BASIC ELECTRICAL

LECTURE NOTES

B TECH (II SEM)

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BASIC ELECTRICAL

Module 1: DC Circuits

Electrical circuit elements (R, L and C), voltage and current sources, Kirchoff current and voltage laws, analysis of simple circuits with dc excitation. Superposition, Thevenin and Norton Theorems. Time-domain analysis of first-order RL and RC circuits.

Module 2: AC Circuits

Representation of sinusoidal waveforms, peak and rms values, phasor representation, real power, reactive power, apparent power, power factor. Analysis of single-phase ac circuits consisting of R, L, C, RL, RC, RLC combinations (series and parallel), resonance. Three phase balanced circuits, voltage and current relations in star and delta connections.

Module 3: Transformers

Magnetic materials, BH characteristics, ideal and practical transformer, equivalent circuit, losses in transformers, regulation and efficiency. Auto-transformer and three-phase transformer connections.

Module 4: Electrical Machines

Generation of rotating magnetic fields, Construction and working of a three-phase induction motor, Significance of torque-slip characteristic. Loss components and efficiency, starting and speed control of induction motor. Single-phase induction motor. Construction, working, torque-speed characteristic and speed control of separately excited dc motor. Construction and working of synchronous generators.

Module 5: Power Converters

DC-DC buck and boost converters, duty ratio control. Single-phase and three-phase voltage source inverters; sinusoidal modulation.

Module 6: Electrical Installation

Components of LT Switchgear: Switch Fuse Unit (SFU), MCB, ELCB, MCCB, Types of Wires and Cables, Earthing. Types of Batteries, Important Characteristics for Batteries. Elementary calculations for energy consumption, power factor improvement and battery backup.

Suggested Text / Reference Books

- D. P. Kothari and I. J. Nagrath, “Basic Electrical Engineering”, Tata McGraw Hill, 2010.
- D. C. Kulshreshtha, “Basic Electrical Engineering”, McGraw Hill, 2009.
- L. S. Bobrow, “Fundamentals of Electrical Engineering”, Oxford University Press, 2011.
- E. Hughes, “Electrical and Electronics Technology”, Pearson, 2010.
- V. D. Toro, “Electrical Engineering Fundamentals”, Prentice Hall India, 1989.

Course Outcomes

- To understand and analyze basic electric and magnetic circuits.
- To study the working principles of electrical machines and power converters.
- To introduce the components of low voltage electrical installations.

Module1

DC circuits

Electrical circuit elements

Resistance - The electrical resistance of a circuit component or device is defined as the ratio of the voltage applied to the electric current which flows through it. It is measure in ohm.

Capacitor - A capacitor is a device that stores electrical energy in an electric field. It is a passive electronic component with two terminals. It is measure in farad.

Inductor - An inductor, also called a coil, choke, or reactor, is a passive two-terminal electrical component that stores energy in a magnetic field when electric current flows through it. An inductor typically consists of an insulated wire wound into a coil. It is measure in hennery.

Voltage source

A **voltage source** is a two-terminal device which can maintain a fixed voltage. An ideal voltage source can maintain the fixed voltage independent of the load resistance or the output current However, a real-world voltage source cannot supply unlimited current.

A voltage source is the dual of current source Real-world sources of electrical energy, such as batteries and generators, can be modelled for analysis purposes as a combination of an ideal voltage source and additional combinations of impedance elements.

Ideal voltage source

An ideal voltage source is a two-terminal device that maintains a fixed voltage drop across its terminals. It is often used as a mathematical abstraction that simplifies the analysis of real electric circuits. If the voltage across an ideal voltage source can be specified independently of any other variable in a circuit, it is called an independent voltage source. Conversely, if the voltage across an ideal voltage source is determined by some other voltage or current in a circuit, it is called a dependent or controlled voltage source. A mathematical model of an amplifier will include dependent voltage sources whose magnitude is governed by some fixed relation to an input signal, for example. In the analysis of faults on electrical power systems, the whole network of interconnected sources and transmission lines can be usefully replaced by an ideal (AC) voltage source and single equivalent impedance.

Current source

A current source is an electronic circuit that delivers or absorbs an electric current which is independent of the voltage across it.

A current source is the dual of a voltage source. The term *current sink* is sometimes used for sources fed from a negative voltage supply. Figure 1 shows the schematic symbol for an ideal current source driving a resistive load. There are two types. An *independent current source* (or sink) delivers a constant current. A *dependent current source* delivers a current which is proportional to some other voltage or current in the circuit.

An ideal current source generates a current that is independent of the voltage changes across it. An ideal current source is a mathematical model, which real devices can approach very closely. If the current through an ideal current source can be specified independently of any other variable in a circuit, it is called an *independent* current source. Conversely, if the current through an ideal current source is determined by some other voltage or current in a circuit, it is called a dependent or controlled current source

The internal resistance of an ideal current source is infinite. An independent current source with zero current is identical to an ideal open circuit. The voltage across an ideal current source is completely determined by the circuit it is connected to. When connected to a short circuit, there is zero voltage and thus zero power delivered. When connected to a load resistance, the current source manages the voltage in such a way as to keep the current constant; so in an ideal current source the voltage across the source approaches infinity as the load resistance approaches infinity (an open circuit).

No physical current source is ideal. For example, no physical current source can operate when applied to an open circuit. There are two characteristics that define a current source in real life. One is its internal resistance and the other is its compliance voltage. The compliance voltage is the maximum voltage that the current source can supply to a load. Over a given load range, it is possible for some types of real current sources to exhibit nearly infinite internal resistance. However, when the current source reaches its compliance voltage, it abruptly stops being a current source.

In circuit analysis, a current source having finite internal resistance is modelled by placing the value of that resistance across an ideal current source (the Norton equivalent circuit). However, this model is only useful when a current source is operating within its compliance voltage

Kirchoff law

- **Kirchhoff's current law** (1st Law) states that the current flowing into a node (or a junction) must be equal to the current flowing out of it. This is a consequence of charge conservation.
- **Kirchhoff's voltage law** (2nd Law) states that in any complete loop within a circuit, the sum of all voltages across components which supply electrical energy (such as cells or generators) must equal the sum of all voltages across the other components in the same loop. This law is a consequence of both charge conservation and the conservation of energy.

Kirchhoff's current law

Current flow in circuits occurs when charge carriers travel around the circuit. Current is defined as the rate at which this charge passes any point in the circuit. A fundamental concept in physics is that charge will always be conserved. In the context of circuits this means that, since current is the rate of flow of charge, the current flowing into a point must be the same as current flowing out of that point.

Kirchhoff's voltage law

As charge carriers flowing through a circuit pass though a component, they either gain or lose electrical energy, depending upon the component (cell or resistor, for example). This is due to the fact that work is done on or by them as a result of the electric forces inside the components. The total work done on a charge carrier by electric forces in supply components (such as cells) must equal the total work done by the charge carrier in other components (such as resistors and lamps) by the time it has gone round the circuit once. This means that the sum of all potential differences across the components involved in a circuit's loop must be zero if we count voltages across supply components as positive and across 'electricity using' components as negative.

Superposition theorem

Superposition theorem is based on the concept of linearity between the response and excitation of an electrical circuit. It states that the response in a particular branch of a linear circuit when multiple independent sources are acting at the same time is equivalent to the sum of the responses due to each independent source acting at a time.

In this method, we will consider only one independent source at a time. So, we have to eliminate the remaining independent sources from the circuit. We can eliminate the voltage sources by shorting their two terminals and similarly, the current sources by opening their two terminals.

Therefore, we need to find the response in a particular branch 'n' times if there are 'n' independent sources. The response in a particular branch could be either current flowing through that branch or voltage across that branch.

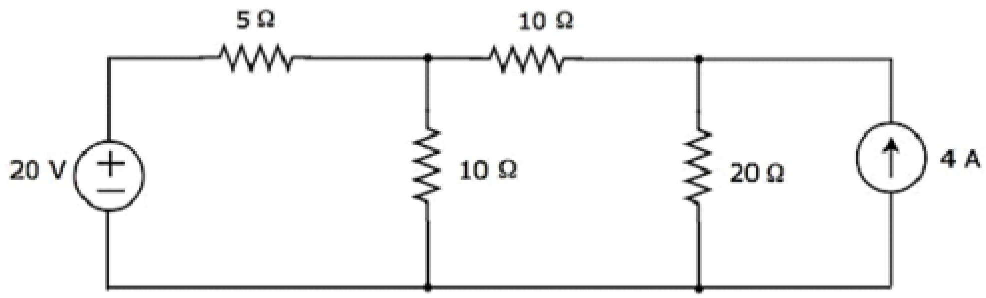
Procedure of Superposition Theorem

Follow these steps in order to find the response in a particular branch using superposition theorem.

Step 1 − Find the response in a particular branch by considering one independent source and eliminating the remaining independent sources present in the network.

Step 2 − Repeat Step 1 for all independent sources present in the network.

Step 3 – Add all the responses in order to get the overall response in a particular branch when all independent sources are present in the network



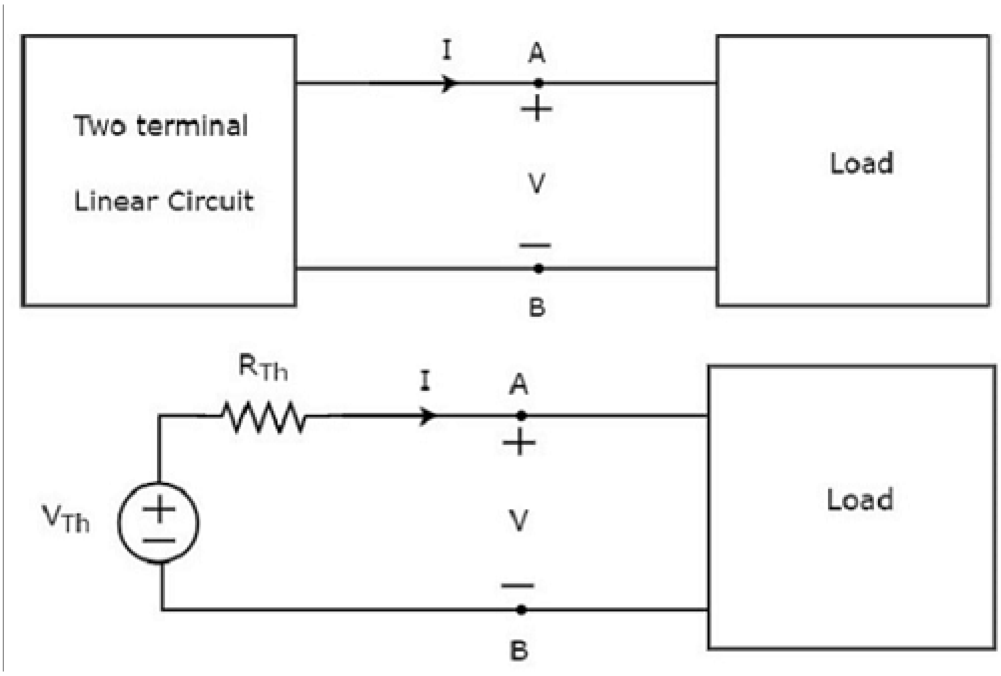
Thevenin's theorem

Thevenin's theorem states that any two terminal linear network or circuit can be represented with an equivalent network or circuit, which consists of a voltage source in series with a resistor. It is known as Thevenin's equivalent circuit. A linear circuit may contain independent sources, dependent sources, and resistors.

If the circuit contains multiple independent sources, dependent sources, and resistors, then the response in an element can be easily found by replacing the entire network to the left of that element with a Thevenin's equivalent circuit.

The response in an element can be the voltage across that element, current flowing through that element or power dissipated across that element.

This concept is illustrated in following figures.



Thevenin's equivalent circuit resembles a practical voltage source. Hence, it has a voltage source in series with a resistor.

- The voltage source present in the Thevenin's equivalent circuit is called as Thevenin's equivalent voltage or simply Thevenin's voltage, V_{Th}.
- The resistor present in the Thevenin's equivalent circuit is called as Thevenin's equivalent resistor or simply Thevenin's resistor, R_{Th}.

Methods of Finding Thevenin's Equivalent Circuit

There are three methods for finding a Thevenin's equivalent circuit. Based on the type of sources that are present in the network, we can choose one of these three methods.

Method 1

Follow these steps in order to find the Thevenin's equivalent circuit, when only the sources of independent type are present.

- Step 1 − Consider the circuit diagram by opening the terminals with respect to which the Thevenin's equivalent circuit is to be found.
- Step 2 − Find Thevenin's voltage V_{Th} across the open terminals of the above circuit.
- Step 3 − Find Thevenin's resistance R_{Th} across the open terminals of the above circuit by eliminating the independent sources present in it.
- Step 4 − Draw the Thevenin's equivalent circuit by connecting a Thevenin's voltage V_{Th} in series with a Thevenin's resistance R_{Th}.

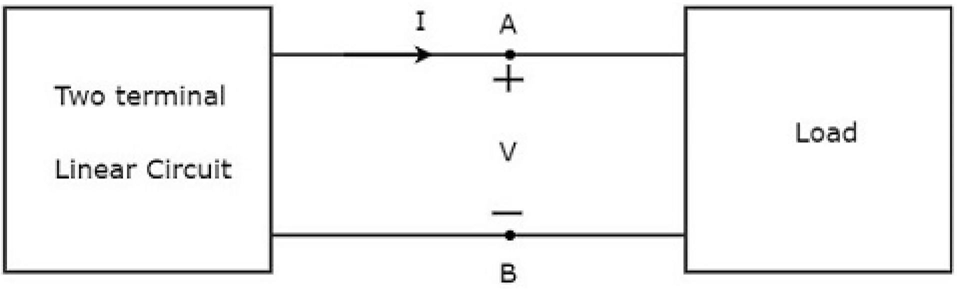
Norton's theorem

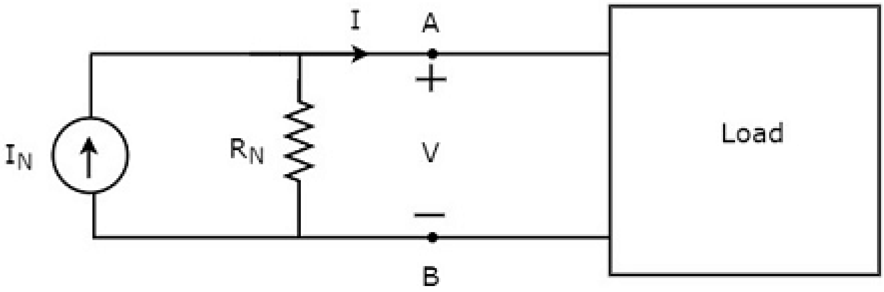
Norton's theorem is similar to Thevenin's theorem. It states that any two terminal linear network or circuit can be represented with an equivalent network or circuit, which consists of a current source in parallel with a resistor. It is known as Norton's equivalent circuit. A linear circuit may contain independent sources, dependent sources and resistors.

If a circuit has multiple independent sources, dependent sources, and resistors, then the response in an element can be easily found by replacing the entire network to the left of that element with a Norton's equivalent circuit.

The response in an element can be the voltage across that element, current flowing through that element or power dissipated across that element.

This concept is illustrated in following figures.





Norton's equivalent circuit resembles a practical current source. Hence, it is having a current source in parallel with a resistor.

- The current source present in the Norton's equivalent circuit is called as Norton's equivalent current or simply Norton's current I_N.
- The resistor present in the Norton's equivalent circuit is called as Norton's equivalent resistor or simply Norton's resistor R_N.

Methods of Finding Norton's Equivalent Circuit

There are three methods for finding a Norton's equivalent circuit. Based on the type of sources that are present in the network, we can choose one of these three methods. Now, let us discuss these three methods one by one.

Method 1

Follow these steps in order to find the Norton's equivalent circuit, when only the sources of independent type are present.

- Step 1 − Consider the circuit diagram by opening the terminals with respect to which, the Norton's equivalent circuit is to be found.
- Step 2 − Find the Norton's current I_N by shorting the two opened terminals of the above circuit.
- Step 3 − Find the Norton's resistance R_N across the open terminals of the circuit considered in Step1 by eliminating the independent sources present in it. Norton's resistance R_N will be same as that of Thevenin's resistance R_{Th}.

- Step 4 − Draw the Norton's equivalent circuit by connecting a Norton's current IN in parallel with Norton's resistance R_N.

Now, we can find the response in an element that lies to the right side of Norton's equivalent circuit.

Method 2

Follow these steps in order to find the Norton's equivalent circuit, when the sources of both independent type and dependent type are present.

- Step 1 − Consider the circuit diagram by opening the terminals with respect to which the Norton's equivalent circuit is to be found.
- Step 2 − Find the open circuit voltage V_{OC} across the open terminals of the above circuit.
- Step 3 − Find the Norton's current I_N by shorting the two opened terminals of the above circuit.
- Step 4 − Find Norton's resistance R_N by using the following formula.

$$RN=VOC / IN$$

- Step 5 − Draw the Norton's equivalent circuit by connecting a Norton's current I_N in parallel with Norton's resistance R_N.

Now, we can find the response in an element that lies to the right side of Norton's equivalent circuit.

Method 3

This is an alternate method for finding a Norton's equivalent circuit.

- Step 1 − Find a Thevenin's equivalent circuit between the desired two terminals. We know that it consists of a Thevenin's voltage source, V_{Th} and Thevenin's resistor, R_{Th}.
- Step 2 − Apply source transformation technique to the above Thevenin's equivalent circuit. We will get the Norton's equivalent circuit. Here,

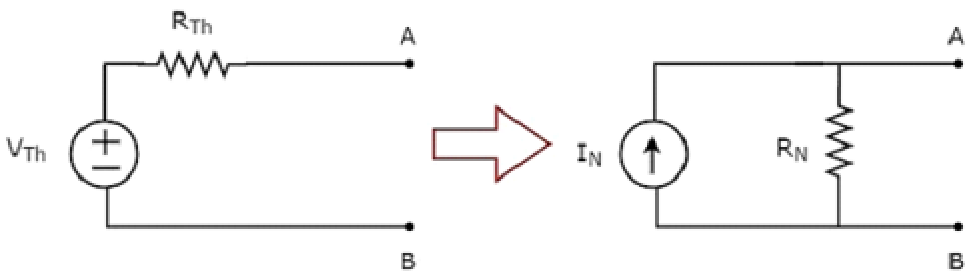
Norton's current,

$$IN=VTh / RTh$$

Norton's resistance,

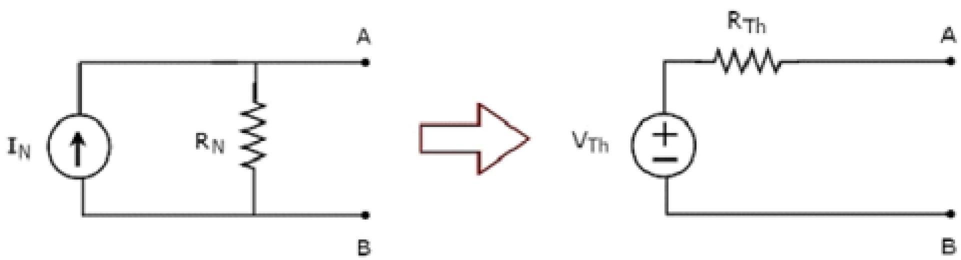
$$RN=RTh$$

This concept is illustrated in the following figure.



Now, we can find the response in an element by placing Norton's equivalent circuit to the left of that element.

Note – Similarly, we can find the Thevenin's equivalent circuit by finding a Norton's equivalent circuit first and then apply source transformation technique to it. This concept is illustrated in the following figure



This is the Method 3 for finding a Thevenin's equivalent circuit.

Time domain analysis of first order RL and RC circuit

If the output of an electric circuit for an input varies with respect to time, then it is called as **time response**. The time response consists of following two parts.

- Transient Response
- Steady state Response

In this chapter, first let us discuss about these two responses and then observe these two responses in a series RL circuit, when it is excited by a DC voltage source.

Transient Response

After applying an input to an electric circuit, the output takes certain time to reach steady state. So, the output will be in transient state till it goes to a steady state. Therefore, the response of the electric circuit during the transient state is known as transient response.

The transient response will be zero for large values of 't'. Ideally, this value of 't' should be infinity. But, practically five time constants are sufficient.

Presence or Absence of Transients

Transients occur in the response due to sudden change in the sources that are applied to the electric circuit and / or due to switching action. There are two possible switching actions. Those are opening switch and closing switch.

- The transient part will not present in the response of an electrical circuit or network, if it contains only resistances. Because resistor is having the ability to adjust any amount of voltage and current.
- The transient part occurs in the response of an electrical circuit or network due to the presence of energy storing elements such as inductor and capacitor. Because they can't change the energy stored in those elements instantly.

Inductor Behavior

Assume the switching action takes place at *t* = 0. Inductor current does not change instantaneously, when the switching action takes place. That means, the value of inductor current just after the switching action will be same as that of just before the switching action.

Mathematically, it can be represented as

$$i_L(0^+)= i_L(0^-)$$

Capacitor Behavior

The capacitor voltage does not change instantaneously similar to the inductor current, when the switching action takes place. That means, the value of capacitor voltage just after the switching action will be same as that of just before the switching action.

