

EE 101 Electrical Engineering (2 Credits)

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Syllabus

Overview (4 hrs)

Electrical Power and National Development, Role of Electrical Engineer, Introduction to Power Generation, Transmission, Distribution and Utilisation including Modern Drives, SI Units, Basic concepts.

Network Theorems (4 hrs)

Ohm's Law, Kirchoff's Law, Superposition Theorem, Thevenin's theorem, Norton's theorem, maximum power transfer theorem, Millmann's theorem; star-delta transformations. Introduction to nodal and mesh analysis..

Alternating Current theory (6 hrs)

Sinusoidal waveform, phasor and complex representation, Impedance, Power and Power factor. Analysis of simple R, L, and C circuits using alternating current Solution of simple network problems by phasor and complex number representation.

Three Phase - Advantage of three phase, Star and Delta configurations. Phase sequence. Balanced and unbalanced systems. Power factor correction.

Electromagnetic and Electrostatic theory (2 hrs)

Basic electrostatic and electromagnetic theory; force and torque development in magnetic circuits.

Electrical Measurements (3 hrs)

Direct deflection and null deflection methods. Ammeters, voltmeters, wattmeters, energy meters. Extension of ranges.

Electrical Installations (3 hrs)

Fuses, miniature circuit breakers, earth leakage circuit breakers, residual current circuit breakers, earthing, electric shock. IEE wiring regulations, basic domestic installations.

1.0 Overview

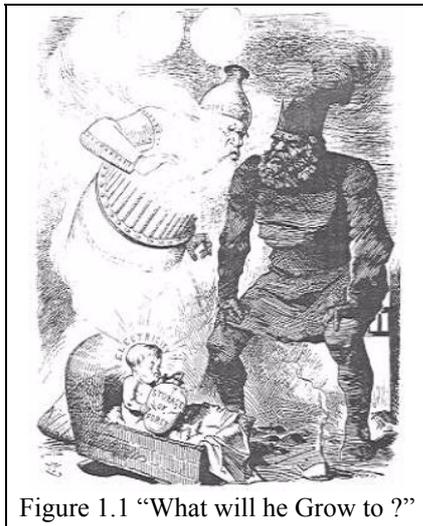


Figure 1.1 "What will he Grow to ?"

You may find it amusing that this lecture series starts with a cartoon which appeared in the magazine *Punch* in London on 25th June 1881 (Figure 1.1). It shows *King Steam* and *King Coal* discussing *Baby Electricity's* chances of success in life. Baby electricity is obtaining nourishment from the feeding bottle marked "storage of force". Prior to 1881, Coal gas was widely used to obtain light and steam was used to drive machinery and as such the advent of baby electricity into this market made King Coal and King Steam become anxious about their future.

It was around this time that electricity started gaining ground for lighting and for power applications. The success was based primarily on the discovery of electromagnetic induction and the construction of the first dynamo by Michael Faraday in 1831.

From ancient times, the use of non human forms of energy transfer has been associated with the development of man. For example, stone age man used spears to hunt animals for food. However he had to be close enough to be able to succeed. But this had a lot of dangers. So he

invented the bow and arrow.

The bow is slowly bent by the hunter in more than a few seconds and energy is stored in the springy wood. However it is released in a fraction of a second on to the arrow so that it moves at many times the velocity that the man could have thrown at, and so can operate it in from a much further distance. [Note that the original muscle energy in man was converted to potential energy in the bow and kinetic energy in the arrow. The man in turn gets his energy from the food - principle of conservation of energy]. Animal power was also used by man to materially improve himself.

Water power in water wheels and wind power through wind mills were the first forms of non-muscle power to be used. The invention of the steam engine in the 1780s was a real breakthrough in that it led to an ever increasing material progress.

With the advent of large scale electrical generation and transmission about 100 years later, the rate of increase of power has been rocketing. Although this is wonderful for our material prosperity, the machines too have to be fed and our limited resources of fossil fuel, as is used today, are fast dwindling.

The standard of living of a country can be measured by the amount of energy consumed per person (*per capita consumption*). While many developed countries need energy to heat the environment during the harsh winter we are fortunate not to have that requirement. Even so our per capita consumption of energy is still too low for us to become an industrialised country.

Engineering economics play a vital role in the development of a country. The role of the electrical engineer is to facilitate the means by which this can be achieved through the proper management of resources. His role is to economically design, operate, maintain and manage the equipment associated with the generation, transmission, distribution and utilisation of electrical energy and at the same time maintaining safety. He should also be able to adequately communicate with the lower and higher rungs of the organisation, and be able to relate to the environment. He must realise that electrical engineering is an ever expanding field and that he needs to continually develop himself to meet the needs of society and that industrial problems rarely have a well defined or unique solution.

Generation, transmission and distribution are directly concerned with electrical power and are handled by supply authorities. Utilisation is by all walks of people for all types of purposes. The electrical equipment would consist not only of purely electrical equipment such as for lighting, heating, machinery, and transport but also for other applications such as computers and communication equipment.

In the past over 90% of motors used in industry have been traditional induction motors. In the present day, more and more power electronic devices are used to control motors.

