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Economic Loading of Power Stations

13.1 Introduction

The sizes of electric power systems are increasing rapidly. A number of power plants can be operated in parallel to supply the system load by means of interconnexion of the stations. Interconnexion increases the reliability of a power system and effects economy in the transmission of power to the load centres. In planning a power system, it is necessary to select suitable types of plant, and to choose their sizes so that the overall cost of the energy delivered at the load centres to the consumers is a minimum. The second important point is to operate the plant units in an economical manner. We have discussed the first point regarding the choice of equipment in different types of station and their combined working in the last few chapters. Here we shall discuss the second point, namely, the economic operation of the generator units in the various types of plant in the system to effect the economy required. The load dispatcher or the control engineer has to consider a number of factors—when to interchange energy from one station to another, how much energy to interchange, the cost of supplying energy to the interconnexion, the cost of energy received from the interconnexion, etc. It is necessary to arrange the operation of each generator set on the system load curve every hour so as to reduce production costs during the year to a minimum. The factors directly affecting the economy of operation are many, such as variation in fuel costs, labour costs and weather conditions, normal and emergency equipment ratings, reserve requirements, voltage limitations, characteristics of the prime movers, transmission losses, etc.

The major factor controlling the most desirable load allocation between various generating units is the total cost. The cost of fuel forms the major portion of the variable costs of the plant, and the aim in scheduling the operation of generator units is to obtain minimum fuel cost. The primary requirement of a power system is to generate at each moment the exact amount of power required by the consumers, and to generate that particular amount of power at the lowest cost. There are fundamentally three kinds of load changes in a power system, which need handling—sustained load changes, transient load changes, and a combination of the two.

In devising the best operating schedule for the units, their input/output curves and incremental rate curves should be studied. The incremental rate is the limit approached by the ratio of the incremental input to the incremental output as the latter approaches zero as the limit. The incremental rate for a plant can be determined by differentiating the input/output equation or by drawing a tangent to the input/output curve at the point corresponding to the output. The maximum efficiency, or the minimum combined input for a given combined output, is obtained when all the machines in the system are operating at outputs which correspond to the same incremental rate. This optimum condition is, however, based on the assumptions that the input/output curves of the machines are continuous, that the incremental rate curves are continuous, and that the incremental rate always increases as the output increases.

13.2 Methods of Loading Steam Stations

When studying methods of loading stations, the best load division on boiler units, steam turbines and generators should be considered.

The methods used for loading boilers are as follows:—

1. The boilers may be operated at loads proportional to their ratings in terms of steam rates.

2. Equal efficiency method. The more efficient boiler units are loaded on base load until a load is reached at which the

efficiencies of two groups of boilers become equal. The boilers are then operated at outputs corresponding to equal efficiencies.

3. Incremental rate method. When the unit system is used, the characteristics of the turbo-alternators and the heat rates of the turbine units decide the loadings on the units. The heat rate curve of a turbine-generator unit is the basic curve from which the incremental rates are derived for load division purposes.

The methods of loading the turbo-alternator units are as follows :—

1. Base loading to capacity The units are successively loaded to capacity in order of their efficiencies. It is assumed that the overall efficiency of a group of units will be highest if all but the most efficient unit are operated at minimum loads until the most efficient one is loaded to capacity.

2. Base loading to most efficient load. The units are successively loaded to their most efficient loads in ascending order of the heat rates of the turbines driving them. When all the units are operating at their most efficient loads, they are loaded to capacity in the same order.

3. Loading proportional to capacity. The units are loaded in proportion to their capacities.

4. Loading proportional to most efficient load. The loads on the units are adjusted and retained in proportion to their most efficient loads. When all the units in the power station reach loadings corresponding to their most efficient loads, the additional load on each unit is made proportional to the difference between the rated capacity and the most efficient load.

5. Incremental loading. The load is divided to keep the units operating at equal incremental rates. The order in which the units are to be brought into action depends on the heat rates. Further loading is adjusted by incremental rates.

For studying the load division among the stations of a system it is approximately correct to use the respective station incremental heat rates adjusted for differential fuel prices. This is because fuel cost is the major item of production cost. The

incremental labour costs are a function of the number of additional boiler and turbine-generator units used in service. Approximately, incremental labour costs will be fixed and independent of the incremental load supplied. Boiler maintenance cost is a function of the amount of coal burned. The maintenance cost of turbine-generator units depends on the number of hours during which the units are used, and not on the energy generated.

13.3 Distribution of Load between Generator Units in a Power Station

To determine the economic load distribution between the various generator units in a station, it is necessary to plot the input/output curve of the generator unit. This is plotted in terms of fuel input, kilocalories/hour versus output in MW. The slope of the input-output curve is the incremental fuel rate and is expressed in terms of kilocalories per kWh, The cost of the fuel in Rs. per kilocalorie is determined to convert the input-output curve in terms of rupees per hour versus output in MW. The slope of this curve is the incremental fuel cost for the unit in rupees per MWh.

When the economical load distribution between a number of generator units is considered, it is found that the optimum generating schedule is effected when an incremental increase at one of the units replaces a compensating decrease at every other unit in turn at the same incremental cost. The economic optimum load distribution is obtained when all the generator units operate at the same incremental rate.

Example 13.1

Two units each of 200 MW in a steam station are operating all the time throughout the year. The maximum and minimum load on each unit is 200 MW and 50 MW respectively. The fuel incremental cost characteristics for the machines are :—

$$\frac{dF_1}{dP_1} = \text{Rs. } (0.08\ P_1 + 15)\ ;\ \frac{dF_2}{dP_2} = \text{Rs. } (0.1\ P_2 + 13)$$

where P_1 and P_2 are loads in MW. If the total load varies between 100 MW and 400 MW, find the incremental fuel cost and

allocation of load between the two units for minimum total cost for various total loads.

At a minimum total load, unit number 1 will operate at 50 MW and will have higher incremental fuel cost than unit no. 2 when the total minimum load is 100 MW, the initial distribution will be 50 MW on unit No. 1 and 50 MW on unit No. 2.

For machine No 1, $\lambda_1 = \frac{dF_1}{dP_1}$ = Rs. $(0.08 \times 50) + 15$

= Rs. 19 per MWh.

For machine No 2, $\lambda_2 = \frac{dF_2}{dP_2}$ = Rs. $(0.1 \times 50) + 13$

= Rs. 18 per MWh.

As λ_2 is smaller than λ_1, the load on machine 2 should be ncreased till $\lambda_2 = \lambda_1$, i.e., till $\frac{dF_2}{dP_2}$ = Rs. 19 per MWh.

The load on machine No. 2 at that time will be X when Rs. $(0.1X + 13) = 19$ or $X = 60$ MW.

Afterwards, go on increasing the load on each unit so that the units operate at the same incremental cost λ, until such time that the load on unit No. 1 reaches the maximum value 200 MW. Then increase the load on the second unit keeping the load on the first unit corresponding to this maximum value of 200 MW, though the units will not then operate at the same incremental cost λ. Increase the load on the second unit till it is 200 MW so that the total load on both the units together would be 400 MW.

Table 13.1

λ Rs./MWh	Unit No 1 P_1 MW	Unit No 2 P_2 MW	Total load MW
18	50	50	100
19	50	60	110
20	62.5	70	132.5
22	87.5	90	167.5
25	125	120	245
28	163	150	313
30	188	170	358
31	200	180	380
32	200	200	400

Table 13.1 shows the distribution of load on each unit for total load of 100 MW to 400 MW and the total load for different values of λ.

13.4. Effect of Transmission Loss

In a system where a number of stations are operating in parallel and are interconnected, transmission loss must be taken into consideration in economic studies. Incremental transmission loss characteristics and incremental plant characteristics must be considered together to determine the optimum system economy.

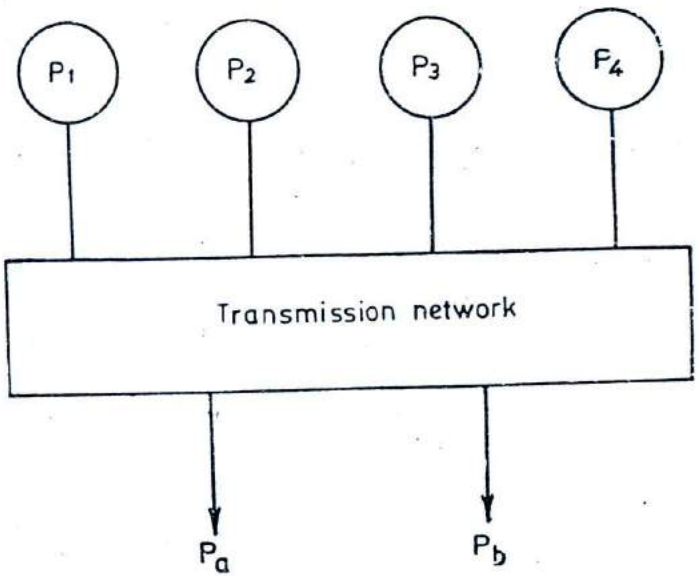


Fig. 13.1. A Sample System.

A sample system is shown in Fig. 13.1. P_1, P_2, P_3, P_4 are the outputs of generators supplying load P_a and P_b through a transmission network. Let F_1, F_2, F_3, F_4 be the fuel costs at the respective plants. and P_{LT} be the transmission loss in the network when transmitting the necessary power from the power stations to the loads. Also let $\triangle P$, $\triangle F$, $\triangle P_{LT}$ be the incremental changes in the respective quantities. Initially,

$$P_1+P_2+P_3+P_4=P_a+P_b+P_{LT} \qquad (13.1)$$

If there is change from the initial conditions,

$$\Delta P_1+\Delta P_2+\Delta P_3+\Delta P_4=\Delta P_a+\Delta P_b+\Delta P_{LT} \qquad (13.2)$$

If the loads P_a and P_b are constant,

$$\Delta P_1+\Delta P_2+\Delta P_3+\Delta P_4=\Delta P_{TL} \qquad (13.3)$$

The total transmission loss is the sum of the I^2R losses in the lines and transformers. These losses depend on the various line currents which in turn depend on the magnitudes of the loads in a given network, the allocation of generation between the different plants, and the operating voltage levels expected. The transmission loss is thus a secondary effect of the adjustment of loads among different generating units in the system.

The total fuel cost, F_t, will be given by

$$F_t=F_1+F_2+F_3+F_4 \qquad (13.4)$$

and a change in the total fuel cost, ΔF_t, by

$$\Delta F_t=\Delta F_1+\Delta F_2+\Delta F_3+\Delta F_4 \qquad (13.5)$$

The total fuel input is consumed partly in supplying the useful load, partly in transmission losses and partly in thermal losses and auxiliary power consumption. The thermal efficiency of a particular plant depends on its output, while the transmission losses are dependent simultaneously on the outputs of all the plants. The aim is to effect optimum overall efficiency The optimum schedule may not yield the maximum station efficiency, or the maximum transmission efficiency but will be a compromise between the opposing effects of station losses and transmission losses.

13.5 Criteria for Optimum Loading of Power Plants

The effect of loading plants could be studied under two conditions :

(a) a change of generation allotment between two plants, the other plants and the loads remaining constant; and

(b) a change in the load supplied by the system.

In the first case assume that plant No 1 takes more generation allotment, plant No 2 being relieved of this generation—

$$\Delta P_1+\Delta P_2=P_{L12} \qquad (13.6)$$

There will be a change in the transmission loss due to change of the generation allotment. Also

$$\triangle F_l = \triangle F_1 + \triangle F_2 \tag{13.7}$$

If the change reduces the total cost or if $\triangle F_1 + \triangle F_2 < O$, transfer of generation from plants No 2 to plant 1 is desirable. If $\triangle F_1 + \triangle F_2 = O$, the original division of power between the two plants should be retained as it is just satisfactory. If $\triangle F_1 + \triangle F_2 > O$, transfer of generation from plant No 2 to plant No. 1 is not desirable ; on the contrary, the change should be from plant No. 1 to plant No. 2. The condition for a correct schedule is

$$\triangle F_1 + \triangle F_2 = O \tag{13.8}$$

Differentiating

$$\frac{dF_1}{dP_1} = \frac{-dF_2}{dP_1} = \frac{-dF_2}{dP_2} \times \frac{dP_2}{dP_1}$$

or

$$R_1 = -R_2 \frac{dP_2}{dP_1} \tag{13.9}$$

where R_1 and R_2 are the incremental rates.

If changes of generation allotments are considered between plants Nos. 1 and 3, the corresponding incremental rates, R, will be related to the incremental power rates by expressions similar to equation (13.9).

The optimum generation schedule is obtained when an incremental increase in generation at one plant replaces a compensating decrease at every other plant in turn at the same increment of cost. When transmission losses are neglected, $\triangle P_2 = -\triangle P_1$ etc., or the optimum loading is obtained when all the plants operate at the same incremental rate.

If the transmission losses are not negligible

$$\triangle P_1 = -(\triangle P_2 - \triangle P_{L12}) \tag{13.10}$$

Solving as in last case,

$$R_1 = \frac{R_2}{1 - \frac{\triangle P_{L12}}{\triangle P_2}} \tag{13.11}$$

and so on for other plants

The optimum schedule between plants is obtained when suitably weighted or penalized, plant incremental rates are all equal, e.g., the weighting, or penalty, factor for plant No. 2 is

$$\frac{1}{1-\frac{\Delta P_{L12}}{\Delta P_2}}$$

The second point to be considered is a change in load and the corresponding change in the generation at one of the plants; the transmission loss will change.

Referring to Fig. 13.1, if the load P_a increases by a small increment ΔP_a and if it is supplied by a small increase ΔP_1 at plant No. 1, all other plant allocation of generation remaining unchanged.

$$\Delta P_1 = \Delta P_a + \Delta P_{L1a} \tag{13.12}$$

Similar changes will occur if the increase in load is supplied by some other plant.

With the optimum generation schedule, an incremental increase in any one load incurs the same increases in fuel cost regardless of which plant supplies the increase in load. If K_a represents the incremental cost of power delivered to a load at location a,

$$\Delta P_a = \Delta P_1 - \Delta P_{L1a}$$

$$\frac{\Delta F_1}{\Delta P_a} = \frac{\Delta F_1}{\Delta P_1}\,\frac{\Delta P_1}{\Delta P_a}$$

$$\frac{\Delta F_1}{\Delta P_a} = R_1 \frac{1}{1-\frac{\Delta P_{L1a}}{\Delta P_1}} = K_a \tag{13.13}$$

If, instead of being supplied from plant No. 1, the load is supplied by plant n, the above equation reduces to

$$\frac{\Delta F_n}{\Delta P_a} = R_n + K_a \frac{\Delta P_{Lna}}{\Delta P_n} = K_a \tag{13.14}$$

At optimum loading, the plant incremental rate plus a suitably "priced" incremental loss term is the same for each plant.

The incremental loss term, $\triangle P_L/\triangle P_n$, is priced at the incremental cost of power delivered to location a

13.6 Co-ordination of Incremental Fuel Cost and Incremental Transmission Loss

In the last section we have seen the basic relations involved in the achievement of optimum loading conditions. The exact method is by the solution of non-linear simultaneous equations. The minimum fuel input is obtained by the solution of the following equations

$$\frac{dF_n}{dP_n} + K\frac{\delta P_L}{\delta P_n} = K \qquad (13.15)$$

where F_n = Cost of fuel input to plant n (Rs. per hour)

P_n = Output of plant n (kW)

$\frac{dF_n}{dP_n}$ = Incremental fuel cost of plant n (Rs per kWh)

P_L = Total transmission loss (kW)

$\frac{\delta P_L}{\delta P_n}$ = Incremental transmission loss at plant n (kW per kW)

K = Incremental cost of received power (Rs per kWh)

Solutions for different load conditions are obtained by varying the magnitude of K.

An approximation can be made if the incremental transmission loss at plant n in the above equation is charged at a constant rate β. Then the non-linear equations reduce to a set of linear simultaneous equations—

$$\frac{dF_n}{dP_n} + \beta\frac{\delta P_L}{\delta P_n} = K \qquad (13.16)$$

Solutions for different load conditions are obtained by varying the magnitude of K.

Another approximate method is the penalty-factor method. If the incremental transmission loss at plant n is charged at a rate corresponding to the incremental fuel cost of that plant, the equation reduces to

$$\frac{dF_n}{dP_n}+\frac{dF_n}{dP_n}\frac{\delta P_L}{\delta P_n}=K \tag{13.17}$$

This may be written

$$\frac{dF_n}{dP_n}L_n=K \tag{13.18}$$

where

$$L_n=1+\frac{\delta P_L}{\delta P_n} \tag{13.19}$$

L_n being the penalty factor of plant n.

In the large power system, a considerable saving is effected by including the effect of transmission loss in the economic scheduling of the generator units.

13.7 Economic Distribution of Load Between Plants Considering Effect of Transmission Loss

The minimum fuel input for a number of plants working together in a system is obtained by the equation—

$$\frac{dF_n}{dP_n}+\lambda\frac{\delta P_L}{\delta P_n}=\lambda \tag{13.20}$$

where λ is the cost in rupees per MWh.

The transmission loss for K plants is given by—

$$P_L=\sum_{m=1}^{K}\sum_{n=1}^{K} P_m\, B_{mn}\, P_n \tag{13.21}$$

and

$$\frac{\partial P_L}{\partial P_n}=\frac{\partial}{\partial P_n}\sum_{m=1}^{K}\sum_{n=1}^{K} P_m\, B_{mn}\, P_n=2\sum_{m=1}^{K} P_m\, B_{mn} \tag{13.22}$$

Example 13.2

The power stations are connected together by a transmission line. The load is located at plant No. 2. When 150 MW are transmitted from plant No. 1, the transmission loss is 15 MW. The incremental fuel costs for plants 1 and 2 are as follows:

$$\frac{dF_1}{dP_1}=(0.08\,P_1+15) \text{ rupees per MWh}$$

$$\frac{dF_2}{dP_2}=(0.1\,P_2+13) \text{ rupees per MWh}$$

Find the required generation from each plant for 25 rupees per MWh.

$$\frac{dF_n}{dP_n}+\lambda\frac{\delta P_L}{\delta P_n}=\lambda \qquad 13.20$$

and
$$\frac{\delta P_L}{\delta P_n}=2\sum_{m=1}^{K} P_m B_{mn} \qquad (13.22)$$

substituting the values,

$$0.08\ P_1+15+2\lambda\ (B_{11}P_1+B_{12}P_2)=\lambda$$

$$0.01\ P_2+13+2\lambda\ (B_{22}P_2+B_{12}P_1)=\lambda$$

As the load is at plant No.2, variation of P_2 does not affect transmission loss and the transmission coefficient

$B_{22}=0$; $B_{12}=0$

When $P_1=150\ MW$, $P_L=15\ MW$

$$15=(150)^2\ B_{11}$$

$$B_{11}=\frac{15}{(150)^2}MW^{-1}=0\ 00067\ MW^{-1}$$

For $\lambda=25$, $0.08\ P_1+2x25x\frac{1}{1500}P_1=25-15=10$

$$0.113\ P_1=10 \text{ or } P_1=88.5\ MW$$

$$0.1\ P_2=25-13=12$$

$$\text{or } P_2=120 \text{ MW}$$

$$\text{Transmission loss } P_L=\frac{1}{1500}\times 88.5^2-5.2 \text{ MW}$$

Power at the receiving end $=88.5+120-5.2=203.3\ MW$.

