32

Fluctuating Loads on Power Plants

32.1. Introduction. 32.2. Load Curves. 32.3. Different Terms and Definitions. 32.4. Effects of Variable Load on Power Plant Design and Operation.

32.1. INTRODUCTION

The load required by the consumer does not remain constant with respect to time (hour, day or month) and it fluctuates according to his requirements. The problem of variable load is vital one because each kilowatt-hour energy is to be put on the transmission line at as low a production cost as possible. The cost of generation and transmission is not only dependent on the improved operating conditions, such as turbine and generators operating at their best efficiency or uniform rate of driving the boilers, but depends upon the first cost of equipment which can be reduced by using simplified control and eliminating the various auxiliaries and regulating devices.

The general arrangement of the electrical power generation, transmission and distribution system is shown in Fig. 32.1. First the energy is sent to the substations which are located at the ends of the primary distribution system. The energy from the substation is carried through the feeders to the distribution transformers as shown in figure. Each transformer is connected to the systems of one or more customers by short low voltage lines.

Each customer has a connected load which is the sum of all equipments located in the customer's house. The connected load of transformer 'I' is the sum of the connected loads of customers *a, b* and *c*. The design of transformers, feeders, substation is fully dependent on the connected loads to the customers.

32.2. LOAD CURVES

A consumer of electric power will use the power as and when required. The load will always be changing with time and will not be constant.

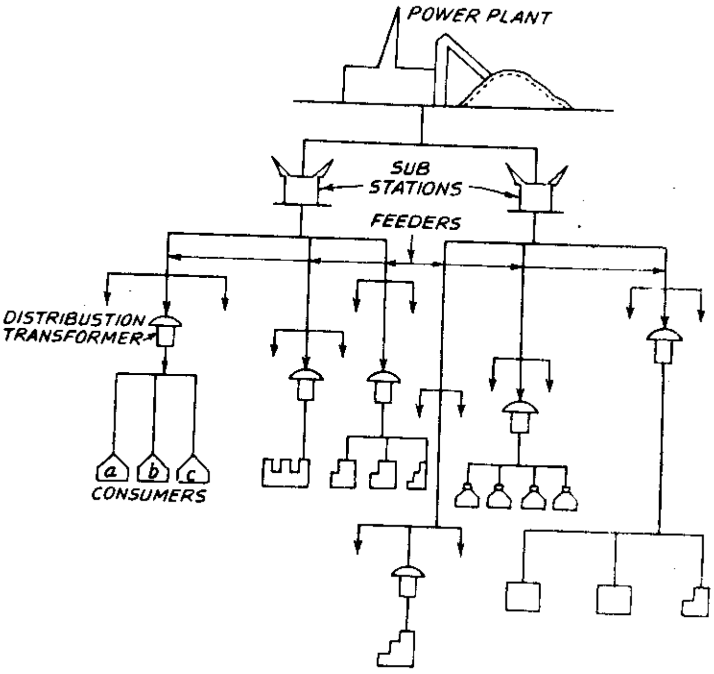


Fig. 32.1. Layout of Generation, Transmission and Distribution of electrical energy to domestic, industrial and commercial consumers.

"A curve showing the load demand (variations) of consumer with respect to time is known as load curve". If the time is in hours then the load curve is known as daily load curve. If the time is in days, the load curve is known as monthly load curve and if the time is in months, the load curve is known as yearly or annual load curve. The load curve shows how the load varies with respect to time. This type of load curve is useful in predicting the annual requirements of energy and capacity of the power plant required to take the peak load.

The load curve of a consumer is shown in Fig. 32.2. The area under the load curve gives total energy consumed by the customer.

The energy consumption of the customer is given by an expression,

$$E = \int_0^{24} (\text{kW}).\, dt.$$

if the load curve is drawn on hourly basis.

The problem in designing the power plant is not only the energy consumed by the customer but the way adopted to use it. The customers *A* and *B* consume the same amount of energy as shown in Fig. 32.3(*a*) and Fig. 32.3 (*b*) but the nature of consumption is different.

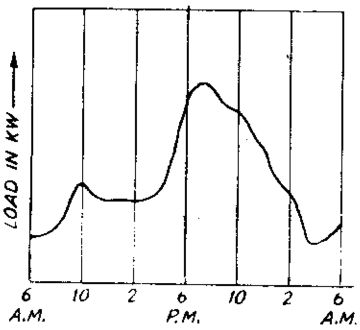


Fig. 32.2. Chronological daily load curve.

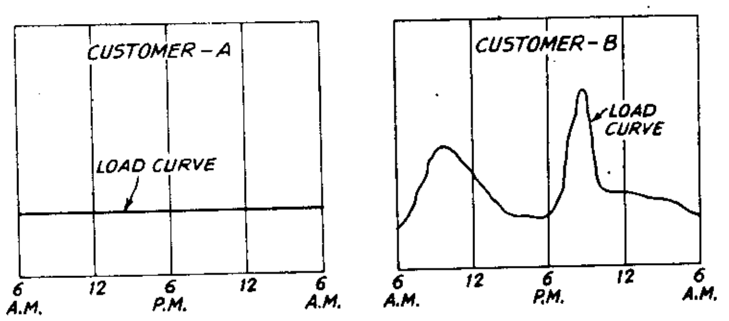


Fig. 32.3. Constant and variable demand load curves.

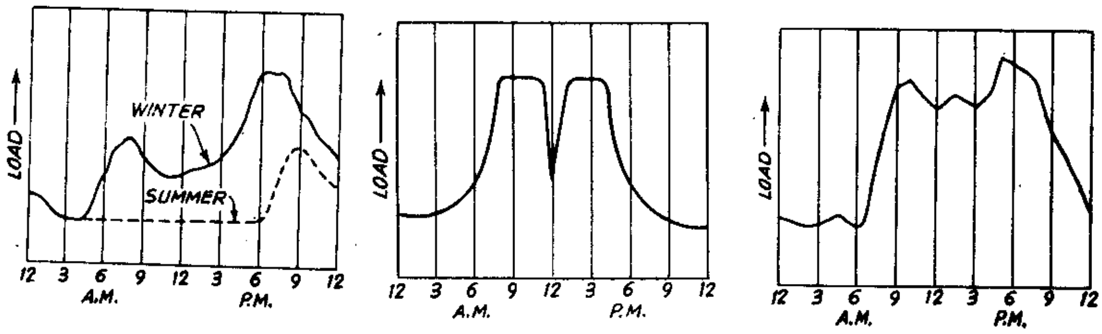
In the second case, the peak load is far greater than the first therefore the generating capacity of the plant required to supply the load of *B* is greater than the capacity required to supply the load of *A*. The plant designed for customer *B* is not only bigger in size but it also runs underload (part load) conditions for majority of the period. Therefore the cost of energy supplied to *B* may be 100% greater than the cost of energy supplied to *A* even the total energy consumed by both customers is same.

Most of the complexities of present day modern power plants operation arise from the inherent variability of the load demanded by the consumers according to the requirements with respect to time. For economical and better operation of the power plant, constant magnitude load is always desirable as it allows the plant to work at highest efficiency and requires simplified control and regulating devices.

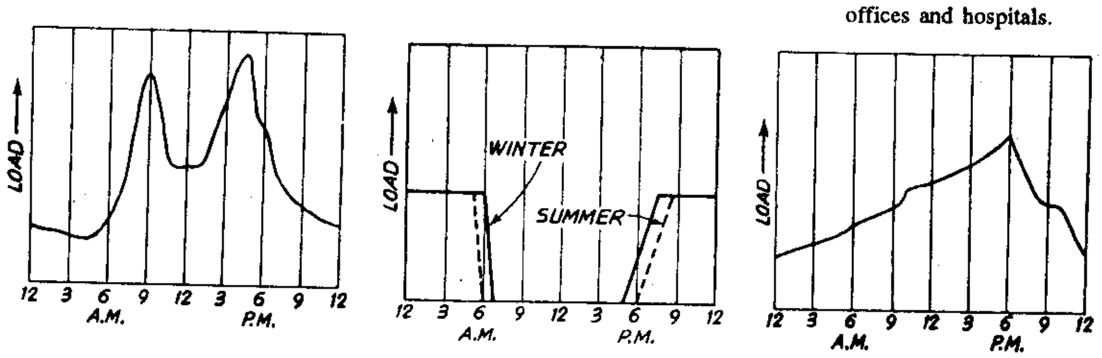
The different types of customers (industrial, commercial, domestic) are supplied from generating plant. The load curve of each customer is different from the other as per the activities of the customer. Few load curves of different customers are shown in Fig. 32.4.

(*a*) The load curve shown in Fig. 32.4 (*a*) is typical of a residential community rather than just one residence. During the early morning hours, the energy is required for lights, refrigerators, water heaters, oil burners, and like. After the breakfast (at 9 A.M.) the demand decreases somewhat and fairly remains constant till about 4 P.M. required to run vacuum cleaners, radios, television sets ; and water heaters. The cooking appliances then cause a slight rise in demand at 4 P.M. After 4 P.M. the early sun-set of winter brings the lights into action and total load rapidly approaches its peak about 5 P.M. during the month of December. The high demand occurs at about 8 P.M. Then the load drops fairly rapidly as the families retire or leave home to seek entertainment outside.

(*b*) The load curve shown in Fig. 32.4 (*b*) is typical of a one shift industrial community. In the early morning hours, the demand is generally for lighting and auxilary drives for heating boiler plants as well as some processes that require continuous energy supply such as refrigeration and electric furnaces. The energy demand increases from 5 A.M. to 8 A.M. as some of the factory machinery starts running for warming prior to operation. By 8 A.M., the entire industry starts running and energy demand remains constant until shortly before noon. Load falls off as some of the machines are shut-down during lunch hours. By 2 P.M. again, the load attains same level as at 8 A.M. Shortly before 4 P.M., the load starts to drop as the shift of work ends. At 6 P.M. most of the machines are shut-down and load gradually tapers off until 10 A.M. when the minimum demand is reached and continues till the start of next working day.



(*a*) Residential load curve. (*b*) Industrial load curve for one shift. (*c*) Commercial loads of shops, offices and hospitals.



(*d*) Urban traction load curve. (*e*) Stress lighting load. (*f*) Water pumping load.

Fig. 32.4. Load curves of different customers.

(*c*) The load curve shown in Fig. 32.4 (*c*) is typical of commercial loads of shops and offices. The lighting in the shops and offices starts at 6 A.M. for cleaning and sweeping and it reaches peak at 10 A.M. when the offices and shops start. The load remains constant more or less during 10 A.M. to 4 P.M. It further increases during 4 to 6 P.M. as more lights are required due to cloudy sky. Then the load rapidly falls during 7 P.M. to 12 night as the offices remain closed. The same load (night lights in shops and offices) remains during 12 night to 6 A.M.

(*d*) The load curve shown in Fig. 32.4 (*d*) is typical of a traction load. From the midnight till 3 A.M., the demand tapers off as the service reaches its minimum level and continues until about 5 A.M. As the early factory workers start for their work, the required train services increase rapidly and the consequent load continuously rises as the factory workers are followed by office workers, school children and early shoppers. The peak load reaches at about 9.30 A.M. The load after 10 A.M. rapidly diminishes as some of the trains return to the yards. The minimum day-load is reached during the noon hours and then rises continuously until the evening rush hours are in full swing with most of the workers go back to their homes. The load (after 6 P.M.) then falls rapidly. After midnight, the load again follows the cycle described.

(*e*) The load curve shown in Fig. 32.4 (*e*) is typical of a street lighting load. Street lighting is the only form of load that does not exhibit peak demands. Normally all lights are made on and are turned off almost simultaneously. The total demand remains more or less constant during the hours of darkness. The turning on and turning off of lights are usually synchronised with the time of sun-set and sun-rise respectively. Hence the road lights will be functioning for a much shorter time during summer time than winter.

(*f*) A typical water pumping load curve is shown in Fig. 32.4 (*f*).

In practice, the true appearance of load curve will not be so smooth as plotted in Fig. 32.4. The lighting load is smoothest curve owing to the constant nature of the energy requirements whereas the traction load, spot welding and stamping curves exhibit violent fluctuations as high demand during starting and no demand during stopping. For loads of wide fluctuations, the plotting of instantaneous readings is generally meaningless and usual practice is to read the integrating metres every hour and plot the difference in readings as an equivalent constant load for corresponding periods on the curve. This gives the stepped shaped curve. Such loads take wide and erratic swings and need special treatment of generator governing systems.

The demand load curve of a power plant is generally found out by adding all the loads mentioned above.

Some special events change the nature of load curves of different requirements. Few of them are listed below :

(1) An important political broadcast ; football game or cricket match may bring many TV sets and radio sets into operation that normally would be idle. This raises a municiple system load above normal but it seldom happens.

(2) Cloudy weather and sudden thunder showers generally requires more lighting in shops, offices and requires extraordinary peak, but normally they are not used. On systems having summer time peaks, this demand might coincide with the annual peak therefore extra capacity may be needed to meet this situation. Normal winter time peaks usually result from early darkness coinciding with existing high industrial loads.

The changes in atmospheric temperature influence the electric loads. A drop in temperature requires electric heating or starting of electric motors that drive burners and air suppliers to generate the steam. A rise in temperature increases the electric loads like refrigerators and fans.

Wind has also notable effect on the requirement of electric power. More wind raises the cooling rate of buildings and so creates demand for more heating energy. In many cases, the effect of wind is more pronounced than the change in atmospheric temperature.

It is therefore necessary to consider the effects of the factors mentioned above for calculating the required generating capacity of the power plant in addition to the different types of loads mentioned earlier.

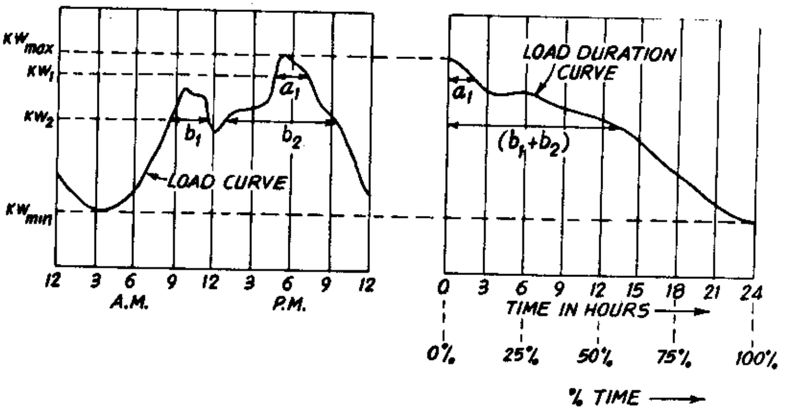
The effect of addition of different types of loads is to reduce the fluctuations of load required by the number of consumers and supplied by a single power plant.

Load Duration Curve. Load duration curve is simply a rearrangement of daily load curve with loads set-up in descending order of magnitude. The areas under the load duration curve and corresponding load curve are equal and measure kW-hr of energy for that period.

To get the load duration curve from chronological load curve, we cut the daily load curve into many many vertical strips and then arrange them in descending order. The graphical method for constructing load duration curve from the load curve is described as shown in Fig. 32.5.

For plotting the load duration curve, makes the abscissa at any load ordinate equal to the length of the abscissa intercepted by that load ordinate on the load curve. Thus the intercept is one point at the maximum demand (kW_{max}) and it is plotted at zero hours as shown in Fig. 32.5 (*b*). At load kW_1, the intercept is a_1 hours and is plotted at a_1 hours on the load duration curve. At load kW_2, the intercepts are $(b_1 + b_2)$

hours and is plotted accordingly as shown in figure. At minimum load kW_{min} ; the intercept covers the entire period of 24 hours and plotted accordingly.



(a) (b)

Fig. 32.5. Preparation of load duration curve from load curve.

Any point of the load duration curve is a measure of the number of hours in a given period during which the given load has prevailed.

Load duration curve offers the advantage of summarising loads for a day, week, month or year. This is advantageous for power plant design as in one simple curve, a whole year can be summarised showing peak demand, the variations in demand down to minimum, the length of the time they existed and total energy involved.

The construction of load duration curve from load curve is exactly similar to the construction of flow duration curve from hydrograph as described in chapter 1.

32.3. DIFFERENT TERMS AND DEFINITIONS

Before considering the methods of load prediction required for the design of power plant, some terms used in connection with power supply must be defined.

Connected Load. The connected load is the sum of ratings in kW of the equipments installed in the consumer's premises. The connected loads in the premises of a consumer are shown in Fig. 32.6.

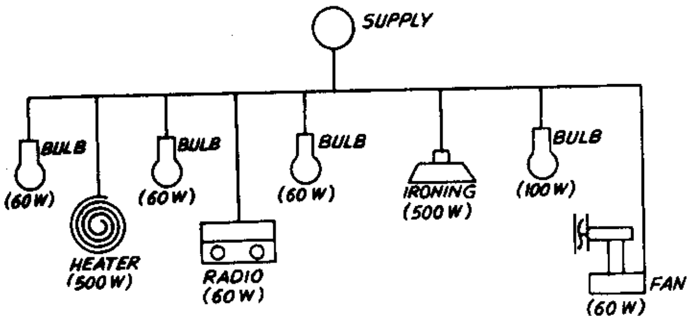


Fig. 32.6. Load in a consumer's premises.

The total connected load in the consumer's premises

$$= 60 + 500 + 60 + 60 + 100 + 500 + 100 + 60 = 1440 \text{ watts.}$$

Maximum Demand. The maximum demand is the maximum load which a consumer uses at any time. It is always less than connected load or equal to connected load. When all the equipments fitted in the consumer's house run to their fullest extent simultaneously then the maximum demand becomes equal to connected load. Generally maximum demand is always less than connected load as all the equipments never run simultaneously and never run at full load. Say ironing is done in day time but the bulbs are off and radio and fan are running, then the simultaneous maximum demand

$$= 60 + 500 + 60 = 620 \text{ watts.}$$

Say the heater is used in evening time during winter and all bulbs are on as well as the radio is running, then the maximum demand

$$= 500 + 60 + 60 + 100 + 100 + 60 = 880 \text{ watts.}$$

The maximum demand of a consumer depends upon the time of day as well as his habits.

(1) Demand Factor. It is defined as the ratio of maximum demand to connected load.

For the above mentioned example, the demand factors for day time and evening time are given by

$$\text{Demand Factor} \qquad (F_d) = \frac{620}{1440} = 0.43 \text{ (day time)}$$

$$= \frac{880}{1440} = 0.61 \text{ (evening time)}$$

The maximum value of the demand factor is unity.

The demand factors for different types of loads are listed in the table given as follows :

Each device will reach its own maximum demand at some time during its operation but the demand factor measures the extent to which it contributes toward the maximum demand of a group of devices of which it is a part.

Type of Load	*Capacity or Type*	*Demand Factor*
Residence Lighting	< 0.25 kW	1.00
	< 0.50 kW	0.60
	> 1 kW	0.50
Commercial Lighting	Restaurant	0.70
	Office	0.70
	Theatre	0.60
	Small Industry	0.60
	School	0.55
	Hotel	0.50
General Power Services	0—10 H.P.	0.75
	10—20 H.P.	0.65
	20—100 H.P.	0.55
	> 100 H.P.	0.50

Average Load. A typical load curve is shown in Fig. 32.7. The average load is calculated dividing the area under the load curve (energy in kW hr) by the time period (24 hours) considered to draw the load curve.

$\therefore$ Average Load

$$= \frac{\text{Area under load curve}}{24} = \frac{\text{Energy consumed in 24 hours}}{24}.$$

As explained earlier in Fig. 32.3, two load curves may represent the same kW-hr production, yet the unit cost of

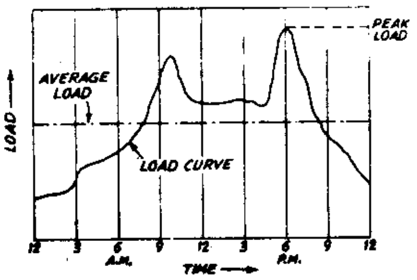


Fig. 32.7. Load curve.

production for one may be more than the other. Some information other than the magnitude of kW-hr energy produced is needed to describe an operating condition. The relationship between the peak load and average load over the time specified is needed to describe an operating condition of the power plants.

If the plant runs continuously at an average load, it generates the same amount of energy that the actual load curve shows.

(2) Load Factor. It is defined as the ratio of average load to the peak or maximum load determined by the consumer.

$$\therefore \qquad \text{Load Factor}(F_l) = \frac{\text{Average load}}{\text{Maximum load}}$$

The load factor can also be given by

$$\text{Load Factor} = \frac{\text{Total energy consumption in 24 hours}}{\text{Peak load} \times 24}$$

The load factor is always less than unity.

The power plants which are used to take the base load run on a high load factor and the plants which are used to take the peak load run on low load factors.

The load factors for different types of consumers are listed in the table given below :

Nature of load	*Load factor*
Residential load	
This includes lights, heaters, TV and radio sets, air-conditioners and refrigerators, electric cookers and water heaters and small pumping sets.	10—15%
Commercial load	
This includes the lighting in shops and used for advertising and electrical equipments in restaurants and markets.	25—30%
Industrial load	
Small scale industries (below 25 kW).	30—50%
Medium and large scale industries (100—500 kW)	60%
Heavy industries (> 500 kW).	80%
Municipal load	
This includes road lights and traffic signals.	25%

Low load factor is an indication of high cost of electric production as the power plant is not used to its full capacity for the whole period (24 hours) considered. For the low production cost of the electric energy, it is always desirable to run the plant to its full capacity for the maximum period of operation to give high load factor. Therefore the base load plants (very high capacity) run at high load factor (nearly unity) and peak load plants are allowed to run at low load factors to reduce the overall production cost.

(3) Diversity Factor. The needs of the consumers are their maximum demands and their energy consumptions during a day. It is always necessary to provide the generating capacity equal to their maximum demands to fulfill their needs and the energy supplied should be charged as minimum as possible. This is only possible if the load factor of all consumers combinely approaches to unity. This is not possible in practice owing to variable load characteristics when a number of consumers with different load requirements at different times during the day are to be supplied. An attempt should be made to supply these loads in such a way to smoothen the load curve of the system and obtain as high a load factor as possible and practicable.

The time distribution of maximum demands for similar types of consumers is measured by the diversity factor. The diversity factor is the ratio of the sum of the maximum demands of the individual consumers and the simultaneous maximum demand of the whole group during a particular time.

$$\text{Diversity Factor} = \frac{\text{Sum of individual maximum demands}}{\text{Simultaneous maximum demand}}$$

As the total maximum demand required at any time during the day is less than the sum of the maximum demands due to diversity, the total load factor of the system increases and which is desirable for the economic operation of the power plant.

Diversity helps in obtaining better conditions for power supply. The power supply engineer persuades the consumers to encourage loads in some places (on already existing load curve) and to discourage them in other places in such a way that the total maximum demand is reduced. This helps to supply more energy with less plant capacity and at a cheaper rate as the power factor of the system improves.

The diversity factor of a group of consumers is always greater than unity. Diversity factors for residential consumers are usually highest at about 5, whereas large industrial consumers may have values of diversity factory as low as 1.3. Since diversity exists between individual maximum demands, the proportion contribution to the system maximum demand by the consumer is always less than his maximum demand.

The diversity factors for different types of consumers are listed in the table given below :

Density Factor

Elements of system	*Residence load*	*Commercial load*	*General power*	*Large users*
Between consumers	2.00	1.46	1.44	—
Between transformers	1.30	1.30	1.35	1.05
Between feeders	1.15	1.15	1.15	1.05
Between substations	1.10	1.10	1.10	1.14
Consumer to transformer	2.00	1.46	1.44	—
Consumer to feeder	2.60	1.90	1.95	1.15
Consumer to substation	3.00	2.19	2.24	1.32
Consumer to generator	3.29	2.41	2.46	1.45

High diversity factor is always desirable for the economic operation of the plant because the load factor increases with an increase in diversity factor. It is to be noted that the consumer's actual maximum demand divided by diversity factor of the consumer will determine his effective demand at the generator. Thus to determine the effective demand of a consumer on the generator, multiply his connected load by the demand factor and divide the product by the diversity factor.

$$\therefore \quad \text{Maximum effective demand} = \frac{\text{Connected load} \times \text{demand factor}}{\text{diversity factor}}$$

The peak demand of a system is made up of the individual demands of the devices that happen to be functioning at the time of the peak. At the time of the system peak demand, the demand of a particular group of similar consumers is seldom at the maximum value that it may reach at some other time of the year. This diversity is measured by peak diversity factor.

$\therefore$ Peak diversity factory

$$= \frac{\text{Maximum effective demand of consumer group}}{\text{Demand of consumer group at the time of system peak demand}}$$

$$\therefore \quad \text{System peak demand} = \frac{\text{Maximum effective demand}}{\text{Peak diversity factor}}.$$

When peak diversity factor is not given, the students are advised to take as unity.

4. Plant capacity factor. The load and diversity factors do not give any idea about the reserve capacity required in the station. Therefore, two following factors are introduced. Capacity factor is defined as the ratio of actual energy produced to the maximum possible energy that could have been produced during the same period.

Thus the annual capacity factors would be the annual kW-hrs produced divided by the kW of the plant capacity times hours of the year.

$$\therefore \text{ Capacity Factor} = \frac{\text{Average load} \times t}{\text{Plant capacity} \times t}$$

$$= \frac{\text{Average load}}{\text{Plant capacity}} = \frac{\text{Peak load} \times \text{Load factor}}{\text{Plant capacity}}$$

The capacity factor shows how near the plant runs to its full rating. When there are several plants on a system, the most efficient (base load plant) runs close to unity capacity factor as a base load plant and least efficient acts as a peaking plant. The difference between load and capacity factors is an indication of reserve capacity.