Mathematically, it can be represented as

$$V_c(0^+)= V_c(0^-)$$

Steady state Response

The part of the time response that remains even after the transient response has become zero value for large values of 't' is known as steady state response. This means, there won't be any transient part in the response during steady state.

Inductor Behaviour

If the independent source is connected to the electric circuit or network having one or more inductors and resistors (optional) for a long time, then that electric circuit or network is said to be in steady state. Therefore, the energy stored in the inductor(s) of that electric circuit is of maximum and constant.

Mathematically, it can be represented by

$$W_L= (Li^2) / 2$$

Therefore, inductor acts as a **constant current source** in steady state.

The voltage across inductor will be

$$VL=LdiL/dt=0V$$

So, the inductor acts as a **short circuit** in steady state.

Capacitor Behavior

If the independent source is connected to the electric circuit or network having one or more capacitors and resistors (optional) for a long time, then that electric circuit or network is said to be in steady state. Therefore, the energy stored in the capacitor(s) of that electric circuit is of maximum and constant.

Mathematically, it can be represented as

$$W_c = Cv^2 / 2$$

Therefore, capacitor acts as a **constant voltage source** in steady state.

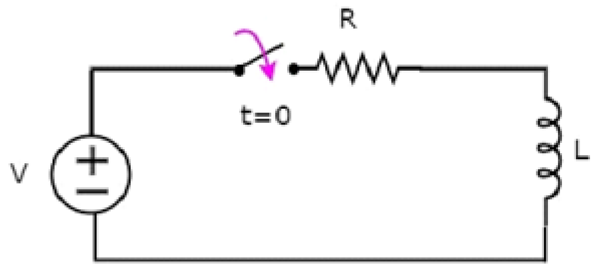
The current flowing through the capacitor will be

$$I_c = 0 \text{ A}$$

So, the capacitor acts as an **open circuit** in steady state.

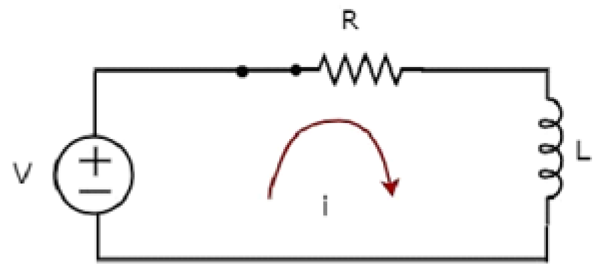
Finding the Response of Series RL Circuit

Consider the following series RL circuit diagram.



In the above circuit, the switch was kept open up to t = 0 and it was closed at t = 0. So, the DC voltage source having V volts is not connected to the series RL circuit up to this instant. Therefore, there are no initial current flows through inductor.

The circuit diagram, when the switch is in closed position is shown in the following figure.



Now, the current ***i*** flows in the entire circuit, since the DC voltage source having ***V*** volts is connected to the series RL circuit.

Now, apply **KVL** around the loop.

$$V = Ri + L\,di/dt$$

$$di/dt + (R/L)i = V/L$$

$i = (V/R) + k\, e^{-(R/L)t}$

We know that there is no initial current in the circuit. Hence, substitute, *t* = 0 and *i* = 0 in Equation

$K = -(V/R)$

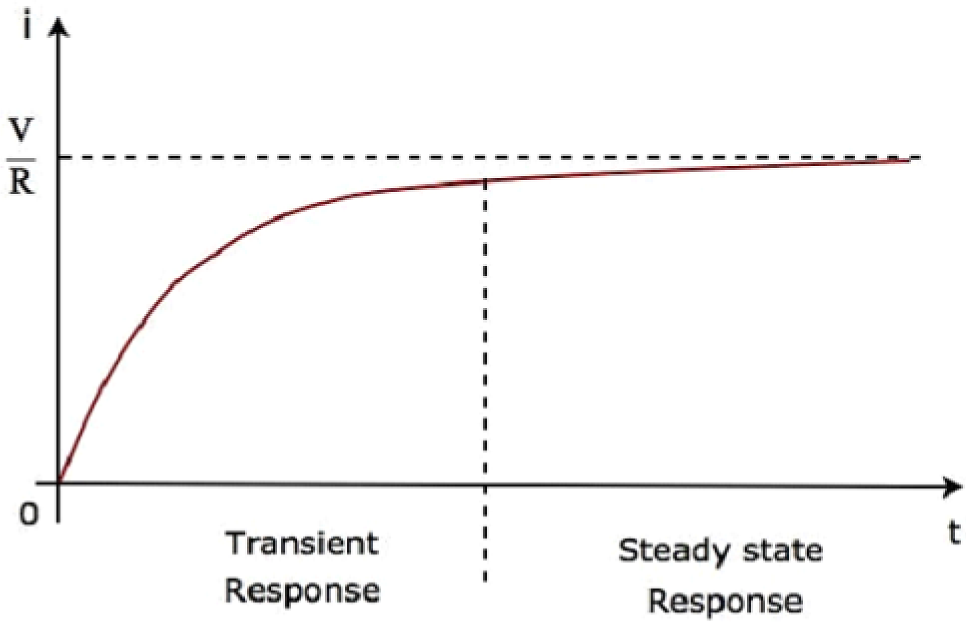
Substitute, the value of k in Equation

$i = (V/R) + (-V/R)e^{-(R/L)t}$

$i = (-V/R)e^{-(R/L)t} + (V/R)$

So, the response of the series RL circuit, when it is excited by a DC voltage source, has the following two terms.

- The first term $(-V/R)e^{-(R/L)}$ corresponds with the **transient response**.
- The second term (V/R) corresponds with the **steady state response**. These two responses are shown in the following figure.



Module 2

AC Circuits

Representation of sinusoidal waveform

AC Waveform Characteristics

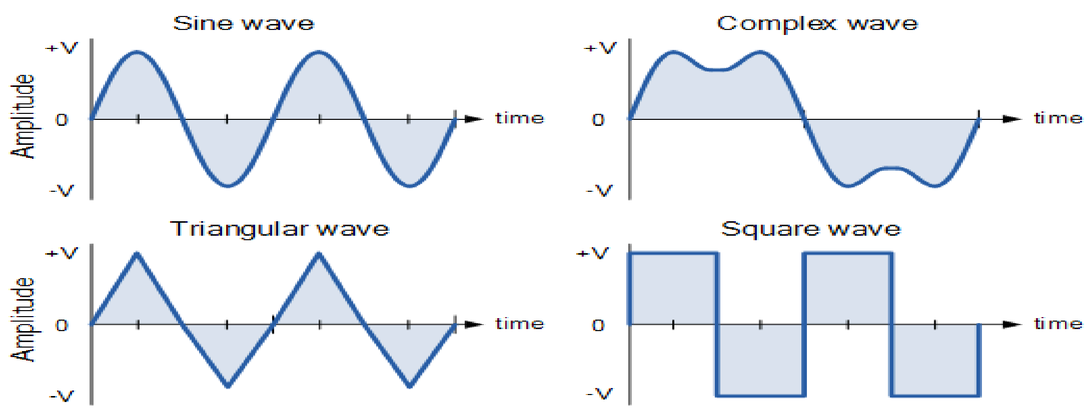
- The Period, (T) is the length of time in seconds that the waveform takes to repeat itself from start to finish. This can also be called the *Periodic Time* of the waveform for sine waves, or the *Pulse Width* for square waves.
- The Frequency, (ƒ) is the number of times the waveform repeats itself within a one second time period. Frequency is the reciprocal of the time period, ($ƒ = 1/T$) with the unit of frequency being the *Hertz*, (Hz).
- The Amplitude (A) is the magnitude or intensity of the signal waveform measured in volts or amps.

Waveforms are basically a visual representation of the variation of a voltage or current plotted to a base of time". Generally, for AC waveforms this horizontal base line represents a zero condition of either voltage or current. Any part of an AC type waveform which lies above the horizontal zero axis represents a voltage or current flowing in one direction.

Likewise, any part of the waveform which lies below the horizontal zero axis represents a voltage or current flowing in the opposite direction to the first. Generally for sinusoidal AC waveforms the shape of the waveform above the zero axis is the same as the shape below it. However, for most non-power AC signals including audio waveforms this is not always the case?

The most common periodic signal waveforms that are used in Electrical and Electronic Engineering are the *Sinusoidal Waveforms*. However, an alternating AC waveform may not always take the shape of a smooth shape based around the trigonometric sine or cosine function. AC waveforms can also take the shape of Complex *Waves*, *Square Waves* or *Triangular Waves* and these are shown below.

Types of Periodic Waveform



The time taken for an AC Waveform to complete one full pattern from its positive half to its negative half and back to its zero baseline again is called a Cycle and one complete cycle contains both a positive half-cycle and a negative half-cycle. The time taken by the waveform to complete one full cycle is called the Periodic Time of the waveform, and is given the symbol "T".

The number of complete cycles that are produced within one second (cycles/second) is called the Frequency, symbol ƒ of the alternating waveform. Frequency is measured in Hertz, (Hz) named after the German physicist Heinrich Hertz.

Then we can see that a relationship exists between cycles (oscillations), periodic time and frequency (cycles per second), so if there is ƒ number of cycles in one second, each individual cycle must take 1/ƒ seconds to complete.

Relationship between Frequency and Periodic Time

$$f = 1/T$$

& $$T = 1/f$$

Amplitude of an AC Waveform

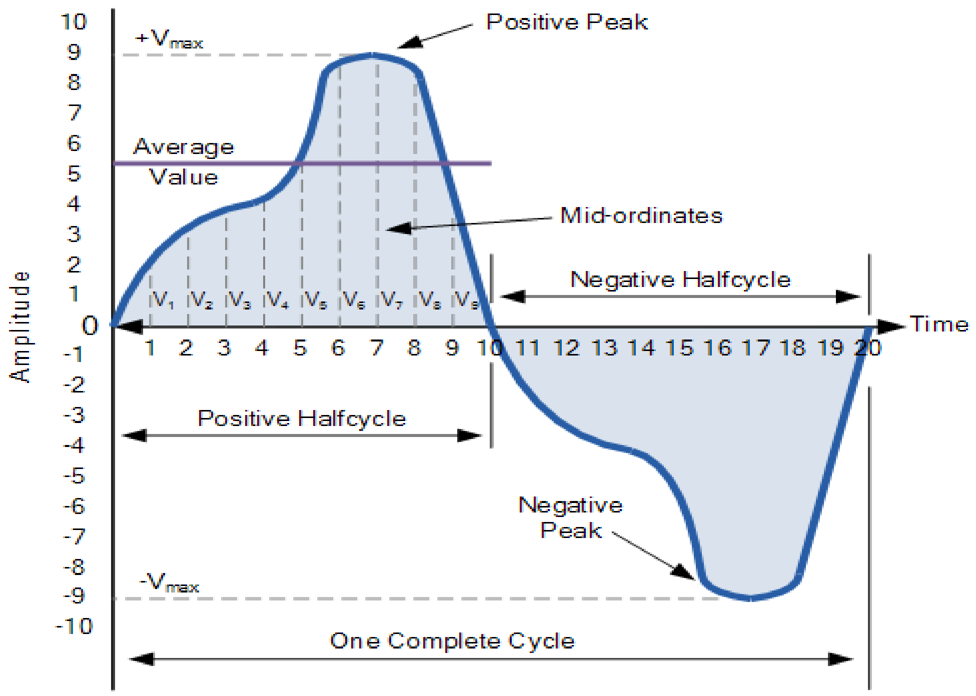
As well as knowing either the periodic time or the frequency of the alternating quantity, another important parameter of the AC waveform is Amplitude, better known as its Maximum or Peak value represented by the terms, V*max* for voltage or I*max* for current.

The peak value is the greatest value of either voltage or current that the waveform reaches during each half cycle measured from the zero baseline. Unlike a DC voltage or current which has a steady state that can be measured or calculated using ohm´s law, an alternating quantity is constantly changing its value over time

For pure sinusoidal waveforms this peak value will always be the same for both half cycles ($+V_m = -V_m$) but for non-sinusoidal or complex waveforms the maximum peak value can be very different for each half cycle. Sometimes, alternating waveforms are given a *peak-to-peak*, V*p-p* value and this is simply the distance or the sum in voltage between the maximum peak value, +V*max* and the minimum peak value, -V*max* during one complete cycle.

The Average Value of an AC Waveform

The average or mean value of a continuous DC voltage will always be equal to its maximum peak value as a DC voltage is constant. This average value will only change if the duty cycle of the DC voltage changes. In a pure sine wave if the average value is calculated over the full cycle, the average value would be equal to zero as the positive and negative halves will cancel each other out. So the average or mean value of an AC waveform is calculated or measured over a half cycle only and this is shown below.



To find the average value of the waveform we need to calculate the area underneath the waveform using the mid-ordinate rule, trapezoidal rule or the Simpson's rule found commonly in mathematics. The approximate area under any irregular waveform can easily be found by simply using the mid-ordinate rule.

The zero axis base line is divided up into any number of equal parts and in our simple example above this value was nine, (V_1 to V_9). The more ordinate lines that are drawn the more accurate will be the final average or mean value. The average value will be the addition of all the instantaneous values added together and then divided by the total number. This is given as.

Average Value of an AC Waveform

$V_{AVERAGE} = (V_1+V_2+V_3+ \ldots\ldots +V_n) \ / \ n$

Where: n equals the actual number of mid-ordinates used.

For a pure sinusoidal waveform this average or mean value will always be equal to $0.637*V_{max}$ and this relationship also holds true for average values of current.

The RMS Value of an AC Waveform

The average value of an AC waveform that we calculated above as being: $0.637*V_{max}$ is NOT the same value we would use for a DC supply. This is because unlike a DC supply which is constant and and of a fixed value, an AC waveform is constantly changing over time and has no fixed value. Thus the equivalent value for an alternating current system that provides the same amount of electrical power to a load as a DC equivalent circuit is called the "effective value".

The effective value of a sine wave produces the same I^2*R heating effect in a load as we would expect to see if the same load was fed by a constant DC supply. The effective value of a sine wave is more commonly known as the Root Mean Squared or simply RMS value as it is calculated as the square root of the mean (average) of the square of the voltage or current.

That is V_{rms} or I_{rms} is given as the square root of the average of the sum of all the squared mid-ordinate values of the sine wave. The RMS value for any AC waveform can be found from the following modified average value formula as shown.

RMS Value of an AC Waveform

$V_{RMS} = \left((V_1^2+V_2^2+V_3^2+ ..... +V_n^2) \ / \ n \right)^{0.5}$

Where: n equals the number of mid-ordinates.

For a pure sinusoidal waveform this effective or R.M.S. value will always be equal too: $1/\sqrt{2}*V_{max}$ which is equal to $0.707*V_{max}$ and this relationship holds true for RMS values of current. The RMS value for a sinusoidal waveform is always greater than the average value except for a rectangular waveform. In this case the heating effect remains constant so the average and the RMS values will be the same.

One final comment about R.M.S. values. Most multimeters, either digital or analogue unless otherwise stated only measure the R.M.S. values of voltage and current and not the average. Therefore when using a multimeter on a direct current system the reading will be equal to I = V/R and for an alternating current system the reading will be equal to Irms = Vrms/R.

Also, except for average power calculations, when calculating RMS or peak voltages, only use V_{RMS} to find I_{RMS} values, or peak voltage, Vp to find peak current, Ip values. Do not mix them together as Average, RMS or Peak values of a sine wave are completely different and your results will definitely be incorrect.

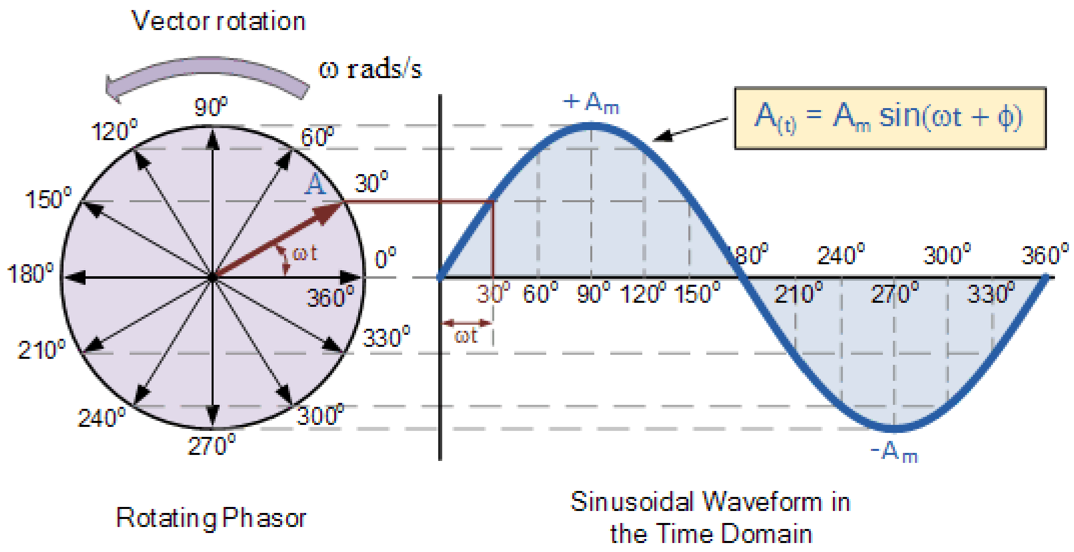
Form Factor and Crest Factor

Although little used these days, both Form Factor and Crest Factor can be used to give information about the actual shape of the AC waveform. Form Factor is the ratio between the average value and the RMS value and is given as.

FORM FACTOR =RMS VALUE / AVERAGE VALUE

CREST FACTOR= PEAK VALUE / RMS VALUE

Phasor Representation



Definition of Active Power

The power which is dissipated or does the useful work in the circuit is known as the active power. It is measured in watts or megawatts. The active power is denoted by the capital alphabet P. The average value of power in the circuit is given by the expression

P=VICOSϕ

The active power derives the circuit and load.

Definition of Reactive Power

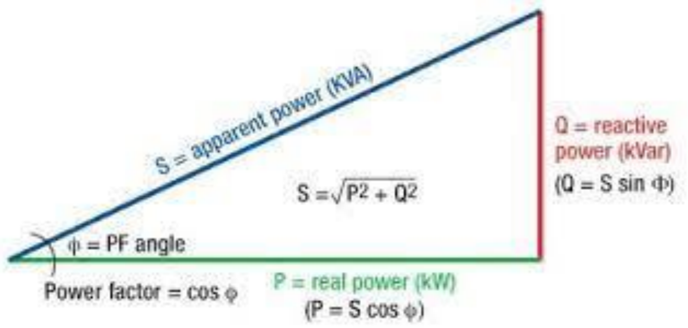
The reactive power moves between the source and load of the circuit. This power is not doing any useful works on the load. Q represents the reactive power, and it is measured in VAR. The reactive power is stored in the circuit, and it is discharged by the induction motor, transformer or by solenoids.

P=VISINϕ

Key Differences between Active and Reactive Power

1. The active power is the real power consumes by the load. Whereas, the reactive power is the useless power.

2. The active power is the product of the voltage, current and the cosine of the angle between them. Whereas, the reactive power is the product of voltage and current and the sine of the angle between them.
3. The active power is the real power, and it is measured in watts. While the reactive power is measured in VAR.
4. The letter P represents the Active power, and the Q represents the reactive power.
5. The torque that develops in the motor, the heat dissipated in the heater and the light that emit through the lamps all these produces because of the active power. The reactive power determines the power factor of the circuit.
6. The wattmeter measures the active power, and the VAR meter is used for measuring the apparent power.



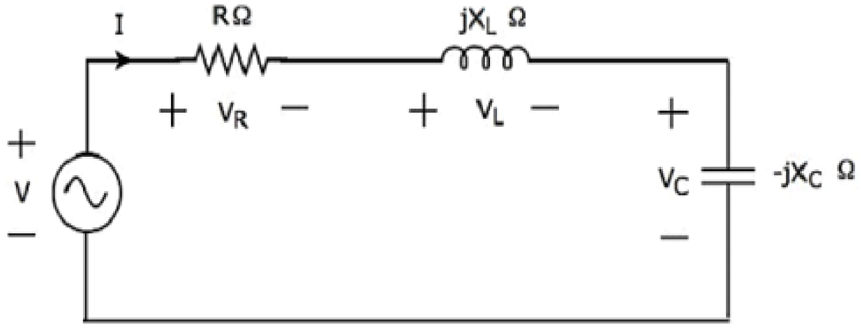
Resonance

Resonance occurs in electric circuits due to the presence of energy storing elements like inductor and capacitor. It is the fundamental concept based on which, the radio and TV receivers are designed in such a way that they should be able to select only the desired station frequency.

There are two types of resonances, namely series resonance and parallel resonance. These are classified based on the network elements that are connected in series or parallel. In this chapter, let us discuss about series resonance.

Series Resonance Circuit Diagram

If the resonance occurs in series RLC circuit, then it is called as Series Resonance. Consider the following series RLC circuit, which is represented in phasor domain.



Here, the passive elements such as resistor, inductor and capacitor are connected in series. This entire combination is in series with the input sinusoidal voltage source.

Apply KVL around the loop.

$$V-V_R-V_L-V_C=0$$

$$V-IR-I(jX_L)-I(-jX_C)=0$$

$$V=I(R+jX_L-jX_C)$$

So

$$Z=R+j(X_L-X_C)$$

Parameters & Electrical Quantities at Resonance

Now, let us derive the values of parameters and electrical quantities at resonance of series RLC circuit one by one.

