

Chapter 4

ECONOMIC DISPATCH AND UNIT COMMITMENT

1 INTRODUCTION

A power system has several power plants. Each power plant has several generating units. At any point of time, the total load in the system is met by the generating units in different power plants. **Economic dispatch control determines the power output of each power plant, and power output of each generating unit within a power plant, which will minimize the overall cost of fuel needed to serve the system load.**

- We study first the most economical distribution of the output of a power plant between the generating units in that plant. The method we develop also applies to economic scheduling of plant outputs for a given system load without considering the transmission loss.
- Next, we express the transmission loss as a function of output of the various plants.
- Then, we determine how the output of each of the plants of a system is scheduled to achieve the total cost of generation minimum, simultaneously meeting the system load plus transmission loss.

2 INPUT – OUTPUT CURVE OF GENERATING UNIT

Power plants consisting of several generating units are constructed investing huge amount of money. Fuel cost, staff salary, interest and depreciation charges and maintenance cost are some of the components of operating cost. Fuel cost is the major portion of operating cost and it can be controlled. Therefore, we shall consider the fuel cost alone for further consideration.

To get different output power, we need to vary the fuel input. Fuel input can be measured in Tonnes / hour or Millions of Btu / hour. Knowing the cost of the fuel, in terms of Rs. / Tonne or Rs. / Millions of Btu, input to the generating unit can be expressed as Rs / hour. Let C_i Rs / h be the input cost to generate a power of P_i MW in unit i . Fig.1 shows a typical input – output curve of a generating unit. For each generating unit there shall be a minimum and a maximum power generated as $P_{i \min}$ and $P_{i \max}$.

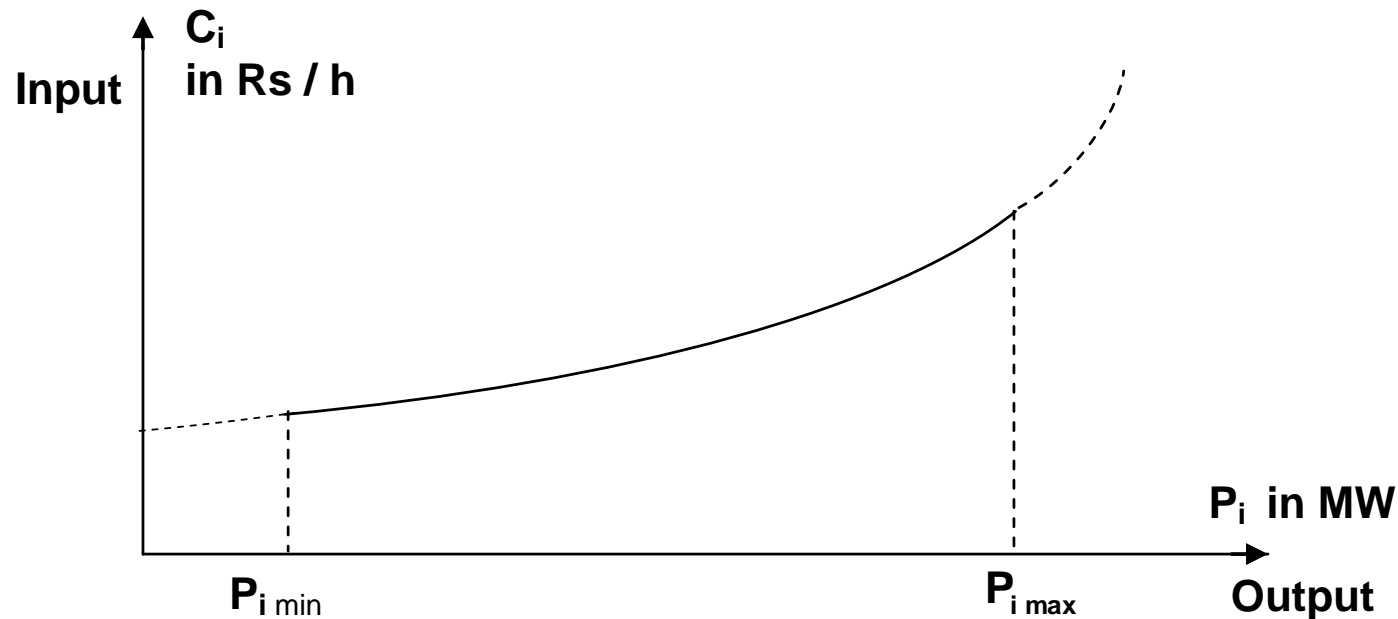


Fig.1 Input-Output curve of a generating unit

If the input-output curve of unit i is quadratic, we can write

$$C_i = \alpha_i P_i^2 + \beta_i P_i + \gamma_i \quad \text{Rs / h} \quad (1)$$

A power plant may have several generator units. If the input-output characteristic of different generator units are identical, then the generating units can be equally loaded. But generating units will generally have different input-output characteristic. This means that, for particular input cost, the generator power P_i will be different for different generating units in a plant.

3 INCREMENTAL COST CURVE

As we shall see, the criterion for distribution of the load between any two units is based on whether increasing the generation of one unit, and decreasing the generation of the other unit by the same amount results in an increase or decrease in total cost. This can be obtained if we can calculate the change in input cost ΔC_i for a small change in power ΔP_i .

Since $\frac{dC_i}{dP_i} = \frac{\Delta C_i}{\Delta P_i}$ we can write $\Delta C_i = \frac{dC_i}{dP_i} \Delta P_i$

$$\Delta C_i = \frac{dC_i}{dP_i} \Delta P_i$$

Thus while deciding the optimal scheduling, we are concerned with $\frac{dC_i}{dP_i}$, INCREMENTAL COST (IC) which is determined by the slopes of the input-output curves. Thus the **incremental cost curve is the plot of $\frac{dC_i}{dP_i}$ versus**

P_i . The dimension of $\frac{dC_i}{dP_i}$ is Rs / MWh.

The unit that has the input – output relation as

$$C_i = \alpha_i P_i^2 + \beta_i P_i + \gamma_i \quad \text{Rs / h} \quad (1)$$

has incremental cost (IC) as

$$IC_i = \frac{dC_i}{dP_i} = 2\alpha_i P_i + \beta_i \quad (2)$$

Here α_i , β_i and γ_i are constants.

A typical plot of IC versus power output is shown in Fig.2.

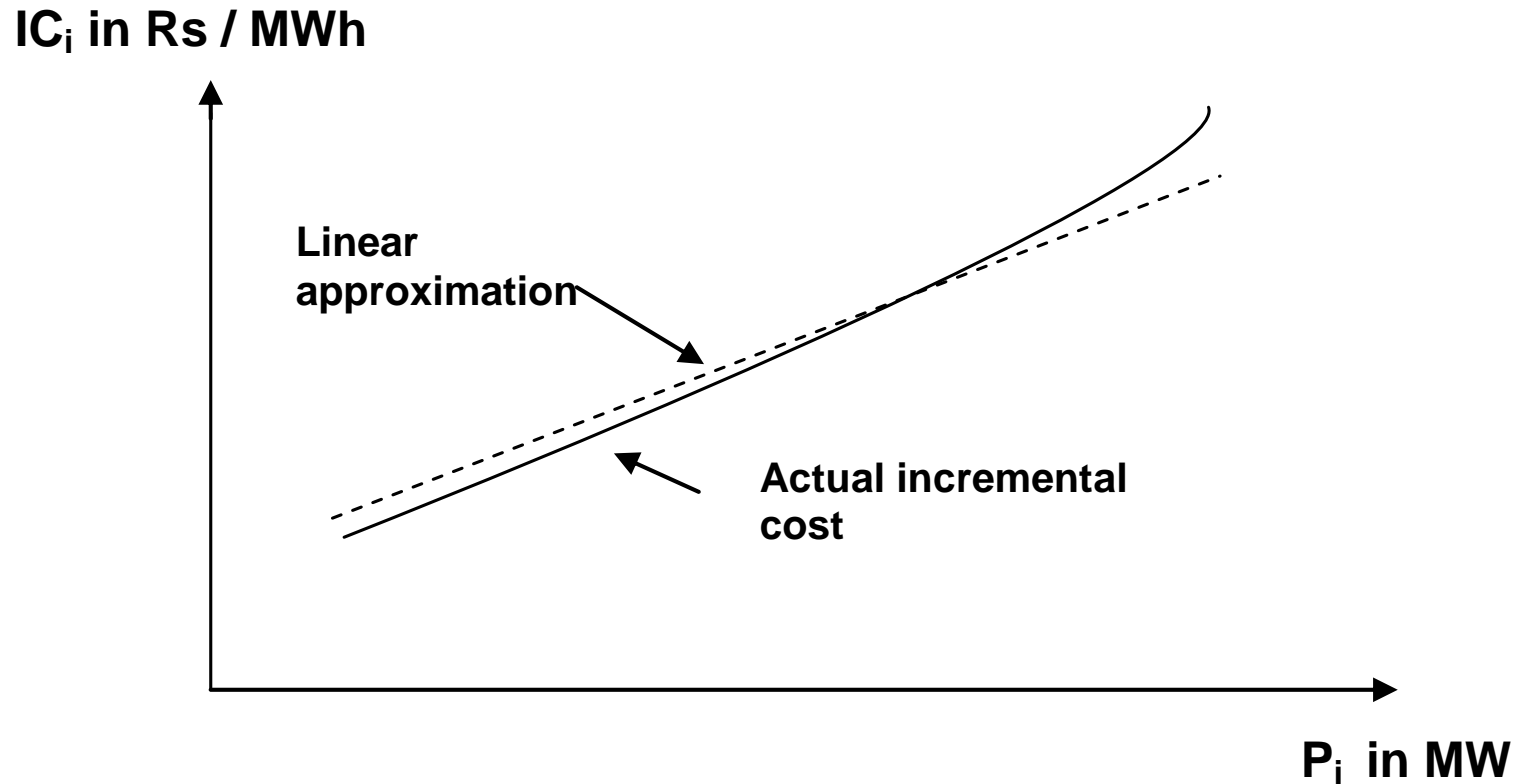


Fig.2 Incremental cost curve

This figure shows that incremental cost is quite linear with respect to power output over an appreciable range. In analytical work, the curve is usually approximated by one or two straight lines. The dashed line in the figure is a good representation of the curve.

We now have the background to understand the principle of economic dispatch which guides distribution of load among the generating units within a plant.

4 ECONOMICAL DIVISION OF PLANT LOAD BETWEEN GENERATING UNITS IN A PLANT

Various generating units in a plant generally have different input-output characteristics. Suppose that the total load in a plant is supplied by two units and that the division of load between these units is such that the incremental cost of one unit is higher than that of the other unit.