13.8 Methods of Loading Hydro-electric Stations

The performance characteristics of different units in hydro-stations may vary, and it is necessary to determine the division of load among the various units considering the incremental cost of power. The information which will be required for the economic scheduling of hydro-plants is as follows: the efficiency curves of each unit, the input/output curve showing the total rate of flow of water against the load, and the incremental rate curve showing the change in the rate of the flow required per unit change in load. The methods of calculating the incremental

costs of thermal stations were studied in the last section. Methods for very accurate determination of the incremental costs of power from hydro-plants have not yet been well developed. Each hydro-plant has a small reservoir near the station for short term regulation of the water required under different loading conditions. The reservoirs for long-term regulation may be situated at a greater distance from the plants and may not affect the head at the plants to an appreciable extent, even with change of load on the plants.

The losses in the water turbines and conduits increase with the rate of flow of water required, and the incremental cost of power from a hydro-plant is higher during peak generation compared to the cost when supplying a low load. The incremental cost varies with the head of water at the plant, different load conditions, and the time of their occurrence. Long transmission lines are usually necessary for hydro-plants, and the effect of transmission losses should be included in economic schedule studies. The incremental cost of power delivered from a hydro-station may be found by the analysis of losses due to short-term regulation. For large plants with large reservoirs, the incremental cost of water at the plants with long-term regulation should be determined. This is a very involved study and needs estimates based on probability calculations of the flow of water available from the expected rainfall. etc., and details of the storage in the reservoirs at various times during the period under review.

The use of hydro-stations either as base-load or peak-load stations depends on the storage available at the plants and how they can fit in the load curve of the power system. Their operation from this point of view has already been considered in Chapters 7 and 8. The general principles of the combined operation of hydro and thermal plants were discussed in Chapter 9.

13.9 Economic Loading of Combined Thermal and Hydro-electric Stations : Short-Range

When both thermal and hydro-plants are available in a power system they should be scheduled over a given period to achieve

the maximum economy by minimizing the cost of fuel consumption of the thermal-station units when using desired amounts of water for the hydro-station units.

The following information is required for the study : hydro- and thermal-plant capacities and their characteristics, the number of units, penalty factors depending on the type of fuel used, transmission loss incurred in respect of each station, load curve, total losses in the system, incremental losses, head at hydro-plants, and average, minimum and maximum flow of water at hydro-plants. If it is assumed that the hydro-plants will work at constant heads, and that the thermal plants will operate with the least cost of fuel during the year; the economic schedule can be worked out by the use of co-ordinate equations—

$$\frac{dF_n}{dP_{Sn}} + K\frac{\delta P_{Lt}}{\delta P_{Sn}} = K \qquad (13.23)$$

$(n = 1, 2, 3.... \alpha)$

$$K'_j \frac{dW_j}{dP_{Hj}} + K\frac{\delta P_{Lt}}{\delta P_{Hj}} = K \qquad (13.24)$$

$(J = \alpha+1, \alpha+2, \alpha+3.... \beta)$

where

$\frac{\delta F_n}{dP_{Sn}}$ = Incremental fuel cost of thermal plant n(Rs. per kWh)

$\frac{\delta P_{Lt}}{\delta P_{Sn}}$ = Incremental transmission loss of thermal plant n.

$\frac{\delta W_j}{dP_{Hj}}$ = Incremental water rate at hydro-plant j (m^3/sec per kWh)

$\frac{\delta P_{Lt}}{\delta P_{Hj}}$ = Incremental transmission loss of hydro-plant j

K'_j = Constant of conversion of incremental water rate into equivalent incremental plant cost

α = Number of thermal stations

β-α = Number of hydro plants

Knowing the amount of water that would be available for use at a hydro-station, K'_j can be chosen. Using this value, solve the

co-ordinate equations for the economic scheduling of plants in the system. Equations can be solved choosing different values of K. If dF_n/dP_{Gn} and dW_j/dP_{Hj} in the above equations are assumed to be linear functions, an approximate solution can be obtained.

Another method of solution would be the equal-incremental-plant-cost method.

Sometimes, the practice is to operate the hydro-plants near the point of maximum efficiency except when surplus water is available. When hydro-plants are operated in this way, the thermal plants can be scheduled either by equal incremental fuel costs or by the solution of co-ordinate equations.

13.10 Economic Loading of Combined Thermal and Hydro-electric Stations : Long Range

When the hydro-plant capacity in a system is ample and the reservoirs are full, the starting of thermal stations should be delayed as long as possible. Normally, the thermal plants should supply part of the load throughout the year and they should supply the deficit during dry seasons. They should be run for sufficient time for the required purpose. When the hydro-capacity in the system is ample and the reservoirs are full, it may be possible as an alternative to supply all the load by hydro-plant for some time and thus delay the starting of thermal stations. When the storage in the reservoirs approaches a minimum level, the water discharge should be reduced and the thermal plants started. In determining the minimum zone of the storage reservoirs, it is necessary to have a detailed statistical analysis of their inflow, evaporation losses, etc. The minimum zone corresponds to the minimum water level in the reservoirs below which the hydro-plants cannot be operated from the reservoir water supply.

The economic long-range scheduling of thermal stations and hydro-plants using large storages is a very complicated problem. A large number of variable factors are involved, resulting in many sets of non-linear equations. It is not possible to solve such problems by long-hand methods. However, with the development of fast computers, it is possible to solve a number of complicated

equations quickly, as well as to arrange programming for the economic working of the plants.

In general, there are two extremes possible. The hydro-plant can be operated at maximum discharge until the allotted water is consumed, after which the plant can be shut down for the rest of the day and the remaining load supplied by the thermal plant or plants. An alternative is to keep the hydro-plant shut down and inoperative as long as possible, and to put it in commission only when there is enough time left during the day to use up the allotted quantity of water. A third method is to reduce the total thermal cost by changing the hourly division of load between the thermal and the hydro-plants using incremental programming. The incremental value of the water should be determined for the purpose. A number of iterations on computers help in finally obtaining the optimum hydro-stations schedule.

13.11 Load Dispatching

In large power systems, a central load dispatcher is necessary to assign loads to various stations and units in accordance with a predetermined schedule. This requires modification from time to time as the actual load differs from predicted load and also should take care of emergencies arising out of loss of generator units or tie lines. Load assignment to a particular station varies with the type and function of the station and its relation to the system. Frequency control is usually assigned to one of the largest generating stations in the system.

On some systems analog computers are used to determine the desired generation from each plant in the system under expected performance of loadings for economic operation. In some cases the computer is used to control output of each station and each plant to the required value automatically. All plant output, and tie line loadings required are monitored by the computer continuously. The computer compares the net interchange of power with the scheduled economic distribution at each point and sends signals to the power plant units which cause them to adjust loadings to the required values for best economic performance. In determining generation at each plant, the computer takes into account the

transmission loss effect and the corresponding penalty factor in arriving at the economical load distribution.

In some systems, analog computers are used to determine the economical and desired load distribution between the various generator units. The load dispatching, however, is not done with automatic control by the computer. It is done by load ratio control and by various monitored signals which are used by the control engineer or load dispatcher to adjust loads between various units. The difference between the expected system load and the actual load is corrected for.

Automatic load and frequency control have been successfully applied to units in one or more generating stations of an interconnected system. Very large systems are sometimes divided into load districts, each having its own load dispatcher. Often central load dispatching arrangements are used for general supervision over the districts.

13.11.1 AUTOMATIC FREQUENCY CONTROL

In this control, station frequency is intermittently or continuously compared with a standard. The control adjusts the difference by regulating the governor of the prime mover through the standard speed adjusting motor of the governor. There are two types of control : (i) One that holds time constant (ii) One that holds frequency constant.

The 'Warren frequency control' is of the first type. An accurate 1 sec pendulum having a high degree of precision is used as a standard to establish correct frequency. Both time and frequency are held constant. There is no interference with the normal functioning of the standard governing equipment. The impulses to change speed or adjust load are transmitted to the synchronizing motor on the Governor.

The system frequency is checked by a synchronous motor driven cam; the position of this cam in relation to that of the pendulum is checked every 2 seconds, the time corresponding to one complete swing of the pendulum. The amount by which the cam is out of phase with the pendulum is a direct measure of the

corresponding integrated frequency error. Contacts operated by a motor mechanism hold the circuit closed for a period proportional to the frequency error. These varying impulses are transmitted through a relay to the motor geared to turn the frame of the synchronous motor driving the cam. The duration of impulses is such as to advance or retard the cam by the amount which it was out of phase with the pendulum. The amount of this additional rotation is the measure of integrated frequency error. This motion is also transmitted to and reproduced in each unit controller. The value of this integrated error is used as a base for loading each unit.

The frequency and load control system for a power station consists of a 'Warren master frequency controller' which determines the frequency error and the amount of correction required; and a 'Warren unit load controller' for each generator unit which determines the load division between the units.

The Leeds and Northrup equipment makes use of an accurately tuned frequency circuit for base frequency control. The deviation of station frequency from the true frequency is used to make a governor motor adjustment to the required extent so as to maintain the frequency constant. The automatic control may be applied to one unit in a plant or system. In this case manual control is used for adjustment of loads on all other units. The automatic control may be applied to all units in the plant or to several plants through pilot wires or by means of proportional loading; in this case the governors of all units are adjusted simultaneously. It may be necessary to have manual adjustments from time to time to hold the tie line loadings within required limits.

13.11.2 LOAD DISPATCHING STATIONS

A modern dispatching station requires the facilities of reliable communication, telemetering, tele-control, and computers.

Communication system : The communication system should not only be reliable but also flexible to permit future additions of the requirements of the equipment to be provided. In Indian Power System development, it is proposed to install a microwave

communication system. P& T system will be limited to those channels provided for back communication systems.

Telemetering system : Telemetering information is the most important basis for load flow calculations, load frequency control and system security monitoring at the load dispatch stations. The telemetering equipment should be standardised and carefully chosen. By telemetering arrangement, the information obtained at each load dispatch station should be—(i) digital type (ii) transmitted in words (iii) provided with security against interference in the communication channel (iv) provided with security against internal faults of the equipment (v) suitable to be fed to the computer interface.

For satisfying these requirements, the telemetering equipment should be of digital type and modular in construction, and capable of generating telemetering information. The equipment should not mismatch when computers are installed in the future.

Control system : Load frequency controllers should be installed at the state load dispatch stations to control the state grids independently. The region may be controlled on the multi area concept with as many control areas as the region consists of. Later on when sufficient strong tie lines are provided for various systems in the region, the region could be operated as a single area by installing a regional controller at the regional load dispatch station.

Computer system : It is necessary to install on line computers. At the state level, the functions to be performed are to communicate directly with network variables. This is to be done frequently.

13.11.3 PLANNING OF LOAD DISPATCH STATIONS IN INDIA

In India, the trend in planning is to install load dispatch stations in the country with a three level hierarchy : state load dispatch stations, regional load dispatch stations, and a national load dispatch station for achieving the integrated operation of power systems across the country.

The main functions of a national load dispatch station would be as follows :—

(a) to co-ordinate the activities of the various regional load dispatch stations to achieve the integrated operation of an All India Grid.

(b) to co-ordinate and monitor the operation of the major hydro, nuclear and super thermal stations in the country.

(c) to arrange exchanges of powet between regions as required to avoid shedding of power in one region and surplus in another.

The functions of the regional load dispatch stations and state load dispatch stations are similar to those above except that they are restricted only to the regions and the states respectively.

If in an emergency. the national load dispatch station were to go out of operation, all regional load dispatch stations would act as back up to the national load dispatch station and control their respective regions. Similarly, if regional load dispatch stations were out, the state load dispatch stations continue to control their grids independently. Their function will include direct operation and control of their state networks.

At the regional level, the functions of the computer would involve receiving information from the state computers, co-ordinating them and feeding the results to the national load dispatch station. optimisation carried out at the regional level in accordance with the directions of the national load dispatch station would be transmitted to the state load dispatch stations for implementation. The data at the third level received from the regional computers would be processed for achieving optimisation at the regional level.

As the system grows, modern techniques of load dispatch should be used and co-ordinated to obtain economic load dispatch, reliability and security of the interconnected large system. The load dispatch stations help in techniques of programming such as load forecasting, system reserve, control of reactive power flows, network control, frequency control, analysis of system, etc.

13.12 General Remarks

The problem of the economic scheduling of various types of station in a power system is very complex, and in the above sections only a very general idea of the principles involved in approaching the solution of this vast problem is given. Some of the variables are changes of loads and their effect, characteristics of thermal and hydro-plants, input/output curves of the plants, incremental cost of fuel, incremental cost of water, variation of head at the hydro-plants, short-term and long-term regulation of reservoirs, cost of different types of fuel, such as gas, oil, coal, etc.

The major advances in solving complicated mathematical equations by programming on computers have been a great help, and the latest methods for the accurate solution of such complicated problems always use these facilities. Analogue computers help in simulating the system conditions and give the operation schedule hour by hour. In fact in some large systems, controls are effected by the use of computers directly. The operation and loading of power plant units can be arranged as required, giving the optimum schedule to obtain overall economy.

We have studied the elements of electrical power station design, with reference to the choice of machines and equipment, their specifications, main dimensions, general layout and applications, and the principles of operating the stations economically in a system. In addition, a power system consists of a transmission and distribution network to take the power to the consumers. The author's companion volume deals with the Elements of Electrical Power Transmission and Distribution Design. It is hoped that the present volume has given the reader a good idea of the basic principles involved in power station design.

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Problems

13.1. Define "incremental rate" for a thermal plant and describe the various methods of determining it from the input/output characteristics of the plant.

13.2. Explain various methods of loading steam stations for economic operation. State the considerations necessary in loading boiler units, steam turbines and generator units.

13.3. How does transmission loss in an interconnected system affect the division of loads on the stations to effect overall economy? Illustrate by an example.

13.4. Derive conditions for the loading of power plants for the most economic operation (*a*) Consider a change in generation allotment between generator units, the load remaining constant at the instant. (*b*) Consider a change in load and show how to supply this by a change in the generation allotment of one generation plant.

13.5. Discuss methods used for the co-ordination of incremental fuel cost and incremental transmission loss in the economic loading studies of power plants.

13.6. Explain methods of loading hydro-electric power plants. How would you determine the incremental cost of water ?

13.7. Explain the methods of economic loading of combined thermal and hydro-stations in a power system. State the basic equations and assumptions made when the analysis is to be done on a short-range basis.

13.8. Discuss the various factors which are involved in the study of the loading of hydro-electric power plants with reservoirs located at a distance from the plants.

13.9. Discuss the loading of combined thermal and hydro-electric stations on a long-range basis when the hydro-plants have storage in distant reservoirs.

13.10. Discuss the latest techniques used in calculating the economic load division between the various plants in a power system. How is the load on the units controlled ?

13.11. Two units each of 100 MW in a steam station are operating all the time throughout the year. The maximum and minimum load on each unit are 100 MW and 20 MW respectively. The fuel incremental cost characteristics for the machines are :

$$\frac{dF_1}{dP_1} = \text{Rs. } (0.1\ P_1 + 13) \text{ per MWh and}$$

$$\frac{dF_2}{dP_2} = \text{Rs. } (0.12\ P_2 + 12) \text{ per MWh}$$

where P_1 and P_2 are loads in MW. If the total load varies between 50 MW and 200 MW, find the incremental fuel cost and allocation of load between the two units for the minimum total cost for various total loads.

(Ans. $\lambda = 15$, $P_1 = 20$ *MW*, $P_2 = 30$ *MW*, $P = 50$ *MW* ;

$\lambda = 24$, $P_1 = 100$ *MW*, $P_2 = 100$ *MW*, $P = 200$ *MW*)

13.12. Two power stations are connected together by a transmission line and load is at power station no. 2. When 100 MW are transmitted from plant No 1, the transmission loss is 10 MW. The incremental fuel costs for plants 1 and 2 are as follows :

$$\frac{dF_1}{dP_1} = (0.1\ P_1 + 13) \text{ rupees per MWh}$$

$$\frac{dF_2}{dP_2} = (0.12\ P_2 + 12) \text{ rupees per MWh}$$

Find the required generation from each plant for $\lambda = 22$, $\lambda = 25$, and $\lambda = 30$ rupees per MWh.

(Ans. $\lambda = 22$, $P_1 = 62.5$ *MW*, $P_2 = 83.5$ *MW*

$\lambda = 25$, $P_1 = 125$ *MW*, $P_3 = 108$ *MW*

$\lambda = 30$ $P_1 = 106$ *MW*, $P_2 = 150$ *MW*)

13.13. Explain the method of load dispatching in a power system.

14

Modern Trends in Power Station Design and Operation

14.1 Load Forecasting

It is necessary to forecast both demand and energy. This can be done by simple extrapolation, curve fitting or stochastic modelling. The forecasting techniques are based on : (i) extrapolation or correlation or a combination of both. (ii) Deterministic, probabilistic or stochastic.

Extrapolation : This can be done by the following methods :

(i) Straight line method : relation $Y=a+bx$
(ii) Parabola relation $Y=a+bx+cx^3$
(iii) s Curve relation $Y=a+bx+cx^2+dx^3$
(iv) Exponential relation $Y=ce^{dx}$
(v) Gompertz relation $Y=ln^{-1}(a+ce^{dx})$

The most common curve fitting technique for finding coefficients and exponents of a function in a given forecast is the method of least squares. The uncertainty of the extrapolated results can be quantified by using statistical entities such as mean and variance. This becomes the probabilistic extrapolation. With regression method, the best estimate of model describing the trend can be obtained and used to forecast the load.

Stochastic models can be used to generate forecast from random inputs derived from the historical data. The inputs to the model tend to be the random change in the trend components, the random slope of the change in seasonal component and associated weighting factor and a general noise component.

The statistics of all the random inputs plus the weighting factor are determined by matching the statistics of the historical demand data with the corresponding statistics for the output of the model. With the model matching to fit historical demand rate, the forecast is obtained by exciting the transformed model by random inputs whose statistics are known. The resulting time series, after an inverse transformation is the forecast desired.

The impact of weather on residential load, commercial loads should be considered. Other seasonal variations are also caused by economic and demographic effects.

With the coming in of solar technology, there may be a tremendous impact on load patterns experienced by the public utilities. This may also be considered when applicable.

Energy Forecasting : Energy forecasting may be done by considering the trend in the sale of electrical energy (i) Residential sales forecasts; (ii) Commercial sales forecasts; (iii) Industrial sales forecasts.

Peak Demand Forecasting Methods

It is necessary to determine weekly peak demand, monthly peak demand and annual peak demand.

The procedure for this would be as follows :

(i) Determine seasonal weather model.

(ii) Separate historical weather sensitive and non-weather sensitive component of weekly peak demand.

(iii) Forecast mean and variance of non-weather component of demand.

(iv) Extrapolate weather load model and forecast mean and variance of weather sensitive component.

(v) Determine mean, variance and density function of total weather forecast.

(vi) Calculate density function of monthly and annual forecast.

Determination of Weather Load Model

Plot scatter diagram of daily peaks vs weather variable such as dry bulb temperature (and sometimes also account for humidity). Use linear regression analysis or curve fitting techniques to determine this model. Separate out weather sensitive and non-weather sensitive components knowing historical data.

