IDC TECHNOLOGIES

Technology Training that Works

Presents

Practical Troubleshooting, Maintenance & Protection of AC Electrical Motors & Drives

Revision 6.1

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Technical Information that Works

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Acknowledgements

Who is IDC Technologies?

IDC Technologies is a specialist in the field of industrial communications, telecommunications, automation and control and has been providing high quality training for more than six years on an international basis from offices around the world.

IDC consists of an enthusiastic team of professional engineers and support staff who are committed to providing the highest quality in their consulting and training services.

The Benefits to you of Technical Training Today

The technological world today presents tremendous challenges to engineers, scientists and technicians in keeping up to date and taking advantage of the latest developments in the key technology areas.

- The immediate benefits of attending IDC workshops are:
- Gain practical hands-on experience
- Enhance your expertise and credibility
- Save $$$s for your company
- Obtain state of the art knowledge for your company
- Learn new approaches to troubleshooting
- Improve your future career prospects

The IDC Approach to Training

All workshops have been carefully structured to ensure that attendees gain maximum benefits. A combination of carefully designed training software, hardware and well written documentation, together with multimedia techniques ensure that the workshops are presented in an interesting, stimulating and logical fashion.

IDC has structured a number of workshops to cover the major areas of technology. These courses are presented by instructors who are experts in their fields, and have been attended by thousands of engineers, technicians and scientists world-wide (over 11,000 in the past two years), who have given excellent reviews. The IDC team of professional engineers is constantly reviewing the courses and talking to industry leaders in these fields, thus keeping the workshops topical and up to date.

Technical Training Workshops

IDC is continually developing high quality state of the art workshops aimed at assisting engineers, technicians and scientists. Current workshops include:

Instrumentation & Control
- Practical Automation and Process Control using PLC's
- Practical Data Acquisition using Personal Computers and Standalone Systems
- Practical On-line Analytical Instrumentation for Engineers and Technicians
- Practical Flow Measurement for Engineers and Technicians
- Practical Intrinsic Safety for Engineers and Technicians
- Practical Safety Instrumentation and Shut-down Systems for Industry
- Practical Process Control for Engineers and Technicians
- Practical Programming for Industrial Control – using (IEC 1131-3;OPC)
- Practical SCADA Systems for Industry
- Practical Boiler Control and Instrumentation for Engineers and Technicians
- Practical Process Instrumentation for Engineers and Technicians
- Practical Motion Control for Engineers and Technicians
- Practical Communications, SCADA & PLC's for Managers

Communications
- Practical Data Communications for Engineers and Technicians
- Practical Essentials of SNMP Network Management
- Practical Field Bus and Device Networks for Engineers and Technicians
- Practical Industrial Communication Protocols
- Practical Fibre Optics for Engineers and Technicians
- Practical Industrial Networking for Engineers and Technicians
- Practical TCP/IP & Ethernet Networking for Industry
- Practical Telecommunications for Engineers and Technicians
- Practical Radio & Telemetry Systems for Industry
- Practical Local Area Networks for Engineers and Technicians
- Practical Mobile Radio Systems for Industry

Electrical

- Practical Power Systems Protection for Engineers and Technicians
- Practical High Voltage Safety Operating Procedures for Engineers & Technicians
- Practical Solutions to Power Quality Problems for Engineers and Technicians
- Practical Communications and Automation for Electrical Networks
- Practical Power Distribution
- Practical Variable Speed Drives for Instrumentation and Control Systems

Project & Financial Management

- Practical Project Management for Engineers and Technicians
- Practical Financial Management and Project Investment Analysis
- How to Manage Consultants

Mechanical Engineering

- Practical Boiler Plant Operation and Management for Engineers and Technicians
- Practical Centrifugal Pumps – Efficient use for Safety & Reliability

Electronics

- Practical Digital Signal Processing Systems for Engineers and Technicians
- Practical Industrial Electronics Workshop
- Practical Image Processing and Applications
- Practical EMC and EMI Control for Engineers and Technicians

Information Technology

- Personal Computer & Network Security (Protect from Hackers, Crackers & Viruses)
- Practical Guide to MCSE Certification
- Practical Application Development for Web Based SCADA

Comprehensive Training Materials

Workshop Documentation

All IDC workshops are fully documented with complete reference materials including comprehensive manuals and practical reference guides.

Software

Relevant software is supplied with most workshops. The software consists of demonstration programs which illustrate the basic theory as well as the more difficult concepts of the workshop.

Hands-On Approach to Training

The IDC engineers have developed the workshops based on the practical consulting expertise that has been built up over the years in various specialist areas. The objective of training today is to gain knowledge and experience in the latest developments in technology through cost effective methods. The investment in training made by companies and individuals is growing each year as the need to keep topical and up to date in the industry which they are operating is recognized. As a result, the IDC instructors place particular emphasis on the practical hands-on aspect of the workshops presented.

On-Site Workshops

In addition to the quality of workshops which IDC presents on a world-wide basis, all IDC courses are also available for on-site (in-house) presentation at our clients' premises. On-site training is a cost effective method of training for companies with many delegates to train in a particular area. Organizations can save valuable training $$$'s by holding courses on-site, where costs are significantly less. Other benefits are IDC's ability to focus on particular systems and equipment so that attendees obtain only the greatest benefits from the training.

All on-site workshops are tailored to meet with clients training requirements and courses can be presented at beginners, intermediate or advanced levels based on the knowledge and experience of delegates in attendance. Specific areas of interest to the client can also be covered in more detail. Our external workshops are planned well in advance and you should contact us as early as possible if you require on-site/customized training. While we will always endeavor to meet your timetable preferences, two to three month's notice is preferable in order to successfully fulfil your requirements. Please don't hesitate to contact us if you would like to discuss your training needs.

Technical Information that Works

Customized Training

In addition to standard on-site training, IDC specializes in customized courses to meet client training specifications. IDC has the necessary engineering and training expertise and resources to work closely with clients in preparing and presenting specialized courses.

These courses may comprise a combination of all IDC courses along with additional topics and subjects that are required. The benefits to companies in using training are reflected in the increased efficiency of their operations and equipment.

Training Contracts

IDC also specializes in establishing training contracts with companies who require ongoing training for their employees. These contracts can be established over a given period of time and special fees are negotiated with clients based on their requirements. Where possible, IDC will also adapt courses to satisfy your training budget.

References from various international companies to whom IDC is contracted to provide on-going technical training are available on request.

Some of the thousands of Companies worldwide that have supported and benefited from IDC workshops are:

Alcoa, Allen-Bradley, Altona Petrochemical, Aluminum Company of America, AMC Mineral Sands, Amgen, Arco Oil and Gas, Argyle Diamond Mine, Associated Pulp and Paper Mill, Bailey Controls, Bechtel, BHP Engineering, Caltex Refining, Canon, Chevron, Coca-Cola, Colgate-Palmolive, Conoco Inc, Dow Chemical, ESKOM, Exxon, Ford, Gillette Company, Honda, Honeywell, Kodak, Lever Brothers, McDonnell Douglas, Mobil, Modicon, Monsanto, Motorola, Nabisco, NASA, National Instruments, National Semi-Conductor, Omron Electric, Pacific Power, Pirelli Cables, Proctor and Gamble, Robert Bosch Corp, Siemens, Smith Kline Beecham, Square D, Texaco, Varian, Warner Lambert, Woodside Offshore Petroleum, Zener Electric

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Basic principles of motor technology

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- To refresh basic electrical concepts
- To define basic concepts of transformer
- To refresh single phase power concepts
- To refresh 3-phase power concepts
- Introduction to rotating electrical machines

1.1 Introduction

A significant proportion of industrial electricity is about single-phase and three-phase transformers, AC and DC machines. In this context, we will study the electrical circuits and their construction, design, testing, operation, and maintenance.