Resonant Frequency

The frequency at which resonance occurs is called as resonant frequency f_r. In series RLC circuit resonance occurs, when the imaginary term of impedance Z is zero, i.e., the value of XL−XC should be equal to zero.

$$\Rightarrow XL=XC$$

Substitute XL=2πfL and XC=1 / 2πfC in the above equation.

$$2\pi fL=1/2\pi fC$$

Therefore, the resonant frequency f_r of series RLC circuit is

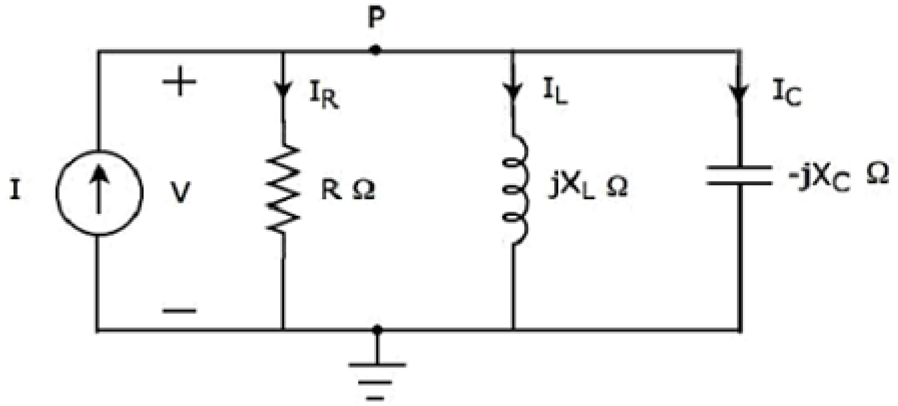
$$fr=1/(2\pi)(LC)^{0.5}$$

Where, L is the inductance of an inductor and C is the capacitance of a capacitor.

The resonant frequency f_r of series RLC circuit depends only on the inductance L and capacitance C. But, it is independent of resistance R.

Parallel Resonance Circuit Diagram

If the resonance occurs in parallel RLC circuit, then it is called as Parallel Resonance. Consider the following parallel RLC circuit, which is represented in phasor domain.



Here, the passive elements such as resistor, inductor and capacitor are connected in parallel. This entire combination is in parallel with the input sinusoidal current source.

Write nodal equation at node P.

$$I=I_R+I_L+I_C$$

$$I = V/ R + V/(jX_L)+ V/(-jX_C)$$

$$I =V[1/R +1/(jX_L-1/(jX_C)]$$

Therefore, the admittance Y of parallel RLC circuit will be

$$Y=[1/R +1/(jX_L-1/(jX_C)]$$

Resonant Frequency

We know that the resonant frequency, f_r is the frequency at which, resonance occurs. In parallel RLC circuit resonance occurs, when the imaginary term of admittance, Y is zero. i.e., the value of XC−XL should be equal to zero

$$\Rightarrow XC=XL$$

The above resonance condition is same as that of series RLC circuit. So, the resonant frequency, f_r will be same in both series RLC circuit and parallel RLC circuit.

Therefore, the resonant frequency, f_r of parallel RLC circuit is

$$Fr =1/2\pi(LC)^{0.5}$$

Where,

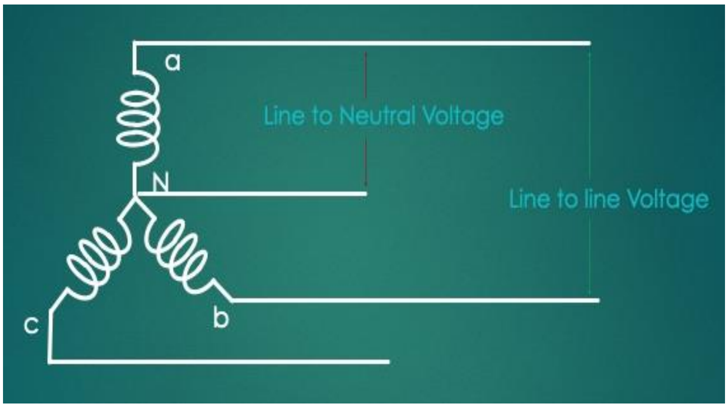
- L is the inductance of an inductor.
- C is the capacitance of a capacitor.

The resonant frequency, f_r of parallel RLC circuit depends only on the inductance ***L*** and capacitance ***C***. But, it is independent of resistance ***R***.

Voltage & current in Start connection

Now, when we talk about star connected three phase system, we must know about these two concepts.

1. Line to line voltage
2. Line to neutral voltage.



the voltage between A and N is called as line to neutral voltage. Similarly, voltage between A and B is called as line to line voltage. Relation between these voltages as well as current changes with the type of connection. So, it is important to understand these relationships for different connections.

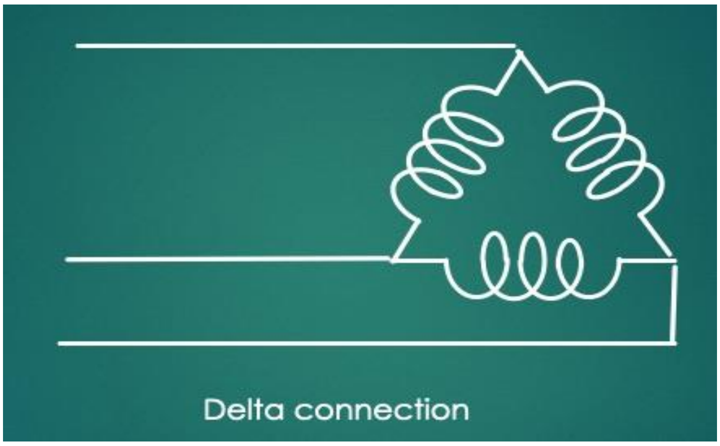
Current is Star connected system

In case of star connection, line to neutral current is equal to line to line current.

Voltage in Star connected system

But in case of voltage, it is different. Consider the above star connected 3 phase 4 wire system. If you apply the Kirchhoff's voltage law to the above circuit, you'll find that, line to line voltage is root 3 times the line to neutral voltage.

Voltage & current in Delta connection



One of the other way to connect three phase system is called as delta connection. The connection is so named because it resembles the greek letter delta .

Voltage & current in Delta connection

Let have a look at the voltage and currents relationship in delta connection.

Voltage in Delta connection

Now in case of delta connection, voltage across each connection is same as line voltage.

Current in Delta connection

But, in case of current, current across each element is different than the line current. If you apply the Kirchhoff's law and do some math, you'll find that the line current is root 3 times greater than the current in each branch of delta connected system.

Application of star & delta connection

Generally, star connection is used where you need a neutral and two separate voltages, like our distribution system.
Delta connection is generally preferred where neutral conductor is not needed like for transmission of high voltage power. Also, delta connection is preferred where 3rd harmonics needs to controlled.

Star and delta connections are almost used everywhere when we talk about 3 phase system.

You'll generally find 3 phase transformer connected in different combinations of star and delta connection. For example,

- Star – star connected transformer is generally used as an auto transformer.
- Delta – delta connected transformer is generally used for high voltage transmission.
- Delta – star connected transformer is generally used as a distribution transformer.

Module 3
Transformers

Magnetic materials

The term *magnet* is typically reserved for objects that produce their own persistent magnetic field even in the absence of an applied magnetic field. Only certain classes of materials can do this. Most materials, however, produce a magnetic field in response to an applied magnetic field – a phenomenon known as magnetism. There are several types of magnetism, and all materials exhibit at least one of them.

The overall magnetic behaviour of a material can vary widely, depending on the structure of the material, particularly on its electron configuration. Several forms of magnetic behavior have been observed in different materials, including:

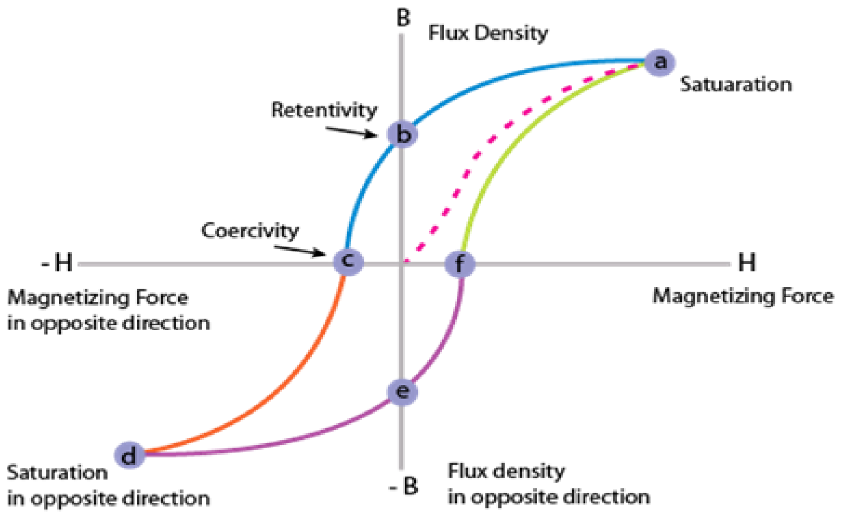
- Ferromagnetic and ferrimagnetic materials are the ones normally thought of as magnetic; they are attracted to a magnet strongly enough that the attraction can be felt. These materials are the only ones that can retain magnetization and become magnets; a common example is a traditional refrigerator magnet. Ferrimagnetic materials, which include ferrites and the oldest magnetic materials magnetite and lodestone, are similar to but weaker than ferromagnetics. The difference between ferro- and ferrimagnetic materials is related to their microscopic structure, as explained in Magnetism.
- Paramagnetic substances, such as platinum, aluminum, and oxygen, are weakly attracted to either pole of a magnet. This attraction is hundreds of thousands of times weaker than that of ferromagnetic materials, so it can only be detected by using sensitive instruments or using extremely strong magnets. Magnetic ferrofluids, although they are made of tiny ferromagnetic particles suspended in liquid, are sometimes considered paramagnetic since they cannot be magnetized.
- Diamagnetic means repelled by both poles. Compared to paramagnetic and ferromagnetic substances, diamagnetic substances, such as carbon, copper, water, and plastic, are even more weakly repelled by a magnet. The permeability of diamagnetic materials is less than the permeability of a vacuum. All substances not

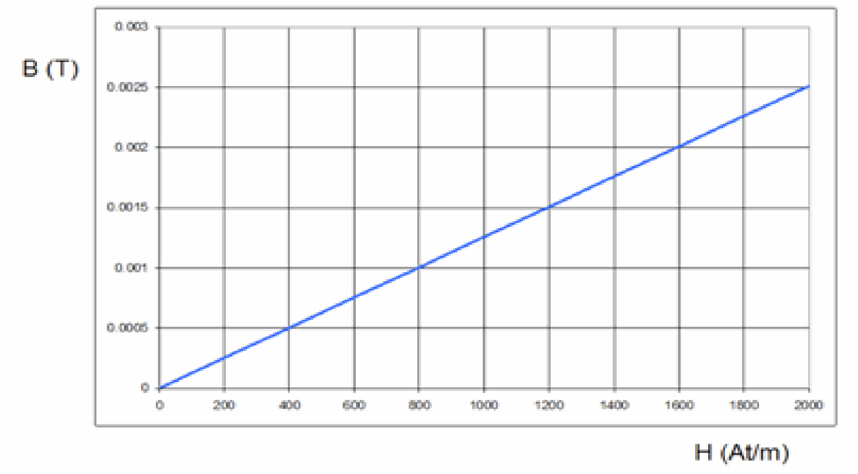
possessing one of the other types of magnetism are diamagnetic; this includes most substances. Although force on a diamagnetic object from an ordinary magnet is far too weak to be felt, using extremely strong superconducting magnets, diamagnetic objects such as pieces of lead and even mice[19] can be levitated, so they float in mid-air. Superconductors repel magnetic fields from their interior and are strongly diamagnetic.

There are various other types of magnetism, such as spin glass, super paramagnetism, super diamagnetism, and metamagnetism.

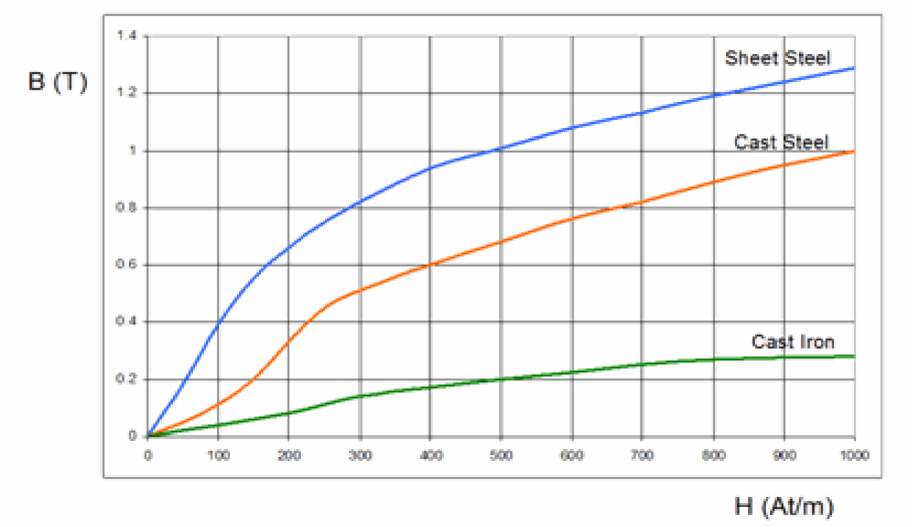
B-H curve

The B-H curve is the curve characteristic of the magnetic properties of a material or element or alloy. It tells you how the material responds to an external magnetic field, and is a critical piece of information when designing magnetic circuits. In the plots below, for a vacuum an H of 800 At/m creates a B of 1 mT. With a sheet steel core, an H of 800 At/m creates a B of 1.2 T. A huge increase in B for the same H! The hysteresis comes into play when the material has been magnetized. The B within the material does not go back to what it was before, but is dependent on the history of its magnetization.





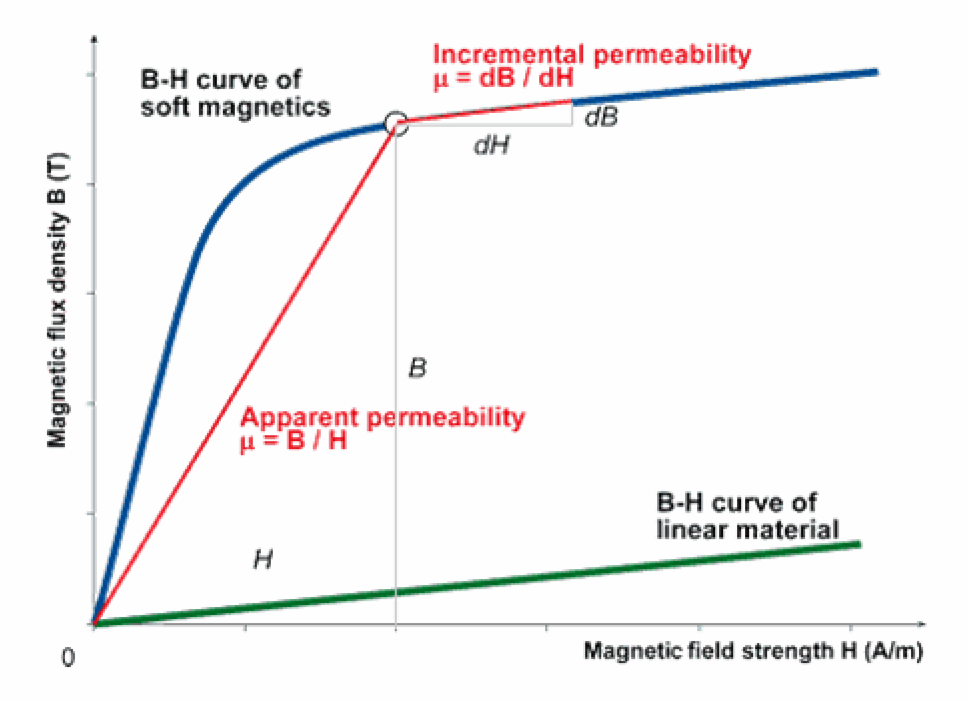
B-H for Vacuum



B-H for various materials

The slope of the curve - [Permeability]

The slope of the B-H curve at some location on its curve is its incremental permeability at that location. However, sometimes the permeability is measured from the origin to the location of interest, and that slope is called its apparent permeability, μ.



For non-magnetic materials that do not saturate, the curve has a fixed slope approximately equal to μ_0

i. Diamagnetic materials have a slightly smaller slope

ii. Paramagnetic materials have a slightly greater slope

Ideal & Practical transformer

Idea transformer is nothing but a transformer which has 100% efficiency. In this transformer there are two purely inductive coils. So this is no iron loss, no copper loss, as well as there is no I^2R losses. Also this is no ohmic resistance drop and no leakage drop. Hence this is concept of ideal transformer.

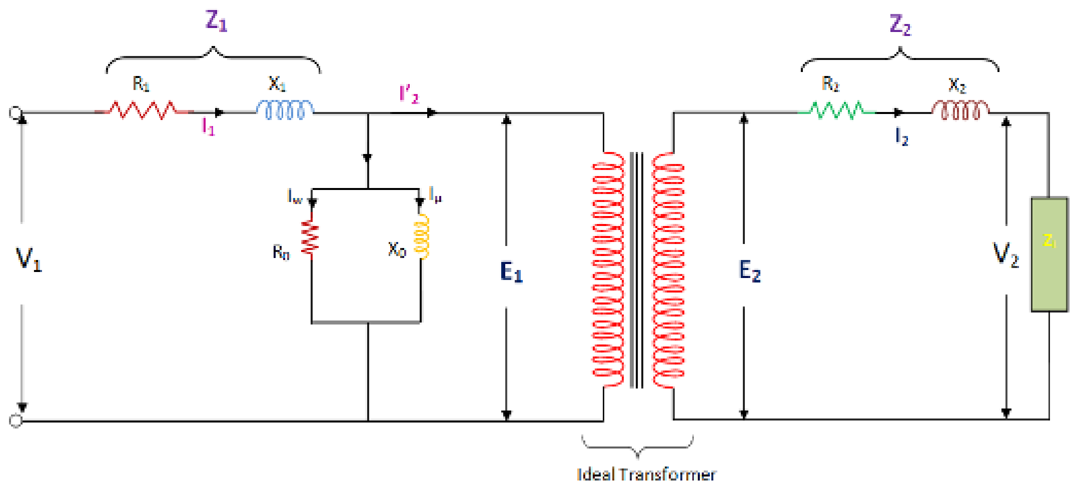
Ideal Transformer	Practical Transformer
It has 100% efficiency.	It has 100% below efficiency.
It has no losses.	It has no losses.
Purely inductive material is used.	It is two purely inductive material used.
It has no I^2R losses.	It has I^2R losses.
It has no iron loss.	It has iron loss.
There is no ohmic resistance drop.	There is ohmic resistance drop.

It has no leakage drop.	It has leakage drop.
In it ideal condition.	In it practical condition.
It is not used in practical condition.	It is used in practical condition.

Equivalent circuit diagram of transformer

Equivalent circuit diagram of a transformer is basically a diagram which can be resolved into an equivalent circuit in which the resistance and leakage reactance of the transformer are imagined to be external to the winding.

The equivalent circuit diagram of transformer is given below:-



Equivalent Circuit diagram of Transformer

Where,
R_1 = Primary Winding Resistance.
R_2= Secondary winding Resistance.
I_0= No-load current.
I_μ = Magnetizing Component,
I_w = Working Component,
This I_μ & I_w are connected in parallel across the primary circuit. The value of E_1 (Primary e.m.f) is obtained by subtracting vectorially I_1 Z_1 from V_1 . The value of $X_0 = E_1 / I_0$ and $R_0 = E_1 / I_w$. We know that the relation of E_1 and E_2 is $E_2 / E_1 = N_2 / N_1 = K$, (transformation Ratio)

From the equivalent circuit, we can easily calculate the total impedance of to transfer voltage, current, and impedance either to the primary or the secondary.

Losses in transformers

Since the transformer is a static machine it doesn't contain any moving or rotating parts as compared to an induction motor. So there are no friction and windage losses due to bearings and due to air resistance. Hence, the various types of losses of a transformer occurring in the windings and core material are,

- Iron or core losses
  - Hysteresis loss
  - Eddy current loss
- Copper or Winding Loss
- Stray loss
- Dielectric loss

Iron or Core Losses :

The losses in the magnetic core which links both the windings by magnetic induction are called iron or core losses of the transformer. The iron practically remains constant under all load conditions i.e., they are independent or irrespective of the load condition. Hence, the iron losses are also called constant losses, and they are composed of two losses. They are,

- Hysteresis loss
- Eddy current loss

Hysteresis Loss :

Since the supply given to the transformer is alternating, the nature of the magnetic flux in the core will be also in alternating nature. Due to this, the randomly oriented magnetic domains which behave like a small magnet will be oriented in the direction of mmf applied. As the nature of magnetic flux applied is alternating the core material undergoes a cycle of magnetization and demagnetization effect.

