Electricity

1. Its Generation, Transmission and Distribution

D P Sen Gupta

D P Sen Gupta graduated in Physics from Presidency College, Calcutta and in Electrical Engineering from IIT Kharagpur. After his Ph.D. from the university of Liverpool, he taught there for five years before joining the Indian Institute of Science where he is presently an Emeritus Fellow.

The experiments of Michael Faraday and Joseph Henry in electromagnetic induction ushered in the era of electricity during the late nineteenth century. Human civilization has undergone a total change since then. This paper in two parts describes the basic principles of AC power generation, its transmission and distribution.

The well known observations made by Oersted that an electric current produces a magnetic field led a number of researchers to investigate whether the converse was true i.e. whether electric current can be produced from a magnetic field. Michael Faraday of England and Joseph Henry of the United States are the best known among these investigators. One can understand the urgency of these investigations when one considers that the only source of current electricity in those days was a *Volta's pile*.

Things have changed since then. Millions of megawatts of electrical power generating sources have been installed all over the world and billions of units (kilowatt hour) of electricity are produced and consumed everyday. The installed capacity in India is more than 85,000 megawatts and the annual energy consumed exceeds 350 billion units and yet we have an acute power and energy crisis.

Essentially an electric generator is a huge electromagnet that is rotated either by thermal power or water power inside a set of coils to produce electricity. The electricity so produced is transmitted, distributed and used in modern gadgets. The running of electric motors is related to the observation made by Oersted that an electric current makes a compass needle move.

Many engineers all over the world have toiled for nearly one and a half centuries to bring the basic observations made by Oersted, Faraday and Henry to bear fruit and transform the face of the earth. Nicola Tesla, Thomas Alva Edison, C P Steinmetz, George Westinghouse are some of the better known among them.

Faraday's first observation led to the construction of transformers and his second observation to generators of electricity.

Faraday's famous experiments on electromagnetic induction may be summarized in two major observations.

- That a voltage is induced in a coil when electric current flowing in another coil placed nearby is either switched on or switched off or changed.
- That a voltage is induced in a coil when a magnet (or an electromagnet) is moved close to or away from it.

It was the genius of Michael Faraday that made him link up these observations into a single law which states that

$$|e| = \frac{d\lambda}{dt} = N\frac{d\phi}{dt},$$

where e is the induced voltage and λ is equal to $N\phi$ termed as *flux linkage*. Faraday *had* observed that the voltage induced was proportional to the number of turns N in the coil in which the voltage was produced and ϕ was the flux produced by the magnet or the electromagnet. Lenz's modification (1835) of Faraday's law assigns direction to the induced voltage and is $e = -d\lambda/dt = -N(d\phi/dt)$, the voltage induced is equal to the negative rate of change of the flux linkage.

Maxwell restated this equation as

$$\nabla \times E = -\frac{\partial B}{\partial t},$$

E and B representing electric and magnetic fields respectively. It is not difficult to see that Faraday's first observation has now led to the construction of *transformers* and the second to the construction of *generators*.

Transformer

In a transformer there are generally two coils called the primary and secondary coils which are stationary with respect to each other. If the current in the primary coil changes with time, the flux it produces also changes with time. When this time varying flux links the secondary coil, a voltage is induced in it. The primary voltage e_1 is

$e_1 = -N_1\,(d\phi/dt)$ where N_1 is the number of turns in the primary winding and the voltage induced in the secondary coil is $e_2 = -N_2\,(d\phi/dt)$, N_2 being the number of turns in the secondary winding.

From these relations, it follows that

$$\frac{e_1}{e_2} = \frac{N_1}{N_2}$$

If we wish to increase or *step up* a voltage, the secondary coil should have larger number of turns than the primary or $N_2 > N_1$. If we intend to decrease or *step down* a voltage, $N_2 < N_1$. In other words if 11 kV alternating (AC) voltage is applied to a transformer whose primary coil has N_1 turns, it will be stepped up to 220 kV if $N_2 = 20N_1$.