1.1 Generation, Transmission and Distribution of Electricity

The consumer needs to use electricity for his day to day activities in his home, office or other workplace. It is neither economical nor feasible to produce electricity (i.e. convert from non electrical form of energy to electrical energy) where it is required. Thus electricity is produced centrally in generating stations. In the home or office, we would normally use electricity at 230 V (110 V is used in the US) between live and neutral wires – *phase voltage*. Voltages higher than that would not be at all safe and voltages lower than that would not be economical as they require larger currents and hence larger size conductors [Note: for the same power output, a lower voltage would require a higher current]. We would also have a protective earth wire to give us additional safety.

The supply is an alternating current at a frequency of 50 Hz. A typical house in Sri Lanka would normally not consume more than about 2 to 3 kW of power even during the peak giving a peak current of about 10 A. Since there are a number of houses down your lane and all of them require electricity a common distribution line is run along the side of the road and power is tapped for each house from it using 2 wires (live and neutral) and the earth wire is provided from an electrode at your premises. When the current flows, there will be a considerable power loss in both the live and neutral wires and a considerable voltage drop [Note: voltage drop is different from the voltage of the line]

You are familiar with the fact that forces along three sides of an equilateral triangle add up to zero. Likewise, three currents, equal in magnitude but with phase angles of the sinusoidal waveform differing by 120° (or $2\pi/3$ rad), would add up to zero.

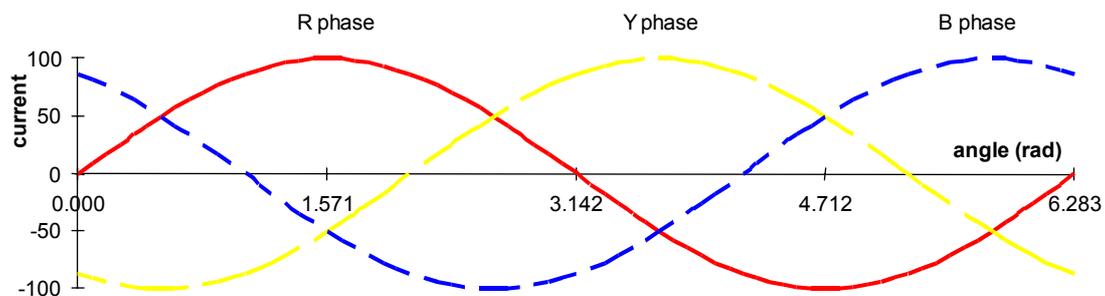
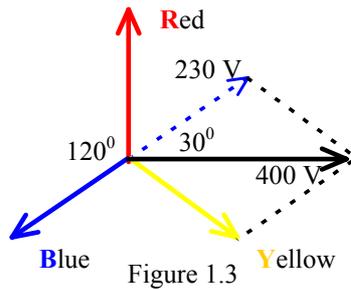


Figure 1.2 - Three phase waveforms

Making use of this property, if we could balance the electrical loads taken by the various households equally into three phases and supply them at different phase angles (as shown in figure 1.2), we would have almost no

neutral current. Thus the total power loss would be effectively halved. Therefore power distribution is normally carried out using three phase.



Using trigonometry, it can be easily shown (figure 1.3) that the voltage between two live wires would now not be 230 V but $2 \times 230 \times \sqrt{3}/2$ or 400 V. [The voltage between live and neutral is still 230 V]. Thus the low voltage distribution from which supply is obtained to your house is called 400 V, 3 phase, 50 Hz supply. The house in turn has a 230 V, 1 phase, 50 Hz supply.

When we consider all the houses down your lane, and perhaps the adjacent lane, the total current may approach around 500 A per phase and would require a power supply of the order of 350 kVA.

Since the power loss in a line is proportional to the square of current (I^2R), the loss rapidly increases with increase in current or power distributed (VI). This power loss may be reduced by sending the power at a higher voltage as power loss is proportional to the square of current, while power distributed is proportional to the current.

Thus power is distributed at a higher voltage such as 3 phase, 11 kV (Lanka Electricity Company) or 3 phase, 33 kV (Ceylon Electricity Board). Big industries (such as Steel Corporation) and large workplaces (such as University of Moratuwa) are supplied at these voltages. The voltage is stepped down from these voltages to 3 phase, 400 V using transformers (usually rated at 100 kVA, 250 kVA, 400 kVA etc) for low voltage distribution. Thus there are two levels of distribution - low voltage and medium voltage (figure 1.4).