For troubleshooting electrical equipment and control circuits, it is important to understand the basic principles on which the electrical equipment works. The following sections will outline the basic electrical concepts.

1.1.1 Basic electrical concepts

In each plant, the mechanical movement of different equipments is caused by an electric prime mover (motor). Electrical power is derived from either utilities or internal generators and is distributed through transformers to deliver usable voltage levels.

Electricity is found in two common forms:

- A.C. (Alternating Current)
- D.C. (Direct Current)

Electrical equipments can run on either of the AC/DC forms of electrical energies. The selection of energy source for equipment depends on its application requirements. Each energy source has its own merits and demerits.

Industrial AC voltage levels are roughly defined as L.V., (Low Voltage) and H.V., (High Voltage) with frequency of 50 Hz. to 60 Hz.

An electrical circuit has the following three basic components irrespective of its electrical energy form:

- Voltage (volts)
- Ampere (Amps)
- Resistance (Ohms)

Voltage is defined as the electrical potential difference that causes electrons to flow.

Current is defined as the flow of electrons and is measured in Amperes.

Resistance is defined as the opposition to the flow of electrons and is measured in Ohms.

All three are bond together with Ohm's law which gives the following relation between the three:

$$\boxed{V = I \times R}$$

where
V   Voltage
I   Current
R   Resistance

Power

In DC circuits, power (watts) is simply a product of voltage and current.

$$\boxed{P = V \times I}$$

For AC circuits, the formula holds true for purely resistive circuits; however, for the following types of AC circuits, power is not just a product of voltage and current.

Apparent power is the product of voltage and Ampere, i.e., VA or KVA is known as apparent power. Apparent power is total power supplied to a circuit inclusive of the true and reactive power.

Real power or true power is the power that can be converted into work and is measured in watts.

Reactive power: If the circuit is of an inductive or capacitive type, then the reactive component consumes power and cannot be converted into work. This is known as reactive power and is denoted by the unit VAR.

Relationship between powers

Apparent Power (VA) = V × A

$$\text{True Power (Watts)} = VA \times \cos\phi$$

$$\text{Reactive Power (VAR)} = VA \times \sin\phi$$

Power factor

Power factor defined as the ratio of real power to apparent power. The maximum value it can carry is either 1 or 100%, which would be obtained in a purely resistive circuit.

$$\text{Power factor} = \frac{\text{True power (Watts)}}{\text{Apparent power (VA)}} = \frac{kW}{kVA}$$

Percentage voltage regulation

$$\% \text{ Reg} = \frac{(\text{No load voltage - Full load voltage})}{\text{Full load voltage}}$$

Electrical energy

This is calculated as the amount of electrical energy used in an hour and expressed as follows:

Kilowatt-hour $= \text{kW} \times \text{h}$

where
kW   kilowatt
h   hour

Types of circuits

There are only two electrical circuits, Series and Parallel circuits.

- **A** *Series circuit* is defined as a circuit in which the elements in a series carry the same current, while voltage drop across each may be different
- **A** *Parallel circuit* is defined as a circuit in which the elements in parallel have the same voltage, but the currents may be different

1.1.2   Transformer

A transformer is a device that transforms voltage from one level to another. They are widely used in power systems. With the help of transformers, it is possible to transmit power at an economical transmission voltage and to utilize power at an economically effective voltage.

Basic principle

A transformer's function is based on mutual emf induction between two coils, which are magnetically coupled.

The AC current flows through one coil, turning the coil into a primary coil, and produces a magnetic field. The magnetic field lines are made to pass through the second coil, called the secondary coil, which results in an induction of an AC potential. Laminated steel sheets provides continuous magnetic path of low reluctance.

Typically, the coil connected to the source is known as the Primary, and the coil applied to the load is the Secondary coil.

A schematic diagram of a single-phase transformer is shown in the Figure 1.1.
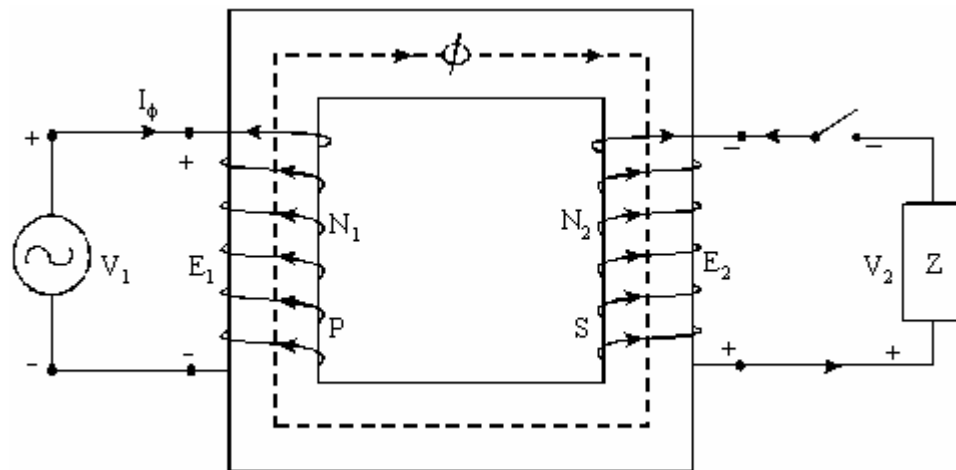
Figure 1.1
Schematic diagram of a single-phase transformer

A single-phase transformer consists mainly of a magnetic core on which two windings – primary and secondary – are wound. The primary winding is supplied with an AC source of supply voltage V1. The current I∑ flowing in the primary winding produce flux which varies with time. This flux links with both the windings and produces induced emf's. The emf produced in the primary winding is equal and opposite of the applied voltage (neglecting losses.) The emf is also induced in the secondary winding due to this mutual flux. The magnitude of the induced emf depends on the ratio of the number of turns in the primary and the secondary windings of the transformer.

Potential induced

There is a very simple and straight relationship between the potential across the primary coil and the potential induced in the secondary coil.

The ratio of the primary potential to the secondary potential is the ratio of the number of turns in each and is represented as follows:

$$\boxed{\dfrac{N_1}{N_2} = \dfrac{V_1}{V_2}}$$

The concepts of step-up and step-down transformers function on similar relation.

A step-up transformer increases the output voltage by taking N2 > N1 and a step-down transformer decreases the output voltage by taking N2 < N1.

Current induced

When the transformer is loaded, then the current is inversely proportional to the voltages and is represented as per follows:

$$\boxed{\dfrac{V_1}{V_2} = \dfrac{I_2}{I_1} = \dfrac{N_1}{N_2}}$$

EMF equation of a transformer:
R.M.S.value of the induced emf in the primary winding is:

$$E_1 = 4.44 \times f \times N_1 \times \phi_m$$

R.M.S.value of the induced emf in the secondary winding is:

$$E_2 = 4.44 \times f \times N_2 \times \phi_m$$

where
N_1 Number of turns in primary
N_2 Number of turns in secondary
ϕ_m Maximum flux in core
f   Frequency of AC input in Hz.