Since no power is generated in a transformer (in fact a small fraction is dissipated), the input power = output power or $e_1 i_1 = e_2 i_2$ if losses are neglected. Therefore,

$$\frac{e_1}{e_2} = \frac{i_2}{i_1} = \frac{N_1}{N_2}$$

If the voltage is stepped up by a factor of 20, the current will be correspondingly stepped down to (1/20th) of the primary current. We shall presently see that it is the time varying nature of alternating current (AC) that enables us to transform voltages and currents as required and makes it suitable for transmission and distribution of bulk power (*Figures 1* and *2*).

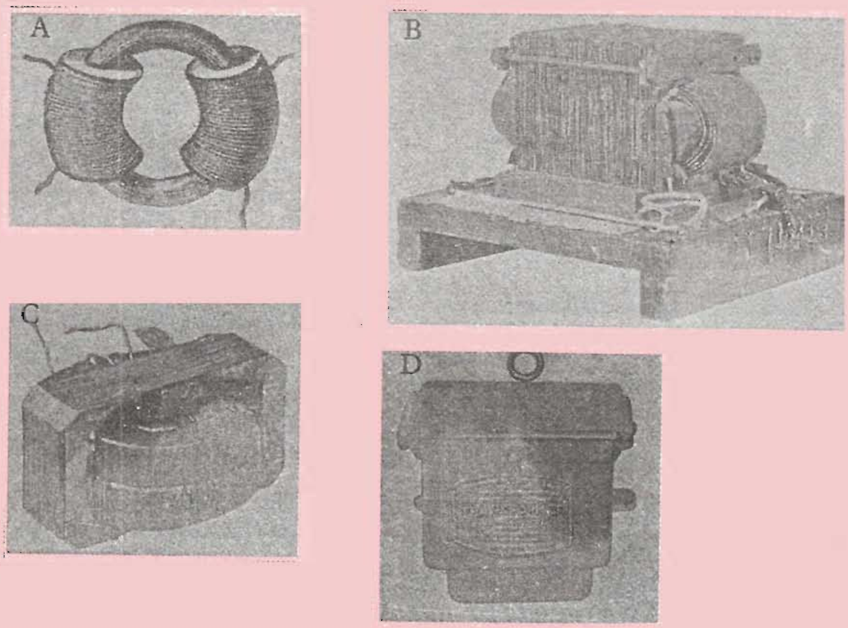


Figure 1 Early development of the transformer. A Faraday experimental model - 1831; B - Stanley original model - 1885; C - one of the first commercial models - 1890; D - case for the 1890 transformer.

Direct current (DC) does not lend itself to similar transformation because it does not vary with time. (see *Box 1*)

Figure 2 A typical substation.

T represents a transformer. The tank placed above it contains oil. The coils of the transformer are wound round a core (made of steel laminations) and immersed in oil which removes the heat produced in the core and the coils.

I represents an isolator which is a kind of 'switch' used to isolate the station from the grid. Note the huge insulators (marked i) that are used.

The steel structures marked S support the conductors through insulators (courtesy: Kirloskar Electric Company, Bangalore).

Box 1

If an alternating voltage is sinusoidal in nature its instantaneous value is

$$v = V_m \sin \omega t,$$

where V_m is the peak value of the voltage and ω (rad/sec) the angular velocity is equal to $2\pi f$, f being the frequency of the voltage in Hz. If this voltage is applied to a coil, the current flowing through it lags the voltage by an angle θ and is $I_m \sin(\omega t - \theta)$. Single phase AC power is given by $P = (V_m I_m \cos\theta)/2 = V_{rms} I_{rms} \cos\theta$ (rms stands for root mean square value. $V_{rms} = V_m / \sqrt{2}$ for sinusoidal voltage). $\cos\theta$ is called the power factor.

