Chapter 3: Variable Load on Power Station

Introduction

The function of a power station is to deliver power to a large number of consumers.

However, the power demands of different consumers vary in accordance with their activities.

The result of this variation in demand is that load on a power station is never constant, somewhat it varies from time to time.

Most of the difficulties of modern power plant operation arise from the inherent changeability of the load demanded by the users.

Unfortunately, electrical power cannot be stored and, therefore, the power station must produce power as and when demanded to meet the requirements of the consumers.
3.1 Structure of Electric Power System

The function of an electric power system is to connect the power station to the consumers’ loads.

The power demanded by the consumers is supplied by the power station through the transmission and distribution networks.

As the consumers’ load demand changes, the power supply by the power station changes accordingly.
3.2 Variable Load on Power Station

The load on a power station varies from time to time due to uncertain demands of the consumers and is known as variable load on the station.

A power station is designed to meet the load requirements of the consumers.

An ideal load on the station, would be one of constant magnitude and steady duration.

However, such a steady load on the station is never realized in actual practice.

The consumers require their small or large block of power in accordance with the demands of their activities.

Thus the load demand of one consumer at any time may be different from that of the other consumer.

The result is that load on the power station varies from time to time.
Effects of variable load. The variable load on a power station introduces many perplexities in its operation.

Some of the important effects of variable load on a power station are:

(i) Need of additional equipment. The variable load on a power station necessitates to have additional equipment.

(ii) Increase in production cost. The variable load on the plant increases the cost of the production of electrical energy.

3.3 Load Curves

The curve showing the variation of load on the power station with respect to (w.r.t) 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 *w.r.t.* time during the day.

Fig. 3.2. shows a typical daily load curve of a power station.
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 *yearly 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*. 
Importance. 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 daily load curve gives the number of units generated in the day.
  
  Units generated/day = Area (in kWh) under daily load curve.

- (iii) The highest point on the daily load curve represents the maximum demand on the station on that day.

- (iv) The area under the daily load curve divided by the total number of hours gives the average load on the station in the day.
  
  Average load = \( \frac{\text{Area (in kWh) under daily load curve}}{24 \text{ hours}} \)
• (v) The load curve helps in selecting the size and number of generating units.

• (vi) The load curve helps in preparing the operation schedule of the station.

• (vii) The ratio of the area under the load curve to the total area of rectangle in which it is contained gives the load factor.

\[
\text{Load factor} = \frac{\text{Average load}}{\text{Max. demand}} = \frac{\text{Average load} \times 24}{\text{Max. demand} \times 24}
\]

\[
= \frac{\text{Area (in kWh) under daily load curve}}{\text{Total area of rectangle in which the load curve is contained}}
\]
3.4 Important Terms and Factors
The variable load problem has introduced the following terms and factors in power plant engineering:

• (i) Connected load. It is the sum of continuous ratings of all the equipments connected to supply system.
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.

• (ii) Maximum demand: It is the greatest demand of load on the power station during a given period.

• (iii) Demand factor. It is the ratio of maximum demand on the power station to its connected load i.e., (The knowledge of demand factor is vital in determining the capacity of the plant equipment).

\[
\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}} < 1
\]
• (iv) **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.

\[
\text{Daily average load} = \frac{\text{No. of units (kWh) generated in a day}}{24 \text{ hours}}
\]

\[
\text{Monthly average load} = \frac{\text{No. of units (kWh) generated in a month}}{\text{Number of hours in a month}}
\]

\[
\text{Yearly average load} = \frac{\text{No. of units (kWh) generated in a year}}{8760 \text{ hours}}
\]

• (v) **Load factor.** The ratio of average load to the maximum demand during a given period is known as load factor i.e.,

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

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

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.

• **(vi) 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.

• (vii) **Plant 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.,

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

\[
\text{Reserve capacity} = \text{Plant capacity} - \text{Max. demand}
\]

It is interesting to note that difference between load factor and plant 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.
(viii) Plant use factor. It is ratio of kWh generated to the product of plant capacity and the number of hours for which the plant was in operation i.e.

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

3.5 Units Generated per Annum

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

The procedure is as follows:

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

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

Units generated/annum = Average load (in kW) \times \text{Hours in a year} = \text{Max. demand (in kW)} \times \text{L.F.} \times 8760
3.6 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.

Fig. 3.3 (i) shows the daily load curve. The daily load duration curve can be readily obtained from it, as in Fig. 3.3 (ii).
3.7 Types of Loads
A device which taps electrical energy from the electric power system is called a load on the system.

The load may be resistive (*e.g.*, electric lamp), inductive (*e.g.*, induction motor), capacitive or some combination of them.