1.1.3   Ideal transformer

The following assumptions are made in the case of an ideal transformer:

- No loss or gain of energy takes place
- Winding have no ohm resistances
- The flux produced is confined to the core of the transformer, which links fully both the windings, i.e., there is no flux leakage
- Hence, there are no I^2R losses and core losses
- The permeability of the core is high so that the magnetizing current required to produce the flux and to establish it in the core is negligible
- Eddy current and hysteresis losses are negligible

1.1.4   Types of transformers

- As per the type of construction
    - *Core type:* Windings surround a considerable part of the core
    - *Shell type:* Core surrounds a considerable portion of the windings
- As per cooling type:
    - *Oil filled self-cooled:* Small and medium sized distribution transformers
    - *Oil filled water-cooled:* High voltage transmission line outdoor transformers
    - *Air blast type:* Low voltage transformers
- As per application:
    - *Power transformer:* These are large transformers used to change voltage levels and current levels as per requirement. Power transformers are usually used in either a distribution or a transmission line
    - *Potential transformer:* These are precision voltage step-down transformers used along with low range voltmeters to measure high voltages

- *Current transformer:* These transformers are used for the measurement of current where the current carrying conductor is treated as a primary transformer. This transformer isolates the instrument from high voltage line, as well as step down the current in a known ratio
- *Isolation transformer:* These are used to isolate two different circuits without changing the voltage level or current level

A few important points about transformers:

- Used to transfer energy from one AC circuit to another
- Frequency remains the same in both the circuits
- No ideal transformer exists
- Also used in metering applications (current transformer i.e. CT, potential transformers, i.e., PT)
- Used for isolation of two different circuits (isolation transformers)
- Transformer power is expressed in VA (Volt amperes)
- Transformer polarity is indicated by using dots. If primary and secondary windings have dots at the top and bottom positions or vice versa in diagrams then it means that the phases are in an inverse relationship

1.1.5 Connections of a single-phase transformer

Depending on the application requirement, two or more transformers have to be connected in a series or parallel circuit. Such connections can be undertaken as depicted in the following diagram examples:

Series connection of two single phase transformers
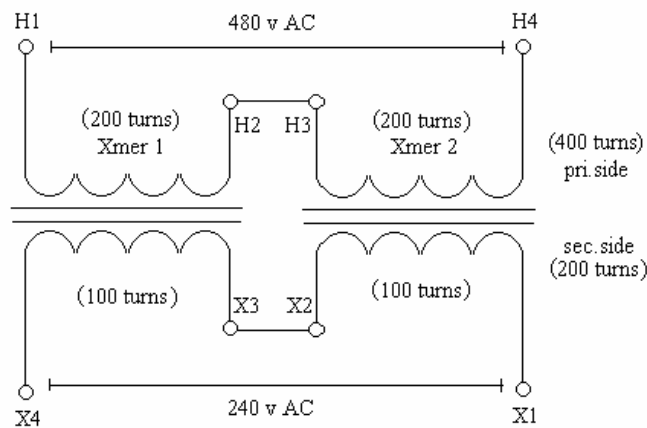
Figure 1.2
Series connection of two single-phase transformers

As shown in the above Figure 1.2, two transformers can be connected in a series connection. If both are connected as above then voltage times, two of voltage rating of the

individual transformer can be applied. Their current rating must be equal and high enough to carry load current. Precaution should be taken to connect transformers windings keeping in mind the polarity. In the above example, primary total turns to secondary total turns are in the 2:1 ratio, leading to half voltage.

Parallel connection of two single-phase transformers
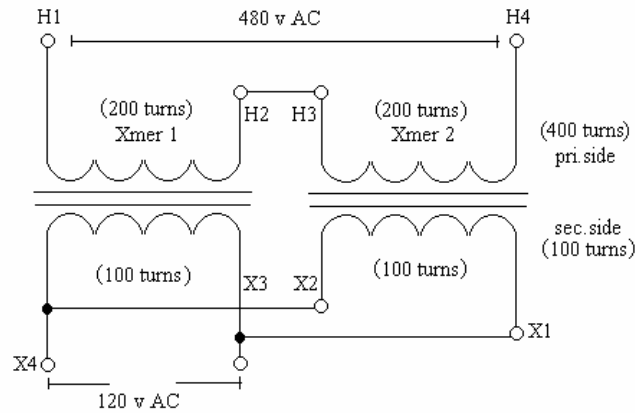
Figure 1.3
Parallel connection of two single-phase transformers

As shown in the above Figure 1.3, two transformers are connected in series on the primary side while the secondary sides are connected in parallel.

On the primary side, the number of turns is added while on the secondary side they remain as it is due to their parallel condition.

This kind of configuration is particularly useful in applications that require a single transformer in standby operation. In addition, it is useful in applications where additional load maybe added to the single transformer. In such instances, rather than replacing the older transformer, connecting one more transformer in parallel with the existing transformer helps to increase the overall KVA ratings.

L.V.D.T. (Linear Voltage Differential Transformer) is the best practical example of the basic transformer and its series connection.

1.1.6   3-phase transformers

Large-scale generation of electric power is generally 3-phasic with voltages in 11 or 32 kvolts. For such high 3-phasic voltage transmission and distribution requires use of the 3-phase step-up and step-down transformers.

Previously, it was common practice to use three single-phase transformers in place of a single 3-phase transformer. However, the consequent evolution of the 3-phase transformer proved space saving and economical as well.

Still, construction wise a 3-phase transformer is a combination of three single-phase transformers with three primary and three secondary windings mounted on a core having three legs.

Commonly used 3-phases are:

- 3-phase three wire (Delta)
- 3-phase four wire (Star)

Delta connection

It consists of 3-phase windings connected end-to-end and 120 degrees apart from each other electrically. Generally, the delta 3-wire system is used for an unbalanced load system. The 3-phase voltages remain constant regardless of load imbalance (see Figure 1.4).
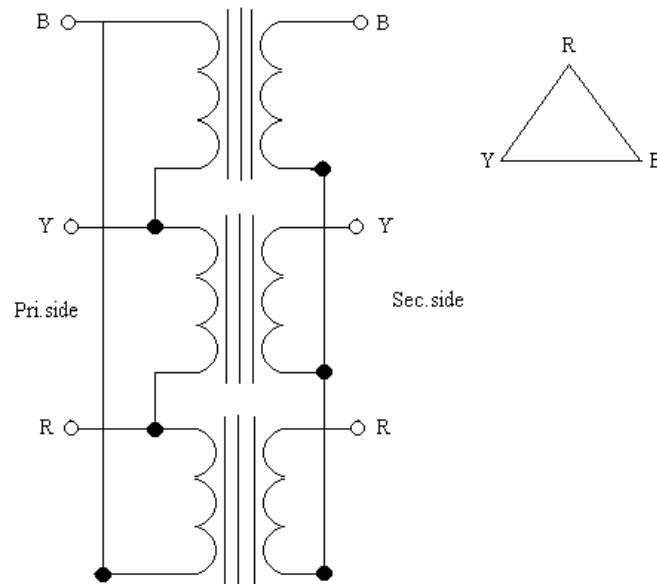
Figure 1.4
3- phase transformer delta connection on primary side

Relationship between line and phase voltages:
$$V_L = V_{ph}$$

where
V_L Line voltage
V_{ph} Phase voltage

Relationship between line and phase currents:
$$I_L = \sqrt{3}\ I_{ph}$$

where
I_L Line current
I_{ph} Phase current

3-Phase 4-wire star connections

The star type of construction allows a minimum number of turns per phase (since phase voltage is $1/\sqrt{3}$ of line voltage), so it is the most economical method. Each winding at one

end is connected to a common end, like a neutral point; therefore, on the whole there are four wires.