Now suppose some of the load is transferred from the unit with higher incremental cost to the unit with lower incremental cost. Reducing the load on the unit with higher incremental cost will result in greater reduction of cost than the increase in cost for adding the same amount of load to the unit with lower incremental cost. The transfer of load from one to other can be continued with a reduction of total cost until the incremental costs of the two units are equal.

This is illustrated through the characteristics shown in Fig. 3

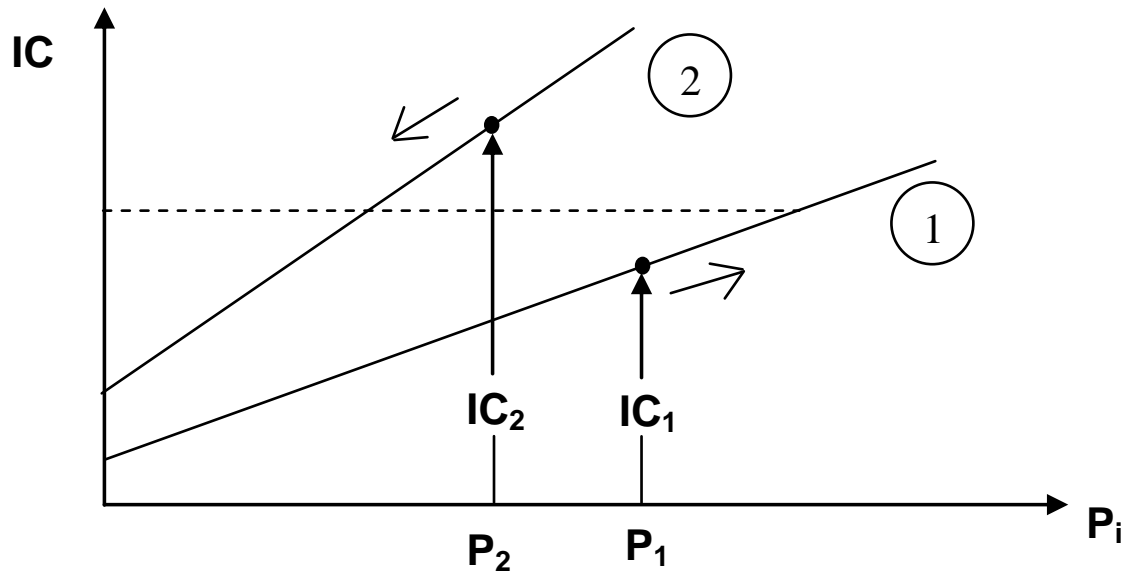


Fig. 3 Two units case

Initially, $IC_2 > IC_1$. Decrease the output power in unit 2 by ΔP and increase output power in unit 1 by ΔP . Now $IC_2 \Delta P > IC_1 \Delta P$. Thus there will be **more decrease in cost** and **less increase in cost** bringing the total cost lesser. This change can be continued until $IC_1 = IC_2$ at which the total cost will be minimum. Further reduction in P_2 and increase in P_1 will in $IC_1 > IC_2$ calling for decrease in P_1 and increase in P_2 until $IC_1 = IC_2$. Thus the total cost will be minimum when the **INCREMENTAL COSTS ARE EQUAL**.

The same reasoning can be extended to a plant with more than two generating units also. In this case, **if any two units have different incremental costs**, then in order to decrease the total cost of generation, decrease the output power in unit having higher IC and increase the output power in unit having lower IC. When this process is continued, a stage will reach wherein incremental costs of all the units will be equal. Now the total cost of generation will be minimum.

Thus the economical division of load between units within a plant is that all units must operate at the same incremental cost. Now we shall get the same result mathematically.

Consider a plant having N number of generating units. Input-output curve of the units are denoted as $C_1(P_1), C_2(P_2), \dots, C_N(P_N)$. Our problem is, for a given load demand P_D , find the set of P_i s which minimizes the cost function

$$C_T = C_1(P_1) + C_2(P_2) + \dots + C_N(P_N). \quad (3)$$

subject to the constraints

$$P_D - (P_1 + P_2 + \dots + P_N) = 0 \quad (4)$$

$$\text{and } P_{i \min} \leq P_i \leq P_{i \max} \quad i = 1, 2, \dots, N \quad (5)$$

Omitting the inequality constraints for the time being, the problem to be solved becomes

$$\text{Minimize } C_T = \sum_{i=1}^N C_i(P_i) \quad (6)$$

$$\text{subject to } P_D - \sum_{i=1}^N P_i = 0 \quad (7)$$

This optimizing problem with equality constraint can be solved by the method of Lagrangian multipliers. In this method, the Lagrangian function is formed by augmenting the equality constraints to the objective function using proper Lagrangian multipliers. For this case, Lagrangian function is

$$L(P_1, P_2, \dots, P_N, \lambda) = \sum_{i=1}^N C_i(P_i) + \lambda(P_D - \sum_{i=1}^N P_i) \quad (8)$$

where λ is the Lagrangian multiplier. Now this Lagrangian function has to be minimized with no constraints on it. The necessary conditions for a minimum are

$$\frac{\partial L}{\partial P_i} = 0 \quad i = 1, 2, \dots, N \quad \text{and} \quad \frac{\partial L}{\partial \lambda} = 0.$$

For a plant with 3 units

$$L(P_1, P_2, P_3, \lambda) = C_1(P_1) + C_2(P_2) + C_3(P_3) + \lambda(P_D - P_1 - P_2 - P_3)$$

Necessary conditions for a minimum are

$$\frac{\partial L}{\partial P_1} = \frac{\partial C_1}{\partial P_1} + \lambda(-1) = 0$$

$$\frac{\partial L}{\partial P_2} = \frac{\partial C_2}{\partial P_2} + \lambda(-1) = 0$$

$$\frac{\partial L}{\partial P_3} = \frac{\partial C_3}{\partial P_3} + \lambda(-1) = 0$$

$$\frac{\partial L}{\partial \lambda} = P_D - P_1 - P_2 - P_3 = 0$$

Generalizing the above, the necessary conditions are

$$\frac{\partial C_i}{\partial P_i} = \lambda \quad i = 1, 2, \dots, N \quad (9)$$

$$\text{and} \quad P_D - \sum_{i=1}^N P_i = 0 \quad (10)$$

Here $\frac{\partial C_i}{\partial P_i}$ is the change in production cost in unit i for a small change in generation in unit i. Since change in generation in unit i will affect the production cost of this unit ALONE, we can write

$$\frac{\partial C_i}{\partial P_i} = \frac{dC_i}{dP_i} \quad (11)$$

Using eqn.(11) in eqn. (9) we have

$$\frac{dC_i}{dP_i} = \lambda \quad i = 1, 2, \dots, N \quad (12)$$

Thus the solution for the problem

$$\text{Minimize } C_T = \sum_{i=1}^N C_i(P_i) \quad \text{subject to } P_D - \sum_{i=1}^N P_i = 0$$

is obtained when the following equations are satisfied.

$$\frac{dC_i}{dP_i} = \lambda \quad i = 1, 2, \dots, N \quad (13)$$

$$\text{and } P_D - \sum_{i=1}^N P_i = 0 \quad (14)$$

The above two conditions give $N+1$ number of equations which are to be solved for the $N+1$ number of variables $\lambda, P_1, P_2, \dots, P_N$. Equation (13) simply says that **at the minimum cost operating point, the incremental cost for all the generating units must be equal**. This condition is commonly known as EQUAL INCREMENTAL COST RULE. Equation (14) is known as POWER BALANCE EQUATION.

It is to be remembered that we have not yet considered the inequality constraints given by

$$\mathbf{P_{i\ min} \leq P_i \leq P_{i\ max} \quad i = 1,2,\dots,\ N}$$

Fortunately, if the solution obtained without considering the inequality constraints satisfies the inequality constraints also, then the obtained solution will be optimum. If for one or more generator units, the inequality constraints are not satisfied, the optimum strategy is obtained by keeping these generator units in their nearest limits and making the other generator units to supply the remaining power as per equal incremental cost rule.

EXAMPLE 1

The cost characteristic of two units in a plant are:

$$C_1 = 0.4 P_1^2 + 160 P_1 + K_1 \text{ Rs./h}$$

$$C_2 = 0.45 P_2^2 + 120 P_2 + K_2 \text{ Rs. / h}$$

where P_1 and P_2 are power output in MW. Find the optimum load allocation between the two units, when the total load is 162.5 MW. What will be the daily loss if the units are loaded equally?

SOLUTION

Incremental costs are:

$$IC_1 = 0.8 P_1 + 160 \text{ Rs. / MW h}$$

$$IC_2 = 0.9 P_2 + 120 \text{ Rs. / MW h}$$

Using the equal incremental cost rule

$$0.8 P_1 + 160 = \lambda \quad \text{and} \quad 0.9 P_2 + 120 = \lambda$$

$$\text{Since } P_1 + P_2 = 162.5 \text{ we get } \frac{\lambda - 160}{0.8} + \frac{\lambda - 120}{0.9} = 162.5$$

$$\text{i.e. } \lambda \left[\frac{1}{0.8} + \frac{1}{0.9} \right] = \frac{160}{0.8} + \frac{120}{0.9} + 162.5 \quad \text{i.e. } 2.3611 \lambda = 495.8333$$

$$2.3611 \lambda = 495.8333$$

This gives $\lambda = 210 \text{ Rs / MWh}$

Knowing $0.8 P_1 + 160 = \lambda$ and $0.9 P_2 + 120 = \lambda$

Optimum load allocation is

$$P_1 = \frac{210-160}{0.8} = 62.5 \text{ MW} \quad \text{and} \quad P_2 = \frac{210-120}{0.9} = 100 \text{ MW}$$

When the units are equally loaded, $P_1 = P_2 = 81.25 \text{ MW}$ and we have deviated from the optimum value of $P_1 = 62.5 \text{ MW}$ and $P_2 = 100 \text{ MW}$.

Knowing $C_1 = 0.4 P_1^2 + 160 P_1 + K_1 \text{ Rs./h}$

$$C_2 = 0.45 P_2^2 + 120 P_2 + K_2 \text{ Rs. / h}$$

Daily loss can also be computed by calculating the total cost C_T , which is $C_1 + C_2$, for the two schedules.