Due to this, the one directionally oriented domains will take the reverse direction for every cycle. So that there will be extra energy consumed in the form of power loss known as 'Hysteresis Loss'. The expression for hysteresis loss is given by,

$$W_h = K_h \, B_m^{1.6} \, f \, V \quad watt$$

Where,

- K_h = Hysteresis constant depends upon the type of core material used
- B_m = Maximum flux density
- f = Supply frequency
- V = Volume of the core material

Eddy Current Loss :

The core of the transformer is made up of conducting material. The laminated sheets which form the core limb will induce their own emf in each sheet when subjected to alternating flux. This results in the circulation of currents in each sheet and causes power loss known as 'Eddy Current Loss'. It is given by,

$$W_e = K_e B_m^2 f^2 V^2 \quad watt$$

Where,

- K_e = Hysteresis constant depends upon the type of core material used
- B_m = Maximum flux density
- f = Supply frequency
- t = Lamination thickness

Since the frequency and flux density of the core material remains constant these losses also called 'Constant losses'. Therefore, the total iron or core or constant loss is the sum of both hysteresis and eddy current losses.

Minimization of Iron Losses:

- The hysteresis losses of the transformer cannot be eliminated completely but can be reduced by choosing a low hysteresis coefficient material like silicon steel.
- The eddy current losses can be reduced by making very thin laminations of silicon steel.

Copper Loss or Winding Loss:

We know that every material posses some resistance even it can be of conducting type. This resistance causes power loss (I^2 R) in the conducting material used for the windings of the transformer. The conducting material used for winding is mostly of copper, hence it is called 'Copper Loss'.

Stray Loss:

The transformer works on the principle of mutual induction i.e., emf induced in the secondary winding is by linkage of flux produced by the primary winding. But, in practice, all the flux produced by the primary winding does not link with secondary winding completely. There will wastage of flux which does not link with secondary winding as the leakage. This leakage flux will cause some losses in the transformer known as 'Stray Loss'.

Dielectric Loss:

As the name suggests these losses depend upon the dielectric strength of the insulating medium used in the transformer (generally oil). Due to the continuous operation of the transformer, the dielectric material used losses its dielectric strength and causes some losses which reduce the overall efficiency of the transformer. These losses can be minimized by periodic testing of the insulating material used.

Regulation & efficiency of a transformer

Transformer Voltage Regulation

Voltage Regulation of single-phase transformers is the percentage (or per unit value) change in its secondary terminal voltage compared to its original no-load voltage under varying secondary load conditions. In other words, regulation determines the variation in secondary terminal voltage which occurs inside the transformer as a result of variations in the transformers connected load thereby affecting its performance and efficiency if these losses are high and the secondary voltage becomes too low.

When there is no-load connected to the transformers secondary winding, that is its output terminals are open-circuited, there is no closed-loop condition, so there is no output load current ($I_L = 0$) and the transformer acts as one single winding of high self-inductance. Note that the no-load secondary voltage is a result of the fixed primary voltage and the turns ratio of the transformer.

Loading the secondary winding with a simple load impedance causes a secondary current to flow, at any power factor, through the internal winding of the transformer. Thus voltage drops due to the windings internal resistance and its leakage reactance causes the output terminal voltage to change.

A transformers voltage regulation change between its secondary terminal voltage from a no-load condition when $I_L = 0$, (open circuit) to a fully-loaded condition when $I_L = I_{MAX}$ (maximum current) for a constant primary voltage is given as:

$$\text{Regulation} = \frac{\text{Change in Output Voltage}}{\text{No-load Output Voltage}}$$

$$\therefore \text{Regulation} = \frac{V_{(\text{no-load})} - V_{(\text{full-load})}}{V_{(\text{no-load})}}$$

Transformer efficiency (η) can be explained as the ratio of the output power to the input power.

$$\eta \triangleq \frac{\text{output power}}{\text{input power}}$$

$$= \frac{\text{output power}}{\text{output power} + \text{copper loss} + \text{iron loss}} \text{ pu}$$

Therefore the per unit efficiency at load current I_2 and power factor cos Φ_2 will be

$$\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + I_2^2 . R_{e_2} + P_i} \text{ pu}$$

And the per unit efficiency at full load is

$$\eta_{fl} = \frac{V_2 I_{2fl} \cos\phi_2}{V_2 I_{2fl} \cos\phi_2 + I_{2fl}^2 . R_{e_2} + P_i}$$

If $S_{2fl} = (VA)_{2fl} = V_2 I_{2fl}$ = full- load VA = rated VA

Then

$$\eta_{fl} = \frac{S_2 \cos\phi_2}{S_2 \cos\phi_2 + P_{cfl} R_{e_2} + P_i}$$

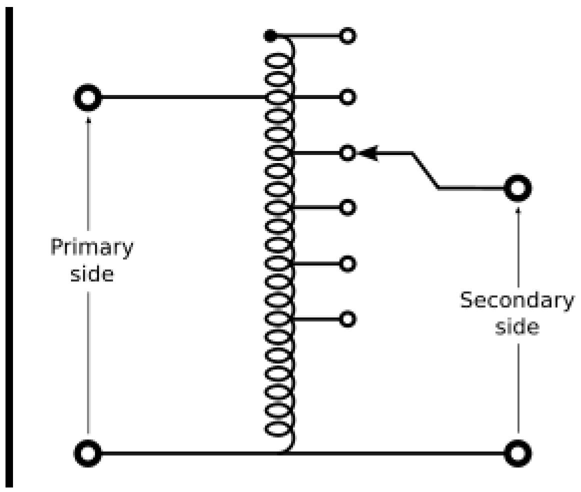
we know that in a transformer there is no rotational part so there are no rotational losses such as windings and frictional losses in a rotating machine. Therefore, we can obtain a maximum efficiency as high as 99% in a well-designed transformer.

Autotransformer

An autotransformer is an electrical transformer with only one winding. The "auto" (Greek for "self") prefix refers to the single coil acting alone, not to any kind of automatic mechanism. In an autotransformer, portions of the same winding act as both the primary winding and secondary winding sides of the transformer. In contrast, an ordinary transformer has separate primary and secondary windings which have no metallic conducting path between them.

The autotransformer winding has at least three taps where electrical connections are made. Since part of the winding does "double duty", autotransformers have the advantages of often being smaller, lighter, and cheaper than typical dual-winding transformers, but the disadvantage of not providing electrical isolation between primary and secondary circuits. Other advantages of autotransformers include lower leakage reactance, lower losses, lower excitation current, and increased VA rating for a given size and mass.[1]

An example of an application of an autotransformer is one style of traveller's voltage converter that allows 230-volt devices to be used on 120 volt supply circuits, or the reverse. An autotransformer with multiple taps may be applied to adjust the voltage at the end of a long distribution circuit to correct for excess voltage drop; when automatically controlled, this is one example of a voltage regulator.



Operation of autotransformer

An autotransformer has a single winding with two end terminals and one or more terminals at intermediate tap points. It is a transformer in which the primary and secondary coils have part of their turns in common. The portion of the winding shared by both the primary and secondary can be, and is often, referred to as the "Common Section". The portion of the winding not shared by both the primary and secondary can be, and is often, referred to as the "Series Section". The primary voltage is applied across two of the terminals. The secondary voltage is taken from two terminals, one terminal of which is usually in common with a primary voltage terminal.

Since the volts-per-turn is the same in both windings, each develops a voltage in proportion to its number of turns. In an autotransformer, part of the output current flows directly from the input to the output (through the series section), and only part is transferred inductively (through the common section), allowing a smaller, lighter, cheaper core to be used as well as requiring only a single winding. However the voltage and current ratio of autotransformers can be formulated the same as other two-winding transformers:

$$V_2 / V_1 = N_1 / N_2 = a \quad (0<V_2<V_1)$$

The ampere-turns provided by the series section of the winding:

$$F_S=(N_1-N_2)I_1 = (1-1/a)N_1I_1$$

The ampere-turns provided by the common section of the winding:

$$F_C= N_2(I_1-I_2)$$

For ampere-turn balance, $F_S = F_C$:

Therefore:

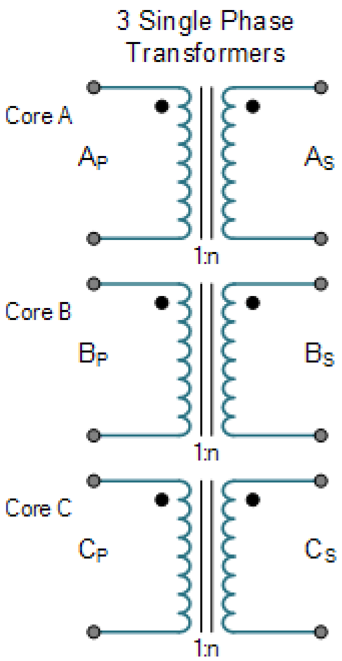
$$(I_1 / I_2) = 1 / a$$

One end of the winding is usually connected in common to both the voltage source and the electrical load. The other end of the source and load are connected to taps along the winding. Different taps on the winding correspond to different voltages, measured from the common end. In a step-down transformer the source is usually connected across the entire winding while the load is connected by a tap across only a portion of the winding. In a step-up transformer, conversely, the load is attached across the full winding while the source is connected to a tap across a portion of the winding. For a step-up transformer, the subscripts in the above equations are reversed where, in this situation, N2 and V2 are greater than N1 and V1, respective.

As in a two-winding transformer, the ratio of secondary to primary voltages is equal to the ratio of the number of turns of the winding they connect to. For example, connecting the load between the middle of the winding and the common terminal end of the winding of the autotransformer will result in the output load voltage being 50% of the primary voltage. Depending on the application, that portion of the winding used solely in the higher-voltage (lower current) portion may be wound with wire of a smaller gauge, though the entire winding is directly connected.

If one of the centre-taps is used for the ground, then the autotransformer can be used as a balun to convert a balanced line (connected to the two end taps) to an unbalanced line (the side with the ground).

Three phase transformer connection



Primary Configuration	Secondary Configuration
Delta (Mesh)	Delta (Mesh)
Delta (Mesh)	Star (Wye)
Star (Wye)	Delta (Mesh)
Star (Wye)	Star (Wye)
Interconnected Star	Delta (Mesh)
Interconnected Star	Star (Wye)

The primary and secondary windings of a transformer can be connected in different configuration as shown to meet practically any requirement. In the case of *three phase transformer* windings, three forms of connection are possible: “star” (wye), “delta” (mesh) and “interconnected-star” (zig-zag).

The combinations of the three windings may be with the primary delta-connected and the secondary star-connected, or star-delta, star-star or delta-delta, depending on the transformers use. When transformers are used to provide three or more phases they are generally referred to as a Polyphase Transformer

Three Phase Transformer Star and Delta Configurations

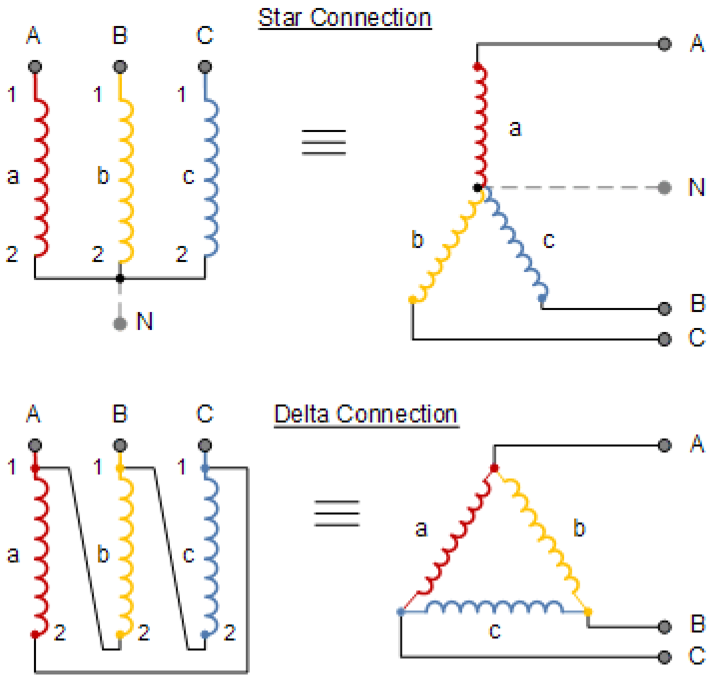
But what do we mean by “star” (also known as Wye) and “delta” (also known as Mesh) when dealing with three-phase transformer connections. A three phase transformer has three sets of primary and secondary windings. Depending upon how these sets of windings are interconnected, determines whether the connection is a star or delta configuration.

The three available voltages, which themselves are each displaced from the other by 120 electrical degrees, not only decided on the type of the electrical connections used on both the primary and secondary sides, but determine the flow of the transformers currents.

With three single-phase transformers connected together, the magnetic flux’s in the three transformers differ in phase by 120 time-degrees. With a single the three-phase transformer there are three magnetic flux’s in the core differing in time-phase by 120 degrees.

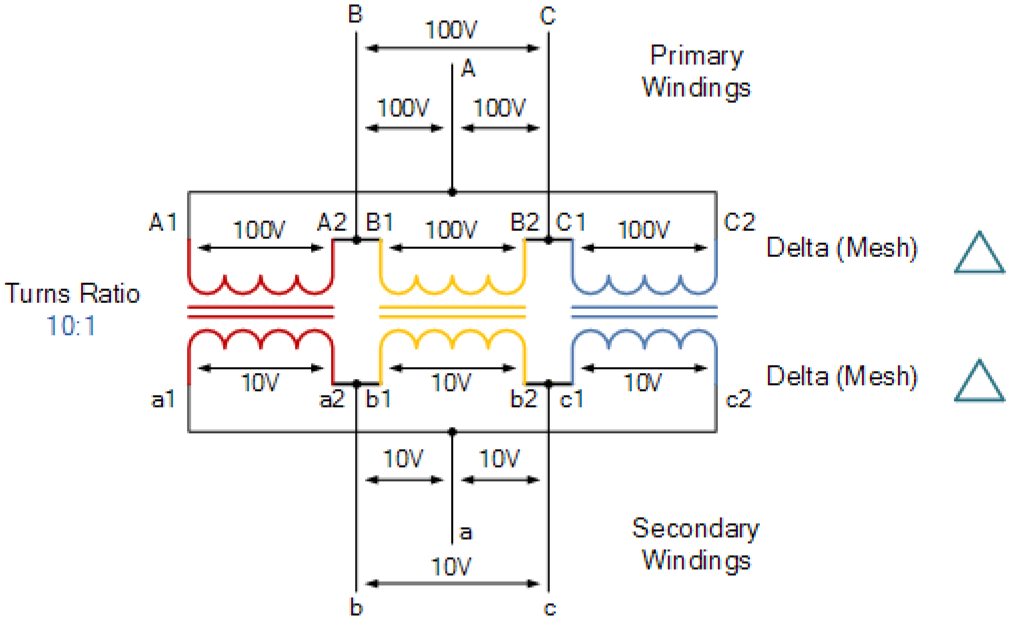
The standard method for marking three phase transformer windings is to label the three primary windings with capital (upper case) letters A, B and C, used to represent the three individual phases of RED, YELLOW and BLUE. The secondary windings are labelled with small (lower case) letters a, b and c. Each winding has two ends normally labelled 1 and 2 so that, for example, the second winding of the primary has ends which will be labelled B1 and B2, while the third winding of the secondary will be labelled c1 and c2 as shown.

Transformer Star and Delta Configurations



Symbols are generally used on a three phase transformer to indicate the type or types of connections used with upper case Y for star connected, D for delta connected and Z for interconnected star primary windings, with lower case y, d and z for their respective secondaries. Then, Star-Star would be labelled Yy, Delta-Delta would be labelled Dd and interconnected star to interconnected star would be Zz for the same types of connected transformers.

Transformer Delta and Delta Connections



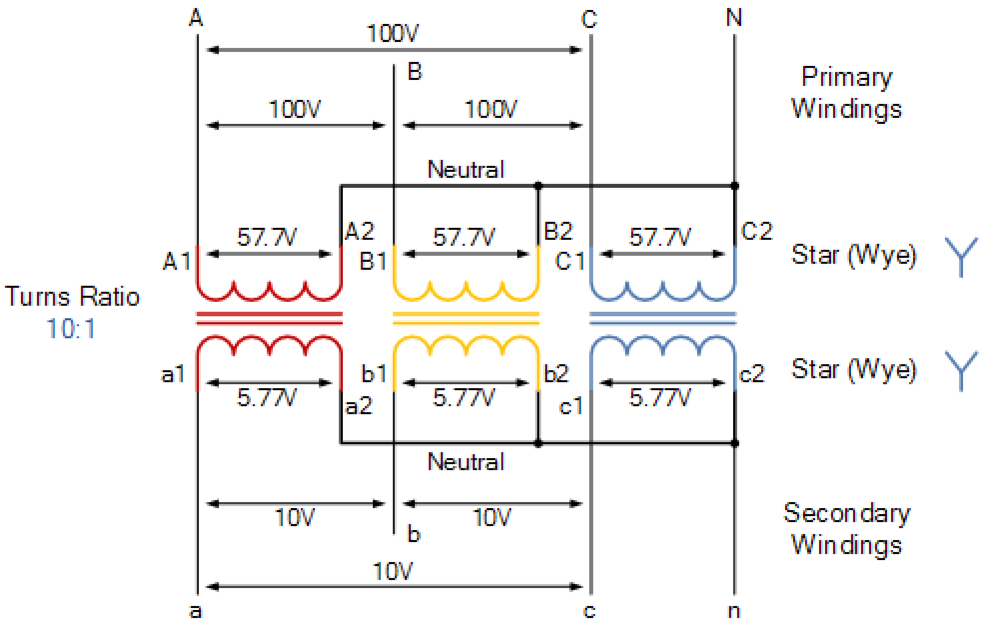
In a delta connected (Dd) group of transformers, the line voltage, V_L is equal to the supply voltage, $V_L = V_S$. But the current in each phase winding is given as: $1/\sqrt{3} \times I_L$ of the line current, where I_L is the line current.

One disadvantage of delta connected three phase transformers is that each transformer must be wound for the full-line voltage, (in our example above 100V) and for 57.7 per cent, line current. The greater number of turns in the winding, together with the insulation between turns, necessitates a larger and more expensive coil than the star connection. Another disadvantage with delta connected three phase transformers is that there is no "neutral" or common connection.

In the star-star arrangement (Yy), (wye-wye), each transformer has one terminal connected to a common junction, or neutral point with the three remaining ends of the primary windings connected to the three-phase mains supply. The number of turns in a transformer winding for star connection is 57.7 per cent, of that required for delta connection.

The star connection requires the use of three transformers, and if any one transformer becomes fault or disabled, the whole group might become disabled. Nevertheless, the star connected three phase transformer is especially convenient and economical in electrical power distributing systems, in that a fourth wire may be connected as a neutral point, (n) of the three star connected secondaries as shown.

Transformer Star and Star Connections



The voltage between any line of the three-phase transformer is called the "line voltage", V_L, while the voltage between any line and the neutral point of a star connected transformer is called the "phase voltage", V_P. This phase voltage between the neutral point and any one of the line connections is $1/\sqrt{3} \times V_L$ of the line voltage. Then above, the primary side phase voltage, V_P is given as.

Module 4

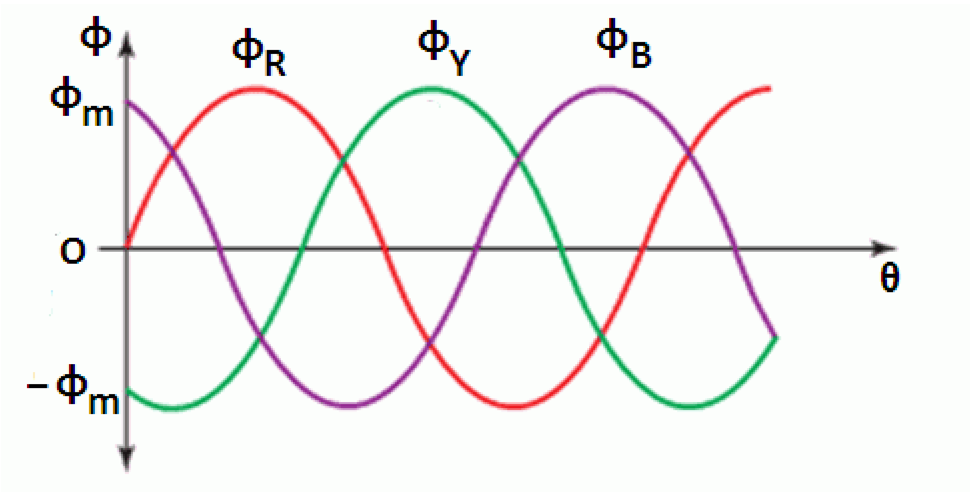
Electrical Machines

Generation of rotating magnetic field

he induction motor rotates due to the rotating magnetic field in induction motor, which is produced by the stator winding in the air gap between the stator and the rotor. The stator has a three phase stationary winding which can be either star connected or delta connected.

Whenever the AC supply is connected to the stator windings, line currents I_R, I_Y, and I_B start flowing. These line currents have phase difference of 120° with respect to each other. Due to each line current, a sinusoidal flux is produced in the air gap. These fluxes have the same frequency as that of the line currents, and they also have the same phase difference of 120° with respect to each other.

