ECONOMIC OPERATION OF POWER SYSTEMS

INTRODUCTION

One of the earliest applications of on-line centralized control was to provide a central facility, to operate economically, several generating plants supplying the loads of the system. Modern integrated systems have different types of generating plants, such as coal fired thermal plants, hydel plants, nuclear plants, oil and natural gas units etc. The capital investment, operation and maintenance costs are different for different types of plants.

The operation economics can again be subdivided into two parts.

i) Problem of economic dispatch, which deals with determining the power output of each plant to meet the specified load, such that the overall fuel cost is minimized.

ii) Problem of optimal power flow, which deals with minimum – loss delivery, where in the power flow, is optimized to minimize losses in the system. In this chapter we consider the problem of economic dispatch.

During operation of the plant, a generator may be in one of the following states:

i) Base supply without regulation: the output is a constant.

ii) Base supply with regulation: output power is regulated based on system load.

iii) Automatic non-economic regulation: output level changes around a base setting as area control error changes.

iv) Automatic economic regulation: output level is adjusted, with the area load and area control error, while tracking an economic setting.

Regardless of the units operating state, it has a contribution to the economic operation, even though its output is changed for different reasons. The factors influencing the cost of generation are the generator efficiency, fuel cost and transmission losses. The most efficient generator may not give minimum cost, since it may be located in a place where fuel cost is high. Further, if the plant is located far from the load centers, transmission losses may be high and running the plant may become uneconomical. The economic dispatch problem basically determines the generation of different plants to minimize total operating cost.
Modern generating plants like nuclear plants, geo-thermal plants etc, may require capital investment of millions of rupees. The economic dispatch is however determined in terms of fuel cost per unit power generated and does not include capital investment, maintenance, depreciation, start-up and shut down costs etc.

**PERFORMANCE CURVES**

**INPUT-OUTPUT CURVE**

This is the fundamental curve for a thermal plant and is a plot of the input in British thermal units (Btu) per hour versus the power output of the plant in MW as shown in Fig 1.

![Input - output curve](image)

**HEAT RATE CURVE**

The heat rate is the ratio of fuel input in Btu to energy output in KWh. It is the slope of the input – output curve at any point. The reciprocal of heat – rate is called fuel – efficiency. The heat rate curve is a plot of heat rate versus output in MW. A typical plot is shown in Fig .2

![Heat rate curve](image)
**INCREMENTAL FUEL RATE CURVE**

The incremental fuel rate is equal to a small change in input divided by the corresponding change in output.

\[
\text{Incremental fuel rate} = \frac{\Delta \text{Input}}{\Delta \text{Output}}
\]

The unit is again Btu / KWh. A plot of incremental fuel rate versus the output is shown in Fig 3.

![Incremental fuel rate curve](image)

**Fig 3: Incremental fuel rate curve**

**Incremental cost curve**

The incremental cost is the product of incremental fuel rate and fuel cost (Rs / Btu or $ / Btu). The curve is shown in Fig. 4. The unit of the incremental fuel cost is Rs / MWh or $ /MWh.
In general, the fuel cost $F_i$ for a plant, is approximated as a quadratic function of the generated output $P_{Gi}$.

$$F_i = a_i + b_i P_{Gi} + c_i P_{Gi}^2 \text{ Rs / h}$$

The incremental fuel cost is given by

$$\frac{dF_i}{dP_{Gi}} = b_i + 2c_i P_{Gi} \text{ Rs / MWh}$$

The incremental fuel cost is a measure of how costly it will be produce an increment of power. The incremental production cost, is made up of incremental fuel cost plus the incremental cost of labour, water, maintenance etc. which can be taken to be some percentage of the incremental fuel cost, instead of resorting to a rigorous mathematical model. The cost curve can be approximated by a linear curve. While there is negligible operating cost for a hydel plant, there is a limitation on the power output possible. In any plant, all units normally operate between $P_{Gmin}$, the minimum loading limit, below which it is technically infeasible to operate a unit and $P_{Gmax}$, which is the maximum output limit.