Thus, Daily loss = $24 \times [C_T(81.25, 81.25) - C_T(62.5, 100)]$

$$= 24 \times [28361.328 + K_1 + K_2 - (28062.5 + K_1 + K_2)] = \text{Rs. } 7171.87$$

EXAMPLE 2

A power plant has three units with the following cost characteristics:

$$C_1 = 0.5P_1^2 + 215P_1 + 5000 \text{ Rs / h}$$

$$C_2 = 1.0P_2^2 + 270P_2 + 5000 \text{ Rs / h}$$

$$C_3 = 0.7P_3^2 + 160P_3 + 9000 \text{ Rs/h}$$

where P_i^s are the generating powers in MW. The maximum and minimum loads allowable on each unit are 150 and 39 MW. Find the economic scheduling for a total load of i) 320 MW ii) 200 MW

SOLUTION

Knowing the cost characteristics, incremental cost characteristics are obtained as

$$IC_1 = 1.0P_1 + 215 \text{ Rs / MWh}$$

$$IC_2 = 2.0P_2 + 270 \text{ Rs / MWh}$$

$$IC_3 = 1.4P_3 + 160 \text{ Rs / MWh}$$

Using the equal incremental cost rule

$$1.0 P_1 + 215 = \lambda; \quad 2.0 P_2 + 270 = \lambda; \quad 1.4 P_3 + 160 = \lambda$$

$$1.0 P_1 + 215 = \lambda; \quad 2.0 P_2 + 270 = \lambda; \quad 1.4 P_3 + 160 = \lambda$$

Case i) Total load = 320 MW

Since $P_1 + P_2 + P_3 = 320$ we have

$$\frac{\lambda - 215}{1.0} + \frac{\lambda - 270}{2.0} + \frac{\lambda - 160}{1.4} = 320$$

$$\text{i.e. } \lambda \left[\frac{1}{1.0} + \frac{1}{2.0} + \frac{1}{1.4} \right] = \frac{215}{1.0} + \frac{270}{2.0} + \frac{160}{1.4} + 320$$

$$\text{i.e. } 2.2143 \lambda = 784.2857 \quad \text{This gives } \lambda = 354.193 \text{ RM / MWh}$$

$$\text{Thus } P_1 = (354.193 - 215) / 1.0 = 139.193 \text{ MW}$$

$$P_2 = (354.193 - 270) / 2.0 = 42.0965 \text{ MW}$$

$$P_3 = (354.193 - 160) / 1.4 = 138.7093 \text{ MW}$$

All P_i 's lie within maximum and minimum limits. Therefore, economic scheduling is

$$P_1 = 139.193 \text{ MW}; \quad P_2 = 42.0965 \text{ MW}; \quad P_3 = 138.7093 \text{ MW}$$

Case ii) Total load = 200 MW

Since $P_1 + P_2 + P_3 = 200$ we have

$$\lambda \left[\frac{1}{1.0} + \frac{1}{2.0} + \frac{1}{1.4} \right] = \frac{215}{1.0} + \frac{270}{2.0} + \frac{160}{1.4} + 200 \quad \text{i.e. } 2.21429 \lambda = 664.2857$$

This gives $\lambda = 300$ Rs / MWh

$$\text{Thus } P_1 = (300 - 215) / 1.0 = 85 \text{ MW}$$

$$P_2 = (300 - 270) / 2.0 = 15 \text{ MW}$$

$$P_3 = (300 - 160) / 1.4 = 100 \text{ MW}$$

It is noted that $P_2 < P_{2 \min}$. Therefore P_2 is set at the min. value of 39 MW.

Then $P_1 + P_3 = 200 - 39 = 161$ MW. This power has to be scheduled between units 1 and 3. Therefore

$$\lambda \left[\frac{1}{1.0} + \frac{1}{1.4} \right] = \frac{215}{1.0} + \frac{160}{1.4} + 161 \quad \text{i.e. } 1.71429 \lambda = 490.2857$$

This gives $\lambda = 286$ Rs / MWh

$$\text{Thus } P_1 = (286 - 215) / 1.0 = 71 \text{ MW}$$

$$P_3 = (286 - 160) / 1.4 = 90 \text{ MW}$$

P_1 and P_3 are within the limits. Therefore economic scheduling is

$$P_1 = 71 \text{ MW}; \quad P_2 = 39 \text{ MW}; \quad P_3 = 90 \text{ MW}$$

EXAMPLE 3

Incremental cost of two units in a plant are:

$$IC_1 = 0.8 P_1 + 160 \quad \text{Rs / MWh} \qquad IC_2 = 0.9 P_2 + 120 \quad \text{Rs / MWh}$$

where P_1 and P_2 are power output in MW. Assume that both the units are operating at all times. Total load varies from 50 to 250 MW and the minimum and maximum loads on each unit are 20 and 125 MW respectively. Find the incremental cost and optimal allocation of loads between the units for various total loads and furnish the results in a graphical form.

SOLUTION

For lower loads, IC of unit 1 is higher and hence it is loaded to minimum value i.e. $P_1 = 20$ MW. Total minimum load being 50 MW, when $P_1 = 20$ MW, P_2 must be equal to 30 MW. Thus initially $P_1 = 20$ MW, $IC_1 = 176$ Rs / MWh, $P_2 = 30$ MW and $IC_2 = 147$ Rs / MWh. As the load increased from 50 MW, load on unit 2 will be increased until its IC i.e. IC_2 reaches a value of 176 Rs / MWh. When $IC_2 = 176$ Rs / MWh load on unit 2 is $P_2 = (176 - 120) / 0.9 = 62.2$ MW. Until that point is reached, P_1 shall remain at 20 MW and the plant IC, i.e. λ is determined by unit 2.

When the plant IC, λ is increased beyond 176 Rs / MWh, unit loads are calculated as

$$P_1 = (\lambda - 160) / 0.8 \text{ MW}$$

$$P_2 = (\lambda - 120) / 0.9 \text{ MW}$$

Then the load allocation will be as shown below.

Plant IC λ Rs/MWh	Load on unit 1 P_1 MW	Load on unit 2 P_2 MW	Total load $P_1 + P_2$ MW
147	20	30	50
176	20	62.2	82.2
180	25	66.6	91.6
190	37.5	77.7	115.2
200	50	88.8	138.8
210	62.5	100.0	162.5
220	75	111.1	186.1
230	87.5	122.2	209.7

Load on unit 2 reaches the maximum value of 125 MW, when $\lambda = (0.9 \times 125) + 120 = 232.5$ Rs / Mwh. When the plant IC, λ increases further, P_2 shall remain at 125 MW and the load on unit 1 alone increases and its value is computed as $P_1 = (\lambda - 160) / 0.8$ MW. Such load allocations are shown below.

Plant IC λ Rs / MWh	Load on unit 1 P_1 MW	Load on unit 2 P_2 MW	Total load $P_1 + P_2$ MW
232.5	90.62	125	215.62
240	100	125	225
250	112.5	125	237.5
260	125	125	250