The current $I_m \sin(\omega t - \theta)$ produces a flux $\phi = \phi_m \sin(\omega t - \theta)$ and when this flux links N_1 turns, $e_1 = -N_1 d\phi/dt$ or emf in the primary winding is $e_1 = N_1 \phi_m \omega \cos(\omega t - \theta)$. On the other hand a direct current is time invariant. i.e. V_{dc} = constant, the flux produced by it is also a constant and $d/dt\,(N_1 \phi_{dc}) = 0$. In fact if a dc voltage V = 100V (say) is applied to the primary coil of a 100/200 volts transformer the coil will burn out since the current that will flow through the coil is very large, $I_{dc} = V/R$, R being a small quantity. For AC the inductance of a coil offers the major impedance and $I_{AC} = V/\sqrt{R^2 + \omega^2 L^2}$ where $\omega L >> R$ and I_{AC} is small.

Generator

Faraday's second observation pertains to the relative movement of a coil and a magnet (or an electromagnet). It is the mechanical work done in moving (rotating) an electromagnet within a set of electrical coils that causes electrical energy to be produced.

If a magnet or an electromagnet is rotated inside a coil, alternating (AC) voltage is generated. It is obvious that the polarity of the voltage produced alternates since the coil is linked by alternating magnetic field (North - South - North - South ....) as the magnet is rotated. *Figure 3* shows that AC voltage is produced by a rotating magnet.

If we have an electromagnet with 4 poles (*Figure 4*) instead of two as in *Figure 3*, for one complete rotation of the rotor, the

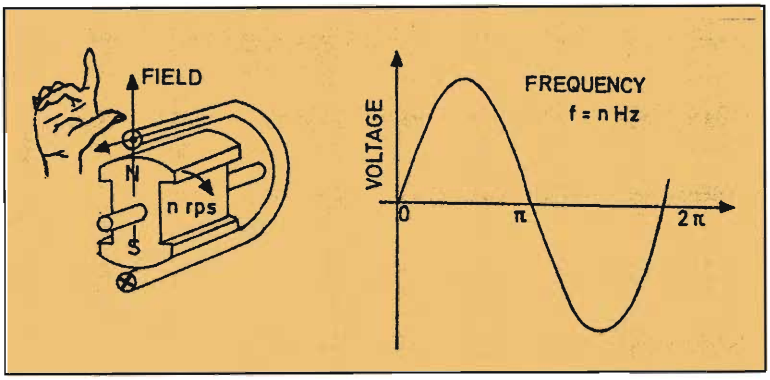


Figure 3 When a magnet (electromagnet) is rotated inside a coil (in reality a set of coils) the magnetic field keeps changing its direction. The voltage/current in the coil correspondingly changes direction or alternates. (Fleming's right hand rule).

voltage would change its polarity four times. This corresponds to two cycles. In other words if the rotor with 4 poles is rotated at n cycles per second, the frequency of the alternating voltage would be $f = 2n$ Hz. If there are 6 poles, the frequency of the voltage will be $f = 3n$ Hz. If, in general, the rotor has p number of poles, the frequency of the voltage generated is $f = (np/2)$ Hz where n is the speed of rotation in rps. Conversely, if the frequency to be generated is f Hz, the number of poles required is $p=(2f/n)$.

This concept is important since it enables us to understand the basic difference between a hydro-generator and a generator driven by a steam turbine.

A steam turbine is driven at a high speed by super-heated steam under pressure. The rotor of the generator coupled to the