**ECONOMIC GENERATION SCHEDULING NEGLECTING LOSSES AND GENERATOR LIMITS**

The simplest case of economic dispatch is the case when transmission losses are neglected. The model does not consider the system configuration or line impedances. Since losses are neglected, the total generation is equal to the total demand $P_D$. 
Consider a system with \( n_g \) number of generating plants supplying the total demand \( P_D \). If \( F_i \) is the cost of plant \( i \) in Rs/h, the mathematical formulation of the problem of economic scheduling can be stated as follows:

Minimize \[ F_T = \sum_{i=1}^{n_g} F_i \]

Such that \[ \sum_{i=1}^{n_g} P_{Gi} = P_D \]

where

- \( F_T \) = total cost.
- \( P_{Gi} \) = generation of plant \( i \).
- \( P_D \) = total demand.

This is a constrained optimization problem, which can be solved by Lagrange’s method.

**LAGRANGE METHOD FOR SOLUTION OF ECONOMIC SCHEDULE**

The problem is restated below:

Minimize \[ F_T = \sum_{i=1}^{n_g} F_i \]

Such that \[ P_D = \sum_{i=1}^{n_g} P_{Gi} = 0 \]

The augmented cost function is given by

\[
\mathcal{L} = F_T + \lambda \left( P_D - \sum_{i=1}^{n_g} P_{Gi} \right)
\]

The minimum is obtained when

\[
\frac{\partial \mathcal{L}}{\partial P_{Gi}} = 0 \quad \text{and} \quad \frac{\partial \mathcal{L}}{\partial \lambda} = 0
\]

\[
\frac{\partial \mathcal{L}}{\partial P_{Gi}} = \frac{\partial F_T}{\partial P_{Gi}} - \lambda = 0
\]

\[
\frac{\partial \mathcal{L}}{\partial \lambda} = P_D - \sum_{i=1}^{n_g} P_{Gi} = 0
\]
The second equation is simply the original constraint of the problem. The cost of a plant 
\( F_i \) depends only on its own output \( P_{Gi} \), hence

\[
\frac{\partial F_i}{\partial P_{Gi}} =\frac{dF_i}{dP_{Gi}}
\]

Using the above,

\[
\frac{\partial F_i}{\partial P_{Gi}} =\frac{dF_i}{dP_{Gi}} = \lambda \ ; \ i = 1\ldots\ldots n_g
\]

We can write

\[
b_i + 2c_i P_{Gi} = \lambda \ ; \ i = 1\ldots\ldots n_g
\]

The above equation is called the co-ordination equation. Simply stated, for economic
generation scheduling to meet a particular load demand, when transmission losses are
neglected and generation limits are not imposed, all plants must operate at equal
incremental production costs, subject to the constraint that the total generation be equal
to the demand. From we have

\[
P_{Gi} = \frac{\lambda - b_i}{2c_i}
\]

We know in a loss less system

\[
\sum_{i=1}^{n_g} P_{Gi} = P_D
\]

Substituting (8.16) we get

\[
\sum_{i=1}^{n_g} \frac{\lambda - b_i}{2c_i} = P_D
\]

An analytical solution of \( \lambda \) is obtained from (8.17) as

\[
\lambda = \frac{P_D + \sum_{i=1}^{n_g} \frac{b_i}{2c_i}}{\sum_{i=1}^{n_g} \frac{1}{2c_i}}
\]

It can be seen that \( \lambda \) is dependent on the demand and the coefficients of the cost function.

**Example 1.**
The fuel costs of two units are given by
Solution:

\[ \frac{dF_1}{dP_{G1}} = 20 + 0.2P_{G1} \text{ Rs / MWh} \]
\[ \frac{dF_2}{dP_{G2}} = 30 + 0.2P_{G2} \text{ Rs / MWh} \]
\[ P_D = P_{G1} + P_{G2} = 200 \text{ MW} \]

For economic schedule

\[ \frac{dF_1}{dP_{G1}} = \frac{dF_2}{dP_{G2}} = \lambda \]
\[ 20 + 0.2 \ P_{G1} = 30 + 0.2 (200 - P_{G1}) \]
Solving we get,
\[ P_{G1} = 125 \text{ MW} \]
\[ P_{G2} = 75 \text{ MW} \]
\[ \lambda = 20 + 0.2 (125) = 45 \text{ Rs / MWh} \]

Example 2

The fuel cost in \$/h for two 800 MW plants is given by
\[ F_1 = 400 + 6.0 \ P_{G1} + 0.004 \ P_{G1}^2 \]
\[ F_2 = 500 + b_2 \ P_{G2} + c_2 \ P_{G2}^2 \]
where \( P_{G1}, \ P_{G2} \) are in MW

(a) The incremental cost of power, \( \lambda \) is \$8 / MWh when total demand is 550MW. Determine optimal generation schedule neglecting losses.

