that lower energy state. The energy is released in the form of heat and light. If the material is translucent such as gallium phosphide

or gallium arsenide phopshide, the light energy released is visible. The phenomenon of conversion of electrical energy to light energy is called

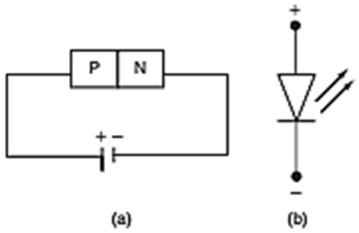


Figure 3.39 | LED: (a) PN junction and (b) symbol.

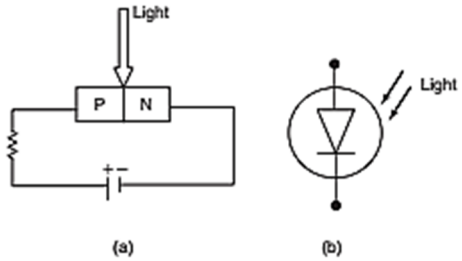


Figure 3.40 | Photodiode: (a) Construction and (b) symbol.

electroluminescence. A PN junction device which emits light when forward-biased is called LED and is an example of the phenomenon electroluminescence. LED symbol is shown in Figure 3.39(b).

Photodiodes

A photodiode is a PN junction device which converts light signal into electrical signals. The PN junction is kept in an opaque casing such that the light rays are allowed to fall on one surface across the junction. When PN junction is reverse-biased, it behaves as a photoconductive device due to changes in resistance with respect to light intensity. This will create hole electron pairs and movement of hole electron pairs can be properly connected in a circuit to obtain current flow. The construction and symbol of photodiode is shown in Figure 3.40.

Optical Isolators (Optocoupler)

Optical isolation is used when signal is required to transfer from one part of a system to another, but direct electrical connection is undesirable or difficult. Examples of application for optical isolators are the instrumentation used for electrical power generating plants, medical electronics, etc. In medical electronics, for safety reasons, it is required to avoid direct electrical connections between patients and the electrical power. As shown in Figure 3.41, the signal to be transferred through an optical isolator is applied through a LED. The signal is then carried by the light wave to a photodiode detector that converts light power back to electrical current. It is imperative that the detector current is proportional to the incident light power. As the signal is carried by a light wave, the detector circuits can be electrically isolated from signal source. The LED driver amplifier will force a current through the diode that is proportional to supply voltage.

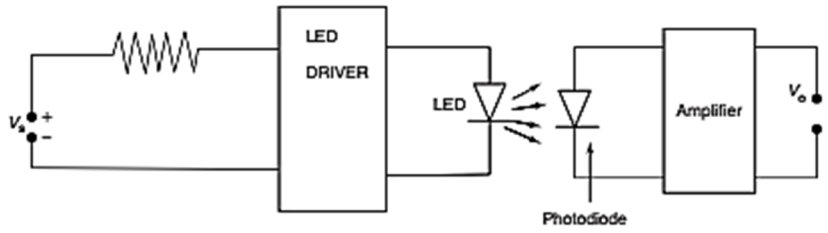


Figure 3.41 | Optical isolator.

Signal Conditioner

A signal conditioner performs operations on signals to convert them to a form suitable for use by another component. The input to a signal conditioner is normally the output from a sensor that is usually described in the form of an analog signal. The analog signal is continuous and time varying. The signals from sensors may not be in the suitable form and will usually be in the millivolt range. In general, a signal undergoes transformation when it passes through different processing, transmission or storing devices. Therefore, a signal can not only be distorted and weakened, but also voluntarily transformed to mitigate background noise as it moves. From this perspective, the operations performed by a signal conditioner include:

1. isolation and impedance conversion;

2. noise reduction;

3. amplification;

4. linearization and conversion.

Isolation and Impedance Conversion

The purpose of isolation and impedance conversion is to avoid or minimize the destruction of the signal measured and to protect the measuring instruments. In some situations, this means electrical isolation of the primary element with an isolation amplifier and supply of high impedance at the input to the signal conditioner.

It is also important that when sensors and transducers, controllers, plant equipment and signal conditioner hardwares are interconnected, the impedances should be matched properly at each interface. Otherwise there will be a loading effect due to improper impedance matching. Voltage followers and isolation amplifiers can be used for the impedance conversion.

