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Introduction

1.1. Requirements of an Electric Supply System

A great deal of effort is required to maintain an electric power supply within the requirements of the various types of customers served. Some of the requirements for electric power supply are recognized by most consumers, such as proper voltage, availability of power on demand, reliability and reasonable cost.

Power must be available to the consumer in any amount that he may require from time to time. For example, motors may be started or shut down, fans and lights may be turned on or off, without giving any advance warning to the electric power supply company. As electric energy cannot be stored, the changing loads impose severe demands on the control equipment of any electrical power system. The operating staff must continuously study load partners to predict in advance those major load changes that follow known schedules.

The proper voltage at the consumer's premises must be held substantially constant. Variations in supply voltage are detrimental in various respects. For example flickering of lamps caused by voltage fluctuations in the power supply network, products damage due to a change in the motor speed caused by the voltage and frequency variations. Motors operated at below normal voltage draw abnormally high currents and may overheat, even when carrying no more than the rated horse power load. Over-voltage on a motor may cause excessive heat loss (Iron losses), wasting energy and perhaps damaging the machine.

An increasing amount of attention is being focused on the reliability or continuity of service as our industrial and social environment has become more complex. Electric power can never be absolutely reliable. Occasional interruptions to service in limited areas will continue, but large number of interruption initiate the customers, cause loss of money not only due to system shut down but also due to

Industrial Customer's equipment deterioration and change in the quality of the products.

The power-supply requirements just discussed are all well known to most of the electric power customers. There are other problems such as harmonics and voltage unbalance that customers are seldom aware that such requirements are of importance. In poorly designed generating equipment, harmonics may be present in the voltage supply and the presence of these harmonics produce unnecessary losses in the customer's equipment. Voltage unbalances produce unnecessary losses in three-phase motors and reduces the maximum starting torque.

The cost of electric power is a prime consideration in the design and operation of electric power systems. This decrease in cost has been possible because of improved efficiency of the generating stations, interconnection of stations, economic operation of power plants and also due to improved efficiency in distribution systems.

1.2. Energy Resources

The natural resources of a country may be great but they can only be turned into wealth if they are developed, used and exchanged for other goods. This cannot be achieved without energy. The major sources of primary energy are :

1. Fossil Fuels – coal, natural gas and oil.
2. Water power – hydro-electric power stations.
3. Nuclear power – fission and fusion.
4. Solar energy – heat radiation from the sun.
5. Geothermal Energy – thermal springs due to inner-strata of the earth at a very high temperature.
6. Wind power – high velocity of wind drives wind mills.
7. Tidal power – tremendous energy in the tides of the ocean.

Out of the above mentioned seven sources of available energy only first three are most dependable and are commonly used for generation of electrical power. The continuity of electrical power from other sources is not certain and depends of Nature.

India is fairly endowed organisationally as well as resource-wise as far as power generation is concerned. Estimated reserves of energy resources in India are shown in Table 1.1.

Table 1.1. Estimated reserves of energy sources

Region	*Coal* 10^9 *t*	*Lignite* 10^9 *t*	*Crude oil* 10^9 *t*	*Natural Gas* 10^9 M^3	*Hydro / Potential M kWh*
Northern	—	0.029	—	—	10.73
Southern	2.06	1.919	—	—	8.10

Western	18.10	0.078	0.056	19.66	7.17
Eastern	59.97	—	—	—	2.70
North-Eastern	0.83	—	0.072	42.82	12.46
All India	80.96	2.026	0.128	62.48	41.16

1.3. Power Plants

The generating plants which use coal (or fuel oil) are called *thermal power plants.* In thermal power plants the heat of combustion of coal (or fuel oil) is utilized in a boiler which delivers steam at a suitable temperature and pressure to a steam turbine, the later driving the electrical generator.