(b) The incremental cost of power is \$10/MWh when total demand is 1300 MW. Determine optimal schedule neglecting losses.

(c) From (a) and (b) find the coefficients \( b_2 \) and \( c_2 \).

Solution:

a) \[ P_{G1} = \frac{\lambda - b_1}{2c_1} = \frac{8.0 - 6.0}{2 \times 0.004} = 250 \text{ MW} \]
\[ P_{G2} = P_D - P_{G1} = 550 - 250 = 300 \text{ MW} \]
b) \[ P_{Go} = \frac{\lambda - b_1}{2C_1} = \frac{10 - 6}{2 \times 0.004} = 500 \text{ MW} \]

\[ P_{G2} = P_D - P_{Go} = 1300 - 500 = 800 \text{ MW} \]

c) \[ P_{G2} = \frac{\lambda - b_2}{2c_2} \]

From (a) \[ 300 = \frac{8.0 - b_2}{2c_2} \]

From (b) \[ 800 = \frac{10.0 - b_2}{2c_2} \]

Solving we get \[ b_2 = 6.8 \]

\[ c_2 = 0.002 \]

**ECONOMIC SCHEDULE INCLUDING LIMITS ON GENERATOR (NEGLECTING LOSSES)**

The power output of any generator has a maximum value dependent on the rating of the generator. It also has a minimum limit set by stable boiler operation. The economic dispatch problem now is to schedule generation to minimize cost, subject to the equality constraint.

\[ \sum_{i=1}^{n_g} P_{Gi} = P_D \]

and the inequality constraint

\[ P_{Gi (min)} \leq P_{Gi} \leq P_{Gi (max)} ; i = 1, \ldots, n_g \]

The procedure followed is same as before i.e. the plants are operated with equal incremental fuel costs, till their limits are not violated. As soon as a plant reaches the limit (maximum or minimum) its output is fixed at that point and is maintained a constant. The other plants are operated at equal incremental costs.

**Example 3**

Incremental fuel costs in \$/MWh for two units are given below:

\[ \frac{dF_1}{dP_{Gi}} = 0.01P_{Gi} + 2.0 \text{ \$/MWh} \]
\[
\frac{dF_2}{dP_{G2}} = 0.012P_{G2} + 1.6 \text{ $/ MWh}$
\]

The limits on the plants are \(P_{\text{min}} = 20 \text{ MW}, \ P_{\text{max}} = 125 \text{ MW}\). Obtain the optimal schedule if the load varies from 50 – 250 MW.

**Solution:**
The incremental fuel costs of the two plants are evaluated at their lower limits and upper limits of generation.

At \(P_{G \ (\text{min})} = 20 \text{ MW}\).

\[
\lambda_{1\ (\text{min})} = \frac{dF_1}{dP_{G1}} = 0.01 \times 20 + 2.0 = 2.2 \text{ $/ MWh}$
\]

\[
\lambda_{2\ (\text{min})} = \frac{dF_2}{dP_{G2}} = 0.012 \times 20 + 1.6 = 1.84 \text{ $/ MWh}$
\]

At \(P_{G \ (\text{Max})} = 125 \text{ MWh}\).

\[
\lambda_{1\ (\text{max})} = 0.01 \times 125 + 2.0 = 3.25 \text{ $/ MWh}$
\]

\[
\lambda_{2\ (\text{max})} = 0.012 \times 125 + 1.6 = 3.1 \text{ $/ MWh}$
\]