Noise Reduction and Filtering

Signal systems exist in an environment filled with high levels of electromagnetic energy causing noise in electric signal lines. It is very important to prevent the noise from entering the signal. Noise reduction is possible with various types of filters; for example, band pass filters, low pass filters, etc.

Amplification

The small voltage produced by the sensors needs to be amplified and converted into an electric signal suitable for use by application devices. Changing the level of an analog signal is often accomplished using an operational amplifier. The operational amplifier is the heart of signal processing. The simplest and most common form of signal processing is amplification. Other forms include signal inversion, differentiation, integration, addition, subtraction and comparison.

Linearization and Signal Conversion

Many primary elements produce nonlinear outputs and the signal must be linearized to produce a nearly ideal calibration. Specialized analog circuits, such as offsetting circuits, proportional output circuits, etc., are used to linearize a signal. Figure 4.1 illustrates the purpose of a linearization circuit to produce an output that varies linearly with some variable.

The most common approach is to provide the nonlinear signal input to a computer to perform the linearization using a computer algorithm.

Sometimes it is necessary to convert the signal from a voltage to a current or vice versa. Simple operational amplifier (op-amp) converter circuits can be used for this purpose. Also, it is necessary to convert one type of electrical signal into another. For example, a bridge circuit can be used to convert the change in resistance of a resistance temperature detector (RTD) into voltage.

Operational Amplifier (Op-amp)

An op-amp is an electronic device that behaves like a voltage-controlled source. The op-amp was developed many years ago for analog computing and was designed to perform mathematical operations. They are highly stable high-gain DC devices. Since there is no capacitive coupling between their various amplifying

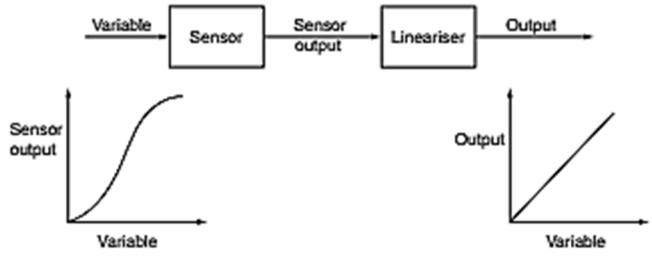


Figure 4.1 | Linearization circuit.

stages, they can handle signals from zero frequency (DC signals) up to a few hundred kHz. Op-amps are among the most widely used electronic components today, and are used in a vast array of consumer, industrial and scientific.

Figure 4.3 illustrates three modes of op-amp depending upon the input voltage. The three modes are: 1. positive saturation, where Vo = Vcc; 2. linear region, where −Vcc Vo +Vcc; 3. negative saturation, where Vo = −Vcc.

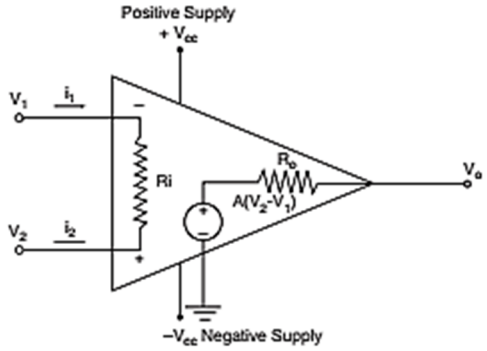


Figure 4.2 | A circuit model of an operational amplifier.

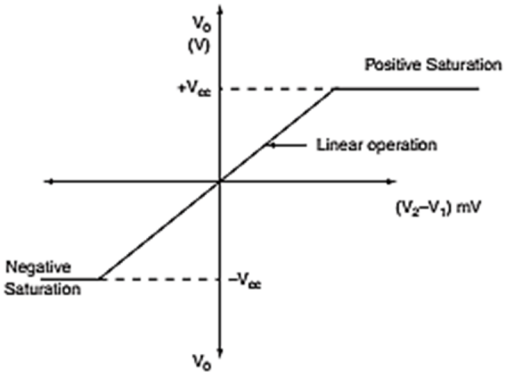


Figure 4.3 | Characteristics of an op-amp.