Let the flux produced by the line currents I_R, I_B, I_Y be ϕ_R, ϕ_B, ϕ_Y respectively.



Fluxes produced by line currents

Mathematically, they are represented as follows:

$\phi_R = \phi_m \sin \omega t = \phi_m \sin \theta$
$\phi_B = \phi_m \sin (\omega t - 120^o) = \phi_m \sin (\theta - 120^o)$
$\phi_Y = \phi_m \sin (\omega t - 240^o) = \phi_m \sin (\theta - 240^o)$

The effective or total flux (ϕ_T) in the air gap is equal to the phasor sum of the three components of fluxes ϕ_R, ϕ_Y and, ϕ_B.

Therefore, $\phi_T = \phi_R + \phi_Y + \phi_B$

Construction and working of three phase induction machine

Types :

There are two types of 3-phase induction motor based on the type of rotor used:

Squirrel cage induction motor.

Slip ring induction motor.

Slip-ring induction motor over squirrel cage Induction motor

<u>Advantages:</u>

It is possible to speed control by regulating rotor resistance.

?

High starting torque of 200 to 250% of full load voltage.

?

Low starting current of the order of 250 to 300% of the full load current.

?

Hence slip ring induction motors are used where one or more of the above requirements are to be met.

?

1. CONSTRUCTIONAL DETAILS

Conversion of electrical power into mechanical power takes place in the rotating part of an electric motor. In A.C. motors, rotor receives electric power by induction in exactly the same way as the secondary of a two-winding transformer receives its power from the primary. Hence such motors are known as a rotating transformer i.e. one in which primary winding is stationary but the secondary is free to rotate.

An induction motor essentially consists of two main parts:

stator and

Rotor.

<u>Stator:</u>

-

The stator of an induction motor is in principle, the same as that of a synchronous motor (or) generator.

It is made up of a number of stampings, which are slotted to receive the windings.

The stator carries a 3-phase winding and is fed from a 3-phase supply.

It is wound for a definite number of poles, the exact number of poles being determined by the requirements of speed.

The number of poles are higher, lesser the speed and vice-versa.

The stator winding, when supplied with a 3-phase currents, produce a magnetic flux, which is of constant magnitude but which revolves at synchronous speed ($N_s = 120 \times f / p$).

This revolving magnetic flux induces emf in rotor by mutual induction.

Rotor:

-

Squirrel cage Rotor:

Motors employing this type of rotor are known as squirrel cage induction motor.

(ii). Phase wound (or) slip-ring Rotor:

Motors employing this type of rotor are widely known as “phase-wound” motors or wound motor or “slip-ring” motors.

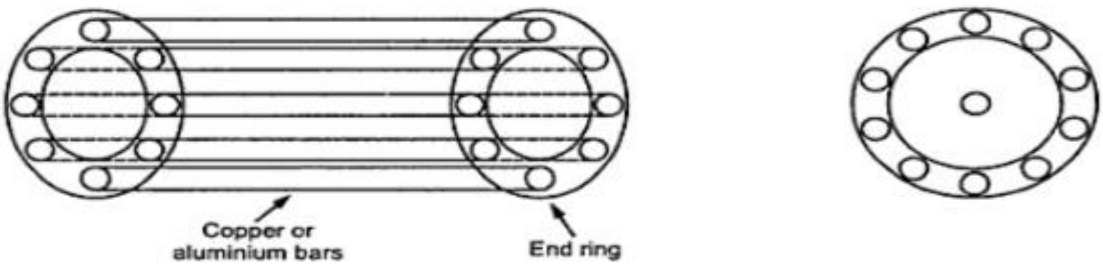
SQUIRREL CAGE ROTOR:

Almost 90 percentage of induction motors are squirrel-cage type, because this type of rotor has the simplest and most rugged construction imaginable and is almost indestructible.

The Rotor consists of cylindrical laminated core with parallel slots for carrying the rotor conductors which, it should be noted clearly, are not wires but consists of heavy bars of copper, aluminium or alloys.

One bar is placed in each slot; rather the bars are inserted from the end when semi-enclosed slots are used.

The rotor bars are brazed or electrically welded or bolted to two heavy and stout short circuiting end-rings, thus giving us, what is called a squirrel cage construction.



(a) Cage type structure of rotor

(b) Symbolic representation

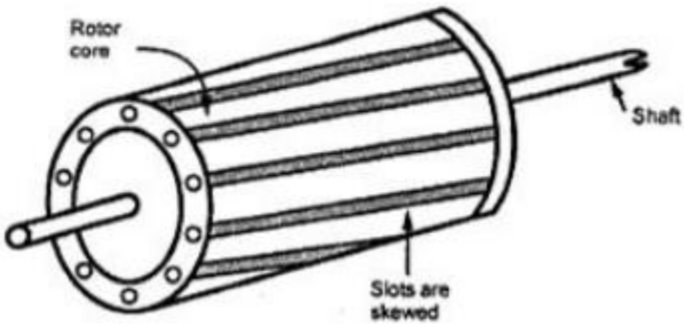


Fig 2.22 Squirrel Cage Rotor

The Rotor bars are permanently short-circuited on themselves; hence it is not possible to add any external Resistance in series with the Rotor circuit for starting purposes.

The rotor slots are not quite parallel to the shaft but are purposely given a slight skew. This is useful in two ways.

It helps to make the motor run quietly by reducing the magnetic hum and

It helps in reducing the locking tendency of the rotor. i.e. the tendency of the rotor teeth to remain under the stator teeth due to direct magnetic attraction between the two.

PHASE-WOUND ROTOR:

This type of rotor is provided with 3-phase, double-layer, distributed winding consisting of coils are used in alternators.

The Rotor is wound for as many poles as the number of stator poles and is always wound 3-phase even when the stator is wound for two-phase.

The three phases are shorted internally.

The other three winding terminals are slip-rings mounted on the shaft with brushes resting on them.

These three brushes are further externally connected to a 3-phase star connected Rheostat.

This makes possible the introduction of additional resistance in the rotor circuit during the starting period for increasing the starting torque of the motor.

When running under normal conditions, slip-rings are automatically short circuited by means of a metal collar, which is pushed along the shaft and connects all the rings together.

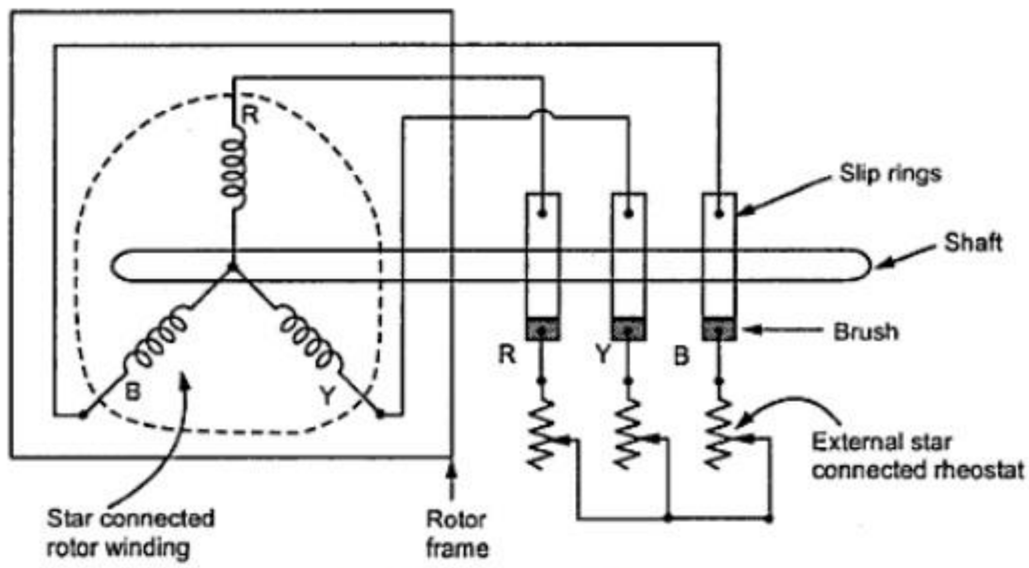


Fig 2.23 Slip ring Rotor

Frame:

Made of close-grained alloy cast iron.

Stator and Rotor core:

Built from high quality low loss silicon steel laminations and flash enameled on both sides.

Stator and Rotor windings:

Have moisture proof tropical insulation and embodying mica and high quality varnishes.

Are carefully spaced for most effective air circulation and are rigidly braced to withstand centrifugal forces and any short circuit stresses.

Air gap:

The stator rabbets and bore are machined carefully to ensure uniformity of air gap.

<u>Shaft and Bearings</u>:

Ball and roller bearings are used to suit heavy duty, trouble free running and for enhanced service life.

<u>Fans:</u>

Light aluminium fans are used for adequate circulation of cooling air and are securely keyed onto the Rotor shaft.

<u>Slip-Rings and Slip-Ring Enclosures</u>:

Slip rings are made of high quality phosphor bronze and are of molded construction.

2. WORKING PRINCIPLE OF THREE PHASE INDUCTION MOTOR

<u>Working principle</u>:

Induction motor works on the principle of electromagnetic induction.

When three phase supply is given to the stator winding, a rotating magnetic field of constant magnetic field is produced.

The speed of rotating magnetic field is synchronous speed, NS r.p.m.

This rotating field produces an effect of rotating poles around a rotor. Let direction of this magnetic field is clockwise as shown.

Now at this instant rotor is stationary and stator flux R.M.F. is rotating. So its obvious that there exists a relative motion between the R.M.F. and rotor conductors.

Now the R.M.F. gets cut by rotor conductors as R.M.F. sweeps over rotor conductors.

Whenever a conductor cuts the flux, emf. gets induced in it. So e.m.f.gets induced in the rotor conductors called rotor induced emf. this is electro – magnetic induction.

As rotor forms closed circuit, induced emf. circulates current through rotor called rotor current.

Any current carrying conductor produces its own flux. So rotor produces its flux called rotor flux. For assumed direction of rotor current, the direction of rotor flux is clockwise as shown.

This direction can be easily determined using right hand thumb rule.

Now there are two fluxes, one R.M.F. and another rotor flux.

Both the fluxes interact with each. On left of rotor conductor, two fluxes are in same direction hence added up to get high flux area.

On right side of rotor conductor, two fluxes are in opposite direction hence they cancel each other to produce low flux area.

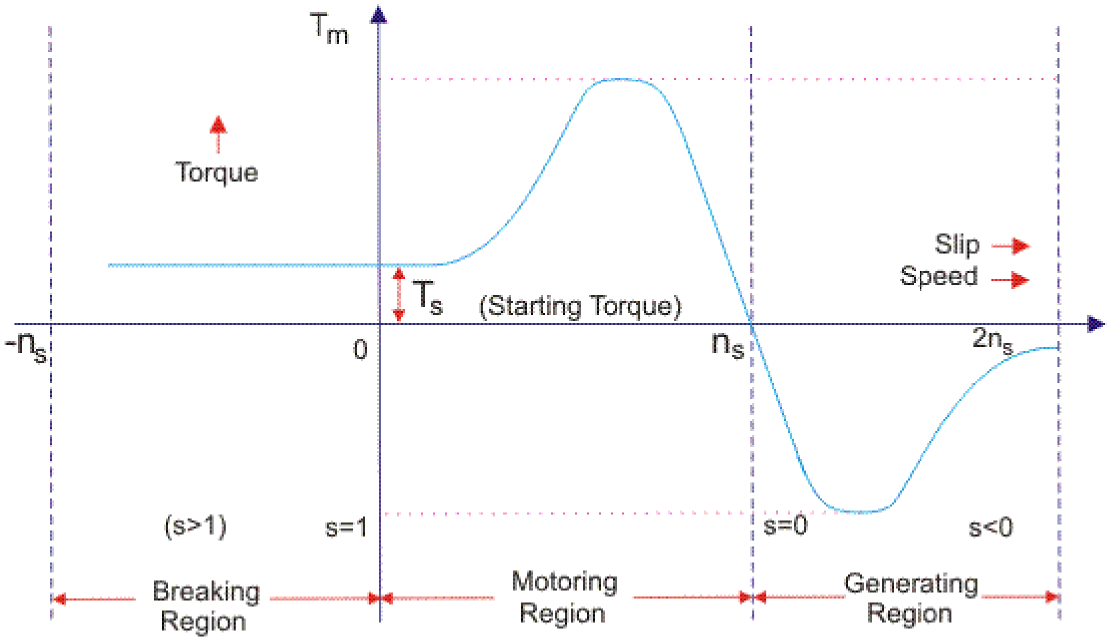
So rotor conductor experiences a force from left to right, due to interaction of the two fluxes.

As all rotor conductor experiences a force, overall rotor experiences a torque and starts rotating.

So interaction of the two fluxes is very essential for a motoring action. As seen from the figure, the direction of force is same as that of rotating magnetic field. Hence rotor starts rotating in the same direction as that of R.M.F.

Torque Slip Characteristics of Three Phase Induction Motor

The torque slip curve for an induction motor gives us the information about the variation of torque with the slip. The slip is defined as the ratio of difference of synchronous speed and actual rotor speed to the synchronous speed of the machine. The variation of slip can be obtained with the variation of speed that is when speed varies the slip will also vary and the torque corresponding to that speed will also vary.
The curve can be described in three modes of operation-



Torque Slip Curve for Three Phase Induction Motor

The torque-slip characteristic curve can be divided roughly into three regions:

- Low slip region
- Medium slip region
- High slip region

Motoring Mode
In this mode of operation, supply is given to the stator sides and the motor always rotates below the synchronous speed. The induction motor torque varies from zero to full load torque as the slip varies. The slip varies from zero to one. It is zero at no load and one at standstill. From the curve it is seen that the torque is directly proportional to the slip. That is, more is the slip, more will be the torque produced and vice-versa. The linear relationship simplifies the calculation of motor parameter to great extent.
Generating Mode
In this mode of operation induction motor runs above the synchronous speed and it should be driven by a prime mover. The stator winding is connected to a three phase supply in

which it supplies electrical energy. Actually, in this case, the torque and slip both are negative so the motor receives mechanical energy and delivers electrical energy. Induction motor is not much used as generator because it requires reactive power for its operation. That is, reactive power should be supplied from outside and if it runs below the synchronous speed by any means, it consumes electrical energy rather than giving it at the output. So, as far as possible, induction generators are generally avoided.

Braking Mode

In the Braking mode, the two leads or the polarity of the supply voltage is changed so that the motor starts to rotate in the reverse direction and as a result the motor stops. This method of braking is known as plugging. This method is used when it is required to stop the motor within a very short period of time. The kinetic energy stored in the revolving load is dissipated as heat. Also, motor is still receiving power from the stator which is also dissipated as heat. So as a result of which motor develops enormous heat energy. For this stator is disconnected from the supply before motor enters the braking mode.

If load which the motor drives accelerates the motor in the same direction as the motor is rotating, the speed of the motor may increase more than synchronous speed. In this case, it acts as an induction generator which supplies electrical energy to the mains which tends to slow down the motor to its synchronous speed, in this case the motor stops. This type of breaking principle is called dynamic or regenerative breaking.

Starting and speed control of 3 phase induction motor

A three-phase Induction Motor is Self Starting. When the supply is connected to the stator of a three-phase induction motor, a rotating magnetic field is produced, and the rotor begins rotating and the induction motor starts. At the time of starting, the motor slip is unity, and the starting current is very large

The purpose of a starter is not to just start the motor, but it performs the two main functions. They are as follows:

- To reduce the heavy starting current,
- To provide overload and under-voltage protection.

The three-phase induction motor may be started by connecting the motor directly to the full voltage of the supply. The motor can also be started by applying a reduced voltage to the motor. The torque of the induction motor is proportional to the square of the applied voltage. Thus, greater torque is exerted by a motor when it is started on full voltage than when it is started on the reduced voltage.

There are three main methods of Starting of Cage Induction Motor. They are as follows:

Direct on-line starter

The direct on-line starter method, of an induction motor, is simple and economical. In this method, the starter is connected directly to supply voltage. By this method, small motors up to 5 kW rating are started to avoid the supply voltage fluctuation.

Star delta starter

The star delta starter method of starting three-phase induction motors is very common and widely used among all the methods. In this method, the motor runs at delta-connected stator windings.

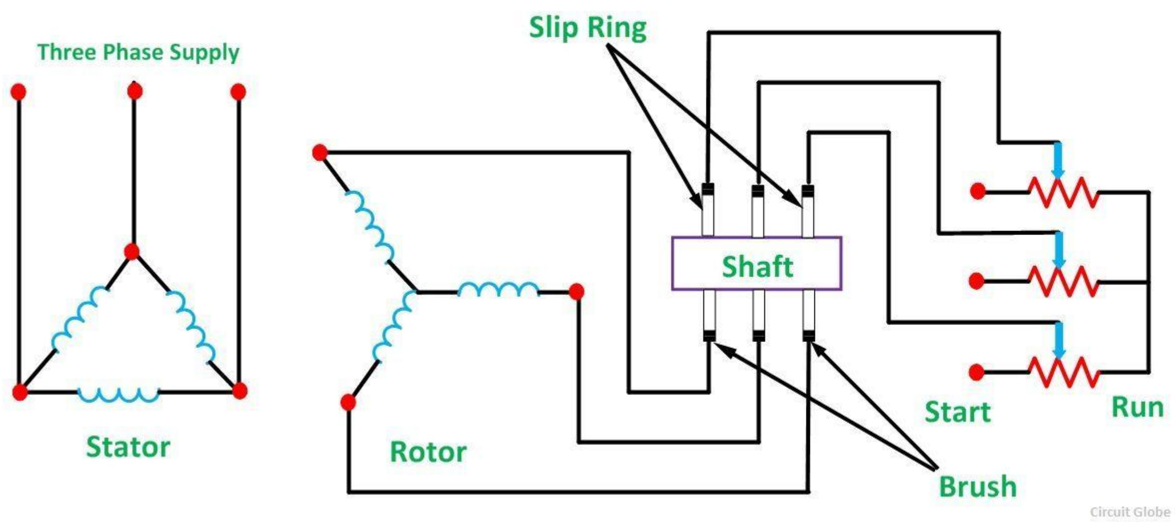
Autotransformer starter

The Autotransformer is used in both types of connections, i.e., either star connected or delta connected. The autotransformer is used to limit the starting current of the induction motor.

The above three starters are used for the cage rotor induction motor.

Slip Ring Induction Motor Starter Method

In the **Slip Ring Induction Motor** starter, the full supply voltage is connected across the starter. The connection diagram of the slip ring starter induction motor is shown below:



Full starting resistance is connected and thus the supply current to the stator is reduced. The rotor begins to rotate, and the rotor resistances are gradually cut out as the speed of the motor increases. When the motor is running at its rated full load speed, the starting resistances are cut out completely, and the slip rings are short-circuited.

The Speed of Induction Motor is changed from Both Stator and Rotor Side. The speed control of three phase induction motor is classified as:

- V / f control or frequency control.
- Changing the number of stator poles.
- Controlling supply voltage.
- Adding rheostat in the stator circuit.
- Adding external resistance on rotor side.
- Cascade control method.
- Injecting slip frequency emf into rotor side.

Speed Control from Stator Side

- V / f Control or Frequency Control

Whenever three phase supply is given to three phase induction motor rotating magnetic field is produced which rotates at synchronous speed given by

$$N_s = \frac{120f}{P}$$

In three phase induction motor emf is induced by induction similar to that of transformer which is given by

$$E \ or \ V = 4.44\phi K.T.f \ or \ \phi = \frac{V}{4.44KTf}$$

Where, K is the winding constant, T is the number of turns per phase and f is frequency. Now if we change frequency synchronous speed changes but with decrease in frequency flux will increase and this change in value of flux causes saturation of rotor and stator cores which will further cause increase in no load current of the motor . So, its important to maintain flux , ϕ constant and it is only possible if we change voltage. i.e if we decrease frequency flux increases but at the same time if we decrease voltage flux will also decease causing no change in flux and hence it remains constant. So, here we are keeping the ratio of V/f as constant. Hence its name is V/ f method. For controlling the speed of three phase induction motor by V/f method we have to supply variable voltage and frequency which is easily obtained by using converter and inverter set.

Controlling Supply Voltage

The torque produced by running three phase induction motor is given by

$$T \propto \frac{sE_2^2R_2}{R_2^2 + (sX_2)^2}$$

In low slip region $(sX)^2$ is very very small as compared to R_2. So, it can be neglected. So torque becomes

$$T \propto \frac{sE_2^2}{R_2}$$

Since rotor resistance, R_2 is constant so the equation of torque further reduces to

$$T \propto sE_2^2$$

The equation above clears that if we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remain the same, and it is only possible if we increase the slip and if the slip increases the motor will run at a reduced speed. This method of speed control is rarely used because a small change in speed requires a large reduction in voltage, and hence the current drawn by motor increases, which cause overheating of the induction motor.

- **Changing the number of stator poles:**

  The stator poles can be changed by two methods

- Multiple stator winding method.
- Pole amplitude modulation method (PAM)
- **Multiple Stator Winding Method**

  In this method of speed control of three phase induction motor, we provide two separate windings in the stator. These two stator windings are electrically isolated from each other and are wound for two different numbers of poles. Using a switching arrangement, at a time, supply is given to one winding only and hence speed control is possible. Disadvantages of this method are that the smooth speed control is not possible. This method is more costly and less efficient as two different stator windings are required. This method of speed control can only be applied to squirrel cage motor.
- **Pole Amplitude Modulation Method (PAM)**

  In this method of speed control of three phase induction motor the original sinusoidal mmf wave is modulated by another sinusoidal mmf wave having the different number of poles.