Now at light loads unit 1 has a higher incremental cost and hence will operate at its lower limit of 20 MW. Initially, additional load is taken up by unit 2, till such time its incremental fuel cost becomes equal to 2.2 $ / MWh at \(P_{G2} = 50 \text{ MW}\). Beyond this, the two units are operated with equal incremental fuel costs. The contribution of each unit to meet the demand is obtained by assuming different values of \(\lambda\); When \(\lambda = 3.1 \text{ $/ MWh},\) unit 2 operates at its upper limit. Further loads are taken up by unit 1. The computations are show in Table

**Table  Plant output and output of the two units**

<table>
<thead>
<tr>
<th>(\frac{dF_1}{dP_{G1}}) $/ \text{MWh}$</th>
<th>(\frac{dF_2}{dP_{G2}}) $/ \text{MWh}$</th>
<th>Plant (\lambda) $/ \text{MWh}$</th>
<th>(P_{G1}) MW</th>
<th>(P_{G2}) MW</th>
<th>Plant Output MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>1.96</td>
<td>1.96</td>
<td>20*</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>20*</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>40</td>
<td>66.7</td>
<td>106.7</td>
</tr>
<tr>
<td>2.6</td>
<td>2.6</td>
<td>2.6</td>
<td>60</td>
<td>83.3</td>
<td>143.3</td>
</tr>
<tr>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td>80</td>
<td>100</td>
<td>180</td>
</tr>
<tr>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>100</td>
<td>116.7</td>
<td>216.7</td>
</tr>
<tr>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
<td>110</td>
<td>125*</td>
<td>235</td>
</tr>
</tbody>
</table>
For a particular value of $\lambda$, $P_{G1}$ and $P_{G2}$ are calculated using (8.16). Fig 8.5 Shows plot of each unit output versus the total plant output.

| 3.25 | 3.1 | 3.25 | 125* | 125* | 250 |

For any particular load, the schedule for each unit for economic dispatch can be obtained.

**Example 4.**

In example 3, what is the saving in fuel cost for the economic schedule compared to the case where the load is shared equally. The load is 180 MW.

**Solution:**

From Table it is seen that for a load of 180 MW, the economic schedule is $P_{G1} = 80$ MW and $P_{G2} = 100$ MW. When load is shared equally $P_{G1} = P_{G2} = 90$ MW. Hence, the generation of unit 1 increases from 80 MW to 90 MW and that of unit 2 decreases from 100 MW to 90 MW, when the load is shared equally. There is an increase in cost of unit 1 since $P_{G1}$ increases and decrease in cost of unit 2 since $P_{G2}$ decreases.
Increase in cost of unit 1 \\
\[ = \int_{80}^{90} \left( \frac{dF_1}{dP_{G_1}} \right) dP_{G_1} \]
\\
\[ = \int_{80}^{90} (0.01P_{G_1} + 2.0) dP_{G_1} = 28.5 \$/h \]

Decrease in cost of unit 2 \\
\[ = \int_{100}^{90} \left( \frac{dF_2}{dP_{G_2}} \right) dP_{G_2} \]
\\
\[ = \int_{100}^{90} (0.012P_{G_2} + 1.6) dP_{G_2} = -27.4 \$/h \]

Total increase in cost if load is shared equally = 28.5 – 27.4 = 1.1 \$/h

Hence the saving in fuel cost is 1.1 \$/h if coordinated economic schedule is used.

**ECONOMIC DISPATCH INCLUDING TRANSMISSION LOSSES**

When transmission distances are large, the transmission losses are a significant part of the generation and have to be considered in the generation schedule for economic operation. The mathematical formulation is now stated as

Minimize \\
\[ F_T = \sum_{i=1}^{n_g} F_i \]

Such That \\
\[ \sum_{i=1}^{n_g} P_{Gi} = P_D + P_L \]

where $P_L$ is the total loss.