The high values of demand factor, load factor, diversity factor and capacity factor are always desirable for economic operation of the plant and to produce the energy at a cheaper rate.

5. Plant use factor. It is defined as the ratio of energy produced in given time to maximum possible energy that could have been produced during the actual number of hours of operation. It shows the extent to which the plant capacity is used to meet the peak demand.

$$\text{Plant use Factor} = \frac{\text{Annual energy produced}}{\text{Capacity of plant} \times \text{No. of hours plant is in operation during year}}$$

As the plant use factor approaches 1, it indicates the need for additional capacity of the plant.

The plant capacity is always designed greater than peak load to take the loads coming in future and to take many unpredicted loads or the load of some special events as cloudy weather, wind velocity, hurricanes and flood damages and so on.

The high value of plant use factor indicates that the plant is used most efficiently. A low utilization factor means the plant is used only for standby purposes on a system comprised of several stations or the capacity has been installed well in advance of need.

In some inter-connected system, the use factor may exceed unity (1.1 to 1.2) which indicates that loads have been carried in excess of the rated capacity of the equipment. This means, the plant carries 10 to 20% more load than its rated nameplate capacity as the equipments are always designed to take nearly 10 to 20% more load than rated.

The different factors are indicated on the diagram as shown in Fig. 32.8.

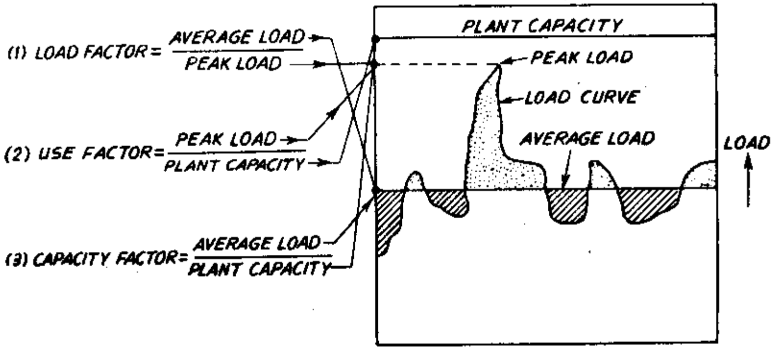


Fig. 32.8. Representation of different factors.

$$\text{Load Factor} \times \text{Use factor} = \frac{\text{Average Load}}{\text{Peak Load}} \times \frac{\text{Peak load}}{\text{Plant capacity}} = \frac{\text{Average load}}{\text{Plant capacity}} = \text{Capacity factor}$$

$$\therefore \text{ Capacity factor} = \text{Load factor} \times \text{Use factor.}$$

No doubt, the annual plant capacity factor (particularly thermal and nuclear) decreases with the age of the plant as the efficiency of the components decreases with an increase in age.

The relation between the capacity factor and use factor in terms of times is given below

$$\text{C.F. (capacity factor)} = \frac{L_a}{L_p} = \frac{\text{Actual power generated/year}}{\text{Maximum possible power generation/year}} = \frac{L_a \times 8760}{L_p \times 8760}$$

$$\text{U.F. (Use factor)} = \frac{\text{Actual energy produced per year}}{L_p \times t \text{ (actual hours of running the plant) per year}} \text{ where } t \le 8760$$

$$= \frac{L_a \times 8760}{L_p \times t.}$$

$$\therefore \quad \frac{\text{C.F.}}{\text{U.F.}} = \frac{L_a \times 8760}{L_p \times 8760} \times \frac{L_p \times t}{L_a \times 8760} = \frac{t}{8760}$$

The effect of age on the plant capacity factor of a thermal plant is shown in Fig. 32.9 and the effect of plant capacity factor on the production cost is shown in Fig. 32.10.

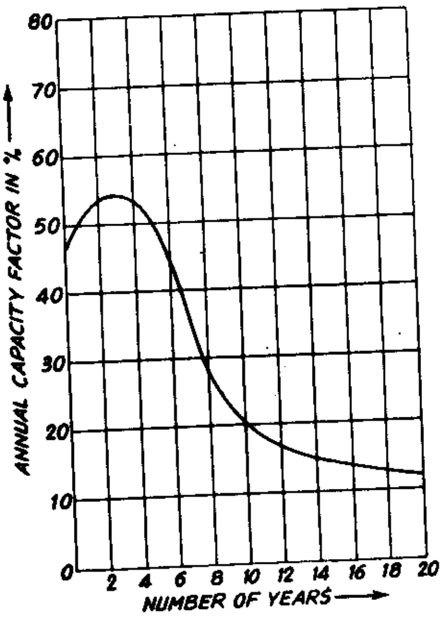


Fig. 32.9. Effect of age on annual capacity factor of thermal plant.

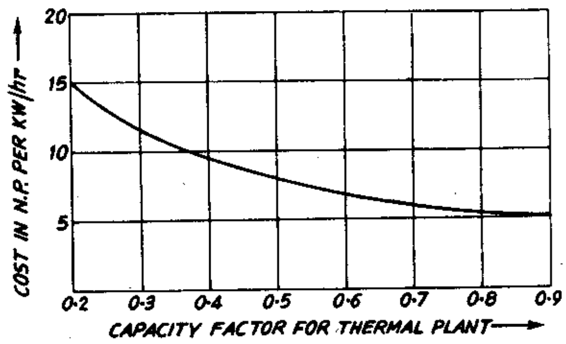


Fig. 32.10. Effect of capacity factor on the cost of production.

32.4. EFFECT OF VARIABLE LOAD ON POWER PLANT DESIGN AND OPERATION

The necessity of supplying a variable load influences the characteristics and method of use of power plant equipments. The generation of power must be regulated according to the demand and governing is necessary to achieve the same. Another requirement of a power plant is a quick response to the load.

In all variable load problems, the major problem is, the generator (and prime mover) must be able to take varying load as quick as possible without the change in voltage and frequency. When the load on the generator increases, the first effect is to slow down the rotor and prime-mover and therefore to reduce the frequency. With the decrease in speed of the prime-mover which is due to the increase in load on generator, the governor must act, admitting more fuel in case of thermal plants and more water in case of hydel plant, enough to bring the speed back to normal and pick up the load. The frequency stabilizers are used to maintain the frequency constant which may change due to response of the equipments.

The raw materials used in thermal power plant are fuel, air and water and to produce variable power from the thermal power plant according to requirement is to vary the raw material correspondingly. With an increase in load on the plant, the governor admits more steam and maintains the turbine speed. The governor response to this point has followed rapidly the change of load but beyond this point, changes are not so rapid. Because, the steam generator operates with unbalance between heat transfer and steam demand long enough to suffer a definite decrease of steam pressure. With fluctuating steam demand, it becomes very difficult to secure good combustion and steady steam pressure because efficient combustion requires the co-ordination of so many services. The co-ordination between the different components and processes is not as simple as supplying of more raw materials, but the reason being that there is certain time lag present in combustion and heat transfer that is not present in electrical generators.

The design of thermal plants for variable loads is always more difficult than diesel or hydraulic plants and it is always desirable to allow the thermal plant to operate as base load plant.

It is always necessary in case of power plants to keep the reserve capacity to meet the peaking loads. This reserve is particularly required for an individual or isolated plant. This reserve capacity always increases the charges of electrical energy supplied. Therefore, it is always desirable to keep the reserve capacity as small as possible.

SOLVED PROBLEMS

The following formulas are used for solving the problems :

(1) Average load $= \dfrac{\text{Total energy}}{\text{Time period}}$

(2) Load factor $= \dfrac{\text{Average load}}{\text{Peak load}}$

(3) Use factor $= \dfrac{\text{Actual energy produced}}{\text{Plant capacity} \times \text{No. of actual hours of running the plant}}$

(4) Capacity factor $= \dfrac{\text{Average load}}{\text{Plant capacity}} = \text{Use factor} \times \text{Load factors}$

(5) Demand factor $= \dfrac{\text{Maximum demand}}{\text{Connected load}}$

(6) Diversity factor $= \dfrac{\text{Sum of individual maximum demand}}{\text{Simultaneously maximum deamand}}$

(7) Maximum effective demand

$$= \frac{\text{Connected load} \times \text{demand factor}}{\text{Diversity factor}}$$

(8) System peak demand

$$= \frac{\text{Maximum effective demand}}{\text{Peak diversity factor}}$$

Problem 32.1. *A residential load of a locality is given below :*

Time (hours)	*0—5*	*5—6*	*6—9*	*9—18*	*18—21*	*21—24*
Load (kW)	2	6	20	*zero*	12	8

Draw the load curve and find out the load factor and energy consumed during 24 hours.

Solution. The load curve is drawn as shown in Fig. Prob. 32.1.

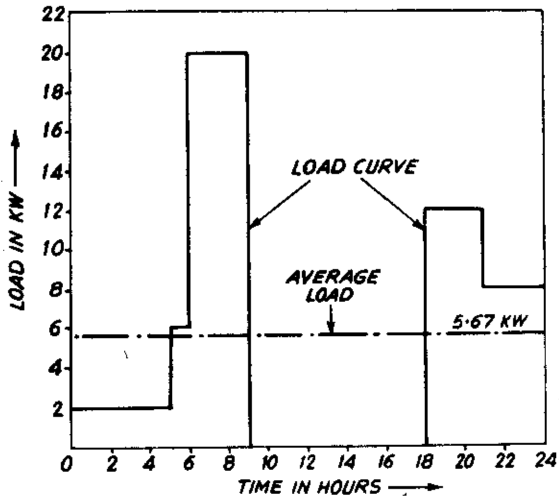


Fig. Prob. 32.1. Load curve.

Total energy consumed during 24 hours

$= 2 \times 5 + 6 \times 1 + 20 \times 3 + 12 \times 3 + 8 \times 3$

$= 10 + 6 + 60 + 36 + 24 = 136$ kW-hrs.

$\therefore$ Average load $= \frac{136}{24} = \mathbf{5.67\ kW}$

Load factor $= \frac{5.67}{20} = \mathbf{0.284.}$

Problem 32.2. *A power station supplies the following loads to the consumers :*

Time in hours	*0—6*	*6—10*	*10—12*	*12—16*	*16—20*	*20—22*	*22—24*
Load in MW	20	50	60	40	80	70	40

Find : (a) The load factor of the plant.

(b) What is the load factor of a stand-by equipment of 20 MW capacity if it takes up all loads above 60 MW ?

Solution. The load curve is drawn for the given loads as shown in Fig. Prob. 32.2.

Energy generated = Area under the load curve

$= 20 \times 6 + 50 \times 4 + 60 \times 2 + 40 \times 4 + 80 \times 4 + 70 \times 2 + 40 \times 2$

$= 120 + 200 + 120 + 160 + 320 + 140 + 80 = 1140$ MW-hrs.

Average load $= \frac{1140}{24} = \mathbf{47.5\ MW}$

Load factor $= \frac{\text{Average load}}{\text{Peak load}} = \frac{47.5}{80} = \mathbf{0.594.}$

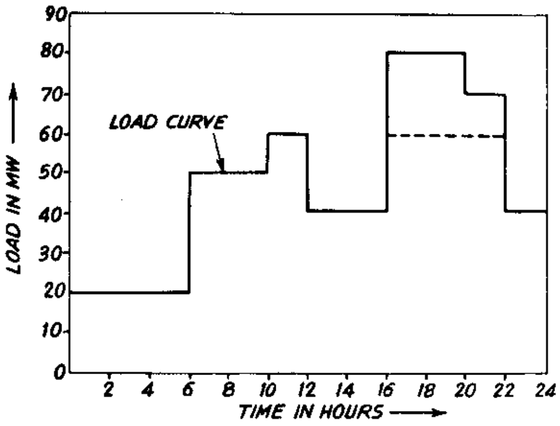


Fig. Prob. 32.2. Load curve.

(*b*) If the load above 60 MW is supplied by a stand-by unit of 20 MW capacity, the energy generated

$$= 20 \times 4 + 10 \times 2 = 80 + 20 = 100 \text{ MW hrs.}$$

Time during which stand-by unit remains in operation

= 6 hours (from the load curve)

$$\therefore \quad \text{Average load} = \frac{100}{6} = \mathbf{16.7\ MW}$$

$$\text{Load factor} = \frac{\text{Average load}}{\text{Peak load}} = \frac{16.7}{20} = \mathbf{0.835.}$$

Problem 32.3. *The peak load on a power station is 30 MW. The loads having maximum demands of 25 MW, 10 MW, 5 MW and 7 MW are connected to the power station. The capacity of the power station is 40 MW and annual load factor is 50%. Find*

(*a*) *Average load on the power station.* (*b*) *Energy supplied per year.* (*c*) *Demand factor.* (*d*) *Diversity factor.*

Solution.

$$(a)\ \text{Load factor} = \frac{\text{Average load}}{\text{Peak load}}$$

$$\therefore \quad \text{Average load} = 30 \times 0.5 = \mathbf{15\ MW.}$$

(*b*) Energy supplied per year

$$= \text{Average load} \times 8760 \text{ kW-hrs}$$

$$= 15 \times 10^3 \times 8760 = \mathbf{131.4 \times 10^6\ kW\text{-}hrs.}$$

$$(c)\ \text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}} = \frac{30}{15 + 10 + 5 + 7} = \frac{30}{37} = 0.81.$$

$$(d)\ \text{Diversity factor} = \frac{\text{Sum of individual maximum demands}}{\text{Simultaneous maximum demand}} = \frac{15 + 10 + 5 + 7}{30} = \frac{37}{30} = \mathbf{1.23.}$$

Problem 32.4. *The maximum load on a thermal power plant of 60 MW capacity is 50 MW at an annual load factor of 60%. The coal consumption is 1 kg per unit of energy generated and the cost of coal is Rs. 600 per ton of coal. Find (a) annual revenue earned if the energy is sold at Re. 1 per kW-hr. (b) The capacity of the plant.*

Sol.

$$\text{Annual load factor} = \frac{\text{Average load}}{\text{Peak load}}$$

$$\therefore \quad \text{Average load} = 50 \times 0.6 = 30 \text{ MW} = 30 \times 10^3 \text{ kW}$$

$$\text{Energy generated per year} = 30 \times 10^3 \times 8760 = 262.8 \times 10^6 \text{ kW-hr.}$$

$$\text{Coal required per year} = \frac{(262.8 \times 10^6) \times 1}{1000} = 262.8 \times 10^3 \text{ tons.}$$

$$\text{Cost of coal per year} = 262.8 \times 10^3 \times 600 = 15768 \times 10^4 \text{ rupees.}$$

$$\text{Cost of energy sold} = \frac{262.8 \times 10^6}{1} \times 1 = 26280 \times 10^2 \text{ rupees.}$$

∴ Revenue earned by the power plant per year

$$= 26280 \times 10^4 - 15768 \times 10^4 = \mathbf{10512 \times 10^4 \text{ rupees.}}$$

Problem 32.5. *A thermal power plant consists of two 60 MW units each running for 8000 hours and one 30 MW unit running for 2000 hours per year. The energy produced by the plant is 876 × 10⁶ kWh per year. Determine plant load factor and plant use factor. Consider maximum demand is equal to plant capacity.*

Solution.

$$\text{Plant capacity} = 60 + 60 + 30 = 150 \text{ MW.}$$

$$\text{Average load} = \frac{\text{Energy produced per year}}{8760} = \frac{876 \times 10^6}{8760} = 10^5 \text{ kW} = \mathbf{100 \text{ MW}}$$

$$\text{Load factor} = \frac{\text{Average load}}{\text{Max. load}} = \frac{100}{150} = 0.67 = \mathbf{67\%}$$

$$\text{Plant use factor} = \frac{\text{Actual energy produced}}{(\text{Max. possible energy which can be produced by the plant})}$$

Max. possible energy which can be produced by the plant

$$= 2 \times 60 \times 8000 + 1 \times 30 \times 2000$$

$$= 96 \times 10^4 + 6 \times 10^4 = 102 \times 10^4 \text{ MWh.}$$

$$= 1020 \times 10^6 \text{ kWh}$$

$$\therefore \quad \text{Plant use factor} = \frac{876 \times 10^6}{1020 \times 10^6} = \mathbf{0.86.}$$

Problem 32.6. *A power plant supplies the loads having maximum demands of 40 MW, 50 MW and 30 MW respectively. The load factor of the plant on the basis of annual load curve is 60% and the diversity factor of the load is 1.2. Determine (a) the maximum load on the power plant, (b) the capacity of the power plant required to take the loads, and (c) annual energy supplied by the power plant.*

Solution.

$$(a) \text{ Diversity factor} = \frac{\text{Sum of individual max. demands}}{\text{Simultaneous max. demand}}$$

∴ Simultaneous max. demand

$$= \frac{40 + 50 + 30}{1.2} = \frac{120}{1.2} = 100 \text{ MW.}$$

This will be maximum load on the power plant.

(*b*) The capacity of the plant can be taken as sum of individual max. demands

$$= 40 + 50 + 30 = 120 \text{ MW.}$$

(c) Load factor $= \dfrac{\text{Average load}}{\text{Max. load}}$

$\therefore$ Average load = 0.6 × 100 = 60 MW.

$\therefore$ Energy supplied per year = Average load × 8760

$= 60 \times 10^3 \times 8760 \text{ kWh} = \mathbf{525.6 \times 10^6 \text{ kWh}}.$

Problem 32.7. *On the basis of annual operation, the use factor and capacity factor of a central plant are 0.5 and 0.4 respectively. Find the number of hours of its operation during the year.*

Solution.

$$\text{Use factor} = \frac{E}{P_c \times t} \qquad \text{...(1)}$$

$$\text{Capacity factor} = \frac{\text{Average load}}{P_c} = \frac{\text{Average load} \times 8760}{P_c \times 8760} = \frac{E}{P_c \times 8760} \qquad \text{...(2)}$$

where E = Energy produced per year (kWh)

P_c = Plant capacity in kW

t = Number of hours the plant remained in operation during the year.

Dividing equations (1) and (2),

$$\frac{\text{Use factor}}{\text{Capacity factor}} = \frac{E}{P_c \times t} \times \frac{P_c \times 8760}{E}$$

$$\therefore \quad \frac{0.5}{0.4} = \frac{8760}{t}$$

$$\therefore \quad t = \frac{8760}{1} \times \frac{4}{5} = \mathbf{7008\ hours.}$$

Problem 32.8. *A diesel power plant consists of two units of 500 kW capacity each and one unit of 200 kW capacity. The fuel used has a calorific value of 40,000 kJ/kg and the fuel consumption is 0.25 kg/kWh. Determine the quantity of fuel required for a month of 30 days and its cost if the fuel cost is Rs. 4000 per tonne. Also find the overall efficiency of the plant.*

Take plant capacity factor on monthly basis = 50%.

Solution.

$$\text{Capacity factor} = \frac{E}{P_c \times t}$$

where E = energy generated during the month.

P_c = plant capacity.

and t = time in hours during the month.

$P_c = 500 + 500 + 200 = 1200$ kW.

$t = 30 \times 24 = 720$ hrs.

$$\therefore \quad 0.5 = \frac{E}{1200 \times 720}$$

$$\therefore \quad E = 1200 \times 720 \times 0.5 = \mathbf{600 \times 720\ kWh/month.}$$

Fuel consumption per month

$= 0.25 \times (600 \times 720) = 150 \times 720$ kg.

$$= \frac{150 \times 720}{1000} = \mathbf{108\ tonnes.}$$

$\therefore$ Fuel cost = 108 × 4000 = 432000 rupees/month.

$$\therefore \quad \text{Cost of energy} = \frac{432000}{600 \times 720} = \text{Rs. 1/kWhr}$$

$$\text{Overall efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{(600 \times 720) \times 3600}{150 \times 720 \times 40{,}000} = 0.36 = \mathbf{36\%}.$$

Problem 32.9. *An yearly load duration curve of a gas turbine power plant is a straight line from 45,000 kW to 5,000 kW. The load is taken by a power plant which consists of two units of 20,000 kW each and one unit of 10,000 kW. Determine (a) load factor and (b) capacity factor of the plant.*

Solution. The load curve is shown in Fig.-Prob. 32.9.

The energy generated per year by the plant = Area under the load curve

$$= 8760 \times 5000 + \tfrac{1}{2} \times 8760 \times (45{,}000 - 5000)$$

$$= 8760\,(5000 + 20{,}000)$$

$$= 8760 \times 25{,}000 \text{ kWh/year}$$

$$\text{Average load} = \frac{8760 \times 25{,}000}{8760} = \mathbf{25{,}000\ kW.}$$

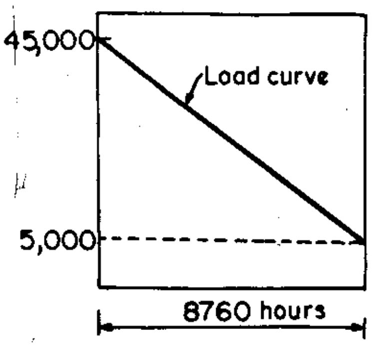


Fig. Prob. 32.9.

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} = \frac{25000}{45000} = \mathbf{0.55}$$

$$\text{Capacity factor} = \frac{\text{Energy generated/year}}{\text{Plant capacity} \times 8760}$$

$$\text{Plant capacity} = 20{,}000 \times 2 + 10{,}000 = \mathbf{50{,}000\ kW.}$$

$$\therefore \quad \text{Capacity factor} = \frac{25{,}000 \times 8760}{50{,}000 \times 8760} = \mathbf{0.5}$$

Problem 32.10. *A load duration curve for a industrial load is served by hydro-thermal plants follows a straight line. The maximum and minimum loads are 30 MW and 10 MW respectively. The hydel-plant is available at the time of minimum regulating flow is just enough to take a peak load of 72 MWh per day. On investigation, it is found economical to pump water from lower reservoir to higher reservoir using the excess power from steam plant during off peak period allowing steam plant to run at 100% load all the times. Determine the capacities of hydel and steam plants required for the purpose.*

Assume efficiency of steam to electric conversion = 45%.

Solution. The load duration curve for the combined system is shown in Fig. Prob. 32.10. Let *OA* is the capacity of thermal plant. *CGB* is the energy available in low flow period and *FED* is the energy available during off-peak period. *BGFA* is the corresponding energy supplied from pump storage plant.

As steam-electric conversion is 45%

$$\therefore \quad BGFA = 0.45 \times \text{Area } FED$$

$$\text{Area } BGFA = \text{Area } CAF - \text{Area } CBG$$

$$= \frac{1}{2}xy - 72$$

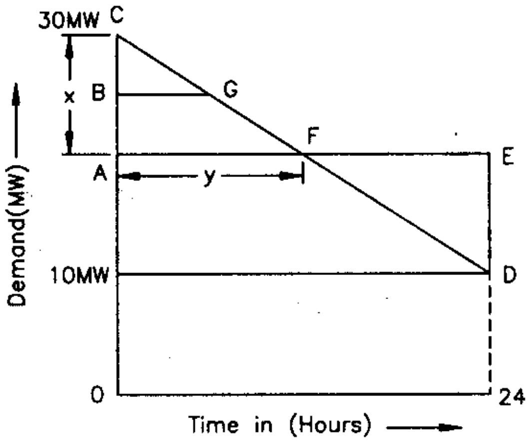


Fig. 32.10.

and Area $$FED = \frac{1}{2} ED \times FE = \frac{1}{2}(20 - x)(24 - y)$$

∴ $$\frac{1}{2} xy - 72 = 0.45\left[\frac{(20 - x)(24 - y)}{2}\right]$$

∴ $$xy - 144 = 0.45(20 - x)(24 - y) \qquad \text{...}(a)$$

Also $$\frac{x}{y} = \frac{20}{24} \qquad \text{...}(b)$$

Substituting $y = 1.2\,x$ from equation (*b*) into equation (*a*), we get

$$1.47\,x^2 + 48\,x - 800 = 0$$

Solving the above equation

x (hydel plant capacity) = **7 MW**

Steam plant capacity = 30 − 7 = **23 MW.**

Problem 32.11. *The commercial, street-lighting and industrial loads are supplied by a power plant as given below :*

All the loads given are in kW.

Find (a) Load factors of each type of load.

(b) Diversity factor of the system.

(c) Load factor of the system.

Time in hours	*Residential load*	*Street lighting load*	*Industrial load*	*Total load*
0—1	80	60	400	540
1—2	80	60	400	540
2—3	80	60	400	540
3—4	80	60	400	540
4—5	80	60	400	540
5—6	100	60	300	460
6—7	120	—	200	320
7—8	120	—	200	320
8—9	120	—	1000	1120
9—10	120	—	1000	1120
10—11	40	—	1000	1040
11—12	40	—	1000	1040
12—13	40	—	400	440
13—14	40	—	1000	1040
14—15	40	—	1000	1040
15—16	40	—	1000	1040
16—17	40	—	1000	1040
17—18	140	—	400	540
18—19	160	60	200	320
19—20	160	60	400	620
20—21	160	60	400	620
21—22	160	60	400	620
22—23	80	60	400	540
23—24	80	60	400	540

Solution. The individual load curves and the load curve for the total load are drawn as shown in Fig. Prob. 32.10.

Total energy consumed by the residential load during 24 hours

$$= 80 \times 5 + 100 \times 1 + 120 \times 4 + 40 \times 7 + 140 \times 1 + 160 \times 4 + 80 \times 2$$

$$= 400 + 100 + 480 + 280 + 140 + 640 + 160 = 2200 \text{ kW-hrs.}$$

$\therefore$ Average load of residential consumers $= \frac{2200}{24}$ kW.