This connection works satisfactorily only if the load is balanced. With unbalanced load to the neutral, the neutral point will drift causing unequal phase voltages (see Figure 1.5).
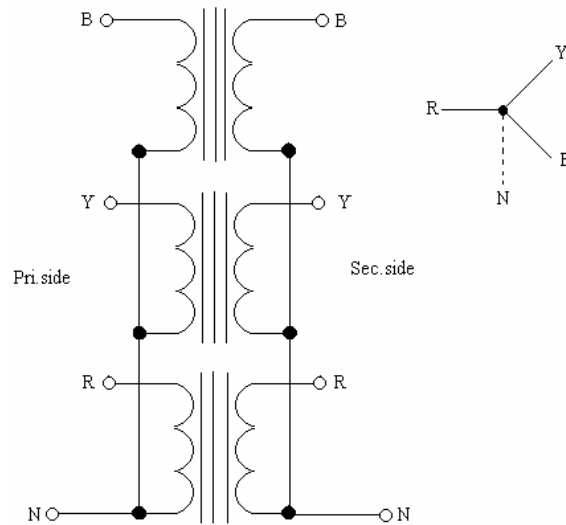
Figure 1.5
Three phase 4-wire transformer star connection

Relationship between line and phase voltages:
$$V_L = \sqrt{3}\ V_{ph}$$

where
V_L Line voltage
V_{ph} Phase voltage

Relationship between line and phase currents:
$$I_L = I_{ph}$$

where
I_L Line current
I_{ph} Phase current

Output power of a transformer in kW:

$$\boxed{P = \sqrt{3} \times V_L \times I_L \times \cos\phi\left[W\right]}$$

where
V_L Line voltage
I_L Line current
$\cos\phi$ power factor

Possible combinations of star and delta

The primary and secondary windings of three single-phase transformers or a 3-phase transformer can be connected in the following ways:

- Primary in delta – secondary in delta
- Primary in delta – secondary in star
- Primary in star – secondary in star
- Primary in star – secondary in delta

Figure 1.6 shows the various types of connections of 3-phase transformers. On the primary side, V is the line voltage and I the line current. The secondary sideline voltages and currents are determined by considering the ratio of the number of turns per phase
(a = N1/N2) and the type of connection.

Table 1.1 gives a quick view of primary line voltages and line currents and secondary phase voltages and currents.

Connection	Line Voltage	Line Current	Phase Voltage	Phase Current
(a) Delta-Delta				
Primary Delta	V	I	V	I / 1.732
Secondary Delta	V/a	Ia	V/ a	Ia / 1.732
(b) Delta-Star				
Primary Delta	V	I	V	I / 1.732
Secondary Star	1.732V/a	Ia / 1.732	V/a	Ia / 1.732
(c) Star-Star				
Primary Star	V	I	V / 1.732	I
Secondary Star	V/a	Ia	V / 1.732 a	Ia
(d) Star-Delta				
Primary Star	V	I	V / 1.732	I
Secondary Delta	V/ 1.732 a	1.732 Ia	V / 1.732 a	Ia

Table 1.1
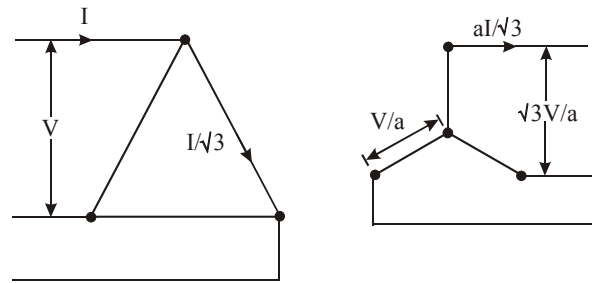*View of primary line voltages and line currents and secondary phase voltages and currents*

The power delivered by the transformer in the ideal condition irrespective of the type of connection = $\sqrt{3}.V_L I_L$ assuming $\cos\phi = 1$.
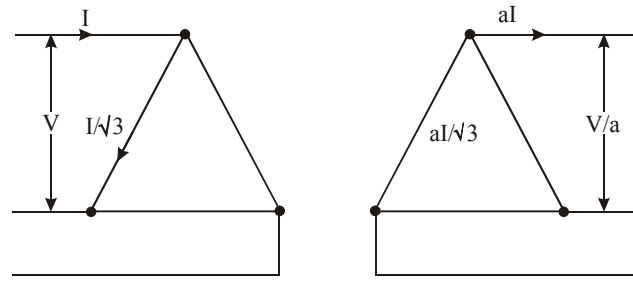
(A) Delta-Delta Connection

(B) Delta-Star Connection
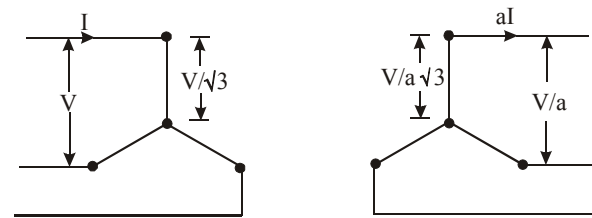
(C) Star-Star Connection
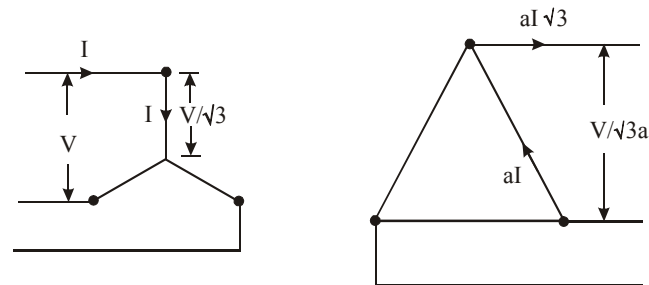
(D) Star-Delta Connection

Figure 1.6
Types of connections for 3-phase transformers

1.1.7   Testing transformers

The following tests are carried out on transformers:

- Measurement of winding resistance
- Measurement of Voltage ratio
- Test Phasor voltage relationship
- Measurement of impedance voltage, short circuit impedance and load loss
- Measurement of no load loss and no load current
- Measurement of insulation resistance
- Dielectric test
- Temperature rise

Why is transformer rating defined in KVA?

The total loss of transformer is due to Cu and Iron loss, which depends on current and voltage respectively. This means that the loss depends on VA and not on an angle between current and voltage. Therefore, rating is always defined in terms of KVA, not in Kilowatts.

Why is power transmitted at higher voltages?

A power station can supply a given amount of power (P=VI) with either a higher current and lower voltage, or a higher voltage and a correspondingly lower current. The power lost in the transmission lines will be Plost = I^2R, where R is the resistance in the transmission lines.

To keep this loss as small as possible, current should be low, which means that the voltage will be high.

At a power generation station, voltage is of the step-up type while at the distribution end, it is stepped-down to the required value.

1.2   Basic principles of electrical machines

1.2.1   Electromechanical energy conversion

The electromechanical energy conversion device is a link between electrical and mechanical systems.

When the mechanical system delivers energy through the device to the electrical system, the device is called a generator.

Generator

| Mechanical System | ⟹ | Electrical System |
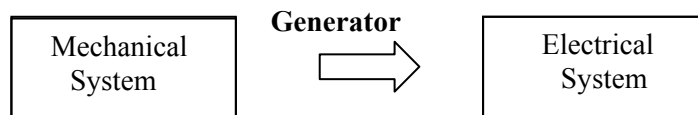
When the electrical system delivers energy through the device to the mechanical system, the device is called a motor.

Motor

| Mechanical System | ⟸ | Electrical System |
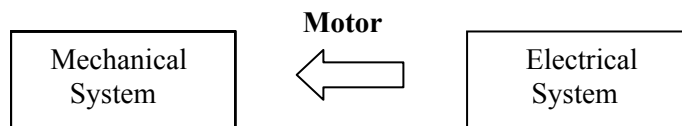
The process is reversible; however, the part of energy converted to heat is lost and is irreversible. An electric machine can be made to work either as a generator or as a motor.

The electromechanical conversion depends on the interrelation between:

- Electric and magnetic fields
- Mechanical forces and motion

In rotating machines, power is generated by the relative motion of the coils.

In case of a generator, winding is rotated mechanically in the magnetic field. That causes   the flux linkages with the windings to change causing induced voltages.

In case of a motor, the current carrying conductor is allowed inside a magnetic field. Mechanical force is exerted on a current carrying conductor in a magnetic field and so a resultant torque is produced to act on the rotor.