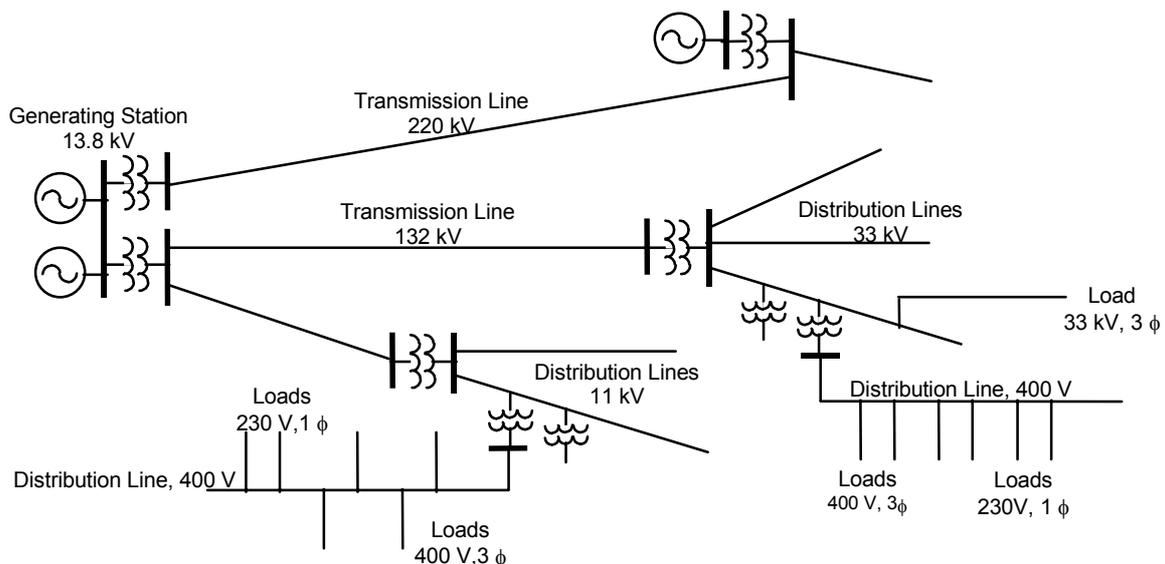


Figure 1.4 - Typical arrangement of part of a power system

Generating stations (ex. Kotmale, Victoria, Laxapana) are commonly located hundreds of kilometers away from the Load Centre (ex: Colombo). Also there would be thousands of transformers supplying the low voltage distribution systems. Thus it is not economical to transmit over long distance at 11 kV or even 33 kV. Also, in such transmission, it is point to point (such as from Kotmale to Kolonnawa) and in bulk. Thus high voltage transmission is carried out in Sri Lanka at 132 kV and more recently at 220 kV to keep the power losses low. The power transfer would be of the order of 100 MW. [For a given conductor size and power transfer, an increase of voltage by a factor of 20 times would reduce the current by a factor of 20 times and the power loss by a factor of 400 times].

In some countries, where the power transfer requirements are much higher and the distances much longer, extra high voltage transmission at voltages higher than about 345 kV (ex: 400 kV, 760 kV etc) are used.

Unfortunately, it is not feasible at present to generate electricity at more than about 25 kV (A Powerformer is being developed in Sweden capable of generating at high voltages required for transmission) so that the normal generation is done using Synchronous Generators at about 11 to 15 kV (typically 13.8 kV). This is stepped up to the transmission voltage using transformers. The transmission voltage in Sri Lanka is 132 kV and 220 kV.

1.2 Bulk Energy Sources

Energy sources for bulk power generation can be categorised into renewable energy sources (ex: hydro-electric, solar, wind etc) and non-renewable energy sources (coal, oil etc). Some of the more common ones are outlined in the following section.

(i) *Hydro-electric power*

Perhaps the oldest form of large scale energy conversion has been by the use of water power which were used in ancient water wheels. In the modern hydro-electric power stations, the energy of water (either in potential form or kinetic form) is first converted to rotational (mechanical) energy in the turbine and then to electric energy in the generator. Although the water which gives the energy is free, a high capital civil engineering cost is associated with the construction and the overall cost per kWh may approach that of conventional thermal plants.

Micro-hydro and mini-hydro plants are also used and connect to the distribution network directly rather than to the transmission network.

(ii) *Conventional thermal power (Coal & Oil)*

The burning of coal or oil in boilers produces steam at high temperature and pressure (conversion of chemical energy to thermal energy and then to kinetic energy). This steam is used to rotate a steam turbine (thermal energy to mechanical energy conversion) which is coupled to an electric generator (mechanical energy to electrical energy). Even though continual advances have been made the efficiency of thermal stations is quite low (around 40%) because of the vast quantities of heat lost to the surroundings.

(iii) *Gas turbines*

Gas turbine plants also operate by burning oil. However the energy transfer is not through steam but through compressed gasses produced in the combustion chamber under high pressure which drives the gas turbine. The gas turbine is mechanically coupled to the electrical generator to produce electricity.

(iv) *Nuclear Power Plants*

The energy source in a nuclear power plant is the energy stored in the nuclei of the atoms of the fuel. Energy is released by the splitting of a nucleus in a process called *fission*. Energy released by the combination of two light nuclei to form a single heavier nucleus is called *fusion*. So far power has only been successfully obtained from the fission reaction. Uranium is the commonly used fuel and U^{235} is fissile. When struck by slow moving neutrons its nucleus splits into two substantial fragments with high kinetic energy (about a million times larger than in a chemical reaction). The fast moving fragments hit surrounding atoms producing heat. The neutrons released in the fission reaction cause further fissions and under correct conditions lead to a chain reaction. The chain reaction is controlled by the use of reaction absorbers placed in control rods. The heat generated is used to produce steam which in turn drives a steam turbine coupled to an electrical generator as in a coal or oil power plant.

(v) *Wind Power Plants*

Wind is continuously regenerated in the atmosphere under the influence of the energy radiated from the sun. (about 20% of the solar energy of the atmosphere is converted to wind energy). The kinetic energy in the wind is used to turn a wind turbine. The energy produced in a wind turbine is proportional to the cube of the wind velocity. Wind turbines (usually 2 or 3 bladed) must be mounted on tall towers for greater efficiency as wind velocity is higher at higher altitudes. To obtain large scale electric power, a large number of wind turbines are arranged in a wind farm. One of the disadvantages of wind power is that it is not continuously available.