Water is a great potential source of energy. The generating plants which obtain energy from water are called *hydro-electric power plants.* Potential energy of water is converted into mechanical energy in a water turbine, which drives the electrical generator. The advantages claimed in this plant are – no fuel, low maintenance costs and quick start-up. The power obtained from nuclear fission is called nuclear power or atomic power and power plants using this energy are called as *Nuclear power plants* or *Atomic power plants.* The materials which undergo nuclear fission are Uranium (U_{235}), thorium (Th_{232}) and Plutonium (PU_{239}). It will be interesting to note that when 1 kg of U_{235} is fissioned 25×10^9 kWh of heat energy can be produced, *i.e.* 1 kg of atomic material is equivalent in heating ability to about 36,000 tonnes of coal. It may be said that basically a nuclear power plant is a thermal power plant in which the nuclear reactor replaces the steam boiler.

In *diesel power plants,* diesel engine is a prime mover which obtains its energy from a liquid fuel generally known as diesel oil and converts this energy into mechanical energy. An alternator or d.c. generator mechanically coupled to it converts the mechanical energy developed into electrical energy. This major advantage of diesel power plants is that they can be started and stopped quickly as and when required.

Table 1.2
Electric Energy growth in India

Year	*Installed capacity (GW)*	*Gross generation (TWh)*	*No. of villages electrified*	*Total length of lines (circuit km)*	*Annual per capita consumption (kWh)*
1950	1.71	5.10	3061	29271	15.55
1955 - 56	2.69	8.59	7294	66421	26.40
1960 - 61	4.65	15.94	21754	157887	37.90

1965 - 66	9.03	32.99	45148	541704	61.30
1970 - 71	14.71	55.83	104942	1117164	89.70
1975 - 76	18.31	74.29	176260	1821848	105.10
1980 - 81	30.20	110.84	272287	2522461	132.30
1985 - 86	42.59	161.25	390560	3411956	192.20
1990 - 91	66.09	264.61	481124	4533414	262.70
1993 - 94	76.75	324.16	494191	4850000	299.00

India has the largest power system among developing countries and fourteenth largest power system in the world. Electric energy growth in India is depicted in Table 1.2.

1.4. Structure of Electric Power System

Electric power systems may be of great complexity and spread over large geographical areas. An electric power system consists of an energy source, a prime mover, a generator, the transmission lines, the distribution systems and loads.

The energy source may be coal, gas or oil burned in a furnace to heat water and generate steam in the boiler; it may be fissionable material which, in a nuclear reactor, will heat water to produce steam; it may be water in a pond at an elevation above the generating station; or it may be oil or gas burned in an internal combustion engine.

The prime mover may be a steam driven turbine, a hydraulic turbine or and internal combustion engine.

The generator may be an alternator, the type of machine that supplies most of the electric power used today. In special cases the generator may be a d.c. machine.

The transmission lines are the connecting links between the generating plants and the distribution systems and lead to other power systems over inter-connections. A distribution system connects all the individual loads in a given locality to the transmission lines.

The electrical load may be lights, heaters, electric motors (Induction motors, synchronous motors etc.), rectifiers, inverters or other devices. The load does not remain constant but varies from minute to minute as different demands occur.

A typical power transmission scheme by which the electrical energy is obtained is depicted in Fig. 1.1. It should be noted that electric power system is never as simple as the one depicted here. In this figure the alternator generates 11 kV which is stepped upto 220 kV at the sending end and power is transmitted over the three phase transmission line. At the receiving stations the voltage is reduced to 33 kV with the help of a step down transformer. From these sub-stations again radiate out a number of feeders, each feeding a bulk consumer or sub-station, where the voltage is further reduced to say 6.6 kV and a number of low voltage distributors radiate out from these sub-stations to transforming stations reducing the voltage to 400/230 volts.