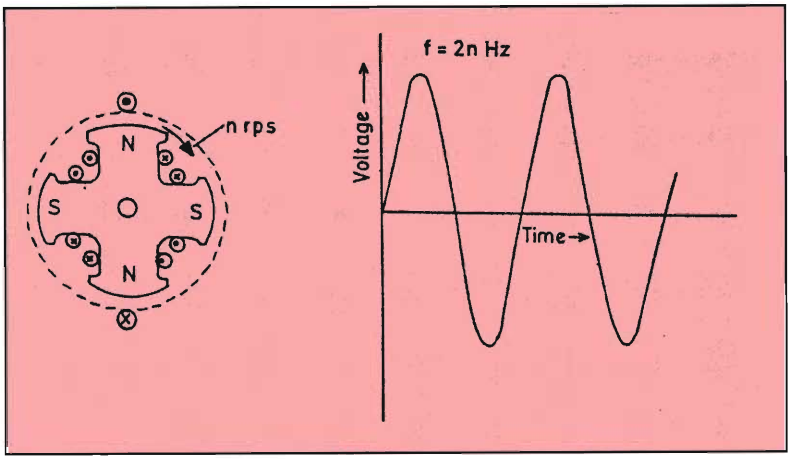


Figure 4 If the rotor has four poles instead of two and is rotated at the same speed n as in Figure 3, the frequency of the voltage generated is 2n. If the frequency has to be kept constant (as is always the case) the rotor should be rotated at n/2 revolutions per second if there are 4 poles and at n/3 rps if there are six poles. In hydro generators, the rotor can be rotated at low speeds only and hence it is to be fitted with a large number of poles.

turbine is a huge cylinder of solid steel and it is wound in a manner that it produces two poles (some times, but seldom, four poles). Since 50 Hz power supply is used in India and also in Europe, the turbine has to be rotated at 50 rps (3000 rpm) for the frequency of the alternating voltage to be

$$f = \frac{2}{2} \times 50 = 50 \text{ Hz. (since } p = 2).$$

In the US and Canada, the frequency of power supply is 60 Hz which means the rotor electromagnets need to be rotated at 60 rps (3600 rpm) (See *Box 2*).

Turbines driven by water (Hydro Electric Power Generation) cannot function very fast (*Figure 5*). Hence the generator electromagnets, that rotate at slow speeds have to have a larger number of poles. Typically a hydro-generator driven at 10 rps would have a rotor fitted with $p = 2f/n = 10$ poles in order that f may be 50 Hz. The power that may be obtained from a generator obviously comes from the mechanical power input into the turbine (either steam power or water power). *Figure 3* represents single phase power generation. It may not be immediately obvious as to what single phase power means until we understand two phase and three phase power generation.

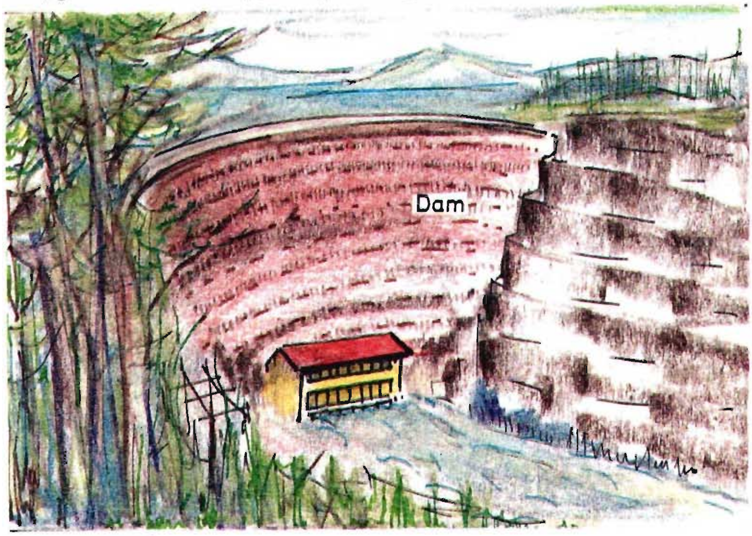


Figure 5 Hydropower generation. Water flowing from tributaries is stored in a suitable valley. A dam is constructed for storing the water which is allowed to overflow if the level exceeds a specified height. The water runs down huge pipes called penstocks and rotates a turbine. This in turn rotates the rotor which has a number of electro-magnets, their number depending on the speed at which the turbine is rotated (see text).