Non-weather Sensitive Forecast

A technique of discounted multiple regression to fit a time polynomial to non-weather sensitive component of historical weekly peak demands is used to obtain non-weather sensitive forecast (NWSF).

$$\text{Mean temperature } \bar{T} = \frac{1}{N} \sum_{i=1}^{N} T_i \tag{14.1}$$

$$\text{Variance } \sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (T_i - \bar{T})^2 \tag{14.2}$$

Calculate means and the variances of the weather sensitive (WS) and non-weather sensitive (NWS) components of peak demand. To obtain total forecast find mean and variance of a particular week, add component means and variances. In the same way find the monthly peak demand forecast and annual peak demand forecast.

14.2 Economic Load Dispatch

While solving the problem of economic dispatch for generator units, it is necessary to consider the types of generator units, their characteristics, and generation cost per unit, (R/hour).

Fig. 14.1 shows a system of N thermal generating units connected to a single bus bar and supplying a load of P_R at the receiving side. The input to each generating unit is shown as F_1 which is fuel consumed at specific rate of the unit in terms of MK cal/hr or may be expressed as generating unit cost in terms of R/hr. The output of the unit i is P_i which is electrical power generated by that unit. If it is initially assumed that the load P_R

is supplied at the bus bars directly and transmission network losses are neglected, the problem can be solved as follows :

$$\text{The total cost } F_T = F_1 + F_2 + F_3 + \ldots + F_i + \ldots + F_N \qquad (14.3)$$

$$= \sum_{i=1}^{N} F_i(P_i)$$

$$\sum_{i=1}^{N} P_i = P_R \qquad (14.4)$$

Using calculus methods involving LaGrange function, it is seen that the necessary condition for minimum operating cost for the thermal system is that the incremental cost rates of all the units be equal to some value λ

$$\frac{dF_i}{dP_i} = \lambda \qquad (14.5)$$

In addition to this, there may be two other conditions, viz. (a) Power output of each unit should be greater than or equal to minimum power permitted on the unit. (b) Power output of each unit should be equal to or less than the maximum power permitted on the particular unit. This will be indicated by the following equations :

$$\frac{dF_i}{dP_i} = \lambda \text{ for } P_i \text{ min} < P_i < P_i \text{ max}$$

$$\frac{dF_i}{dP_i} \leqslant \lambda \text{ for } P_i = P_i \text{ max} \qquad (14.6)$$

$$\frac{dF_i}{dP_i} \geqslant \lambda \text{ for } P_i = P_i \text{ min.}$$

Example 14.1

Three steam generator units of the following ratings are to take up total load of 1000 MW.

Unit 1 : Maximum output = 800 MW, Minimum output = 200 MW, Input-output curve is given by—

$$H_1 \left(\frac{M \text{ kilocalories}}{\text{hour}} \right) = 125.0 + 1.8\, P_1 + 0.002\, P_1^2$$

Unit 2 : Maximum output = 500 MW, Minimum output = 100 MW, Input-output curve is given by—

$$H_2\left(\frac{\text{(M kilocalories)}}{\text{hour}}\right)=75.0+1.9\ P_2+0.002P_2^2$$

Unit 3 : Maximum output=250 MW, Minimum output= 50 MW Input-output curve is given by—

$$H_3\left(\frac{\text{M Kilocalories}}{\text{hour}}\right)=20.0+2\ P_3+0.004\ P_3^2$$

where H_1, H_2 H_3 are heat rates of the units. Fuel costs of units are given by—

For Unit 1, fuel cost=4.4 R/M kilocalories

For Unit 2, fuel cost=4 R/M kilocalories

For Unit 3, fuel cost=4 R/M kilocalories

where R is the cost rate per million kilocalories.

Determine the economic load distribution on the units.

$F_1(P_1)=H_1(P_1)\times 4.4$ R/M kilocalories

$=550+7.92\ P_1+0.0088\ P_1^2$ R/hr

$F_2(P_2)=H_2(P_2)\times 4.0$ R/M kilocalories

$=300+7.6\ P_2+0.008\ P_2^2$ R/hr

$F_3(P_3)=H_3(P_3)\times 4.0$ R/M kilocalories

$=80.0+8\ P_3+0.016\ P_3^2$ R/hr

For optimum dispatch,

$$\frac{dF_1}{dP_1}=7.92+0.0176\ P_1=\lambda \qquad (1)$$

$$\frac{dF_2}{dP_2}=7.6+0.016\ P_2=\lambda \qquad (2)$$

$$\frac{dF_3}{dP_3}=8.0+0.032\ P_3=\lambda \qquad (3)$$

$$P_1+P_2+P_3=1000 \qquad (4)$$

Solving the above equations,

(1) $\times$ 1.818, $14.4+0.032\ P_1=1.818\ \lambda$

(2) $\times$ 2, $15.2+0.032\ P_2=2\ \lambda$

(3) Adding, $\dfrac{8.0+0.032\ P_3=\lambda}{37.6+0.032(P_1+P_2+P_3)=4.818\ \lambda}$

Substituting (4),

$$37.6 + 0.032 \times 1000 = 4.818\,\lambda$$

$$\lambda = \frac{69.6}{4.818} = 14.446 \text{ R/Mwh}$$

Substituting the value ot λ in the above equations,

$P_1 = 370.6$ MW

$P_2 = 428.0$ MW

$P_3 = 201.4$ MW

TOTAL $= 1000.0$ MW

The distribution of load on each unit satisfies the maximum and minimum limits of load permissible on the respective units. So it is alright.

If in the problem, the maximum and or minimum load permissible on any unit or units is not satisfied, the particular unit has to be put on load on maximum or minimum without exceeding the limits permissible, and work out values of λ for each unit satisfying equations (14.6) and then work out the distribution of load on each unit.

14.3 Economic Load Dispatch on Units considering Transmission Network Losses

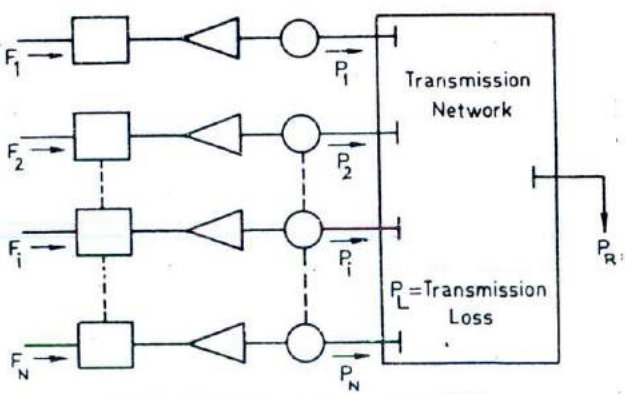


Fig. 14.1 System with N thermal Units

Fig. 14.1 shows a power system of N steam generators supplying load P_R through a transmission network having losses P_L.

$$\text{Here } P_R + P_L = \sum_{i=1}^{N} P_i \tag{14.7}$$

and the condition for minimum cost operation of the system is given by—

$$\frac{dF_i}{dP_i} = \lambda\left(1 - \frac{\partial P_L}{\partial P_i}\right) = 0 \tag{14.8}$$

$$\text{or } \frac{dF_i}{dP_i} + \lambda \frac{\partial P_L}{\partial P_i} = \lambda$$

It is then necessary to solve a set of equations (14.7) and (14.8) to solve the problem of division of loads on the generator units operating in the system for their operation at minimum cost.

The transmission network loss P_L in the system can be expressed as the power output function of each of the units. Alternatively, incorporate the load flow equations as essential constraints in solving optimization problem.

The proceedure to solve the problem will be as follows :

Step 1 : Pick up a set of starting values of P_1, P_2, etc. such that their sum is equal to the total load P_R

Step 2 : Calculate the incremental losses $\frac{\partial P_L}{\partial P_i}$ as well as total network losses P_L ..

Step 3 : Solve for λ using equation (14.8)

Step 4 : Calculate P_1, P_2, ... P_i ... etc.

If these values are different than initially assumed, return to step 2, recalculate incremental losses with these new P_i for units obtained as well as the total losses P_L with these new incremental losses and total losses solve for new value of λ. Calculate P_1, P_2, P_i ... etc.

Repeat the procedure till division of loads on the units P_1, P_2, P_i etc. satisfy equation (14.7).

The method is known as The Lamda-Iteration Method of solution. Fig. 14 2 shows the block diagram of the method,

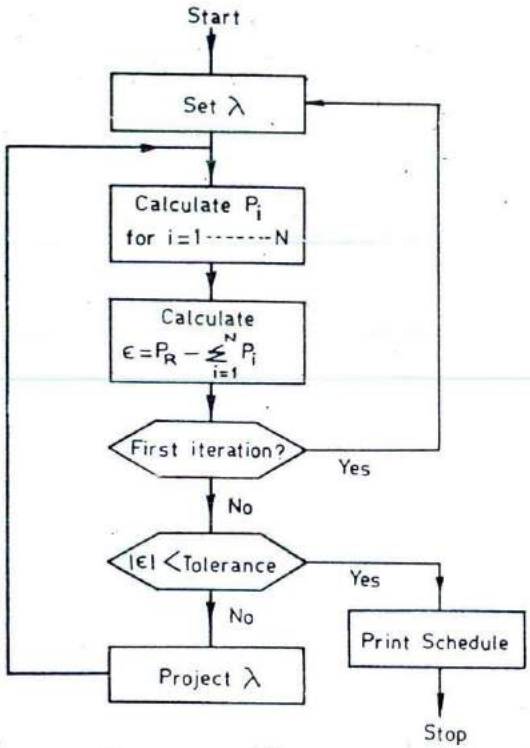


Fig. 14.2 Economic dispatch by the Method of Lamda iteration

The steps are obvious as mentioned earlier. The procedure can be adopted for a computer implementation. The Newton-Raphson method may be used to select the adjusted value of incremental cost λ to make the error between computed and desired generation to zero.

First-Order Gradient Method : The gradient search techniques lways start off with feasible solution i.e. solution in which condi-ions are met, and search for the optimum solution along the ajectory that maintains the feasible solution all the time.

$$F_T + \Delta F_T = F_1(P_1) + F_2(P_2) + \ldots + F_i(P_i) + \ldots\ldots + F_N(P_N) \quad (14.9)$$

$$F_T=\frac{dF_1}{dP_1}\triangle P_1+\frac{dF_2}{dP_2}\triangle P_2+\ \ldots\ +\frac{dF_i}{dP_i}\triangle P_i+\ldots+\frac{dF_N}{dP_N}\triangle P_N \tag{14.10}$$

The constraint equation is :

$$\sum_{i=1}^{N} P_i=0 \tag{14.11}$$

This means that the sum of the changes in all the power outputs must be zero.

Choose one unit as dependent variable : say the x^{th} unit. Then the change in the power output for this x^{th} unit is negative of the sum of the change in power outputs of the remaining $N-1$ units.

$$P_x=-\sum_{\substack{i=1\\ i\neq x}}^{N} P_i \tag{14.12}$$

The change in F_T as a function of the change in power output of each of the $N-1$ independent machines is given by the equation—

$$F_T=\sum_{i\neq x}\left(\frac{dF_i}{dP_i}-\frac{dF_x}{dP_x}\right)\triangle P_i=\sum_{i\neq x}\frac{\partial F_T}{\partial P_i}\triangle P_i \tag{14.13}$$

The economic dispatch by the method of first order gradient search is shown in Fig. 14.3.

The steps in the algorithm are obvious for proceeding with the problem.

Step 1 : Assume feasible powers : P_i where $i=1\ \ \ldots\ \ N$

Step 2 : Select P_x, the dependable variable

Step 3 : Calculate the difference between $\frac{dF_i}{dP_i}$ and $\frac{dF_x}{dP_x}$

This is $\frac{\partial F_T}{\partial P_i}$ where $i=1\ \ \ldots\ \ N$ and $i\neq x$.

Step 4 : If the maximum load is $P_{i\ max}$ for $i=i_{max}$ select $i=i_{max}$ adjust $P_{i\ max}$, P_x This gives max $\frac{\partial F_T}{\partial P_i}$

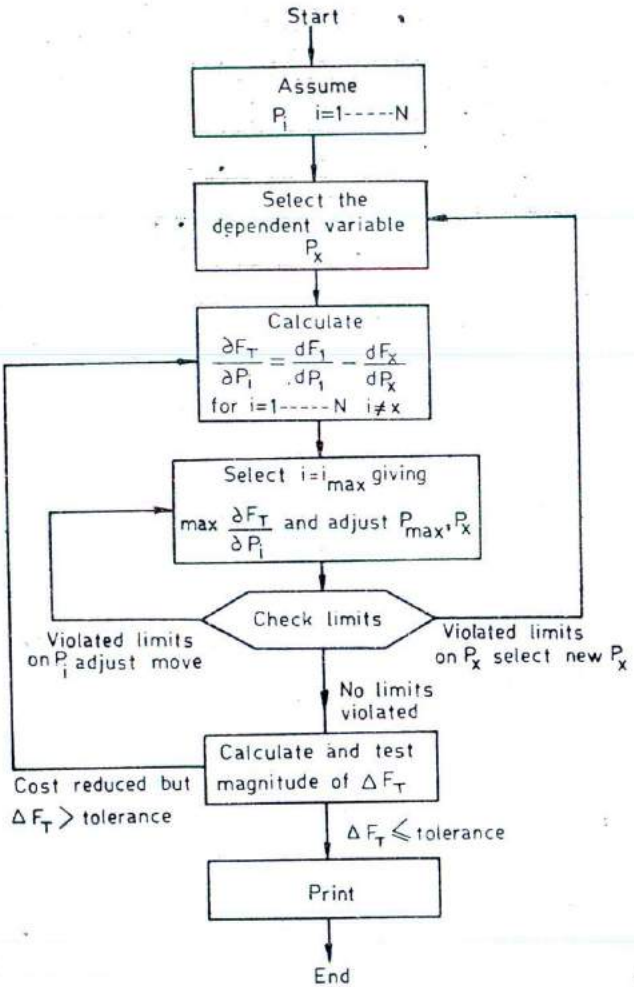


Fig. 14.3 Economic load dispatch by the method of first order gradient search

Step 5 : Check, $P_{i\ max}$, P_x. If not in the limits as required, adjust corresponding P_i and P_x by moving them in proper direction so that both i^{th} unit and x^{th} unit are within the operating constraints.

Step 6 : If the above condition for limits is satisfied, calculate the magnitude of the incremental cost $\triangle F_T$ and test it.

Step 7 : If the incremental cost $\triangle F_T$ is within the tolerance limit, the problem is over and the results can be printed to give the schedule of loading the generator units for economic dispatch.

14.4 Unit Commitment

The economic dispatch problem assumes that all the N units are already connected to the system. The unit commitment problem is more difficult to solve. To 'commit' a generating unit is to 'turn it on', i.e. synchronise it and connect it to the system so that it can deliver power to the load in the system. If the number of sets N with their capacities are given, and the daily or weekly load forecast is known, including the details of the load curve, the problem in unit commitment is which of the units should be on or off for a certain given time during the day or the week in order to obtain the minimum operating cost. A great deal of money can be saved by turning off the units when they are not needed for the time. If the operation of the system is to be optimised, the units should be shut down when the load falls and the capacity of units is not required. The problem is which of the units should be dropped or shut down and which should be left on the line. Also as the load rises again, which of the units should be recommitted ?

14.4.1 CONSTRAINTS IN UNIT COMMITMENT

1. *Spinning reserve* : This means the total generation available from all units synchronised on the system bus less the load and the losses at the particular time of operation. The reserve should be sufficient to take up load in case of a generator unit failure. The reserves should be properly allocated among

fast responding units and slow responding units in such way that with automatic generation control, it should be possible to restore system frequency to normal quickly in case of generator unit outage. The reserves may be 'off line' reserves e.g. quick starting diesel engine sets or gas turbine units, hydro and pumped hydro units. The reserves should be well spread out in the system to avoid transmission line – tie line limitations.

2. *Thermal Unit Constraints.* In case of thermal units, the temperature changes gradually and takes time for the thermal unit to bring it on the line. There are therefore constraints for thermal units. (a) Minimum/up time : If the unit is running, it should not be turned off immediately. (b) Minimum down time : If the unit is stopped, there is certain minimum time required to start it and put it on the line. (c) The unit commitment should take into account the unscheduled maintenance outages of the equipment in the thermal plants.

14.4.2 UNIT COMMITMENT SOLUTION METHODS

The techniques used for solving the unit commitment problem are : (a) Priority list schemes (b) Dynamic programming method.

(a) *Priority List Schemes.* The top priority list schemes would have steps for shutting down a unit as follows which may be put in form of an algorithm and worked out as necessary.

1. At each hour when the load is dropping, find out whether taking off the next unit on the priority list will have sufficient capacity to supply the load as well as provide the spinning reserve required. If yes, go to next step; if not, do not drop the unit but continue the operation with the units as it is.

2. Determine the number of hours after which the unit will need to be committed again.

3. If the number of hours is less than the minimum shut down time for the unit, then keep the unit on as it is. If not then go to the next step.

4. Calculate the hourly cost of production for the number of hours with unit in operation. Compare this with the cost for

situation with unit down plus starting up costs. (may be completely cooling or banking). See which is economical to shut down the unit or to keep it running.

5. Repeat the procedure for the next unit on the priority list. Continue for each next unit.

The priority list should be made considering the grouping of units to satisfy the various constraints.

(b) *Dynamic Programming Method.* Dynamic programming has the advantage of reduction in the dimensionality of the problem. The procedure is set for determining the optimal schedule and the minimum total fuel cost. This is done either by 'Backward Dynamic Approach' or by 'Forward Dynamic Approach' method. The detailed algorithms and problems are given in reference 14.3.

14.5 Loading of Hydro Units

Each hydro electric plant is different from the other. This is because of differences in watershed, differences in storage and release requirement of water and constraints on the operation of hydroelectric systems. For best use of hydraulic resources, the hydro unit should operate at its best efficiency gate position and near the designed head. Water release schedules must be coordinated with the reservoir inflows to maintain as high head on the turbine as possible. The incremental 'water rate' is defined as cubic metres per kWh or per Mwh.

14.5.1 SCHEDULING OF HYDRO UNITS IN HYDRO AND THERMAL SYSTEM

(a) In case of hydro units without thermal units in the system the problem is simple. The economic scheduling consists of scheduling water release to satisfy the hydraulic constraints and to satisfy the electrical energy demand.

(b) Where hydrothermal systems are predominantly hydro, scheduling may be done by scheduling the system to produce minimum cost for the thermal system.

(c) A large number of hydro thermal systems are such that there is good balance between thermal and hydro electric resources; or there may be systems where hydro component is small compared to total system capacity. In such cases, schedules should minimise the thermal production costs satisfying the hydraulic constraints.

14.6 Hydro Thermal Scheduling

In such system, the problem is of energy scheduling. If a steam plant and hydro plant is supplying the system load, it may be that the hydro plant can supply the load for limited time as energy available from it is not enough to supply load requirement all the time. The problem would be to use up the energy from hydro plant such that the cost of running the steam plant is minimum.

The steam plant should be run at constant incremental cost for the period it is run.

If a steam plant and a hydro plant is to supply load for given period, and the characteristics of the plants are given in terms of cubic metres/hr for hydro plant and heat rate for the steam plant, and capacity of each plant, the problem may be considered in two ways : (i) Limit the energy supplied by hydro (in Mwh), find energy which should be supplied by steam plant. Solve for time of running steam plant. Knowing the energy to be supplied by the steam plant and the load which it can supply at maximum efficiency, find the time for which it should be run. Then find the load on hydro and steam plant for the period for which each should run.