We have about 150-200 MW of wind potential in the coastal belt in Sri Lanka.

(vi) *Solar Energy*

Energy generated by the sun is due to a nuclear reaction called fusion. The energy that is received on the earth from the sun is over 10,000 times the present energy requirements of the earth. The average solar radiation received by the earth is about 0.2 kW/m^2 .

In large scale installations, the sun's rays may be concentrated by lenses or mirrors. These lenses or mirrors need to have steering mechanisms to follow the motion of the sun and to focus the heat on solar towers. The heat can be used to produce steam to drive steam turbines.

Photo-voltaic power using solar cells is also used to produce electricity. In these the solar radiation is directly converted into electricity. At present solar cells are expensive and are not used for large scale generation of power but may be used in some rural electrification schemes. However these require power storage as electricity is not produced at night when it is most needed for lighting.

A very important use of Solar energy is in powering remote power applications such as repeater stations, transmitters at hill tops, and in extra terrestrial applications.

(vii) *Geothermal Energy*

Geothermal energy is the heat from the inside of the earth. The temperature of the earth crust increases from about 20°C at the earth's surface to about 1000°C at a depth of 40 km. Energy can be obtained by drilling at suitable locations to release high pressure steam or hot water which is produced by ground water coming into contact with molten rock. These can be circulated through a heat exchanger to produce steam to run a steam turbine. In areas where the ground water supply is limited, water could be pumped into a cavity created in the hot rock to obtain hot water and steam.

(viii) *Ocean Energy*

Energy from the ocean can be developed in three different ways. These are (a) tidal power, (b) ocean waves and (c) ocean thermal gradient.

In tidal power, we make use of the tide which occurs twice a day and rises and falls by as much as 10m. When the tide rises, water flows in to the land and when the tide falls, water flows out. This vast amount of energy transfer can be used to generate electrical energy using hydro turbines.

Ocean waves are created by the wind and a vast amount of energy is available in the waves. A kilometer long, one meter wave would contain about 10 MW of power. Reciprocating generators are commonly used. The mechanism to trap the wave energy would be moored in the middle of the ocean (say 80 km from shore).

Ocean thermal energy conversion (OTEC) uses the natural temperature difference between the warm surface water (25°C) and the cooler ocean bed at 5°C. Due to the low temperature difference, the turbines use fluids such as ammonia as the working fluid.

About 50 km away from the coast line in Sri Lanka, in Mannar, Trincomalee and Unawatuna, are some of the best sites for OTEC in the world. A 1 MW OTEC plant is under construction near Mannar.

(ix) *Magneto hydro-dynamic (MHD) Generation*

Magneto hydro dynamic generation is also based on Faraday's laws of induction. The main difference from a conventional generator is that the conductor is a gas at a very high temperature and pressure where it is conductive. The gas may also be seeded with a small amount of vaporised metal such as potassium.

In MHD generation, the gas passes through a pipe (whose cross-section gradually increases from beginning to end) across which a magnetic field is applied (in a perpendicular direction to the flow of gas). An emf is thus induced in a circuit in a third mutually perpendicular direction.

(x) *Fuel Cells*

Fuel cells use hydrogen-oxygen interaction through a catalyser to yield a flow of electrons in a load connected externally. Each cell develops about 0.7V and sufficient modules in series yield an output voltage of around 11-15 kV and can reach power outputs of around 1 MW.

(xi) *Biomass energy*

Biomass is the abbreviation for biological mass, the amount of living material provided by a given area of the earth's surface. Biomass energy may be obtained from forests, vegetation and animal refuse. In various forms, it is probably the major supplier of energy in Sri Lanka.

1.3 Utilisation

(i) *Electric Drives*

Due to the various advantages of electric drives, they are universally used in industry. They may operate on either alternating current (a.c.) or direct current (d.c.). Most applications use a.c. induction motors. However they operate at almost constant speed and low starting torque. For variable speed drives and high starting torque applications d.c. has been preferred. However, with modern power electronic controlled drives a.c. motors may also be controlled relatively easily.

(ii) *Electrical Heating*

The heating characteristic of an electric current is used extensively in industrial and domestic heating applications. They have relatively high efficiency (>75%), clean, easy to control, low maintenance and can be protected against overheating easily.

Electric heating can be obtained from (a) resistance heating, (b) induction heating, (c) eddy current heating (d) dielectric heating, and (e) electric arc heating.

(iii) *Electric Welding*

The word welding means the joining of two metals together by heating them to melting point. In electrical welding, a very high electric current produces the heat needed to melt the material. Due to the reliability of the

welded joints in comparison to riveted or bolted joints, electrical welding has been adopted in many fields of engineering. The types of electric welding are resistance welding and arc welding.

(iv) *Air Conditioning*

By air conditioning, the temperature, humidity and the purity of the air are controlled. In tropical countries like Sri Lanka, air conditioning only cools the air and not heats it, but in cold countries both modes are available. The working substance in the cooling type of air conditioner is the refrigerant vapour which readily evaporates and condenses.