The Lagrange function is now written as

\[ \mathcal{L} = F_T - \lambda \left( \sum_{i=1}^{n_g} P_{Gi} - P_D - P_L \right) = 0 \]

The minimum point is obtained when

\[ \frac{\partial \mathcal{L}}{\partial P_{Gi}} = \frac{\partial F_T}{\partial P_{Gi}} - \lambda \left( 1 - \frac{\partial P_L}{\partial P_{Gi}} \right) = 0 ; \ i = 1 \ldots n_g \]

\[ \frac{\partial \mathcal{L}}{\partial \lambda} = \sum_{i=1}^{n_g} P_{Gi} - P_D + P_L = 0 \quad \text{(Same as the constraint)} \]

Since

\[ \frac{\partial F_T}{\partial P_{Gi}} = \frac{dF_i}{dP_{Gi}} \quad \text{, (8.27) can be written as} \]

\[ \frac{dF_i}{dP_{Gi}} + \lambda \frac{\partial P_L}{\partial P_{Gi}} = \lambda \]
\[ \lambda = \left( \frac{dF_i}{dP_{Gi}} \right) \left( \frac{1}{1 - \frac{\partial P_L}{\partial P_{Gi}}} \right) \]

The term \( \frac{1}{1 - \frac{\partial P_L}{\partial P_{Gi}}} \) is called the penalty factor of plant \( i \), \( L_i \). The coordination equations including losses are given by

\[ \lambda = \frac{dF_i}{dP_{Gi}} L_i; \quad i = 1 \ldots \ldots n \]

The minimum operation cost is obtained when the product of the incremental fuel cost and the penalty factor of all units is the same, when losses are considered.

A rigorous general expression for the loss \( P_L \) is given by

\[ P_L = \sum_m \sum_n P_{Gm} B_{mn} P_{Gn} + \sum_n P_{Gn} B_{no} + B_{oo} \]

where \( B_{mn} \), \( B_{no} \), \( B_{oo} \) called loss – coefficients, depend on the load composition. The assumption here is that the load varies linearly between maximum and minimum values.

A simpler expression is

\[ P_L = \sum_m \sum_n P_{Gm} B_{mn} P_{Gn} \]

The expression assumes that all load currents vary together as a constant complex fraction of the total load current. Experiences with large systems has shown that the loss of accuracy is not significant if this approximation is used.

An average set of loss coefficients may be used over the complete daily cycle in the coordination of incremental production costs and incremental transmission losses. In general, \( B_{mn} = B_{nm} \) and can be expanded for a two plant system as

\[ P_L = B_{11} P_{G1} + 2 B_{12} P_{G1} P_{G2} + B_{22} P_{G2}^2 \]
Example 5
A generator is supplying a load. An incremental change in load of 4 MW requires
generation to be increased by 6 MW. The incremental cost at the plant bus is Rs 30 /
MWh. What is the incremental cost at the receiving end?

Solution:

\[
\frac{dF_1}{dP_{G1}} = 30
\]

\[
\frac{dF_2}{dP_{G2}} = 30
\]

\[
\frac{\Delta P_G}{\Delta P_D} = 6 \times \frac{4}{4} = 2 \text{ MW}
\]

\[
\lambda = \frac{\frac{dF_1}{dP_{G1}} \Delta P_G}{\Delta P_D} = 30 \times 6 = 45 \text{ Rs / MWh}
\]

or \[
\lambda = \frac{\frac{dF_1}{dP_{G1}}}{1 - \frac{\Delta P_L}{\Delta P_G}} = \frac{30}{1 - 2} = 45 \text{ Rs / MWh}
\]

Example 6
In a system with two plants, the incremental fuel costs are given by

\[
\frac{dF_1}{dP_{G1}} = 0.01 P_{G1} + 20 \text{ Rs / MWh}
\]

\[
\frac{dF_2}{dP_{G2}} = 0.015 P_{G2} + 22.5 \text{ Rs / MWh}
\]

The system is running under optimal schedule with \( P_{G1} = P_{G2} = 100 \text{ MW} \).

