Chapter 1

Structure of Power Systems

1.1 Power Systems

Generation, Transmission and Distribution systems are the main components of an electric power system. Generating stations and distribution systems are connected through transmission lines. Normally, transmission lines imply the bulk transfer of power by high-voltage links between main load centers. On the other hand, distribution system is mainly responsible for the conveyance of this power to the consumers by means of lower voltage networks. Electric power is generated in the range of 11 kV to 25 kV, which is increased by stepped up transformers to the main transmission voltage. At sub-stations, the connections between various components are made, for example, lines and transformers and switching of these components is carried out. Transmission level voltages are in the range of 66 kV to 400 kV (or higher). Large amounts of power are transmitted from the generating stations to the load centers at 220 kV or higher. In USA it is at 345 kV, 500 kV and 765 kV, in Britain, it is at 275 kV and 400 kV and in Egypt it is at 500 kV and 750 kV. The network formed by these very high
voltage lines is sometimes called as the super grid. This grid, in turn, feeds a sub-transmission network operating at 132 kV or less. In Egypt, networks operate at 132 kV, 66 kV, 33 kV, 11 kV or 6.6 kV and supply the final consumer feeders at 380 volt three phase, giving 220 volt per phase.

Figure 1.1 and Figure 1.2 shows the schematic diagram of a power supply network. The power supply network can be divided into two parts, i.e., transmission and distribution systems. The transmission system may be divided into primary and secondary (sub-transmission) transmission system. Distribution system can be divided into primary and secondary distribution system. Most of the distribution networks operate radially for less short circuit current and better protective coordination.

Distribution networks are different than transmission networks in many ways, quite apart from voltage magnitude. The general structure or topology of the distribution system is different and the number of branches and sources is much higher. A typical distribution system consists of a step-down transformer (e.g., 132/11 kV or 66/11 kV or 33/11 kV) at a bulk supply point feeding a number of lines with varying length from a few hundred meters to several kilometers. Several three-phase step-down transformers, e.g., 11 kV/400 V are spaced along the feeders and from these, three-phase four-wire
networks of consumers are supplied which give 220 volt single-phase supply to houses and similar loads. Figure 1.3 shows part of a typical power system.

![Diagram of power supply system](image)

**Figure 1.1 Schematic diagram of a power supply system.**
Figure 1.2: One-line diagram of a simple electric power system.
1.2 Reasons for Interconnection

Generating stations and distribution systems are connected through transmission lines. The transmission system of a particular area (e.g., state) is known as a grid. Different grids are interconnected through tie-lines to form a regional grid (also called power pools). Different regional grids are further connected to form a national grid. Cooperative assistance is one of the planned benefits of interconnected operation.
Interconnected operation is always economical and reliable. Generating stations having large MW capacity are available to provide base or intermediate load. These generating stations must be interconnected so that they feed into the general system but not into a particular load. Economic advantage of interconnection is to reduce the reserve generation capacity in each area. If there is sudden increase of load or loss of generation in one area, it is possible to borrow power from adjoining interconnected areas. To meet sudden increases in load, a certain amount of generating capacity (in each area) known as the "spinning reserve" is required. This consists of generators running at normal speed and ready to supply power instantaneously.

It is always better to keep gas turbines and hydro generators as "spinning reserve". Gas turbines can be started and loaded in 3 minutes or less. Hydro units can be even quicker. It is more economical to have certain generating stations serving only this function than to have each station carrying its own spinning reserve. Interconnected operation also gives the flexibility to meet unexpected emergency loads.

1.3 Load Types

Total load demand of an area depends upon its population and the living standards of people. General nature of load is characterized by the load factor, demand factor, diversity
factor, power factor and utilization factor. In general, the types of load can be divided into the following categories: (1) Domestic (2) Commercial (3) Industrial (4) Agriculture.

**Domestic Load:** Domestic load mainly consists of lights, fans, refrigerators, air-conditioners, mixer, grinders, heaters, ovens, small pumping motors etc.

**Commercial Load:** Commercial load mainly consists of lighting for shops, offices, advertisements etc., fans, heating, air-conditioning and many other electrical appliances used in commercial establishments such as market places, restaurants etc.

**Industrial Loads:** Industrial loads consist of small-scale industries, medium-scale industries, large-scale industries, heavy industries and cottage industries.

**Agriculture Loads:** This type of load is mainly motor pump-sets load for irrigation purposes. Load factor for this load is very small, e.g., 0.15-0.20.

### 1.4 Load Curves

The curve showing the variation of load on the power station with reference to time is known as a load curve.