(ii) There may be a limit on the volume of water to be drawn from the reservoir for the hydro plant. Find the characteristics of hydro plant $q\ v/\ s\ P$. Find the time for which steam plant should run.

The following information is required for the study of the problem. Hydro and thermal plant capacities and their characteristics, the number of units, penalty factors depending on the

type of fuel used, transmission loss at each station, load curve, total losses in the system, incremental losses, head at hydro plants, average, minimum and maximum flow of water at hydro plants. If it is assumed that the hydro plants work at constant heads and the thermal plants will operate with the least cost of the fuel during the year, the economic schedule can be worked out by the use of co-ordinate equations.

For the operation in hour k,

$$n_k \frac{d^F (P_{sk})}{d P_{sk}} + \lambda_k \frac{\partial P_{loss\ k}}{\partial P_{sk}} = \lambda_k \qquad (14.14)$$

$$\gamma\ n_k \frac{dq(P_{HK})}{d P_{HK}} + \lambda_k \frac{\partial P_{loss\ k}}{\partial P_{HK}} = \lambda_k \qquad (14.15)$$

n_k is the k^{th} interval

subscript s is for steam plant,

subscript H is for hydro plant

q is cubic meters/hour

λ_k is incremental cost in k^{th} interval

γ=constant of conversion of incremental water rate into equivalent incremental plant cost.

The hydrothermal scheduling can be worked out by iteration scheme. Check that δ_1, the tolerance on load balance and δ_2 the tolerance on water balance are within the limits permissible.

The short term hydro thermal scheduling can also be done by a Gradient Approach, or by Dynamic programming approach (reference 14.3)

14.7 Generation Allocation Control

Electrical power systems will consist of control areas with many generator units with outputs which must have economical loads. It is therefore necessary to couple economic load dispatch calculations and control mechanism together to know the requirement of generation from each individual generation unit in the area. Analog computers or digital computers can be used for

allocation of output from each unit as per economic load dispatch calculation. An analog computer can be used to provide the economic load dispatch and allocation of generation in an area on an instantaneous basis through the use of function generators set to unit's incremental heat rate curves. When using digital computers, it is first necessary to calculate economic dispatch calculations at intervals of every minute or so for several minutes. The output is fed to another program in the computer that carries out the control functions.

The allocation of individual generator output out of total generation is obtained by using base points and participation factors. Base point generation output of each unit is obtained by the economic dispatch calculation. This is $P_{i\ base}$ for i^{th}unit in the system. The rate of change of each unit's output with reference to a change in total generation is termed the unit's participation factor, *pf*.

$$P_{i\ des}=P_{i\ base}+pf_i\Delta P_{total} \tag{14.16}$$

where $$\Delta P_{total}=P_{new\ total}-\Sigma P_{i\ base} \tag{14.17}$$

$P_{i\ des}$ is new desired generation of unit i

ΔP_{total}=change in total generation

When direct digital control is used, the generation allocation would be done by running a computer code that was programmed to satisfy (14.16).

14.7.1 AUTOMATIC GENERATION CONTROL

The modern automatic generation control schemes consist of a central location where information about the system is telemetered. Control required is determined in a digital computer and then transmitted to the generator units via the same telemetry channels. The following information is needed at the control centre.

(i) Unit megawatt output for each unit on the line

(ii) Megawatt flow over each tie line

(iii) System frequency.

For controlling the output of each unit, raise or lower pulses of varying lengths are transmitted to the unit. Control equipment changes the unit's load reference set point up or down in proportion to the length of the pulse signal. The basic reset control loop for a unit consists of an integrater with gain K. The basic generation control loop is shown in Fig. 14.4

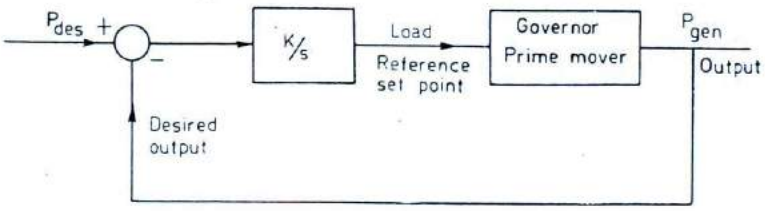


Fig. 14.4 Basic Generation Control Loop

P_{des}, the control input is a function of system frequency deviation—net interchange error—and each unit's deviation from its scheduled economic output. Area control error (ACE) is the error in total generation from total desired generation. Sum of the unit output errors is added to Area Control Error to form a composite error signal. This drives the entire control system. The overall control system will try to drive ACE to zero, also drive each unit's output to its required economical value.

A good automatic generation control (AGC) should have the following criteria :

(i) The standard deviation of ACE should be small.

(ii) Integral of ACE over an appropriate time should be small.

(iii) The amount of control action called for by the AGC should be kept to minimum.

14.8 Generation System Reliability

In planning generation capacity requirements in a power system, probability methods are used. The technique asssigns a

probability to the generating capacity available, describes load demands, and provides measure of probability of failure to supply expected load or energy.

The probability methods used for the study are :

(1) The loss of load method.

(2) The loss of energy method

(2) The frequency and duration method.

The first method measures the failure probability of meeting peak loads. The second measures reliability of meeting expected energy. The third method calculates the expected frequencies of outages, of various capacities of units and their expected durations of outages, knowing these and forecast loads and reliability standards. It is possible to determine the reserve capacity margin required. For long term operation of the unit such as a day, the availability of the unit is shown in Fig. 14.5.

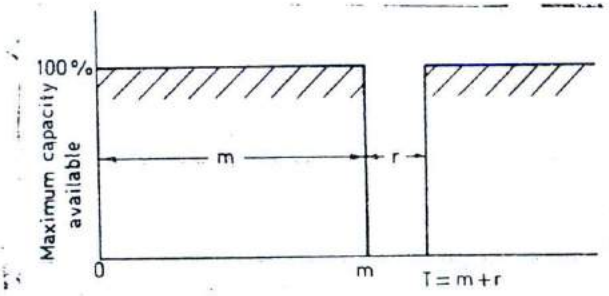


Fig. 14.5 Average availability cycle of a generating unit

m = average time the unit is available.

r = average repair time for the unit.

$T = m + r$ = mean time between failures.

From this, the rates of availability and outage for the unit are defined :

$$p = \frac{m}{T} = \text{availability rate per unit} \qquad (14.18)$$

and

$$q = 1 - p = \frac{r}{T} = \text{outage rate per unit.} \qquad (14.19)$$

or non-aaailability rate per unit

The Patton's security function estimates qualitatively the probability that the available generation capacity at a particular hour is less than the system load at that time. The sum of the capacities of the units committed

$$S = \Sigma p_i r_i \qquad (14.20)$$

where p_i = probability of system in state i

r_i = probability that system state i causes breach of system security.

The reliability or security methods are used to calculate optimal unit commitment with the given or required constraints. Probability methods are used for loads to be served and energy and capacity resources and mathematical models developed. Production cost programs are developed recognising unit forced outages. Economic scheduling can be done allowing for the probability of unit outages.

14.9 Power System Security

System security requires practices designed to keep the system operating when the components fail e. g. if there is failure in the auxilary equipment, a generating unit may have to be taken off the line. The deficit load can be taken up by the spinning reserve. A transmission line may be automatically taken out of system in case of fault such as damage by storm. If proper care is taken in units commitment and dispatching generation properly over transmission system, after the faulty line is out, the remaining transmission lines can take up the increased load.

The system security has three major functions to be carried out in operation control centre :

(1) System monitoring
(2) Contingency analysis
(3) Corrective action analysis.

The system monitoring provides uptodate information of the system condition to the system operators. Telemetry systems of measurement monitor voltages, currents, power flows, circuit breaker operation status in various sub-stations, etc. Also

frequency and generator unit outputs. The digital computers at the control centres gather the telemetered data, process them. The computers also check the data acquisition incoming information against prestored information ano give alarm to the operators in case of overloads or high voltage etc.

The security contingency analysis allows the systems to be operated defensively. The modern computers are equipped with contingency analysis programs which model possible system troubles before they arise. They study outage events and alarm the operators to possible overloads or overvoltages etc. The system operators can then operate with defensive states of the system. This avoids cascade failures. Contingency analysis develops operating constraints which can help economic dispatch and unit commitment program.

The corrective action analysis help operators to adjust the operation of the system in case of serious problem due to outage, etc. The action may e. g. involve shifting of generation from one unit to the other.

References

14.1 R. L. SULLIVAN., *Power System Planning*, McGraw-Hill International Book Company, 1977.

14.2 I. J. NAGRATH, D. P. KOTHARI, *Modern Power System Analysis*, Tata McGraw-Hill Publishing Co. Ltd., 1980

14.3 ALLEN J. WOOD, BRUCE F. WOLLENBERG, *Power Generation, Operation, and Control*, John Wiley & Sons, 1984.

Problems

14.1 Explain the methods of forecasting peak loads and energy demands.

14.2 Explain the principle of economic load dispatch between thermal station generator units. Illustrate by an example.

14.3 Discuss economic load dispatch on units considering losses in transmission system.

14.4 Explain the economic load dispatch on generator units by (i) the method of Lamda iteration: (ii) first order gradient search.

14.5 What is meant by 'Unit Commitment' ? What are the various constraints in the problem ? What techniques are used to solve unit commitment problem ?

14.6 Explain the methods of loading Hydro units.

14.7 Explain Hydro-thermal scheduling and loading the units.

14.8 How is the generation allocation controlled ?

14.9 Explain generation system reliability. What are the methods used to determine it ?

14.10 What is meant by 'Power system Security' ? State the main functions of system security and how they are carried out at the operation control centre.

15

Modern Trends in Power Plant Instrumentation and Control

15.1 Solid State Relaying

Solid state relays are those in which the response is developed by electronic, magnetic or other components without mechanical motion. The solid state components used are transistors, diodes, resistors, capacitors, etc. The functions of comparison and measurement are effected by static circuits.

Advantages of static relays

(i) Low burden on current and potential transformers,
(ii) No mechanical inertia,
(iii) Fast operation,
(iv) Low maintenance,
(v) Quick reset,
(vi) Greater sensitivity,

Basic construction of solia state relays

Besically, solid state protection relays are analogue-binary signal converters with measuring functions. The variables are voltage, current, phase angle or frequency and derived values obtained by differentiation, integration, etc. These appear as measuring signals at the input. The output is the binary signal OFF or ON for relay operation.

The signals from the measuring unit are fed to converter unit. The converter connects the measuring signals which are then processed by the measuring element. The measuring ele-

ment will be operated when the input signal reaches the desired value to close signal at its output. The output element amplifies the binary signal and transfers it to controlled elements, which carry out the final function such as opening/closing of circuit breakers.

Converter element

In relays for 2 quantities, the converter element is fed at its input by 2 electrical quantities. Comparison is done either of the amplitude or phase between two signals. The signals are converted to voltage or current signals. Figs. 15.1 and 15.2 show the principle.

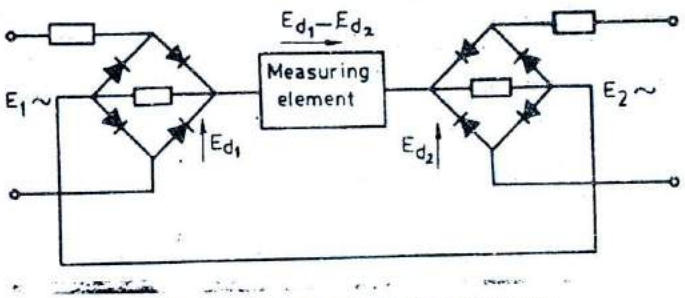


Fig. 15.1 Voltages comparison of signals

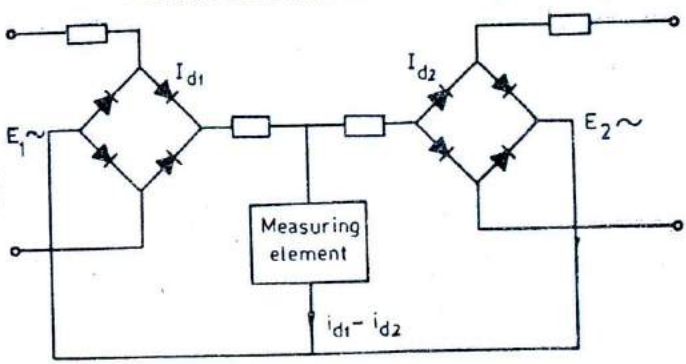


Fig. 15.2 Current comparison of signals

There is also phase type comparison. In this method of comparison, one of the variables is converted into pulse when

passing through zero, and the second is converted into a rectangular block. When the pulse and the block coincide, a close signal is obtained at the output of the comparator circuit. In phase comparison, the response is very short.

In circuit of Fig. 15.1, E_1 and E_2 are alternating voltages input signals to rectifier converters which convert to E_{d1} and E_{d2} *dc* signals and the difference between the two is fed to the measuring element.

In circuit of Fig. 15.2 the rectifier converters convert E_1 and E_2 alternating voltage signals into *dc* current i_{d1} and i_{d2} and the difference of these current signals is fed to the measuring unit.

Measuring element is analog binary signal converter with measuring functions. The Schmitt trigger circuit is the basic circuit for this purpose. This is shown in Fig. 15.3.

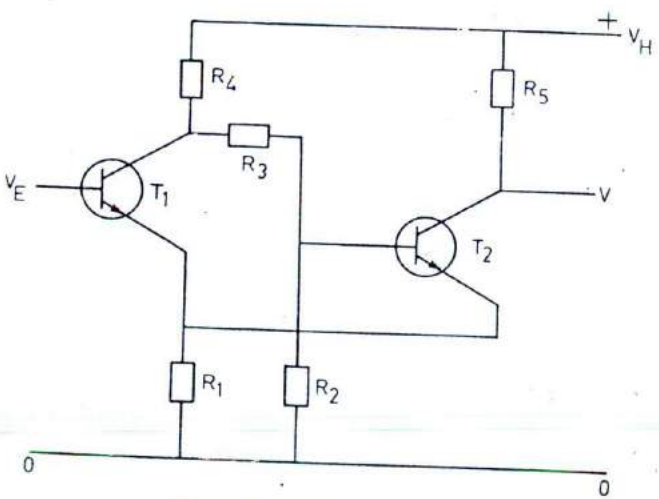


Fig. 15.3 Schmitt trigger circuit

In this circuit, transistors are used in common emitter mode giving high input resistance and large current gain. The circuit acts as level detector. It gives a step output when the input voltages exceed the specified level.

The Output element amplifies signal from the measuring element. It may be in form of bistable or monostable vibrator circuit modulated by logic circuits. When large power is required such as operating trip coil of circuit breakers SCR are used after the logic element.

15.2 Overcurrent Relays

There are two categories of overcurrent relays : (i) instantaneous and (ii) Time overcurrent.

The block digram of instantaneous overcurrent relays is shown in Fig. 15.4.

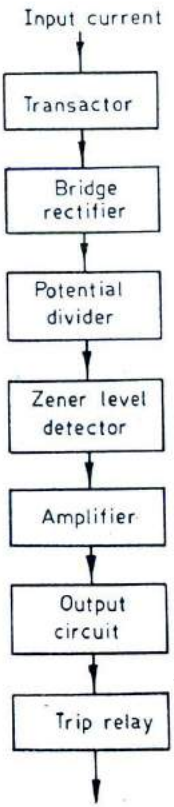


Fig. 15.4 Block diagram of Instantaneous overcurrent relay

Input current is current from the main C. T. which is fed to the transactor which produces proportional *ac* voltage. This voltage is rectified through a bridge rectifier. A fixed portion of the rectified voltage is compared against the breakdown voltage of Zener diode. This is amplified, given to output circuit and then to trip relay.

Time Overcurrent Relays

The time overcurrent relays are of the following types :

		approximate relation $I^n t = K$
(i)	Definite time	$I^\circ t = K$
(ii)	Inverse definite minimum time	$I\ t = K$
(iii)	Very inverse	$I^2 t = K$
(iv)	Exteremelv inverse	to $I^3 t = K$

where I=fault current, K is constant, t=time in seconds, n exponent.

Definite time overcurrent relays are used for wide variation of system conditions, as back up relays for differential and distance protection, differential protection of transformers to prevent maloperation during magnetization in rush currents. Inverse time relays are used where source impedance is much smaller than the line impedance. Extremely inverse overcurrent relays are used for fuse co-ordination and thermal protection of transformers and induction motors.

The general expression for the operating time of a time current relay is—

$$t = \frac{KM}{I^n - I_p{}^n} \qquad (15.1)$$

where I=multiple of tap current

I_p=multiple of tap current at which pick up occurs

K=design constant

M=time multiplier setting

If relay picks up at top value of current

$$t = \frac{KM}{I^n - 1} \qquad (15.2)$$

The induction disc relays have non-linear design factors. For relays to be converted to static form, approximate mathematical form used in India and U. K. are :

(i) IDMT $\quad t = \dfrac{0.14}{(I^{0.02} - 1)}$

(ii) Very inverse $\quad t = \dfrac{13.5}{(I - 1)}$

(iii) Extremely inverse $\quad t = \dfrac{80}{(I^2 - 1)}$

In static relays it is advantageous to choose a circuit accommodating a wide range of alternative inverse time characteristics, precise minimum operating levels, definite minimum times and additional high set features if necessary.

15.3 Differential Relays

Static differential relays : In static relays of this type, rectifier bridge amplitude comparator is most common static form for application as a differential relay element. Fig. 15.5 shows static type percentage differential relay.

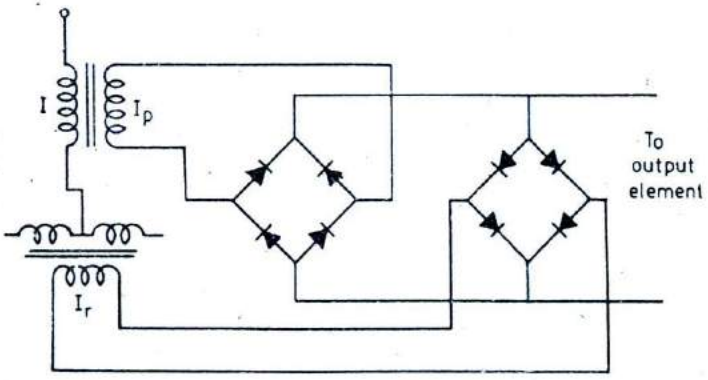


Fig. 15.5 Static type percentage differential relay

The difference between the current in operating coil and restraining coil is given to the output element for operation of the relay.