(v) *Electric Lighting*

Light is electromagnetic radiation of a wavelength to which the eyes are sensitive (380 nm to 780 nm), bounded at one end by infra-red radiation of 780 to 10,000 nm and ultra-violet radiation of 10 nm to 380 nm wave length at the other end. The colour associated with the various wavelengths are given in table 1.

Wave length (nm)	380-420	420-495	495-566	566-589	589-627	627-780
colour	violet	blue	green	yellow	orange	red

table 1

The eye is most sensitive to the colour yellow-green (wavelength = 555 nm).

Light sources are based on one of the following principles.

- (a) *Incandescent type* - Incandescent filament type lamps emit light when heated to high temperature. Typical incandescent lamps emit about 10 to 15 lm/W.
- (b) *Fluorescent type* - Fluorescent lamps operate by transforming ultra violet rays into radiation of longer wavelength lying in the visible spectrum. Typical fluorescent lamps emit about 50-70 lm/W.
- (c) *Gas discharge type* - Operate on the principle of visible radiation when an electric discharge occurs in a gas or metal vapour. Sodium vapour lamp is a typical example of a gas discharge lamp and have efficacies of about 100 lm/W.

(vi) *Electric Traction*

Two major application of electric traction are electric trains and electric hoists. The good controllability of speed and torque of electrical drives without resorting to lossy gear systems is used in these applications. In addition to this characteristic, the very high initial torque and almost constant power requirement in a vast range of speed torque combinations of a DC series motor is frequently utilised. This allows the Internal Combustion (IC) engine in a train, supplying power to the generator, to run at relatively low range of speeds, even at high running speeds of the train. This enhances efficiency and cuts down wear and tear of the engine significantly.

(vii) *Electrochemistry and Electrometallurgy*

Electrical energy is extensively used in metallurgical and chemical industries for the extraction, refining and deposition of metals and manufacture of chemicals. Though the various processes are different in apparent detail, they are fundamentally alike, being based on the principle of electrolysis.

Extraction and refining of metals are similar electrochemical processes except that extraction is the term used for the production of metals with commercially acceptable purity, while refining is the process by which a highly concentrated of metals is subjected to electro-chemical treatment for recovering not only the principal metal in pure form, but also the precious metals like silver gold etc which may be present in the form of minute traces.

(viii) *Electronics*

Electronics is the branch of science that deals with flow of electrons and other charged particles through gases, vacuum and semiconductor materials. The principle electronic devices are the vacuum tubes, gas-filled tubes, and semiconductor devices like selenium rectifiers, silicon diodes, transistors and silicon controlled rectifiers.

The applications of electronic devices and their circuit arrangements are numerous and varied

(ix) *Information storage and transmission*

The computer is the most powerful tool designed by man. Today's computer is a complex electronic machine capable of storing, processing, manipulating and retrieving large volumes of data/information at incredibly high speeds. Consequently they are finding ever increasing applications in every field of industrial, commercial and business activity, science and space research, medical diagnostics etc resulting in greater production, higher productivity, reduced costs and more reliable and accurate results.

(x) *Biomedical Systems*

Bioelectrical Engineering is the area of biomedical engineering concerning bioelectric activity, which encompasses the nervous system and regulates most life processes. The bioelectrical engineer assists this

regulation and uses bioelectric signals for diagnostic purposes. Developments have led to the invention of the pacemaker, the defibrillator, and the electrocardiograph. The monitoring of many other bioelectric functions by means of electrodes plays an important part in surgical recovery rooms and intensive-care units.

1.4 Electric Drives

1.4.1 Electromechanical energy conversion:

Electrical Energy is obtained by the conversion of other forms of energy, based on the principle of conservation of energy. The main advantage of this conversion is that energy in electrical form can be transmitted, utilised and controlled more easily, reliably and efficiently than in any other form.

An electro-mechanical energy conversion device is one which converts electrical energy into mechanical energy (electric motors) or mechanical energy into electrical energy (electric generators). The electro-mechanical energy conversion process is a reversible process. However, devices are designed and constructed to suit one particular process rather than the other. In an energy conversion device, out of the total input energy, some energy is converted into the required form, some energy is stored and rest is dissipated.

For practical application we need to convert electrical energy into the required useful form, such as mechanical energy, heat, light, sound and electromagnetic waves. One of the major applications is electric drives which uses motors.

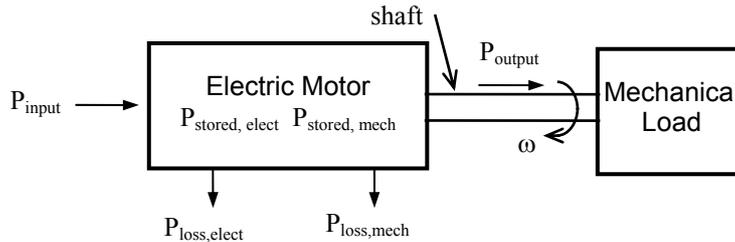


Figure 1.5 - Power flow in an electric motor

The energy balance for a motor (shown in block diagrammatic form in figure 1.5) can be written as

$$\text{Total electrical energy input} = \text{mechanical energy output} + \text{total energy stored} + \text{total energy dissipated}$$

In a motor, energy is stored in the magnetic field and mechanical system. The energy dissipated is in the electric circuit as ohmic losses, in the magnetic circuit as core losses (hysteresis and eddy-current losses), and in the mechanical system as friction and windage losses. [ω is the angular velocity of rotation].