Box 2

It may be interesting to figure out why we settled for 50Hz or 60Hz for AC power supply rather than choosing lower or higher frequencies (say 25 Hz or 200 Hz). Indeed some of the generators installed in the early part of this century did produce electricity at 25Hz. The Sivasamudram hydroelectric generators set up in 1902 to supply power to the Kolar gold fields in Karnataka produce electricity at 25Hz. They still generate about 33MW, half of which is converted to 50Hz and fed into the main grid and the other half is still supplied to the Kolar gold mines at 25Hz.

It may be useful to know that power P generated from a machine is

$$P = kD^2Ln \text{ watts},$$

where D is the rotor diameter, L the length and n is the rotor speed, k being a constant. Larger speed n obviously means less D^2L (machine volume). In other words, smaller machines which run at higher speeds can produce a large amount of power. High rotor speed means high frequency [$f = np/2$] and it would seem there is a very good reason to choose high frequency power generation. (In fact generators used in aircrafts produce 400 Hz power so that the volume and the weight can be kept low).

High frequency power, however, produces a major problem in transmitting it over a distance. Transmission lines offer high impedance z to the flow of current if the frequency is high. $z = \sqrt{R^2 + X_L^2}$, X_L = line reactance = $2\pi fL$. L, the line inductance, increases with the line length. The effective resistance R of the line also increases with the frequency due to skin effect. This explains why engineers chose 25Hz generation to transmit power from Sivasamudram to the Kolar gold fields, along the longest transmission line (~ 150 km) of the time. High frequency power transmission may interfere with communication.

Lower frequency generation means lesser power from a machine. High frequency power is difficult to transmit owing to high line impedance. The frequency of 50 or 60 Hz was therefore a compromise between the two. Once one of these frequencies was chosen, all generators connected to the grid (Part II) must conform and the frequency comes to stay.

If we have two sets of coils *Figure 6* and rotate a magnet inside in the direction shown, obviously the voltage produced in coil 2 will lag the voltage produced in coil 1 by 90^0. The alternating voltage produced in these two coils (two phases) will be as shown in *Figure 6*. If we have three coils, at 120^0 with respect to each other, the voltages produced in these coils will be phase shifted by 120^0 as in *Figure 7*.

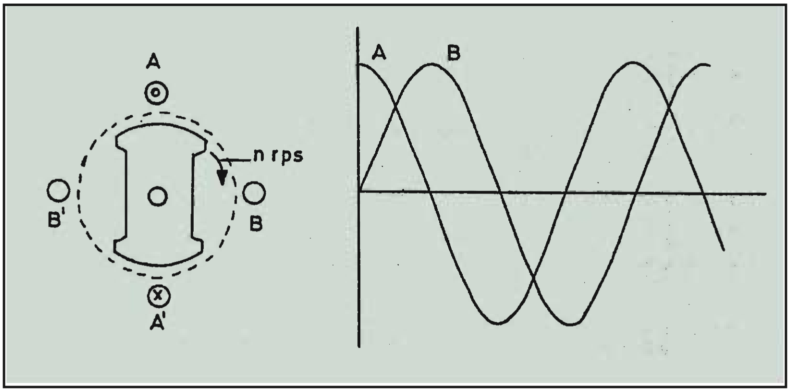
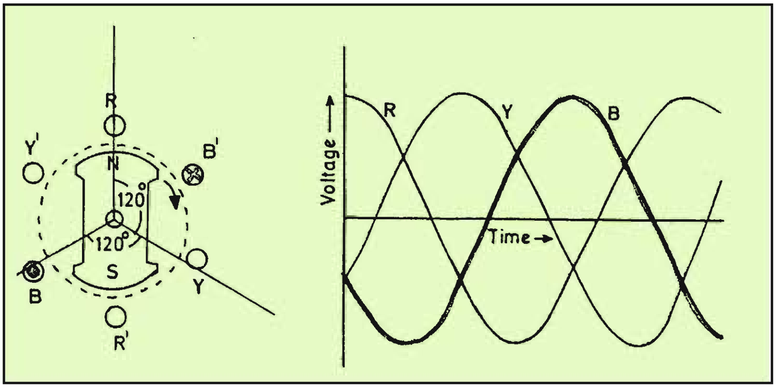


Figure 6 If an electromagnet is rotated and two sets of coils are present in the stator (a cylindrical casing in which coils are embedded) as shown, making 90° w.r.t. each other, the voltage generated in the set AA', leads that in BB' by 90°. A generator like this could be called a 2-phase generator (seldom made).