The various types of loads on the power system are:

- **(i) Domestic load.** Domestic load consists of lights, fans, refrigerators, heaters, television, small motors for pumping water etc. Most of the residential load occurs only for some hours during the day (*i.e.*, 24 hours) *e.g.*, lighting load occurs during night time and domestic appliance load occurs for only a few hours. For this reason, the load factor is low (10% to 12%).

- **(ii) Commercial load.** Commercial load consists of lighting for shops, fans and electric appliances used in restaurants etc. This class of load occurs for more hours during the day as compared to the domestic load. The commercial load has seasonal variations due to the extensive use of air conditioners and space heaters.
(iii) Industrial load. Industrial load consists of load demand by industries.

- Small scale industry requires load up to 25 kW,
- Medium scale industry between 25kW and 100 kW and
- Large-scale industry requires load above 500 kW.

Industrial loads are generally not weather dependent.

(iv) Municipal load. Municipal load consists of street lighting, power required for water supply and drainage purposes.

- Street lighting load is practically constant throughout the hours of the night.
- For water supply, water is pumped to overhead tanks by pumps driven by electric motors.

Pumping is carried out during the off-peak period, usually occurring during the night. This helps to improve the load factor of the power system.
(v) **Irrigation load.** This type of load is the electric power needed for pumps driven by motors to supply water to fields. (It is used to assist in the growing of agricultural produces).

Generally this type of load is supplied for 12 hours during night.

(vi) **Traction load.** This type of load includes tram cars, trolley buses, railways etc.

This class of load has wide variation.

- During the morning hour, it reaches peak value because people have to go to their work place.
- After morning hours, the load starts decreasing and
- Again rises during evening since the people start coming to their homes.
Example 3.1. The maximum demand on a power station is 100 MW. If the annual load factor is 40%, calculate the total energy generated in a year.

Solution.

\[
\text{Energy generated/year} = \text{Max. demand} \times \text{L.F.} \times \text{Hours in a year}
\]
\[
= (100 \times 10^3) \times (0.4) \times (24 \times 365) \text{ kWh}
\]
\[
= 3504 \times 10^5 \text{ kWh}
\]

Example 3.2. A generating station has a connected load of 43 MW and a maximum demand of 20 MW; the units generated being \(61.5 \times 10^6\) per annum. Calculate (i) the demand factor and (ii) load factor.

Solution.

(i) Demand factor \[= \frac{\text{Max. demand}}{\text{Connected load}} = \frac{20}{43} = 0.465\]

(ii) Average demand \[= \frac{\text{Units generated/annum}}{\text{Hours in a year}} = \frac{61.5 \times 10^6}{8760} = 7020 \text{ kW}\]

\[\therefore \text{Load factor} = \frac{\text{Average demand}}{\text{Max. demand}} = \frac{7020}{20 \times 10^3} = 0.351 \text{ or } 35.1\%\]
Example 3.3. A 100 MW power station delivers 100 MW for 2 hours, 50 MW for 6 hours and is shut down for the rest of each day. It is also shut down for maintenance for 45 days each year. Calculate its annual load factor.

Solution.

Energy supplied for each working day

\[
= (100 \times 2) + (50 \times 6) = 500 \text{ MWh}
\]

Station operates for = 365 - 45 = 320 days in a year

\[\therefore \text{ Energy supplied/year } = 500 \times 320 = 160,000 \text{ MWh} \]

Annual load factor = \[
\frac{\text{MWh supplied per annum}}{\text{Max. demand in MW} \times \text{Working hours}} \times 100
\]

\[= \frac{160,000}{(100 \times (320 \times 24)) \times 100} = 20.8\%
\]

Example 3.4. A generating station has a maximum demand of 25 MW, a load factor of 60%, a plant capacity factor of 50% and a plant use factor of 72%. Find (i) the reserve capacity of the plant (ii) the daily energy produced and (iii) maximum energy that could be produced daily if the plant while running as per schedule, were fully loaded.

Solution.

(i) Load factor = \[
\frac{\text{Average demand}}{\text{Maximum demand}}
\]

\[0.60 = \frac{\text{Average demand}}{25}
\]

\[\therefore \text{ Average demand } = 25 \times 0.60 = 15 \text{ MW}
\]

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

\[\therefore \text{ Plant capacity } = \frac{15}{0.5} = 30 \text{ MW}
\]
Reserve capacity of plant = Plant capacity – maximum demand
= 30 – 25 = 5 MW

(ii) Daily energy produced = Average demand × 24
= 15 × 24 = 360 MWh

(iii) Maximum energy that could be produced

\[
\text{Actual energy produced in a day} \div \text{Plant use factor} = \frac{360}{0.72} = 500 \text{ MWh/day}
\]

Example 3.5. 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 = \(\frac{1500 + 750 + 100 + 450}{2500}\) = 1.12

(ii) Average demand = \(\frac{\text{kWh generated/annum}}{\text{Hours in a year}}\) = \(45 \times 10^5/\text{8760}\) = 513.7 kW

\[\therefore \text{Load factor} = \frac{\text{Average load}}{\text{Max. demand}} = \frac{513.7}{2500} = 0.205 = 20.5\%\]
Example 3.6. A power station has a maximum demand of 15000 kW. The annual load factor is 50% and plant capacity factor is 40%. Determine the reserve capacity of the plant.