The results are shown in graphical form in Fig. 4

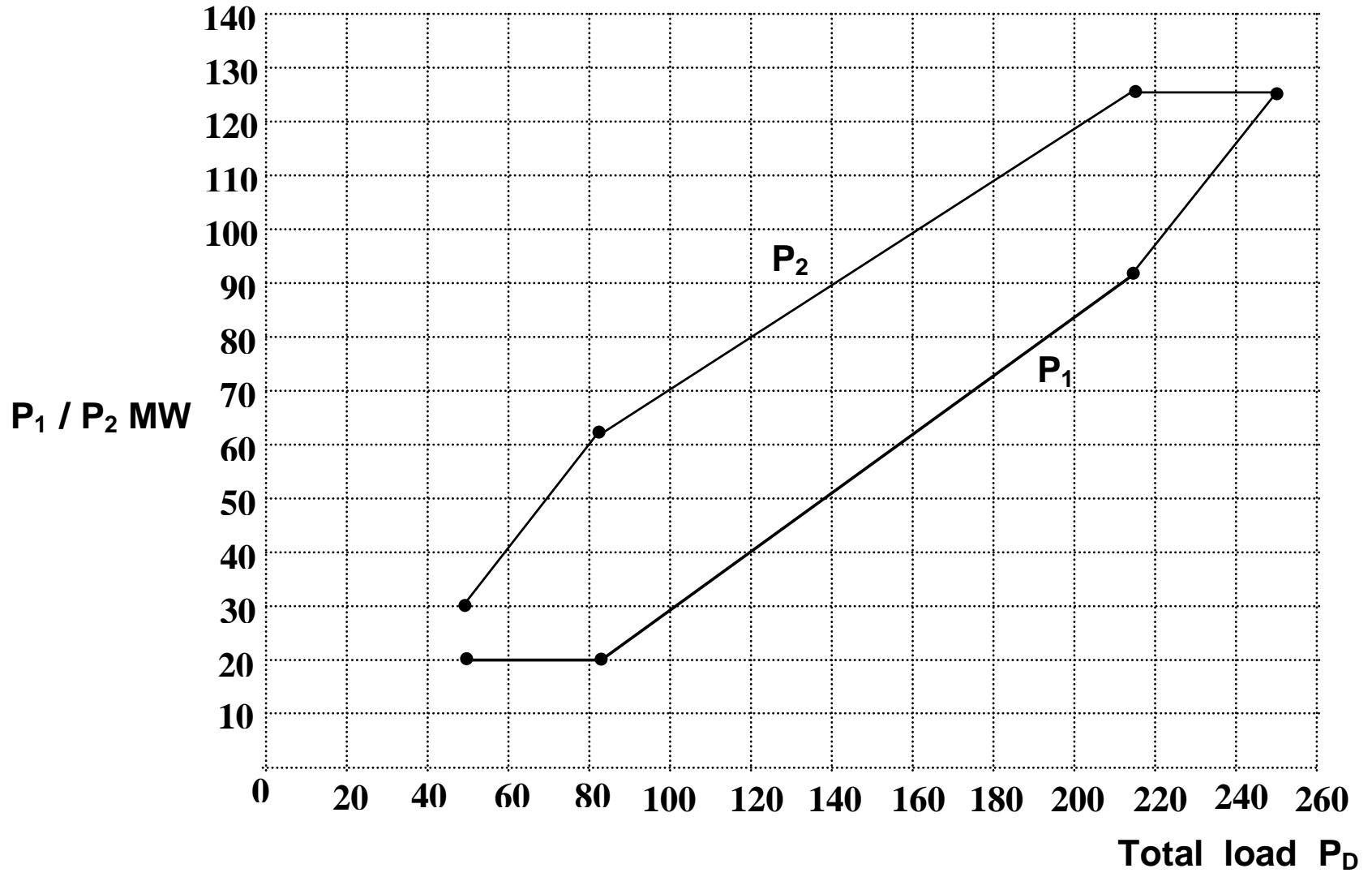


Fig. 4 Load allocation for various plant load

Alternative way of explanation for this problem is shown in Fig. 5

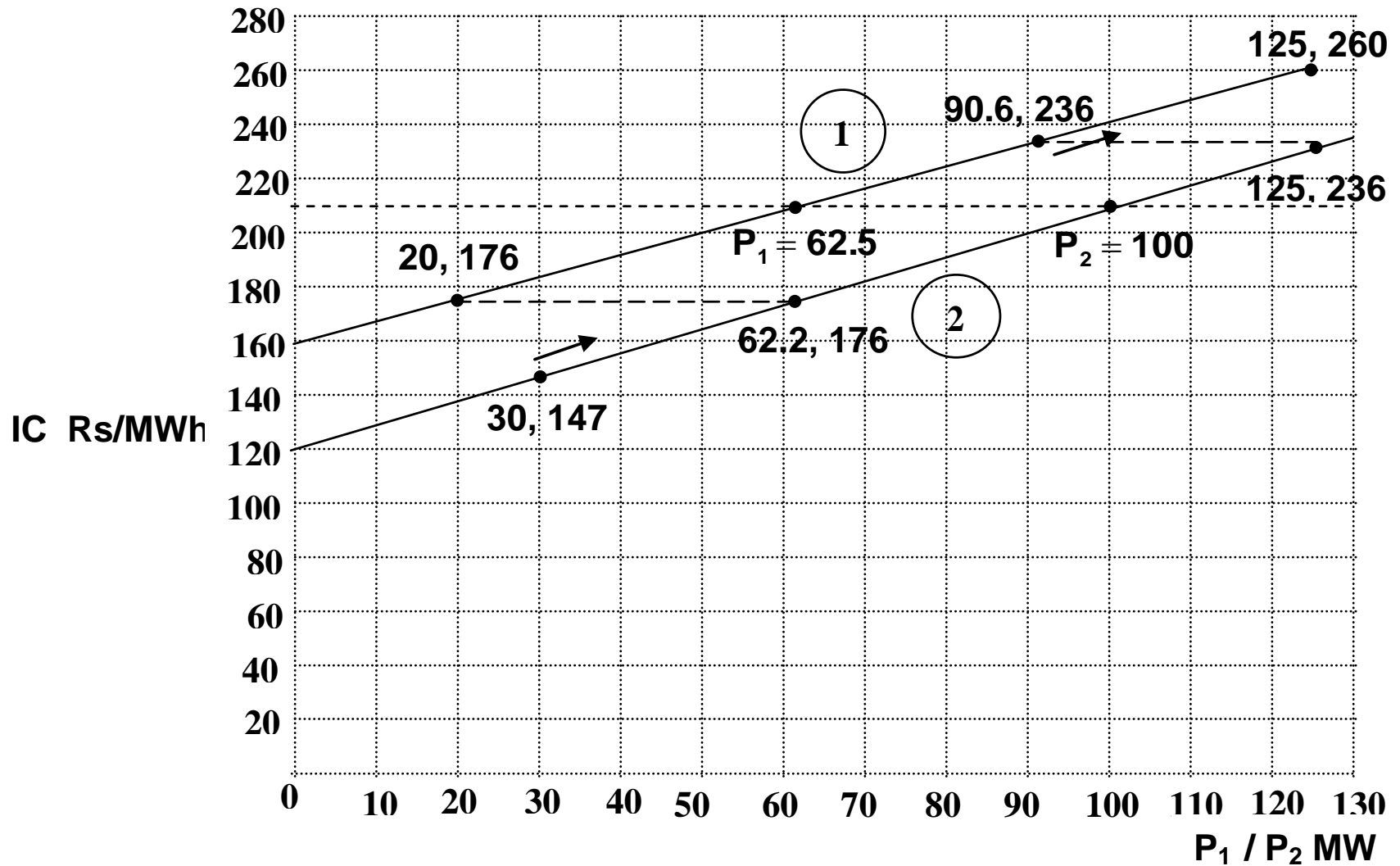


Fig. 5 Load allocation between two units

5 TRANSMISSION LOSS

Generally, in a power system, several plants are situated at different places. They are interconnected by long transmission lines. The entire system load along with transmission loss shall be met by the power plants in the system. Transmission loss depends on i) line parameters ii) bus voltages and iii) power flow. Determination of transmission loss requires complex computations. However, with reasonable approximations, for a power system with N number of power plants, transmission loss can be represented as

$$P_L = [P_1 \quad P_2 \quad \dots \quad P_N] \begin{bmatrix} B_{11} & B_{12} & \dots & B_{1N} \\ B_{21} & B_{22} & \dots & B_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ B_{N1} & B_{N2} & \dots & B_{NN} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_N \end{bmatrix} \quad (15)$$

where P_1, P_2, \dots, P_N are the powers supplied by the plants 1,2,...,N respectively.

$$\mathbf{P}_L = [\mathbf{P}_1 \quad \mathbf{P}_2 \quad \dots \quad \mathbf{P}_N] \begin{bmatrix} \mathbf{B}_{11} & \mathbf{B}_{12} & \dots & \mathbf{B}_{1N} \\ \mathbf{B}_{21} & \mathbf{B}_{22} & \dots & \mathbf{B}_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{B}_{N1} & \mathbf{B}_{N2} & \dots & \mathbf{B}_{NN} \end{bmatrix} \begin{bmatrix} \mathbf{P}_1 \\ \mathbf{P}_2 \\ \vdots \\ \mathbf{P}_N \end{bmatrix} \quad (15)$$

From eq.(15) $\mathbf{P}_L = [\mathbf{P}_1 \quad \mathbf{P}_2 \quad \dots \quad \dots \quad \mathbf{P}_N] \begin{bmatrix} \sum_{n=1}^N \mathbf{B}_{1n} \mathbf{P}_n \\ \sum_{n=1}^N \mathbf{B}_{2n} \mathbf{P}_n \\ \vdots \\ \sum_{n=1}^N \mathbf{B}_{Nn} \mathbf{P}_n \end{bmatrix}$

$$= \mathbf{P}_1 \sum_{n=1}^N \mathbf{B}_{1n} \mathbf{P}_n + \mathbf{P}_2 \sum_{n=1}^N \mathbf{B}_{2n} \mathbf{P}_n + \dots + \mathbf{P}_N \sum_{n=1}^N \mathbf{B}_{Nn} \mathbf{P}_n$$

$$= \sum_{m=1}^N \mathbf{P}_m \sum_{n=1}^N \mathbf{B}_{mn} \mathbf{P}_n = \sum_{m=1}^N \sum_{n=1}^N \mathbf{P}_m \mathbf{B}_{mn} \mathbf{P}_n$$

Thus \mathbf{P}_L can be written as $\mathbf{P}_L = \sum_{m=1}^N \sum_{n=1}^N \mathbf{P}_m \mathbf{B}_{mn} \mathbf{P}_n \quad (16)$

$$P_L = \sum_{m=1}^N \sum_{n=1}^N P_m B_{mn} P_n \quad (16)$$

When the powers are in MW, the B_{mn} coefficients are of dimension 1/ MW. If powers are in per-unit, then B_{mn} coefficients are also in per-unit. Loss coefficient matrix of a power system shall be determined before hand and made available for economic dispatch.

For a two plant system, the expression for the transmission loss is

$$P_L = \begin{bmatrix} P_1 & P_2 \end{bmatrix} \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}$$

$$= \begin{bmatrix} P_1 & P_2 \end{bmatrix} \begin{bmatrix} B_{11} P_1 + B_{12} P_2 \\ B_{21} P_1 + B_{22} P_2 \end{bmatrix} = P_1^2 B_{11} + P_1 P_2 B_{12} + P_1 P_2 B_{21} + P_2^2 B_{22}$$

Since B_{mn} coefficient matrix is symmetric, for two plant system

$$P_L = P_1^2 B_{11} + 2 P_1 P_2 B_{12} + P_2^2 B_{22} \quad (17)$$

In later calculations we need the Incremental Transmission Loss (ITL),

$$\frac{\partial P_L}{\partial P_i}.$$

For two plant system

$$\frac{\partial P_L}{\partial P_1} = 2B_{11} P_1 + 2B_{12} P_2 \quad (18)$$

$$\frac{\partial P_L}{\partial P_2} = 2B_{12} P_1 + 2B_{22} P_2 \quad (19)$$

This can be generalized as

$$\frac{\partial P_L}{\partial P_m} = \sum_{n=1}^N 2 B_{mn} P_n \quad m = 1, 2, \dots, N \quad (20)$$

6 ECONOMIC DIVISION OF SYSTEM LOAD BETWEEN VARIOUS PLANTS IN THE POWER SYSTEM

It is to be noted that different plants in a power system will have different cost characteristics.

Consider a power system having N number of plants. Input-output characteristics of the plants are denoted as $C_1(P_1), C_2(P_2), \dots, C_N(P_N)$.

Our problem is for a given system load demand P_D , find the set of plant generation P_1, P_2, \dots, P_N which minimizes the cost function

$$C_T = C_1(P_1) + C_2(P_2) + \dots + C_N(P_N) \quad (21)$$

subject to the constraints

$$P_D + P_L - (P_1 + P_2 + \dots + P_N) = 0 \quad (22)$$

$$\text{and } P_{i \min} \leq P_i \leq P_{i \max} \quad i = 1, 2, \dots, N \quad (23)$$

Inequality constraints are omitted for the time being.

The problem to be solved becomes

$$\text{Minimize } C_T = \sum_{i=1}^N C_i(P_i) \quad (24)$$

$$\text{subject to } P_D + P_L - \sum_{i=1}^N P_i = 0 \quad (25)$$

For this case the Lagrangian function is

$$L(P_1, P_2, \dots, P_N, \lambda) = \sum_{i=1}^N C_i(P_i) + \lambda (P_D + P_L - \sum_{i=1}^N P_i) \quad (26)$$

This Lagrangian function has to be minimized with no constraint on it.