$\therefore$ Load factor $= \frac{2200}{24} \times \frac{1}{160} = \mathbf{0.574.}$

Total energy consumed by street lighting load

$$= 60 \times 12 = 720 \text{ kW-hrs.}$$

$\therefore$ Load factor $= \frac{720}{24} \times \frac{1}{60} = \mathbf{0.5}$

Total energy consumed by the industrial load

$$= 400 \times 5 + 300 \times 1 + 200 \times 2 + 1000 \times 4 + 400 \times 1 + 1000 \times 4 + 400 \times 1 + 200 \times 1 + 400 \times 5$$

$$= 2000 + 300 + 400 + 4000 + 400 + 4000 + 400 + 200 + 2000$$

$$= \mathbf{13700 \text{ kW-hrs.}}$$

$\therefore$ Load factor $= \frac{13700}{24} \times \frac{1}{1000} = \mathbf{0.57}$

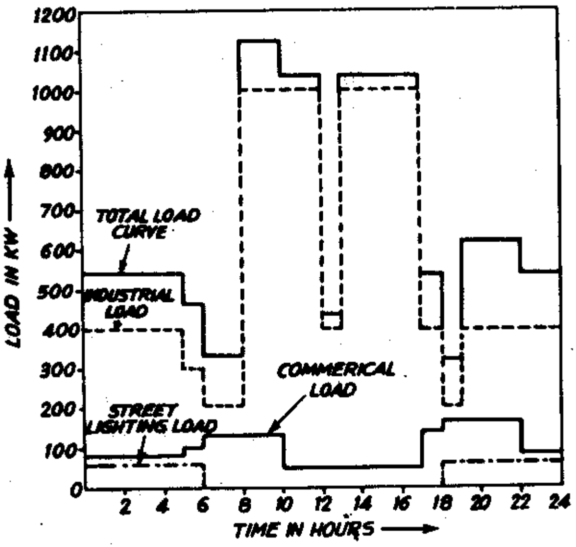


Fig. Prob. 32.10.

Simultaneous maximum demand = 1040 kW

Sum of individual maximum demand

$$= 160 + 60 + 1000 = 1220 \text{ kW}$$

$\therefore$ Diversity factor $= \frac{1220}{1040} = \mathbf{1.172}$

Load factor of the system

$$= \frac{\text{Total energy consumed in 24 hours}}{\text{Total maximum demand} \times 24}$$

$$= \frac{2200 + 720 + 13700}{1040 \times 24} = \frac{16620}{1040 \times 24} = \mathbf{0.675}$$

This shows that the load factor of the system is higher than the individual load factors.

Problem 32.12. *A power plant has the following annual factors. Load factor = 70%. Capacity factor = 50%. Use factor = 60%*

Maximum demand is 20 MW. Find

(*a*) *Annual energy production.*

(*b*) *Reserve capacity over and above peak load.*

(*c*) *Hours during which the plant is not in service per year.*

Sol.

(*a*) $$\text{Load factor} = \frac{\text{Average load}}{\text{Peak load}}$$

$\therefore$ Average load = 20 × 0.7 = 14 MW = **14000 kW.**

$\therefore$ Annual energy produced

$$= 14000 \times (365 \times 24)$$

$$= 14000 \times 8760 = \mathbf{122.8 \times 10^6 \text{ kW-hrs.}}$$

$\therefore$ Annual capacity factor

$$= \frac{\text{Average load}}{\text{Plant capacity}}$$

$$\therefore \quad \text{Plant capacity} = \frac{14}{0.5} = 28 \text{ MW}$$

$\therefore$ Reserve capacity over and above peak load

$$= 28 - 20 = 8 \text{ MW}.$$

(*c*) $$\text{Annual use factor} = \frac{\text{Energy generated per year}}{\text{Plant capacity} \times t_1}$$

where t_1 is the actual number of hours of the year for which the plant remains in operation.

$$\therefore \quad 0.6 = \frac{112.8 \times 10^6}{28 \times 10^3 \times t_1}$$

$$\therefore \quad t_1 = \frac{112.8 \times 10^6}{28 \times 10^3 \times 0.6} = \mathbf{6700 \text{ hrs}}$$

$\therefore$ Hours not in service

$$= 8760 - 6700 = \mathbf{2060 \text{ hrs in a year.}}$$

Problem 32.13. *A consumer has installed a load of 1500 MW. His demand pattern for a day is as follows : Midnight to 5 a.m. = 50 kW, 5 a.m. to 8 a.m. = No demand, 8 a.m. to 12 noon = 1200 kW, 12 noon to 4 p.m. = 1000 kW and 4 p.m. to midnight = 500 kW.*

Calculate the load factor and his monthly bill assuming a two part tarrif as Rs. 40 kW and Rs. 1.5 kWh.

Solution. The load curve is drawn as shown in Fig. Prob. 32.13 for the given load pattern.

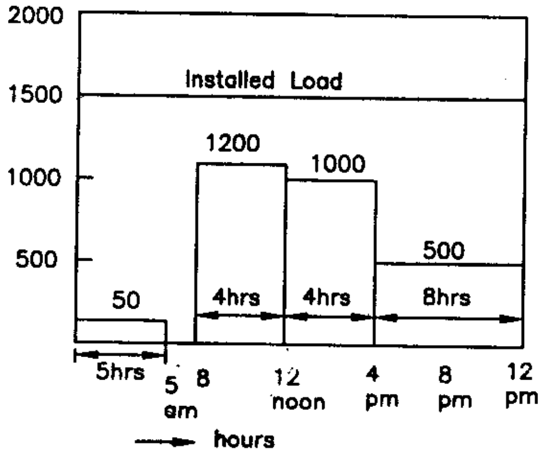


Fig. Prob. 32.13.

The load factor is given by

$$\text{L.F.} = \frac{\text{Energy consumed/day}}{\text{Maximum load} \times 24}$$

$$= \frac{50 \times 5 + 1200 \times 4 + 1000 \times 4 + 500 \times 8}{1200 \times 24}$$

$$= \frac{250 + 4800 + 4000 + 4000}{1200 \times 24} = \frac{2.5 + 48 + 40 + 40}{12 \times 24} = \frac{130.5}{288} = \mathbf{0.453}$$

Monthly bill = Fixed amount + Cost for energy consumed

Fiexed amount = Installed load × 40

= 1500 × 40 = Rs. 60,000

Cost for energy consumed per month

= (250 + 4800 + 4000 + 4000) × 30 × 1.5 = 587250

$\therefore$ Monthly bill = **Rs. 60000 + Rs. 58725 = Rs. 118725**

Problem 32.14. *A power station has annual factors as follows : Load factor = 0.6, capacity factor = 0.4 and use factor = 0.45. The maximum demand from the power station = 20 MW. Determine*

(*a*) *Annual energy produced (b) Reserve capacity over and above peak load (c) Number of hours per year during which plant is not working.*

Solution. (*a*) Annual energy produced = Average load × 24 × 365

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

$\therefore$ Average load = 20 × 0.6 = 12 MW = 12×10^3 kW

Annual energy produced = $12 \times 10^3 \times 24 \times 365 = \mathbf{105.12 \times 10^6}$ **kWh**

(*b*) $\text{Capacity factor} = \dfrac{\text{Average load}}{\text{Plant capacity}}$

$\therefore$ $\text{Plant capacity} = \dfrac{12}{0.4} = 30 \text{ MW}$

$\therefore$ Reserve capacity = 30 – 20 = **10 MW.**

(c) $\dfrac{\text{Use factor}}{\text{Capacity facitor}} = \dfrac{8760}{t}$

where t is the number of hours, the plant remains in operation during the year

$$\therefore \qquad t = \frac{8760}{1} \times \frac{0.4}{0.45} \approx 7787 \text{ hours}$$

Number of hours during which plant is out of operation during the year
= 8760 − 7787 = **973 hours**

Problem 32.15. *The following loads are connected to a power plant :*

Type of load	*Max. demand (MW)*	*Diversity factor*	*Demand factor*
Domestic	*15*	*1.25*	*0.70*
Commercial	*25*	*1.20*	*0.90*
Industrial	*50*	*1.30*	*0.98*

If the overall diversity factor is 1.5, determine (a) The maximum demand and (b) Connected load of each type.

Solution. (a) The sum of maximum demands from all consumers
= 15 + 25 + 50 = 90 MW

As the system diversity factor = 1.5 (given)

$$\therefore \quad \text{Maximum demand of the plant} = \frac{90}{1.5} = 60 \text{ MW.}$$

(b) Maximum domestic load demand
= Maximum domestic demand × Diversity factor
= 15 × 1.25 = 18.75 MW

∴ Connected domestic load

$$= \frac{\text{Maximum domestic load demand}}{\text{Demand factor}} = \frac{18.75}{0.7} \approx \mathbf{26.78\ MW}$$

Similarly,

$$\text{Connected commercial load} = \frac{25 \times 1.2}{0.9} = \mathbf{33.33\ MW}$$

$$\text{Connected industrial load} = \frac{50 \times 1.3}{0.98} = \mathbf{66.33\ MW}$$

Total connected load to the plant
= 26.78 + 33.33 + 66.33 = **126.44 MW.**

Problem 32.16. *A thermal power station has maximum demand of 500 MW. The annual load factor = 0.5 and capacity factor = 0.4 for the station. Find the reserve capacity of the plant.*

Solution. Energy generated per year
= Maximum demand × L.F. × Hours in a year
= 500 × 0.5 × 8760 = **2.19 × $\mathbf{10^6}$ MWh**

$$\text{Capacity factor} = \frac{\text{Units generated per year}}{\text{Plant capacity} \times \text{Hours in year}}$$

$$\text{Plant capacity} = \frac{500 \times 0.5 \times 8760}{0.4 \times 8760} = \mathbf{625\ MW}$$

∴ Reserve capacity of the plant = 625 − 500 = **125 MW.**

Problem 32.16A. *A 1000 MW power plant delivers 1000 MW for 2 hours, 500 MW for 6 hours and shut down for the rest of the day. The plant is also shut-down for 60 days annually. Find the annual load factor of the plant.*

Solution. The amount of energy generated per day

$$= 1000 \times 2 + 500 \times 6 = 5000 \text{ MWh/day}$$

No. of days (the plant is working) = 365 – 60 = 305 days.

The amount of energy generated per year

$$= 5000 \times 305 = \mathbf{1525 \times 10^3 \ MWh}$$

$$\text{Annual load factor} = \frac{\text{MWh supplied/year}}{\text{Max. capacity} \times \text{Working hours/year}}$$

$$= \frac{1525 \times 10^3}{1000 \times (305 \times 24)} = \mathbf{0.208}$$

Loading the Power Plants

Problem 32.17. *A 1000 MW thermal power plant delivers 1000 MW for 2 hours, 500 MW for 6 hours, 300 MW for 8 hrs and shut down for the rest of each day. It is also completely shut-down for 50 days in a year for maintenance. Determine the annual load factor for the plant.*

Solution. Energy generated per working day

$$= 1000 \times 2 + 500 \times 6 + 300 \times 8 = 74000 \text{ MWh}$$

Working days per year for the plant = 365 – 50 = 315 days

Energy supplied/year = 7400 × 315 MWh

$$\text{Annual load factor} = \frac{\text{Actual energy supplied}}{\text{Max. possible energy to be supplied}}$$

$$= \frac{7400 \times 315}{1000 \times (315 \times 24)} = \mathbf{0.308.}$$

Problem 32.17A. *A generating power plant supplies the following loads to various consumers as listed below :*

Industrial = 750 MW, Commercial = 350 MW

Domestic power = 10 MW and Domestic light = 50 MW

If the maximum demand on the station is 1000 MW and energy generated is 50×10^5 MWh per year, determine (a) Diversity factor (b) Annual load factor.

Solution.

$$\text{Diversity factor} = \frac{\text{Sum of Max. demand of all consumers}}{\text{Max. capacity of the plant}}$$

$$= \frac{750 + 350 + 10 + 50}{1000} = \frac{11160}{1000} = \mathbf{1.16}$$

$$\text{Average demand} = \frac{\text{MWh generated per year}}{\text{Working hours per year}}$$

$$= \frac{50 \times 10^5}{8760} = \mathbf{570.8 \ MW}$$

$$(b) \ \text{Annual load factor} = \frac{\text{Average demand}}{\text{Max. capacity}} = \frac{570.8}{1000} = \mathbf{0.5708}$$

Problem 32.18. *A 24-hour load curve of a power plant is sinusoidal with maximum and minimum demand of 6000 MW and 2000 MW respectively. If the plant capacity is 7000 MW, find (a) Average load on the plant (b) Plant load factor and (c) Plant capacity factor.* (P.U. May, 1997)

Solution. The load-curve for the given condition is shown in Fig. Prob. 32.18.

The load (L) variation with respect to time is given by

$$L = 2000 + 4000 \sin\left(\frac{\pi t}{24}\right)$$

If $t = 0, \quad L = 2000$

$t = 12, \quad L = 6000$

$t = 24, \quad L = 2000$

The given conditions are satisfied by the above equation used for load variation during 24-hours.

The average load on the plant is given by

$$L_{av} = \frac{1}{24}\int_0^{24} L \,.\, dt$$

$$= \frac{1}{24}\int_0^{24}\left[2000 + 4000 \sin\left(\frac{\pi t}{24}\right)\right].dt$$

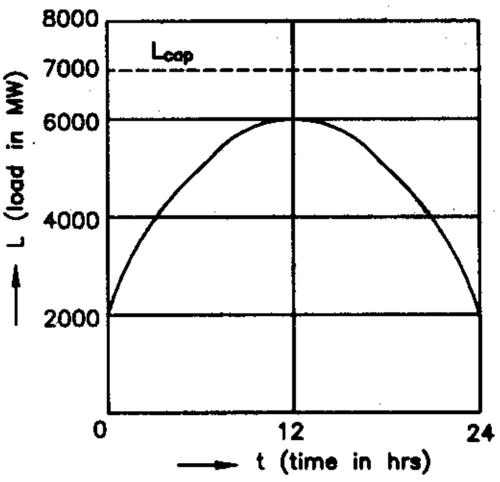


Fig. Prob. 32.18.

$$= \frac{1}{24}\left[2000\, t - 4000 \,.\, \frac{24}{\pi}\cos\left(\frac{\pi t}{24}\right)\right]_0^{24}$$

$$= \frac{1}{24}\left[\left\{2000 \times 24 - 4000 \times \frac{24}{\pi}\cos(\pi)\right\} - \left\{0 - 4000 \times \frac{24}{\pi}\cos(0)\right\}\right]$$

$$= \frac{1}{24}\left[2000 \times 24 + 4000 \times \frac{24}{\pi} + 4000 \times \frac{24}{\pi}\right]$$

$$= 2000 + 8000 \times \frac{1}{\pi} = 2000 + 2546.5 = \mathbf{4546.5\ MW}$$

$$\text{PLF (Plant load factor)} = \frac{L_{av}}{L_{max.}} = \frac{4546.5}{6000} = \mathbf{0.758}$$

$$\text{PCF (Plant capacity factor)} = \frac{L_{av}}{L_{cap.}} = \frac{4546.5}{7000} = \mathbf{0.65}$$

Problem 32.19. *The load in a particular factory reaches maximum at 12 noon and that is 5 MW. The load at 6 A.M. becomes zero and it also becomes zero at 6 p.m. The load curve during 12 hours follows half elliptical curve. Find out the following :*

(*i*) *Load factor of the factory.*

(*ii*) *Energy consumed by the factory during 12 hrs.*

(*iii*) *Plant capacity factor if the plant capacity is 7 MW.*

Solution. The load curve for the given condition is shown in the Fig. Prob. (32.19).

The load curve for elliptical variation can be represented by an equation

$$y = \frac{b}{a}\sqrt{2ax - x^2}$$

and $$y_{av} = \frac{1}{2a}\int_0^{2a}\left(\frac{b}{a}\right)\sqrt{2ax - x^2}$$

where y is load and x is time and $2a$ is along X-axis and $2b$ is along Y-axis.

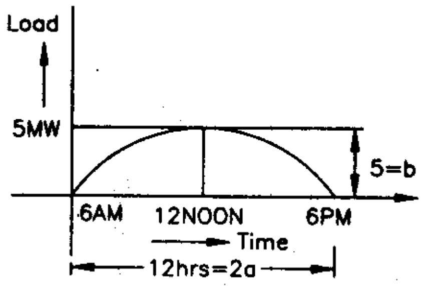


Fig. 32.19.

This satisfies the given load conditions as

$$t = 0,\ L = 0 \text{ and } t = 12,\ L = \frac{5}{6}\sqrt{12 \times 12 - 12^2} = 0$$

and $t = 6$
$$L = \frac{6}{6}\sqrt{12 \times 6 - 6 \times 6} = \frac{5}{6} \times 6 = 5$$

The average load on the plant is given by

$$L_{av} = \frac{1}{2a}\int_0^{2a} L \, . \, dt$$

$$= \frac{1}{2a}\int_0^{2a} \frac{b}{a}\sqrt{2at - t^2}\, dt$$

$$= \frac{b}{2a^2}\int_0^{2a} (\sqrt{2at - t^2})\, dt$$

$$= \frac{b}{2a^2}\int_0^{2a} \sqrt{t} \, . \, \sqrt{2a - t} \, . \, dt$$

Let
$$t = 2a \sin^2 \theta$$

$\therefore$
$$dt = 4a \sin \theta \cos \theta \, . \, d\theta$$

$$t = 0,\ \theta = 0, \text{ and } t = 2a,\ \theta = \frac{\pi}{2}.$$

$\therefore$
$$L_{av} = \frac{b}{2a^2}\int_0^{\pi/2} \sqrt{2a \sin^2 \theta} \, . \, \sqrt{2a - 2a \, . \, \sin^2 a} \, . \, 4a \sin \theta \, . \cos \theta \, . \, d\theta$$

$$= \frac{b}{2a^2}\sqrt{2a} \, . \, \sqrt{2a} \, . \, 4a \int_0^{\pi/2} \sin^2 \theta \, . \, \cos^2 \theta \, . \, d\theta$$

$$= 4b \int_0^{\pi/2} \sin^2 \theta \, . \, \cos^2 \theta \, . \, d\theta$$

$$= 4b \int_0^{\pi/2} \left(\frac{2 \sin \theta \, . \, \cos \theta}{2}\right)^2$$

$$= b \int_0^{\pi/2} \sin^2 2\theta \, . \, d\theta$$

$$= b\int_0^{\pi/2} \frac{1-\cos 4\theta}{2}\, d\theta$$

$$= \frac{b}{2}\left[\theta - \frac{\sin 4\theta}{4}\right]_0^{\pi/2}$$

$$= \frac{b}{2}\left[\frac{\pi}{2} - \frac{1}{4}\sin\left(4\times\frac{\pi}{2}\right)\right]$$

$$= \frac{b}{2}\left[\frac{\pi}{2} - \frac{1}{4}\sin 2\pi\right] = \frac{b}{2}\left(\frac{\pi}{2} - 0\right) = \boxed{\frac{\pi b}{4}} \qquad \text{...}(i)$$

$$= \frac{\pi}{4}\times 5 = \frac{5\pi}{4} = \mathbf{3.925\ MW} \text{ as } b = 5$$

(*i*) Load factor $= \dfrac{L_{av}}{L_{max}} = \dfrac{3.925}{5} = \mathbf{0.785}$

(*ii*) Energy used during 12-hrs period

= Average load × 12

= 3.925 × 12 = **47.1 MW**

(*iii*) Capacity factor $= \dfrac{\text{Average load}}{\text{Plant capacity}} = \dfrac{3.925}{7} = \mathbf{0.561}$

Now consider the following different ellipses having same maximum load but time period (along *x*-axis) is different.

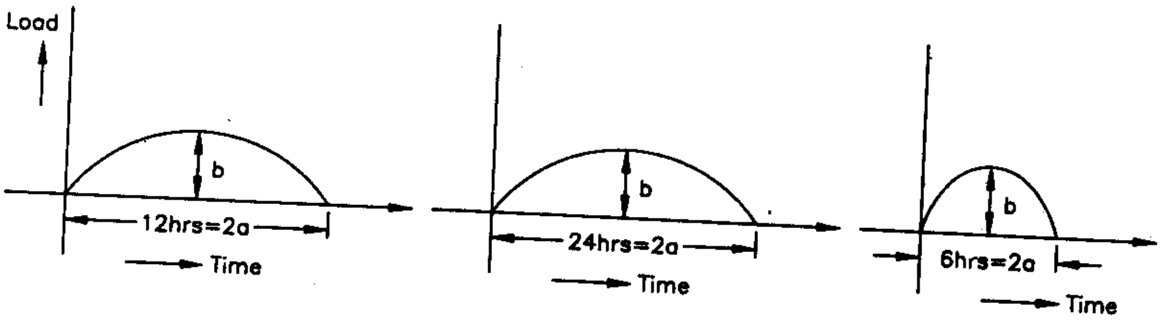


Fig. Prob. 32.19.

In all three cases $L_{av} = \frac{\pi}{4}\, b$ as it is independent of value of *a*. This indicates that the average load is constant irrespect to period of working (2*a*) if the maximum load is same.

(*b*) **If the working period of the factory is from 10 a.m. to 6 p.m. and minimum load at the starting and closing of the factory is 2 MW, then find average load of the factory.**

Hint. The load curve becomes

$$L = 2 + \frac{b}{a}\sqrt{2at - t^2}$$

where $b = 5$, and $a = 4$ (as total working hours are 8).

The boundary conditions are

$t = 0$, $L = 2$, $t = 8$, $L = 2$ and $t = 4$, $L_{max} = 5$.

Problem 32.19. *(a) A load curve of a factory follows a parabola and it works for eight hours a day from 10 A.M. to 6 P.M. The minimum and maximum loads of the factory are 1 MW and $\sqrt{3}$ MW. The capacity of the diesel power plant supplying the power to the factory is 2 MW. Find (i) Load factor and capacity factor of the plant supplying power to the factory.*

(ii) Energy consumption of the factory per month assuming it works for 26 days per month and 8-hrs per day.

(iii) Electrical charges to be paid by the factory if the charges are Rs. 50/kW for maximum load during a day and Rs. 2.5 per kW/hr.

Note. *The time at 6 A.M. should be taken as zero.*

Solution. The load curve is shown in Fig. Prob. 32.19 (*a*).

The load curve is given by

$y^2 = ax$ where x represents time in hours and y represents load in MW.

The boundary conditions are

$y = 0$ at $x = 0$ and $y = 1$ at $x = 4$

$$\therefore \quad 1 = a \times 4 \quad \therefore \quad a = \frac{1}{4}$$

$$\therefore \quad y^2 = \frac{x}{4} \text{ or } y = \frac{1}{2}\sqrt{x} \text{ (load curve)} \qquad \ldots(a)$$

The above load curve also fulfills the another condition which is

$y = \sqrt{3}$ at $x = 12$

$$\therefore \ (\sqrt{3})^2 = \frac{12}{4} \quad \therefore \quad 3 = 3.$$

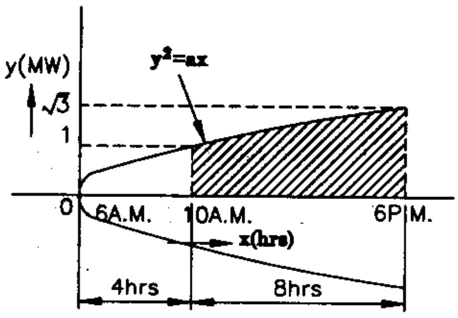


Fig. Prob. 32.19. (*a*)

The average load of the factory on the plant is given by

$$L_{av} = \frac{1}{8}\int_4^{12} y \, . \, dx = \frac{1}{8}\int_4^{12} \frac{1}{2}\sqrt{x} \, . \, dx$$

$$= \frac{1}{16}\left[\frac{2}{3}(x)^{1.5}\right]_4^{12} = \frac{1}{24}\left[(12)^{1.5} - (4)^{1.5}\right] = 1.4 \text{ MW} = \mathbf{1400 \ kW}$$

(*i*) Load factor $= \dfrac{L_{av}}{L_{max}} = \dfrac{1.4}{\sqrt{3}} = \dfrac{1.4}{1.73} = \mathbf{0.809}$

Capacity factor $= \dfrac{L_{max}}{\text{Plat capacity}} = \dfrac{1.73}{2} = \mathbf{0.865}$

(*ii*) Energy consumption per month is given by

$$E = (L_{av} \times 8) \times 26 = (1.4 \times 1000 \times 8) \times 26 = \mathbf{291200 \ kWhr}$$

(*iii*) Electrical charges to be paid by the factory

$= L_{max} \times 50 + E \times 2.5$

$= 1.73 \times 1000 \times 50 + 291200 \times 2.5$

$= 86500 + 728000 =$ **Rs. 814500**

Problem 32.20. *Take the following data for a thermal power plant of 500 MW capacity :*
Capacity factor = 0.45, Annual load factor = 0.6.
Cost of fuel used/year = Rs. 1000 × 10^6.
Capital cost of the plant = Rs. 10000 × 10^6.
Annual interest and depreciation = 15%.
Calculate (a) Minimum reserve capacity of the station (b) The cost per kWh generated.