Solution.

Energy generated/annum = Max. demand × L.F. × Hours in a year
= (15000) × (0.5) × (8760) kWh
= 65.7 × 10^6 kWh

Plant capacity factor = \[ \frac{\text{Units generated/annum}}{\text{Plant capacity} \times \text{Hours in a year}} \]

∴ Plant capacity = \[ \frac{65.7 \times 10^6}{0.4 \times 8760} \] = 18,750 kW

Reserve capacity = Plant capacity – Max. demand
= 18,750 – 15000 = 3750 kW
Example 3.7. A power supply is having the following loads:

<table>
<thead>
<tr>
<th>Type of load</th>
<th>Max. demand (kW)</th>
<th>Diversity of group</th>
<th>Demand factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic</td>
<td>1500</td>
<td>1.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Commercial</td>
<td>2000</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>Industrial</td>
<td>10,000</td>
<td>1.25</td>
<td>1</td>
</tr>
</tbody>
</table>

If the overall system diversity factor is 1.35, determine (i) the maximum demand and (ii) connected load of each type.

Solution.

(i) The sum of maximum demands of three types of loads is = 1500 + 2000 + 10,000 = 13,500 kW. As the system diversity factor is 1.35,

\[ \text{Max. demand on supply system} = \frac{13,500}{1.35} = 10,000 \text{ kW} \]

(ii) Each type of load has its own diversity factor among its consumers.

Sum of max. demands of different domestic consumers

\[ = \text{Max. domestic demand} \times \text{diversity factor} \]

\[ = 1500 \times 1.2 = 1800 \text{ kW} \]

\[ \therefore \text{Connected domestic load} = \frac{1800}{0.8} = 2250 \text{ kW} \]

Connected commercial load = \[ 2000 \times 1.1 \div 0.9 = 2444 \text{ kW} \]

Connected industrial load = \[ 10,000 \times 1.25 \div 1 = 12,500 \text{ kW} \]
Example 3.10. 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. For the given load cycle, the load curve is shown in Fig. 3.6.

(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.

∴ Maximum demand = 70 MW
(ii) Units generated/day = Area (in kWh) under the load curve
    = $10^3 [40 \times 6 + 50 \times 4 + 60 \times 2 + 50 \times 4 + 70 \times 4 + 40 \times 4]$
    = $10^3 [240 + 200 + 120 + 200 + 280 + 160] \text{ kWh}$
    = $12 \times 10^5 \text{ kWh}$

(iii) Average load = \( \frac{\text{Units generated/day}}{24 \text{ hours}} \) = \( \frac{12 \times 10^5}{24} \) = \( 50,000 \text{ kW} \)

(iv) Load factor = \( \frac{\text{Average load}}{\text{Max. demand}} \) = \( \frac{50,000}{70 \times 10^3} \) = 0.714 = 71.4%

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**Example 3.12.** The daily demands of three consumers are given below:

<table>
<thead>
<tr>
<th>Time</th>
<th>Consumer 1</th>
<th>Consumer 2</th>
<th>Consumer 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 midnight to 8 A.M.</td>
<td>No load</td>
<td>200 W</td>
<td>No load</td>
</tr>
<tr>
<td>8 A.M. to 2 P.M.</td>
<td>600 W</td>
<td>No load</td>
<td>200 W</td>
</tr>
<tr>
<td>2 P.M. to 4 P.M.</td>
<td>200 W</td>
<td>1000 W</td>
<td>1200 W</td>
</tr>
<tr>
<td>4 P.M. to 10 P.M.</td>
<td>800 W</td>
<td>No load</td>
<td>No load</td>
</tr>
<tr>
<td>10 P.M. to midnight</td>
<td>No load</td>
<td>200 W</td>
<td>200 W</td>
</tr>
</tbody>
</table>
Plot the load curve and find (i) maximum demand of individual consumer (ii) load factor of individual consumer (iii) diversity factor and (iv) load factor of the station.

Solution. Fig. 3.8 shows the load curve.