In both a generator as well as a motor, current carrying conductor is in the magnetic field. The conductors and flux travel with respect to each other at a definite speed. In rotating machines, both voltage and torque are produced. Only the direction of power flow determines whether the machine is working as a generator or a motor. For a generator, e and i are in same direction.

$$\mathbf{T_m = T_e + T_f}$$

where
Tm   Mechanical Torque
Te   Electrical Torque
Tf   Torque lost due to friction

For a motor, e and i are in opposite direction.

$$\mathbf{T_m = T_e + T_f}$$

In a generator, the power is supplied by the prime mover. Electrical power is produced by the action of the generator and the resultant power produced due to friction is lost. Whereas in the case of the motor, the power is supplied by the electrical power supply inputs, and there is a slight loss of the resultant mechanical power produced due to friction.

1.2.2   Basic principles of electromagnetism

Magnetic and electric fields

As you are aware, each electric charge has its own electric field, i.e. lines of force. Electric field lines point away from the positive charges and towards negative charges. Each charge exerts force on the other charge, which is always tangential to the lines of force created by the other charge.
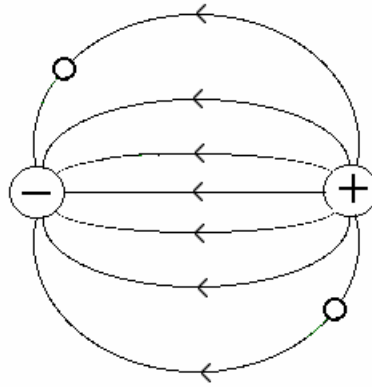
Figure 1.7
Electric force line of a charge

Similarly, the magnetic field lines "flow" away from the N-pole and towards the S-pole. Magnetic field is created by current by moving the electric charges. Every orbiting electron forms a current loop that creates its own magnetic field. Magnetic field lines always form circles around the current creating them (see Figures1.7 and 1.8).
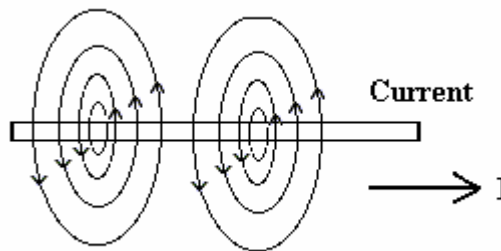
Figure 1.8
Magnetic field lines around a current carrying conductor

Magnetic field produced by a current carrying conductor

If a conductor carries a current, it produces a magnetic field surrounding it. The direction of the current and the direction of the field so produced have a definite relation that is given by the following rules:

Right-hand rule

Hold the conductor in the right hand with the fingers closed around the conductor and the thumb pointing towards in the direction of the current. The fingers will point towards the direction of the magnetic lines of the flux produced around the conductor.

Flux produced by current carrying coil

Flux can be produced by causing the current to flow through a coil instead of a conductor. Introduction of magnetic material as the core on which the coil is wound increases flux. The direction of the magnetic flux in the coil is given by the Right-hand rule.

In the case of a motor, the direction of the emf induced is such as to oppose the flow of current. Whereas, in a generator the emf induced is in such a direction as to establish a current.

Fleming's left-hand rule

This gives the relation between the direction of the current, the direction of field, and the direction of the motion. If the forefinger of the left hand points in the direction of the field, the middle finger points in the direction of the current, and the thumb points in the direction of the motion.

1.2.3   Basic principle of motor

Basic working of motor is based on the fact that when "a current carrying conductor is placed in a magnetic field, it experiences a force".

If you take a simple DC motor, it has a current carrying coil supported in between two permanent magnets (opposite pole facing) so the coil can rotate freely inside. When the coil ends are connected to a DC source, then the current will flow through it and it behaves like a bar magnet as shown in the figure. As the current starts flowing, the magnetic flux lines of the coil will interact with the flux lines of the permanent magnet. This will cause motion of coil (Figure 1.9. -1,2,3,4) due to force of attraction and repulsion between two fields. The coil will rotate until it achieves the 180 degrees position, because now the opposite poles will be in front of each other (figure 1.9-5) and the force of attraction or repulsion will not exist.

The role of the commutator: The commutator brushes just reverse the polarity of DC supply connected to the coil. This will cause change in the direction of current of the magnetic field and start rotating the coil by another 180 degrees (figure 1.9-6).

The brushes will move on like this to achieve continuous coil rotation of the motor.

Similarly, the AC motor also functions on the above principle, except here, the commutator contacts remain stationery, because AC current direction continually changes during each half cycle (every 180 degrees.)
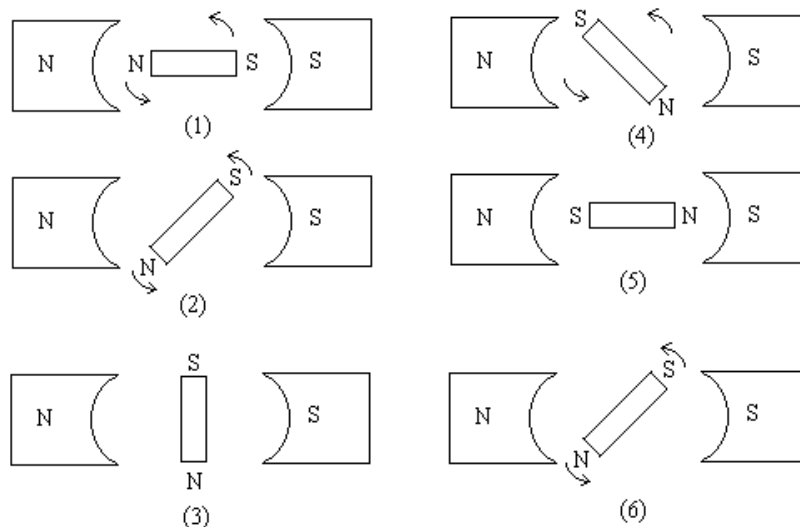
Figure 1.9
A motor action

1.2.4 Basic principle of generator

We have discussed the basic working of a motor and, through the diagrams, we have seen a generator's action as well.

In principle, an AC generator's construction is similar to the construction of the motor. Instead of putting current in, current is taken out from the coil in an alternator.

A mechanical prime mover rotates the coil in between the poles of a permanent magnet and an AC potential is induced in the coil. To further clarify, if an AC current will make a coil turn, then turning the coil will create an AC current.

As per Faraday's law, when a wire is moved in to cut across magnetic field lines, a force is exerted on the charge (electrons) in the wire by trying to move them along the wire. This is how current will start flowing if a complete circuit is provided to it. The magnetic field is provided not by magnets, but by field coils.

The coil in which the voltage is induced is called armature winding, while the coil that provides the magnetic field is called field winding.

Practically in high voltage generators, it is not good practice to have armature rotating due to current collecting brushes of high ratings are required to be installed. Rather the armature is kept stationary and field is kept rotating.

Alternators of low capacity use a permanent magnet as a field, while in high capacity alternators, field winding supply is derived from the exciter assembly, which is a small alternator connected on the same shaft.

1.2.5 Idealized machines

There is a stationary member called a stator and a rotating member called a rotor. The rotating member is mounted on bearings fixed to the stationary member. The stator and the rotor have cylindrical iron cores, separated by an air gap. Windings are wound on the stator and the rotor core. A common magnetic flux passes across the air gap from one core to another forming a combined magnetic circuit. Two cylindrical iron surfaces with an air gap between them move relative to each other. The cylindrical surface may be divided by an even number of salient poles with spaces in between, or it may be continuous with slot openings uniformly spaced round the circle. This structure may be for either of the stator or the rotor.

The common features of an ideal electrical machine are shown in the Figure 1.10. For windings, conductors run parallel to the axis of the cylinders near the surface. The conductors are connected into coils by the end connections outside the core and the coils are connected to form the windings of the machine.

The operation of the machine depends on the distribution of the currents around the core surfaces and the voltages applied to the windings.