The necessary conditions for a minimum are

$$\frac{\partial L}{\partial P_i} = 0 \quad i = 1, 2, \dots, N$$

$$\text{and } \frac{\partial L}{\partial \lambda} = 0.$$

$$L(P_1, P_2, \dots, P_N, \lambda) = \sum_{i=1}^N C_i(P_i) + \lambda (P_D + P_L - \sum_{i=1}^N P_i) \quad (26)$$

For a system with 2 plants

$$L(P_1, P_2, \lambda) = C_1(P_1) + C_2(P_2) + \lambda(P_D + P_L - P_1 - P_2)$$

$$\frac{\partial L}{\partial P_1} = \frac{\partial C_1}{\partial P_1} + \lambda \left(\frac{\partial P_L}{\partial P_1} - 1 \right) = 0$$

$$\frac{\partial L}{\partial P_2} = \frac{\partial C_2}{\partial P_2} + \lambda \left(\frac{\partial P_L}{\partial P_2} - 1 \right) = 0$$

$$\frac{\partial L}{\partial \lambda} = P_D + P_L - P_1 - P_2 = 0$$

Generalizing this, for system with N plants, the necessary conditions for a minimum are

$$\frac{\partial C_i}{\partial P_i} + \lambda \left[\frac{\partial P_L}{\partial P_i} - 1 \right] = 0 \quad i=1,2,\dots,N \quad (27)$$

$$\text{and} \quad P_D + P_L - \sum_{i=1}^N P_i = 0 \quad (28)$$

As discussed in earlier case, we can write

$$\frac{\partial C_i}{\partial P_i} = \frac{dC_i}{dP_i} \quad (29)$$

Using eqn. (29) in eqn. (27) we have

$$\frac{dC_i}{dP_i} + \lambda \frac{\partial P_L}{\partial P_i} = \lambda \quad i=1,2,\dots,N \quad (30)$$

$$\text{and} \quad P_D + P_L - \sum_{i=1}^N P_i = 0 \quad (31)$$

$$\frac{dC_i}{dP_i} + \lambda \frac{\partial P_L}{\partial P_i} = \lambda \quad i=1,2,\dots,N \quad (30)$$

$$\text{and} \quad P_D + P_L - \sum_{i=1}^N P_i = 0 \quad (31)$$

These equations can be solved for the plant generations P_1, P_2, \dots, P_N .

As shown in the next section the value of λ in eqn. (30) is the INCREMENTAL COST OF RECEIVED POWER.

The eqns. described in eqn. (30) are commonly known as COORDINATION EQUATIONS as they link the incremental cost of plant $\frac{dC_i}{dP_i}$, incremental cost of received power λ and the incremental transmission loss (ITL) $\frac{\partial P_L}{\partial P_i}$. Equation (31) is the POWER BALANCE EQUATION.

Coordination equations

$$\frac{dC_i}{dP_i} + \lambda \frac{\partial P_L}{\partial P_i} = \lambda \quad i=1,2,\dots,N \quad (30)$$

can also be written as

$$IC_i + \lambda ITL_i = \lambda \quad i = 1,2,\dots,N \quad (32)$$

The N number of coordinate equations together with the power balance equation are to be solved for the plant loads P_1, P_2, \dots, P_N to obtain the economic schedule.

7 INCREMENTAL COST OF RECEIVED POWER

The value of λ in the coordination equations is the incremental cost of received power. This can be proved as follows:

The coordination equations $\frac{\partial C_i}{\partial P_i} + \lambda \frac{\partial P_L}{\partial P_i} = \lambda$ can be written as

$$\frac{\partial C_i}{\partial P_i} = \lambda \left[1 - \frac{\partial P_L}{\partial P_i} \right] \quad (33)$$

$$\text{i.e. } \frac{\Delta C_i}{\Delta P_i} \frac{1}{1 - \frac{\Delta P_L}{\Delta P_i}} = \lambda \quad \text{i.e. } \frac{\Delta C_i}{\Delta P_i - \Delta P_L} = \lambda \quad (34)$$

$$\text{Since } P_D = \sum_{i=1}^N P_i - P_L \quad \frac{\partial P_D}{\partial P_i} = 1 - \frac{\partial P_L}{\partial P_i} \quad \text{i.e. } \Delta P_D = \Delta P_i - \Delta P_L \quad (35)$$

$$\text{Using eqn.(35) in eqn.(34) gives } \frac{\Delta C_i}{\Delta P_D} = \frac{\partial C_i}{\partial P_D} = \lambda \quad (36)$$

Thus λ is the incremental cost of received power.

8 PENALTY FACTORS

To have a better feel about the coordination equations, let us rewrite the

same as
$$\frac{dC_i}{dP_i} = \lambda \left[1 - \frac{\partial P_L}{\partial P_i} \right] \quad i = 1, 2, \dots, N \quad (37)$$

Thus
$$\left[\frac{1}{1 - \frac{\partial P_L}{\partial P_i}} \right] \frac{dC_i}{dP_i} = \lambda \quad i = 1, 2, \dots, N \quad (38)$$

The above equation is often written as

$$L_i \frac{dC_i}{dP_i} = \lambda \quad i = 1, 2, \dots, N \quad (39)$$

where, L_i which is called the PENALTY FACTOR of plant i , is given by

$$L_i = \frac{1}{1 - \frac{\partial P_L}{\partial P_i}} \quad i = 1, 2, \dots, N \quad (40)$$

The results of eqn. (39) means that minimum fuel cost is obtained when the incremental cost of each plant multiplied by its penalty factor is the same for the plants in the power system.

9 OPTIMUM SCHEDULING OF SYSTEM LOAD BETWEEN PLANTS

- SOLUTION PROCEDURE

To determine the optimum scheduling of system load between plants, the data required are i) system load, ii) incremental cost characteristics of the plants and iii) loss coefficient matrix. The iterative solution procedure is:

Step 1

For the first iteration, choose suitable initial value of λ . While finding this, one way is to assume that the transmission losses are zero and the plants are loaded equally.

Step 2

Knowing $C_i = \alpha_i P_i^2 + \beta_i P_i + \gamma_i$ i.e. $IC_i = 2 \alpha_i P_i + \beta_i$ substitute the value of λ into the coordination equations

$$\frac{dC_i}{dP_i} + \lambda \frac{\partial P_L}{\partial P_i} = \lambda \quad i = 1, 2, \dots, N$$

$$\text{i.e. } (2\alpha_i P_i + \beta_i) + \lambda \sum_{n=1}^N 2B_{mn} P_n = \lambda \quad i = 1, 2, \dots, N$$

The above set of linear simultaneous equations are to be solved for the values P_i 's.

Step 3

Compute the transmission loss P_L from $P_L = [P] [B] [P^t]$

where $[P] = [P_1 P_2 \dots P_N]$ and $[B]$ is the loss coefficient matrix.

Step 4

Compare $\sum_{i=1}^N P_i$ with $P_D + P_L$ to check the power balance. If the power

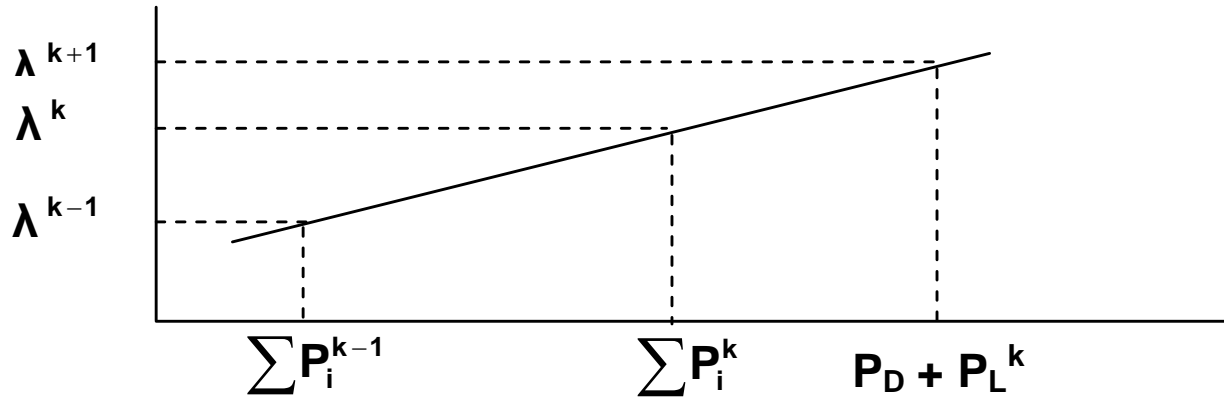
balance is satisfied within a specified tolerance, then the present solution is the optimal solution; otherwise update the value of λ .

First time updating can be done judiciously.

Value of λ is increased by about 5% if $\sum_{i=1}^N P_i < P_D + P_L$.

Value of λ is decreased by about 5% if $\sum_{i=1}^N P_i > P_D + P_L$

In the subsequent iterations, using linear interpolation, value of λ can be updated as



$$\lambda^{k+1} = \lambda^k + \frac{\lambda^k - \lambda^{k-1}}{\sum_{i=1}^N P_i^k - \sum_{i=1}^N P_i^{k-1}} [P_D + P_L^k - \sum_{i=1}^N P_i^k] \quad (41)$$

Here $k-1$, k and $k+1$ are the previous iteration count, present iterative count and the next iteration count respectively.

Step 5

Return to Step 2 and continue the calculations of Steps 2, 3 and 4 until the power balance equation is satisfied with desired accuracy.

The above procedure is now illustrated through an example.

EXAMPLE 4

Consider a power system with two plants having incremental cost as

$$IC_1 = 1.0 P_1 + 200 \text{ Rs / MWh}$$

$$IC_2 = 1.0 P_2 + 150 \text{ Rs / MWh}$$

Loss coefficient matrix is given by $B = \begin{bmatrix} 0.001 & -0.0005 \\ -0.0005 & 0.0024 \end{bmatrix}$

Find the optimum scheduling for a system load of 100 MW.

SOLUTION

Assume that there is no transmission loss and the plants are loaded equally. Then $P_1 = 50 \text{ MW}$. Initial value of $\lambda = (1.0 \times 50) + 200 = 250 \text{ Rs / MWh}$.

Coordination equations $\frac{dC_i}{dP_i} + \lambda \frac{\partial P_L}{\partial P_i} = \lambda$

$$1.0 P_1 + 200 + 250 (0.002P_1 - 0.001 P_2) = 250$$

$$1.0 P_2 + 150 + 250 (-0.001P_1 + 0.0048P_2) = 250$$

i.e. $1.5 P_1 - 0.25 P_2 = 50$ and $-0.25P_1 + 2.2 P_2 = 100$

$$\begin{bmatrix} 1.5 & -0.25 \\ -0.25 & 2.2 \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} = \begin{bmatrix} 50 \\ 100 \end{bmatrix}; \text{ On solving}$$

$$P_1 = 41.6988 \text{ MW} \quad \text{and} \quad P_2 = 50.1931 \text{ MW}$$

$$\begin{aligned}
 P_L &= [41.6988 \quad 50.1931] \begin{bmatrix} 0.001 & -0.0005 \\ -0.0005 & 0.0024 \end{bmatrix} \begin{bmatrix} 41.6988 \\ 50.1931 \end{bmatrix} \\
 &= [41.6988 \quad 50.1931] \begin{bmatrix} 0.01660 \\ 0.09961 \end{bmatrix} = 5.6919 \text{ MW}
 \end{aligned}$$

$$P_1 + P_2 = 91.8919 \text{ MW} \quad \text{and} \quad P_D + P_L = 105.6919 \text{ MW}$$

Since $P_1 + P_2 < P_D + P_L$, λ value should be increased. It is increased by 4 %.