If \( \frac{\partial P_L}{\partial P_{G2}} = 0.2 \), find the plant penalty factors and \( \frac{\partial P_L}{\partial P_{G1}} \).
**Solution:**

For economic schedule,

\[
\frac{dF_i}{dP_{Gi}} = \lambda; \quad L_i = \frac{1}{1 - \frac{\partial P_i}{\partial P_{Gi}}};
\]

For plant 2, \( P_{G2} = 100 \) MW

\[ \therefore (0.015 \times 100 + 22.5) \frac{1}{1 - 0.2} = \lambda. \]

Solving, \( \lambda = 30 \) Rs / MWh

\[
L_2 = \frac{1}{1 - 0.2} = 1.25
\]

\[
\frac{dF_1}{dP_{G1}} L_1 = \lambda \Rightarrow (0.01 \times 100 + 20) L_1 = 30
\]

\[ L_1 = 1.428 \]

\[
L_1 = \frac{1}{1 - \frac{\partial P_l}{\partial P_{Gi}}}; \quad \text{Solving} \quad \frac{\partial P_l}{\partial P_{Gi}} = 0.3
\]

**Example 7**

A two bus system is shown in Fig. 8.8. If 100 MW is transmitted from plant 1 to the load, a loss of 10 MW is incurred. System incremental cost is Rs 30 / MWh. Find \( P_{G1}, P_{G2} \) and power received by load if

\[
\frac{dF_1}{dP_{G1}} = 0.02 P_{G1} + 16.0 \text{ Rs / MWh}
\]

\[
\frac{dF_2}{dP_{G2}} = 0.04 P_{G2} + 20.0 \text{ Rs / MWh}
\]
Solution:
Since the load is connected at bus 2, no loss is incurred when plant two supplies the load.

Therefore in (8.36) \( B_{12} = 0 \) and \( B_{22} = 0 \)

\[
P_L = B_{11} P_{G1}^2; \quad \frac{\partial P_L}{\partial P_{G1}} = 2B_{11}P_{G1}; \quad \frac{\partial P_L}{\partial P_{G2}} = 0.0
\]

From data we have \( P_L = 10 \) MW, if \( P_{G1} = 100 \) MW

\[
10 = B_{11} (100)^2
\]

\( B_{11} = 0.001 \quad \text{MW}^{-1} \)

Coordination equation with loss is

\[
\frac{dF_i}{dP_{Gi}} + \lambda \frac{\partial P_L}{\partial P_{Gi}} = \lambda
\]

For plant 1 \[
\frac{dF_1}{dP_{G1}} + \lambda \frac{\partial P_L}{\partial P_{G1}} = \lambda
\]

\[
(0.02 P_{G1} + 16.0) + 30 (2 \times 0.001 \times P_{G1}) = 30
\]

\( 0.08 \ P_{G1} = 30 - 16.0 \). From which, \( P_{G1} = 175 \) MW

For Plant 2 \[
\frac{dF_2}{dP_{G1}} + \lambda \frac{\partial P_L}{\partial P_{G2}} = \lambda
\]

\[
0.04 \ P_{G2} + 20.0 = 30 \text{ or } P_{G2} = 250 \text{ MW}
\]

Loss = \( B_{11} P_{G1}^2 = 0.001 \times (175)^2 = 30.625 \text{ MW} \)

\[
P_D = (P_{G1} + P_{G2}) - P_L = 394.375 \text{ MW}
\]

DERIVATION OF TRANSMISSION LOSS FORMULA

An accurate method of obtaining general loss coefficients has been presented by Kron. The method is elaborate and a simpler approach is possible by making the following assumptions:

(i) All load currents have same phase angle with respect to a common reference

(ii) The ratio \( X / R \) is the same for all the network branches.
Consider the simple case of two generating plants connected to an arbitrary number of loads through a transmission network as shown in Fig a

Let’s assume that the total load is supplied by only generator 1 as shown in Fig 8.9b. Let the current through a branch K in the network be $I_{K1}$. We define

$$N_{K1} = \frac{I_{K1}}{I_D}$$

It is to be noted that $I_{G1} = I_D$ in this case. Similarly with only plant 2 supplying the load current $I_D$, as shown in Fig 8.9c, we define

$$N_{K2} = \frac{I_{K2}}{I_D}$$
\(N_{K1}\) and \(N_{K2}\) are called current distribution factors and their values depend on the impedances of the lines and the network connection. They are independent of \(I_D\). When both generators are supplying the load, then by principle of superposition

\[I_K = N_{K1} I_{G1} + N_{K2} I_{G2}\]

where \(I_{G1}, I_{G2}\) are the currents supplied by plants 1 and 2 respectively, to meet the demand \(I_D\). Because of the assumptions made, \(I_{K1}\) and \(I_D\) have same phase angle, as do \(I_{K2}\) and \(I_D\). Therefore, the current distribution factors are real rather than complex. Let

\[\sigma_1, 2\] phase angles of \(I_{G1}\) and \(I_{G2}\) with respect to a common reference.