Solution. C.F. (Capacity factor) $= \dfrac{\text{Average load}}{\text{Installed capacity}}$ ...(1)

L.F. (Load factor) $= \dfrac{\text{Average load}}{\text{Max. demand}}$ ...(2)

From equations (1) and (2), we get

$$\frac{\text{C.F.}}{\text{L.F.}} = \frac{\text{Max. demand}}{\text{Installed capacity}}$$

$$\text{Max. demand} = \frac{\text{C.F.}}{\text{L.F.}} \times \text{Installed capacity}$$

$$= \frac{0.45}{0.6} \times 500 = 375 \text{ MW}$$

∴ Reserved capacity = 500 − 375 = **125 MW**

(*b*) No. of units generated per year

$$= \text{Maximum demand} \times \text{L.F.} \times 8760$$

$$= 375 \times 10^3 \times 0.6 \times 8760 = \mathbf{1971 \times 10^6} \textbf{ kW-hr}$$

Annual fixed charges = Annual interest and depreciation

$$= 10000 \times 10^6 \times \frac{15}{100} = \text{Rs. } 1500 \times 10^6$$

Annual running charges = cost of fuel

$$= \text{Rs. } 1000 \times 10^6$$

Total annual charges = (1500 + 1000) × 10^6 = Rs. 2500 × 10^6

Cost of generation (Rs./kW-hr)

$$= \frac{2500 \times 10^6}{1971 \times 10^6} = \textbf{Rs. 1.27.}$$

Problem 32.21. *The daily load curve for a power plant is given by the following equation :*

$$L = 350 + 10\,t - t^2$$

where t is time in hours from 0 to 24 hrs and L is in MW.

Draw load curve and load duration curve and calculate

(i) Value of maximum load and when it occurs and

(ii) Load factor of the plant. *(P.U. May 2001)*

Solution. The condition for finding the value of maximum load is

$$\frac{dL}{dt} = 0$$

$$\therefore \quad \frac{d}{dt}[350 + 10\,t - t^2] = 0$$

$$\therefore \quad 10 - 2t = 0$$

$$\therefore \quad t = 5 \text{ hrs.}$$

The maximum load occurs at 5th hour during the day.

$$\therefore \quad L_{max} = 350 + 10 \times 5 - 25 = \mathbf{375 \text{ MW}}$$

The average load on the plant is given by

$$L_{av} = \frac{1}{24}\int_0^{24} L \,.\, dt$$

$$= \frac{1}{24}\int_0^{24} [350 + 10\,t - t^2]\, dt$$

$$= \frac{1}{24}\left[350\,t + 10 \times \frac{t^2}{2} - \frac{t^3}{3}\right]_0^{24}$$

$$= \frac{1}{24}\left[350 \times 24 + 10 \times 24 \times 12 - \frac{(24)^3}{3}\right]$$

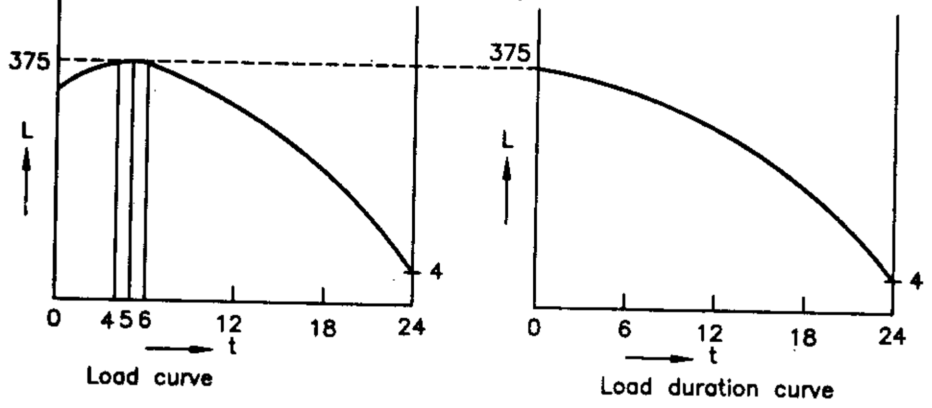
$$= \frac{1}{24} \times 24\,[350 + 120 - 192] = \mathbf{278\ MW}$$

$\therefore$ Load factor $= \frac{L_{av}}{L_{max}} = \frac{278}{375} = \mathbf{0.7413}$

We can calculate the values of L when $t = 0, 1, 2, \ldots\ldots 24$ and these values are tabulated.

t	1	2	3	4	5	6	7	8	9	10	11	12
L	350	364	371	374	375	374	371	366	359	350	339	326
t	13	14	15	16	17	18	19	20	21	22	23	24
L	311	294	275	254	231	206	179	150	119	86	51	04

The load curve is the representation of load with respective to time and load duration curve is the representation load with respective to time is decending order.



Load curve

Load duration curve

Fig. Prob. 32.21.

Note. From the above table also, we can find out the maximum value and average value also, but that is not a correct method at graduate level.

Problem 34.22. *A base load plant of 32 MW capacity and peak load plant of 20 MW capacity are connected to a common grid. The energy output from base plant is 135 × 10^6 kWh and from peak load plant is 9.5 × 10^6 kWh. The maximum load taken by the peak load plant is 15 MW and used for 2900 hrs during a year. The maximum load on base plant is 25 MW. Determine the following for both plants (a) Annual load factor (b) Plant use factor and (c) Capacity factor.*

Solution. (A) Base load plant

(*a*) Annual load factor (ALF) $= \frac{E}{M\,.\,T}$

where

E = Energy generated per year
M = Maximum demand
T = Hours during the year (8760)

$$\therefore \qquad \text{A.L.F.} = \frac{135 \times 10^6}{(25 \times 1000) \times 8760} = \mathbf{0.594}$$

(*b*) Plant use factor (PUF)
$$= \frac{M}{\text{Capacity of the plant } (C)}$$
$$= \frac{25}{32} = \mathbf{0.78}$$

(*c*) Capacity factor (C.F.)
$$= \frac{E}{C \times t}$$

where t is number of hours used during the year

$$\therefore \qquad \text{C.F.} = \frac{135 \times 10^6}{(32 \times 1000) \times 8760} = \mathbf{0.48}$$

(B) Peak load plant

(*a*)
$$\text{ALF} = \frac{E}{M.t} = \frac{9.5 \times 10^6}{(15 \times 1000) \times 8760} = \mathbf{0.073}$$

$$\text{P.U.F.} = \frac{M}{C} = \frac{15}{20} = 0.75$$

$$\text{C.F.} = \frac{E}{C.t} = \frac{9.5 \times 10^6}{(20 \times 1000) \times 2900} = \mathbf{0.164}$$

Problem 32.23. *A new housing development is to be added to the lines of public utility. There are 1000 apartments, each having a connected load of 5 kW. The services as given below in the table are also to be included in that development :*

Type of Service	*No.*	*Connected load of each in kW*	*Demand Factors*
Laundry	2	20	0.68
Temples	2	10	0.56
Restaurant	2	60	0.54
Book store	1	5	0.68
General store	4	8	0.75
Drug store	2	10	0.82
Shoe store	1	2	0.71
Cloth store	2	5	0.55
Theatre	2	120	0.60
Saloon	2	4	0.72
Flour mill	2	7	0.65
Vegetable market	1	5	0.88

The demand factor of the apartments is 40%. The group diversity factor of the residential system is 3.2 and peak diversity factor is 1.5. The diversity of the commercial group load is 1.6 and peak diversity factor is 1.2.

Find the increase in peak demand resulting from addition of this housing development on the distribution system. Assume line losses as 5% of delivered energy.

Solution. Demand of power from 1000 apartments $= 1000 \times 5 \times 0.4 = 2000$ kW

Maximum demand of 1000 apartments
$$= \frac{2000}{3.2} = 625 \text{ kW}$$

Demand at the time of system peak
$$= \frac{625}{1.5} = 416 \text{ kW}$$

The demand of power from the commercial loads can be calculated as follows :

Type of Service	*Total connected Load (kW)*	*Demand Factor*	*Maximum Demand in kW*
a	*b*	*c*	$d = b \times c$
Laundry	40	0.68	27.20
Tamples	20	0.56	11.20
Restaurant	120	0.54	64.80
Book store	5	0.68	3.40
General store	32	0.75	24.00
Drug store	20	0.82	16.40
Shoe store	2	0.70	1.40
Cloth store	10	0.55	5.50
Theatre	240	0.60	144.00
Saloon	8	0.72	5.76
Flour mill	14	0.65	9.10
Vegetable market	5	0.88	4.40
Total	—	—	317.16

Maximum demand of commercial group $= \frac{317.16}{1.6} = 198$ kW

Demand at the time of system peak $= \frac{198}{1.2} = 165$ kW

∴ Total maximum demand for this housing development considering 5% losses

$= (416 + 165) \times 1.05 = 581 \times 1.05 =$ **610 kW.**

Problem 32.24. *A 60 MW turbo-generator set has an overall efficiency of 25%. The calorific value of coal used is 30000 kJ/kg. Find the consumption of coal for kW-hr. and per day of 24 hours if the load factor is 30%.*

Sol. Input × η_0 (overall efficiency) = output

If output is 1 kW-hr, then

Input $= \frac{1}{0.25} = 4$ kW-hrs $= 4 \times 3600$ kJ

∴ Consumption of coal per kW-hr.

$$\frac{4 \times 3600}{30000} = 0.48 \text{ kg}$$

Load factor $= \frac{\text{Energy consumed in 24 hours}}{\text{Peak load} \times 24}$

∴ Energy consumed in kW-hrs within 24 hours

$= 0.3 \times 60 \times 10^3 \times 24 = 432 \times 10^3$ kW-hr.

∴ Consumption of coal per day $= \frac{432 \times 10^3 \times 0.48}{1000} =$ **202.7 tons.**

Problem 32.25. *The loads supplied to the two types of consumer groups are tabulated below :*

Time	0–4	4–6	6–8	8–12	12–13	13–17	17–19	19–20	20–24
Group A (Load in kW)	50	150	300	50	50	50	300	200	100
Group B (Load in kW)	20	20	100	600	100	600	50	20	20

The energy charges as per the load factor are given below :

Load Factor	1-0.8	0.8-0.6	0.6-0.4	0.4-0.2	Below 0.2
Charge in Rs. per kW-hr	1	1.6	2.4	5	8

Find the total revenue earned from both groups of the consumers.

Sol. Total energy consumed by group A

$= 50 \times 4 + 150 \times 2 + 300 \times 4 + 50 \times 4 + 50 \times 1 + 50 \times 2 + 300 \times 2 + 200 \times 1 + 100 \times 4$

$= 200 + 300 + 1200 + 200 + 50 + 100 + 600 + 200 + 400 =$ **3250 kW-hrs.**

Load factor of group A

$$= \frac{3250}{24} \times \frac{1}{300} = \frac{3250}{7200} = \mathbf{0.452}$$

∴ Revenue earned from group A

$= 3250 \times 2.4 =$ **7800 rupees**

Total energy consumed by group B

$= 20 \times 4 + 20 \times 2 + 100 \times 2 + 600 \times 4 + 100 \times 1 + 600 \times 4 + 50 \times 2 + 20 \times 1 + 20 \times 2$

$= 80 + 40 + 200 + 2400 + 100 + 2400 + 100 + 20 + 40 =$ **5380 kW-hr.**

Load factor of group $B = \frac{5380}{24} \times \frac{1}{600} = \mathbf{0.374.}$

∴ Revenue earned from group B

$= 5380 \times 5 = 26900$ rupees

∴ Total revenue earned per day from both groups

$= 7800 + 26900 =$ **Rs. 34700/day.**

Problem 32.26. *The loads of a group of industry are tabulated below for 24 hours. Draw the load duration curve and find the power required for 50% of the time of the day. If the capacity of plant is 25 MW, find the capacity factor of the power plant.*

Time	*6 A.M. to 8 A.M.*	*8 A.M. to 9 A.M.*	*9 A.M. to 11 A.M.*	*11 A.M. to 2 P.M.*	*2 P.M. to 5 P.M.*	*5 P.M. to 8 P.M.*	*8 P.M. to 12 night*	*12 night to 5 A.M.*	*5 A.M. to 6 A.M.*
Load	800	600	2000	1200	1400	2000	1000	500	600

If the load is supplied by two power plants, one is acting as base load plant having a capacity of 15 MW and other as peak load plant having a capacity of 10 MW, find load factor, capacity factor and use factor of both power plants.

Sol. The load curve for the given loads is drawn as shown in Fig. Prob. 32.15 (a).

From the load curve, the loads and corresponding number of hours are tabulated as given below :

Load	*No. of hours urged*	*Percentage of time*
500	24	100
600	19	79.2
800	18	75
1000	16	66.7
1200	12	50
1400	9	37.5
1600	6	25
2000	5	20.8

The load duration curve is drawn by using the above tabulated data as shown in Fig. Prob. 32.15 (b).

From the load duration curve, the required load for 50% of time (50% of 24 hours) is 10 MW.

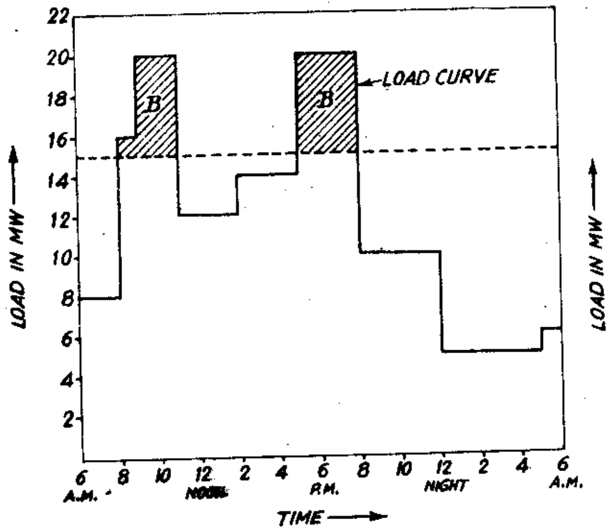


Fig. Prob. 32.26 (*a*).

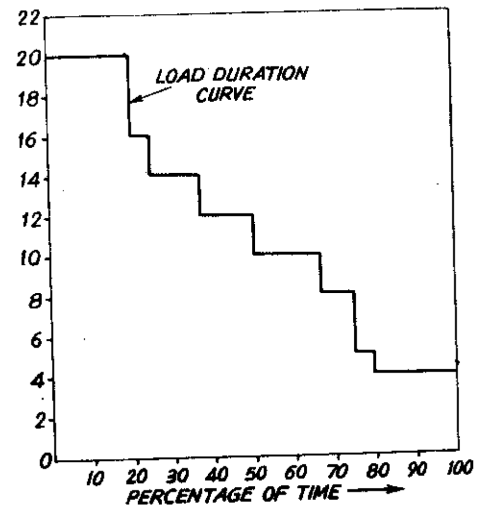


Fig. Prob. 32.26 (*b*).

The total energy generated in 24 hours

$= 8 \times 2 + 16 \times 1 + 20 \times 2 + 12 \times 3 + 14 \times 3 + 20 \times 3 + 10 \times 4 + 5 \times 5 + 6 \times 1$

$= 16 + 16 + 40 + 36 + 42 + 60 + 40 + 25 + 6 =$ **281 MW-hrs.**

$$\text{Capacity Factor} = \frac{\text{Total energy generated}}{\text{Capacity of the plant} \times 24} = \frac{281}{26 \times 24} = 0.468 = \mathbf{46.8\%}.$$

The base load plant (15 MW capacity) works for 100% of the time and the peak load plant works only when its services are required.

The actual power generated by the base load plant from load curve

$= 8 \times 2 + 15 \times 3 + 12 \times 3 + 14 \times 3 + 15 \times 3 + 10 \times 4 + 5 \times 5 + 6 \times 1$

$= 16 + 45 + 36 + 42 + 45 + 40 + 25 + 6 =$ **225 MW-hrs.**

Load factor of base load plant

$$= \frac{\text{Actual energy produced}}{\text{Peak load (in this case plant capacity)} \times 24}$$

$$= \frac{255}{15 \times 24} = \frac{255}{360} = 0.708 = \mathbf{70.8\%}.$$

As there is no reserve capacity for base load plant therefore the capacity factor will be equal to load factor. The plant is also running for all 24 hours of a day continuously, therefore, its use factor is also equal to capacity factor or load factor.

The load above 15 MW capacity is supplied by a 10 MW capacity peak load plant.

The actual energy produced by the peak load plant within 24 hours from load curve

$= 1 \times 1 + 5 \times 5 = 1 + 25 = 26$ MW-hrs (area B as shown on load curve)

Peak load plant works only for 6 hours a day.

Load factor based on whole day working of the plant

$$\frac{\text{Average load}}{\text{Peak load}} = \frac{26}{5 \times 24} = \frac{26}{120} = 0.217 = \mathbf{21.7\%}$$

Capacity factor (on the day basis)

$$= \frac{26}{10 \times 24} = \frac{26}{240} = \mathbf{10.85\%}$$

$$\text{Use factor} = \frac{26}{10 \times 6} = \frac{26}{60} = 0.434 = \mathbf{43.4\%}$$

Problem 32.27. *A power station supplies the loads as tabulated below :*

Time hours	6 A.M. to 8 A.M.	8 A.M. to 9 A.M.	9 A.M. to 12 noon	12 noon to 2 P.M.	2 P.M. to 6 P.M.	6 P.M. to 8 P.M.	8 P.M. to 9 P.M.	9 P.M. to 11 P.M.	11 P.M. to 5 A.M.	5 A.M. to 6 A.M.
Load (kW)	1200	2000	3000	1500	2500	1800	2000	1000	500	800

(*a*) *Draw the load curve and find the load factor on the basis of 24 hours.*

(*b*) *Choose the proper number and size of generator units to supply this load.*

(*c*) *Find the reserve capacity of the plant and plant capacity factor.*

(*d*) *Calculate the plant use factor.*

Solution. (*a*) The load curve is drawn as shown in Fig. Prob. 32.27.

The hydraulic, diesel or gas turbine units can be used to feed the load as shown in Fig. Prob. 32.27. The steam plant can also be used if local conditions are suitable.

The method and considerations for the selection of generator size and number are common irrespective of the type of power plant so far as fitting in the load curve is concerned.

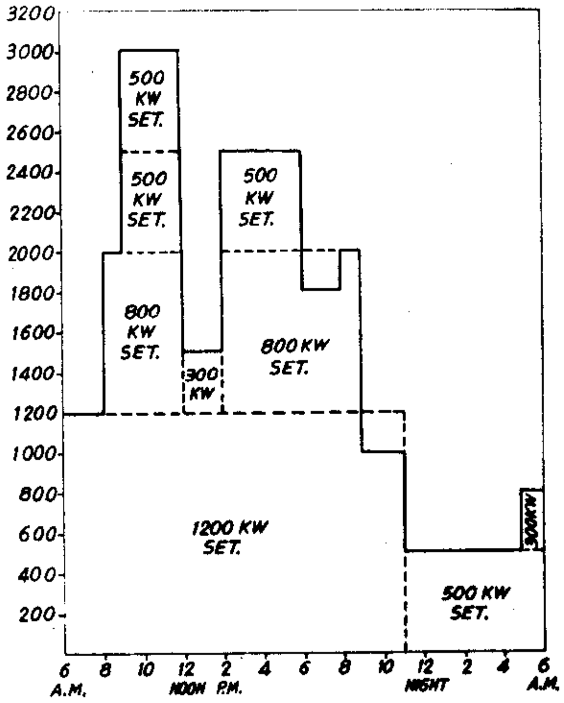


Fig. Prob. 32.27. Load curve.

(*a*) Total power generated during 24 hours

= 1200 × 2 + 2000 × 1 + 3000 × 3 + 1500 × 2 + 2500 × 4 + 1800 × 2 + 2000 × 1 + 1000 × 2 + 500 × 6 + 800 × 1

= 2400 + 2000 + 9000 + 3000 + 10,000 + 3600 + 2000 + 2000 + 3000 + 800 = **37,800 kW-hrs.**

$$\text{Load factor} = \frac{\text{Energy generated during 24 hours}}{\text{Maximum demand} \times 24} = \frac{37800}{3000 \times 24} = \mathbf{0.525.}$$

(*b*) It is obvious from the load curve that the number of sets required are 5 in number.

One set of 1200 kW.

One set of 800 kW.

Two sets of 500 kW.

One set of 300 kW.

(*c*) The reserve capacity required is always equal to the largest size of the generator unit used in the station. In this case, the reserve capacity = 1200 kW.

Total installed capacity of the station

$$= 1200 + 800 + 500 \times 2 + 300 \times 1 + 1200 \text{ (reserve)} = \mathbf{4500\ kW.}$$

$$\text{Plant capacity factor} = \frac{\text{Energy produced in 24 hours}}{\text{Installed capacity} \times 24} = \frac{37800}{4500 \times 24} = 0.35 = \mathbf{35\%.}$$

(*d*) The actual energy generated within 24 hours

$$= \mathbf{37800\ kW\text{-}hrs.}$$

The energy that could have been generated by the capacity of the plant running for the schedule time

$= 1200 \times 17 + 800 \times 11 + 500 \times 3 + 500 \times 7 + 500 \times 7 + 300 \times 3$

$= 20400 + 8800 + 1500 + 3500 + 3500 + 900 = 38600$ kW-hr.

$$\therefore \quad \text{Plant use factor} = \frac{\text{Actual energy produced}}{\text{Capacity of the generators} \times \text{number of hours the generator has been inoperation}}$$

$$= \frac{37800}{38600} = 0.98 = \mathbf{98\%.}$$

The variations of the load and unit sizes of the generators chosen exactly fit the load curve, therefore the plant use factor reaches nearly to unity.

In practice, it is not possible to get such high use factor as it is difficult to choose the generators which fit the load exactly and run at full load capacity for the maximum period. However the use factor is always greater than the capacity factor when some reserve capacity is required.

The starting and stopping the generators is easy in case of hydro, diesel and gas turbine units as their response is quick but it is time-consuming in steam and nuclear power stations as the response is very poor.

EXERCISES

32.1. Define 'connected load', 'maximum demand', demand factor and load factor. Explain the importance of each in a power plant operation.

32.2. Define the "Diversity factor" and state the advantages of the diversity of load in a power supply system. Prove that the load factor of the power plant is improved by an increase in diversity of load.

32.3. What different load curves are considered in designing a power plant ? What is the effect of its nature on the working of power plant ?

32.4. Define load duration curve. Explain the method of its construction and state its advantages in the design of power plant.

32.5. Define the plant "Use factor" and plant "capacity factor" and state their uses in the design and operation of the power plant. Also state the effect of these factors on the choice of the size of the generator units, the number, reserve capacity of the plant and operating schedule of the station.

32.6. What are the effects of variable load on the power plant design and operation ?

32.7. What is the indication that the national load factor is increasing ? When it reaches highest ? Explain your answer with graphs.

32.8. The loads on a power plant with respect to time for 24 hours are listed below :

Time (hours)	0-6	6-8	8-12	12-14	14-18	18-22	22-24
Load (MW)	40	50	60	50	70	80	40

Draw the load curve and find the load factor of the power station. If the loads above 60 MW are taken by a stand-by unit of 20 MW capacity, find the load factor of the stand-by unit. **[Ans.** 0.71 and 0.75]

32.9. The daily load of a power station is given by the following data :

Time	12	3	6	8	10	11	12 noon
Load in MW	95	60	60	150	175	180	175
1	3	4	5	6	7	9	12
180	200	250	310	170	140	160	105

Plot the load curve and find the load factor. What is the daily load factor of the stand-by unit that takes all peak loads over 200 MW ?

32.10. The daily load of a power station is given below :

Time	12 night	2 A.M.	6 A.M.	8 A.M.	12 noon	12-30 P.M.	1 P.M.	5 P.M.	6 P.M.	12 night
Load (MW)	20	10	10	50	50	40	50	50	70	20

(*a*) Plot load and load duration curves for the system.
(*b*) Plot the load energy curve for the system.
(*c*) Find the load factor.
(*d*) What is the Use-Factor of the plant serving this load if its capacity is 100 MW ?

32.11. A power plant load is represented by an average daily load given below :

Time	*Load in (kW)*	*Time*	*Load in (kW)*
A.M.		P.M.	
1	230	1	500
2	200	2	620
3	190	3	670
4	180	4	760
5	180	5	1000
6	200	6	930
7	300	7	900
8	410	8	870
9	560	9	850
10	590	10	720
11	610	11	600
12 (noon)	605	12 (noon)	380

This load is carried by one 1200 kW steam turbo-generator unit which has a steam demand represented by the equation

Steam in kg = 1000 + 50 kW.

Find (*a*) load factor, (*b*) capacity factor, and (*c*) steam used in kg per day.

32.12. A daily load curve of a certain region is tabulated as given below.
It is proposed to carry this load with a new diesel engine power station. Sizes of engines available are 300 kW, 480 kW, 600 kW, 720 kW and 960 kW. Plot the load curve and fit it with selections from the given engines so that there will be good balance between the capacity factor and number of units installed. Also find out (*a*) Capacity of the plant, and (*b*) Use factor of each unit.

Time	*Load in (kW)*	*Time*	*Load in (kW)*
A.M.		P.M.	
1	220	1	500
2	200	1-30	590
3	190	2	620
4	180	3	670
5	180	4	760
6	200	5	1000
7	300	5-30	960
8	410	6	930
9	560	7	900
10	590	8	870
11	610	9	850
12	605	10	720
12-30	490	11	600
		12	380

32.13. An electrical railway system has severely fluctuating loads that instantaneous wattmeter reading does not define its load curve adequately. The readings given below of such system have been taken from the integrating meter. The meter constant is 10000 to convert to kW hr.