4.3 Noise Reduction

Special circuits called filters are used to reduce noise in the signals. Actually, filter is a device that allows only the desirable part of a signal to pass through, rejecting the unwanted part. In typical applications the filters are used to remove a certain band of frequencies from the signal and allow other signals to transmit. The range of frequencies allowed to transmit is known as a pass band.

Passive and Active Filters

Passive analog filters employ circuits containing elements such as resistors and capacitors, and do not require an external power source. Active filters use active components such as transistors and an op-amp including passive elements. Here, external power is needed for the operation of active elements. Active filters are widely used due to their following advantages:

1. The loading effect is negligible.

2. Low signal level can be amplified along with filtering.

3. They are available in a low cost and compact IC form.

4. They are free from electromagnetic interference.

However, passive filters can be used at very high frequencies, do not require power supply and are less expensive.

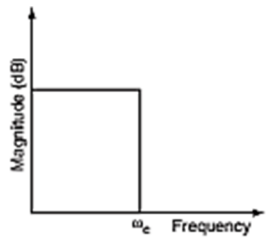


Figure 4.16 | Ideal frequency response curve for low pass filter.

Types of Filters

There are four categories of filters:

1. low pass filter;

2. high pass filter;

3. band pass filter;

4. band reject (notch) filter.

Low Pass Filters

A low pass filter allows all signals below certain frequency to pass through. This frequency is called cut-off or break-point frequency as shown in Figure 4.16.

All components of the signal that are above the cut-off frequency are reduced in amplitude. The simplest circuit of the low pass filter is shown in Figure 4.17(a) with RC passive elements. The passive filter is associated with the circuit loading that arises because the input impedance is not sufficiently high. This can be resolved using an active filter as shown in Figure 4.17(b) with very high input impedance and low output impedance, while maintaining unit voltage gain. In the case of the low pass filter, the actual variation of rejection with frequency is shown in Figure 4.17(c). Analog low pass filters are very common in signal conditioning, as they can be designed to reduce noise without affecting the information content of the signal. Analog active filters are also widely used as anti-aliasing filters in digital signal processing.

The equation of low pass filter can be obtained as

$$\tau \frac{dV_o}{dt} + V_o = V_i$$

where $\tau = RC$ is the time constant. The transfer function relating input and output is given by

$$\frac{V_o(s)}{V_i(s)} = \frac{1}{\tau s + 1}$$

The cut-off frequency can be derived as $\omega_c = 1/\tau$. If the attenuation factor A, defined as the ratio of the amplitude before filtering to the amplitude after filtering, is known then is given as $\omega_c = A/\tau$.

4.4 Bridge Circuits

Abridge circuit is used for detecting form of measurement such as change in resistance, change in inductance, change in capacitance, etc. It is the traditional method of measuring small change in the resistance of an element. There are two basic methods of making the measurement.

1. bridge balance method;

2. imbalance output method.

A bridge is said to be balanced when the output shows zero voltage. In the bridge balance method, the bridge is initially balanced but when measurement is made, the balance is disturbed due to variation in the quantity measured. The bridge is balanced again by varying one of the arms. The change required in one of the arms to restore the zero voltage output is measured. In the imbalance output method, the bridge is initially balanced. The balance of bridge will be upset as a result of the change in variable during measurement. The output of the bridge itself is measured as the bridge measurement.

The Wheatstone bridge is the most common bridge circuit used. The circuit shown in Figure 4.25 is the resistance bridge, with a constant DC voltage, and it has been extensively used to convert a resistance change to a voltage change. This full bridge circuit has four arms.

The output voltage Vo can be determined by applying voltage divide rule at points A and B.

$$V_o = V_A - V_B$$
$$= \left(\frac{R_1}{R_1 + R_2}\right) V_s - \left(\frac{R_3}{R_3 + R_4}\right) V_s$$

Current-to-Voltage and Voltage-to-Current Converters

One of the important applications of op-amps is to frequently convert input voltage into output current. This type of op-amp finds its application where the sensors produce a variable voltage, and the control circuit requires a changing current such as 4–20 mA signal. Figure 4.26 shows a circuit for voltage-to-current amplifier. The load is connected as a feedback resistance, and the input voltage is connected to a negative terminal. Note that the load current will flow through the input resistor that is connected to the positive terminal. Therefore, there is a change in voltage drop at positive input with the change in input signal being at the inverting input.