We can write

\[|I_K|^2 = (N_{K1}|I_{G1}|\cos \sigma_1 + N_{K2}|I_{G2}|\cos \sigma_2)^2 + (N_{K1}|I_{G1}|\sin \sigma_1 + N_{K2}|I_{G2}|\sin \sigma_2)^2\]

\[= N_{K1}^2|I_{G1}|^2 \left[\cos^2 \sigma_1 + \sin^2 \sigma_1\right] + N_{K2}^2|I_{G2}|^2 \left[\cos^2 \sigma_2 + \sin^2 \sigma_2\right] + 2N_{K1}N_{K2}|I_{G1}|I_{G2}| \cos \sigma_1 \cos \sigma_2\]

Now

\[|I_{G1}| = \frac{P_{G1}}{\sqrt{3}|V_1| \cos \phi_1} \quad \text{and} \quad |I_{G2}| = \frac{P_{G2}}{\sqrt{3}|V_2| \cos \phi_2}\]

where \(P_{G1}, P_{G2}\) are three phase real power outputs of plant 1 and plant 2; \(V_1, V_2\) are the line to line bus voltages of the plants and \(\phi_1, \phi_2\) are the power factor angles.

The total transmission loss in the system is given by

\[P_L = \sum_k |I_K|^2 R_k\]

where the summation is taken over all branches of the network and \(R_K\) is the branch resistance. Substituting we get

\[P_L = \frac{P_{G1}^2}{|V_1|^2 (\cos \phi_1)^2} \sum_k N_{K1}^2 R_k + \frac{2P_{G1}P_{G2} \cos(\sigma_1 - \sigma_2)}{|V_1||V_2| \cos \phi_1 \cos \phi_2} \sum_k N_{K1}N_{K2}R_k\]

\[+ \frac{P_{G2}^2}{|V_2|^2 (\cos \phi_2)^2} \sum_k N_{K2}^2 R_k\]

\[P_L = P_{G1}^2 B_{11} + 2P_{G1}P_{G2}B_{12} + P_{G2}^2 B_{22}\]

where

\[B_{11} = \frac{1}{|V_1|^2 (\cos \phi_1)^2} \sum_k N_{K1}^2 R_k\]
The loss coefficients are called the B–coefficients and have unit MW\(^{-1}\).

For a general system with \( n \) plants the transmission loss is expressed as

\[
P_L = \frac{P_{G1}^2}{|V_1|^2 (\cos \phi_1)^2} \sum_k N_{K1}^2 + \ldots + \frac{P_{Gn}^2}{|V_n|^2 (\cos \phi_n)^2} \sum_k N_{Kn}^2 R_K + 2 \sum_{p,q=1 \atop p \neq q}^n \frac{P_{Gp} P_{Gq} \cos(\sigma_p - \sigma_q)}{|V_p||V_q| \cos \phi_p \cos \phi_q} \sum_k N_{Kp} N_{Kq} R_K
\]

\[
B_{pq} = \frac{\cos(\sigma_p - \sigma_q)}{|V_p||V_q| \cos \phi_p \cos \phi_q} \sum_k N_{Kp} N_{Kq} R_K
\]

B – Coefficients can be treated as constants over the load cycle by computing them at average operating conditions, without significant loss of accuracy.