<table>
<tr><td><i>Time</i></td><td colspan="2">12 P.M.</td><td colspan="2">1 A.M.</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td></tr>
<tr><td><i>Meter reading</i></td><td colspan="2">5595</td><td colspan="2">5597</td><td>5602</td><td>5605</td><td>5611</td><td>5918</td><td>5629</td><td>5624</td><td>5633</td></tr>
<tr><td></td><td>1 P.M.</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>12</td></tr>
<tr><td></td><td>5636</td><td>5639</td><td>5643</td><td>5648</td><td>5654</td><td>5661</td><td>5667</td><td>5672</td><td>5676</td><td>5678</td><td>5682</td></tr>
</table>

(*a*) Plot hourly chronological load curve and load-duration curve.

(*b*) Plot the load energy curve for the average hourly loads.

(*c*) Find the load factor based on average hourly load.

(*d*) If the instantaneous peak is 85 MW, what is the load factor ?

(*e*) What is the utilization factor of the plant serving this load by 100 MW.

32.14. A central power station has annual load factor, capacity factor and use factor as 60%, 40% and 45% respectively. The maximum demand is 15 MW. Find

(*a*) Annual energy production and revenue earned if the cost of energy is Rs. 2/kW-hr.

(*b*) Reserve capacity over and above peak load.

(*c*) Hours per year not in service.

32.15. The annual peak load on 30 MW power station is 25 MW. The power station supplies loads having maximum demand of 10 MW, 8.5 MW, 5 MW and 4.5 MW. The annual load factor is 4.5%. Find

(*a*) average load (*b*) energy supplied per year (*c*) diversity factor (*d*) demand factor.

32.16. A steam power station has a maximum demand of 20 MW. If the coal consumption is 1 kg/kW-hr and cost is Rs. 4000 per ton, find the cost of coal per year. Take annual load factor as 50%.

32.17. A 30 MW turbo-generator set has an overall efficiency of 24%. If the coal burnt has calorific value of 30,000 kJ/kg, find the coal consumption per kW-hr and per day of 24 hours if the load factor is 27%.

32.18. A consumer has the following connected loads as 10 lamps of 60 watts each and 2 heaters of 1 kW each. His maximum demand is 1.5 kW. On average, he uses 8 lamps for 5 hours a day and each heater for 3 hours a day. Find his average load, monthly energy consumption and load factor.

32.19. The annual peak load on a 15 MW power plant is 10.5 MW. Two substations are supplied by this plant. Annual energy dispatched through substation *A* is 27500 × 10^3 kW-hrs with a peak at 8.9 MW while 16500 × 10^3 kW-hrs are sent through *B* with a peak at 6.65 MW. Neglect line losses. Find the diversity factor between substation and capacity factor of the power plant.

32.20. A power plant had a use factor of 48.5% and a capacity factor of 42.5%. How many hours did it operate during a year ?

32.21. A power station has annual load factor 58.5%, capacity factor 41% and use factor 45.5%.
The reserve carried over and above the peak load is 9000 kW. Find

(*a*) Installed capacity.

(*b*) Annual energy production, and

(*c*) Number of hours per year not in service.

32.22. There are four consumers having different load requirements at different times. Consumer No. 1 has an average load of 1 kW and its maximum demand is 5 kW at 8 P.M. Consumer No. 2 has a maximum demand 2 kW at 9 P.M., a demand of 1.6 kW at 8 P.M. and daily load factor of 0.15. Consumer No. 3 has a maximum demand of 2 kW at 12 noon, a load of 1 kW at 8 P.M. and an average load of 0.5 kW. Consumer No. 4 has a maximum demand of 10 kW at 5 P.M. and a load of 5 kW at 8 P.M. and daily load factor of 0.25. The maximum demand occurs at 8 P.M. Find

(*a*) The diversity factor,

(*b*) The load factor and average load of each consumer,

(*c*) The average load and load factor of the combined loads.

[**Ans.** (*a*) 1.51. (*b*) No. 1, 1 kW, 20% No. 2, 0.3 kW, 15% No. 3, 0.5 kW, 24% No. 4, 2.5 kW, 25%, (*c*) 4.3 kW, 34.2%]

32.23. A power plant supplies the following loads :

(*a*) Residential lighting load ; maximum demand of 1000 kW at load factor 20% and diversity between consumers is 1.3.

(*b*) Commercial load : maximum demand of 2000 kW, load factor 30% and diversity factor between commercial loads is 1.1.

(*c*) Industrial load : maximum demand 5000 kW, load factor 80% and diversity factor between industrial loads is 1.2.

The overall diversity may be taken as 1.4. Find :

(1) Maximum demand on the power plant.

(2) Daily energy consumption of each load and total energy consumption.

(3) Load factor of the power plant.

[**Ans.** (1) 5714 kW (2) (*a*) 4800 kW-hrs, (*b*) 14400 kW-hrs. (*c*) 96000 kW-hrs, Total = 115200 kW-hrs. (3) 84%]

32.24. A town has the following loads in kW :

Time	1 A.M.	2	3	4	5	6	7	8	9	10	11	12 Noon
Lighting Load	50	20	20	20	20	30	—	—	—	—	—	—
Industrial Load	—	—	—	—	—	—	2000	3000	2800	2800	2500	2000
	1 P.M.	2	3	4	5	6	7	8	9	10	11	12
Lighting load	—	—	—	—	—	500	2000	5000	4000	3000	2000	500
Industrial load	1000	2000	2500	2500	2000	1500	1000	1000	500	500	—	—

It is proposed to add a municipal water load to the existing system. Find the effect of water-load of maximum demand of 1500 kW when supplied uniformly at off-peak period between 11-30 P.M. and 6-30 A.M.

[**Ans.** Load factor increases from 0.325 to 0.397]

32.25. Determine the maximum demand for the group of energy consumers shown below :

Type of Service	*Total Connected Load (in dW)*	*Demand factor*	*Group diversity factor*	*Peak diversity factor*
Public Buildings	100	0.35	1.6	1.00
Apartments	1000	0.55	4.0	1.20
Hospitals	200	0.45	1.0	1.05
Theatre	150	0.60	1.6	1.00
Laundries	50	0.70	1.8	1.05
Residences	3000	0.40	4.0	1.20
Stores	500	0.65	1.6	1.05
Offices	100	0.70	1.8	1.05
Street Lightings	600	1.00	1.0	1.00
Foundry	3500	0.80	1.1	1.05
Boiler Factory	4000	0.90	1.1	1.05
Hotel	700	0.25	1.8	1.20
Motor Factory	5000	0.75	1.1	1.05

32.26. The daily loads on a generating station whose maximum capacity in 10 MW is tabulated below :

Time	6 A.M. to 8 A.M.	8 A.M. to 12 noon	12 noon to 1 P.M.	1 P.M. to 5 P.M.	5 P.M. to 7 P.M.	7 P.M. to 9 P.M.	9 P.M. to 11 P.M.	11 P.M. to 6 A.M.
Load (MW)	3.5	8	3	7.5	8.5	10	4.5	2

(*a*) Choose the size and number of generator units. (*b*) What reserve capacity is required ? (*c*) Find load factor, capacity factor and plant use factor for the given power plant.

[**Ans.** (*a*) Three units of 5, 2.5 and 2.5 MW capacity. (*b*) 5 MW capacity.
(*c*) Load factor = 0.55, Capacity factor = Use factor = 0.865].

32.27. The daily loads, on a generating station, are tabulated below :

Time	6 A.M. to 7 A.M.	7 A.M. to 9 A.M.	9 A.M. to 12 noon	12 noon to 1 P.M.	1 P.M. to 5 P.M.	5 P.M. to 7 P.M.	7 P.M. to 9 P.M.	9 P.M. to 11 P.M.	11 P.M. to 5 A.M.	5 A.M. to 6 A.M.
Load (kW)	1000	2000	2500	1500	2500	2000	2500	1000	500	750

Draw the load curve and find : (*a*) The load factor. (*b*) choose the number and size of generator units to supply this load if the stability of supply is to be maintained. (*c*) Find the reserve capacity of the plant and plant capacity factor. (*d*) Draw the operating schedule of the units in the station. (*e*) Find the plant use factor.

[**Ans.** (*a*) 0.647. (*b*) Two sets each 1000 kW capacity and one set of 500 kW capacity.
(*c*) 1000 kW, total capacity = 3500 kW, capacity factor = 0.46. (*d*) 0.994]

32.28. The following data is collected from a daily load curve of a power plant :

Load in kW	15000	12000	10000	8000	6000	4000	2000
No. of hours at load	875	876	1752	2628	4380	7000	8760

(*a*) Draw the load duration curve and find the load factor of the system.
(*b*) If the load is supplied by two plants, one is acting as base load plant of 10,000 kW capacity and other as peak load plant of 7500 kW capacity, find the annual load factor, annual capacity factor and annual use factor for both plants.

[**Ans.** (*a*) 0.468. (*b*) Base load plant load factor = 0.84 capacity factor = 0.84, use factor = 0.84
peak load plant load factor = 0.93, capacity factor = 0.62, use factor = 0.31].

32.29. The maximum demand of a consumer group is 15 MW, load factor of 70%, capacity factor of 52.5% and plant use factor of 85%. Find (*a*) Energy produced per day. (*b*) Reserve capacity of the plant. (*c*) The maximum energy that could be produced daily if the plant is in operation all the time. (*d*) The maximum energy that could be produced daily if the plant operating in accordance with operating schedule is fully loaded when in operation.

[**Ans.** (*a*) 252 MW-hrs. (*b*) 5 MW. (*c*) 480 MW-hrs. (*d*) 297 MW-hrs].

□□□

33

Peak Load Plants

33.1. Introduction. 33.2. What is Peak Load Plant ? 33.3. Requirements of Peak Load Plants. 33.4. Means of Meeting the Total Load Demand. 33.5. Pump-Storage Power Plants. 33.6. Compressed Air-storage Plants. 33.7. Steam Power Stations as Peak Load Plants.

33.1. INTRODUCTION

The peak load carries a special significance in the power generation industry. Higher the peak load, the greater will be capacity of power generation if the total load of the system is taken by a single power plant. In addition to this, a plant designed to take base load as well as peak load will run at part load conditions during off-peak hours and costs more. Because, all types of power plants (hydel, thermal, nuclear) give low efficiency of generation if they run at part load conditions. This can be overcome by installing small units, say 10 units of 10 MW each to take a load of 100 MW. With this arrangement, six units may take the base load running continuously and the remaining four will take peak loads as per the demand allowing all units to run at rated conditions giving highest possible generation efficiency.

No doubt, this is a positive solution to overcome the difficulty of low generation efficiency of single big unit but it is not at all an economical solution. Because, with an increase in a number of units, the capital cost of the plant increases rapidly as the land requirements, component costs, maintenance and repair charges increase. It has been discussed earlier that the capital cost (Rs. per kW installed capacity) decreases rapidly with an increase in unit capacity. Therefore, presently the general trend is to build higher and higher capacity units for power generation. The units of 1000 MW capacity are already in operation in USA and USSR and units of 1500 MW capacity are already planned in USSR.

For the reason mentioned above, the total load is generally taken by the base load and peak load plants. The base load plant is always allowed to run at full load condition to ensure maximum efficiency of generation and surity of return of the capital invested providing the cheapest energy to the public. The peak load plant may work at full load or part load as per the demand but only for few hours in a day (3 to 5 hours) during the peak load demand and remain idle for the remaining period of the day. Therefore, the cost of peak load generation will be always higher as the capital invested in peak load plants remains idle for 80% of the period. The peak demand requirements can be partly nullified with the help of diversifying the consumers' demands as mentioned in previous chapter. The peak load demand can be further reduced by interconnecting the supply lines of different power plants (hydel, thermal, nuclear and gas turbine) and providing a common national grid for all states. Irrespective of all the measures taken, still peak load demands exist and power supplier has to take into account the peak load at the time of designing the plants and grid.

33.2. WHAT IS PEAK LOAD PLANT ?

Electrical power systems today have a rapidly increasing need for peak load generating capacity. The power requirement of a particular locality or city or state or nation can be suitably represented by load curve as discussed in the previous chapter. If the load curve were a horizontal straight line (constant power demand with respect to time), things would be simple for design and operation of the plants. In such idle case, one would need only base-load plant which could run continuously at constant load. Natural factors, such as geographical location, climatic conditions and time of the year in addition to the habits of consumers have a major influence on the shape of a load curve.

The peak can occur in the morning, afternoon or early evening depending on the country and season. In south USA, peak occurs between 4 to 5 p.m. On the other hand, in Switzerland, the peak occurs between 10 A.M. and noon. During severe winter, there is large peak in the evening when heating and lighting are required in addition to commercial and industrial loads.

Supplier of electricity can affect it (load curve) as little as he can after the rhythm of life. The division into working hours, sleeping period, Sundays and holidays cannot be influenced by the power company. However, supplier must try to arrive at a curve as well balanced as possible in order to make the best use of the generating plant and transmission and distribution networks. Different tariff rates for peak and off-peak time induce house owner to charge up their hot water tanks and storage heaters during the night time dip in the load, preventing the use of high consumption appliances at time of peak demand (between 9 to 11 A.M. and 4 to 6 P.M.) is unpopular but effective way of smoothing out the load curve. All through these measures are already taken into account by the suppliers, there still remain beside the night-time low, the peaks at morning and evening as shown in Fig. 33.1. The height and shape of the peaks vary during the course of year but the basic character of the curves, 'peak' by day and 'valley' by night is always retained. The maximum peak and its period depends mostly on the climatic conditions. In a very hot region, the peak *occurs* during 12 noon to 2 P.M. as the load of air-conditioning will be maximum, whereas in very cold region, the load peak generally occurs during evening time (4 to 6 P.M.) as the temperature of atmosphere goes down. The peak never occurs at night even though the atmospheric temperature is still low because of low demand of industrial load. The peak rating may be twice or thrice of minimum load on the plant.

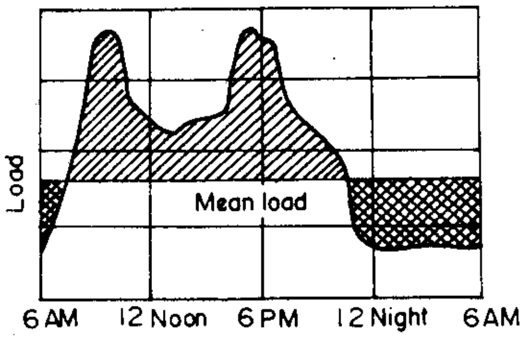


Fig. 33.1. Daily Load Curve.

It is obvious from Fig. 33.1 that the surplus energy is available during night time and extra load is required during day time if a generating plant is designed to operate at constant mean load. The extra load required during day time can be met if some storage plants are designed to store *mechanical energy* during periods of lower power demand and supply the same in the forms of electric power when peak loads occur. The arrangements used for such storage during off-peak and supply during peak demand are known as peak load power plants.

33.3. REQUIREMENTS OF PEAK LOAD PLANTS

The peak load plant has to fulfill the following few requirements :

1. The response of the peak load plant to load variations should be as quick as possible.
2. The capital cost of the plant should be as low as possible as its working hours during a year (1000 to 1500 hours) are very less compared with base load plants (6000 to 8000 hours per hour.)
3. The voltage and frequency of generation must remain constant during the fluctuations of load.
4. The special governing and control systems required to fulfill the above requirements cost more when all the strides are made to reduce the cost of the plant with proper design.

The power plants which are commonly used as peak load plants are

1. Storage type hydro-plant.
2. Hydro in parallel with steam plant.
3. Diesel or Gas Turbine Plant.
4. Special thermal plants designed to take peak loads.
5. Pump storage plants.
6. Air storage plants.

The applications of the first two as peak load plants are already discussed in the respective chapters. The use of diesel or gas turbine as peak load plant plays vital role in the power industry as the response of these plants to the fluctuating power is very high and they can be built anywhere irrespective of site available provided the ample fuel is available at low cost. The use of these plants in India for power generation does not arise at all due to limited sources of oil and gas in the country which are essential and required for industrial and transport purposes.

The use of old thermal plants and simple steam plants designed specially to take peak loads are in use in our country and outside for many years. The use of pump storage and air storage plants for peak load is recent and more economical compared with any other system. Therefore, much attention has been given in developing these plants throughout the world. The pump-storage plants are also planned in India recently even they are used in other countries for the last two decades. The technique required to design air-storage plants is not known in many of the countries and the design of such plants has just started in few countries like Germany and U.S.A.

The present chapter is devoted to discuss only the last three types of peak load plants which carry special interest and are not discussed earlier.

33.4. MEANS OF MEETING THE TOTAL LOAD DEMAND

The total deaily load demand can be met in number of ways.

1. The capacity of the base load plant is set at constant level which allows the energy stored at night using pump storage or air storage to meet the peak load-requirements during the day time as shown in Fig. 33.2.

Pump storage hydro or air storage facilities are analogous to huge storage batteries, in that they provide a system into which, surplus off-peak energy from base loaded steam plants can be stored for later use as valuable peaking capacity.

2. The base load is set at a low value, making it unnecessary to store energy during low load demand periods (if suitable means as pump storage or compressed air storage are not available). The daily peaks are met by specially designed thermal power plants as shown in Fig. 33.3.

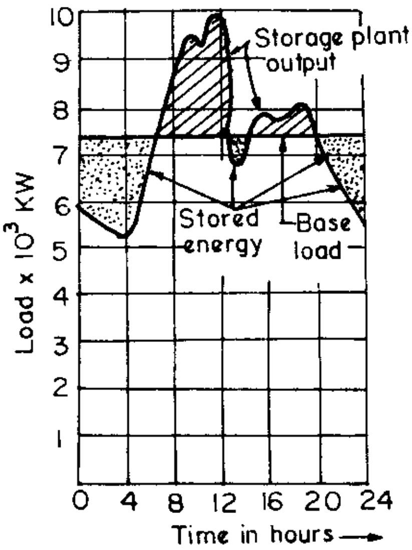


Fig. 33.2. Daily load curve—The energy stored during the night meets the complete, medium and peak load demand of the following day.

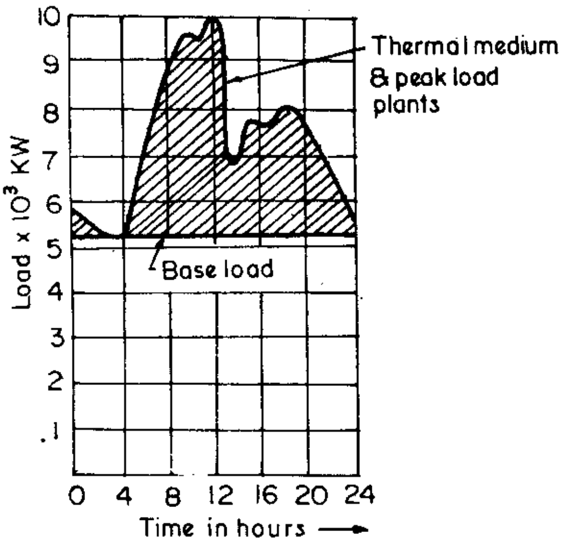


Fig. 33.3. Daily load curve—Medium and peak load demand is met by the output from specially designed thermal power plants.

3. A combination of base load and peak load power plants as shown in Fig. 33.4 can also be used. Base load is met by thermal plant in combination with storage plant and extreme peak is met by specially designed thermal, diesel or gas turbine plants which are generally named as standby plant. Standby plants generally operate for a short period of a day (2 to 4 hours) during high peak periods.

The adoption of a particular method to take the peak load depends on the overall planning concept and on local electricity costs.

Classification of Power Plant. Broadly, the power plants are classified as base load plants and peak load plants according to the load.

Base Load Plants. Thermal, nuclear and storage type hydroplants are generally considered as base load plants. Hydro-plants specially can be operated as base load or peak load as it can be started or stopped frequently without much difficulty and without much loss in efficiency with the use of modern prime-movers.

The scarcity of dam site and water availability for large scale hydro-power development has led to an increasing number of thermal plants. Thermal plants cannot be turned on or off as easily as hydro-plants. Therefore, such plants are normally designed to take constant load for continuous operation and peaking energy is supplied to accommodate load fluctuations.

It is always undesirable to subject large, high efficiency fossil fuelled or nuclear plants to large load changes ; since the induced thermal stresses can reduce the useful life of the plants. *In addition, the capital cost per kW-hr as well as running cost per kW-hr produced decrease* as the thermal generated output increases. Covering of peak load demands with steam or nuclear power station is economically undesirable and is not adaptable due to slow peak-up. Thus, for economical reasons, it is advantageous to operate these high cost thermal plants at full load even during low load demand periods and incorporating some means to store the excess energy generated.

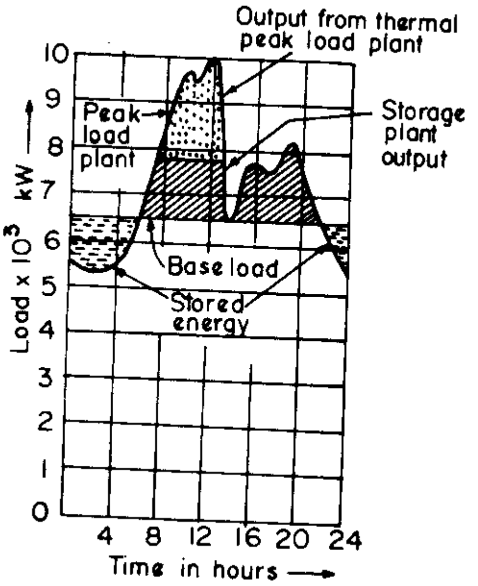


Fig. 33.4. Daily load curve—The daily medium and peak load demand is met by the output from specially designed thermal power plants and pumped storage plants.

Peak Load Plants. They are for use during load peaks. Accordingly, they have to be started up and shut-down several times a day. (If peak load plant is a separate plant). If the peak load plant is a storage type then it works all 24 hours with base load plant except it stores energy during off-peak on base plant and supplies energy during peak demand. *Separate* peak load plants are used to unforeseen load peaks. (Unusually popular television programme).

The method adopted for taking the peak load (part of the load curve) should not be only economical but also adoptable. The peak load plants adopted in practice are gas turbine, diesel engine, simple steam plant as stand-by units and pump storage and air storage as storage type plants. The use of stand-by diesel and gas turbine units has been restricted to regional areas. In interconnected systems, with high peak load requirements, the storage type hydro-plants are the most suitable plants. Where such a storage of potential water power is not available, the pump storage and air storage plants are in race.

33.5. PUMP STORAGE POWER PLANTS

Pump storage plants for peak load operations in interconnected system are more suitable where the quantity of water available for power generation is insufficient but natural site for high dam construction is most suitable.

The pump storage power plant essentially consists of a head water pond and a tail water pond. During the off-peak period of an interconnected power plants system (steam+pump-storage), the water from the tail water pond is pumped (with the help of a pump using the extra energy available from thermal power plant during off-peak hours as shown in Fig. 33.5). With surplus available energy (E_a) during off-peak period, is stored in the form of hydraulic potential energy by lifting the water from lower level to higher level. The same stored hydraulic energy is used during peak load period by supplying the water from the upper basin to the water turbine through the penstocks.

The quantity of water pumped back may be equal to all the water passing through the water turbine during peak load period or part of that depending on the requirements.

The requirement of ideal pump storage plant is $E_a\eta = E_s$
where η is known as the efficiency of the pumped storage plant.

If $E_a\eta > E_s$, then the quantity of water pumped back during off-peak period is less than the quantity of water supplied during peak load conditions. If $E_a < E_s$ then the thermal plant capacity is designed in such a way that $E_a.\eta$ becomes equal to E_s. Every care has been taken in the design of interconnected system to equalise E_s with $E_a.\eta$.

The concept of pump storage for meeting peak loads and decreasing thermal station operating cost is not new and number of inter-connected pump storage hydro-plants with capacities ranging up to 1000 MW are in successful operation. The present trend to establish large capacity thermal or nuclear plants at high capital outlay has emphasized more and more importance and growing popularity of interconnected pump storage plants in countries where the water power resources are limited or have been almost fully utilized.

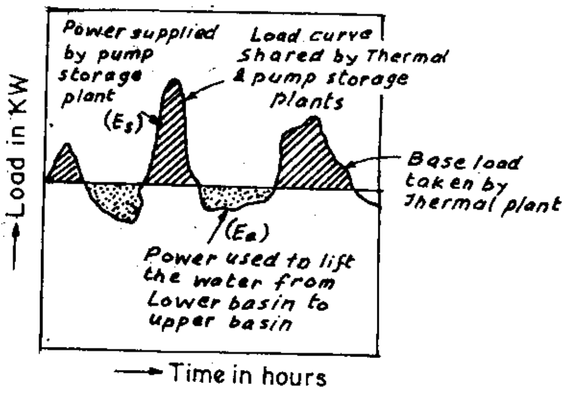


Fig. 33.5. Load Curve.

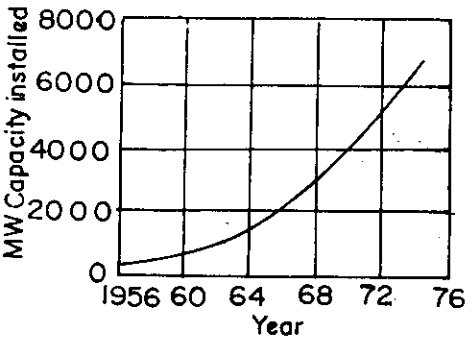


Fig. 33.6. Growth of Pump-storage units in USA.