The load on a power station is never constant; it varies from time to time. These load variations during the whole day (i.e. 24 hours) are recorded half-hourly or hourly and are plotted against time on the graph. The curve thus obtained is
known as *daily load curve* as it shows the variations of load with reference to time during the day. Fig. 1.4 shows a typical daily load curve of a power station. It is clear that load on the power station is varying, being maximum at 6 P.M. in this case. It may be seen that load curve indicates at a glance the general character of the load that is being imposed on the plant. Such a clear representation cannot be obtained from tabulated figures.

![Daily Load Curve](image)

*Fig. 1.4 Daily load curve*

The *monthly load curve* can be obtained from the daily load curves of that month. For this purpose, average values of power over a month at different times of the day are calculated and then plotted on the graph. The monthly load curve is generally used to fix the rates of energy. The load curve is obtained by considering the monthly load curves of that particular year. The *yearly load curve* is generally used to
determine the annual load factor.

**Important Notes:**

The daily load curves have attained a great importance in generation as they supply the following information readily:

i. The daily load curve shows the variations of load on the power station during different hours of the day.

ii. The area under the load curve gives the number of units generated in the day.

\[
\text{Units generated/day} = \text{Area (in kWh) under daily load curve.}
\]

iii. The highest point on the load curve represents the maximum demand on the station on that day.

iv. The area under the load curve divided by the total number of hours gives the average load on the station.

\[
\text{Average load} = \frac{\text{Area (in kWh) under daily load curve}}{24 \text{ hours}}
\]

v. The ratio of the area under the load curve to the total area of rectangle in which it is contained gives the **load factor**.

\[
\text{Load factor} = \frac{\text{Average load}}{\text{Max. demand}} = \frac{\text{Area (in kWh) under daily load curve}}{\text{Max. demand} \times 24}
\]

vi. The load curve helps in selecting the size number of generating units.
1.5 Units Generated per Annum

It is often required to find the kWh generated per annum from maximum demand and load factor.

\[
\text{Load factor} = \frac{\text{Average load}}{\text{Max. demand}}
\]

\[
\text{Average load} = \text{Max. demand} \times \text{L.F.}
\]

Units generated/annum = Average load (in kW) × Hours in a year
= Max. demand (in kW) × L.F. × 8760

1.6. Base Load and Peak Load on Power Station

The changing load on the power station makes its load curve of variable nature. Figure 1.4, shows the typical load curve of a power station. It is clear that load on the power station varies from time to time. The load curve shows that load on the power station can be considered in two parts, namely; (i) Base load (ii) Peak load

➢ Base load: The unvarying load which occurs almost the whole day on the station. Referring to the load curve of Fig. 1.5, it is clear that 20 MW of load has to be supplied by the station at all times of day and night i.e. throughout 24 hours. Therefore, 20 MW is the base load of the station. As base load on the station is almost of constant nature, therefore, it can be suitably supplied (as discussed in the next Article) without facing the problems of variable load.
➢ **Peak load:** The various peak demands of load over and above the base load of the station. Referring to the load curve of Fig. 1.5, it is clear that there are peak demands of load excluding base load. These peak demands of the station generally form a small part of the total load and may occur throughout the day.

![Fig. 1.5](image)

### 1.7. Method of Meeting the Load

The total load on a power station consists of two parts: base load and peak load. In order to achieve overall economy, the best method to meet load is to interconnect different power stations. The more efficient plants are used to supply the base load and are known as **base load power stations**. The less efficient plants are used to supply the peak loads and is known
as *peak load power stations*. There is no hard and fast rule for selection of base load and peak load stations as it would depend upon the particular situation. For example, both hydroelectric and steam power stations are quite efficient and can be used as base load as well as peak load station to meet a particular load requirement.

**Illustration:** The interconnection of steam and hydro plants is a beautiful illustration to meet the load. When water is available in sufficient quantity as in summer and rainy season, the hydroelectric plant is used to carry the base load and the steam plant supplies the peak load as shown in Fig 1.6 (i). However, when the water is not available in sufficient quantity as in winter, the steam plant carries the base load, whereas the hydro-electric plant carries the peak load as shown in Fig. 1.6 (ii)

![Fig. 1.6 Load division on Hydro-steam system](image-url)
1.8 Load duration Curve

When the load elements of a load curve are arranged in the order of descending magnitudes, the curve thus obtained is called a load duration curve.