It is observed that

$$i_{R_i} = i_{\text{load}} \text{ and } i_{R_i} = \frac{V_i}{R_i}$$

$$i_{load} = \frac{V_i}{R_i}$$

Figure 4.27 shows the electrical circuit for a current-to-voltage converter. The non-inverting input of op-amp is grounded. The input current is connected to the inverting terminal that has high impedance; therefore, all the current from the source will flow through the feedback resistor Rf. The voltage across the load resistor is the output voltage which is proportional to the input current, that is Vo = ii ×Rf.

Voltage-to-Frequency and Frequency-to-Voltage Converters

I n some of industrial applications such as frequency modulation, analog-to-digital conversion, signal generation, etc., it is necessary to produce an output signal whose frequency is proportional to the level of the input signal. These devices are known as voltage-to-frequency converters (VFC) or voltage-controlled oscillators. A common type of VFC circuit using a capacitor is shown in Figure 4.28. Here, the capacitor is made to periodically charge and discharge. As the time required for charging a capacitor with a fixed voltage level is inversely proportional to the charging voltage, the output will be fixed amplitude with frequency dependent on the charging voltage. This means that the frequency that is the inverse of the charge–discharge period, depends upon the charging voltage. In order to achieve this, a voltage-sensitive switch is connected

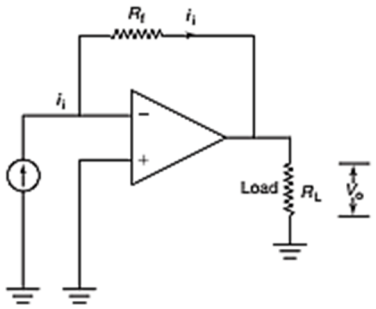


Figure 4.27 | Circuit for a current-to-voltage converter.

across the feedback capacitor. The switch will close when the voltage across it exceeds a reference level, and will open when the voltage falls below a lower limit. A frequency-to-voltage converter (FVC) produces an output voltage, which depends upon the frequency of the input signal. The circuit shown in Figure 4.29 consists of comparator and capacitor circuits. The comparator circuit will have two inputs: one is the frequency input and the other one is for a reference voltage.

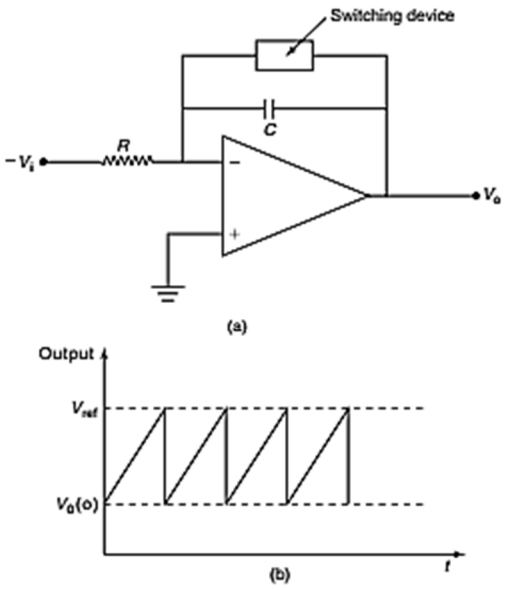


Figure 4.28 | (a) Circuit for a voltage-to-frequency converter and (b) output signal.

The comparator circuit will produce either negative signal or positive signal depending upon the input signal in relation with the reference voltage. The sign change (say negative to positive) in the comparator will trigger a switching circuit for charging the capacitor to a fixed voltage. The next sign change (positive to negative) will cause the switching circuit to short circuit and thereby cause an instantaneous discharge of the capacitor. Note that the voltage to which the capacitor is charged purely depends upon the frequency of the input signal. Therefore, the output voltage of the capacitor will be related to the input signal frequency.

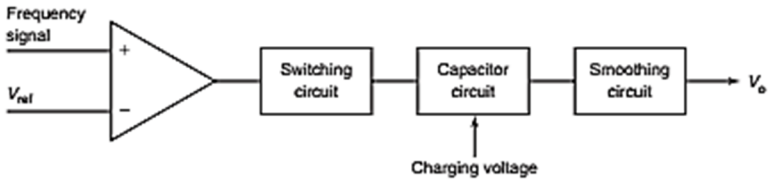


Figure 4.29 | Circuit for a frequency-to-voltage converter.