This method of accumulating and generating electricity to supply during peak period had been developed first in West Germany about 35 years ago. Now the pumped storage station plays an increasingly important role in interconnected power supply systems round the world. The first plant of its kind was erected in Germany in 1928 at Ruhrgebiet. Twenty years later about 600 MW pumped storage capacity was available in Germany. Up to 1960, the nations in the world were not very keen to develop these types of power plants. There were only two installations in USA by the end of 1960. But, since that time, the number of installed and proposed projects has increased very rapidly in USA. The growth of installed capacity and the increases made in unit rating are shown in Fig. 33.6 and Fig. 33.7. Presently, much attention has been given throughout the world to develop such type of power plants due to its inherent advantages over other systems and increased power crisis. Germany and Japan are among the countries particularly interested in pump storage plants because the water resources in those countries are very limited.

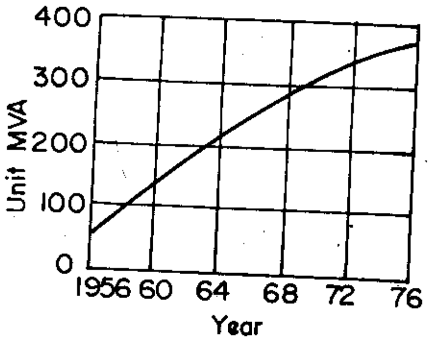


Fig. 33.7. Increase in MVA rating of pump storage turbine-generator units with time.

The site of the pump storage plant with power house is shown in Fig. 33.8 and a pump storage plant in conjunction with thermal power plant is shown in Fig. 33.9.

Efficiency and time scheduling of the pump storage plant. The time available for pumping is the time during which the power demand is below the average or mean which is supplied by base load thermal plant.

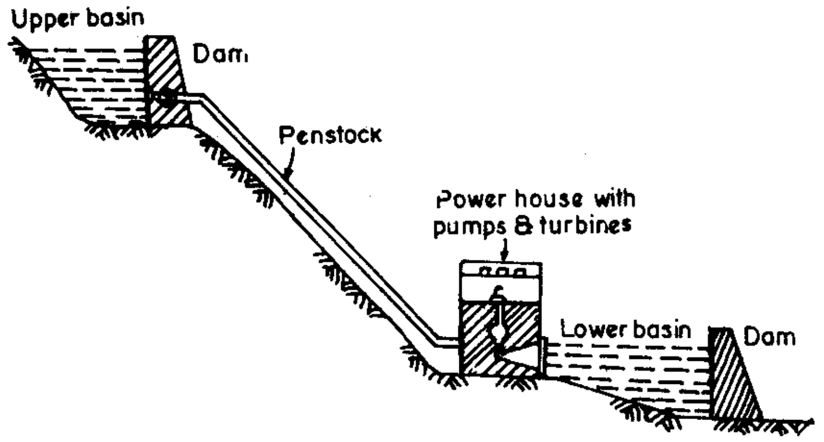
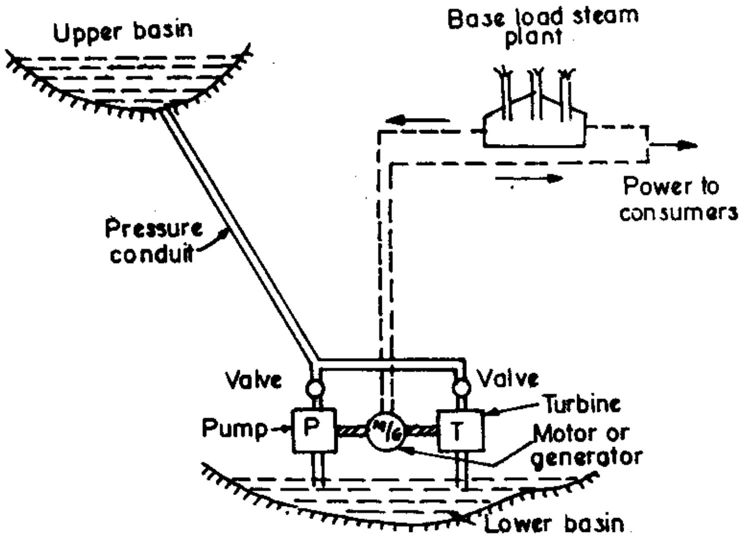


Fig. 33.8. Arrangement of different components of pump storage hydro-electric power plant.



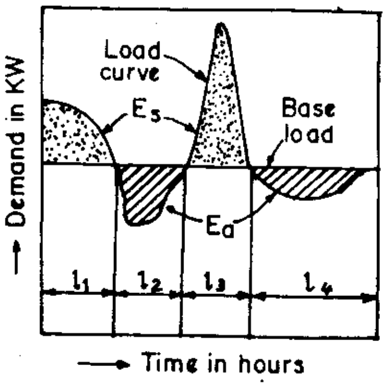


Fig. 33.9. Pumped storage power plant for peak load in conjunction with stream plant as base load plant.

Fig. 33.10. Load curve.

The time ($t_2 + t_4$) as shown in Fig. 33.10 is the time used for pumping the water during off-peak period by the pump from lower basin to the upper basin and time ($t_1 + t_3$) is the time during which the water is supplied for generating electricity when peak load occurs.

For ideal condition of interconnected power plant, $E_a.\eta = E_s$

or $$\frac{E_s}{E_a} = \eta.$$

where E_a in kW-hrs and η is overall efficiency of energy conversion.

The total quantity of water pumped by the pump during off-peak period and total quantity of water supplied to the turbine during peak period must be same to maintain equilibrium of the system.

Q_p = Total quantity of water pumped in time ($t_2 + t_4$) hours

Q_p = Also the quantity of water passed through the turbine in time ($t_1 + t_3$) hours

$$\therefore \quad E_a = \frac{Q_p}{(t_2 + t_4)} \cdot \frac{\rho . g . H}{75 \times 3600} \times \frac{1}{\eta_p} \times 0.736\ (t_2 + t_4) \text{ kW-hrs.}$$

$$E_s = \frac{Q_p}{(t_1 + t_3)} \cdot \frac{\rho . H}{75 \times 3600} \times \eta_t \times 0.736\ (t_2 + t_4) \text{ kW-hrs.}$$

$$\therefore \quad \frac{E_q}{E_s} = \frac{1}{\eta_p \eta_t}$$

where η_p and η_t are the efficiencies of pump and turbine respectively.

The common values of η_p and η_t are 0.8 and 0.9.

$$\therefore \quad \frac{E_a}{E_s} = \frac{1}{0.8 \times 0.9} = \frac{1}{0.4} \simeq 1.4.$$

Therefore, per kW-hr energy developed by the water turbine during peak requires nearly 1.4 kW-hr energy to be supplied to the pump during off-peak period.

Generally, the pumping of water from the lower basin to an upper basin is done during the night time and the same stored energy (hydraulic form) is used during peak periods in day time. The time period allowed for pumping may vary from 4 to 10 hours according to the nature of the load curve. The pump used in the system is designed to pump the water Q_a litres in the minimum time allowed for pumping.

The reservoirs in pump storage plants are selected large enough to provide for the plant's operation over the top of the peak load of the system, it is designed to serve. The reservoir capacity that will permit full capacity operation of the plant for 4 to 10 hours is usual.

The reservoir capacity also depends upon the total time base used for plant operation. The size of the reservoir on week basis would be greater than the size of the reservoir on day basis because the pumping will be done only at the week-end (Sunday) if the time base selected is a week.

Economical Justification of Pump Storage Plant. About 1.5 kW-hr energy is required in pumping for each kW-hr energy generated by pump-storage plant. However, the operation is economically justified because of the premium value of peaking power in contrast to the relatively lower value of power used in pumping. Further the pump storage plant in conjunction with thermal power plant can substantially reduce the size of the thermal plant and increase the flexibility to meet emergency requirements.

The economical justification of pump storage plant is proved by giving the following numerical example :

(*A*) Say the required load curve is shown in Fig. 33.11.

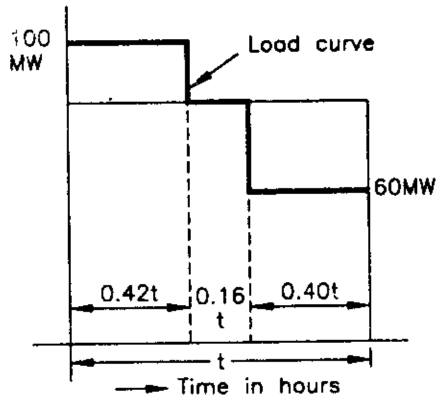


Fig. 33.11. Load cnrve.

If the thermal plant is designed for 100 MW capacity then the total energy generated by the thermal plant

$$= 100 \times 0.42t + 84 \times 0.16t + 60 \times 0.4t$$
$$= 42t + 13.44t + 24t$$
$$= 79.44t \text{ MW-hrs}$$

and the total energy supplied to the plant in form of heat

$$= \frac{100 \times 0.42t}{0.4} + \frac{84 \times 0.16t}{0.35} + \frac{60 \times 0.4t}{0.3} = 105t + 38.4t + 80t$$
$$= 223.4t \text{ MW-hrs.}$$

where 0.4, 0.35 and 0.3 are the thermal efficiencies of the thermal plant when working at 100%, 84% and 60% of full load.

Therefore, the overall efficiency of the plant

$$= \frac{\text{Total output}}{\text{Total input}} = \frac{79.44t}{223.4t} = 0.358 = 35.8\%.$$

Instead of having a thermal plant of 100 MW capacity, the thermal plant is designed for 84 MW capacity and inter-connected with pump storage system allows to work at full load of 84 MW throughout the period. During the off-peak period the extra thermal energy of thermal plant can be used for pumping the water and the same water is used to generate the power during peak period. The total thermal input to the thermal plant in this case as it is working at full load throughout the period

$$= \frac{84 \times t}{0.4} = 210t \text{ MW-hrs.}$$

where 0.4 is the full load thermal efficiency.

The total output = output of thermal + output of pump storage plant

$$= 84 \times 0.6t + 60 \times 0.4t + [(84 - 60) \times 0.4t] \times 0.7$$

$$= 50.4t + 24t + 6.72t = 81.12t \text{ MW-hrs.}$$

where 0.7 is the overall efficiency of the pump storage plant. The underlined term indicates the power stored using extra energy of thermal plant during off-peak period stored in form of pump storage plant.

∴ Overall efficiency of the combined plants (thermal + pump storage)

$$= \frac{\text{Total output}}{\text{Total input}} = \frac{81.12t}{210t} = 0.387 = 38.7\%.$$

This numerical example shows that the inter-connection of pump-storage plant with thermal plant increases the overall efficiency and decreases the capacity of the thermal plant needed and gives the better response to the peak load variations. The working of pump-storage plant with run-of-river plant also helps to increase the economical working of combined system. In run of river plant, the energy generated from surplus water during off-peak period is used to pump the water in pump storage plant and same is used during peak period.

Mixed Type Pump Storage Plant. The site concerning the topography and geology is favourable for high head reservoir pump storage plant but there is not enough water from the catchment area for filling the reservoir and if the water course approaches the reservoir in the lower valley, the water is pumped into the reservoir from the lower valley reservoir against a static head of H_1 and the same amount of water is passed through the power station with a higher head H_2 as shown in Fig. 33.12. Such arrangement is known as mixed type pump storage plant.

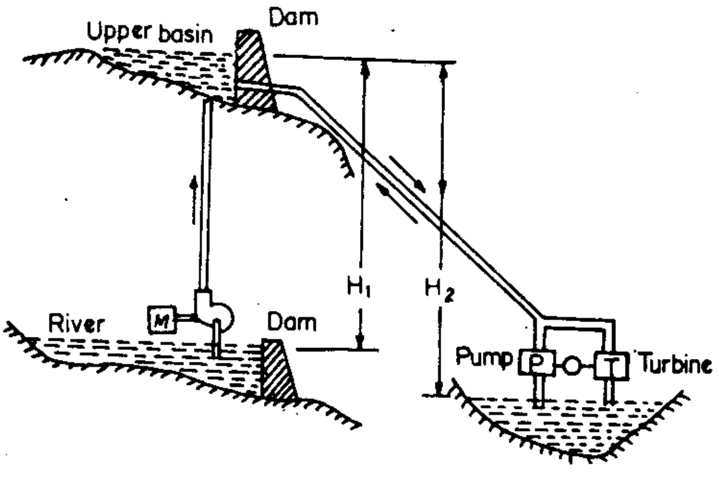


Fig. 33.12. Mixed type pumped storage plant.

Underground Pumped Storage Plants

In many cases, the capacities of the existing conventional hydro-electric facilities with reasonable heads and adequate storage can be increased substantially by constructing lower pool after bays and by installing some reversible pump/turbines. This type of combined development usually has some advantages in flexibility of operation because of large upper reservoirs that are normally available.

A strong trend towards underground pumped storage has been developing over the past 20 years, influenced by the deep submergence requirements of high-head reversible pump/turbines and by improved excavation methods and construction techniques. Underground hydrostorage should be considered where construction of two open reservoirs is not topographically feasible.

A conceptual layout of a pumped storage plant using an underground cavern for lower pool is shown in Fig. 33.13.

Increases in operating, maintenance, and fossil-fuel cost are particularly significant when a utility must consider its future generating capacities, and, although hydro may not have been considered competitive a few years ago, a re-examination of these variable costs may now lead to some new and different conclusions.

Any analysis of the annual cost of a typical large hydroelectric facility will show the most important component to be fixed charges : return on equity, interest on capital, depreciation, federal and state income taxes, and insurance. All of these are a direct function of the initial capital costs ; therefore, they do not vary during the life of a plant because they are not subject to inflation. Moreover, the only variable costs (operating and maintenance) for a large modern hydro plant—one with remote control and/or automation of the entire station—are less than 20% of the total costs. Therefore, hydro plants produce electricity at costs that are almost inflation-free.

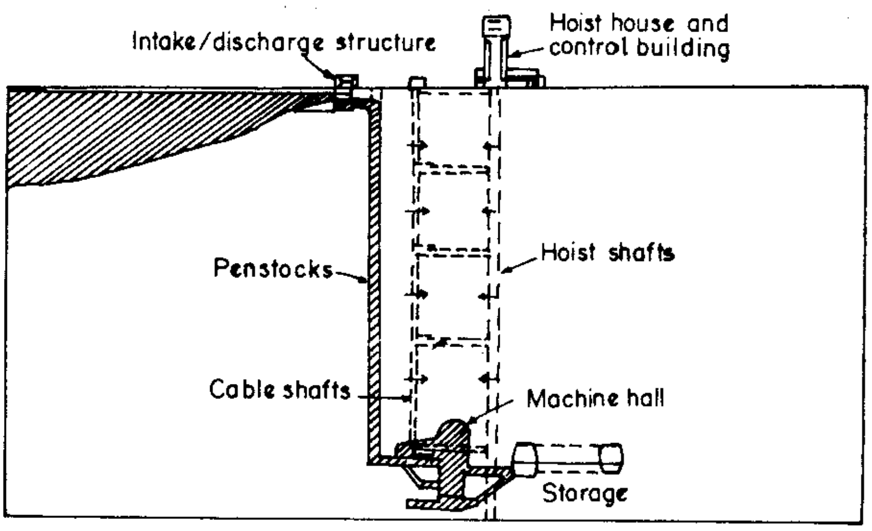


Fig. 33.13. Underground pump storage plant.

Machines for pump storage plant. The pump storage plants comprise normal turbo-generator with the addition of centrifugal pump. The centrifugal pump may be either coupled directly to the turbo-generator in which case, during pumping cycle, the generator is used as motor to drive the pump or it may be an independent unit driven by separate motor.

The early pumped storage plants consisted of a synchronous generator set capable of serving as a synchronous motor with the turbine and pump units mounted on a common shaft as shown in Fig. 33.12. Couplings were provided so as to enable the turbine to be disconnected and thereby eliminate turbine losses during pumping.

In modern designs, the turbine and pump units are combined in a single reversible machine. This arrangement allows the capital cost of the machine and power-house to be reduced substantially.

The first reversible hydraulic machine of the world was installed in 1931 at Baldeney Power Station in Germany. The most remarkable unit of this type was used for pump storage plant at Himassee Dam, Tennessee built in 1957 with a discharge capacity of 110 m^3/sec against a delivery head of 63 metres. The greatest capacity machine of this type is installed at the pumped storage plant Cornwass in USA with 290 MW capacity where the pump turbine machine operates against the head of 350 metres.

Vianden in Luxemburg with a total of 1100 MW peak load power, working on the German network is considered one of the biggest pump storage plants in the world where reversible pump-turbines for heads of 1200 m have been built.

The reversible hydraulic machine operates as turbine when revolving in one direction and as a pump when rotates in the opposite direction. With reversible hydraulic machines, no continuous change-over from one operation to other is possible. The machine set must be brought to complete standstill for every change-over. That means, the beginning of covering the peak load demand will be later than with separated hydraulic machines.

Advantages and Disadvantages of Pump Storage Systems

(1) The complementary nature of pumped storage plant to the thermal plant capacity and the possibilities of using storage sites which would not be economical for hydropower alone, have made pumped storage schemes attractive to the power utilities.

(2) By adopting pump-storage-plant in conjunction with thermal plant reduces the capacity of the thermal plant (used as base load plant) and allowed the thermal plant to operate at almost 100% load factor. It also reduces the start-stop time of thermal plants. This method is more economical than conventional particularly when an incremental cost of hydro-plant is comparatively low and cost of imported fuel is very high.

(3) The pump storage plants can be constructed near load centres more easily than conventional hydro or thermal plant.

(4) Pumped storage plants are unique among all the hydro-power plants as no flowing water supply is required. Once the head or tail pond is filled, then only inflow required is to compensate for evaporation and seepage losses.

(5) Pump storage plant has one more notable advantage over conventional hydro-electric installations. In latter type, if the reservoir level goes too low, the firm capacity is sacrificed, whereas in pump storage plant under such condition, the firm capacity is maintained by additional off-peak pumping.

(6) The cost of electricity during high demand period is much more than that during off-peak periods. Thus pumping the water back, the potential for high cost energy is increased at the cost of low value energy.

(7) By seasonal storage through pumping, the stream flow in other rivers could be used which would otherwise run to waste.

(8) Since the storage is usually on a daily or at the most weekly basis therefore the size of the reservoirs required is only a fraction of that required for conventional hydro-plants where seasonal storage has to be provided.

(9) Its capacity is not controlled or limited by river flow and seasonal variations in the flow.

(10) By constructing a pumped storage plant nearby the nuclear or thermal plant and using one of its reservoirs for cooling the thermal units, nearly $40 million will be saved on cooling cost of nuclear or thermal plant. In addition to this, the proximity of the two stations is valuable not only because the necessity to build cooling towers for the thermal or nuclear plant is avoided, but also because it facilitates the transfer of power to the pumped storage plant during off-peak hours. The short transmission lines required will keep losses to a minimum and of course will cost less to erect than those between plants separated by the normally much greater distances.

(11) Completely static excitation systems are more desirable for reversible generator/motor sets. They have several advantages, particularly where synchronous or semi-synchronous starting is used because full excitation is always available at any speed. The high response ratio obtained with this excitation system tends towards increased system stability. The cost is also reduced as compared to conventional rotating exciters. A system successfully used is at Arizona pumped storage plant of 47 MW reversible unit.

(12) As with conventional hydro units, pump storage plants also have a much lower forced-outage rate than do steam-generating units. The average availability at the Ludington pump storage plant (six 312 MW units) has been 95% since it went into service in 1973 is a specific example.

(13) An additional circumstance in favour of pumped storage system is that, if an emergency develops on system while the hydro units are in the pumping mode, this load can be shed quickly, and the hydro units can be brought back on line in the generating mode to meet system demand. For shifting from no load to full load ; a thermal power station needs nearly 30 to 60 minutes where the hydro plant requires hardly 20 to 60 seconds for this operation. A large number of steam generator units are necessary to fulfill the same task as one hydro-electric peak load station is able to do this. Therefore machines of pumped storage stations are also used for regulating purposes.

(14) Further the reserves of thermal plants consume appreciable amounts of energy because of necessity for keeping boilers warm. Whereas the pump storage plants do not require any additional energy to keep them ready for service. Because of their ability to pick up load almost instantly, they are also used as emergency reserve stations in the power supply system.

(15) In a combination of thermal as base load and pump storage as peak load, the transmission requirements are also reduced which should have increased if these plants were constructed at widely separately locations.

Every pump storage scheme suffers from the economic disadvantage that a duel conversion of energy is required. Another disadvantage is, rather high heads are required, the minimum being 200 metres.

Pumped storage schemes have proved technologically the most attractive. Since 1965, a number of large pump storage installations, having unit rating of 400 MW capacity have been developed mostly in USA, Western Europe and Russia. India has not lagged behind. The 6 × 200 MW capacity Reversible Francis turbine sets at the ongoing Sardar Sarover Hydro-Electric Scheme on Narmada river in Gujarat is the largest pumped storage development in India at present. The 150 MW Bhira pumped storage unit-I of Tata Electric CO. which is under construction, promises to be one of the most sophisticated systems. Similar large plants like Bhira Unit-II, Bhivpuri-Unit-I at Khopoli are planned for future. A 12 MW small unit is working for many years at Jayakwadi Irrigation Project in Maharashtra near Aurangabad.

The Tamil Nadu Electricity Board proposes to set up a 400 MW power plant at Kadamparai in Coimbatore district based on pumped-water storage, at a cost of about Rs. 73.5 crore. The project, for which approval has been accorded, is the first of its kind in the country. The begin with the power station will have two units of 100 MW each, and two more such units will be added in due course. The preliminary work on the first two units on civil works has been already undertaken. Andhra Pradesh Government also proposes to have one at Nagarjuna Sagar.

33.6. COMPRESSED AIR-STORAGE PLANTS

***Energy**—If you can't use it, store it. The philosophy of storing energy during off-peak periods for use during times of peak demand is not new. But, its popularity has increased as high prices and limited supplies of petroleum and natural gas have forced electric utilities to look for alternate sources of primary energy. Use of new storage concepts could save utilities as many as 1 million bbl of oil per day according to estimates of the U.S. Department of Energy. Peaking units presently in use, like gas turbines and diesel engines, consume nearly 2 million bbl of oil daily.*

The common methods of energy storage are pump storages and compressed air plants. The pump storage is in use for many years and has been successfully used in many countries of the world. The compressed air plants are in childhood stage as they are not so commonly used. The technology involved is not yet developed as the parameters controlling the system are many more. Therefore, before selecting such plants, lot of site investigations and laboratory work are necessary.

Geological conditions do not always permit the installation of pump storage plants. Consequently in flat regions, the compressed air storage plant may be a suitable alternative. Instead of pumping the water to the upper reservoir, air is compressed to high pressure and stored in an air-tight underground cavern. When peak load energy is required ; this air is heated up and expanded in gas turbine plant where the gas turbine drives generator.

Presently, the peak power is generated using gas turbines, special steam turbines, water turbines and, in a few places, pump storage plants. Of these plants, only pumped storage plant has the ability of storing off-peak power for peak load power. But this desirable property is also possessed by an air-storage power plant equipped with a gas turbine which can produce power by burning fuel in the air as it is withdrawn from the storage. Furthermore, it can produce continuous power when operated as a conventional gas turbine.

A unique method of using a conventional gas turbine to store compressed air underground during off-peak period of combined (steam + peak load plant) system and later use the stored air to drive the generator during the peak-power demand was described by Dr. H.K.A. Olsson who claimed that the cost of such plant would be about 70% of that of a conventional gas turbine installation.

Working of the Plant. The arrangement of the plant is shown in Fig. 33.14. A unique feature of this arrangement is a combined Generator-Motor unit (similar to pump-turbine unit in pump storage plant) is incorporated which works as a motor or generator. The outlet terminals of this generator-motor unit are connected to the main grid of the supply system.

(*a*) During off-peak periods, the turbine will be disconnected with the help of clutch (2) and the compressors are driven by the generator-motor set which works as a motor taking its power from grid. The compressed air during this period is stored in a large cavern.

(*b*) During the peak load periods, the compressor is disconnected from the system with the help of clutch (1) and the compressed air stored in cavern is supplied to the gas turbine through combustion chamber as shown in figure. The entire output of the turbine will be used to generate the electricity. The generator-motor unit during this period works as generator and supplies the power to the main grid.

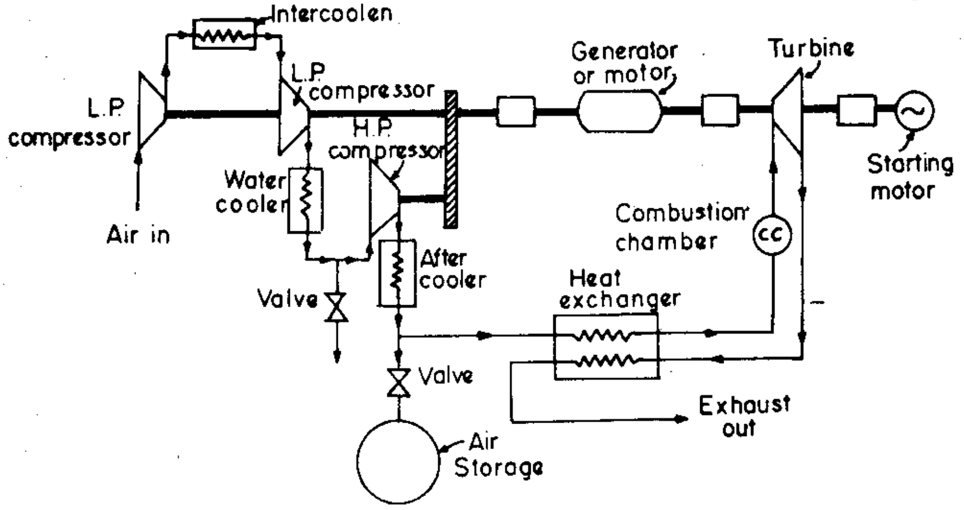


Fig. 33.14. General arrangement of air-storage power plant.