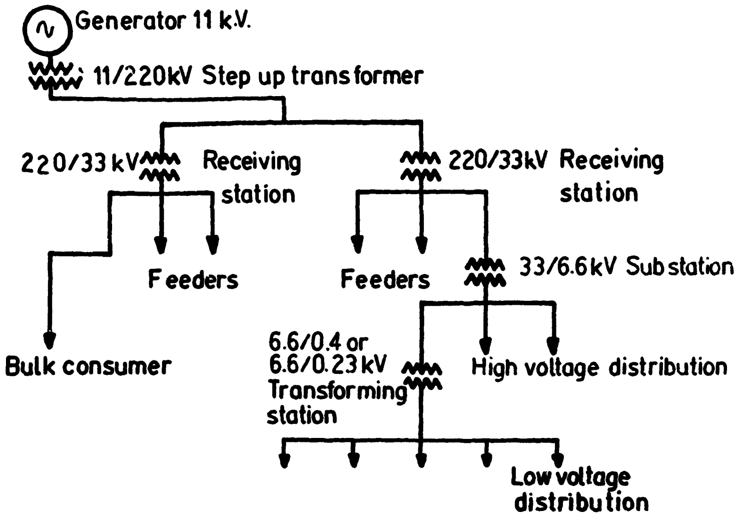

Fig. 1.1. Power system structure.

1.5. Static Load Model

An accurate representation of electric loads under steady state conditions is of interest for the purpose of more detailed system behaviour studies by simulation. For example the importance of proper load representation, especially in stability studies by simulation, is widely recognized. In dealing with the problem of load modelling, the major difficulty encountered relates to the nature of system loads in general, and their variety of level and changing composition. Of the various models suggested for load representation under steady-state conditions, the exponential relationship (chapter 4) appears to be the most suitable for computational purposes. The static load models are of great use in load flow studies, load frequency control, stability studies and simulation of faults in power systems etc.

1.6. Load Forecasting

As the name indicates the problem of load forecasting is that of estimating the future load demand of a given power system. The active power demand on a given power system varies with time for various reasons. Depending upon the time period of interest, a specific forecasting procedure may be classified as very short term, short term, medium term and long term technique. Very short term load forecasting and short term load forecasting are generally required by the system operators for the purpose of economic generation scheduling and load dispatching, as also for security checking. Medium term forecast helps in allocation of spinning reserves. Finally, the long term load forecasts are essential for power system planning. The long-term aspect is important because of the time required to construct major power-system components. The construction of large generating plants takes many years. This means that the planner must determine his generating needs well in advance. Further the long-term forecasts influence the selection and sequence of generation additions. In any case load forecasting technique must be used as tools to aid the planner ; good judgment and experience can never be completely ignored.

1.7. A.C. Power Transmission

Electric power has to be transmitted in the most efficient manner and under conditions most favourable both electrically and aesthetically. Basically power could be transmitted by alternating or direct current systems depending on the type of generation available and the type of load for which power is needed at the other hand. Similarly power could be transmitted either by overhead lines or underground cables depending on the route over which the power line has to pass.

Transmission of large blocks of power by a.c. systems of transmission has been the accepted practice at the present time. It has been established that the cost of transmission decreases with the increase in voltage, and it is thus found that there is a tendency at the present time to use higher and higher voltages for transmission. As we know that the power transfer formula is expressed as the product of the magnitude of the two terminal voltages and the sine of the angle between them divided by the reactance, thus large block of power is transmitted over long distances with higher voltages. The power transfer capability of such lines (E.H.V. lines) can be increased by providing series capacitors. The transmission lines above 230 kV are designated as *extra high voltage lines* (E.H.V. lines). The voltages of transmission in use in this country at present are 3.3, 6.6, 11, 33, 66, 110, 132, 220 kV while 400 kV transmission lines are under construction.*

Generally shunt reactors are provided in E.H.V. lines to absorb part of shunt capacitance VA of the line, for example between 40 to 100% of line shunt capacitive power may be thus compensated at light load in order to prevent overvoltages on the line. But to restrict insulation stresses caused by over-voltages following sudden load rejection, a substantial part of the shunt reactive compensation (Sec. 9.4.3) is usually left permanently connected.