  - **Adding Rheostat in Stator Circuit**

  In this method of speed control of three phase induction motor rheostat is added in the stator circuit due to this voltage gets dropped .In case of three phase induction motor torque produced is given by $T \propto sV_2^2$. If we decrease supply voltage torque will also decrease. But for supplying the same load, the torque must remains the same and it is only possible if we increase the slip and if the slip increase motor will run reduced speed.

Speed Control from Rotor Side

- Adding External Resistance on Rotor Side

  In this method of speed control of three phase induction motor external resistance are added on rotor side. The equation of torque for three phase induction motor is

$$T \propto \frac{sE_2^2R_2}{R_2^2 + (sX_2)^2}$$

  The three-phase induction motor operates in a low slip region. In low slip region term $(sX)^2$ becomes very very small as compared to R_2. So, it can be neglected. and also E_2 is constant. So the equation of torque after simplification becomes,

$$T \ \propto \ \frac{s}{R_2}$$

Now if we increase rotor resistance, R_2 torque decreases but to supply the same load torque must remain constant. So, we increase slip, which will further result in the decrease in rotor speed. Thus by adding additional resistance in the rotor circuit, we can decrease the speed of the three-phase induction motor. The main advantage of this method is that with an addition of external resistance starting torque increases but this method of speed control of three phase induction motor also suffers from some disadvantages:

- The speed above the normal value is not possible.
- Large speed change requires a large value of resistance, and if such large value of resistance is added in the circuit, it will cause large copper loss and hence reduction in efficiency.
- Presence of resistance causes more losses.
- This method cannot be used for squirrel cage induction motor.

Construction of Synchronous Motors

A synchronous motor is generally made up of two parts, a stator the stationary part of the machine that carries the armature winding in which the voltage is generated, and a rotor the rotating part of the machine that produces the main field flux. Of course, this motor has other parts and components. But electric motors are generally known by these two parts. In the following, we will get acquainted with all these components and parts, and we will mention the function and role of each in the motor.

1. Stator Construction

The stationary part of the machine is called Stator. It includes various parts like stator frame, stator core, stator windings, and cooling arrangement. They are explained below in detail.

1.1. Stator Frame

It is the outer body of the machine made of cast iron, and it protects the inner parts of the machine.

1.2. Stator Core

The stator core is made of silicon steel material. It is made from many stamps which are insulated from each other. Its function is to provide an easy path for the magnetic lines of force and accommodate the stator winding.

1.3. Stator Winding

Slots are cut on the inner periphery of the stator core in which 3 phase or 1 phase winding is placed. Enameled copper is used as a winding material. The winding is star connected. The winding of each phase is distributed over several slots. When the current flows in a distributed winding it produces an essentially sinusoidal space distribution of EMF.

2. Rotor Construction

The rotating part of the machine is called the Rotor. There are two types of rotor construction, namely the salient pole type and the cylindrical rotor type. In the following, we will deal with each of these two types of rotors and you can find their differences in their structure and operation.

2.1. Salient Pole Rotor

The term salient means projecting. Thus, a salient pole rotor consists of poles projecting out from the surface of the rotor core. The end view of a typical 6 pole salient pole rotor is shown below in the figure.

Since the rotor is subjected to changing magnetic fields, it is made of steel laminations to reduce eddy current losses. Poles of identical dimensions are assembled by stacking laminations to the required length. A salient pole synchronous machine has a non-uniform air gap. The air gap is minimized under the pole centers and it is maximum in between the poles.

They are constructed for medium and low speeds as they have a large number of poles. A salient pole generator has a large diameter. The salient pole rotor has the following important parts.

Non-Salient Pole Rotor or Cylindrical Rotor

In this type of rotor, unlike Salient Pole Rotor, there are no projected poles, but the poles are formed by the current flowing through the rotor exciting winding. Cylindrical rotors are usually made from solid forgings of high-grade nickel chrome-molybdenum steel. It has a comparatively small diameter and long axial length.

This type of Rotor is useful in high-speed machines. The cylindrical rotor has two or four poles on the rotor. Such a construction provides greater mechanical strength and allows more accurate dynamic balancing. The smooth rotor of the machine makes fewer windage losses and the operation is less noisy because of the uniform air gap. Cylindrical Rotors are driven by steam or gas turbines. The machines are built in many ratings from 10 MVA to over 1500 MVA. The biggest size used in India has a rating of 500 MVA installed in the super thermal power plant.

Cylindrical Rotors have the following seven parts and components. We have listed all these parts and components below and have prepared a brief and useful explanation for each of them for more familiarity.

1) Rotor Core

The rotor core is made of silicon steel stampings. The rotor core is placed on the shaft (we will explain what the shaft is). At the outer periphery, slots are cut in which exciting coils are placed.

2) Rotor Winding (Exciting Winding)

It is placed on the rotor slots, and the current is passed through the winding in such a way that the poles are formed according to the requirement.

3) Pole Core and Pole Shoe

It is made of laminated sheet steel material. The Pole core provides the least reluctance path for the magnetic field and the pole shoe distributes the field over the whole periphery uniformly to produce a sinusoidal wave.

4) Spider

It is made of cast iron to provide an easy path for the magnetic flux. It is keyed to the shaft and at the outer surface, pole core and pole shoe are keyed to it.

5) Field Winding (Exciting Winding)

It is wound on the former and then placed around the pole core. DC supply is given to it through slip rings. When direct current flow through the field winding, it produces the required magnetic field.

6) Damper Winding

At the outermost periphery, holes are provided in which copper bars are inserted and short-circuited at both sides by rings forming Damper winding.

7) Rings

Slip rings provide DC supply to the rotor windings.

3. Miscellaneous Parts and Components

We mentioned at the beginning of this section that in addition to the rotor and stator and their components, there are other components in a synchronous motor. In the following, you will become more familiar with these parts and their role. The miscellaneous parts are given below.

A) Brushes

Brushes are made of carbon, and they slip over the slip rings. A DC supply is given to the brushes. Current flows from the brushes to the slip rings and then to the exciting windings.

B) Bearings

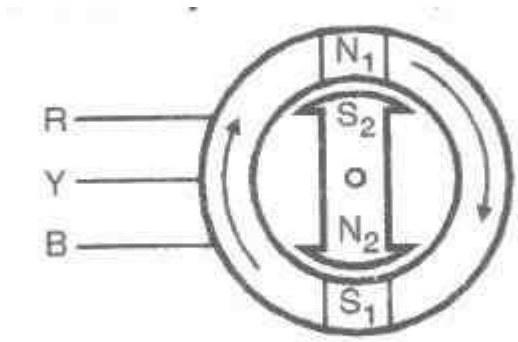
Bearings are provided between the shaft and the outer stationary body to reduce friction. They are made of high carbon steel.

C) Shaft

The shaft is made of mild steel. Mechanical power is taken or given to the machine through the shaft.

Working of Synchronous Motor

The **synchronous motor working principle** is based on the principle of magnetic locking between stator and rotor poles.
To understand the *working of synchronous motor*, let the stator of the synchronous motor be wound for two poles. Let the rotor also produces two poles when they are excited by the external DC source.



As the three-phase AC supply is connected to the stator winding, a rotating magnetic field (RMF) is produced. This field rotates at the synchronous speed N_s. The two poles produced are N_1 and S_1, as shown in the Figure.
These stator poles (N_1 and S_1) rotate in the air gap between stator and rotor at synchronous speed in the clockwise direction.
The rotor is then excited by the external DC source. It produces two poles N_2 and S_2, as shown in the Figure.
The rotor is accelerated, to rotate in the clockwise direction by some external engine. This is because the synchronous motor is not self-starting.

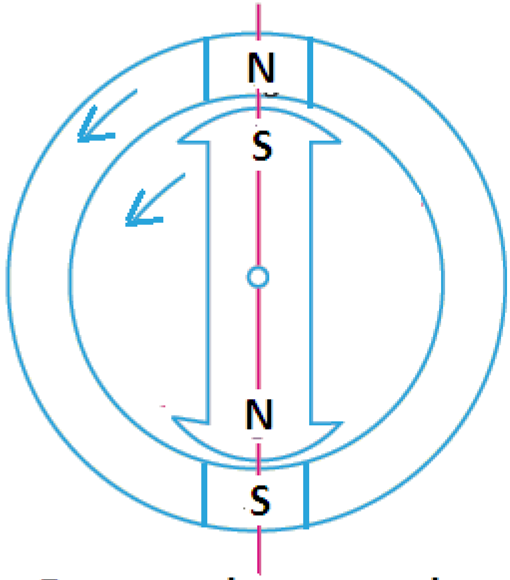
If unlike poles $N_1 – S_2$ and $S_1 – N_2$ come close to each other, then due to the strong force of attraction, magnetic locking takes place between them.
Once the stator and rotor poles are locked magnetically with each other, the rotor will continue to rotate at synchronous speed along with the rotating magnetic field. Then external engine coupled to the rotor can be decoupled.

The rotor will rotate at N_s as long as the magnetic lock between the stator and rotor continues to exist.

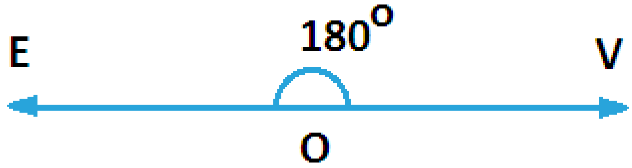
Working of Synchronous Motor on Load

When a synchronous motor is connected to the lines and started by some external means, it starts rotating at synchronous speed. If the motor is running at no-load and has no losses, then induced EMF, **E** is equal and opposite to the applied voltage, and the stator and rotor poles are in line with each other, as shown in Figure.
The resultant EMF, E_r, and hence the current drawn by the motor is zero. Thus the motor is said to be floating on the lines.

Ideal synchronous motor at no-load



Rotor and stator poles are in line with each other



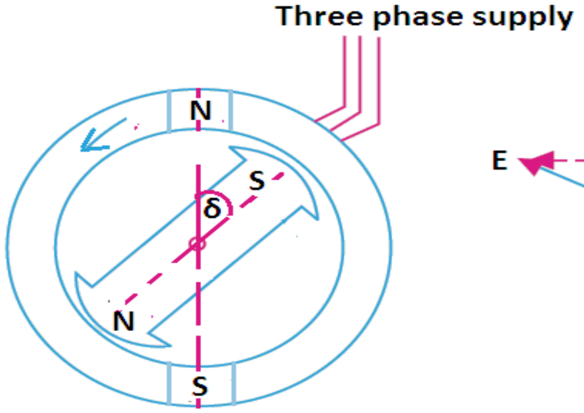
Induced EMF, E = applied voltge, V

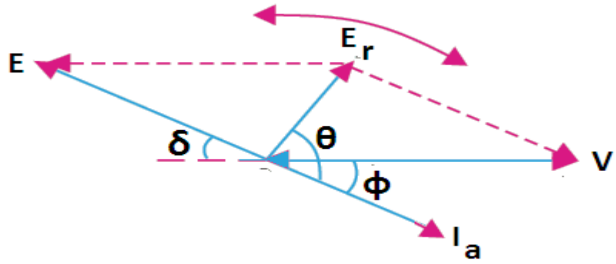
Resultant voltage, $E_r = 0$

Line current = 0

However, in an actual machine, some losses are always present with the result induced EMF; **E** falls back by a small angle, and the rotor poles also fall back by the same angle relative to the stator poles.

This causes a resultant voltage, E_r across the armature and the motor draws no-load current from the mains. The power drawn by the motor is just sufficient to make the motor running continuously at the synchronous speed.





When the load is applied rotor falls back by angle, δ

Now, when the load is applied to the shaft of the motor, the rotor falls back a little more relative to stator poles. Hence the torque angle or load angle, **δ** increases with the increase in load. This increases the resultant voltage, E_r, which in turn increases the current drawn by the motor from mains.

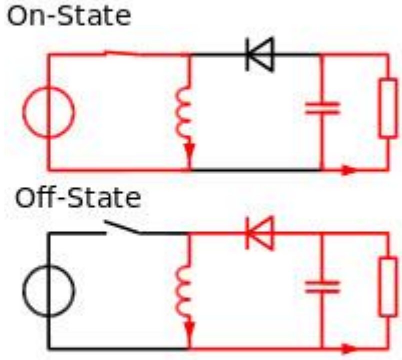
Thus a synchronous motor is able to supply the increasing mechanical loads, not by the decrease in speed, but by shifting the position of rotor poles with respect to the stator poles.
When the load applied to the shaft of the motor is further increased, the rotor poles and induced EMF falls back further. Hence the load angle, **δ**, increases with the increase in the load. When **δ** increases, the resultant voltage E_r increases, and so does the armature current.
If a too high mechanical load is applied to the synchronous motor, the rotor is pulled out of synchronism. And it comes to a standstill.
The maximum value of torque that a motor can develop without losing its synchronism is called pull-out torque.

Module 5

Power converter

DC DC buck and boost converter

It is a type of DC to DC converter and it has a magnitude of output voltage. It may be more or less than equal to the input voltage magnitude. The buck boost converter is equal to the fly back circuit and single inductor is used in the place of the transformer. There are two types of converters in the buck boost converter that are buck converter and the other one is boost converter. These converters can produce the range of output voltage than the input voltage. The following diagram shows the basic buck boost converter.



Working principle of Buck-Boost Converter

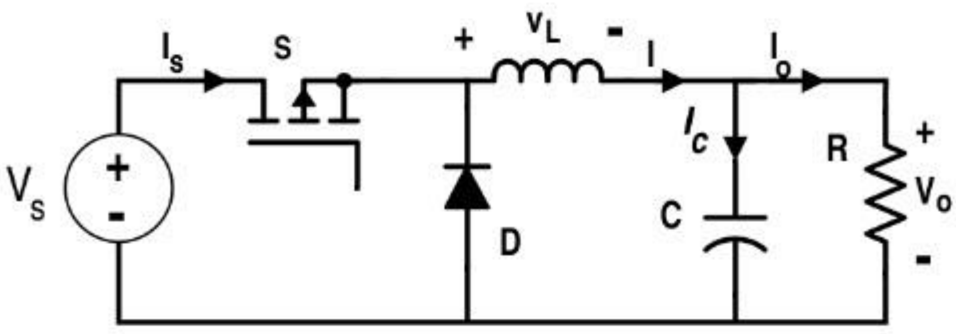
The working operation of the DC to DC converter is the inductor in the input resistance has the unexpected variation in the input current. If the switch is ON then the inductor feed the energy from the input and it stores the energy of magnetic energy. If the switch is closed it discharges the energy. The output circuit of the capacitor is assumed as high sufficient than the time constant of an RC circuit is high on the output stage. The huge time constant is compared with the switching period and make sure that the steady state is a constant output voltage Vo(t) = Vo(constant) and present at the load terminal.

There are two different types of working principles in the buck boost converter.

- Buck converter.
- Boost converter.

Buck Converter Working

The following diagram shows the working operation of the buck converter. In the buck converter first transistor is turned ON and second transistor is switched OFF due to high square wave frequency. If the gate terminal of the first transistor is more than the current pass through the magnetic field, charging C, and it supplies the load. The D1 is the Schottky diode and it is turned OFF due to the positive voltage to the cathode.

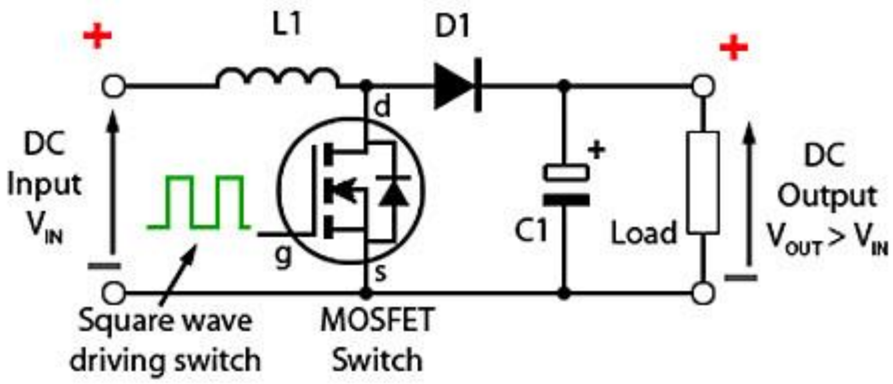


The inductor L is the initial source of current. If the first transistor is OFF by using the control unit then the current flow in the buck operation. The magnetic field of the inductor is collapsed and the back e.m.f is generated collapsing field turn around the polarity of the voltage across the inductor. The current flows in the diode D2, the load and the D1 diode will be turned ON.

The discharge of the inductor L decreases with the help of the current. During the first transistor is in one state the charge of the accumulator in the capacitor. The current flows through the load and during the off period keeping Vout reasonably. Hence it keeps the minimum ripple amplitude and Vout closes to the value of Vs

Boost Converter Working

In this converter the first transistor is switched ON continually and for the second transistor the square wave of high frequency is applied to the gate terminal. The second transistor is in conducting when the on state and the input current flow from the inductor L through the second transistor. The negative terminal charging up the magnetic field around the inductor. The D2 diode cannot conduct because the anode is on the potential ground by highly conducting the second transistor.



Boost Converter Working

By charging the capacitor C the load is applied to the entire circuit in the ON State and it can construct earlier oscillator cycles. During the ON period the capacitor C can discharge regularly and the amount of high ripple frequency on the output voltage. The approximate potential difference is given by the equation below.

VS + VL

During the OFF period of second transistor the inductor L is charged and the capacitor C is discharged. The inductor L can produce the back e.m.f and the values are depending up on the rate of change of current of the second transistor switch. The amount of inductance the coil can occupy. Hence the back e.m.f can produce any different voltage through a wide range and determined by the design of the circuit. Hence the polarity of voltage across the inductor L has reversed now.

The input voltage gives the output voltage and atleast equal to or higher than the input voltage. The diode D2 is in forward biased and the current applied to the load current and it recharges the capacitors to VS + VL and it is ready for the second transistor.

Modes Of Buck Boost Converters

There are two different types of modes in the buck boost converter. The following are the two different types of buck boost converters.

- Continuous conduction mode.
- Discontinuous conduction mode.

Continuous Conduction Mode

In the continuous conduction mode the current from end to end of inductor never goes to zero. Hence the inductor partially discharges earlier than the switching cycle.

Discontinuous Conduction Mode

In this mode the current through the inductor goes to zero. Hence the inductor will totally discharge at the end of switching cycles.

Applications of Buck boost converter

- It is used in the self regulating power supplies.
- It has consumer electronics.
- It is used in the Battery power systems.
- Adaptive control applications.
- Power amplifier applications.

Advantages of Buck Boost Converter

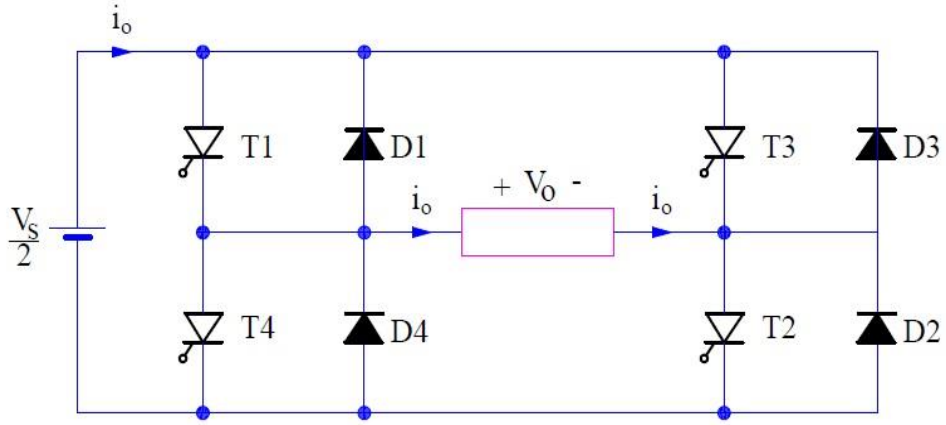
- It gives higher output voltage.
- Low operating duct cycle.
- Low voltage on MOSFETs

Single phase phase inverter

Single Phase Full Bridge Inverter is basically a voltage source inverter. The output frequency can be controlled by controlling the turn ON and turn OFF time of the thyristors.