**Example 8**

Calculate the loss coefficients in pu and MW\(^{-1}\) on a base of 50MVA for the network of Fig below. Corresponding data is given below.

| \( I_a \) | 1.2 – j 0.4 pu |
| \( I_b \) | 0.4 – j 0.2 pu |
| \( I_c \) | 0.8 – j 0.1 pu |
| \( I_d \) | 0.8 – j 0.2 pu |
| \( I_e \) | 1.2 – j 0.3 pu |
| \( Z_{a} \) | 0.02 + j 0.08 pu |
| \( Z_{b} \) | 0.08 + j 0.32 pu |
| \( Z_{c} \) | 0.02 + j 0.08 pu |
| \( Z_{d} \) | 0.03 + j 0.12 pu |
| \( Z_{e} \) | 0.03 + j 0.12 pu |
**Solution:**

Total load current

\[ I_L = I_d + I_e = 2.0 - j 0.5 = 2.061 \angle -14.03^0 \text{ A} \]

\[ I_{L1} = I_d = 0.8 - j 0.2 = 0.8246 \angle -14.03^0 \text{ A} \]

\[ \frac{I_{L1}}{I_L} = 0.4; \quad \frac{I_{L2}}{I_L} = 1.0 - 0.4 = 0.6 \]

If generator 1 supplies the load then \( I_1 = I_L \). The current distribution is shown in Fig a.

Similarly the current distribution when only generator 2 supplies the load is shown in Fig b.
\[ N_{a2} = 0; N_{b2} = -0.4; N_{c2} = 1.0; N_{d2} = 0.4; N_{e2} = 0.6 \]

From Fig 8.10, \[ V_1 = V_{ref} + Z_a I_a \]
\[ = 1 \angle 0^0 + (1.2 - j 0.4) (0.02 + j0.08) \]
\[ = 1.06 \angle 4.78^0 = 1.056 + j 0.088 \text{ pu.} \]

\[ V_2 = V_{ref} - I_b Z_b + I_c Z_c \]
\[ = 1.0 \angle 0^0 - (0.4 - j 0.2) (0.08 + j 0.32) + (0.8 - j 0.1) (0.02 + j 0.08) \]
\[ = 0.928 - j 0.05 = 0.93 \angle -3.10^0 \text{ pu.} \]

**Current Phase angles**

\[ \sigma_1 = \text{angle of } I_1(=I_a) = \tan^{-1}\left(\frac{-0.4}{1.2}\right) = -18.43^0 \]

\[ \sigma_2 = \text{angle of } I_2(=I_c) = \tan^{-1}\left(\frac{-0.1}{0.8}\right) = -7.13^0 \]

\[ \cos(\sigma_1 - \sigma_2) = 0.98 \]

**Power factor angles**

\[ \phi_1 = 4.78^0 + 18.43 = 23.21^0; \cos\phi_1 = 0.92 \]

\[ \phi_2 = 7.13^0 - 3.10^0 = 4.03^0; \cos\phi_2 = 0.998 \]

\[ B_{11} = \frac{\sum_k N_{k1}^2 R_k}{|V_1|^2 (\cos\phi_1)^2} = \frac{1.0^2 \times 0.02 + 0.6^2 \times 0.08 + 0.4^2 \times 0.03 + 0.6^2 \times 0.03}{(1.06)^2 \times (0.920)^2} \]

\[ = 0.0677 \text{ pu} \]

\[ = 0.0677 \times \frac{1}{50} = 0.1354 \times 10^{-2} \text{ MW}^{-1} \]

\[ B_{12} = \frac{\cos(\sigma_1 - \sigma_2)}{|V_1|/|V_2| (\cos\phi_1)(\cos\phi_2)} \sum_k N_{k1} N_{k2} R_k \]
\[
\begin{align*}
B_{22} &= \frac{0.98}{(1.06)(0.93)(0.998)(0.92)} \left[ -0.4 \times 0.6 \times 0.08 + 0.4 \times 0.4 \times 0.03 + 0.6 \times 0.6 \times 0.03 \right] \\
&= -0.00389 \text{ pu} \\
&= -0.0078 \times 10^{-2} \text{ MW}^{-1}
\end{align*}
\]

\[
\begin{align*}
B_{22} &= \frac{\sum N_k^2 R_k}{|V_2|^2 (\cos \phi_2^2)} \\
&= \frac{(-0.4)^2 0.08 + 1.0^2 \times 0.02 + 0.4^2 \times 0.03 + 0.6^2 \times 0.03}{(0.93)^2 (0.998)^2} \\
&= 0.056 \text{ pu} = 0.112 \times 10^{-2} \text{ MW}^{-1}
\end{align*}
\]