New value of $\lambda = 250 \times 1.04 = 260 \text{ Rs / MWh}$.

Coordination equations:

$$1.0 P_1 + 200 + 260 (0.002P_1 - 0.001 P_2) = 260$$

$$1.0 P_2 + 150 + 260 (-0.001P_1 + 0.0048P_2) = 260$$

$$\text{i.e. } 1.52 P_1 - 0.26 P_2 = 60 \quad \text{and} \quad -0.26 P_1 + 2.248 P_2 = 110$$

$$\begin{bmatrix} 1.52 & -0.26 \\ -0.26 & 2.248 \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \end{bmatrix} = \begin{bmatrix} 60 \\ 110 \end{bmatrix}; \text{ On solving}$$

$$P_1 = 48.8093 \text{ MW} \quad \text{and} \quad P_2 = 54.5776 \text{ MW}$$

$$\begin{aligned}
 P_L &= \begin{bmatrix} 48.8093 & 54.5776 \end{bmatrix} \begin{bmatrix} 0.001 & -0.0005 \\ -0.0005 & 0.0024 \end{bmatrix} \begin{bmatrix} 48.8093 \\ 54.5776 \end{bmatrix} \\
 &= \begin{bmatrix} 48.8093 & 54.5776 \end{bmatrix} \begin{bmatrix} 0.02152 \\ 0.10658 \end{bmatrix} = 6.8673 \text{ MW}
 \end{aligned}$$

$$P_1 + P_2 = 103.3869 \text{ MW}; \quad P_D + P_L = 106.8673 \text{ MW}$$

$$P_1 + P_2 \neq P_D + P_L$$

Knowing two values of λ and the corresponding total generation powers, new value of λ is computed as

$$\lambda^{k+1} = \lambda^k + \frac{\lambda^k - \lambda^{k-1}}{\sum_{i=1}^N P_i^k - \sum_{i=1}^N P_i^{k-1}} [P_D + P_L^k - \sum_{i=1}^N P_i^k]$$

$$\lambda = 260 + \frac{260 - 250}{103.3869 - 91.8918} (106.8673 - 103.3869) = 263 \text{ Rs / MWh}$$

With this new value of λ , coordination equations are formed and the procedure has to be repeated.

The following table shows the results obtained.

λ	P_1	P_2	P_L	$P_1 + P_2$	$P_D + P_L$
250	41.6988	50.1931	5.6919	91.8919	105.6919
260	48.8093	54.5776	6.8673	103.3869	106.8673
263	50.9119	55.8769	7.2405	106.789	107.2405
263.3	51.1061	55.9878	7.2737	107.0939	107.2737
263.5	51.2636	56.0768	7.3003	107.3404	107.3003
263.467	51.2401	56.0659	7.2969	107.3060	107.2969

Optimum schedule is $P_1 = 51.2401 \text{ MW}$
 $P_2 = 56.0659 \text{ MW}$

For this transmission loss is 7.2969 MW

10 BASE POINT AND PARTICIPATION FACTORS

The system load will keep changing in a cyclic manner. It will be higher during day time and early evening when industrial loads are high. However during night and early morning the system load will be much less.

The optimal generating scheduling need to be solved for different load conditions because load demand P_D keeps changing. **When load changes are small, it is possible to move from one optimal schedule to another using PARTICIPATING FACTORS.**

We start with a known optimal generation schedule, $P_1^0, P_2^0, \dots, P_N^0$, for a particular load P_D . This schedule is taken as BASE POINT and the corresponding incremental cost is λ^0 . Let there be a small increase in load of ΔP_D . To meet with this increased load, generations are to be increased as $\Delta P_1, \Delta P_2, \dots, \Delta P_N$. Correspondingly incremental cost increases by $\Delta\lambda$.

Knowing that for i^{th} unit, $C_i = \alpha_i P_i^2 + \beta_i P_i + \gamma_i$, incremental cost is

$$IC_i = 2 \alpha_i P_i + \beta_i = \lambda \quad (42)$$

Small change in incremental cost and corresponding change in generation

are related as
$$\frac{\Delta \lambda}{\Delta P_i} = 2 \alpha_i \quad (43)$$

Thus
$$\Delta P_i = \frac{\Delta \lambda}{2 \alpha_i} \quad \text{for } i = 1, 2, \dots, N \quad (44)$$

Total change in generations is equal to the change in load.

Therefore
$$\sum_{i=1}^N \Delta P_i = \Delta P_D \quad \text{i.e.} \quad \Delta P_D = \Delta \lambda \sum_{i=1}^N \frac{1}{2 \alpha_i} \quad (45)$$

From the above two equations
$$\frac{\Delta P_i}{\Delta P_D} = \frac{\frac{1}{2 \alpha_i}}{\sum_{i=1}^N \frac{1}{2 \alpha_i}} = k_i \quad \text{for } i = 1, 2, \dots, N \quad (46)$$

The ratio $\frac{\Delta P_i}{\Delta P_D}$ is known as the PARTICIPATION FACTOR of generator i ,

represented as k_i . Once all the k_i s, are calculated from eq.(46), the change

in generations are given by
$$\Delta P_i = k_i \Delta P_D \quad \text{for } i = 1, 2, \dots, N \quad (47)$$

EXAMPLE 5

Incremental cost of three units in a plant are:

$$IC_1 = 0.8 P_1 + 160 \text{ Rs / MWh}; \quad IC_2 = 0.9 P_2 + 120 \text{ Rs / MWh}; \quad \text{and}$$

$$IC_3 = 1.25 P_3 + 110 \text{ Rs / MWh}$$

where P_1 , P_2 and P_3 are power output in MW. Find the optimum load allocation when the total load is 242.5 MW.

Using Participating Factors, determine the optimum scheduling when the load increases to 250 MW.

Solution

Using the equal incremental cost rule

$$0.8 P_1 + 160 = \lambda; \quad 0.9 P_2 + 120 = \lambda; \quad 1.25 P_3 + 110 = \lambda$$

$$\text{Since } P_1 + P_2 + P_3 = 242.5 \text{ we get } \frac{\lambda - 160}{0.8} + \frac{\lambda - 120}{0.9} + \frac{\lambda - 110}{1.25} = 242.5$$

$$\text{i.e. } \lambda \left[\frac{1}{0.8} + \frac{1}{0.9} + \frac{1}{1.25} \right] = \frac{160}{0.8} + \frac{120}{0.9} + \frac{110}{1.25} + 242.5 \text{ i.e. } 3.1611 \lambda = 663.8333$$

This gives $\lambda = 210 \text{ Rs / MWh}$

Optimum load allocation is

$$P_1 = \frac{210 - 160}{0.8} = 62.5 \text{ MW}; \quad P_2 = \frac{210 - 120}{0.9} = 100 \text{ MW}; \quad P_3 = \frac{210 - 110}{1.25} = 80 \text{ MW}$$

Participation Factors are:

$$k_1 = \frac{\frac{1}{0.8}}{\frac{1}{0.8} + \frac{1}{0.9} + \frac{1}{1.25}} = \frac{1.25}{3.1611} = 0.3954$$

$$k_2 = \frac{\frac{1}{0.9}}{\frac{1}{0.8} + \frac{1}{0.9} + \frac{1}{1.25}} = \frac{1.1111}{3.1611} = 0.3515$$

$$k_3 = \frac{\frac{1}{1.25}}{\frac{1}{0.8} + \frac{1}{0.9} + \frac{1}{1.25}} = \frac{0.8}{3.1611} = 0.2531$$

Change in load $\Delta P_D = 250 - 242.5 = 7.5$ MW

Change in generations are:

$$\Delta P_1 = 0.3954 \times 7.5 = 2.9655 \text{ MW}$$

$$\Delta P_2 = 0.3515 \times 7.5 = 2.6363 \text{ MW}$$

$$\Delta P_3 = 0.2531 \times 7.5 = 1.8982 \text{ MW}$$

Thus optimum schedule is:

$$P_1 = 65.4655 \text{ MW}; P_2 = 102.6363 \text{ MW}; P_3 = 81.8982 \text{ MW}$$

Example 6

A power plant has two units with the following cost characteristics:

$$C_1 = 0.6 P_1^2 + 200 P_1 + 2000 \text{ Rs / hour}$$

$$C_2 = 1.2 P_2^2 + 150 P_2 + 2500 \text{ Rs / hour}$$

where P_1 and P_2 are the generating powers in MW. The daily load cycle is as follows:

6:00 A.M. to 6:00 P.M. 150 MW

6:00 P.M. to 6:00 A.M. 50 MW

The cost of taking either unit off the line and returning to service after 12 hours is Rs 5000.

Maximum generation of each unit is 100 MW.

Considering 24 hour period from 6:00 A.M. one morning to 6:00 A.M. the next morning

- a. Would it be economical to keep both units in service for this 24 hour period or remove one unit from service for 12 hour period from 6:00 P.M. one evening to 6:00 A.M. the next morning ?**
- b. Compute the economic schedule for the peak load and off peak load conditions.**
- c. Calculate the optimum operating cost per day.**
- d. If operating one unit during off peak load is decided, up to what cost of taking one unit off and returning to service after 12 hours, this decision is acceptable ?**
- e. If the cost of taking one unit off and returning to service after 12 hours exceeds the value calculated in d, what must be done during off peak period?**

Solution

To meet the peak load of 150 MW, both the units are to be operated.

However, during 6:00 pm to 6:00 am, load is 50 MW and there is a choice

- i) both the units are operating
- ii) one unit (either 1 or 2 – to be decided) is operating

- i) When both the units are operating

$$IC_1 = 1.2 P_1 + 200 \text{ Rs / MWh}$$

$$IC_2 = 2.4 P_2 + 150 \text{ Rs / MWh} \quad \text{Using equal IC rule}$$

$$\frac{\lambda - 200}{1.2} + \frac{\lambda - 150}{2.4} = 50; \quad 1.25 \lambda = 279.1667 \quad \text{and} \quad \lambda = 223.3333$$

$$\text{Therefore } P_1 = 19.4444 \text{ MW}; \quad P_2 = 30.5555 \text{ MW}$$

$$\text{Then } C_T = C_1(P_1 = 19.4444) + C_2(P_2 = 30.5555) = 14319.42 \text{ Rs / h}$$

$$\text{For 12 hour period, cost of operation} = \text{Rs } 171833.04$$

i) Cost of operation for 12 hours = Rs. 171833.04

ii) If unit 1 is operating, $C_1|_{P1=50} = 13500$ Rs / h

If unit 2 is operating, $C_2|_{P2=50} = 13000$ Rs / h

Between units 1 and 2, it is economical to operate unit 2. If only one unit is operating during off-peak period, cost towards taking out and connecting it back also must be taken.