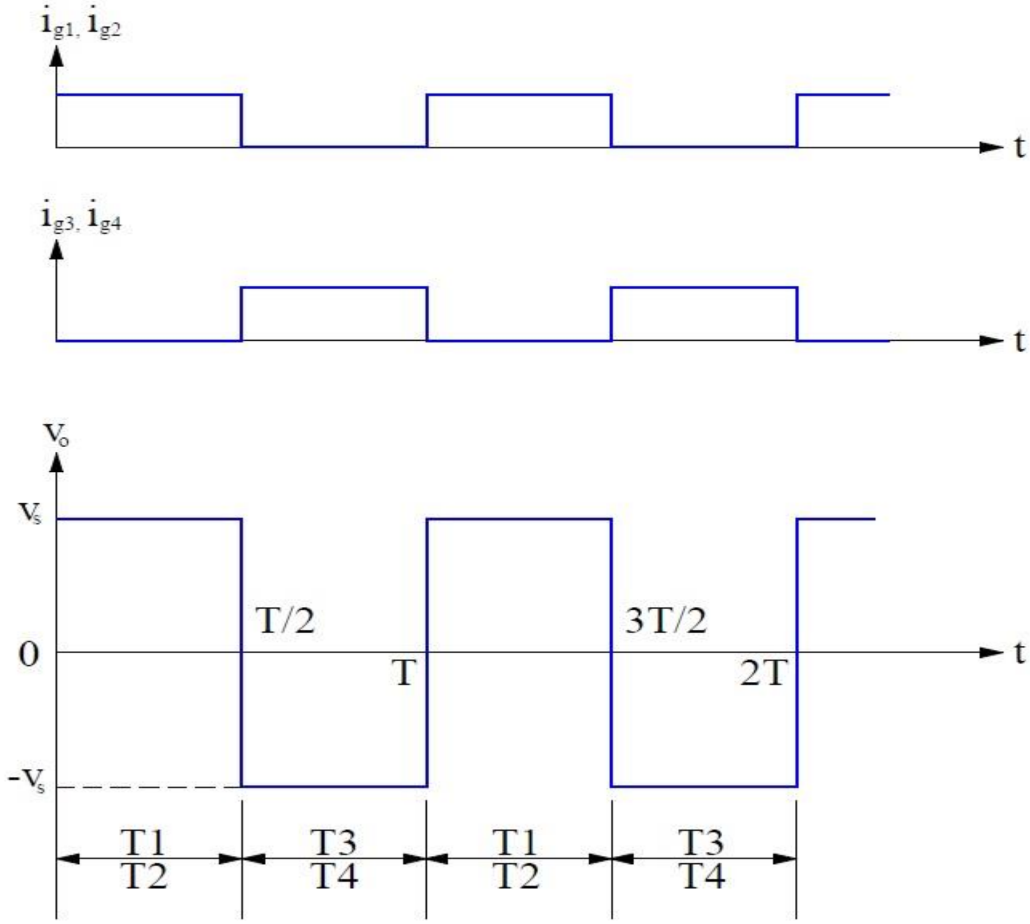
Circuit Diagram of Single Phase Full Bridge Inverter:

The power circuit of a single phase full bridge inverter comprises of four thyristors T1 to T4, four diodes D1 to D1 and a two wire DC input power source V_s. Each diode is connected in antiparallel to the thyristors viz. D1 is connected in anti-parallel to T1 and so on. The power circuit diagram of a single phase full bridge inverter is shown in the figure below.



It may be noted that the circuitry for turning ON and turning OFF the thyristor is not shown in the above circuit diagram to maintain simplicity. Further, it is assumed that each of the thyristor only conducts for the period its gate signal is present and as soon as the gate signal is removed, the thyristors gets turned OFF.

The gating signal and output voltage waveform of a single phase full bridge inverter is shown below

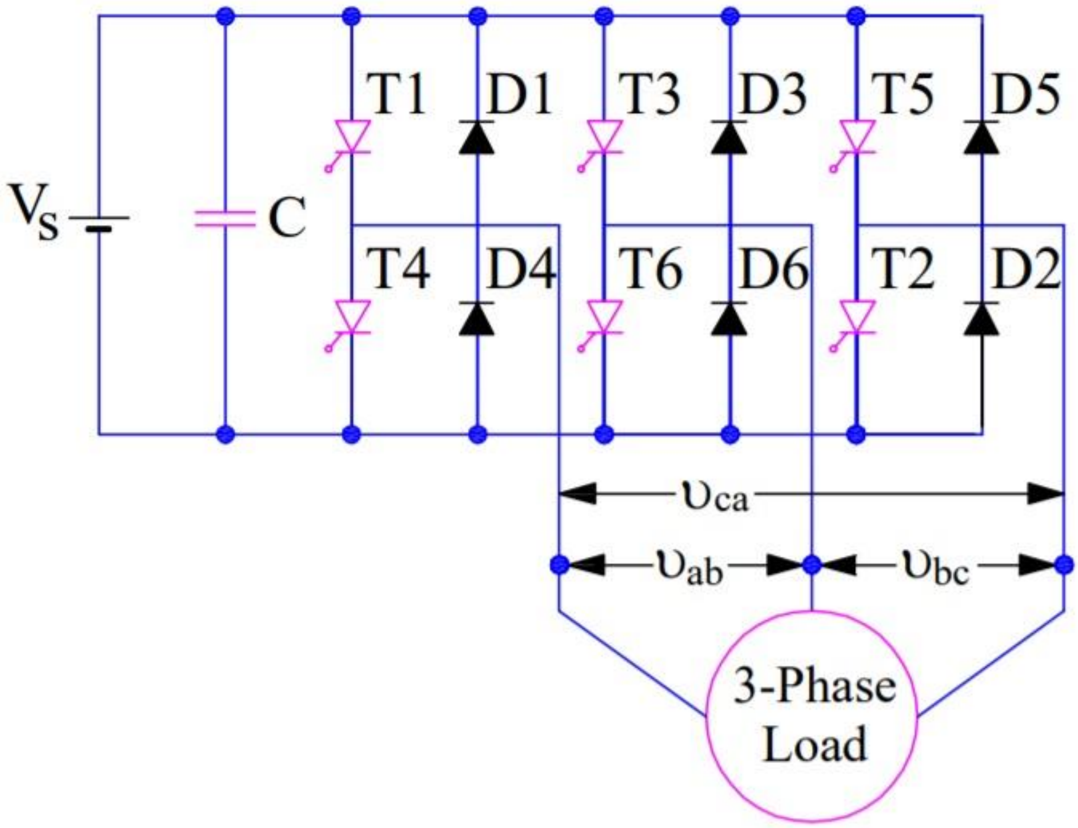


Working Principle of Single Phase Full Bridge Inverter:
The working principle of single phase full bridge inverter is based on the sequential triggering of thyristors placed diagonally opposite. This means, for half of time period, thyristors T3 & T4 will be triggered while for the remaining half of time period, T1 & T2 will be triggered. Only two thyristors are turned ON in half of the time period.
Carefully observe the waveform of the gating signal. You will notice that thyristors T1 & T2 are triggered simultaneously for a time T/2. Therefore, load is connected to source through T1 & T2 and hence, the load voltage is equal to the source voltage with positive polarity. This is the reason; the load voltage is shown positive & equal to V_s in the output voltage waveform.
As soon as the gate signal (i_{g1} & i_{g2}) are removed, T1 and T2 gest turned OFF. However, at the same instant gate signal (i_{g3} & i_{g4}) are applied and hence, T3 & T4 are turned ON. When T3 & T4 are conducting, load gets connected to the source. The load voltage magnitude is again V_s but with reverse polarity. This is the reason, the output voltage is shown negative in the voltage waveform.
To summarize,
For the time $0<t\leq(T/2)$, thyristors T1 & T2 conducts and load voltage $\mathbf{V_o = V_s}$.
For the time $(T/2)<t\leq T$, thyristors T3 & T4 conducts and load voltage $\mathbf{V_o = -V_s}$.
I think you have understood the working principle of single-phase half bridge inverter. But I am sure that you might be thinking the purpose of diodes D1 to D4. I will explain.
Purpose of Diodes D1 to D4:

If the load is purely resistive, there is no need to put diode D1 to D4 as the output voltage and current are always in phase. But unfortunately, for loads other than purely resistive, the load current (i_o) will not be in phase with the load voltage (v_o). For such case, the diode connected in anti-parallel with the thyristor will allow the current to flow when main thyristor is turned off. When these diode conducts, the energy is fed back to the DC source and hence, these diodes (D1 to D4) are called flyback diode.

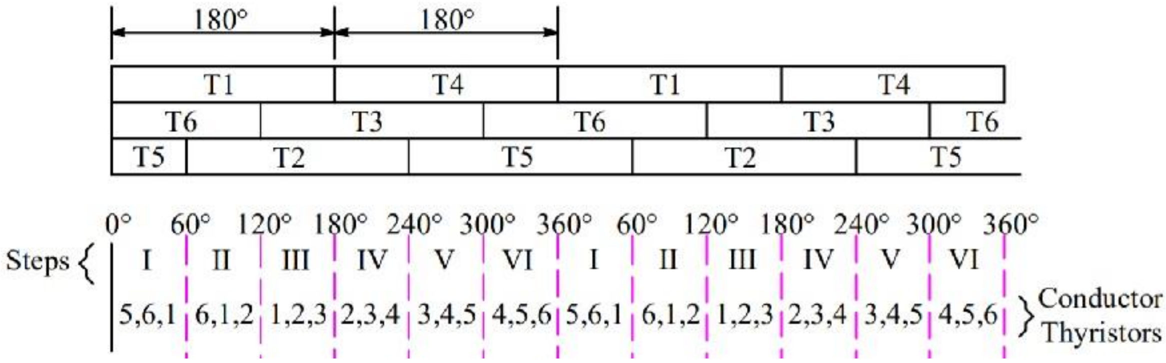
Three phase inverter

A three phase bridge inverter is a device which converts DC power input into three phase AC output. Like single phase inverter, it draws DC supply from a battery or more commonly from a rectifier.
A basic three phase inverter is a six step bridge inverter. It uses a minimum of 6 thyristors. In inverter terminology, a step is defined as a change in the firing from one thyristor to the next thyristor in a proper sequence. For getting one cycle of 360°, each step is of 60° interval. This means thyristors will be gated at a regular interval of 60° in a proper sequence so that three phase AC output voltage is synthesized at its output.
Circuit Diagram of Three Phase Bridge Inverter:
Figure below shows a simple power circuit diagram of a three phase bridge inverter using six thyristors and diodes.



A careful observation of the above circuit diagram reveals that power circuit of a three phase bridge inverter is equivalent to three half bridge inverters arranged side by side. The three phase load connected to the output terminals a, b and c of inverter is assumed to be STAR connected. In the circuit diagram, the numbering of thyristors is done in the sequence in which they are triggered to obtain voltages v_{ab}, v_{bc} & v_{ca} at the output terminals a, b & c.

Working Principle of Three Phase Bridge Inverter:
There are two possible patterns of gating the thyristors. In one pattern, each thyristor conducts for 180° and in other, each thyristor conducts for 120°. But in both these patters the gating signals are applied and removed at 60° interval of the output voltage waveform. Therefore, both these models require a six step bridge inverter. Now, we will discuss 180° model of this three phase inverter. 120° mode inverter will be explained in the next article.
180° Conduction Mode of Three Phase Inverter:
In 180° conduction mode of three phase inverter, each thyristor conducts for 180°. Thyristor pair in each arm i.e. (T1, T4), (T3, T6) and (T5, T2) are turned on with a time interval of 180°. It means that T1 remains on for 180° and T4 conducts for the next 180° of a cycle. Thyristors in the upper group i.e. (T1, T3 & T5) conducts at an interval of 120°. It implies that if T1 is fired at wt = 0° then T3 will be fired at 120° and T5 at 240°. Same is also true for lower group thyristors i.e. (T4, T6 & T2).
On the basis of the above mentioned firing scheme, a table has been prepared which shows the conduction period of various thyristors of three phase inverter.



You may notice from the first row of the above table that T1 conducts for 180° while T4 conducts for next 180° and then again T1 for 180° and so on. In the second row, T3 from the upper group is shown conducting 120° after T1 starts conducting. After T3 conducting for 180°, T6 conducts for the next 180° and again T3 for next 180° and so on. Further, in the third row, T5 from the upper group starts conducting 120° after T3 or 240° after T1. After T5 conduction for 180°, T2 conducts for next 180°, T5 for the next 180° and so on. In this way, the pattern for firing of thyristors are identified.

From the above table, the six steps for firing of thyristors may be formulated. As you can see from the table that, the overlapping period of the three SCRs are only 60°, this is the reason, it is said that each step for a three phase bridge inverter is 60°. Let us now try to define the steps.

Step-I: In step-I, thyristors T1, T6 and T5 conducts.

Step-II: T1, T2 and T6 conducts. Mind that T5 is turned off.

Step-III: Now, will have to turn off T6. Therefore, this step will comprise of conduction of thyristors T1, T2 and T3.

Step-IV: This time, T1 has to be turned off and hence, T2, T3 and T4 shall conduct is this step.

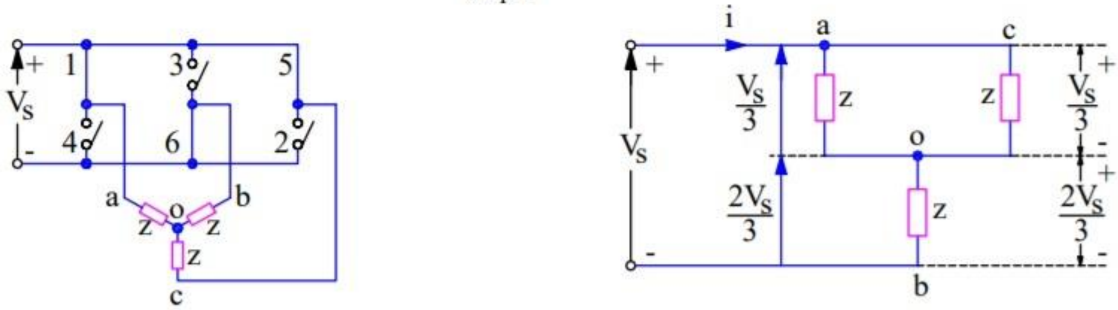
Step-V: T4, T3 and T5 conducts and T2 is turned off.

Step-VI: T4, T6 and T5 conducts and T3 is turned off.

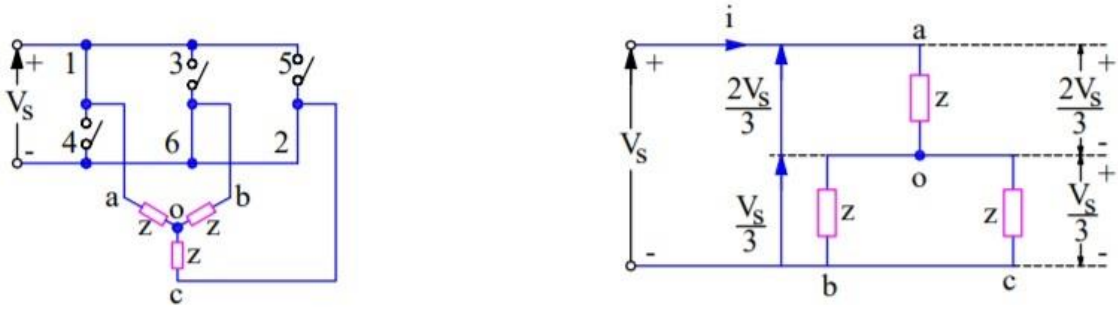
From the above steps, you may notice that in each step of 60°, only three SCRs are conducting – one from the upper group and two from the lower group or two from the upper group & one from lower group.

Well, it is time now to draw equivalent circuit diagram for each of the steps. Equivalent circuit for Step-I & II are shown below.

Step-I

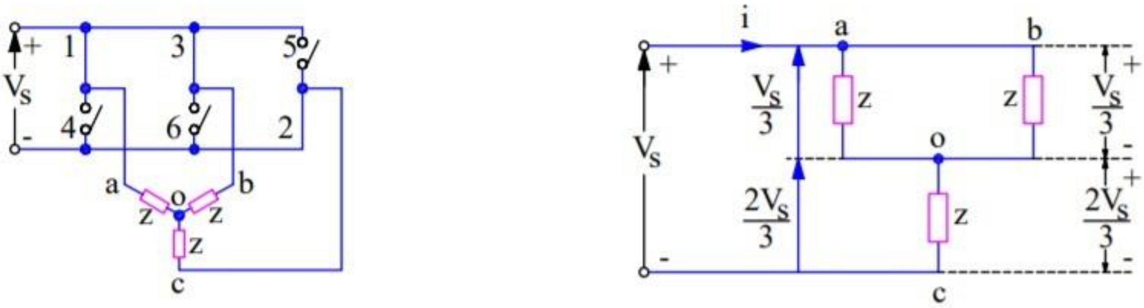


Step-II

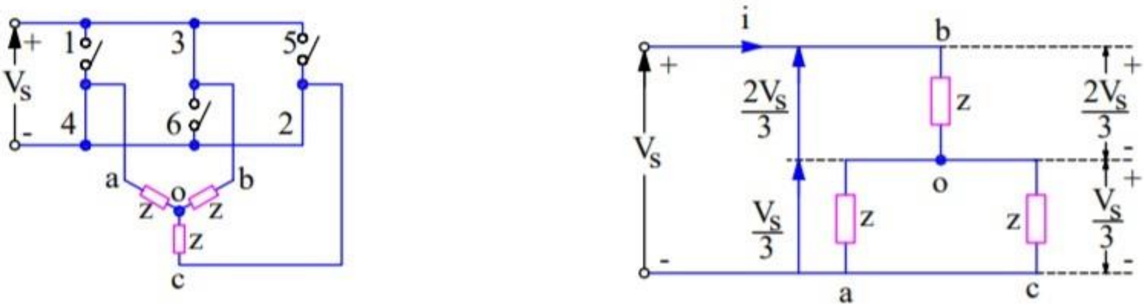


Equivalent circuit for Step-III & IV for three phase bridge inverter is shown below.

Step-III



Step-IV



During Step-I, SCRs 5, 6 & 1 are conducting. These are shown as closed switches and the non-conducting SCRs are shown as open switches. The load terminals a & c are connected to the positive bus of DC source whereas terminal b is connected to the negative bus of DC source. The load voltage $v_{ab} = v_{bc} = V_s$ in magnitude. The magnitude of neutral voltage can be calculated as shown below:

$$During\ Step-I, o \leq \omega t \leq \frac{\pi}{3} SCRs\ 5{,}6\ \&\ 1\ are\ only\ conducting$$

$$Current\ i = \frac{Vs}{Z + \frac{Z}{2}}$$

$$= \frac{2}{3}(\frac{Vs}{Z})$$

$$The\ line\ to\ neutral\ voltages\ are\ given\ as$$

$$Vao = Vco = \frac{iZ}{2} = \frac{Vs}{3}$$

$$Vob = iZ = \frac{2Vs}{3}$$

The above line to neutral voltage may be written as Vao = Vco= (Vs/3) and Vbo = -(2Vs/3).

$$During\ Step-II, \frac{\pi}{3} \leq \omega t \leq \frac{2\pi}{3} SCRs\ 6, 2\ \&\ 1\ are\ only\ conducting$$

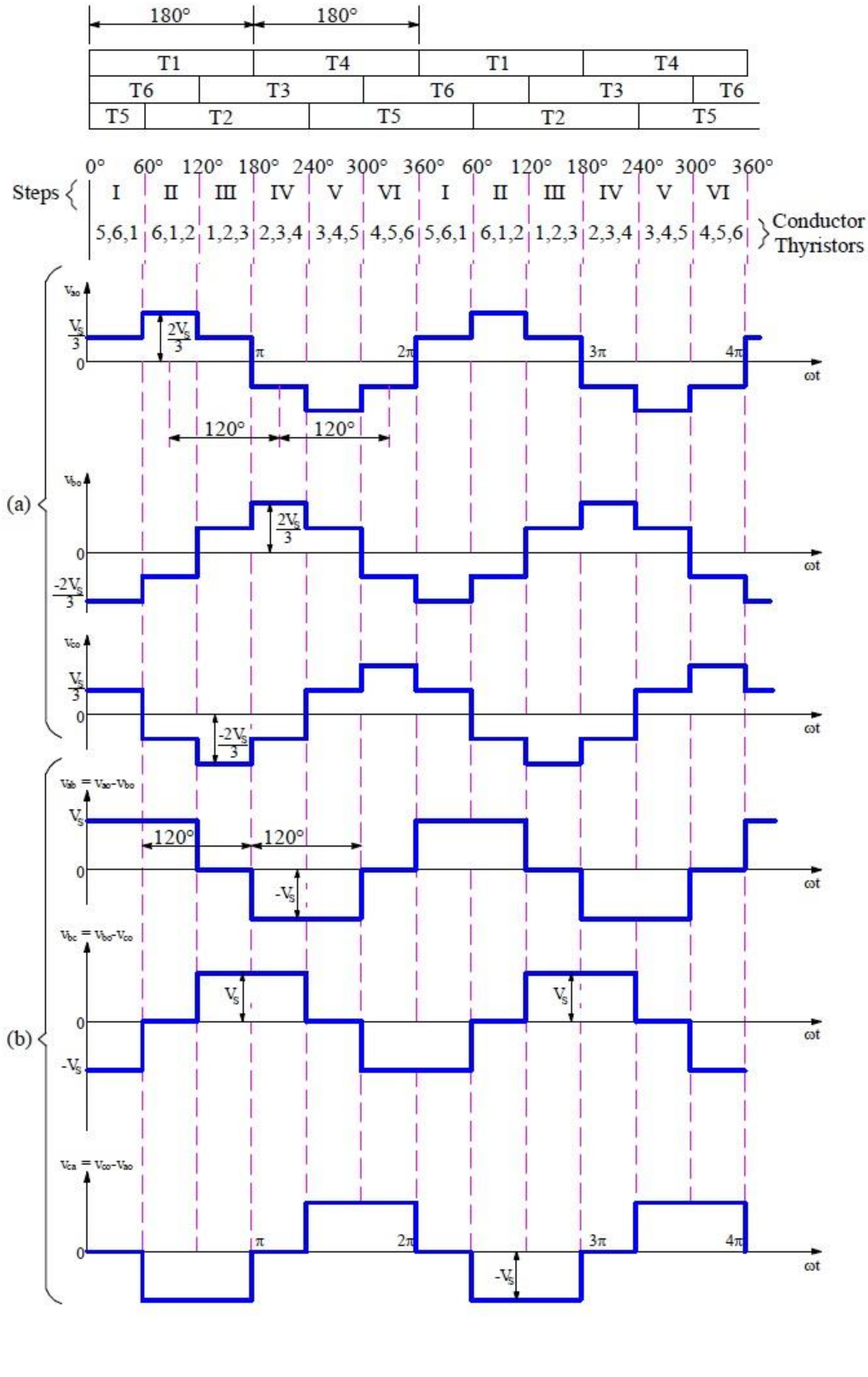
$$Current\ i = \frac{2}{3}(\frac{Vs}{Z})$$

$$The\ line\ to\ neutral\ voltages\ are\ given\ as$$

$$Vob = Voc = \frac{iZ}{2} = \frac{Vs}{3}$$

$$Vao = iZ = \frac{2Vs}{3}$$

The above line to neutral voltage may be written as Vbo = Voc= -(Vs/3) and Vao = (2Vs/3). The output voltages as calculated for step-I & II are plotted to get the output voltage waveform of the three phase bridge inverter. The variation in phase voltages for remaining steps are calculated in the same manner and plotted. The output voltage waveform is shown below.