The load duration curve is obtained from the same data as the load curve but the ordinates are arranged in the order of descending magnitudes. In other words, the maximum load is represented to the left and decreasing loads are represented to the right in the descending order. Hence the area under the load duration curve and the area under the load curve are equal. Fig. 1.7 (i) shows the daily load curve. The daily load duration curve can be readily obtained from it.

![Daily load duration curve](image)

**Fig. 1.7 Daily load duration curve**

It is clear from daily load curve [See Fig. 1.7. (i)], that load elements in order of descending magnitude are : 20 MW for 8 hours; 15 MW for 4 hours and 5 MW for 12 hours. Plotting
these loads in order of descending magnitude, we get the daily load duration curve as shown in Fig. 1.7 (ii).

Here are some important points about load duration curve:

- The load duration curve gives the data in a more presentable form. In other words, it readily shows the number of hours during which the given load has prevailed.
- The area under the load duration curve is equal to that of the corresponding load curve. Obviously, area under daily load duration curve. Obviously, area under daily load duration curve (in kWh) will give the units generated on that day.
- The duration curve can be extended to include any period of time. By laying out the abscissa from 0 hour to 8760 hours, the variation and distribution of demand for an entire year can be summarized in one curve. The obtained curve is called the annual load duration curve.

1.9 Basic Definitions of Commonly Used Terms

Electrical engineers use the following terms and factors to describe energy flow in power systems:

- **Connected load**: It is the sum of continuous ratings of all the equipment connected to supply system.

  A power station supplies load to thousands of consumers.
Each consumer has certain equipment installed in his premises. The sum of the continuous ratings of all the equipments in the consumer’s premises is the “connected load” of the consumer. For instance, if a consumer has connections of five 100-watt lamps and a power point of 500 watts, then connected load of the consumer is $5 \times 100 + 500 = 1000$ watts. The sum of the connected loads of all the consumers is the connected load to the power station.

- **Maximum demand:** *It is the greatest demand of load on the power station during a given period.*

  The load on the power station varies from time to time. The maximum of all the demands that have occurred during a given period (say a day) is the maximum demand. Thus referring back to the load curve of Fig. 1.4 the maximum demand on the power station during the day is 6 MW and it occurs at 6 P.M. Maximum demand is generally less than the connected load because all the consumers do not switch on their connected load to the system at a time. The knowledge of maximum demand is very important as it helps in determining the installed capacity of the station. The station must be capable of meeting the maximum demand.
Demand factor. It is the ratio of maximum demand on the power station to its connected load i.e.

\[
\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}}
\]

The value of demand factor is usually less than 1. It is expected because maximum demand on the power station generally less than the connected load. If the maximum demand on the power station is 80 MW and the connected load is 100 MW, then demand factor = \( \frac{80}{100} = 0.8 \). The knowledge of demand factor is vital in determining the capacity of the plant equipment.

Average load. The average of loads occurring on the power station in a given period (day or month or year) is known as average load or average demand.

- Daily average load = \( \frac{\text{No. of units (kWh) generated in a day}}{24 \text{ hours}} \)
- Monthly average load = \( \frac{\text{No. of units (kWh) generated in a month}}{\text{Number of hours in a month}} \)
- Yearly average load = \( \frac{\text{No. of units (kWh) generated in a year}}{8760 \text{ hours}} \)

Load factor. The ratio of average load to the maximum demand during a given period is known as load factor.

\[
\text{Load factor} = \frac{\text{Average load}}{\text{Max. demand}}
\]
If the plant is in operation for $T$ hours,

\[
\text{Load factor} = \frac{\text{Average load} \times T}{\text{Max. demand} \times T} = \frac{\text{Units generated in } T \text{ hours}}{\text{Max. demand} \times T \text{ hours}}
\]

The load factor may be daily load factor, monthly load factor or annual load factor if the time period considered is a day or month or year. Load factor is always less than 1 because average load is smaller than the maximum demand. The load factor plays key role in determining the overall cost per unit generated. Higher the load factor of the power station, lesser will be the cost per unit generated (It is because higher load factor means lesser maximum demand. The station capacity is so selected that it must meet the maximum demand. Now, lower maximum demand means lower capacity of the plant which, therefore, reduces the cost of the plant).

- **Diversity factor.** *The ratio of the sum of individual maximum demands to the maximum demand on power station is known as diversity factor i.e.*

\[
\text{Diversity factor} = \frac{\text{Sum of individual max. demands}}{\text{Max. demand on power station}}
\]

A power station supplies load to various types of consumers whose maximum demands generally do not occur at the same time. Therefore, the maximum demand on the
power station is always less than the sum of individual maximum demands of the consumers. Obviously, diversity factor will always be greater than 1. The greater the diversity factor, the lesser is the cost of generation of power (Greater diversity factor means lesser maximum demand. This in turn means that lesser plant capacity is required. Thus, the capital investment on the plant is reduced).