The operating criterion is

$$K_p\,(n_p\,I_p) = K_r\,(n_r\,I_r) + K' \qquad (15.3)$$

where K_p and K_r are design constants, n_p . n_r

are number of turns in operating and restraining coils

K' = spring control torque constant

If, $I_{p\ min}$ = minimum *pick* up current

$$K' = K_p\,(I_{p\ \ min}\,n_p)$$

Therefore,
$$K_p\,n_p\,I_p - K_r\,n_r\,I_r = K_p\,I_{p\ min}\,n_p$$

$$I_p = K_R\,I_r + I_{p\ min} \qquad (15.4)$$

where
$$K_R = \left(\frac{K_r\,n_r}{K_p\,n_p}\right)$$

The differential relay characteristics are shown in Fig. 15.6

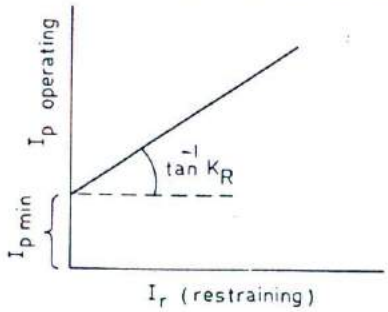


Fig. 15.6. Differential relay characteristics

The differential current schemes do not react to pea k currents caused by overloads or swings, also due to dissimilarity in C.T.s, inrush magnetizing current in transformer protection.

Static relays schemes

In general, the static relay schemes use comparator, and feed the difference to output through amplifier. The output is used

for indication and/or trip circuit. The rectifier bridge comparator for static schemes is shown in Fig. 15.7.

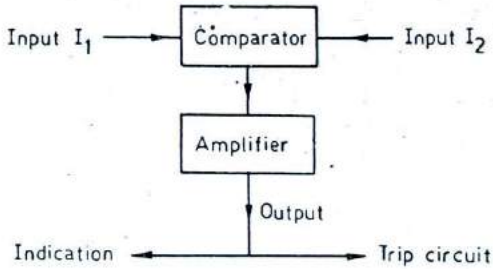


Fig. 15.7 Rectifier bridge comparator for static schemes

Static schemes compare voltage outputs or current outputs. The static schemes unlike electromagnetic schemes are capable of being combined into polyphase schemes. In static protection schemes, the power consumption is negligible. The line as well as auxiliary current transformers with secondary burden should have accuracy limit factor corresponding to maximum through fault current of at least 20 times the rated current.

15.4 Trends in Power Plant Instrumentation and Control

As the size of the units goes up, it is necessary to go in for more sophisticated instrumentation and control system for higher reliability and the maximum availability of the unit. In India the first 500 MW unit is installed recently at Trombay. Some of the salient features of the instrumentation and control system introduced for the Unit are as follows :

Measurement system

(a) This system uses adoption of electronic transmitti transducers with signal range of 4—20 mA DC and 2 wire system to obtain flexibility and standardisation of signal range with computerised data acquisition system.

(b) The system uses independent transmitter/transducers for control functions of each controlled process variable for indication or recording.

(c) The system has automatic compensation for variation in operating conditions to obtain accurate measurement.

(d) All analog and digital signals are signal conditioned in signal conditioning cards in control room. This helps in distribution of signals to different systems ; also for monitoring the health of the cables.

(e) The system has arrangements of continuous monitoring of quality of steam condensate and demineralised water by analytical instruments for measurement of phosphate, silica, sodium and dissolved oxygen.

(f) The system has arrangement to monitor flue gas for automatically positioning excess air control and also for combustibles in exit flue gases.

(g) The system has pollution control monitoring equipment for measurement of SO_2, NO_x and smoke density to keep pollutants within limits.

Analog Control System

(a) Co-ordinated feed forward control is used to co-ordinate operation of steam and turbine generators.

(b) For minimising/avoiding occurrence of furnace explosions and implosions both air flow control devices and flue gas flow control devices are provided with directional blocking system in addition to conventional control systems.

(c) Flue gas flow through each ID fan is controlled by deviation in fan suction pressure from desired value.

(d) Feedwater flow to steam generator at higher loads (30% MCR) is regulated by adjusting boiler feed pump (turbine driven) speeds through steam turbine speed control.

Digital Control Systems, Protection and Interlock System

(a) The system uses advanced solid state electronic devices.

(b) Start up and shut down of unit is effected in short duration with minimum manual intervention.

(c) To have better reliability and availability of unit the principle of redundency is adopted on vital systems.

(d) Safety protection system is segragated from normal automatic system.

15.5 Pollution Control

In thermal stations—steam electric generating stations, using fossil fuels, pollution is caused due to polluted condition of water, air, solid waste, etc. in the process. It is necessary to have performance standards and controls to check the pollution within limits. 'Environment Impact Assessment Guidelines for New Source Fossil Fueled Steam Electric Generating Stations' gives the pollution control measures used and the performance standards in U.S.A. Some of the points from it are mentioned below :

I In Process Controls for Water, Air, Solid Waste

(*a*) *Ash handling waste*

The performance standards state that there will be no discharge of suspended solids from flyash transport water. To do this—

(i) Use dry ash handling systems in place of wet systems.

(ii) Recycling of ash handling water with evaporation.

(iii) Treatment and reuse of ash handling water.

(iv) Possible use of ash as cement additive.

(*b*) *Air pollution emissions*

Reduce air pollution emissions by combustion modifications to reduce nitrogen oxides in the stack gases and the use of low sulphur coal.

(*c*) *Solid waste*

The sources for this are ashes and sludges from water treatment and stack gas scrubbing. Choose proper process to reduce these.

II Standards of Performance Technology : End of Process Controls

Major pollutants in power plant wastes are metals, suspended solids, oil and grease and chlorine. Reduce them by process of oxidation, neutralisation and settling. The methods used are :

(i) raise pH to neutral or slightly alkaline values.

(ii) allow sufficient time for chlorine to dissipate.

(iii) use settling tank to remove settleable solids and floating materials.

III Standards of Performance Technology : End of Process Control : Air

Fuel combustion in generating stations results in emission of sulphur oxides, nitrogen oxides and flyash. New sources of performance standards place limitations on SO_λ, NO_x and particular matter emissions from fossil fuel fired power plants. Pollution control methods are used to keep these within limits.

(*a*) *Flyash control*

(*i*) *Electrostatic Precipitators* : Electrostatic precipitator chambers contain flat parallel plates from 15 to 30 cm apart with rod or wire electrodes between them. A high voltage is applied to the electrodes, the wire or rod serving as negative discharge electrode and grounded collection plate as the positive electrode. A direct current high voltage corona is estabilished in the inter electrode space around the discharge electrodes. This ionizes the molecules of electro negative gases such as O_2, CO_2 and SO_2 present in the flue gas. The gas ions move rapidly towards the collecting electrode, the magnitude of force depending on charge and intensity of field. The accumulated dust is removed from the collection electrode by rapping at intervals to dislodge the deposits.

The efficiency is between 99% to 99.9%. The flyash (0.4 to 1% of total flyash) which escapes the precipitator is smaller than 1 or 2 microns in size.

(*ii*) *Wet scrubbers* : Wet scrubbers remove particles by impacting them with water droplets. For power plant, Ventury and moving bed type scrubbers are used. Inertial impact is considered in collection mechanism. Flue gas velocities are in the

range of 60-120 m/sec to produce a high relative velocity between gas and liquid collector droplets. Efficiency is about 99% and the method is capable of flyash removal to 0.02 gram per 0.03 cu. m. In moving bed scrubbers, a perforated plate held within a cylindrical shell supports the movable packing, while the liquid is sprayed downwards over the bed of spheres. Fabric filters usually in form of baghouses remove particles by filtering the gas through a porous flexible fabric—e. g. glass fibers.

(*b*) *SO_x Control*

1. *Use low sulphur coal* : This reduces operating and maintenance costs and solid waste disposal problems of flue gas desulphurization.

2. *Coal Benefication* : This consists of crushing the coal and separating heavier pyritic sulphur bearing particles which are $3\frac{1}{2}$ times as dense as coal from higher coal by mechanical means. Sulphur reduction can be as high as 46% and ash reduction as much as 65%.

3. *Flue gas desulphurization* :

For this the control systems are :

(i) lime/limestone scrubbing

(ii) double alkali scrubbing

(iii) magnetic scrubbing

(iv) the Weeman-Lord process.

The first two systems are throw away systems while the last two are regenerable.

(*i*) *lime/limestone scrubbing*

In this process, SO_2 in the flue gas comes in contact and chemically reacts with a recirculating lime or limestone slurry in a scrubber to form a precipitate or sludge. Through oxidation of sulphites, sulphates are formed. The reacted lime or limestone slurry from the scruober goes to the reaction tank where calcium sulphite and calcium sulphate precipitate as hydrated solids when fresh lime or lime stone is added. The cleaned gas is reheated

above its dew point and released through the stack. The process removes about 90% SO_2 from flue gases.

(*ii*) *Double Alkali scrubbing*

SO_2 in the flue gas reacts with sodium sulphite (Na_2SO_3) liquor :

$$SO_2 + Na_2SO_3 + H_2O \rightarrow 2\ NaHSO_3$$

The spent scrubber effluent is then regenerated with lime/limestone scrubbing process. Make up water and alkali are first added to the separator effluent liquor before being recycled to the scrubber. Na_2SO_4 is removed from the process through a liquid purge stream. Efficiency 90-97%.

(*iii*) *Magnesia scrubbing*

This regenerable process uses a magnesium sulphite ($MgSO_3$) slurry to react with the SO_2 in the flue gas. The spent scrubber liquor is regenerated with magnesium oxide (MgO). MgO is regenerated by concentrating a part of the magnesium sulphite ($MgSO_3$) slurry in a solid liquid separator, drying the concentrated solid, and calcining the dried solid to form MgO and SO_2. The SO_2 is recovered by sending it to the sulphuric acid plant to produce 98% H_2SO_4.

(iv) Wellman-Lord process uses a sodium sulphite (Na_2SO_3) liquor to react with the flue gas SO_2. The spent liquor is thermally regenerated in an evaporator/crystallizer. Water from gas stream from the evaporator is recovered by means of a condenser and separated from SO_2 rich gas stream and then returned to the scrubbing loop. SO_2 is recovered in a sulphuric acid plant.

(c) *Coal beneficiation combined with flue gas desulphurization : Intermittent Control Systems*

Intermittent control system rather than continuous emission control may be more cost effective for compliance with emission standards, when short term ground level concentrations of SO_x near the source are to be controlled.

In case of unfavourable atmospheric conditions methods used for control are—

(i) temporarily burn low sulphur fuel.

(ii) Load switching : Take electric load to another generating plant that has available capacity and can comply with emission standards.

IV Nitrogen Oxide (NO_x) Control

NO_x formed in combustion originates from—

(i) Thermal fixation of atmospheric oxygen in the combustion air to form NO_x

(ii) NO_x production from the conversion of chemically bound N in the coal.

Overall control of excess air consistant with efficient burner operation can reduce NO_x.

Another method of NO_x control is by staged combustion. Create two combustion zones—a primary reducing zone and a lower temperature post flame oxidizing zone. Reduction is by 50 to 65%.

V End of process control—Solid waste disposal

Flyash collected from any of the last three methods is conveyed to a mixing tank, is mixed with the bottom ash slurry or piped directly to ash ponds. Dewatered flyash may be disposed of in land fill sites, fertilizer, asphalt mixes, roads, cement, etc.

Removal of SO_2 from flue gas results in waste sludge by-product. This can be dewatered to about 50% solids and transferred to settling ponds. Add flyash to the limestone scrubber sludge before transferring to the evaporation ponds. After evaporation, material is taken to off site lanfill area.

Slag and bottom ash drops in water filled hopper. The ash and water slurry from wet and dry bottom boilers is sometimes mixed with flyash and piped to settling ponds.

15.6 Performance Standards

Air Pollution Performance Standards

New Source Performance Standards (NSPS) (40 CFR 60) specify the emissions allowed from fossil fueled steam generators as follows :

Table 15.1

Pollutant	Coal	Oil	Gas
Sulphur dioxide	2.16 kg/10^6 kilocalories	1.44 kg/10^6 kilocal.	1.44 kg/10^6 kilocal.
Nitrogen oxides	1.08 kg/10^6 kilocal.	0.54 kg/10^6 kilocal.	0.36 kg/10^6 kilocal.
Particular matter	0.18 kg/10^6 kilocal.	0.18 kg/10^6 kilocal.	0.18 kg/10^6 kilocal.

For coal, a 90% reduction in SO_2 is required at all times except where emissions to atmosphere is less than 1.1 kg/10^6 kilocal. When SO_2 emissions are less than 1.1 kg/10^6 kilocal, 70% reduction in emission is required.

For oil and gaseous fuels, 90% reduction in SO_2 is required when SO_2 emission to atmophere is less than 0.4 kg/10^6 kilocal. reduction requirement does not apply.

Table 15.2

Federal ambient air quality standards

Emission	Primary	Secondary
Sulphur dioxide	80 $\mu g/m^3$ annual arithmetic mean 365 $\mu g/m^3$ max. 24 hr. concentration.	1300 $\mu g/m^3$ maximum 3 hr concentration

Emission	Primary	Secondary
Particular	75 $\mu g/m^3$ annual geometric mean 260 $\mu g/m^3$ max 24 hr concentration	150 $\mu g/m^3$ max 24 hr concentration 60 $\mu g/m^3$ annual geometric mean
Nitrogen dioxide	100 $\mu g/m^3$ annual arithmetic mean	100 $\mu g/m^3$ annual arithmetic mean
Ozone	0.12 ppm (235 $\mu g/m^3$) max 1 hr concentration	0.12 ppm (235 $\mu g/m^3$) max 1 hr concentration
Carbon monoxide	10 mg/m^3 (9 ppm) max 1 hr concentration 40 mg/m^3 (35 ppm) max 1 hr concentration	10 mg/m^3 (9 ppm) max 8 hr concentration 40 mg/m^3 (35 ppm) max 1 hr concentration

Table 15.3

Maximum allowable increase

Pollutant	Class I $\mu g/m^3$	Class II $\mu g/m^3$	Class III $\mu g/m^3$	Class I exception $\mu g/m^3$
Prticular matter				
Annual geometric mean	5	19	37	19
24 hr max	10	37	75	37
Sulphur dioxide				
Annual arithmetric mean	2	20	40	20
24 hr max	5	91	182	91
3 hr max	/25	512	700	325

Source : Public law 95-95 1977 Clean Air Act Amendment of 1977

Water Pollution Standards of Performance

Federal Water Pollution Control Act (Public Law 92-500) Standards FR 39 No. 196 gives the maximum allowable concentration of impurities in the various waste streams from a steam electric generating station.

1. The pH of all discharges shall be within the range of 6.0—9.0

2. There shall be no discharge of polychlorinated biphenyl compounds, e. g. those used for transformer fluids.

3. Pollutants discharged in bottom ash water

$$= \frac{\text{flow of bottom ash water} \times \text{concentration C}}{20}$$

Value of C for—

Total suspended solids : 100 mg/l max for any 1 day
30 mg/l max average of 30 consecutive days.

Oil and grease : 20 mg/l daily max.
15 mg/l max 30 day average

4. No discharge of total suspended solids or oil and grease is allowed in discharges of flyash transport water.

5. Concentration of pollutants in the discharge of boiler blowdown and metal cleaning wastes shall not exceed—

Total suspended solids	100 mg/l daily max.
	30 mg/l 30 day average
Oil and grease	20 mg/l daily max.
	15 mg/l 30 day average
Copper, total	1 mg/l daily max.
Iron total	1 mg/l daily max.

6. The discharge of various other low volume wastes, such as ion exchange wastes, floor drains etc. shall not contain pollutants in excess of

total suspended solids	100 mg/l daily max.
	30 mg/l 30 day average
oil and grease	20 mg/l daily max.
	15 mg/l 30 day average

7. The free available chlorine in the discharge of oncethrough cooling water of cooling tower blowdown is limited to 0.5 mg/l max. and 0.2 mg/l average concentration.

15.7 Application of Computers in Power Systems

In power systems, typical real time computer control applications include control systems for Nuclear generating stations, training simulators for nuclear plants. Computer data acquisition for transformer stations and data acqusition and control for power transmission networks.

System Reliability

The system consists of two identical central processor units (CPU's), one master and the other slave. Both CPU's are normally on line, only master unit is connected (via switchover system) to transient command to the system peripherals and the remote terminal units (RTU's). The slave CPU's data base is updated continuously to the same level as the data of the master CPU to allow rapid change switchover from master CPU to the slave CPU. This is done by connecting all input signals to both CPU's, while the outputs are switched to the master CPU.

The transfer from the master to the slave CPU is automatically initiated by an external supervisory device or the master CPU if the latter detects malfunctions degrading the system. Dual communication lines and dual computer interfaces are used between the control centre and each remote terminal unit. The switching arrangement is an optimised translation of the customer's reliability requirements into a simple communication interface system.

Operator's Display System

Data logging is done on printers with graphic printout capability. Mimic board diagram shows the main equipment being monitored and controlled at the RTU's, e. g. generators, main circuit breakers, transformers, transmission lines. Two state devices such as circuit breakers are represented by indicator

lights. Telemetry readings are represented by numerical display units.

The special function control keyboard has groups of illuminated push buttons for the most frequently used operator commands. The push button groups allow direct RTU selection, display type selection, display assignment and editing, RTU field device control (On-Off, raise-lower, etc.) analog limit controls, alarm acknowledge and lamp test.

CRT display

On every CRT picture, the top two lines are used to display command messages from the operator to the computer and alarm error and information messages from the computer.

RTU field device commands are entered by the operator via display edit keyboard or via push buttons on control board. When the operator is satisfied that the right selection has been made, he presses the 'execute' botton, whereon the computer transmits a select-check-execute message signal to the RTU. When the selected field device has completed its operation, the computer displays the new device status to the operator.

Computers can also be used to have better maintenance and disgnostics to ensure high equipment availability. This is becoming more important as control equipment is becoming more complex.

References

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Problems

15.1. State the principle of solid state relays. Explain the method of current comparison, voltage comparison. State advantages of solid state relays, explain their basic construction, the functions of converter element and measuring element.

15.2. What are the various types of overcurrent relays used in power systems. Explain their functions, show block diagram of instantaneous overcurrent relay.

15.3. Explain static type percentage differential relays. Explain their operating characteristics and applications.

15.4. Enumerate various trends in power plant instrumentation and control systems in modern high capacity generating stations.

15.5. What are the sources of pollution in thermal power plants ? Explain in process controls for water, air and solid wastes.

15.6. Explain the pollution controls of the following :

(a) Flyash control

(b) SO_x control

(c) NO_x control

(d) Solid waste control.

15.7. State Air pollution performance standards for coal oil and gas burned as fuel in steam generating stations. What are the Federal ambient air quality standards—primary and secondary—that should be maintained ? What is the maximum permissible increase in particular matter and SO_2 ?

15.8. State the water pollution standards of performance expected in thermal stations.

15.9. Explain application of computers in power systems with reference to (a) System reliability (b) Operator's display system (c) CRT display.

15.10. What are the functions of (i) main computer, (ii) Slave computer and (iii) Remote terminal units. ?

16

Unconventional Sources of Energy and Plants

16.1 Need for Search of Unconventional Sources of Energy and Plants

The reserves of fossil fuels in the world is depleting very fastl and if they are used at the same rate indiscriminately, they wil soon be exhausted. The non-renewable fuels are solid fuels, crude oils; natural gas. There is, therefore, urgent need to consider the problem as total energy needs and how to supply them for the people in the country. The energy requirements can be considered as commercial and non-commercial; also the needs of the energy for urban and rural areas. It is necessary to find out the various resources and use them economically. There is urgent need to find out renewable sources of energy and their conversion into useful power for use of the community.

The various types of fuels used at present and their efficiencies in terms of coal equivalent (metric tons coal equivalent—mtce—) and coal replacement units (metric tons of coal replacement—mtcr—) are given in Table 16.1.