180°
180°
T1
T4
T1
T4
T6
T3
T6
T3
T6
T5
T2
T5
T2
T5
0° 60° 120° 180° 240° 300° 360° 60° 120° 180° 240° 300° 360°
Steps
I II III IV V VI I II III IV V VI
5,6,1 6,1,2 1,2,3 2,3,4 3,4,5 4,5,6 5,6,1 6,1,2 1,2,3 2,3,4 3,4,5 4,5,6
Conductor Thyristors
(a)
(b)
ωt
120°
120°
$v_{ab} = v_{ao} - v_{bo}$
$v_{bc} = v_{bo} - v_{co}$
$v_{ca} = v_{co} - v_{ao}$

From the above waveform, it is clear that for each cycle of output voltage of each phase, six steps are required and each step has a duration of 60°.

The line voltage $V_{ab} = V_{ao} + V_{bo}$ or $V_{ab} = V_{ao} – V_{bo}$ is obtained by reversing V_{bo} and adding it to V_{ao}. This is shown in the output waveform (b). Similarly, line voltages V_{bc} & V_{ca} are plotted.

Following points may be noted from the output waveform of three phase bridge inverter:

- Phase voltages have six steps per cycle.
- Line voltages have one positive pulse and one negative pulse each of 120° duration.
- The phase and line voltages are out of phase by 120°.
- The line voltages represent a balanced set of three phase alternating voltages. These voltages are independent of the nature of load which may consists of any combination of resistance, inductance or / and capacitance or load may be balanced or unbalanced, linear or non-linear.

The purpose of diode D1 to D6 is to allow the flow of current through them when the load is inductive in nature.

Formula of Line and Phase Voltage:

RMS value of Line voltage V_L is given as below.

$$\mathbf{V_L = 0.8165V_s}$$

RMS Value of phase voltage V_p is given as below:

$$\mathbf{V_p = 0.4714V_s}$$

RMS value of fundamental line voltage V_{L1}

$$\mathbf{= 0.7797V_s}$$

RMS value of fundamental phase voltage V_{p1}

$$\mathbf{= 0.4502V_s}$$

Electrical installation

Component of LT Switchgear

Switch fuse unit (SFU) :

Switch fuse unit is compact combination, generally metal enclosed of a switch and a fuse.

It is very widely used for low and medium voltages.

The ratings of switch fuse units are in the range of 30,60,100,200, 400, 600 and 800 amperes.

Switch fuse units are available as 3 pole and 4 pole units.

They are developed for making capacities upto 46 kA.

They can safely break, depending upon ratings, currents of the order of 3 times the load current.

Switch fuse units can be installed on metal-clad switchgear.

The accurate current limiting operation and high breaking capacity office has resulted in a number of ingenious combination of switches and fuse to get an economical unit combining the best performance of each.

MCB :

MCB stands for Miniature Circuit Breaker. It automatically switches OFF electrical circuit during any abnormal condition in the electrical network such as overload & short circuitconditions. However, fuse may sense these conditions but it has to be replaced though MCB can be reset. The MCB is an electromechanical device which guards the electric wires &electrical load from overcurrent so as to avoid any kind of fire or electrical hazards. Handling MCB is quite safer and it quickly restores the supply.When it comes to house applications, MCB is the most preferred choice for overload and short circuit protection. MCB can be reset very fast & don't have any maintenance cost. MCB works on bi-metal respective principle which provides protection against overload current&solenoidshort circuit current.

ELCB :

ELCB stands for Earth Leakage Circuit Breaker. They have the same function as RCCB but are voltage sensor devise. However, this is an old technology & is not in common use. ELCB refers to voltage operated earth leakage device. It is not preferable as it can only detect current that flow back through the main earth wire. ELCB is working based on Earth leakage current. These devices measured the voltage on the earth conductor; if this voltage was not zero this indicated a current leakage to earth.

MCCB :

MCCB stands for Molded Case Circuit Breaker. It is another type of electrical protection device which is used when load current exceeds the limit of a miniature circuit breaker. The **MCCB** provides protection against overload, short circuit faults and is also used for switching the circuits. It can be used for higher current rating and fault level even in domestic applications. The wide current ratings and high breaking capacity in MCCB find their use in industrial applications. **MCCB** can be used for protection of capacitor bank, generator protection and main electric feeder distribution. It offers adequate protection whenever an application requires discrimination, adjustable overload setting or earth fault protection.

Types of wires and cables

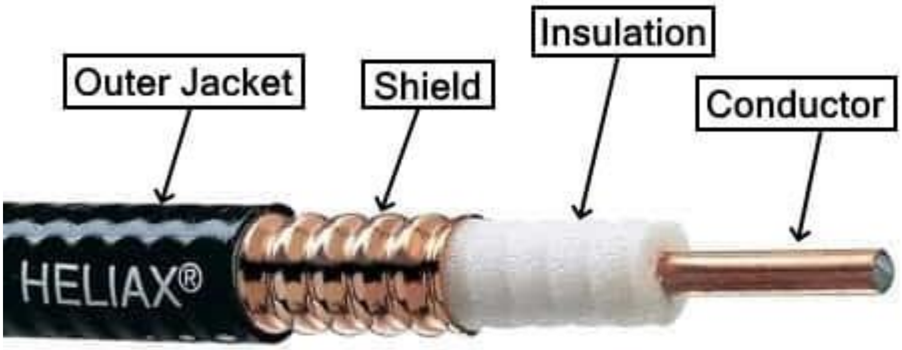
Electrical cable and wires are considered as a same thing. In fact they are quite different. A wire is made of a single electrical conductor while a cable is a group or bundle of multiple wires inside a common sheathing. Both of them are used for carrying electrical current.

Communications Cable

The types of cables and wires that are used for communication or signal transmission purposes are called communication cable. There sole purpose is to transmit information. Here are 3 types of communications cables:
Coaxial Cable

Coax or coaxial cable is type of electrical cable made from four layers, forming coaxial shape (having common axis or center). The central part of coaxial cable is a conductor covered by an insulating plastic layer which is surrounded by a metallic shield. On top that is a fourth layer of plastic insulation.
The coaxial cable is used for transmission of high frequency signal. This is why the metallic shield is used for blocking noise interference. It is commonly used for cable television signal distribution, signal transmission between antennas, transmitter and receiver.
The coaxial cable is further divided into various types and each of them has their own application.
Hard line Coaxial or Heliax Cable

Hardline coaxial or mostly known by its trademark name Heliax cable is a thick coaxial cable with its center solid conductor made from copper and the shield made from copper or silver tubing. It is specifically used for high frequency broadcast transmission. It can carry hundreds of channels and is usually installed between a transmitter on ground and aerial antenna.



Radiating or Leaky Coaxial Cable

Radiating or leaky coaxial cable is another type of coaxial cable where the shield is deliberately designed in such way to radiate RF waves. The shield is made with slots tuned for specific RF wavelength that provide bi directional leakage effect between transmitter and receiver. This type of coaxial cable is used in places where antenna is not feasible such as underground tunnels, elevator shafts etc.

RG-6 Coaxial Cable

RG-6 is the most common type of coaxial cable used for signal transmission in residential and commercial applications. It is made from a solid copper wire with plastic insulation covered by an aluminum foil and a braided shield for protection against interference. It is used for audio and video signal transmission in application such as cable TV, Satellite TV signal and radio etc.

Triaxial or Triax Cable

Triaxial is another type of coaxial cable which includes another layer of insulation and shield over the top of existing shield. The second or outer shield is grounded to protect the inner shield from electromagnetic interference.

Twin-axial or Twinax Cable

Twinax cable is type of coaxial cable similar to RG-6 but with two inner conductors instead of one. The two insulated inner conductors are twisted together surrounded by a braided shield. It is used for high-speed short-range signal communication usually for 10 Gigabit Ethernet Network.

Semi-rigid Coaxial Cable

Semi-rigid coax cable is another type of coax cable where the outer sheath is from solid copper with an inner conductor. The outer shield provides better interference protection. Due to the tube like structure of the shield, it is not very flexible and is not meant to bent after initial forming.

Earthing

The process of transferring the immediate discharge of the electrical energy directly to the earth by the help of the low resistance wire is known as the electrical earthing. The electrical earthing is done by connecting the non-current carrying part of the equipment or neutral of supply system to the ground. Mostly, the galvanised iron is used for the earthing. The earthing provides the simple path to the leakage current. The shortcircuit current of the equipment passes to the earth which has zero potential. Thus, protects the system and equipment from damage

Types of Electrical Earthing

The electrical equipment mainly consists of two non-current carrying parts. These parts are neutral of the system or frame of the electrical equipment. From the earthing of these two non-current carrying parts of the electrical system earthing can be classified into two types.

- Neutral Earthing
- Equipment Earthing.

Neutral Earthing

In neutral earthing, the neutral of the system is directly connected to earth by the help of the GI wire. The neutral earthing is also called the system earthing. Such type of earthing is mostly provided to the system which has star winding. For example, the neutral earthing is provided in the generator, transformer, motor etc.

Equipment Earthing

Such type of earthing is provided to the electrical equipment. The non-current carrying part of the equipment like their metallic frame is connected to the earth by the help of the conducting wire. If any fault occurs in the apparatus, the short-circuit current to pass the earth by the help of wire. Thus, protect the system from damage.

Importance of Earthing

The earthing is essential because of the following reasons

- The earthing protects the personnel from the shortcircuit current.
- The earthing provides the easiest path to the flow of shortcircuit current even after the failure of the insulation.
- The earthing protects the apparatus and personnel from the high voltage surges and lightning discharge.

Earthing can be done by electrically connecting the respective parts in the installation to some system of electrical conductors or electrodes placed near the soil or below the ground level. The earthing mat or electrode under the ground level have flat iron riser through which all the non-current-carrying metallic parts of the equipment are connected.

When the fault occurs the fault current from the equipment flows through the earthing system to the earth and thereby protect the equipment from the fault current. At the time of the fault, the earth mat conductors rise to the voltage which is equal to the resistance of the earth mat multiplied by a ground fault.

Types of Battery

NICKEL CADMIUM BATTERIES

The active components of a rechargeable NiCd battery in the charged state consist of nickel hydroxide (NiOOH) in the positive electrode and cadmium (Cd) in the negative electrode. For the electrolyte, potassium hydroxide (KOH) is normally used. Due to their low internal resistance and the very good current conducting properties, NiCd batteries can supply extremely high currents and can be recharged rapidly. These cells are capable of sustaining temperatures down to -20°C. The selection of the separator (nylon or polypropylene) and the electrolyte (KOH, LiOH, NaOH) influence the voltage conditions in the case of a high current discharge, the service life and the overcharging capability. In the case of misuse, a very high-pressure may arise quickly. For this reason, cells require a safety valve. NiCd cells generally offer a long service life thereby ensuring a high degree of economy.

NICKEL METAL HYDRIDE BATTERIES

The active components of a rechargeable NiMH battery in the charged state consist of nickel hydroxide (NiOOH) in the positive electrode and a hydrogen storing metal alloy (MH) in the negative electrode as well as a potassium hydroxide (KOH) electrolyte. Compared to rechargeable NiCd batteries, NiMH batteries have a higher energy density per volume and weight.

LITHIUM ION BATTERIES

The term lithium ion battery refers to a rechargeable battery where the negative electrode (anode) and positive electrode (cathode) materials serve as a host for the lithium ion (Li+). Lithium ions move from the anode to the cathode during discharge and are intercalated into (inserted into voids in the crystallographic structure of) the cathode. The ions reverse direction during charging. Since lithium ions are intercalated into host materials during charge or discharge, there is no free lithium metal within a lithium-ion cell. In a lithium ion cell, alternating layers of anode and cathode are separated by a porous film (separator). An electrolyte composed of an organic solvent and dissolved lithium salt provides the media for lithium ion transport. For most commercial lithium ion cells, the voltage range is approximately 3.0 V (discharged, or 0 % state-of-charge, SOC) to 4.2 V (fully charged, or 100% SOC).

SMALL SEALED LEAD ACID BATTERIES

Rechargeable small sealed lead acid (SSLA) batteries, which are valve-regulated lead acid batteries, (VRLA batteries) do not require regular addition of water to the cells, and vent less gas than flooded (wet) lead-acid batteries.SSLA batteries are sometimes referred to as "maintenance free" batteries. The reduced venting is an advantage since they can be used in confined or poorly ventilated spaces.

There are two types of VRLA batteries,

- Absorbed glass mat (AGM) battery
- Gel battery ("gel cell")

An absorbed glass mat battery has the electrolyte absorbed in a fiber-glass mat separator. A gel cell has the electrolyte mixed with silica dust to form an immobilized gel.

SSLA batteries include a safety pressure relief valve. As opposed to flooded batteries, a SSLA battery is designed not to spill its electrolyte if it is inverted.

Specifications, Standards and Hype

Batteries may be advertised as Long Life, High Capacity, High Energy, Deep Cycle, Heavy Duty, Fast Charge, Quick Charge, Ultra and other, ill defined, parameters and there are few industry or legal standards defining exactly what each of these terms means. Advertising words can mean whatever the seller wants them to mean. Apart from the basic battery design, performance actually depends on how the batteries are used and also on the environmental conditions under which they are used, but these conditions are rarely, if ever, specified in mass market advertising. For the consumer this can be very confusing or misleading. The battery industry itself however does not use such vague terms to specify battery performance and specifications normally include a statement defining or limiting the operating or environmental conditions within which the claimed performance can be delivered.
The following section outlines key parameters used to characterise the cells or batteries and shows how these parameters may vary with the operating conditions.

Discharge Curves

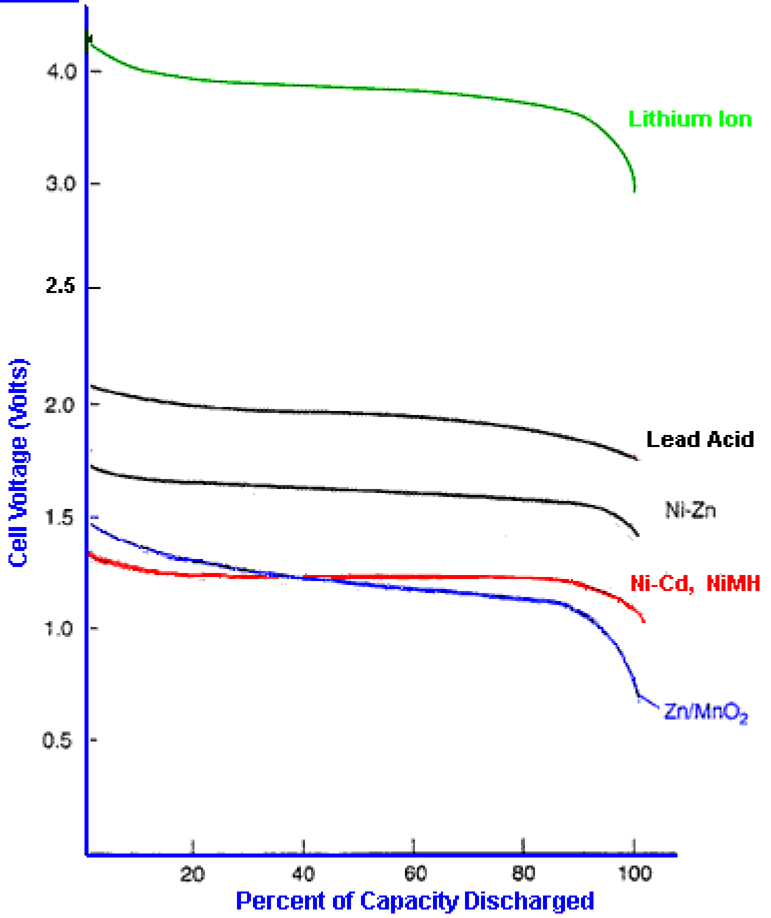
Energy cells have been developed for a wide range of applications using a variety of different technologies, resulting in a wide range of available performance characteristics. The graphs below show some of the main factors an applications engineer should take into account when specifying a battery to match the performance requirements of the end product.

Cell Chemistry

The nominal voltage of a galvanic cell is fixed by the electrochemical characteristics of the active chemicals used in the cell, the so called cell chemistry. The actual voltage appearing at the terminals at any particular time, as with any cell, depends on the load current and the internal impedance of the cell and this varies with, temperature, the state of charge and with the age of the cell.

The graph below shows typical discharge discharge curves for cells using a range of cell chemistries when discharged at 0.2C rate. Note that each cell chemistry has its own characteristic nominal voltage and discharge curve. Some chemistries such as Lithium Ion have a fairly flat discharge curve while others such as Lead acid have a pronounced slope. The power delivered by cells with a sloping discharge curve falls progressively throughout the discharge cycle. This could give rise to problems for high power applications towards the end of the cycle. For low power applications which need a stable supply voltage, it may be necessary to incorporate a voltage regulator if the slope is too steep. This is not usually an option for high power applications since the losses in the regulator would rob even more power from the battery.

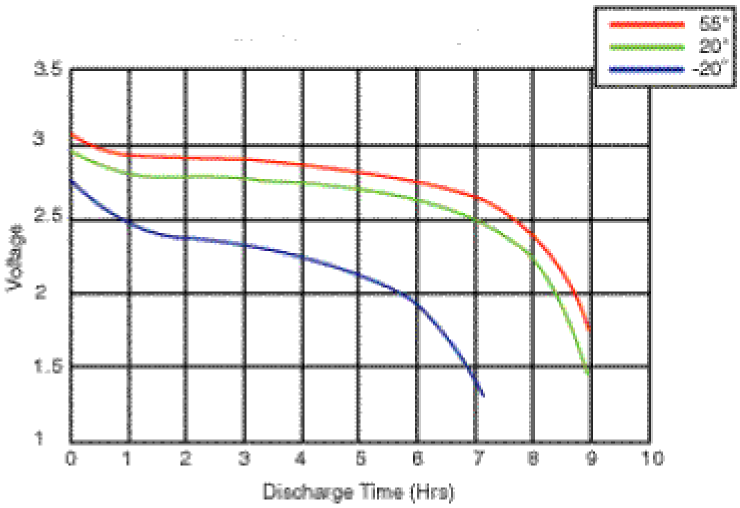
A flat discharge curve simplifies the design of the application in which the battery is used since the supply voltage stays reasonably constant throughout the discharge cycle. A sloping curve facilitates the estimation of the State of Charge of the battery since the cell voltage can be used as a measure of the remaining charge in the cell. Modern Lithium Ion cells have a very flat discharge curve and other methods must be used to determine the State of Charge



The X axis shows the cell characteristics normalised as a percentage of cell capacity so that the shape of the graph can be shown independent of the actual cell capacity. If the X axis was based on discharge time, the length of each discharge curve would be proportional to the nominal capacity of the cell.

Temperature Characteristics

Cell performance can change dramatically with temperature. At the lower extreme, in batteries with aqueous electrolytes, the electrolyte itself may freeze setting a lower limit on the operating temperature. At low temperatures Lithium batteries suffer from Lithium plating of the anode causing a permanent reduction in capacity. At the upper extreme the active chemicals may break down destroying the battery. In between these limits the cell performance generally improves with temperature. See also Thermal Management and Battery Life for more details.



The above graph shows how the performance of Lithium Ion batteries deteriorates as the operating temperature decreases.
Probably more important is that, for both high and low temperatures, the further the operating temperature is from room temperature the more the cycle life is degraded.
See Lithium Battery Failures.

Self Discharge Characteristics

The self discharge rate is a measure of how quickly a cell will lose its energy while sitting on the shelf due to unwanted chemical actions within the cell. The rate depends on the cell chemistry and the temperature.