➢ **Capacity factor.** *It is the ratio of actual energy produced to the maximum possible energy that could have been produced during a given period i.e.*

\[
\text{Plant capacity factor} = \frac{\text{Actual energy produced}}{\text{Max. energy that could have been produced}}
\]

Suppose the period is \( T \) hours then:

\[
\text{Plant capacity factor} = \frac{\text{Average demand} \times T}{\text{Plant capacity} \times T} = \frac{\text{Average demand}}{\text{Plant capacity}}
\]

Thus if the considered period is one year,

\[
\text{Annual plant capacity factor} = \frac{\text{Annual kWh output}}{\text{Plant capacity} \times 8760}
\]

The plant capacity factor is an indication of the reserve capacity of the plant. A power station is so designed that it has some reserve capacity for meeting the increased load demand in future.
Therefore, the installed capacity of the plant is always somewhat greater than the maximum demand on the plant.

**Reserve capacity = Plant capacity - Max. demand.**

It is interesting to note that difference between load factor and capacity factor is an indication of reserve capacity. If the maximum demand on the plant is equal to the plant capacity, then load factor and plant capacity factor will have the same value. In such a case, the plant will have no reserve capacity.

➢ **Plant use factor.** *It is the ratio of kWh generated to the product of plant capacity and the number of hours for which the plant was in operation i.e.*

\[
\text{Plant use factor} = \frac{\text{Station output in kWh}}{\text{Plant capacity} \times \text{Hours of use}}
\]

Suppose a plant having installed capacity of 20 MW produces annual output of \(7.35 \times 10^6\) kWh and remains in operation for 2190 hours in year. Then:

\[
\text{Plant use factor} = \frac{7.35 \times 10^6}{(20 \times 10^3) \times 2190} = 0.167 = 16.7\%
\]
Solved Examples

Example 1.1: A diesel station supplies the following loads to various consumers:

Industrial consumer = 1500 kW; Commercial establishment = 750 kW
Domestic power = 100 kW; Domestic light = 450 kW
If the maximum demand on the station is 2500 kW and the number of kWh generated per year is $45 \times 10^5$, determine (i) the diversity factor and (ii) annual load factor.

Solution:

(i) Diversity factor = $(1500 + 750 + 100 + 450)/2500 = 1.12$

(ii) Average demand = yearly kWh generated/Hours in a year

$= 45 \times 10^5/8760 = 513.7$ kW

Load factor = Average load/Max. demand

$= 513.7/2500 = 0.205 = 20.5\%$

Example 1.2: A power station supplies the following load

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>Load (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 AM — 8 AM</td>
<td>1.2</td>
</tr>
<tr>
<td>8 AM — 9 AM</td>
<td>2.0</td>
</tr>
<tr>
<td>9 AM — 12 Noon</td>
<td>3.0</td>
</tr>
<tr>
<td>12 Noon — 2 PM</td>
<td>1.50</td>
</tr>
<tr>
<td>2 PM — 6 PM</td>
<td>2.50</td>
</tr>
<tr>
<td>6 PM — 8 PM</td>
<td>1.80</td>
</tr>
<tr>
<td>8 PM — 9 PM</td>
<td>2.0</td>
</tr>
<tr>
<td>9 PM — 11 PM</td>
<td>1.0</td>
</tr>
<tr>
<td>11 PM — 5 AM</td>
<td>0.50</td>
</tr>
<tr>
<td>5 AM — 6 AM</td>
<td>0.80</td>
</tr>
</tbody>
</table>
(a) Plot the load curve and find out the load factor.
(b) Determine the proper number and size of generating units to supply this load.
(c) Find the reserve capacity of the plant and capacity factor.
(d) Find out the operating schedule of the generating units selected.

**Solution:**

(a) The following figure shows the plot of load curve

Units generated during 24 hours =\( (2 \times 1.2 + 1 \times 2 + 3 \times 3 + 2 \times 1.5 + 4 \times 2.5 + 2 \times 1.8 + 1 \times 2 + 2 \times 1 + 6 \times 0.5 + 1 \times 0.8) = 37.80 \text{ MWhr} \)

Average load = Units generated / Time in hours

Average load = \( \frac{37.80}{24} = 1.575 \text{ MW} \).