16.2 Energy Supply Options

The fossil fuels are used for conventional power stations for producing electricity and supply power. For supplying part of the energy requirement to rural areas in particular, biogas, and biomass plants can be used. Renewable sources of energy such as solar energy and energy from wind can be harnessed to meet energy requirements.

Table 16.1

A comparison of efficiencies of different fuels in terms of coal equivalent and coal replacement units

Fuel	cal/kg	mtce	mtcr	η relative to coal
Coal	7000	1	1	1
Crude oil	10290	1.47	1.47	1
Kerosene	11130	1.59	6.60	4.08
Natural-Gas	11620	1.67	3.40	2.0
Electricity (1000 kwh)	—	0.123	0.24	2.0
Firewood	4500	0.64	0.64	1
Agricultural Waste	4500	0.64	0.64	1
Dung	3300	0.47	0.47	1

16.2.1 SOLAR ENERGY APPLICATIONS

Solar energy is useful and advantageous for non seasonal and day time applications. In remote areas where conventional power or energy is not available, solar devices are useful. At present, the costs of solar applications are high in comparison with the other options, the factor being 10 to 20 depending on application and specific conditions. Where energy is required at night, costs of storage have to be added which makes the capital costs still higher.

(*a*) *Solar Thermal Applications* : These are based on flat collectors or concentrators. Solar cookers, Solar dryers for crops, rural industries, solar desalisation in areas where water is saline, solar pumps based on thermal energy to obtain drinking water from moderate depths.

(*b*) *Solar Mechanical Applications* : Solar pumps, refrigeration and generation of electricity from steam where heat is converted to mechanical power by the engine. Solar pumps are used for drinking water. For large irrigation, they are not economical.

(*c*) *Photovoltaic solar cells for production of electric power* : They are at present still expensive. Photovoltaic cell and solar power will be dealt with in detail in later section.

16.2.3 ROLE OF ELECTRICITY

Electrical energy is most suitable form of energy for driving machines, pumps for irrigation and industries.

(*a*) *Small Hydro Schemes* : Micro-hydro plants can be installed in suitable hilly areas having small falls of 10 to 20 m. The potential of the hydro power that can thus be generated can be estimated and micro hydro turbines can be used to supply micro power of the range 40 to 250 kW in areas of villages, districts in the region.

(*b*) *Windmills* : In coastal and mountaneous regions, wind can be used as a source of energy. The wind velocities of 8 to 25 km/hr are required for obtaining mechanical power for pumping and 15 to 40 km/hr for production of electricity. The Cretan windmills start pumping at a velocity of 8 km/hr and reach optimum performance of 25 revolutions/minute at 13 km/hr. The wind pump will increase its speed upto about 40 revs/min in high velocity winds. It will pump 3000 litres per hour and lift to a height of 5 metres for 10—12 hrs per day 4 to 5 months in a year. The expected life of the windmill is about 20 years.

(*c*) *Geothermal energy* : In regions having natural geysers, and volcanic surroundings, the heat obtained from the earth can be converted to electricity. This, however, is not uniform and the process is complicated.

16.3 Methods of Forecasting Energy Demands

For predicting the energy demand for the future period of a few years, simulation model for energy demand is used for demand projections for developing countries. A simulation model (SIMCRED) is developed to estimate commercial, non-commercial and electrical energy demand. The energy demand is considered in two parts : Energy demand for rural areas ; energy demand

for urban areas. Urban energy supply generally depends on large scale centralised energy systems. Rural energy supply can be given by small scale decentralised systems.

Countrywise regressions of energy consumption are carried out and used to estimate future energy demands through simulation. For simulations, the variables required are : Total population, urban population, and the growth rate of GNP.

The variables are determined as functions as below :

	Variables determined	*As a function of*
(i)	$\frac{\textit{Agricultural GNP}}{\text{Total GNP}}$	GNP per capita and $\frac{\textit{Rural Population}}{\text{Total population}}$
(ii)	Demand of Commercial energy per capita	Consumption per capita ; $\frac{\textit{Non agricultural GNP}}{\text{Total GNP}}$
(iii)	$\frac{\textit{Commercial energy}}{\text{Non-commercial energy}}$	$\frac{\textit{Urban population}}{\text{Rural population}}$ Consumption per capita
(iv)	Electrical energy consumption	$\frac{\textit{Urban population}}{\text{Total population}}$ GNP per capita

The relations of the four sub-models are derived from multiple regressions, using national data.

16.3.1 EQUATIONS FOR SIMCRED

Let N=population ; NU=urban population ;

NR=rural population ; NNA=rural non-agricultural population ; Y=Gross National Product (GNP)

YA=Agricultural *GNP* ; YNA=non-agricultural *GNP*

YR=rural *GNP* ; $YNNA$=rural non-agricultural *GNP* ;

C=final consumption ; EC=commercial energy ;

ENC=non-commercial energy ; ET=Total energy $=EC+ENC$; EEL=electrial energy (in 1000 kWh)

ER=rural energy.

Units used in the expressions : *GNP* in billions *US*$ Energy in millions tons of coal equivalent (mtce) population in millions ; per capita energy in mtce ; per capita *GNP* in *US*$.

Agricultural GNP : The relationship between agricultural *GNP* and the total *GNP* may be expressed by the following multiple regression.

$$\log (YA/Y) = 0.458 \log (NR/N) - 0.365 \log (YN) \qquad (16.1)$$

Commercial energy demand : The relationship between *GNP* per capita and energy consumption per capita is given by

$$\log (EC/N) = a_0 + a_1 \log (Y/N) \qquad (16.2)$$

Non-Commercial energy demand is given by the relation

$$\log (EC/ENC) + 1.37 \log (Y/N) = 6.86 + 0.633 \log (NU/NR) \qquad (16.3)$$

Electrical energy demand is given by the relation

$$\log (EEL/N) = -0.896 + 1.1581 (\log Y/N) + 0.499 \log (NU/N) \qquad (16.4)$$

Non-commercial energy consumption is (i) Firewood (including charcoal) ; (ii) Agricultural waste including animal dung.

The energy from the agricultural waste can be estimated from the availability of dry combustible matter, its utilisation and its energy constant by the following :

$$E_{AG} = C_{er} \cdot \text{Res} = V_A \quad C_A \qquad (16.5)$$

where C_{er} = serial production ($10^6 t$)

Res = Average crop residue coefficient (=1.5)

V_A = Utilization factor (=0.5)

C_A = energy conversion to coal equivalent units (3450/6900=0.5)

Energy consumption from commercial and non-commercial sources in India (1973) in kgce (kilogram coal equivalent) per capita :

Commercial	Firewood	Agricultural waste	Total
137.8	134.1	87.9	359.8
38.1%	37.5%	24.4%	100%

16.4 Rural Energy Demand

Determine per capita income in the agricultural and non-agricultural sectors. Determine agricultural and non-agricultural populations.

The following relation gives the estimate of the rural share of non-agricultural activities and rural energy consumption.

$$\log (EC/N) = 1.6 \log \frac{YNA}{Y} + 1.27 \log \frac{(C)}{N} - 7.5 \quad (16.6)$$

Table 16.2

Per capita Rural Energy consumption in India for different fuels

Fuel	Annual consumption kg.	Coal equivalent units
Coke	2.00	1.43
Coal	4.28	3.06
Firewood	326.82	221.77
Dung	121.92	57.48
Other fuels	17.91	5.61
Kerosene	5.35	7.64
Electricity	3.65	0.45
(1 kg=7000 k cal)	(1000 kWh/yr)	
	Total	297.44

about 300 kgce/year per capita.

The general energy needs of rural sector are :

(*a*) *Basic needs* : (i) Potable drinking water supply ; (ii) Cooking ; (iii) Domestic and street lighting; (iv) Operating educational and entertainment aids.

(*b*) *Agricultural needs* (i) Water pumping for irrigation ; (ii) storage and drying agricultural crops ; ((iii) green house for vegetables ; (iv) hot water for poultry, food processing sterilization ; (v) fuel to operate farm machinery ; (vi) energy for transport of fertilizers and pesticides.

(*c*) *Industrial needs* : (i) rural industries—manufacture of soap, bricks, pottery, charcoal, metal products, leather and agro-industrial products, weaving, handicraft, printing, handloom industry : (ii) Operating agricultural implements ; (iii) Cold storage.

To supply the needs of the rural energy, obtain the data : (i) Estimate the minimum required energy per capita in rural area (ii) Assess the potential of locally available renewable energy sources (iii) Evaluate the state of technology available in meeting the specific needs of the area. (iv) Solar insolation and climatic data over the year to find out if solar devices can be used. (v) Try to use various renewable sources of energy to supply the needs of the rural area if possible. A typical example below illustrates the possible use of various resources.

Consider a village of population of 500 people—100 families, 6 cattle per family – Average needs of basic energy and technology available is shown in Table 16.3.

Table 16.3

Energy consumption per day

Requirements	Energy required	Use of devices
1. Pumping potable water 10 m well to an overhead tank at 20 m height. Consumption 10 litres per person per day. Pumping efficiency 20%	2.2 kWh	(a) Solar cells (b) Biogas operating engine (c) Solar thermal pump (d) Wind mills
2. Water purification 5000 litres/day		(a) Solar stills
3. Water for cattles, etc. 10,000 litres/day and for sanitation. 25 % 500 = 12,500 litres/day Total 25,000 litres/day	7.0 kWh	Same as (1)

4. Cooking needs : each family using about 4800 kJ per day for cooking corresponding to 1.3 kWh per day per family for 3 hrs a day.	130 kWh	(a) bio-gas ovens (b) Solar cookers (c) Low pressure steam from flat plate collectors.
5. Lighting :		
Domestic: 2 lamps 60W each per family ; 4 hrs a day	48 kWh	(a) Solar cells (b) gasfired engines generating electricity.
Street : 20 lamps of 60 W each per village	4.8 kWh	(c) Windmill and battery storage
6. TV, Educational aids, communication devices 120 W operating 4 hrs a day.	4.8 kWh	(d) Solar therma pumps generating electricity
Total basic energy needs per day		197.8 kWh
Total basic energy needs per person per day		0.395 kWh.

The solar cells technology is not yet cheap and economical in India but it is hoped that with the decrease in the price of solar cells, it should be available in a decade or so.

At present rural electrification program is undertaken and most of the villages with a population of over 1000 people are electrified. This, however, is also not cheap and there is need to develop and find out alternative sources of energy both to conserve the solid fuels and to supply the energy needs locally from local sources as far as possible.

Table 16.4 gives comparison of scheme to supply energy from Grid or by autogeneration locally when power is supplied at different load factors.

Table 16.4

Average cost of different scheme (cents per kWh)

Load factor %	Supplies from main Grid 4 km	20 km	Autogeneration
10	18	40	21
25	7	17	12
50	4	8	9

Source : World Bank (1975)

It is seen from the Table that the supply from the main Grid is profitable compared to autogeneration for load factors of 25% and above and for short distance of 4 to 20 km from the main Grid.

Input norms for energy uses in various types of rural industries, e. g., name of the industry, consumption of electricity per day, and the average consumption of raw materials needed for the industries by units are available from the perspective plan for rural electrification in the Telangana region of Andhra Pradesh, India. The data is shown in Table 16.5 and is taken from National Council of Applied Economic Research, New Dehli

Table 16.5

A Typical Energy Consumption in Rural Industries

Name of industry	Consumption of Electricity kWh/day	Average consumption of raw materials by units
1	2	3
Coffee works	1	Coffee seeds 33 kg/day
Rice mill	32	paddy 40 qtls/day
Flour mill	36	paddy 24 qtls/day ; (greese/lubricants 1.5 kg/month ; diesel oil 550 litres/month ; Mobile oil 12 litres/ month)

1	2	3
Poultry farm	47	Water 1000 litres/day
Dairy farm	50	N. A.
Sericultural farm	1.1	Urea 1/2 kg per acre/ year Ammonia 50 kg/ acre/yr ; CAL 50 kgs/ acre/yr.
Textile mill	95	cotton 1373 kg/day mobile oil 0.56 litre/day coal 0.66 tons/day boiler combustion oil 6.58 litres/day
Wool carding	N. A.	Wool 1.64 kg/day ; Diesel oil 1 litre/day ; mobile oil 0.27 litre/day
Straw Board	N. A.	Waste paper 1.7 tons/ day
Press	3.02	Rs. 1833.3/month service charges, mobile oil 2 litres/month
Oil mills	63.20	Groundnut 2.96 tons/ day ; mobile oil 0.96 litres/day
Painting	16	paints 16.7 litres/day turpentine 5 litres/month tannery 5 litres/ month
Potteries	33.3	water 40 litres/day Greese 12 kg/month Mobile oil 30 litres/ month ; kerosene oil 50 litres/month
Engineering works	30	lubricant 10 litres/ month ; transformer oil 20 litres/month.

1	2	3
		Welding rods 200/month M. S. sheets 3.2 tons/month
Aluminium utensils	18.9	Aluminium 133.33 kg/day
Mechanical works	3.29	Rs. 1500/month repair and service charges.
Tyre works	3.29	Rubber 12.36 kg/day solution 0.46 qtls/day petrol 1.37 litres/day water 3288 litres/day

16.5 Biogas Plants and Applications

Organic waste available in rural areas is agricultural waste, human waste, piggery waste, etc. If this waste is anaerobically fermented with oxygen, it gives rise to a gas which is 60% methane. This is an efficient and versatile fuel. The left over sludge can be used as fertilizer. It takes 3 to 5 animals to run a biogas plant for a family of 5 or 6. Therefore, 0.5 cattle per person is required to provide energy for subsistance and fertilizers. Use dung for composting. In India, the cost of a family size biogas plant for 5 persons is about Rs. 2000 to Rs. 2500. On large size, village biogas plant may also be used for dairies, hospitals, etc.

Gas plant based on anaerobic process is not so efficient as the yield is only 0.35 m^3 of gas (60% is mathane) per kg of solid waste with the energy value of about 8500-12,500 kJ. On the other hand, production of methane can be efficiently done by the fermentation of algae grown in pond, fed by sewage. With 0.1 kg of solid content in sewage per person per day 0.3 kg of dry algae can be grown with 65% efficiency of its conversion to methane : energy about 3500 kJ. The residue has all N and Phosphorus which can be used as fertilizers.

The stored gas can be used in two ways :

(i) run methane gas motors driving electric generators,

(ii) Use directly for cooking by burning it.

16.6 Biomass plants and applications

Photosynthesis is at the base of all biomass production and food chains. It converts physical energy into chemical energy and generates oxygen, the life sustaining gas. Various types of biomass and/or biofuels available are : firewood, agricultural alcohols, vegetable oils, hydro carbon plants, particularly those yielding rubber and petrolium like materials fresh weeds; sewage grown algae; algal hydrocarbons; and biological production of hydrogen using halobacteria algae, azolla and even higher plants. Bio-conversion process to generate solid, liquid and gaseous fuels are : anaerobic and enazymatic digestion and thermochemical conversion.

Take to the photosynthetic model of development through large scale use of biomass particularly firewood. Once such program is successful, dung and plant based residues would become available as organic fertiliser and as industrial feed stock respectively. For firewood plantations productivity in short time, high density and short rotation biomass of fast and hardy species of deciduous trees and shrubs should be raised exclusively on non-agricultural or marginal lands.

Energy from wood should be from renewable forest energy resources. Eucalyptus plantations and refining of natural forest schemes should be undertaken on large scale.

16.7 Solar-Electric System: Principle and Applications

Sun's 'insolation' or solar power density at earth's surface I_0 is approximately 1000 W/m^2. The indirect and direct estimates of global radiation received annually on horizontal surfaces are measured and are available for most of the regions of the world. Since the solar power density at the Earth's surface is a function of cosine of the angle between the direct Sun rays and the normal to the Sun,

$$P = I_0 A \cos \theta \ kW \qquad (16.6)$$

where A=horizontal area in m^2

At noon θ corresponds to the latitude of the place. Then time variable translates this to special angle.

$$\text{Energy } W = \int_0^{t\ hrs} I\,dt \qquad (16.7)$$

= area under insolation time curve.

16.7.1 SOLAR CELL OR PHOTOVOLTAIC CELL

A solar cell is composed of a thin layer of N type silicon only a few μm thick and a much thicker substrate of P type silicon. Electric contact to the thin top layer is effected through the comb-like upper metal contact grid. The solar cell consists of large area P-N junction. It behaves as a semi-conductor diodc when unilluminated. Semi-conductor properties : Semi-conductors have electronic structure such that one band of allowed states virtually completely occupied by electrons—the valence band—is separated by a forbidden energy gap from the next band of allowed states which is virtually devoid of electrons—the conduction band—. The current flow in the semi-conductors is due to both motion of electrons in the conduction band and the effective motion of the vacancies or holes in the valence band. Specialised impurities—dopants—are introduced into semi-conductors and can control relative concentrations of electrons in the conductance band of a semi-conductor and holes in valence band. Carriers in these bands can flow by drift and diffusion, when appropriate perturbances are present.

The solar cell consists of a large area P-N junction. It behaves as semi conductor diode when unilluminated. The junction has small reverse leakage current. Fig. 16.1 shows a typical rectangular cell and Fig. 16.2 shows P-N junction characteristics of solar cell.

When the junction is illuminated, it has the effect of shifting the current voltage (I-V) characteristics downwards. This is now in the fourth quadrant and produces power instead of absorbing it. Voltage is in forward direction but current flows in opposite direction to what it would flow in the forward biased mode.

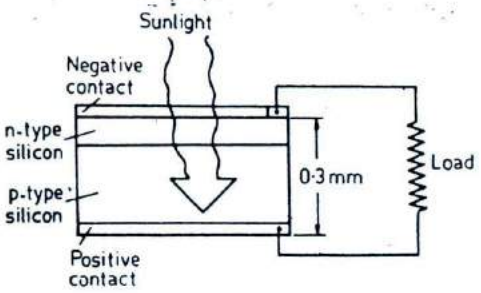


Fig. 16.1 . A typical rectangular solar cell

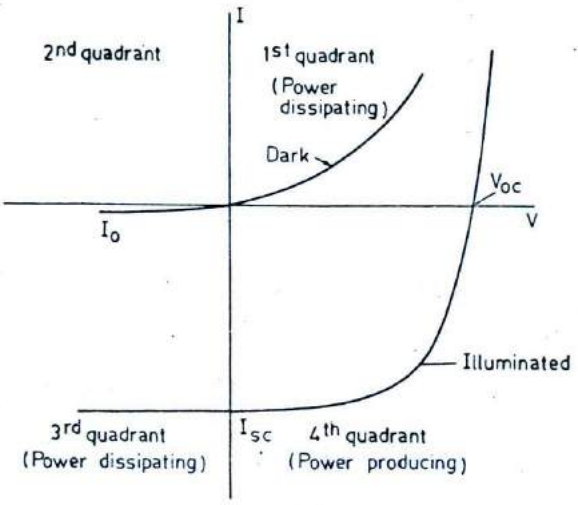


Fig. 16.2 *P-N* junction characteristics of solar cell

The solar cells have open circuit voltage in the range of 0.6 *V* per cell. The short circuit current is a function of the cell area. The effect of changing the insolation on a typical solar cell is shown in Fig. 16.3.