(*c*) The same system also can be used as a conventional gas turbine plant generating power continuously and supplying to the main grid. During this mode of operation, the compressed air from the compressor is taken to the gas turbine without passing to the air-storage cavern and the power generated will be supplied to the main grid. The supply of power during this mode of operation will be hardly 30% of the power supplied during the mode of operation described in (*b*) because most of the power generated would be used to run the compressor which is not the case when plant is running in the mode (*b*). The arrangement of different components of this system is shown in Fig. 33.15.

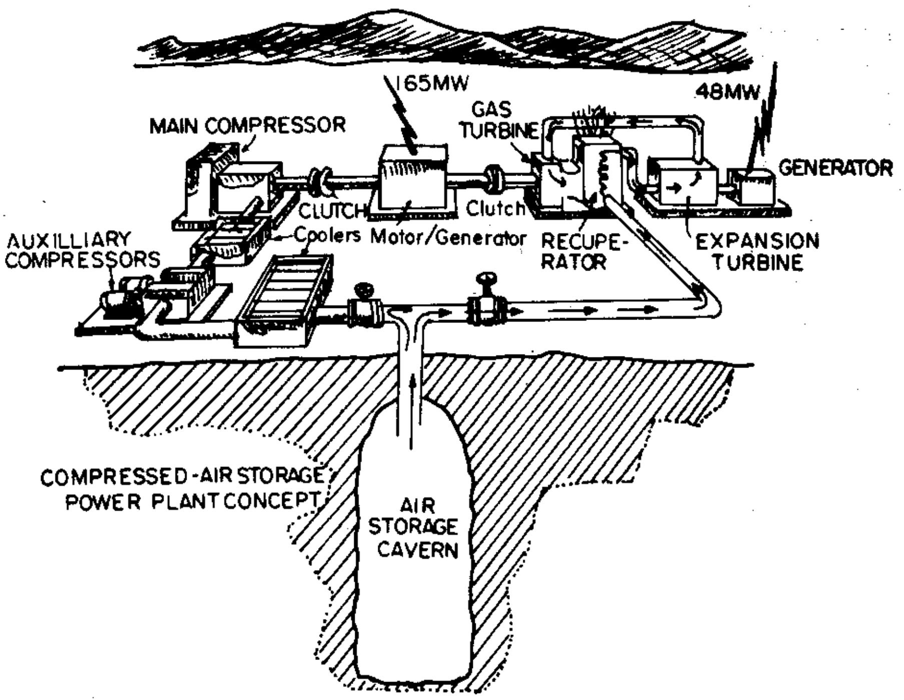


Fig. 33.15. Arrangement of the components of air-storage plant.

A rural electric cooperative in Illinois has purchased the first compressed air energy storage plant in USA, first of its kind. Sulzer Ltd. is going to provide 160 MW compressor train for the plant.

The compressor train includes three of the largest compressors. The low pressure stage is the axile design with 11-stages, the medium is the centrifugal compressor and high pressure case is the barrel compressor which is now in operation at very high pressure. The compressed air storage plant is likely to be commissioned in 1986.

Air-Storage Systems

(*a*) **Storage with Variable Pressure**

In this system of storing the air, the volume of the storage reservoir remains constant and the pressure changes during the charging and discharging processes. This is suitable for its simplicity of the installation. To operate the gas turbine at constant pressure, the air is throttled from its maximum variable pressure to selected constant inlet pressure of the gas turbine. This throttling being an irreversible process represents a certain loss of energy.

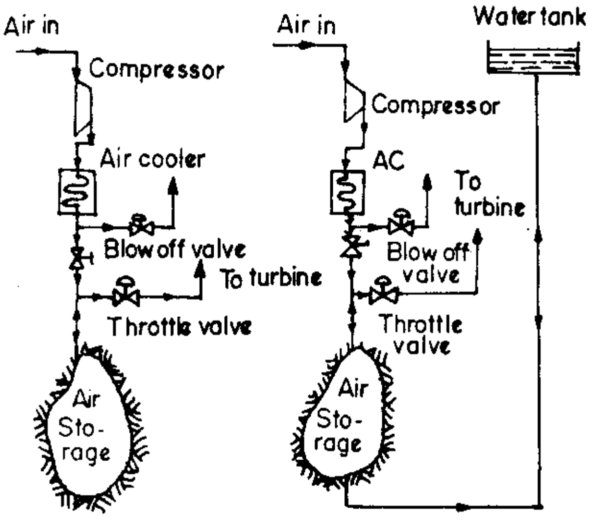
This storage system is used at Huntorf plant in Germany operating from 1978 onwards which is first plant in the world of its type.

(*b*) **Storage with Constant Pressure**

The simplest way of maintaining the reservoir pressure constant is to use the static pressure of an upper water reservoir placed on the ground surface. The cavity excavated in salt deposit cannot be used and cavities made in aquifers or anhydrite rocks are only preferable. The tightness of the cavity can be accomplished by plastic lining.

With a constant pressure reservoir, the storage volume will be smaller than the one required with variable pressure (only 25%), since practically the whole mass of the stored air can be used and no throttling is necessary. The cost of this system is much higher, compensating to a large extent, the disadvantage of lower efficiency of a sliding pressure. With a constant pressure reservoir, the storage volume will be smaller than the one required with a variable pressure since the whole mass of stored air can be used and no throttling necessary. The storage volume is about four times smaller. However, the costs of a constant pressure system are much higher, compensating to a large extent the disadvantage of the lower efficiency of a variable pressure.

There is a further disadvantage related to the constant pressure system. A large quantity of air will be dissolved at high pressure in the water which could be even saturated. During the loading period, the water is displaced into the upper water reservoir by the compressed air. The static pressure will diminish, calling for more air separation and leading to an unstable situation. This phenomenon is yet to be studied. Both the systems are shown in Fig. 33.16.

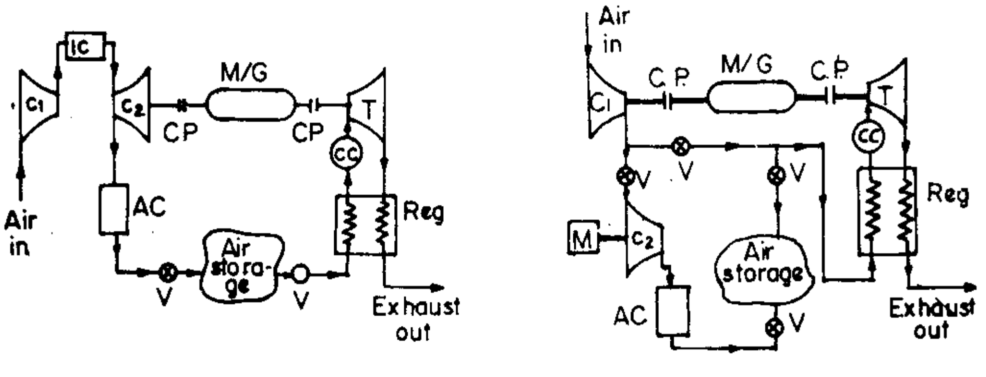


(*a*) Variable pressure air storage. (*b*) Constant pressure air storage.

Fig. 33.16.

Arrangements of the Equipments of Air Storage Plants. An arrangement of equipments of basic compressed air plant can be varied to suit the needs of the air storage volume. Four possible configurations are shown in Figs. 33.17 (*a*) to 33.17 (*d*).

(*a*) This configuration would be used where the turbine pressure is moderate but the air storage pressure losses are high. In this case, the air is stored at a pressure somewhat greater than the turbine inlet pressure. The inter-cooler provided between the two compressors will reduce the power requirement and inter-cooler provided after the H.P. compressor will reduce the storage volume required.



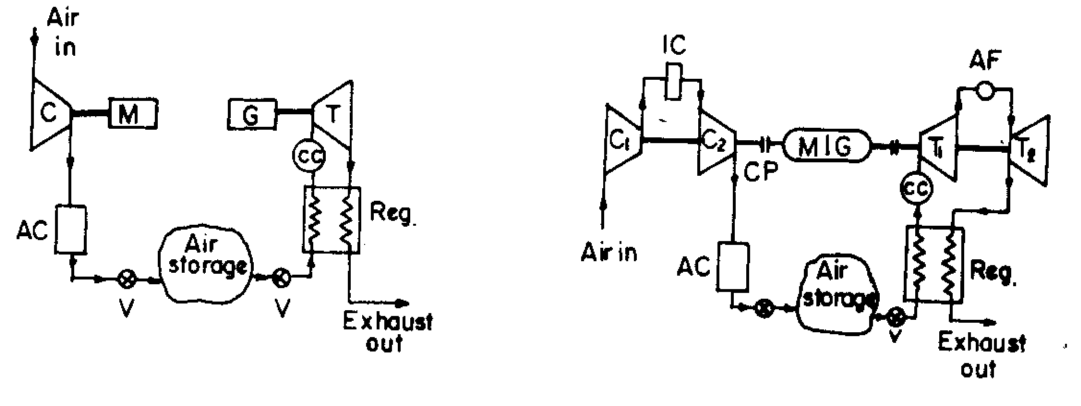
(*a*) (*b*)

Fig. 33.17.

(*b*) This configuration will be suitable for a plant with small pressure losses due to air storage. In this system, the second stage compressor is driven by a separate motor. In a long term emergency, the plant could work as a conventional gas turbine plant continuously when the air in the storage is exhausted. Net output would be decreased because major part of the turbine power is used to drive the compressor.

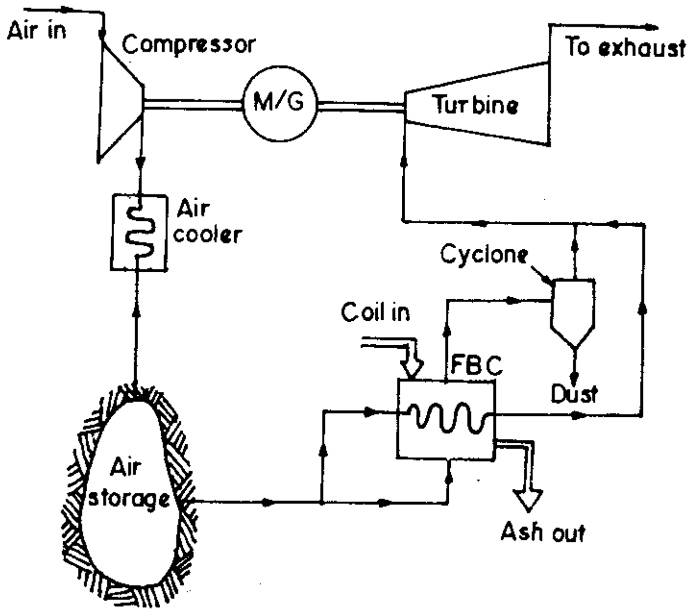
This cycle of operation is proposed for two 440 MW units for Soyland Power Corporation of Illinois.

(*c*) This configuration is a special system which would be applicable if the load curve shows short periods of peak demand and long overnight of surplus base plant capacity. The compressor size will be small in relation to turbine size and its power demand will be low. The compressor is driven by its own motor, directly connected while the generator is directly connected to the turbine.



(*c*) (*d*)

C = Compressor, *IC* = Inter-cooler, *AC* = After-cooler, *V* = Valve, *Reg* = Regenerator, *C.C.* = Combustion chamber
C.P = Coupling, *T* = Turbine, *M* = Motor, *G* = Generator,
M/G = Motor/Generator, *AF* = After-burner.



(*e*) Compressed air system with Fluidized Bed Combustion System (FBC)

Fig. 33.17. Different type arrangement of compressed air plant.

(*d*) This configuration is preferred for high pressure air storage. The studies have shown that this system would be more economical for mixed air storage utilities as a given mass of stored air requires less storage volume and therefore mining could be kept to a minimimum.

Air Storage System with FBC

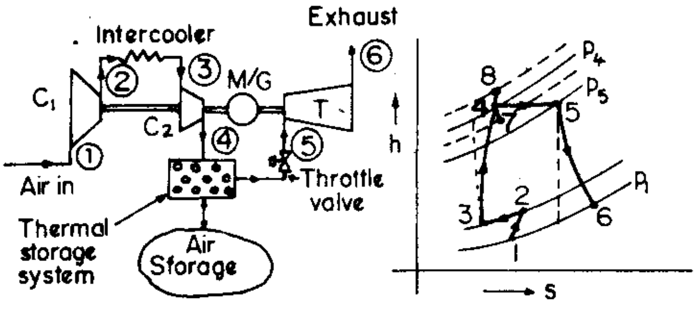
(*e*) To utilize the coal which is available in plenty instead of oil to run the gas turbine, a fluidized bed combustion (FBC) system with air storage is also proposed. A pressurised FBC system combined with compressed air storage system is shown in Fig. 33.17 (*e*).

(*f*) **Adiabatic Compressed Air-Storage System**

Adiabatic compression of air to 50 bar increases its temperature to about 650 °C. Transfer of this thermal energy to a storage bed would permit the air to be heated again during the power generation cycle.

A fully adiabatic system is shown in Fig. 33.18 (*a*) and its corresponding h-s diagram is shown in Fig. 33.18 (*b*).

Iron-pebbles, crushed granites or Denstone can be used as heat absorbing materials in thermal storage system. These materials are lower in cost than magnesite or alumina which are commonly used in small thermal storage applications. This type of air storage plant is interesting from environmental point of view. In the above system, it is assumed that the whole heat of air is given to pebbles during charging and the same is reabsorbed by the air during discharging period.



(*a*) (*b*)

7—8→Variable pressure in cavern, p_7→Pressure before charging, p_8→Pressure after charging

Fig. 33.18.

A hybrid adiabatic system is shown in Fig. 33.19. In this design, operation flexibility and the turbine output are both enhanced by topping to the operating temperatures of the basic oil fired cycle.

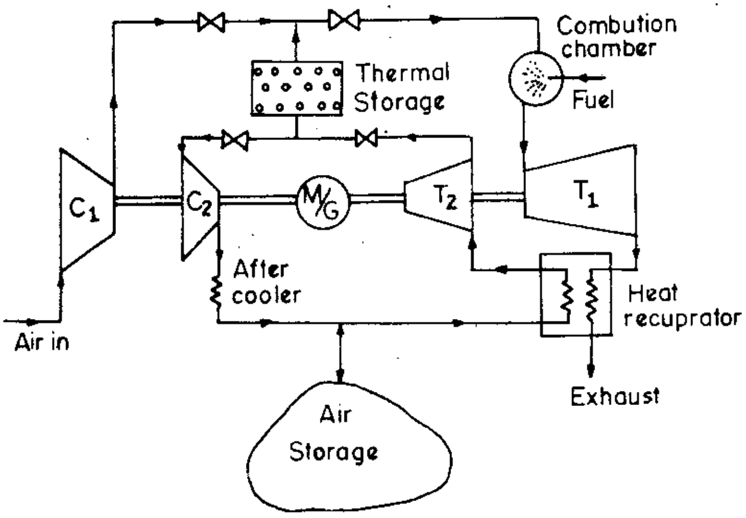


Fig. 33.19. Hybrid adiabatic system.

Analysis of Compressed Air-Storage System

E_m = Energy supplied to motor per kWhe generated

m_f = Fuel supplied to gas turbine per kWhe generated (kWht) equivalent

η_t = Thermal efficiency of thermal base load plant

$\eta_{overall}$ = Overall efficiency of the combined air-storage and thermal plant

η_{as} = Efficiency of the air storage system

$$\therefore \quad \eta_t = \frac{\text{Output}}{\text{Input}} = \frac{1}{\frac{E_m}{\eta_t} + m_f} \quad \eta_{as} = \frac{1}{m_f \eta_t + E_m}$$

The ratio of the heat rejected to the surrounding to the generated energy is given by

$$R = \frac{1 - \eta_{overall}}{\eta_{overall}}$$

Various cases are *analysed* for $\eta_t = 0.38$ and the results are tabulated as below. The electrical energy absorbed by the motor for each kWhe, electric generated E_m is smaller than unity only if an additional energy is supplied to the system in the form of fossil fuel in the combustion chamber. This valve is smaller if the reservoir is operating at constant pressure avoiding the throttling losses inherent to the variable pressure system.

Type of Network	*Type of storage scheme*	E_m	m_f	η_{as}	$\eta_{overall}$	R
	Variable pressure no recovery of exhaust heat	0.805	1.63	0.70	0.267	2.74
Fossile fuel	Variable pressure exhaust heat recovery	0.805	1.21	0.79	0.300	2.33
$\eta_t = 0.38$	Constant pressure exhaust heat recovery	0.715	1.21	0.85	0.323	2.09
	Adiabatic system	1.45	—	0.69	0.262	2.82
	Pump storage	1.25	—	0.80	0.304	2.29

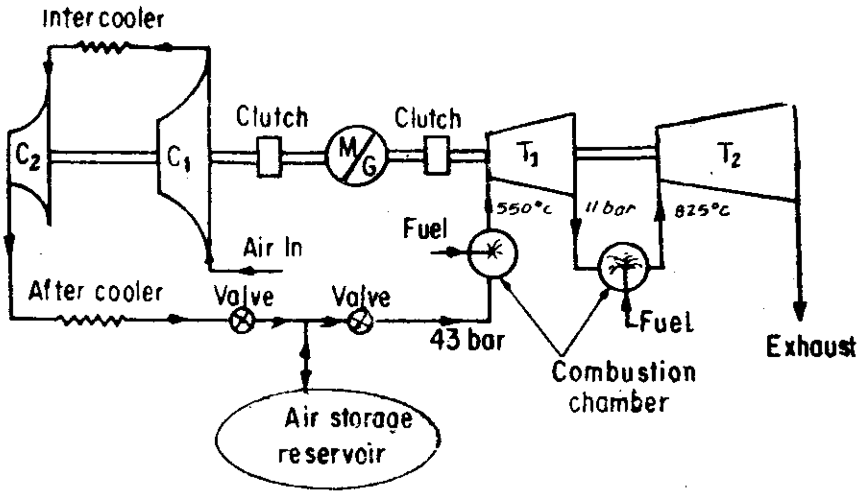


Fig. 33.20.

Staged combustion may result in longer flames which, if not properly controlled, can lead to flame

If exhaust heat is recovered, a substantial fuel saving can be achieved. This influence is shown by the lower valve of m_f, giving the kWht of the fuel supplied to the combustion chamber, referred to one kWhe generated. A fuel saving of some 26% has been admitted.

Compared with gas turbine plant as a peak load plant, the overall η of this system is smaller. However, the great advantage of a peak load storage plant is that, it contributes to the equilibrium of a large network and generates expensive peak energy, while absorbing cheaper off-peak energy.

A further advantage of the air storage system is that the power delivered during the generating cycle is far greater than that available from a gas turbine of same size, as 60% of the power otherwise necessary to drive the compressor in a conventional gas turbine is available as additional shaft power for generation.

Huntorf-Air Storage System in West Germany

This is the first air storage type peak load plant in the world which is successfully operating from 1978 onwards. The air reservoir consists of two caverns having a total capacity of about 300×10^3 m^3 made by the extraction of rock salt from the ground, leaching a salt dome at a depth of 650 to 800 m below the earth's surface. The pressure in the reservoir varies between 75 bar to 45 bar.

The arrangement of the basic components of the system is shown in Fig. 33.21. At peak power demands, the compressed air in the caverns is released for use in the combustion cycle of a two-stage turbine. When surplus power is generated, it feeds to the generator which acts as a motor and drives air compressor. The compressor compresses the air and forces it into the 150 m high caverns.

During peak demands, the compressed air is released. The pressure is reduced from 75 bar to 45 bar and supplied to high pressure combustion chamber of the turbine where natural gas is supplied as fuel. The combustion gases pass through H.P. turbine which is coupled to the generator. Upon leaving the high pressure turbine, the gases are further heated by natural gas in the second combustion chamber before going to the L.P. turbine. The gases coming out of L.P. turbine at atmospheric pressure are discharged to atmosphere through silencers and stack.

The method of controlling the output is different from the one used for conventional power gas turbines, for which part load is adjusted by the inlet temperature. In the case of air storage plants, the flow rate of air is matched to the required output and inlet temperature of the high pressure turbine, together with the exhaust temperature of the low pressure turbine. Part load efficiency is better with this regulation.

The control of the plant is done from Hamburg, 150 km away from the plant. Eleven minutes after receiving the command to start, the plant is able to feed its full output automatically into the network.

The details of the plant are given below :

Capacity—290 MW, Compressor power requirement—60 MW

Storage space—300×10^3 m^3 (between 650 and 800 m depth)

Pressure variation—75 bar to 45 bar

Loading period—8 hrs and generation period—2 hrs.

Air flow rate—417 kg/sec

RPM of motor-generator—3000

Heat consumption—5800 kJ/kWe and 4300 kJ/kWe (with heat recuperator)

The Huntorf air storage plant has opened the way to an interesting and rational solution to diminish the load fluctuations of large interconnected electrical networks. This pioneer installation has demonstrated the high availability of such system and it is hoped that such system will be used in future.

The second air storage plant is still in planning stage. Soyland Power Co-operative in U.S. is planning to construct 220 MW plant of this type which will be the first compressed air storage plant in USA.

Optimum Cycle Pressure Ratio. The cavern volume required for a certain mass flow of compressed air is inversely proportional to the air pressure and proportional to the required number of hours of peak

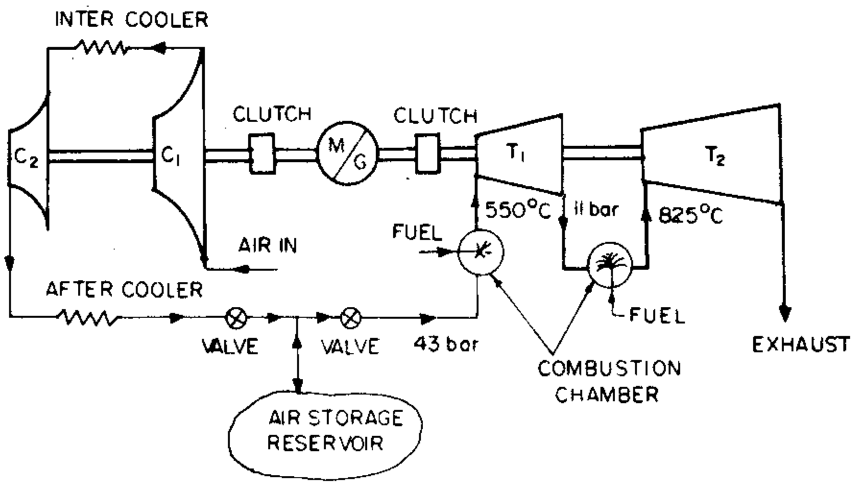


Fig. 33.2..

load operation per day. A higher air pressure requires a deeper cavern (10 m/bar). The cost per unit volume of cavern will increase slightly with increasing depth. However, the total volume needed will decrease, and the specific cost per kW will reach a minimum at a storage pressure of about 40 bar. This is shown in Fig. 33.22, where the specific cost of the above-ground equipment and total specific cost are also given. The costs are given as the percentage of specific cost of a conventional gas turbine installation, Rs. 600/kW on the basis of the price in 1970.

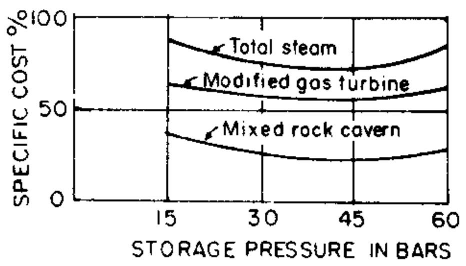


Fig. 33.22. Storage pressure *versus* specific cost.

Air Reservoirs. The size of the air reservoir is determined by the amount of energy to be stored, the size of the compressor can also be varied according to the required length of time during which it fills the reservoir. The volume of the reservoir might perhaps be sized to run the turbine for one hour at full load, while the compressor is designed to refill the container in four hours. In this case, the charging ratio is 1 : 4 because the compressor is sized for only 1/4 of the turbine's. Hence it is evident that the air storage gas turbine can be designed for various charging ratios (1 : 1, 1 : 2, 1 : 3 and so on) according to the requirements. The capacity of the reservoir has prominent effect on the charging period required and the compressor size. The volume of the air reservoir and hence its installation cost is governed not only by the number of full load turbine hours but also by the pressure and temperature of the stored air.

If the pressure during the charging and discharging process changes, then the electrical output will also vary. But this would not appeal to the operator owing to the load conditions in his distribution network and so the turbine is run at a constant inlet pressure in order to maintain a constant electrical output.

The air reservoirs which are used for air-storage type peak plants are classified mainly in two groups.

(1) Man-made Caverns. Artificial caverns are best suited for construction in hill side and are lined to prevent air leakage. This type of reservoir can be created by mining methods in the underground rock formation. This is done by sinking a shaft 500 m deep and 6 m in diameter. At this depth, tunneling machine then bores a horizontal tunnel of 5.5 m in diameter which is used to store air.