Therefore, for off-peak period (with unit 2 alone operating) cost of operation = $(13000 \times 12) + 5000 = \text{Rs. } 161000$

Between the two choices (i) and (ii), choice (ii) is cheaper. Therefore, during 6:00 pm to 6:00 am, it is better to operate unit 2 alone.

b. During the peak period, $P_D = 150$ MW. With equal IC rule

$$\frac{\lambda - 200}{1.2} + \frac{\lambda - 150}{2.4} = 150; \quad 1.25 \lambda = 379.1667 \quad \text{and} \quad \lambda = 303.3333$$

Therefore $P_1 = 86.1111$ MW; $P_2 = 63.8889$ MW

Thus, economic schedule is:

During 6:00 am to 6:00 pm $P_1 = 86.1111$ MW; $P_2 = 63.8889$ MW

During 6:00 pm to 6:00 am $P_1 = 0$; $P_2 = 50$ MW

c. Cost of operation

for peak period $= 12 [C_1 |_{P_1 = 86.1111} + C_2 |_{P_2 = 63.8889}]$

$$= 12 \times 40652.78 = \text{Rs } 487833$$

Cost of operation for off-peak period = Rs 161000

Therefore, optimal operating cost per day = Rs 648833

d. If both the units are operating during off-peak period, cost of operation = Rs 171833

$$\left. \begin{array}{l} \text{If unit 2 alone is operating during} \\ \text{off-peak period, cost of operation} \end{array} \right\} \begin{array}{l} = \text{Rs } (13000 \times 12) + x \\ = \text{Rs } 156000 + x \end{array}$$

For Critical value of x: $156000 + x = 171833$

$$x = \text{Rs } 15833$$

Therefore, until the cost of taking one unit off and returning it to service after 12 hours, is less than Rs 15833, operating unit 2 alone during the off-peak period is acceptable.

e. If the cost of taking one unit off and returning it to service exceeds Rs.15833, then both the units are to be operated all through the day.

11 UNIT COMMITMENT

Economic dispatch gives the optimum schedule corresponding to one particular load on the system. The total load in the power system varies throughout the day and reaches different peak value from one day to another. Different combination of generators, are to be connected in the system to meet the varying load.

When the load increases, the utility has to decide in advance the sequence in which the generator units are to be brought in. Similarly, when the load decreases, the operating engineer need to know in advance the sequence in which the generating units are to be shut down.

The problem of finding the order in which the units are to be brought in and the order in which the units are to be shut down over a period of time, say one day, so the total operating cost involved on that day is minimum, is known as Unit Commitment (UC) problem. Thus UC problem is economic dispatch over a day. The period considered may a week, month or a year.

But why is this problem in the operation of electric power system? Why not just simply commit enough units to cover the maximum system load and leave them running? Note that to “commit” means a generating unit is to be “turned on”; that is, bring the unit up to speed, synchronize it to the system and make it to deliver power to the network. “Commit enough units and leave them on line” is one solution. However, **it is quite expensive to run too many generating units when the load is not large enough.** As seen in previous example, a great deal of money can be saved by turning units off (decommitting them) when they are not needed.

Example 7

The following are data pertaining to three units in a plant.

Unit 1: Min. = 150 MW; Max. = 600 MW
 $C_1 = 5610 + 79.2 P_1 + 0.01562 P_1^2$ Rs / h

Unit 2: Min. = 100 MW; Max. = 400 MW
 $C_2 = 3100 + 78.5 P_2 + 0.0194 P_2^2$ Rs / h

Unit 3: Min. = 50 MW; Max. = 200 MW
 $C_3 = 936 + 95.64 P_3 + 0.05784 P_3^2$ Rs / h

What unit or combination of units should be used to supply a load of 550 MW most economically?

Solution

To solve this problem, simply try all combination of three units.

Some combinations will be infeasible if the sum of all maximum MW for the units committed is less than the load or if the sum of all minimum MW for the units committed is greater than the load.

For each feasible combination, units will be dispatched using equal incremental cost rule studied earlier. The results are presented in the Table below.

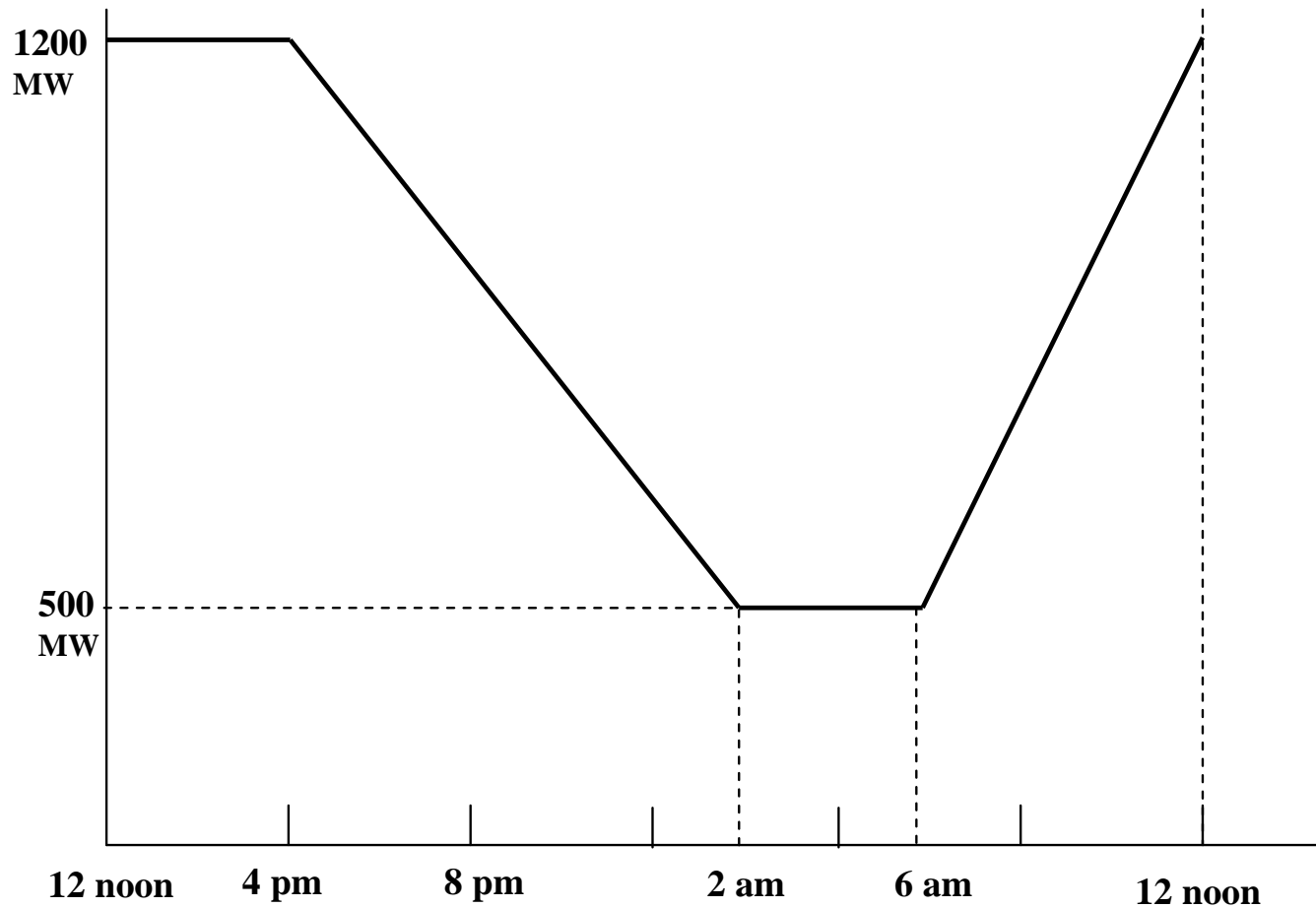
Unit	Min	Max
1	150	600
2	100	400
3	50	200

Unit 1	Unit 2	Unit 3	Min. Gen	Max. Gen	P ₁	P ₂	P ₃	Total cost
Off	Off	Off	0	0	Infeasible			
On	Off	Off	150	600	550	0	0	53895
Off	On	Off	100	400	Infeasible			
Off	Off	On	50	200	Infeasible			
On	On	Off	250	1000	295	255	0	54712
Off	On	On	150	600	0	400	150	54188
On	Off	On	200	800	500	0	50	54978
On	On	On	300	1200	267	233	50	56176

Note that the least expensive way of meeting the load is not with all the three units running, or any combination involving two units. Rather it is economical to run unit one alone.

Example 8

Daily load curve to be met by a plant having three units is shown below.



Data pertaining to the three units are the same in previous example.

Starting from the load of 1200 MW, taking steps of 50 MW find the shut-down rule.

Solution

For each load starting from 1200 MW to 500 MW in steps of 50 MW, we simply use a brute-force technique wherein all combinations of units will be tried as in previous example. The results obtained are shown below.

Load	Optimum combination		
	Unit 1	Unit 2	Unit 3
1200	On	On	On
1150	On	On	On
1100	On	On	On
1050	On	On	On
1000	On	On	Off
950	On	On	Off
900	On	On	Off
850	On	On	Off
800	On	On	Off
750	On	On	Off
700	On	On	Off
650	On	On	Off
600	On	Off	Off
550	On	Off	Off
500	On	Off	Off

Load	Optimum combination		
	Unit 1	Unit 2	Unit 3
1200	On	On	On
1150	On	On	On
1100	On	On	On
1050	On	On	On
1000	On	On	Off
950	On	On	Off
900	On	On	Off
850	On	On	Off
800	On	On	Off
750	On	On	Off
700	On	On	Off
650	On	On	Off
600	On	Off	Off
550	On	Off	Off
500	On	Off	Off

The shut-down rule is quite simple.

When load is above 1000 MW, run all three units; more than 600 MW and less than 1000 MW, run units 1 and 2; below 600 MW, run only unit 1.

The above shut-down rule is quite simple; **but it fails to take the economy over a day**. In a power plant with N units, for each load step, (neglecting the number of infeasible solutions) economic dispatch problem is to be solved for $(2^N - 1)$ times. During a day, if there are M load steps, (since each combination in one load step can go with each combination of another load step) to arrive at the economy over a day, in this brute-force technique, economic dispatch problem is to be solved for $(2^N - 1)^M$. This number will be too large for practical case.