The change in output current is shown for the insolation levels of 82 mW/cm², 100 mW/cm² and 140 mW/cm². It is seen that the short circuit current I_{sc} increases linearly with insolation. Open circuit voltage changes little and practically remains the

same viz. 0.6 *V*. The effect of rise of temperature produces fall off of the solar output power.

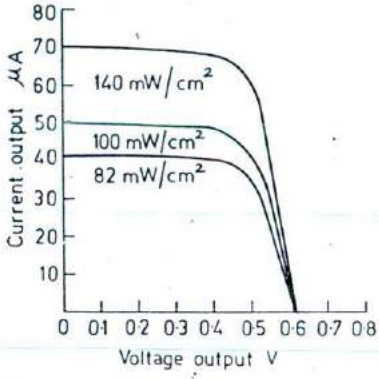


Fig. 16.3. *I—V* characteristic of a 1 × 2 cm solar cell at 3 different illumination levels

Fill factor (FF) is another important parameter for systems engineer when comparing alternative solar cells Fill factor is found out from the solar cell *I-V* characteristics or equivalent *J-V* characteristics. *J-V* curve is better for comparison. If the cells have different areas and characteristics, current density *V* curve (*J*)-*V* curve is found out. Fig. 16.4 shows *J-V* curve of typical solar cell and shows definition of fill factor (FF) Find the maximum power point on the curve. The voltage corresponding

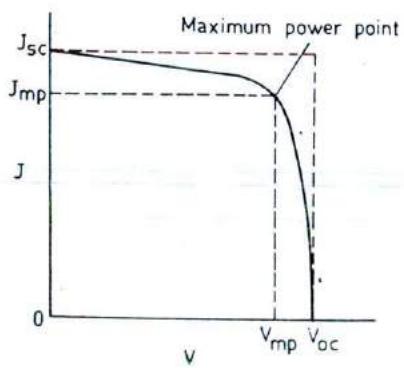


Fig. 16.4 Fill factor of a solar cell

to this point is V_{mp} and current density J_{mp} while J_{sc} shows the short circuit current density and V_{oc} open circuit voltage. Fill factor is defined as the ratio of the areas $V_{mp} \times J_{mp} / V_{cc} \times I_{sc}$

$$\text{Fill factor (FF)} = \frac{V_{mp} \times J_{mp}}{V_{oc} \times J_{sc}} \qquad (16.8)$$

The fill factor may be 0.8 or higher for well designed solar cell.

The approximate equivalent circuit model for a solar cell can be represented as shown in Fig. 16.5 using lumped constants.

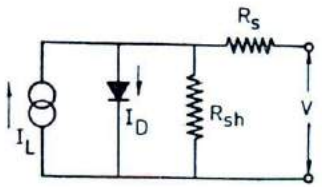


Fig. 16.5. Approximate lumped circuit constant equivalent circuit of a solar cell

I_L is the forcing function constant current generator, I_D is the diode current. R_s is the voltage drop across the diode. This is made low. R_{sh} may be assumed infinity. This has effect to some extent only at the time of very low illumination on the cell.

$$I_L = q\eta(\lambda)\phi(\lambda) \text{ amps.} \qquad (16.9)$$

where q=electronic charge

$\eta(\lambda)$=quantum η

=number of hole-electron pairs released within the *P-N* junction per quantum of incident light energy at wavelength λ

$\phi(\lambda)$=Photon flux incident on the cell

λ=wavelength of incident light on the cell junction if R_s drop across the diode is low, then $I_L \sim I_{sc}$

Diode current $I_D = I_0(e^{\alpha v j} - 1)$ amps (16.10)

where I_0=reverse leakage current of diode

$\alpha = q/\eta\, kT$; η = diode ideality factor

V_j=junction voltage

If R_{sh} is assumed as $\sim$, Load current $I = I_L - I_D$ (16.11)

If load area/cell area = J cell density, then power generation density $P = V \times J$ watts/cm²

P = area of cell = Absolute power output of cells (array of parallel cells)

$$\text{Conversion efficiency} = \frac{P_1\ (mW)}{I \times A(mW)} \tag{16.12}$$

A = area (cm²)

I = Insolation in mW/cm^2 (assumed normal to the cell)

Accounting for fill factor,

$$\text{Conversion efficiency} = \frac{V_{oc} \times I_{sc}}{I \times A} \times \text{Fill factor} \tag{16.13}$$

16.7.2 A BASIC PHOTOVOLTAIC SYSTEM INTEGRATED WITH GRID

A basic photovoltaic system consists of (i) Solar array; (ii) Blocking diode; (iii) Battery storage; (iv) Inverter/converter. This is shown in Fig. 16.6.

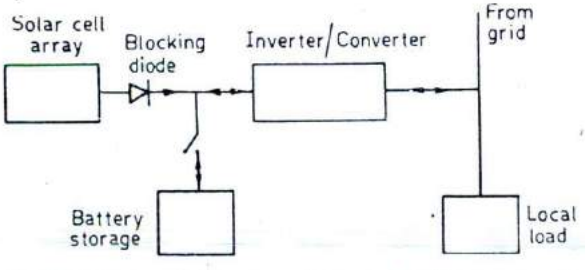


Fig. 16.6 Photovoltaic system integrated with power grid

The solar arrays covert the insolation of the Sun to useful d.c. electric power. The blocking diode lets array generated power flow only towards battery or grid. When the power generated by the solar cell array is more than required by the local load, it is used to charge the battery.—(lead sulphuric acid battery)—The

inverter is provided (solid state) to convert battery bus voltage to ac of frequency and phase to match with that of grid so that the system can be integrated.

Solar photovoltaic arrays : These can be (i) Flat plate arrays or, (ii) Concentrating arrays. They may be (i) Fixed arrays or tracking arrays where they are mechanically always kept perpendicular to Sun array line. Generally flat plate type of arrays are used. Concentrating type of arrays need tracking arrangement and cost is more.

Solar arrays connection schemes : The schemes used for arrangement of solar arrays are shown in Fig. 16.7.

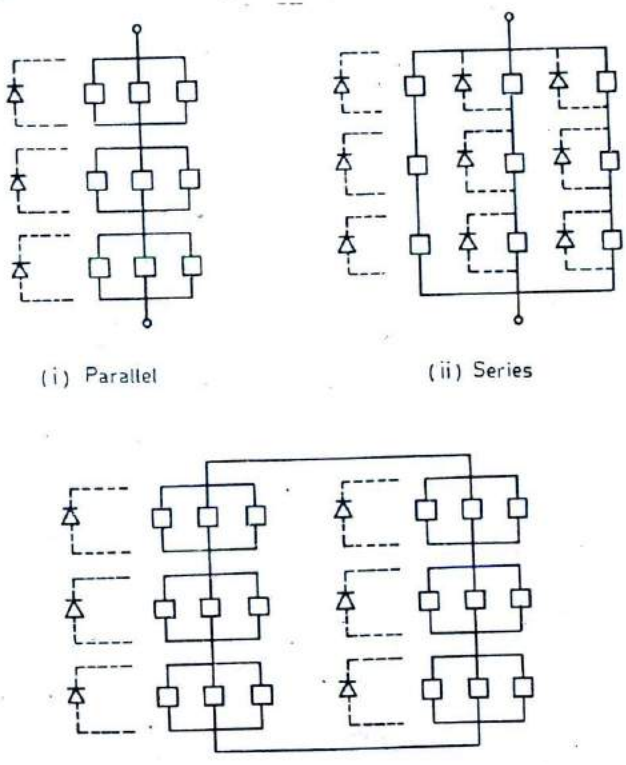


Fig. 16.7 Solar cell arrays connection schemes
(i) Parallel (ii) Series (iii) Preferred interconnection

Cells in parallel are arranged to get the desired current; while the cells are arranged in series to get the desired voltage. (i) and (ii) show connections in parallel and in series respectively. Groups and subgroups of cells are added together as required to obtain the voltage and current requirements. In connection (i) if a cell shorts, output of the whole row of the cells tends to feed current into the shorted cell. If the cell is open circuited, it has little effect. In case of connection (ii), a shorted cells in series string has minimum effect while an open cell results in power loss of the series string of the cells. The connection shown in (iii) is optimum considering the effect of cell shorting, unequal cell *I-V* characteristics and non-uniform illumination. This type of connection has the fewest number of shunt diodes; this connection gives highest array reliability. Diodes are placed across cells to force current through them and reduce hot spot temperature rise problems of shaded cells.

16.7.3 USE OF PHOTOVOLTAIC SYSTEMS

(i) Photovoltaic system with energy storage can be used as isolated small stations to supply power to rural areas.

(ii) Large photovoltaic systems can be used as centralised stations if and when the system becomes economically viable.

Costs : The acceptable costs per kW of solar array to use them for power production are $ 100 to $ 500/kW while the actual price (1978 price) of the arrays is $ 6000 to $ 7000 per kW. which is very expensive. The costs have to come down to 1/10th a least of the existing costs to make solar power economically viable. If solar cells can be available at $ 5.0/m^2 area of the cell electricity by use of solar cells will be cheaper than by other, forms. The advantages of using solar energy are :

Cleanliness, availability, conserves fuels, safe, no fuel cost. Disadvantages are : not concentrated energy source, sensitive to atmosphere, variable both dicernally and seasonally. Large area is needed for bulk energy; system storage of energy is needed. High costs; integration with the existing energy systems is a problem.

Concentrating system

Maximum concentration ratio $C_{m(2D)} = \frac{1}{\sin(\theta_m/2)}$ (16.14)

for a 2 dimensional or linear concentrator.

$$C_{m(3D)} = \frac{1}{\sin^2(\theta_m/2)} \quad (16.15)$$

for 3 dimensional or point concentrator.

cost of the system can be displaced from the photovoltaic system to the cost of the concentrating elements and Sun tracking system.

Decentralised solar electrics : (i) Decentralisation matches distributed nature of solar energy; (ii) simple, elegant; (iii) modular in nature ; microwatts to kW or even upto MW when modules are combined into large area arrays and suitably connected; (iv) Dispersed generating capacity is worth two and half or more times centralised generating capacity; (v) eliminates transmission lines; (vi) elimnates fuel transport; (vii) eliminates distribution network; (viii) serves remote areas; (ix) Uses local materials and labour; (x) safe.

Centralised solar electrics : (i) This system permits plant location in maximum insolation area, (ii) Can obtain large power and energy with suitable cell arrays, (iii) Reliable for large interconnected system (iv) Ease of transporting electrical energy.

The overall efficiency of the system = Product of efficiencies of the system component parts.

16.7.4 THE STANDARD TECHNOLOGY FOR MANUFACTURE OF SOLAR CELLS

The main steps in the making of solar cells are :

1. Reduce sand to metallurgical grade silicon.
2. Purification of this to semi-conductor silicon.
3. Conversion of semi-conductor silicon grade to single crystal wafers.

4. Process single crystal wafers into solar cells.

5. Encapsulation of solar cell into weather-proof solar cell modules.

Advanced technologies are being developed for producing low cost silicon solar cells modules : Direct growth of silicon ribbons, advanced processing sequences, thin film technology.

The *P-N* junction has to lie close to the surface of the cell to give maximum current output.

Materials used in solar cells

There are materials that may prove viable alternatives to single crystal silicon which forms the basis of the present solar cell industry. Gallium arsenide is a semi-conductor with well developed technology and nearly ideal band gap for solar photovoltaic energy conversion. Homo-junction, heteroface and heterojunction cells have been shown capable of high efficiency. The high cost of this material is its major limitation.

Copper sulphide-cadmium sulfide cells can be fabricated very simply on small grained polycrystalline cadmium sulfide. This is low cost technology, however, there is difficulty in obtaining 10% efficiency on production basis.

Polycrystalline silicon has the disadvantage that large grain sizes are required. The most promising silicon thin film technology is that based on amorphus silicon alloys.

16.7.5 ENERGY STORAGE

With solar energy and power use, there is urgent need for energy storage. The storage will permit solar energy to be captured when insolation is highest and then later used when the need is greatest. This also makes it possible to deliver electric load when insolation is below normal or non-existant.

The amount of storage required for a given solar electric system is determined by—

(i) The size of the solar electric generator.

(ii) The shape, magnitude and the timing of the load demand.

(iii) Whether the system is to be operated in a peak shaving mode or a load levelling mode.

(iv) Insolation data history for the particular plant site.

(v) Cost per kWh of the stored energy.

(vi) Permissible capital cost allowed to storage.

(vii) Environmental and safety considerations.

Storage may be in form of (a) battery; (b) thermal; (c) water; (d) air; (e) Hydrogen; (f) flywheel; (g) superconducting magnets; (h) chemical.

The most common form of storage for solar electric power station is battery (lead sulphuric acid).

16.8 Solar Electric System : Preliminary Design :

16.8.1 STAND ALONE SYSTEM

Fig 16.8 shows a simplified diagram of a stand alone solar power system.

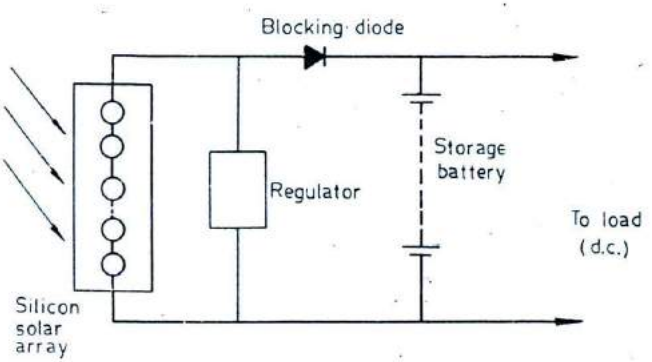


Fig. 16.8 Stand alone solar power system

This is small reliable stand alone solar power system which can supply power to remote areas. Silicon solar arrays connected in suitable modules is a source of supply. Blocking diode is to

prevent loss of battery charge overnight. Regulator is to prevent overcharge of the battery during high insolation levels.

Solar array modules are arranged so that there are sufficient series connected solar cells to generate enough voltage to charge a 12 V battery. Modules are arranged in series to increase the system voltage and modules are arranged in parallel to increase the system output current. Lead acid battery of nominal voltage 12 V needs over 14 V to fully charge it. Silicon blocking diode needs about 0.6 V to forward bias it. The effect of temperature should also be considered. Open circuit voltage V_{oc} decreases by about 0.4% for each 1°C increase in temperature. Generally V_{oc} is specified at 25°C. The temperature may rise upto 60°C Lead acid batteries are commonly used for storage ; Nickel Cadmium batteries can be used but they are costly. For seasonal nature of storage, a battery with low self discharge characteristics is essential. High charge storage efficiency is also desirable.

$$\text{Charge } \eta = \frac{\text{(charge that can be extracted from the battery)}}{\text{(Charge put in battery)}}$$

For best performance, modules are mounted so that they face south in the northern hemisphere and north in the Southern hemisphere, at an angle from the horizontal approximately equal to the latitude of the site. For systems with 10 to 30 days of battery storage, the optimum value of the angle increases by about 15° to boost the winter output of the system.

16.8.2 DESIGN PROCEDURE

1. *Determine load data*

In case of microwave repeater stations, the load is easily determined and is practically constant. In other applications such as radio, telephones, it depends on the user call rate.

2. Obtain the available solar radiation data for the intended site every day for the whole year. Find average daily insolation or radiation intensity of the Sun at the site.

3. *Select the battery size*

This depends on local climatic conditions and on latitude.

The storage battery provides reserve capacity to cover the period without sunshine. Also it provides seasonal storage. Normally reserve capacity of 10 to 20 days is quite adequate. In selecting the capacity of the battery, the effect of temperature and discharge rate on the battery should be taken into consideration. Decide on depth of discharge available. Generally this is taken as 25%. If reserve capacity of battery is C_R and $d=$ fractional depth of discharge desired,

$$\text{Total capacity of battery} = C_R (1 \quad d) \qquad (16.16)$$

4. *Select size of solar array*

Select open circuit voltage V_{oc} and Current output required. The voltage output is selected to be large enough to allow battery to be efficiently charged throughout the year. The current output is chosen to ensure that the battery does not discharge below the selected depth of discharge due to seasonal effects.

5. *Select the array inclination*

Fig. 16.9 (i) shows the solar radiation at solar noon on a solar array inclined to the horizontal surface by an angle β; α is

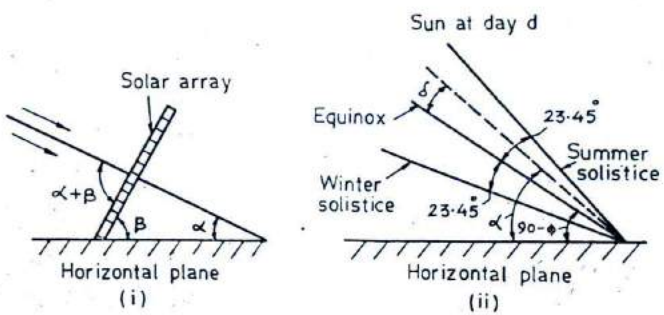


Fig. 16.9 Solar radiation on solar array inclined to horizontal

(i) Horizontal plane inclined at an angle β

(ii) Relation between latitude (ϕ), declination (δ), and altitude of the Sun. (α).

the altitude of the Sun Fig. 16.9 (ii) shows relation between altitude of the Sun α latitude ϕ and declination. (δ).

If global radiation of Sun on a horizontal surface = R; and diffused radiation = D, mean direct daily radiation on horizontal plane S is given by

$$S = R - D \tag{16.17}$$

In Fig. 16.9 (i), the solar array is tilted at an angle β to the horizontal, and the Sun's altitude is α. The angle between the sun's rays and the solar array is $\alpha + \beta$. The direct component on a surface at an angle

$$S_\beta = S \frac{\sin(\alpha + \beta)}{\sin \alpha} \tag{16.18}$$

Fig. 16.9 (ii) shows the method of determining α on any day during the year and shows the relation between latitude of the place, declination of Sun and the Sun's altitude.

$$\alpha = 90° - \phi \pm \delta \tag{16.19}$$

where δ is the declination of the Sun from the equinox position; ϕ is the latitude of the place. δ is taken as positive in the northern hemisphere; and negative in the southern hemisphere.

The declination of the Sun δ is given by

$$\delta = 23.45° \sin\left[\frac{360}{365}(d - 81)\right] \tag{16.20}$$

where d = number of days from the beginning of the year.

Assuming that the diffuse radiation is independent of the array inclination, the total radiation on the array

$$R_\beta = S \frac{\sin(\alpha + \beta)}{\sin \alpha} + D \tag{16.21}$$

6. Estimate lower and upper bounds on array size from the average and minimum monthly radiation falling on the array of the selected inclination.

7. Find optimum array size to keep batteries above a certain percentage charge throughout the year.

8. Modify array inclination to find optimum. Specify array voltage at maximum operating temperature at which it is desired to supply full load current.

Example 16.1

Design a stand alone photovoltaic system for a location at latitude 18°*N*. The system is to supply a constant load of 250 *W* at 24 *V. d.c.* The average radiation of the Sun at the site for the whole year is 25 MJ/m^2/day .; minimum radiation during the worst month in the year is 21.6 MJ/m^2/day. Maximum temperature 60°C.

The load requires $\frac{250}{24} \times 24 = 250A$ *h*/day.

Storage capacity of 10 days is selected.

Therefore, storage required $= 250 \times 10 = 2500A$ *h*.