The phenomena of corona loss is an important factor in case of E.H.V. lines as it seriously affects the performance of the line. So, it is

* First 400 kV Obra-Sultanpur line in U.P. was commissioned in Dec. 1977.

of considerable economic importance to keep the corona loss to a low value. The corona loss is reduced considerably by having two or more conductors per phase in close proximity compared with the spacing between phases. Such a line is said to be composed of *bundled* conductors. As the bundle construction considerably reduces the line inductance and increases the capacitance per phase, it results into reduction of surge impedance of the line. The decrease of surge impedance increases the surge impedance loading (SIL) of the transmission line, which is an important property and indicates the maximum amount of power that could be transmitted over a line without loss of stability.

The radio interference originates from the same source at the corona and has an important bearing in the design of E.H.V. lines. Conductors should be selected to give the least radio interference at the lowest possible cost. Radio interference in the vicinity of a transmission line is the disturbance radiated from the various conductors as a result of corona discharge on the conductors and is usually measured in microvolts per metre. Bundle conductors offer an economical solution for minimising corona loss and radio interference in E.H.V. lines.

1.8. Load Flow Studies

Load flow studies provide information to enable the active and reactive power flows to be determined at various points in a power system network, together with other pertinent information such as bus-bar voltage, current, tap-change and reactive compensation requirements. Load studies may be carried out in connection with the existing requirements of a power system, or for any other contemplated mode of operation, as required by consideration of demand and plant outage conditions. These conditions may vary considerably, and such studies are essential in planning because satisfactory operation of the system depends on knowing the interconnections with other power systems before installation. These studies are essential in minimizing system losses and provide information of the stability and general security of the power system. The load flow studies also enable us to study the economic load dispatch problems such as allocation of the real power generations between the system generators with the aim to minimize the fuel cost.

For many years, load flow studies were carried out with the aid of network analysers, but with the rapid development of digital computers in the 1950's the attention of power engineers has been directed towards a rapid digital computer studies of the load flow problems by various algorithms we shall study in chapter 13, how such studies are carried out and examine various algorithms for solving load flow problems.

1.9. Economic Dispatch

The purpose of economic dispatch is to reduce fuel costs for the power system. Minimum fuel costs are achieved by the *economic load* *scheduling* of the generating units in the power system. By economic load scheduling we mean to find the generation so that the total fuel cost is minimum, and at the same time the total demand and the losses at any instant must be met by the total generation. Good power system operating practice dictates the generation capability exceeding the existing power system load must be kept operating at all times. Excess generation capability is needed because forced outages may remove some of the existing generation from the power system, or loss of transmission capacity may make some of the generation inaccessible to the load. The selection of the excessive generation that should be running is a separate complex problem based on system reliability, economics, and the physical condition of the power system at the time the choice is made.

We shall see in chapter 14 how such studies are made on the computer.

1.10. Load-Frequency Control

It is necessary to maintain the network frequency constant so that the power stations run satisfactorily in parallel, the various motors operating in the system run at the desired speed, correct time is obtained from the synchronous clocks in the system, and the entertaining devices function properly. In order to maintain the frequency constant, it is necessary to achieve a balance between the generation and the connected load.

Automatic advanced load-frequency control systems are now available for maintaining the frequency of the system within the tolerable limits. Conventional load-frequency control is based upon the tie-line bias control where each area tends to reduce the area control error to zero. When this is achieved the system frequency equals the desired value and the interchange schedule is met. With the development of modern control theory, several concepts of load frequency control have been investigated which go beyond the simple tie-line bias control. The fundamental approach is the use of more extended mathematical models. In retrospect, the *ACE* (chapter 15) can also be considered as a model of the area. The recent concepts however, involve the representation of the dynamics of the area, or even of the completed system.

1.11. Fault Studies

It is inevitable that faults of various kinds will occur in any transmission system. These may be caused by spontaneous failure of a piece of equipment, by accidental damage or short circuit to overhead transmission lines or by insulation failure from lightning surges. On high-voltage systems where economics forces maximum reduction in insulations, arcs are occasionally caused from switching surges. Switching surges result from rapid changes in the flow of current that can occur when energizing or de-energizing lines and equipment. Such operations can induce travelling waves that may flash lines or equipment and points of low insulation.