Load factor (LF) = Maximum load / Maximum load

Maximum load = 3 MW

\[ \therefore \text{LF} = \frac{1.575}{3} = 0.525 \]

(b) Maximum demand = 3 MW. Therefore, 4 generating units of rating 1.0 MW each may be selected. During the period of
maximum demand 3 units will operate and 1 unit will remain as stand by.

(c) Plant capacity = 4 x 1.0 = 4.0 MW

Reserve capacity = 4 - 3 = 1 MW

From eqn. (1.3),

\[
\text{Plant capacity factor} = \frac{\text{Actual energy produced}}{\text{Max. energy that could have been produced}}
\]

Actual energy produced = 37.80 MWhr

Maximum plant rating = 4 MW

Time duration T = 24 hours

\[\therefore \quad \text{Plant Capacity Factor} = \frac{37.80}{(4 \times 24)} = 0.39375.\]

(d) Operating schedule will be as follows:

One generating unit of 1 MW: — 24 hours

Second generating unit of 1 MW: — 6 AM — 9 PM

(15 hours)

Third generating unit of 1 MW: — 9 AM — 12 Noon

2 PM — 6 PM

(7 hours)

**Example 1.3:** A generating station has the following daily load cycle:

<table>
<thead>
<tr>
<th>Time (Hours)</th>
<th>0—6</th>
<th>6—10</th>
<th>10—12</th>
<th>12—16</th>
<th>16—20</th>
<th>20—24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (MW)</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>50</td>
<td>70</td>
<td>40</td>
</tr>
</tbody>
</table>

Draw the load curve and find (i) maximum demand (ii) units generated per day (iii) average load and (iv) load factor.
**Solution:**

Daily curve is drawn by taking the load along $Y$-axis and time along $X$-axis and is shown in Figure.

(i) It is clear from the load curve that maximum demand on the power station is 70 MW and occurs during the period 16-20 hours. $\therefore$ Maximum demand $= 70$ MW

(ii) Units generated/day $= \text{Area (in kWh) under the load curve}$

\[
= 10^3 \left[ 40 \times 6 + 50 \times 4 + 60 \times 2 + 50 \times 4 + 70 \times 4 + 40 \times 4 \right]
\]

\[
= 12 \times 10^5 \text{ kWh}
\]

(iii) Average load $= \frac{\text{Units generated per day}}{24 \text{ hours}}$

\[
= \frac{12 \times 10^5}{24} = 50,000 \text{ kW}
\]

(iv) Load factor $= \frac{\text{Average load}}{\text{Max. demand}} = \frac{50,000}{70 \times 10^3} = 0.714$

**Example 1.4:** A power station has to meet the following demand:

- **Group A:** 200 kW between 8 A.M. and 6 P.M.
- **Group B:** 100 kW between 6 A.M. and 10 A.M.
- **Group C:** 50 kW between 6 A.M. and 10 A.M.
- **Group D:** 100 kW between 10 A.M. and 6 P.M. and then between 6 P.M. and 6 A.M.
Plot the daily load curve and determine (i) diversity factor (ii) units generated per day (iii) load factor

**Solution:**

The given load cycle can be tabulated as under:

<table>
<thead>
<tr>
<th>Time (Hours)</th>
<th>0—6</th>
<th>6—8</th>
<th>8—10</th>
<th>10—18</th>
<th>18—24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group A</td>
<td>—</td>
<td>—</td>
<td>200 kW</td>
<td>200 kW</td>
<td>—</td>
</tr>
<tr>
<td>Group B</td>
<td>—</td>
<td>100 kW</td>
<td>100 kW</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Group C</td>
<td>—</td>
<td>50 kW</td>
<td>50 kW</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Group D</td>
<td>100 kW</td>
<td>—</td>
<td>—</td>
<td>100 kW</td>
<td>100 kW</td>
</tr>
</tbody>
</table>

| Total load on power station | 100 kW | 150 kW | 350 kW | 300 kW | 100 kW |

Plotting the load on power station versus time, we get the daily load curve as shown in Figure. It is clear from the curve that maximum demand on the station is 350 kW and occurs from 8 A.M. to 10 A.M. i.e.,

- Maximum demand = 350 kW
- Sum of individual maximum demands of groups = 200 + 100 + 50 + 100 = 450 kW

(i) Diversity factor = 450/350 = 1.286
(ii) Units generated/day = Area (in kWh) under load curve = 100×6 + 150×2 + 350×2 + 300×8 + 100×6 = 4600 kWh
(iii) Average load = 4600/24 = 191.7 kW

∴ Load factor = 191.7/350 = 0.548