If the design depth of discharge is chosen as 25%, the total installed capacity of battery $= 2500/(1-0.25) = 3333$ —*h*; Take discnarge rate of 360 *h* (15 days).

Find the size of the solar module : Take optimum angle of tilt of the fixed array to the horizontal $= \beta =$ latitude $+ 15° = 18° + 15° = 33°$

Raw radiation data is to be converted to radiation on surface at an angle β.

$$\alpha = 90 - \phi = 90 - 18 = 72°$$

$$S_\beta = S \frac{\sin(\alpha + \beta)}{\sin \alpha}$$

$$= S \frac{\sin(72° + 33°)}{\sin 72°}$$

$$= S \frac{\sin(105°)}{\sin 72°} = S \times \frac{0.9659}{0.9510} = 1.01S$$

Average daily radiation on arrays oriented at 33° from the horizontal at this location can be taken as $S = 25$ MJ/m^2 approximately.

Lower bound for current generating capacity of the array is estimated by equating the input charge to the array over the year to the charge required by the load.

Load requires 250 $A - h$/day.

Average daily radiation intensity on the inclined array $=25 MJ/m^2$; converting this to kwh by dividing by 3.6 average radiation intensity $=25/3.6=6.94$ Kwh/m^2 or 694 mWh/cm^2. This corresponds to 6.94 hours of bright sunshine at peak sunshine intensity of 100 mW/cm^2. Hence solar array peak current rating at 100 mA/cm^2 radiation intensity has to be at least 250 $A-h/6.94$ $h=36$ A. Accounting for degradation performance of battery, dust accumulation, etc, this current $=36/0.95\times0.90=42.10$ A.

The upper bound can be estimated by repeating the calculation using minimum radiation data for the worst month during the year. Here this is 21.6 MJ/m^2/day.

This is, therefore $=42.10\times25/21.6=48.7$ A.

The optimum peak current rating may be taken as 45 A.

The array must be capable of supplying peak load current at the highest temperature : 45 A at 29 V at maximum temperature of 60°C.

Taking 2.35 V per cell on full charge and 12 cells, voltage $=(12\times2.35+0.8$ V for blocking diode$)=29$ V.

Array peak rating $=29\times45=1305$ W at 60°C.

Power falls off at the rate of 0.5% per °C.

Therefore, the rating at 25°C,

$$=\frac{1305}{[1-\frac{0.5}{100}\times(60-25)]}=1582\ W.$$

and incident insolation level of 100 mW/cm^2

Thus the system data is :

Site : 18°N

Load : 250 W, 24 V $d.c.$

Array inclination : 33° to the horizontal

Battery capacity : 3333 $A-h$

Peak array current rating : 45 A

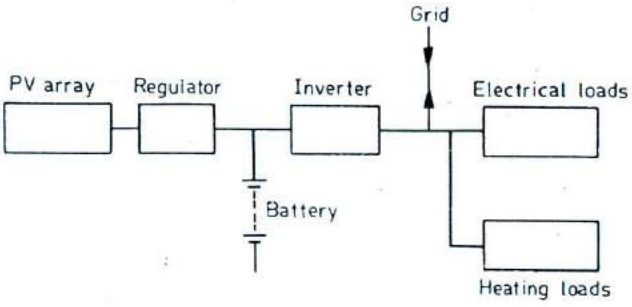
Both the module and storage requirements may have to be modified to make them multiples of commercially available units.

Applications : Microwave repeater stations, navigational aids, meteorological stations and corrosion protection. Photovoltaics can also be used for small scale water pumping.

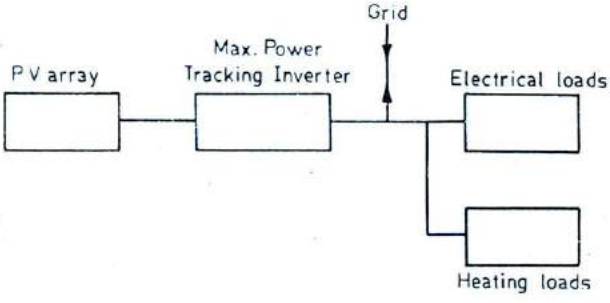
The arrays may be connected to pump motor without battery storage. Instead of battery storage, it can best be implemented by storing pumped water and used for irrigation in developing coun tries. The power required may be about 250 *W*.

For most ideal stand alone installations, the peak rating of the array must be about 5 times the average power the system is to provide.

Residential Photovoltaic systems. Connecting photovoltaic system to grid eliminates long term energy storage. Integral part of these systems is an inverter to convert solar cell d.c. output to



(a)



(b)

Fig. 16.10 *System configurations*
(a) with battery storage (b) wtthout storage

a.c. Module mounting optimum size is 0.8×2.5 m, weight 25 kg installed on the roofing.

Fig. 16.10 (a) and (b) show two system configurations.

(a) shows photovoltaic arrays, regulator, battery, inverter and then connect the ac. supply to grid. Also to electric and heating loads.

(b) shows a system without battery storage. Here photovoltaic arrays are connected to inverter without storage stage. The inverter can be designed to ensure that the module delivers power at its maximum power point. This system consists of photovoltaic arrays connected to maximum power tracking inverter and to the grid. Electrical and heating loads can be supplied by the system.

Central Power Plants. Ultimate aim of developing solar electric technology is to generate large quantity of electricity. For this, the solar modules must be inexpensive—less expensive

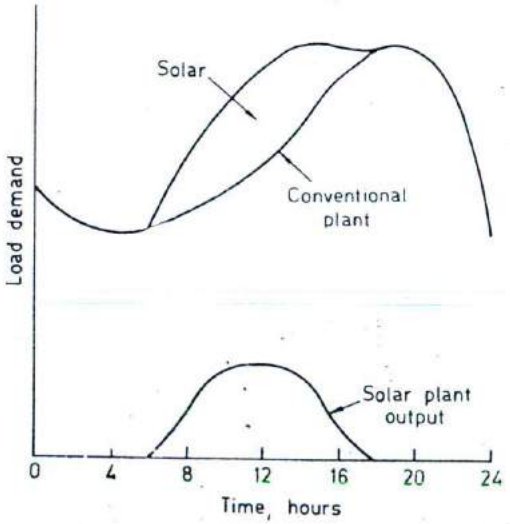


Fig. 16.11. Load curve for conventional and solar Plant in a system

than those that can be used for residential use and stand alone systems. Array efficiency must be at least 10%. Lower efficiency increases the area of the array for a given output. This increases costs, site preparation, large land structures, installation, maintenance, power conditioning equipment—the balance of systems costs.

Optimum module size for large scale application 1.2×2.4 m. Photovoltaics can be used without storage provided they contribute less than 10% of the total generating capacity of the network. The effect of solar plant upon the load supplied and the load curve is shown in Fig. 16 11 for a hypothetical system.

16.9 Wind Electric System : Principle and Applications

The wind power P_w through cross sectional area for uniform wind velocity, V is $P_w = K\ V^3$ where K is a constant. High average wind velocity is the principal fundamental parameter for initially appraising site for wind electric supply system. The considerations for choosing the site are :

(i) Survey historical wind area

(ii) Contour map of terrain and wind are consulted

Insovents or contours of constant average wind velocity (m/sec)

Isodynes or contours of constant wind power (watts/m^2 of area perpendicular to wind flow)

(iii) Potential sites are visited

(iv) Best sites are instrumented approximately for one year.

(v) Choose optional site.

16.9.1 Wind Energy Conversion

If M is an air mass moving with a speed, V (m/sec), Kinetic energy $E = \frac{1}{2} M\ V^2$ Joules (16.22)

air mass per unit volume ρ = air density

Volume of air passes through an area A normal to air velocity $= A\ V$, and kinetic energy in volume of air during time t sec

$$E=\tfrac{1}{2}(\rho\ A\ V\ t)V^2=\tfrac{1}{2}\rho\ A\ V^3\ t \text{ Joules} \quad (16.23)$$

and power $P=\frac{1}{2}\ \rho\ A\ V^3$ watts

air density ρ at sea level $= 1.225$ kg/m^3

Instantaneous power $P_a(t)-\frac{1}{2}\rho\ A\ [V(t)]^3$ (16.24)

Average power $\overline{P_a(t)}=\frac{1}{2}\rho\ A\ [\overline{V(t)^3}]$ watts

$$\frac{\overline{P_a(t)}}{A}=\frac{1}{2}\ \rho\ [\overline{V(t)^3}[\ \text{watts/m}^2 \quad (16.25)$$

The average available wind power per unit area is directly proportional to the average of the wind speed cubed.

16.9.2. BASIC COMPONENTS OF WIND ELECTRIC SYSTEM

(i) Aeroturbines : These convert energy in moving air to air rotary mechanical energy (ii) Step up gear : This steps up the speed of the aeroturbine and with suitable (iii) coupling transmits rotary mechanical energy to electrical generator at the suitable rated speed of the generator. (iv) the output of the generator is connected to load or grid. Fig. 16.12 shows the basic components of the wind Electric System together with the basic controls through the controller.

The controller senses wind speed, wind direction, shaft speeds and torques at one or more points; also generator temperature, and power output of the generator. The controller sends appropriate signals for control of speed and direction of aeroturbine, and matches electrical output to wind energy input. Controls on the aeroturbines are yaw control and pitch control in case of horizontal wind axis machines.

The aero generator is placed on tower structure. The aeroturbine is downwind. The aeroturbine has main parts : Blades, hub, pitch changes, mounting. Transmission system consists of speed increaser, drive shaft and bearings, brake, clutch and coupling. Electric generator ; controls and indicators.

16.9.3 CLASSIFICATION OF WIND ELECTRIC SYSTEM

(a) Horizontal axis machines : Axis of rotation is horizontal. Aeroturbine plane is vertical facing the wind.

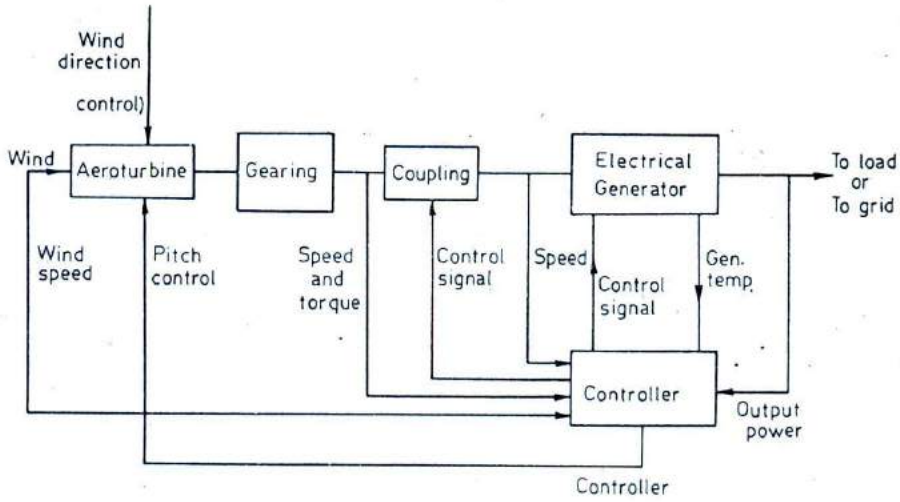


Fig. 16.12 Basic components of wind Electric System

(b) Vertical axis machine : Blades vertical ; axis of rotation-vertical.

classification by size of machines :

(i) Small scale upto 2 KW size: Use on farms and remote area applications.

(ii) Medium scale 2 to 100 kw. : Use for residential systems.

(iii) Large scale 100 kW and up : Single generator : multiple generators sited at several places over an area. Classification by type of output :

(a) D.C. output : D. C. generator or alternator-rectifier.

(b) A.C. output : (i) variable frequency, variable or constant voltage a. c.

(ii) Constant frequency, variable or constant voltage.
Classification by rotational speed of the aeroturbine :

(i) Constant speed with variable pitch blades ; Synchronous generator with constant frequency output.

(ii) Nearly constant speed with fixed pitch blades : Induction generator.

(iii) Variable speed with fixed pitch blades. Constant frequency output.

(i) Field modulated generator system.

(ii) *A. C.—D. C.—A. C.* link.

(iii) *A. C.* Commutator generator.

(iv) Other variable speed constant frequency generating systems.

Classification by utilisation point of view :

(a) Battery storage

(b) Direct connection to an electro-mechanical energy converter.

(c) Interconnection with conventional electric utility grids.

Overall efficiency conversion of an aerogenerator system :

$$\eta_{ov} = \frac{\text{Useful power output}}{\text{Wind power input}} = \eta_A \, \eta_G \, \eta_C \, \eta_{Gen}.$$

where η_A=efficiency of aeroturbine
η_G=Efficiency of gearing
η_C=Efficiency of mechanical coupling
η_{GEN}=Efficiency of generator.

16.10 Wind Electric System : Preliminary Design

1. Plot actual wind speed curve $V(t)$ *vs* time. This is obtained by anemometry data as for one year From this data prepare statistical wind speed duration curve. Fig. 16.13 (a) shows such a curve for a wind electric power system site. Show on the diagram the peak wind speed V_P rated speed at the turbine hub, V_R. mean wind speed V_M. Cut in speed of the wind V_C at which the wind electric generator may start working and furling speed or cut out speed V_F at which the generator is out of the system for working are also shown. V_F and V_C depend on aero generator design.

2. Plot specific power KW/m^2 vs time for the power in the wind.

$$\frac{\overline{P_a(t)}}{A} = \frac{1}{2}\rho\ [\overline{V(t)]^3}\ \text{watts}/m^2 \qquad (16.26)$$

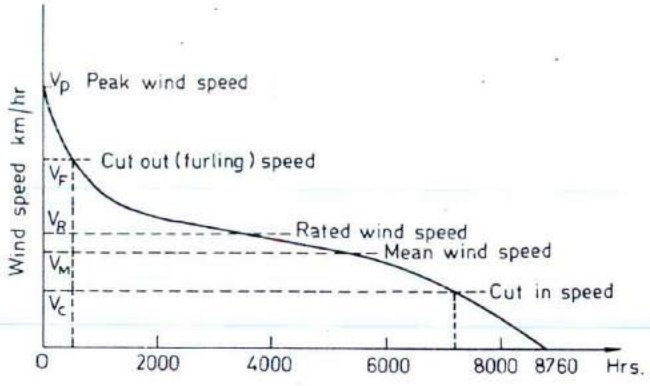
Then convert this to power duration curve. The power duration curve is shown in Fig. 16.13 (b). Constant speed constant frequency system is shown. Then curve shows Power in wind, cut out energy loss, mechanical shaft power output, cut in energy loss. rated electric output KW/m^2. The shaded area gives the electrical energy output in KWh/year/m^2.
Gross energy output per year=specific output χ swept area of the aeroturbine.

$$\text{Plant capacity factor} = \frac{\text{Shaded area}}{\text{area } P_R \times 8760} \qquad (16.27)$$

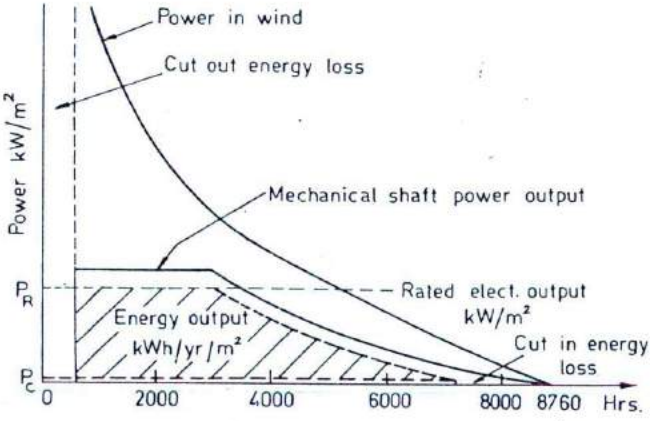
16.10.1 ECONOMICS OF WIND ELECTRIC SYSTEM

Coefficient of performance C_P of an aeroturbine in ideal case is given by

$$C_P \frac{\text{Useful shaft power output}}{\text{wind Power input.}} \qquad (16.28)$$



(a) Wind speed duration curve



(b) Power duration curve

Fig. 16.13 Estimating energy output/year from wind electric generator
(a) Wind speed duration curve
(b) Power duration curve.

This is maximum 59.3% theoretically.

In general the overall efficiency of wind electric system varies between 20% to 30%.

The sizes available in large capacities are 100 kW, 200kW, Some upto 1500 2000 kW machines.

For considering economics of wind electric system,

(i) Busbar energy cost to the user per kWh and Capital cost per kWh has to be considered.

100 kW system costs about $ 1980/kW while 1000kW system costs $ 568/- kW.

If located at sites with average wind velocity of 20 to 32 km/hour, cost of the wind electric power at the busbars is about 3¢ per kWh. Wind electric power system costing $ 560/- kWe may be equivalent to a fossil fuel plant capital cost of $ 400/KWe where figures are over the life cycle. The wind electric system has the advantage that it has no fuel cost.

References

16.1. RAMAKUMAR R. *A Review of Wind Electric Conversion Technology*, Proceedings of Miami International Conference on Alternative Energy Sources, December, 1977.

16.2. SUMAN B. RASTOGI, *Technological and Commercialisation Aspects of Solar Energy Utilization in Rural Areas* Paper 94, Proceedings National Solar Energy Convention, I.I.T. Bombay, 1979.

16.3. ROBERT L. BAILEY. *Solar Electrics – Research and Development*, Ann Arbor Science Publishers 1980.

16.4. JYOTI K. PARIKH, Energy Systems and Development, Oxford University Press, 1980.

16.5. MARTIN A. GREEN, Solar Cells, Prentice Hall Inc., 1982.

Problems

16.1. What are the unconventional sources of energy ? How would you use them for energy supply options ? Why is there need to develop these sources ?

16.2. Explain SIMCRED model to estimate the commercial, non-commercial and electrical energy demand.

16.3. Give typical energy requirement of rural consumers and state the possible alternative sources of energy or their combination that can be used to meet the demand.

16.4. State typical rural industries and their expected energy consumption.

16.5. State the principle of bio-gas plants and its applications.

16.6. State principle and applications of biomass plants.

16.7. State the principle and working of a solar cell. Explain P N junction characteristics of solar cell.

16.8. Explain current voltage characteristics of a solar cell at different levels of illuminations.

What is fill factor ?

16.9. Explain approximate equivalent circuit of a solar cell.

16.10. Explain different methods of connecting solar cell arrays, their advantages and disadvantages.

16.11. Explain photovoltaic system integrated with power grid. State the function and working of its component parts.

16.12. What are the different methods of storing energy from solar cells ?

16.13. Explain in detail the stand alone system of photovoltaic cells with reference to (i) Design procedure (ii) Applications.

16.14. Explain Photovoltaic systems for residential power supply and Central Power plants.

What is the effect of solar plant in combination with the conventional power plant on the load curve of the system.

16.15. Explain the principle and applications of wind electric system. State the basic components of the wind electric system. What controls are used ?

16.16. State classifications of wind electric systems.

16.17. Explain preliminary design of a wind electric system.

16.18. State economic considerations for—(i) Solar electric system (ii) Wind electric system.

16.19. Design a stand alone photovoltaic system for location at latitude 25° North. The system is to supply constant load of 400 W at 48 V d. c. The average radiations of the sun at the site for the whole year is 22 MJ/m²/day ; minimum radiation during the worst month in the year is 16 MJ/m²/day. Maximum temperature 60 °C.