An electric motor provides the driving torque necessary to keep machinery running at the required speed, with provision being made for speed control and reversal of rotation. The electrical motor is required to start, accelerate, drive and decelerate its load, within certain limitations.

There are three main types of motors - Direct Current Motor, Induction Motor and Synchronous Motor

Direct Current (dc) Motors

Direct current (dc) motors operate on a magnetic field produced by the field winding in the stator (stationary part of the motor) interacting with the field produced by the armature winding in the rotor (rotating part). The basic constructional features of a typical two-pole dc motor are shown in figure 1.6 and the circuit model in figure 1.7.

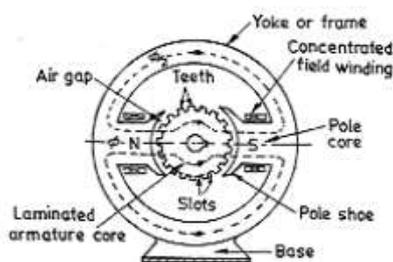


Figure 1.6 - two-pole dc motor

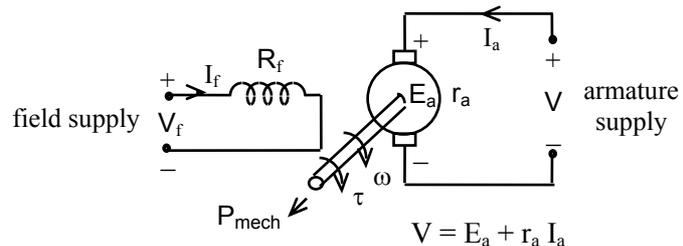


Figure 1.7 - Circuit model of a dc motor

The dc motor needs slip rings or split rings (commutator) on the rotor shaft and a set of brushes positioned over them to supply the armature winding. [symbol for the armature basically shows the rotor and a pair of brushes]

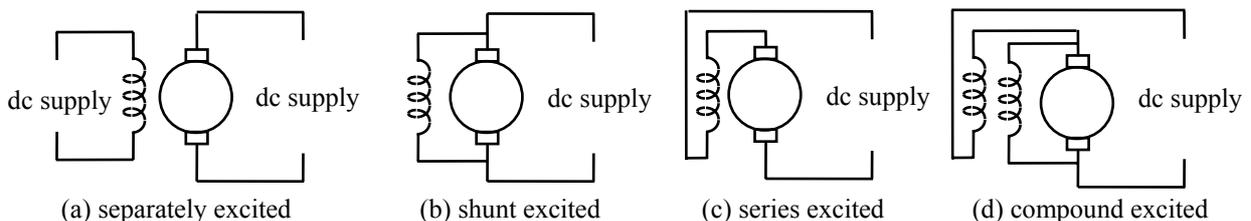


Figure 1.8 - categorisation of dc motors

The dc motors can be categorised into four basic types dependent on the method of connection of the field winding (figure 1.8). These are the (a) separately excited field, (b) shunt connected field, (c) series connected field, and (d) compound connected field.

In the separately excited type, the field winding is connected to a separate or external dc source. In the shunt excited type, the field winding is connected in parallel with the armature winding so that the same dc voltage source is used. In the series excited type, the field winding is connected in series with the armature winding, again making use of the same dc voltage source. Compound excitation involves both the series and shunt excited windings.

In the case of very small motors, the field may be created by a permanent magnet rather than having a field winding. These are known as permanent magnet dc motors.

Speed-torque characteristics of dc motors

The shunt, series and compound motors exhibit distinctive speed-torque characteristics, which are best suited for specific tasks. Thus a study of motor characteristics is essential for one to decide on a specific application using these motors. Figure 1.9 shows the speed-torque characteristics of dc motors. In addition, other characteristics such as torque-current should be considered when selecting motors.

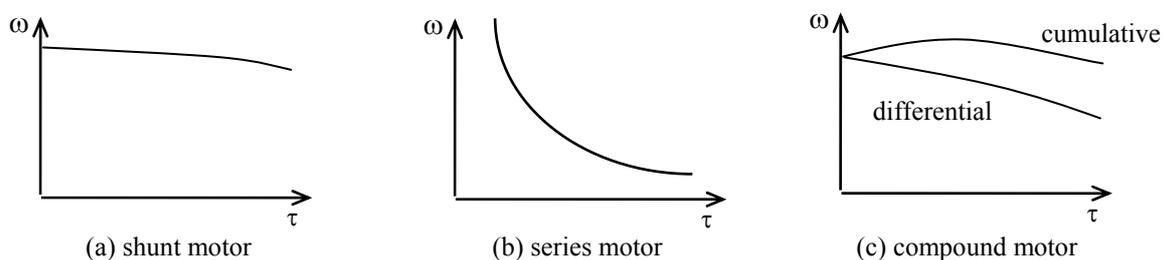


Figure 1.9 - Speed-torque characteristics of dc motors

DC motor applications

Although ac supplies are now universal, there are many applications, where the dc motor finds its place.