UC problem becomes much more complicated when we need to consider power system having several plants each plant having several generating units and the system load to be served has several load steps.

So far, we have only obeyed one simple constraint: *Enough units will be connected to supply the load*. There are several other constraints to be satisfied in practical UC problem.

11 CONSTRAINTS ON UC PROBLEM

Some of the constraints that are to be met while solving UC problem are listed below.

- 1. Spinning reserve:** There may be sudden increase in load, more than what was predicted. Further there may be a situation that one generating unit may have to be shut down because of fault in generator or any of its auxiliaries.

Some system capacity has to be kept as spinning reserve

- i) to meet an unexpected increase in demand and**
 - ii) to ensure power supply in the event of any generating unit suffering a forced outage.**
- 2. Minimum up time:** When a thermal unit is brought in, it cannot be turned off immediately. Once it is committed, it has to be in the system for a specified minimum up time.
 - 3. Minimum down time:** When a thermal unit is decommitted, it cannot be turned on immediately. It has to remain decommitted for a specified minimum down time.

4. **Crew constraint:** A plant always has two or more generating units. It may not be possible to turn on more than one generating unit at the same time due to non-availability of operating personnel.
5. **Transition cost:** Whenever the status of one unit is changed some transition cost is involved and this has to be taken into account.
6. **Hydro constraints:** Most of the systems have hydroelectric units also. The operation of hydro units, depend on the availability of water. Moreover, hydro-projects are multipurpose projects. Irrigation requirements also determine the operation of hydro plants.

7. **Nuclear constraint:** If a nuclear plant is part of the system, another constraint is added. A nuclear plant has to be operated as a base load plant only.
8. **Must run unit:** Sometime it is a must to run one or two units from the consideration of voltage support and system stability.
9. **Fuel supply constraint:** Some plants cannot be operated due to deficient fuel supply.
10. **Transmission line limitation:** Reserve must be spread around the power system to avoid transmission system limitation, often called “bottling” of reserves.

12 PRIORITY- LIST METHOD

In this method the full load average production cost of each unit is calculated first. Using this, priority list is prepared.

$$\left. \begin{array}{l} \text{Full load average} \\ \text{production of a unit} \end{array} \right\} = \frac{\text{Production cost corresponding to full load}}{\text{Full load}}$$

Example 9

The following are data pertaining to three units in a plant.

Unit 1: Max. = 600 MW

$$C_1 = 5610 + 79.2 P_1 + 0.01562 P_1^2 \text{ Rs / h}$$

Unit 2: Max. = 400 MW

$$C_2 = 3100 + 78.5 P_2 + 0.0194 P_2^2 \text{ Rs / h}$$

Unit 3: Max. = 200 MW

$$C_3 = 936 + 95.64 P_3 + 0.05784 P_3^2 \text{ Rs / h}$$

Obtain the priority list

Solution

$$\left. \begin{array}{l} \text{Full load average} \\ \text{production of a unit 1} \end{array} \right\} = \frac{5610 + 79.2 \times 600 + 0.01562 \times 600^2}{600} = 97.922$$

$$\left. \begin{array}{l} \text{Full load average} \\ \text{production of a unit 2} \end{array} \right\} = \frac{3100 + 78.5 \times 400 + 0.0194 \times 400^2}{400} = 94.01$$

$$\left. \begin{array}{l} \text{Full load average} \\ \text{production of a unit 3} \end{array} \right\} = \frac{936 + 95.64 \times 200 + 0.05784 \times 200^2}{200} = 111.888$$

A strict priority order for these units, based on the average production cost, would order them as follows:

Unit	Rs. / h	Max. MW
2	94.01	400
1	97.922	600
3	111.888	200

The shutdown scheme would (ignoring min. up / down time, start – up costs etc.) simply use the following combinations.

Combination	Load P_D
2 + 1 + 3	$1000 \text{ MW} \leq P_D < 1200 \text{ MW}$
2 + 1	$400 \text{ MW} \leq P_D < 1000 \text{ MW}$
2	$P_D < 400 \text{ MW}$

Note that such a scheme would not give the same shut – down sequence described in Example 7 wherein unit 2 was shut down at 600 MW leaving unit 1. With the priority – list scheme both units would be held on until load reached 400 MW, then unit 1 would be dropped.

Most priority schemes are built around a simple shut – down algorithm that might operate as follows:

At each hour when the load is dropping, determine whether dropping the next unit on the priority list will leave sufficient generation to supply the load plus spinning reserve requirements. If not, continue operating as is; if yes, go to next step.

Determine the number of hours, H , before the unit will be needed again assuming the load is increasing some hours later. If H is less than the minimum shut – down time for that unit, keep the commitment as it is and go to last step; if not, go to next step.

Calculate the two costs. The first is the sum of the hourly production costs for the next H hours with the unit up. Then recalculate the same sum for the unit down and add the start – up cost. If there is sufficient saving from shutting down the unit, it should be shut down; otherwise keep it on.

Repeat the entire procedure for the next unit on the priority list. If it is also dropped, go to the next unit and so forth.

Questions on “ Economic Dispatch and Unit Commitment”

1. What do you understand by Economic Dispatch problem?
2. For a power plant having N generator units, derive the equal incremental cost rule.
3. The cost characteristics of three units in a power plant are given by

$$C_1 = 0.5 P_1^2 + 220 P_1 + 1800 \text{ Rs / hour}$$

$$C_2 = 0.6 P_2^2 + 160 P_2 + 1000 \text{ Rs / hour}$$

$$C_3 = 1.0 P_3^2 + 100 P_3 + 2000 \text{ Rs / hour}$$

where P_1 , P_2 and P_3 are generating powers in MW. Maximum and minimum loads on each unit are 125 MW and 20 MW respectively. Obtain the economic dispatch when the total load is 260 MW. What will be the loss per hour if the units are operated with equal loading?

4. The incremental cost of two units in a power stations are:

$$\frac{dC_1}{dP_1} = 0.3 P_1 + 70 \text{ Rs / hour}$$

$$\frac{dC_2}{dP_2} = 0.4 P_2 + 50 \text{ Rs / hour}$$

a) Assuming continuous running with a load of 150 MW, calculate the saving per hour obtained by using most economical division of load between the units as compared to loading each equally. The maximum and minimum operational loadings of both the units are 125 and 20 MW respectively.

b. What will be the saving if the operating limits are 80 and 20 MW ?

5. A power plant has two units with the following cost characteristics:

$$C_1 = 0.6 P_1^2 + 200 P_1 + 2000 \text{ Rs / hour}$$

$$C_2 = 1.2 P_2^2 + 150 P_2 + 2500 \text{ Rs / hour}$$

where P_1 and P_2 are the generating powers in MW. The daily load cycle is as follows:

6:00 A.M. to 6:00 P.M. 150 MW

6:00 P.M. to 6:00 A.M. 50 MW

The cost of taking either unit off the line and returning to service after 12 hours is Rs 5000. Considering 24 hour period from 6:00 A.M. one morning to 6:00 A.M. the next morning

a. Would it be economical to keep both units in service for this 24 hour period or remove one unit from service for 12 hour period from 6:00 P.M. one evening to 6:00 A.M. the next morning ?

b. Compute the economic schedule for the peak load and off peak load conditions.

c. Calculate the optimum operating cost per day.

d. If operating one unit during off peak load is decided, up to what cost of taking one unit off and returning to service after 12 hours, this decision is acceptable ?

6. What do you understand by “Loss coefficients”?

7. The transmission loss coefficients B_{mn} , expressed in MW^{-1} of a power system network having three plants are given by

$$B = \begin{bmatrix} 0.0001 & -0.00001 & -0.00002 \\ -0.00001 & 0.0002 & -0.00003 \\ -0.00002 & -0.00003 & 0.0003 \end{bmatrix}$$

Three plants supply powers of 100 MW, 200 MW and 300 MW respectively into the network. Calculate the transmission loss and the incremental transmission losses of the plants.

8. Derive the coordination equation for the power system having N number of power plants.

9. The fuel input data for a three plant system are:

$$f_1 = 0.01 P_1^2 + 1.7 P_1 + 300 \text{ Millions of BTU / hour}$$

$$f_2 = 0.02 P_2^2 + 2.4 P_2 + 400 \text{ Millions of BTU / hour}$$

$$f_3 = 0.02 P_3^2 + 1.125 P_3 + 275 \text{ Millions of BTU / hour}$$

where P_i 's are the generation powers in MW. The fuel cost of the plants are Rs 50, Rs 30 and Rs 40 per Million of BTU for the plants 1,2 and 3 respectively. The loss coefficient matrix expressed in MW^{-1} is given by

$$B = \begin{bmatrix} 0.005 & -0.0005 & -0.001 \\ -0.0005 & 0.01 & -0.0015 \\ -0.001 & -0.0015 & 0.0125 \end{bmatrix}$$

The load on the system is 60 MW. Compute the power dispatch for $\lambda = 120 \text{ Rs / MWh}$. Calculate the transmission loss.

Also determine the power dispatch with the revised value of λ taking 10 % change in its value.

Estimate the next new value of λ .

10. What are Participating Factors? Derive the expression for Participating Factors.

11. Incremental cost of three units in a plant are:

$$IC_1 = 1.2 P_1 + 21 \quad \text{Rs / MWh}$$

$$IC_2 = 1.5 P_2 + 15 \quad \text{Rs / MWh}$$

$$IC_3 = 1.6 P_3 + 24 \quad \text{Rs / MWh}$$

where P_1 , P_2 and P_3 are power output in MW. Find the optimum load allocation when the total load is 85 MW.

Using Participating Factors, determine the optimum scheduling when the load decreases to 75 MW.

12. What is “Unit Commitment” problem? Distinguish between Economic Dispatch and Unit Commitment problems.

13. Discuss the constraints on Unit Commitment problem.
14. Explain what is Priority List method.

ANSWERS

3. 64.29 MW 103.575 MW 92.145 MW Rs 449.09
4. Rs 111.39 Rs 57.64
5. It is economical to operate unit 2 alone during the off peak period.
86.1111 MW 63.8889 MW 0 50 MW Rs 648833 Rs 15833
7. 30.8 MW 0.004 0.06 0.164
9. 18.7923 MW 15.8118 MW 18.5221 MW
23.6506 MW 18.5550 MW 20.5290 MW
139.769 Rs / MWh
11. 32.5 MW; 30.0 MW; 22.5 MW
28.579 MW; 26.863 MW; 19.559 MW