In various types of electrical machines, the arrangement differs in the distribution of the conductors, windings, and in core constructions depending on whether it is a continuous or a salient pole type. The magnetic flux permeates the iron cores in a complex manner. However, as the iron has a high permeability, the accurate working of a machine can be determined by considering the flux distribution in the air gap. The conductors are actually located in slots formed in the laminations of the core.
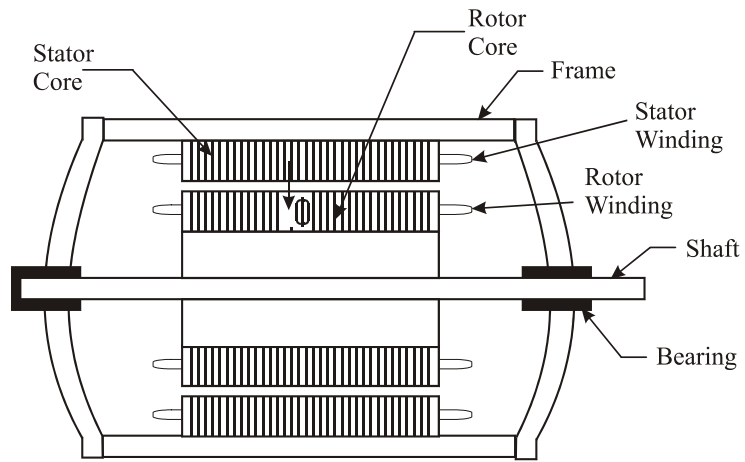
Figure 1.10
Common features of an ideal electric machine

(A)

(B)
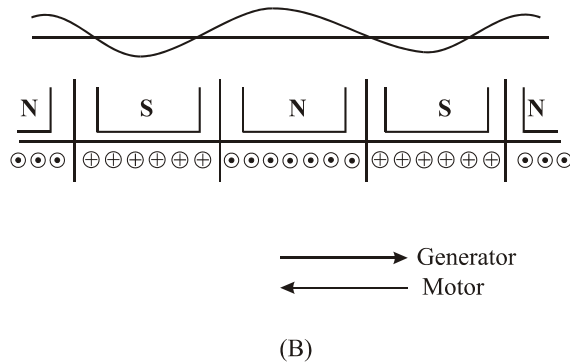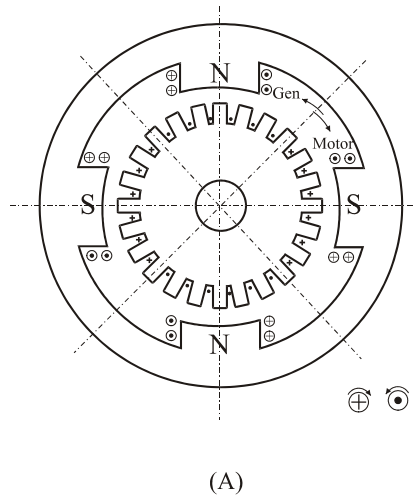
Figure 1.11
Typical cross section and development of an electrical machine

A typical cross section and the corresponding development diagram of an electrical machine with four poles, perpendicular to the axis of the cores is shown in Figure 1.11. As shown in the diagram, the distribution of flux and current repeats itself at every pair of poles. On the poles, the windings are so wound that the current flows in the opposite direction and produces a field corresponding to the north and south polarities. Maximum flux is along the center of the pole and reduces to zero between the inter-pole gaps.

1.2.6   Basic principles of electrical machines

In an electrical machine, the currents in all the windings combine to produce the resultant flux. The field system produces flux. Voltages are induced in the windings such as those of an armature. When the armature carries current, the interaction between the flux and the current produces torque.

Types of electrical machine windings

Coil winding

The winding consists of coils wound on all the poles of the machine and connected together to form a suitable series or parallel circuit. The direction of the current in the alternate pole will be opposite so that when one pole is the north pole, the other adjacent pole will be a south pole. This produces the flux in the proper direction, completing the magnetic circuit from the north pole to the south pole through the iron cores of both the stator and the rotor.

The coil may be wound on the stator or on the rotor, forming the salient or non-salient poles of the machine. DC supply is given to these windings and they produce a field proportional to the magnitude of the current through the windings. If the poles are on the stator, a stationary field is produced in the air gap.

Commutator winding

The commutator winding is on the rotor. The armature has open slots and the conductors are located in these slots and connected to the commutator segments in a continuous sequence.

Polyphase winding

The polyphase winding is a distributed winding. Individual conductors are distributed in slots in a suitable way and connected into a number of separate circuits, one for each phase. The group of conductors forming the phase bands is distributed in a regular sequence over the successive pole pitches so there is balanced winding that produces an equal voltage per phase. This type of winding is mainly used for the stator. When supplied with 3-phase currents it produces a rotating field in the air gap. This is of a constant magnitude but rotating at a constant synchronous speed.

1.2.7   Types of electrical machines

Depending on the type of combinations of windings used on the stator and the rotor, electrical machines are classified in different types as follows:

DC machines

DC machines have an edge over AC when it comes to the speed control of a motor.

Shunt motor

This machine has field winding mounted in yoke and the armature winding is mounted on rotor. The shunt motor is used where speed regulation is important.

Self-excited

Field winding is connected in parallel (shunt) with the armature winding on the same supply. Changing the field current can vary the speed.
Torque is proportional to armature current.
This machine can also act as a generator. To limit the high starting current of the motor drive releases the voltage in ramp. For this motor, a variable resistor is connected in series with the field circuit to change the flux value and the speed by a small amount.

Separately excited

Field winding is connected in parallel (shunt) with the armature winding with separate excitation.

Torque is proportional to armature current. In a separately excited shunt motor, speed can be varied up to a certain limit by changing armature voltage. After that using field weakening (reducing field current), it is possible to increase the speed of motor above base speed. Other features remain same as that of the self excited one.

Series motor

As the name suggests in this type of motors, field winding is connected in series with the armature winding. Naturally, heavy current will pass through it, so field winding is of a thicker gauge. Series motor is used where speed regulation is not important.

The main advantage of this motor is that a high torque can be obtained, which makes it useful for applications such as diesel locomotives, cranes, et cetera.

The relationship between Torque and current is as follows:

$$T \propto Ia^2$$

It is important to start this motor in a loaded condition else it could lead to damage of the motor and its surroundings.

Compound motor

If we combine both series and shunt motor then we will have a compound motor. This combines the good features of both types such as high torque characteristics of series motor and the speed regulation of shunt motor.

AC machines

Squirrel cage induction motor

AC machines are simple and sturdy. A simple definition for an AC induction motor is that it is essentially a rotating transformer. The most common machine of this type is the Squirrel cage induction motor (name was derived from its construction type.)

The basic construction of this will be dealt with in the next section. Speed of this motor is given by the following relation:

N (RPM) = 120 f / p

where

f   frequency

p   number of poles.

For example, if the motor has two poles, then at 50 Hz frequency motor rpm will be 3000 rpm.

However, you will not find 3000 rpm or 1500 rpm on the motor nameplate because the motor rpm will not be 3000 rpm at full load. This is because of a slip associated with an induction motor.

RPM of the motor is controlled by controlling the frequency (f); as frequency increases, motor speed will also increase. High starting current is limited using star delta starter or reduced voltage starters.

Wound rotor motor

This is similar in construction to the squirrel cage and works similar to the squirrel cage machines except that slip rings are provided. The main feature of the slip ring motor is that the starting current is limited by resistors, which are connected in series with the rotor circuit.

The motor starts with a full resistance bank, but as speed of the motor increases, the resistances are shorted, one by one. As the motor reaches full speed, the whole bank of resistance is shorted out and the motor now runs as a normal induction motor.