The dc shunt motor has a fairly constant speed against a varying load or torque. Thus, applications include situations where a constant speed is required such as in lathes, conveyors, fans and machine-tool drives. Since the dc series motor is able to create large torques at low speeds (high starting torque), it can be used to accelerate very heavy loads from standstill. Thus, dc series motors are used for driving cranes, electric locomotives, group drive shafts (where the motor is used as a drive for a whole assembly line), steel-rolling mills and so on. Compound motors combine the characteristics of both shunt and series wound motors. The series winding gives good starting torque and shunt winding ensures a comparatively constant speed. The actual characteristics of the compound motor can be varied by varying the ratio of shunt to series field turns. They are used in applications such as planers, shears, guillotines, printing machines and power presses that need peak loads at certain instances (normally used with fly wheels to even out the load). Separately excited motors are used in applications where an independent armature control and field control is required. Examples of their use are in steel and aluminium rolling mills (high power) and control motors (low power).

In addition, permanent magnet motors are used for low power applications. These are specially used in automobiles as starter motors, wiper motors, blowers in heaters and air-conditioners, in raising and lowering windows. They are also used in such other applications as toys, electric tooth-brushes.

Stepper Motors

In certain applications, it is necessary to spin quickly and move to a precise point, such as in computer disk drives. This can be accomplished by using a stepper motor. Stepper motors can be viewed as electric motors without commutators. Typically, all windings in the motor are part of the stator, and the rotor is either a permanent magnet or, in the case of variable reluctance motors, a toothed block of some magnetically soft material. The motors and controllers are designed so that the motor may be held in any fixed position as well as being rotated one way or the other. Most stepper motors can be stepped at audio frequencies, allowing them to spin quite quickly, and with an appropriate controller, they may be started and stopped precisely.

AC Motors

With almost the universal adoption of the ac system of distribution of electric energy for light and power, the field of application of ac motors has widened considerably. There are a number of different types of ac motors, each of which offers certain specific advantages.

The supply for these motors is either 3-phase or single-phase. 3 phase motors are found in larger sizes and have mainly industrial applications. Single-phase motors are used mainly for domestic and agricultural applications. In the fractional kilowatt sizes, they are used in large numbers for washing machines, refrigerators and so on.

AC motors are classified to various groups based on their principle of operation; most common are the induction motor and synchronous motor.

Induction Motors

As the name implies, the induction motor is based on the induced voltage in a winding in the rotor. The rotor does not receive electric power by conduction but by induction in exactly the same way as the secondary of a transformer receives its power from the primary. Of all the ac motors, the three-phase induction motor is the one which is extensively used for various kinds of industrial drives.

An induction motor consists essentially of two main parts, namely (a) a stator and (b) a rotor (figure 1.10).

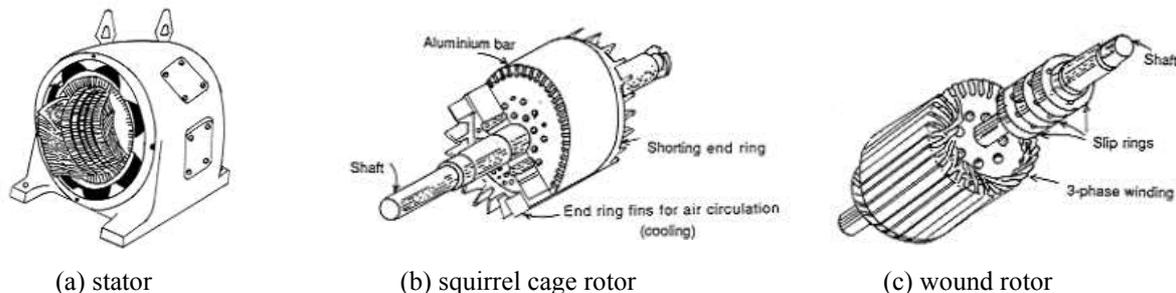


Figure 1.10 - rotor construction of induction motors

In the three phase induction motor the stator carries a 3-phase winding fed from a 3-phase supply. The stator windings, when supplied with 3-phase currents, produce a magnetic flux which is of constant magnitude but which revolves (or rotates) at a constant speed (at synchronous speed). On a 50 Hz supply, the synchronous speed for a 2-pole machine is 3000 rpm and for a 4-pole machine is 1500 rpm.

This revolving magnetic flux induces an emf in the rotor by mutual induction. This causes a current to flow through the rotor conductors and produce a torque with the interaction of stator magnetic field. This torque causes the rotor to start rotating to drive a load. The rotor-load combination settles at a lower speed than the synchronous speed (typically around 2850 – 2975 rpm for a 3000 rpm synchronous speed) as power can be transferred only when there is a relative speed. The difference between synchronous speed and rotor speed is termed as the “slip”. Slip is usually defined as a ratio or percentage of the speed to the synchronous speed. Typically, slip is about 1-5 %.

$$\text{slip} = \frac{\text{synchronous speed} - \text{rotor speed}}{\text{synchronous speed}}, \quad s = \frac{N_s - N}{N_s}$$

The rotor of an induction motor can be of two types, namely (a) squirrel cage and (b) wound rotor as seen in figure 6(b) and 6(c).

(a) Squirrel cage rotor

About 90% of induction motors are squirrel cage type, because this type of rotor has the simplest and most rugged construction and is almost indestructible. The rotor consists of a cylindrical core with parallel slots for carrying the rotor conductors which are not wires but heavy bars of copper, aluminium or alloys. The rotor bars are permanently short-circuited at the ends to form the winding.