By placing a water tank above the cavern as shown in Fig. 33.23 and connecting tank and cavern by a shaft, the pressure in the cavern can be held constant during discharge, since the air leaving is continuously replaced by inflowing water. With this type of air storage design, the water tank must be situated at such a level above the cavern that the head of the water in the shaft and the pressure in the tank are in equilibrium. If the air pressure in the cavern is 60 bar, the column of the water in the interconnecting shaft must be 600 m high. As alternative to a water column whose head corresponds to the air cavern pressure, a pump can be used to transfer the required water quantity into the cavern during the discharge period. In such caverns, the air pressure in storage remains relatively constant regardless of the column of air in the cavity and, therefore, turbine inlet pressure remains stable as the air is drained off from the storage. However, water compensation requires a surface water reservoir and is thus more costly.

With constant pressure reservoirs, the storage volume required is considerably smaller than with sliding type because virtually the whole mass of air can be used to do the work in the turbine and there are no additional throttling losses. To run a 290 MW capacity plant, a full load of one hour requires a constant pressure reservoir of 30,000 m^3 which is about a quarter of the capacity needed with the sliding pressure reservoir. Because of this, the higher construction cost per m^3 of storage capacity for a constant pressure reservoir can be almost balanced out and the cost per installed kW is roughly the same as for sliding pressure reservoir.

Mined hard-rock caverns and caverns formed by nuclear explosions may be made available where conditions permit. The requirement for the latter types of storage is massive rock formations of granite, shale or limestone, all of which are commonly found in many countries near major population centres.

(2) **Natural Caverns.** Solution mined air storage cavity is quite inexpensive to form and are possible to those regions of the country with salt deposits. The main drawback of this storage is that the solubility of salt prohibits the use of water as a means of maintaining constant pressure. Therefore, they must be oversized to maintain relatively constant turbine inlet pressure and this may raise their cost to a level where other storage means become more attractive. The air pressure in a sliding pressure reservoir changes during charging and discharging process, therefore, the pressure in the reservoir is throttled to the turbine inlet pressure. For a generator output of 290 MW and turbine inlet pressure of 46 bar and assuming the pressure in the reservoir varies by 20 bar, one needs a reservoir capacity of about 1,30,000 m^3/hr of full load turbine operation.

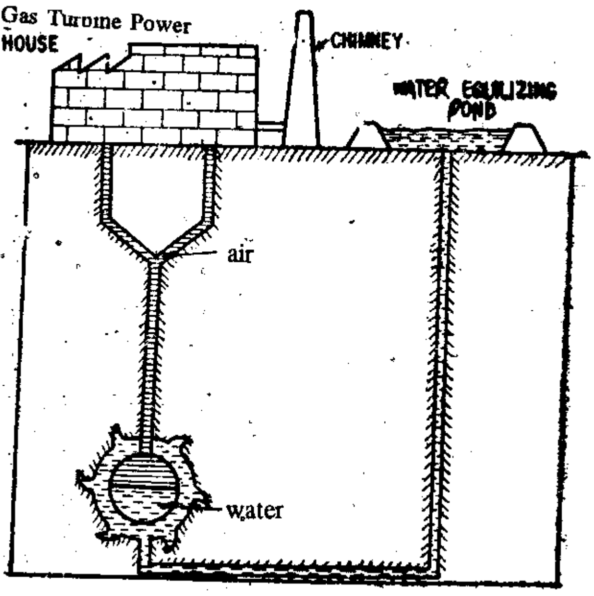


Fig. 33.23. Air Storage Gas Turbine Power Plant with Constant Pressure Reservoir

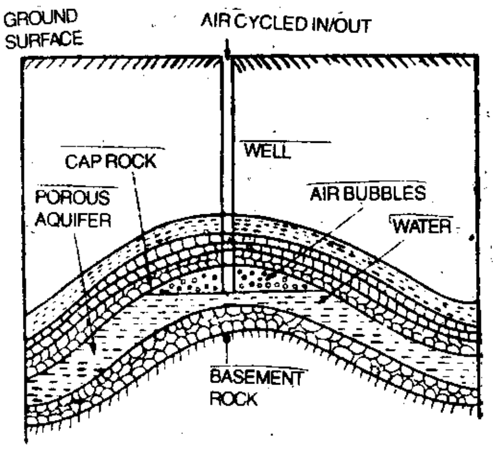


Fig. 33.24. Aquifer Air Storage Systems.

The air entering into the storage may have a temperature of 200° to 300°C which would tend to deform the salt walls. If the after-cooler is used, the system first cost would increase. But more important, the air entering into the storage would be at or near saturation and would tend to pick up salt from the cavity walls. The potential for damage to turbine blading is obvious.

An economical way of obtaining a sliding pressure reservoir consists in leaching brine from underground salt deposits. The process is shown in Fig. 33.25. Two concentric pipes are introduced into a bore-hole. Fresh water pumped through the inner pipe dissolves the salt and becomes saturated with it. The resulting brine is pumped up through the water pipe and, if possible, taken directly to the sea. The shape of the cavity formed in this way is monitored with an echo sounder. The form is controlled with a buffer gas which is of lower specific weight than the brine and does not react with the salt. By varying the level of the brine, it is thus possible to define a zone within which no more salt is dissolved.

(3) Oil and Gas Wells. Depleted oil and gas reservoirs make ideal air storage volumes. Their first cost per unit of storage volume is normally quite low. They have proved closure and are usually of a size adequate for a compressed air storage plant. But they are not necessarily located near the major load centres serviced by large base plants.

(4) Aquifers. Aquifers—naturally occurring porous rock formations—are also suitable for air storage and have been used for natural gas storage for more than 50 years. But, unlike natural gas, compressed air requires daily rather than annual cycling. Air also has twice the viscosity of natural gas, contains O_2 and may have to be stored at elevated temperatures. The areas of investigation include low frequency fatigue of porous media, reservoir material properties, temperature changes, air-water interface movement and geochemical reactions. A natural occurring aquifer is shown in Fig. 33.24.

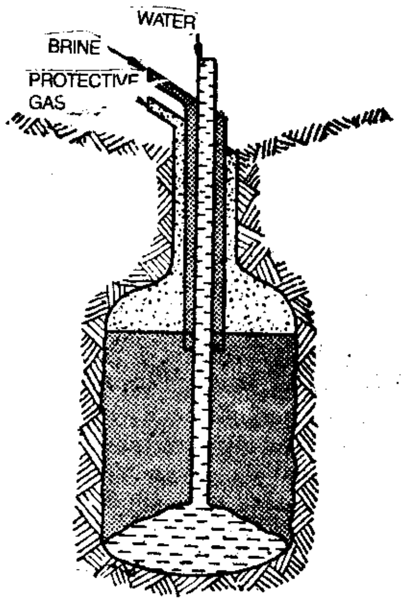


Fig. 33.25. Leaching process for an air reservoir in an underground Salt Deposit.

Starting and Control. Starting and operation of the modified gas turbine system is fully automatic and remotely controlled as is the practice for conventional gas turbine installations.

Normally, the gas turbine is started by compressed air from the cavern. The air is heated by burning fuel in the combustion chamber. When the peak load operation is required, the compressor clutch is disengaged and when compressor or gas turbine operation is required, both clutches are engaged. In case of compressor operation, the turbine will be shut down as soon as the generator is synchronized to the grid.

Some other means of starting is needed when no stored air is available. This situation would normally exist only at the first start-up of the system and would be handled by using small electrically driven screw compressors. When the gas turbine unit is to be used as a conventional gas turbine plant during the cavern construction period, it will be necessary to use an electric starting motor.

Air storage power plant responds very rapidly to load changes. Combustion temperature is kept constant at different loads by the air regulator valve. This valve, as well as the isolator, is electro-hydraulically controlled and is able to respond quickly. This is necessary for overspeed reasons at sudden load drops.

The control system is more complicated than in a conventional gas turbine system due to different modes of operation and control of the different air valves.

Advantages and Limitations of Air Storage System

(1) The air storage plant combines the feature of a pumped storage plant and a gas turbine plant, as it can both transfer energy along the time axis and produce an active output. From 1 kWh off-peak power,

the air storage plant produces 1.3 kWh peak power as compared with 0.76 kWh for a pumped water storage system.

(2) The further advantage of this system over gas turbine is that the power delivered during generating cycle is far greater than the gas turbine as 65% of the power of gas turbine is used to drive the compressor in conventional system.

(3) Three normal modes of operation of the storage power plant are shown in Fig. 33.17 together with a fourth mode where the turbine is operated at part load and the difference in air flow from the compressor and to the combustion chamber is used for filling the air storage. The 19 available hours are enough for 5 hours peak load generation.

(4) For air storage, an excavated cavern gives the widest possible choice in geographic location, to the benefit of lower power transmission and fuel transportation costs.

(5) The plant has a short starting time for unforeseen power requirements and is suitable for remote control. The response in load changes is very rapid and could be used for stabilizing the grid.

(6) An air storage power plant is cheaper than a conventional gas turbine both with respect to fixed and running costs and is generally also cheaper than a pumped storage plant.

(7) Greater premium fuel economy is another outstanding feature of the air storage plant, since the fuel used for the air compression is base plant fuel (coal or nuclear) and all premium fuel goes directly to net output. Consequently, the net heat rate for premium fuel for the compressed air plant can be as 4000 kJ/kWh against the heat rate of 12800 kJ/kWh when the plant works as a conventional gas turbine plant.

(8) Another advantage of this system is that the required volume per unit of energy produced is smaller than the equivalent storage capacity of water storage reservoir.

(9) With respect to the operating advantages, the hydraulic and air storage systems are almost comparable. The time required for going from absorption to energy generation or vice versa is smaller for pump storage plant (2.5 minutes). It is also relatively short for air storage system (11 minutes for Huntorf plant).

When topographical conditions permit, pump storage may be better way of storing electrical energy during off-peak period of base load plants. However, in flat area, where the landscape lacks enough variations in altitude to make pump storage economical, air-storage may be a suitable alternative.

Consideration will only be given to building air storage plant in areas where the local topography precludes the building of hydraulic pumped storage plants but permits the construction of compressed air storage receivers. As compressed air storage plants require water for cooling the compressed air and are only economical if the compressed air temperature within the cavern approximates to the ambient temperature. The amount of air that can be stored in a cavern at a given pressure falls as the air temperature increases. In addition to this, availability of air tight cavern is most essential for the economical working of the plant.

Another interesting concept to take the peak load would combine compressed air and underground pumped-hydro storage techniques. During the off-peak hydro-pumping and air compression cycle, the storage cavern is filled with compressed air, while the water is being evacuated and pumped to the upper reservoir. During the generating mode, water spins the hydro-turbines as it flows by gravity back into the lower cavern. At the same time, the compressed air is evacuated to serve its own generating machinery.

The first plant of its kind is going to be commissioned by the end of this year in Germany.

33.7. STEAM POWER STATIONS AS PEAK LOAD PLANTS

The simplified steam power cycles and old steam plants are still used as peaking stations as they were built long back because the pump storage schemes are hardly a two-decade old whereas air storage systems are yet to be born. This article would discuss the different steam power cycles which are used for peak load purposes.

In finding thermal power station layout for peak load purposes, the interplay between costs of capital and fuel presents a wide range of possibilities. With long operating times, the accounts show high plant efficiency and hence low fuel costs to be the optimum arrangement. But this advantage is paid for with a high capital investment. Conversely, high fuel costs can be acceptable if operating hours are few and plant costs can be reduced. Between these two extremes, there is almost unlimited number of variations on the theme of capital and fuel costs.

Load peaks, according to plan, which can be anticipated from the load diagram, can be taken by the same generating plant, but in addition, by extremely simple steam stations or simple combined cycle plant. For these peak load stations, high speed load variation is essential and short start-up and shut-down times are desirable on economic grounds.

Another possible way of covering peak loads is temporary overloading base-load power stations. This method is used, but with an added output of only 5 to 10% and it is not the real solution to the problem. Most important kinds of power stations used for peak load plants are already discussed. In this article, specially designed steam power plants to take peak loads will be discussed.

The requirements to be met by a steam power station for covering predicted peaks can be summarized as *fast and cheap*. Cheap, because the station is out of service for 3/4 of the time, or more, and fast in order to respond to system load peaks, most of which reach their full height within an hour or so and in general amounts to 25% of the daily maximum load. The need is thus for low plant cost, and high rate of change of load. Fast start-up and shut-down are desirable on economic grounds.

(1) Simple Steam Power Station. The above-mentioned desirable features can be obtained by means of simplified steam power station as less extracting steam points and minimum components as possible. By eliminating reheat and high pressure feed-heating, the steam cycle is made more simple as shown in Fig. 33.26.

The steam conditions are set low so that the walls of the boiler tubes, turbine and piping can be made using low cost ferritic steel.

Instead of using a flue gas heated air heater, a heater fed with steam bled from turbine is used to raise the air temperature to 100°C.

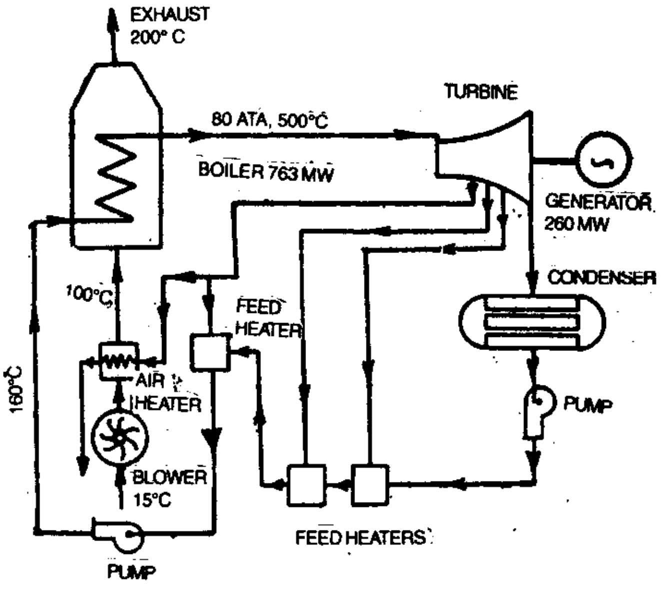


Fig. 33.26. Simple steam plant for peak load.

The fuel used for such plants is either oil or gas (for quick response). For both of these, the response time is much shorter than any kind of coal.

Simplifying the plant means, providing only one of those components which are normally duplicated, such as pumps, blowers, motors, valves, etc. The idea behind this is, there will be time to repair any faulty parts and therefore parts can be easily replaced without waiting for repair. All these measures result in a simple turbine hall and correspondingly compact power station.

Comparing a peak load station of this type with base load shows a reduction of 20 to 30% in plant cost for a 25 to 30% drop in plant efficiency.

Simple Steam Power Station for Peak Load in USA. The demand for peak load in USA is much more than any other country. The peak load stations, which are required to run for only a few hundred hours per year, are even simpler, and hence less costly in construction. This is particularly true with the natural circulation steam generator which receives unheated atmospheric air and has a flue gas temperature of 420°C. The feed water is not heated at all. At 60 bar and 480°C before the turbine, the line steam conditions are extremely low and so the turbine is usually a simple two casing machine without extraction for feed heating purposes. Only isolated examples of such plants exist, with capacities between 100 to 150 MW.

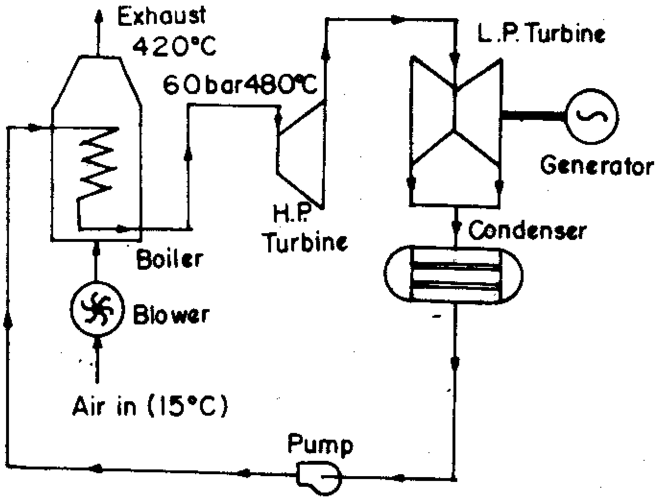


Fig. 33.27. Simple Steam Power Station for Peak Load.

Steam-Gas Power Stations for Peak Loads

(*a*) **Steam-Gas Plant with Waste Heat Boiler.** Using the exhaust gas from gas turbine cycle in a waste heat boiler gives additional output from the steam set amounting to 40 to 50% of the gas turbine rating. This improves the plant efficiency up to 40% as mentioned in chapter No. 25. The exhaust gas temperatures of gas turbines lie between 400 to 500°C depending on turbine type and inlet temperature of the gas and so allow only a low pressure steam process. There is wide range of choice for the steam pressure and temperature, but the mass flow of the steam which can be produced is greater : the lower the steam pressure. The maximum attainable additional output is reached when the product of steam flow and available drop obtainable from

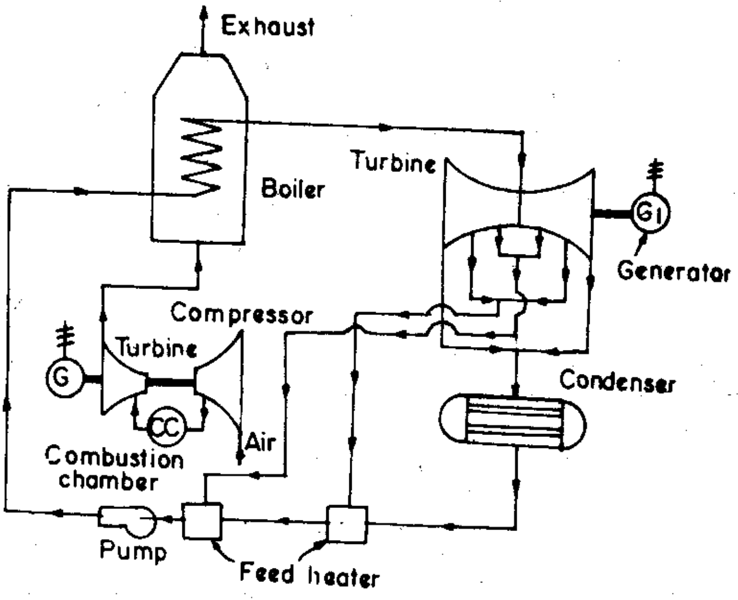


Fig. 33.28. Combined steam/gas plant with waste heat boiler for peak load.

the turbine is itself a maximum. With a '*pinch point*' for the waste heat boilers of, say, 40°C (base-load plants are designed with values of 15 to 20°C), this is the case between 20 and 30 bar. With this kind of plant, *feed heating* with bled steam has no thermodynamic advantage as a higher final feed water temperature raises the flue gas temperature and so increases stack losses.

(*b*) **Steam-Gas Plant with Dual-Pressure Waste Heat Boiler with Secondary Firing.** The efficiency of the plant can be further reaised by means of two pressure systems in the steam generator. The dual pressure waste heat boiler not only supplies high pressure line steam, but also secondary steam at lower pressure which is introduced into the steam turbine at suitable point as shown in Fig. 33.29. By making better use of the waste heat, the cycle efficiency can be raised by 2%.

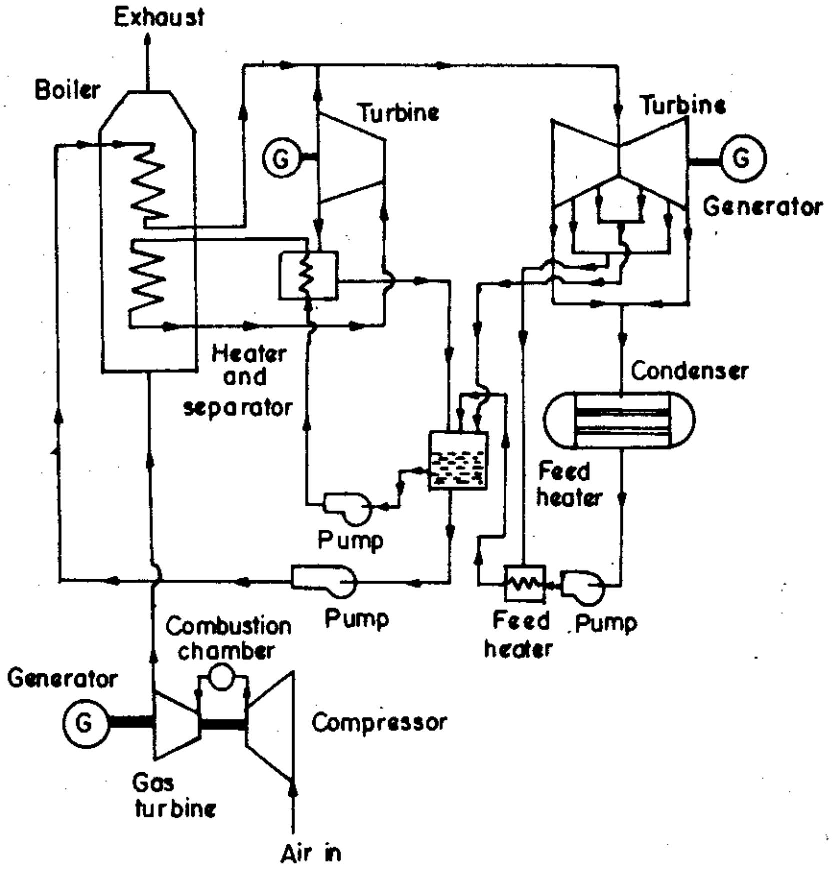


Fig. 33.29. Steam-gas plant with dual pressure waste heat Boiler for medium and peak load.

In the combined cycles which are described earlier are mostly dominated and restricted by the gas turbine output. This difficulty can be partly solved with the use of secondary firing. In this system, the gas turbine exhaust gases are used as combustion air. The large quantity of air in the turbine exhaust (80%) is sufficient to allow refiring in order to raise gas-temperature before entering the waste heat boiler as shown in Fig. 33.30 with the higher gas temperature, higher steam condition can be achieved for the subsequent steam cycle. The heat supplied at the second combustion point can be anything between zero and an amount corresponding to complete combustion of the excess air. The maximum temperature after second combustor should not exceed 750°C because this is the limit beyond which the boiler would need cooled furnace walls or a refractory lining.

With 750°C, the waste heat boiler can produce steam which can raise the output of the steam turbine to between roughly 110% to 120% of the gas turbine capacity. Compared with waste heat cycle without secondary combustion, the present system has a drawback in that, unlike the gas turbine combustor, heavy oil is burned on grounds of cost which emits considerable NO_x adding the burden on the environment. The added disadvantage is fouling on the heating surfaces with secondary combustion of heavy oil. This can be overcome with soot blowers at increased cost.

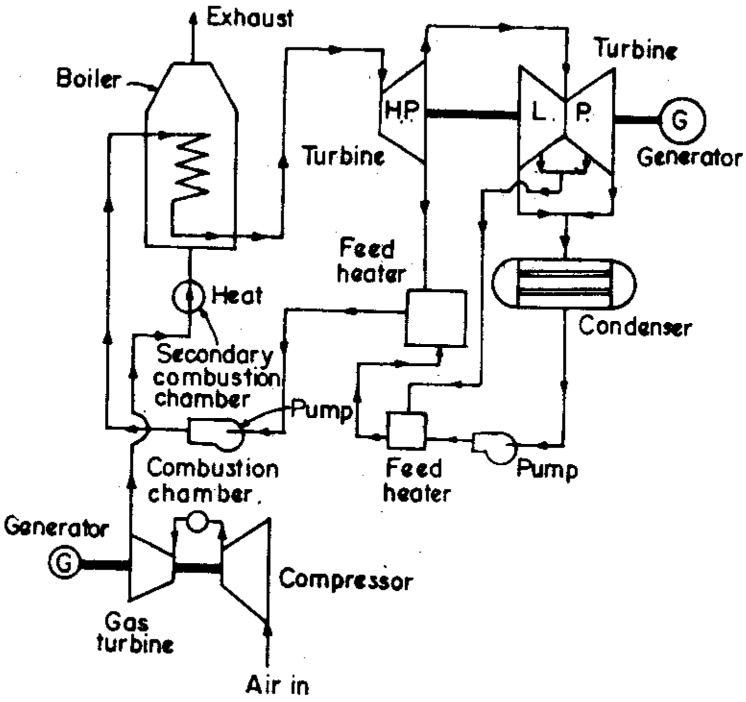


Fig. 33.30. Steam-gas plant with waste heat boiler and secondary firing for medium and peak load.

EXERCISES

33.1. What do you understand by peak load and peak load plant ? What are the difficulties experienced to meet the peak load ?

33.2. What are the basic requirements of a peak load plant ?

33.3. Draw a neat diagram of a pump storage plant and explain its working as a peak load plant.

33.4. Discuss the advantages and disadvantages of pump storage plant as peak load plant.

33.5. Draw a neat diagram showing all components of compressed air-storage plant which is used as peak load plant and explain its all modes of operation.

33.6. What do you understand by variable and constant pressure air storage systems ? Illustrate with diagrams and discuss their relative merits and demerits.

33.7. Illustrate, with component arrangements, different air storage plants with neat diagrams and discuss their relative advantages and disadvantages.

33.8. What are the different types of Caverns used for air storage plants ? State their relative advantages and disadvantages.

33.9. List out the advantages and limitations of air storage system over water storage systems when used as peak load plants.

33.10. What are the different arrangements of the components of thermal power plant when used as peak load plant ? List out the specific features of each.