Synchronous motors

Synchronous motor is a constant speed motor which can be used to correct the power factor of the 3-phase system. Like the Induction motor in terms of the stator, the synchronous machine has either a permanent magnet arrangement or an electromagnet (with current supplied via slip rings) rotor. In simple terms, the rotor will keep locking with the rotating magnetic field in the stator. So, a 2-pole machine will run at exactly 3000 RPM. In many synchronous machines, a squirrel cage is in incorporated into the rotor for starting. Therefore, the machine acts as an induction motor when starting and as it approaches synchronous speed, it will suddenly 'lock in' to the synchronous speed.

1.2.8 Basic characteristics of electrical machines

The following are the basic characteristics of electrical machines:

- The voltages induced in the windings, the load currents, and the terminal voltages depend on the following different loading conditions
- The speed at which the machine works under different loading conditions and the frequency
- The power input or the output received from the machine
- The torque produced under different loading conditions

1.3 AC power systems

1.3.1 Single phase power system

The power in a single-phase system is shown in Figure 1.12. In the figure current (I) lags Voltage (V) by an angle ϕ. The current has two components – the energy component and the watt less component.

   Only the energy component has a power value. Hence, the power in a single-phase circuit is given by the following equation:

P = V x I x cos ϕ
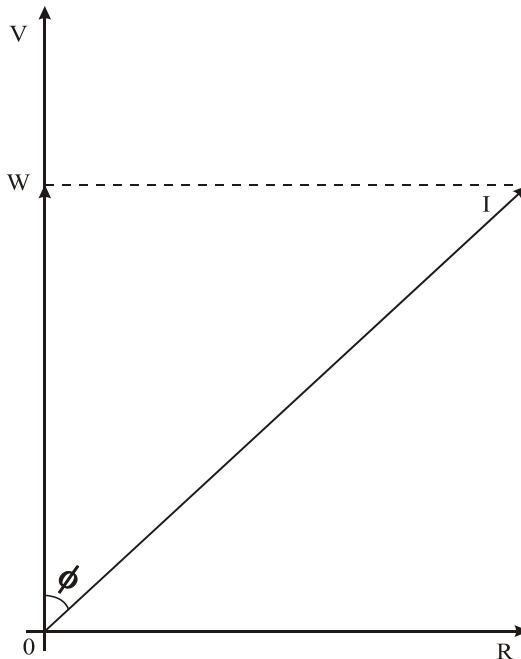
where
P   power (watts)
V   voltage (rms)
I   current (rms)
Cos ϕ = power factor

$$\boxed{\frac{P}{V \times I}}$$

Figure 1.12
Single-phase power system

1.3.2 3-phase power systems

The three windings of a 3-phase transformer or an alternator can be connected in either of two ways – Delta or Star as shown in the Figure 1.13.

The relationship between the phase voltages and the currents, and the line voltages and the currents are as follows:

For Delta-connected system
Line Voltage = Phase Voltage
Line Current = √3 x Phase Current

For Star-connected system
Line Voltage = √3 x Phase Voltage
Line Current = Phase Current

In a star connection, a neutral point is available. Generators are generally star wound and the neutral point is used for earthing. 3-phase motors can be either delta or star connected. Usually, delta connections are used for low voltage, small size motors to reduce the size of the windings.
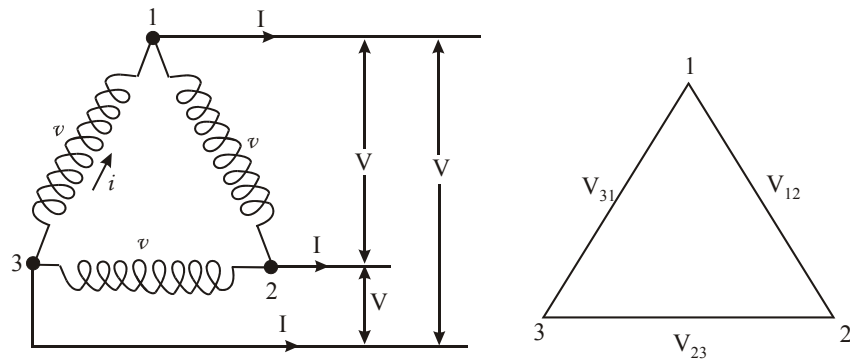
(A) 3-Phase Delta Connection
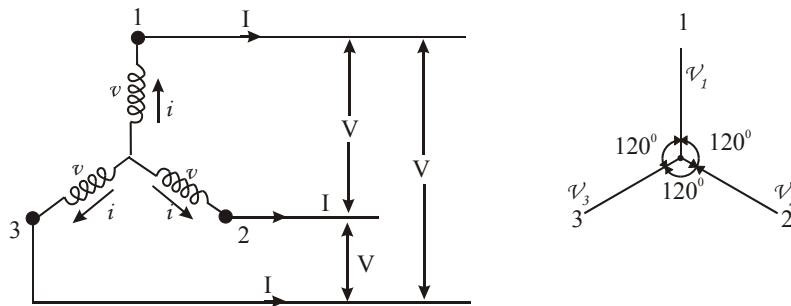
(B) 3-Phase Star Connection

Figure 1.13
Three phase circuit connections

3-phase currents are determined considering each phase separately and calculating the phase currents from the phase voltages and impedances. In practice, the calculations are simple and straightforward as 3-phase systems are usually symmetrical, the loads being

balanced. Most of the 3-phase motors can be assumed as balanced loads. The calculations for currents, power, et cetera can be done using the expression given below. However, for unsymmetrical or unbalanced systems, the calculations and expressions given below do not hold good, and complex calculations are required.

 The power in a 3-phase system is the sum of the power of the three phases. Let us consider a balanced delta or star connected system.

The total power for the 3-phase system will be:

P = √3 x V x I x cos ϕ (Watts)

where
V   line voltage
I   line Current
Cos ϕ power factor

1.3.3   Power measurement in 3-phase system

Electrical power is measured with a wattmeter. Wattmeter consists of a current coil which is connected in series with load, while the other potential coil is connected parallel with load. Depending on the strength of each magnetic field movement, the pointer gets affected.

The true or real power is directly shown in a wattmeter.

In 3-phase systems, power can be measured using several methods. For temporary measurements, a single wattmeter can be used. However, for permanent measurements, a 3-phase wattmeter having two elements are used which indicate both balanced and unbalanced loads. For an unbalanced load, two wattmeters must be used as shown in the Figure 1.14. The total power is calculated by adding the measurement readings given by the two wattmeters. With this method, the power factor can also be obtained.

When using the two-wattmeter method, it is important to note that the reading of one wattmeter should be reversed if the power factor of the system is less than 0.5. In such a case, the leads of one wattmeter may have to be reversed in order to get a positive reading. In the case of a power factor less than 0.5, the readings must be subtracted instead of added. The power factor of the 3-phase system, using the two wattmeter method (W1 and W2) can be calculated as follows:

tan ϕ = √3 (W1 – W2)
                (W1 + W2)

The sum and subtraction of readings are done to calculate the total true power of a 3-phase system. However, these methods shown are not used practically in industry. Rather, 3-phase power analyzers are used as they are more user-friendly.
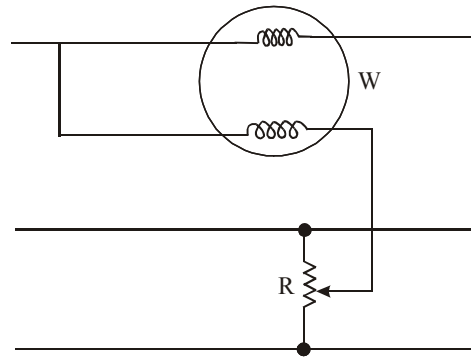
(A) One Wattmeter Method for
Balanced Load
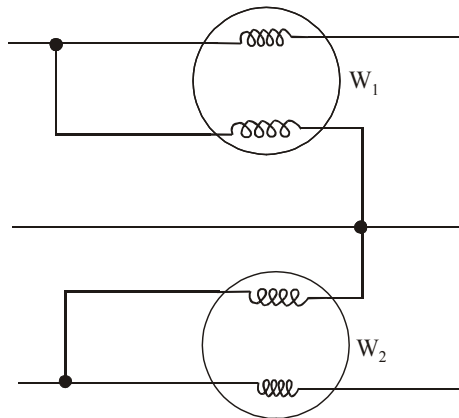
(B) Two Wattmeter Method for
Balanced/Un-balanced Loads

Figure 1.14
Methods of measuring the power in three-phase systems

Power factor meter

A power factor meter is similar to a wattmeter in principle; only two armature coils are provided with mounting on a single shaft. They are 90 degrees apart from each other. Both armature coils rotate as per their magnetic strengths. One coil moves proportional to the restive component of the power, while the other coil moves proportional to the inductive component of the power.