This would constitute what is called a 3-phase system (*Box 3*). Three phase power generation is found to be the most economical way to generate electrical power and is used all over the world. The three phases are often designated as Red, Yellow and Blue or RYB. (In some countries these are called ABC).

In the next part of this article we will discuss the merits of AC vs DC, Tesla's induction motor and the power system and domestic connection.

Figure 7 Instead of two sets of coils placed 90° w.r.t each other, if there are three sets, placed at 120° w.r.t. each other the voltages generated in them are 120° phase displaced. The voltage generated in the coil marked RR', leads the voltage in the coil YY' by 120° which leads the voltage in coil BB' by 120° again. (It is a 3 phase system with the phase - sequence RYB. If the rotor were to be rotated in the counter clock wise direction, the sequence of the voltages would be RBY.



Address for Correspondence
D P Sen Gupta
Department of Electrical Engineering
Indian Institute of Science
Bangalore 560 012, India

Box 3 The Three Phase System

The three windings of a three phase system have six terminals which can be connected either as Star or as Delta (*Figure 8*). If the three windings of a generator (or of a transformer) are connected as a star, it will have four accessible points RYB and N where N stands for Neutral.

If we measure the voltage between R and N, or the two ends of the red phase, we measure what is called the phase voltage $V_R = V_m \sin\omega t$. The phase voltage V_Y lags V_R by 120°. So $V_Y = V_m \sin(\omega t - 120°)$.

$$V_{RY} = \vec{V}_R - \vec{V}_Y = V_m[\sin\omega t - \sin(\omega t - 120°)]$$
$$= \sqrt{3}\, V_m \sin(\omega t + 30°),$$

which shows that the line to line voltage is $\sqrt{3}$ times the line to neutral (or phase) voltage. If the phases are connected in Delta, the line to line voltage is the same as the phase voltage. In star connection the line current and the phase current are the same. In delta connection the line current is $\sqrt{3}$ times the phase current. Power in either case is given as

$$P = \sqrt{3}\, VI \cos\theta,$$

where V and I are the root mean square values of the line voltage and line current respectively.

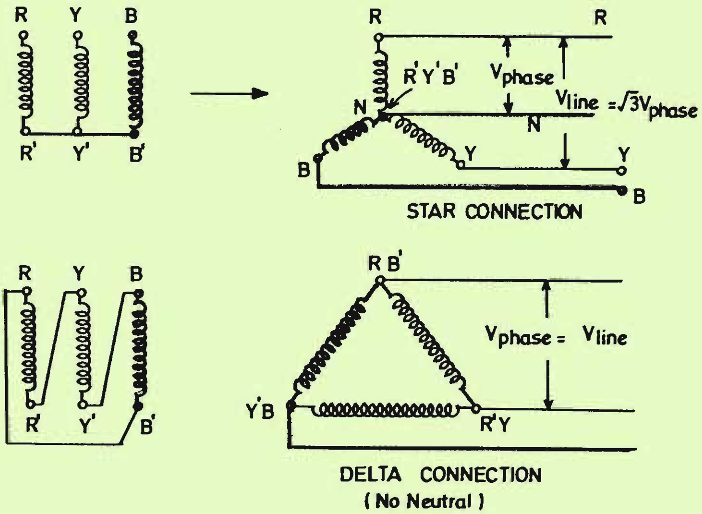


***Figure 8** Three phases can be connected either in star (Y) or as Delta (Δ). In star connection the line and phase currents are one and the same. But the line to line voltage is $\sqrt{3}$ times the voltage between a line (or phase) and the neutral. In domestic connections a wire from the neutral and any one of the phases are brought in.*