Because of the absence of moving parts in the circuitry, the motor is useful for duties in hazardous areas. It finds applications for most industrial drives, where speed control is not required. These are specially used with loads requiring low starting torque and substantially constant speeds. It can be shown that by increasing the effective rotor resistance, the torque-speed characteristic can be modified such that the starting torque is increased. However the operating slip also increases. With low rotor resistance, these are used in fans, centrifugal pumps, most machine tools and wood working tools. With high rotor resistance, they are used in compressors, crushes, reciprocating pumps etc. With very high rotor resistance, are used in punching presses, shears, hoists and elevators.

(b) Wound rotor

Unlike the cage rotor type, the wound rotor type is provided with a three-phase winding in the rotor. Usually, the three phases are connected internally as a star. The other three winding terminals are brought out and connected to three insulated slip-rings mounted on the shaft with brushes resting on them. This makes possible the introduction of additional resistance in the rotor circuit during the starting period for increasing the starting torque of the motor and for changing its speed-torque/current characteristics.

When running under normal conditions, the slip-rings are automatically short-circuited and the brushes lifted from the slip-rings. Hence, it is seen that under normal running conditions, the wound rotor is short-circuited on itself just like the squirrel cage rotor. Applications of the wound rotor type include high-inertia drives requiring variable speed, fly wheel machine drives, air-compressors, ram pumps, crushing mills, cranes, hoists, winches and lifts.

Typical Torque-speed characteristics of an induction motor are shown in figure 1.11. The effect of increasing the rotor resistance on the characteristic is also shown.

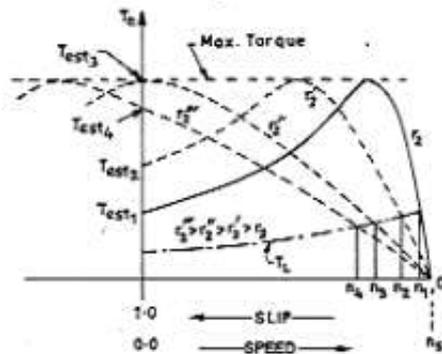


Figure 1.11 - Torque-speed characteristics of an induction motor

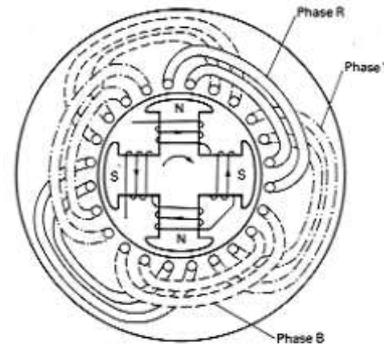


Figure 1.12 - Synchronous Motor

Synchronous Motors

Synchronous motors operate on the same fundamental principles of electromagnetic induction as dc motors. They usually consists of a 3-phase stator winding and a rotor winding which carries a dc current (figure 1.12). When the 3-phase stator winding is fed by a 3-phase supply, a magnetic flux of constant magnitude but rotating at synchronous speed, is produced (as in 3-phase induction motors). This field interacts with the field produced by the dc field winding on the rotor and produces a torque which can be used to rotate a load. It runs at a constant speed (synchronous speed). However, the synchronous motor is not self-starting and hence needs additional means for starting.

$$N_s = \frac{3000}{p}; \quad \text{where } p = \text{pairs of poles}$$

Although the induction motor is cheaper for small power applications, the synchronous motor is preferred for applications above 50 kW. Typical applications include Banbury mixers (used to mix raw ingredients for rubber production), cement grinding mills, centrifugal compressors, mine ventilating fans, pumps, reciprocating compressor drives, electric ship propulsion drives, large low head pumps, rolling mills, ball mills, pulp grinders, etc. They are also used for power factor correction and voltage regulation.

Single-Phase Motors

Single phase motors are designed to operate from a single-phase supply and are manufactured in a large number of types to perform a wide variety of useful services in homes, offices, factories, workshops, vehicles, air crafts, power tools, etc.

Single-phase motors are usually classified based on their operating principle and method of starting, such as

- (1) Induction motors (split-phase, capacitor, shaded-pole etc.)
- (2) Repulsion motors (some times called inductive series motors)
- (3) AC series motors
- (4) Synchronous motors.

The single-phase induction motor is similar to a three-phase induction motor except that its stator is provided with a single phase winding and a special mechanism employed for starting purposes (It does not develop a rotating field but a pulsating field). It has a distributed stator winding and a squirrel cage rotor. Special mechanisms are employed for starting and there are different motor types based on starting method such as split-phase (fans, blowers, centrifugal pumps, washing machines, small machine tools, duplicating machines, domestic refrigerators), capacitor start (small power drives) and shaded-pole (small fans, toys, instruments, hair dryers, ventilators, circulators, electric clocks). Repulsion type motor applications include machine tools, commercial refrigerators, compressors, pumps, hoists, floor-polishing and grinding devices, garage air-pumps, petrol pumps, mixing machines, lifts and hoists. The ac series motor is a modified ordinary dc series motor that can be connected to an ac supply. A similar one is the universal motor, which is a small version of ac series motor. This can work with both ac and dc and used in applications such as vacuum cleaners, food mixers, portable drills and domestic sewing machines. Single-phase synchronous motors are typically used in signaling devices, recording instruments and in many kinds of timers and house hold electric clocks.