Energy meter

This shows the amount of power (electric energy) used over a certain period. In watt-hour meter, there are two sets of windings. One is the voltage winding while the other is current winding. The field developed in the voltage windings causes current to be induced in an aluminum disk. The torque produced is proportional to the voltage and current in the system. The disk in turn is connected to numeric registers that show electric energy used in terms of kilowatt-hours.

1.4   Meters used in troubleshooting

For troubleshooting electrical circuits and systems, the following meters are used depending on the requirements of the parameters to be measured or detected for faultfinding:

- Multi-range Voltmeters
- Clip around or Clamp-on Ammeters
- Electrostatic Voltmeters (high voltage measurements)
- Multimeter or Volt-Ohm-Milli-ammeter (voltage, resistance, current, et cetera)
- Thermocouple meters (indirect current measurement)
- True Wattmeters (directly measurement of power in watts)
- Pseudo Wattmeters
- Digital Voltmeters
- Heterodyne wavemeter (analogue measurement of frequency)
- Digital Frequency meters
- Continuity testers
- Analog Ohmmeters
- Digital Ohmmeters
- Insulation Testers
- Digital Capacitance meters
- Q meter (measuring inductance and capacitance)
- Oscilloscope (measuring wave forms, amplitude, frequency, phase, et cetera)
- Dip meter (radio frequencies)
- Logic level probe testers
- Logic Analyzers (diagnosing logic systems problems)
- Spectrum Analyzers

Certain important meters from the above list are explained in detail in the following chapters as and when required.

1.5   Harmonics in a power system

The increase in the use of non linear electric devices like AC and DC drives for improving the operating efficiency of many processes has created an undesirable side effect called harmonics in the power system. These non linear electric devices use power semi conductors like diodes, SCRs, transistors etc. which draw current in a non-sinusoidal fashion that is not proportional to the applied voltage. The generation of harmonics results in distortion of the power system's voltage and current waveforms, cause problems of additional losses and are a source of electromagnetic interference (EMI).

The fundamental frequency of AC power supply distribution system is either 50Hz or 60Hz. A harmonic frequency is any sinusoidal frequency, which is a multiple of the fundamental frequency. The harmonic frequencies can be even or odd multiples of the sinusoidal fundamental frequency. Following are some examples of harmonic frequencies of 50Hz fundamental frequency.

Even Harmonics		Odd Harmonics	
2nd Harmonic	100 Hz	3rd Harmonic	150 Hz
4th Harmonic	200 Hz	5th Harmonic	250 Hz
6th Harmonic	300 Hz	7th Harmonic	350 Hz

Harmonics are generated by the loads that are connected to a power supply system. Loads can be subdivided into two types namely linear loads and non linear loads. A linear load is a load, which draws a purely sinusoidal current when connected to a sinusoidal voltage source. Examples of linear loads are resistors, capacitors and inductors. Equipments like transformers, motors and heaters have linear characteristics. Non linear load is a load, which draws non-sinusoidal current when connected to a sinusoidal voltage source. Examples of non linear loads are diode bridges, SCR bridges etc. Equipments like variable speed drives, rectifier bridges and UPS have non linear characteristics.

The non sinusoidal voltage and current wave forms drawn by the non linear loads can be resolved into a number of sinusoidal wave forms of various amplitudes and frequencies. These multiple frequency wave forms are called harmonics. Figure 1.15 shows a cycle in a distorted wave form and its third harmonic sinusoidal cycle.
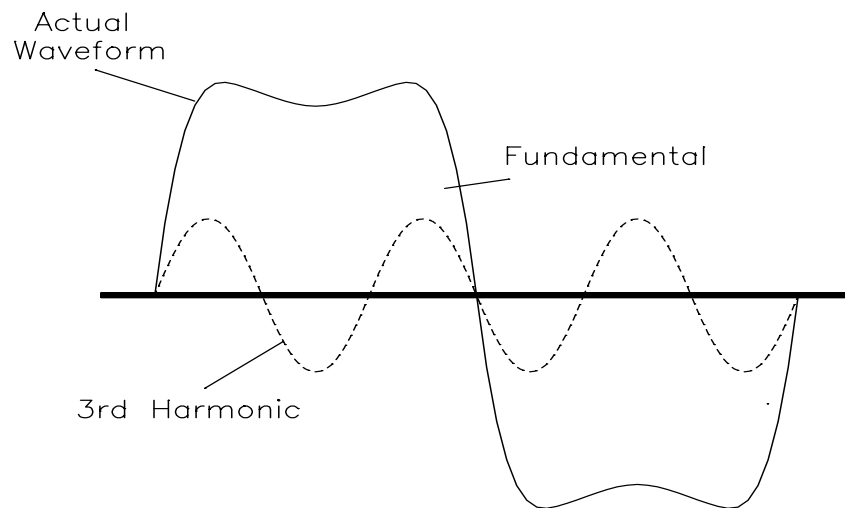
Figure 1.15
Distorted fundamental actual cycle of a wave form and its 3rd harmonic cycle

The resolving of the distorted voltage and current wave forms into various sinusoidal component wave forms is done by using a mathematical technique called as Fourier Transformation. The complex calculations of Fourier transformation can be performed

very quickly by using microprocessor based electronic equipment using a methodology called FFT (Fast Fourier transform).

Harmonic currents and voltages have the undesirable effects of creating losses and heating. For example, a total harmonic distortion of 2.5% can cause an additional temperature rise of 4 deg C in induction motors. In the case of capacitors, harmonics can cause heating up of the capacitors and result in their premature failure. The higher frequencies of the harmonics also result in a phenomenon called skin effect. Skin effect causes the current in an electrical conductor to get closer towards the surface of the conductor. That is, the current density is less in the center of the conductor and gradually gets higher towards the periphery of the conductor. Skin effect thus causes an increase in the effective resistance of the conductor. This in turn implies that the actual conductor has to be de-rated when used for carrying harmonic currents. Equipments like transformers, motors, cables, busbars carrying harmonic currents thus need to be de-rated.

The current industry standard for controlling harmonic distortion is IEEE 519-1992. The IEEE 519 standard provides recommended limits for overall voltage distortion and current distortion. The recommended limit for the total voltage distribution is 5% for general power distribution systems. The standard also provides techniques that can be employed to reduce levels of harmonic distortions if the distortion happens to be higher than the recommended limits.

1.5.1   Reducing harmonic distortion

A number of techniques are available to reduce the levels of harmonics if such a problem is faced. Some of these techniques are the use of input line reactors, isolation transformers, trap filters and the use of 12 pulse rectifier bridges. Harmonic distortion is directly dependant on the source reactance. Increasing the source reactance reduces the harmonic levels. In a VFD this can be easily achieved by the use of a DC link reactor on the DC bus of the drive. Harmonic filters tuned to a particular harmonic frequency can be used to filter out that frequency. A 12 pulse VFD eliminates the 5th and 7th harmonics by using phase shifting transformers on the input side.