Faults on power systems are unpredictable both as to location and time of occurrence. When a system study is made to determine the behaviour during a fault, it is necessary to assume the location of the fault, the configuration of lines, transformers, and generators that exists previous to the fault, and in some cases the loading of the system. For a system of some complexity, the possibilities of assignment of initial conditions combined with a choice of fault location may result in a very large number of required solutions. These studies provide the engineer with information by which he can design to assure the prompt disconnection of faulted equipment with a minimum of damage and a minimum of disturbance to the operation of the remaining system. Thus the knowledge of expected system short circuits is essential in the economic planning and design of the power system.

In order to protect the lines and equipment from undue currents and/or abnormal voltages due to the faults (or short circuits) protective devices such as relays and circuit breakers are provided. To obtain proper settings of these relays, the value of such currents and voltages must be known. The four basic types of faults in order of frequency of occurrence are : Single line to ground, line to line, double line to ground, and balanced three phase. The first three types constitute severe unbalanced operating conditions and the analysis of these faults requires the knowledge of symmetrical components (chapter 16), which make the calculation of unsymmetrical faults almost as easy as the calculation of three phase faults. Chapter 17 is entirely devoted to balanced three phase faults and bus impedance matrix method for computing three phase faults is also introduced. The bus impedance matrix method is almost indispensible tool to-day in the area of fault studies and has come to the forefront largely as a result of the emphasis upon the use of the digital computer. Unsymmetrical faults are studied in chapter 18.

1.12. Stability Studies

Power system generators connected through a transmission network must run in synchronism, that is, at the average speed. Automatic load, and frequency control systems and individual machine speed-governing systems tend to keep generator speeds, and consequently speed differences, within narrow bounds, but it is the effect of variational power flow through the network which forces speed differences to be zero on the average. If any generator runs faster than another, the angular position of its rotor relative to that of the slower machine will continue to advance as long as the speed difference exists, and its generated voltage will likewise advance in phase relative to the voltage of the slower machine. The resultant phase difference, within limits, shifts a load from the slow machine to the fast one, tending to reduce the speed difference.

The shift in load between generators is a non-linear function of the difference in rotor angles, and above a certain angle difference, nominally 90°, the incremental load shift due to incremental angle change reverses, and the forces which tended to reduce speed differences become forces tending to increase speed differences. This, in essence, is the loss-of-synchronism phenomena. Moreover, as machines lose synchronism, currents and voltages vary over wide ranges, and protective apparatus should operate, and normally will, to trip affected generators and lines.

Power system stability is primarily concerned with variations in speeds, rotor positions, and generator loads. It focuses attention on the transmission network, since it is the network, more than power plant or system control, which provides for the power shifts between generators required to maintain synchronism. Power system engineers have found it useful to identify three types of stability, designated *steady-state stability, transient stability* and *dynamic stability.* There are no universally accepted precise definitions of this terminology, and there is no intent to imply definitions in what follows. Instead, the purpose is simply to describe generally several ways in which stability occurs. A synchronous power system has *steady state stability* if, after a small slow disturbance, it can regain and maintain synchronous speed ; a small slow disturbance is taken to mean normal load fluctuations, including the action of the automatic voltage regulators and turbine governors. A power system has *transient stability* if after a large sudden disturbance, it can regain and maintain synchronous speed ; a large sudden disturbance is one caused by faults and switching. In order to develop the main principles simply it is assumed that the automatic voltage regulators and turbine governors are too slow to act, during the period of analysis. *Dynamic stability* refers to the case of transient stability when the regulators and governors are fast-acting and are taken into account in the analysis. The *stability limit* of a system is the maximum (steady-state) power which can be transferred through the system without loss of stability. The limit depends also on the magnitude, type and location of the disturbance. The various aspects of power system stability are covered in chapter 19.

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