![Load Curve Graph](image)
(i) Max. demand of consumer 1 = 800 W
Max. demand of consumer 2 = 1000 W
Max. demand of consumer 3 = 1200 W

(ii) L.F. of consumer 1 = \( \frac{\text{Energy consumed / day}}{\text{Max. demand} \times \text{Hours in a day}} \times 100 \)
\[ = \frac{600 \times 6 + 200 \times 2 + 800 \times 6}{800 \times 24} \times 100 = 45.8\% \]
L.F. of consumer 2 = \( \frac{200 \times 8 + 1000 \times 2 + 200 \times 2}{1000 \times 24} \times 100 = 16.7\% \)
L.F. of consumer 3 = \( \frac{200 \times 6 + 1200 \times 2 + 200 \times 2}{1200 \times 24} \times 100 = 13.8\% \)

(iii) The simultaneous maximum demand on the station is 200 + 1000 + 1200 = 2400 W and occurs from 2 P.M. to 4 P.M.

\[ \therefore \text{Diversity factor} = \frac{800 + 1000 + 1200}{2400} = 1.25 \]

(iv) Station load factor = \( \frac{\text{Total energy consumed / day}}{\text{Simultaneous max. demand} \times 24} \times 100 \)
\[ = \frac{8800 + 4000 + 4000}{2400 \times 24} \times 100 = 29.1\% \]
Example 3.15. A power station has the following daily load cycle:

<table>
<thead>
<tr>
<th>Time in Hours</th>
<th>6—8</th>
<th>8—12</th>
<th>12—16</th>
<th>16—20</th>
<th>20—24</th>
<th>24—6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load in MW</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>20</td>
<td>50</td>
<td>20</td>
</tr>
</tbody>
</table>

Plot the load curve and load duration curve. Also calculate the energy generated per day.

Solution. Fig. 3.9 (i) shows the daily load curve, whereas Fig. 3.9 (ii) shows the daily load duration curve. It can be readily seen that area under the two load curves is the same. Note that load duration curve is drawn by arranging the loads in the order of descending magnitudes.

Units generated/day = Area (in kWh) under daily load curve

\[
= 10^3 \left[ 20 \times 8 + 40 \times 4 + 60 \times 4 + 20 \times 4 + 50 \times 4 \right]
\]

\[
= 840 \times 10^3 \text{ kWh}
\]
Example 3.16. The annual load duration curve of a certain power station can be considered as a straight line from 20 MW to 4 MW. To meet this load, three turbine-generator units, two rated at 10 MW each and one rated at 5 MW are installed. Determine (i) installed capacity (ii) plant factor (iii) units generated per annum (iv) load factor and (v) utilisation factor.

Solution. Fig. 3.10 shows the annual load duration curve of the power station.

(i) Installed capacity = \(10 + 10 + 5 = 25\) MW

(ii) Referring to the load duration curve,

\[
\text{Average demand} = \frac{1}{2} \left[20 + 4\right] = 12\text{ MW}
\]

\[
\therefore \text{Plant factor} = \frac{\text{Average demand}}{\text{Plant capacity}} = \frac{12}{25} = 0.48 = 48\%
\]

(iii) Units generated/annum = Area (in kWh) under load duration curve

\[
= \frac{1}{2} \left[4000 + 20,000\right] \times 8760\text{ kWh} = 105,12 \times 10^6\text{ kWh}
\]

(iv) Load factor = \(\frac{12,000}{20,000} \times 100 = 60\%\)

(v) Utilisation factor = \(\frac{\text{Max. demand}}{\text{Plant capacity}} = \frac{20,000}{25000} = 0.8 = 80\%\).
Assignment # 1

PB1
A power station is to supply four regions of loads whose peak values are 10,000 kW, 5000 kW, 8000 kW and 7000 kW. The diversity factor of the load at the station is 1.5 and the average annual load factor is 60%. Calculate the maximum demand on the station and annual energy supplied from the station.

\[ [20,000 \text{ kW} ; 105.12 \times 10^6 \text{ kWh}] \]

PB2
A power station has to meet the following load demand:

<table>
<thead>
<tr>
<th>Load</th>
<th>Peak Load (kW)</th>
<th>Operating Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load A</td>
<td>50</td>
<td>between 10 A.M. and 6 P.M.</td>
</tr>
<tr>
<td>Load B</td>
<td>30</td>
<td>between 6 P.M. and 10 P.M.</td>
</tr>
<tr>
<td>Load C</td>
<td>20</td>
<td>between 4 P.M. and 10 A.M.</td>
</tr>
</tbody>
</table>

Plot the daily load curve and determine (i) diversity factor (ii) units generated per day (iii) load factor.

\[ [(i) 1.43 (ii) 880 \text{ kWh} (iii) 52.38\%] \]

PB3
The yearly load duration curve of a certain power station can be approximated as a straight line; the maximum and minimum loads being 80 MW and 40 MW respectively. To meet this load, three turbine-generator units, two rated at 20 MW each and one at 10 MW are installed. Determine (i) installed capacity (ii) plant factor (iii) kWh output per year (iv) load factor.

\[ [(i) 50 \text{MW} (ii) 48\% (iii) 210 \times 10^6 (iv) 60\%] \]