Chapter 3

Load Flow Analysis and Protection

LEARNING OBJECTIVES

After reading this chapter, you will be able to understand:

- Bus admittance matrix
- Sparsity in Y_{bus} matrix
- Load flow analysis
- Formation of power flow equations
- Load bus
- Generator bus
- Load flow algorithm
- Optimal operation of generators
- Power system protection
- Protective zones
- Time multiplier setting

Bus Admittance Matrix

Nodal admittance matrix or admittance matrix or Y matrix or Y_{bus} is an $n \times n$ matrix describing a power system with 'n' buses. It represents the nodal admittance of the buses in a power system.

In realistic systems which contain thousands of buses, the Y_b matrix is quite sparse. Each bus in a real power system is usually connected to only a few other buses through the transmission lines. The Y matrix is also one of the data requirements needed to formulate a power flow study

$$Y_{bus} = \begin{bmatrix} y_{11} & y_{12} & \cdots\cdots\cdots & y_{1n} \\ y_{21} & y_{22} & \cdots\cdots\cdots & y_{2n} \\ \cdot & & & \cdot \\ y_{n1} & y_{n2} & \cdots\cdots\cdots & y_{nn} \end{bmatrix}$$

Consider a four-bus power system shown in figure below.

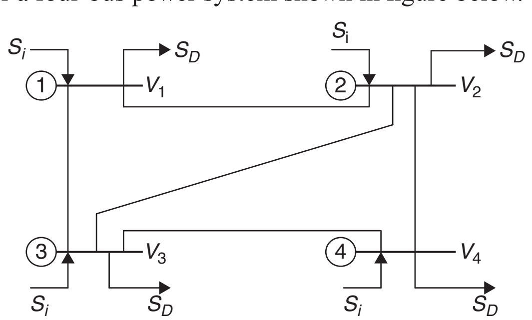


Figure 1 Single-line diagram of a four bus network

Equivalent network of the above single-line diagram is given by

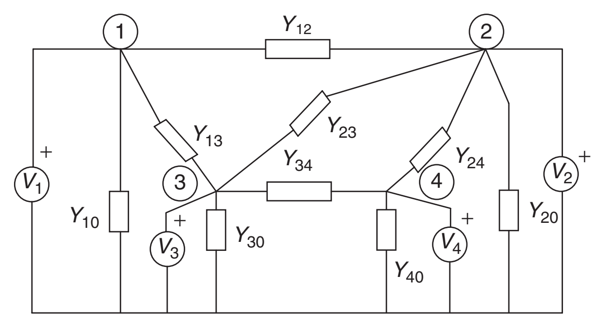


Figure 2 Equivalent circuit of the single-line diagram shown above

Apply Kirchhoff's current law for the above network,

$$I_1 = V_1 y_{10} + (V_1 - V_2)y_{12} + (V_1 - V_3)y_{13}$$

$$I_2 = V_2 y_{20} + (V_2 - V_1)y_{12} + (V_2 - V_3)y_{23} + (V_2 - V_4)y_{24}$$

$$I_3 = V_3 y_{30} + (V_3 - V_1)y_{13} + (V_3 - V_2)y_{23} + (V_3 - V_4)y_{34}$$

$$I_4 = V_4 y_{40} + (V_4 - V_2)y_{24} + (V_4 - V_3)y_{34}$$

Rearrange the equations and rewrite them in matrix form

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} y_{10}+y_{12} \\ +y_{13} & -y_{12} & -Y_{13} & 0 \\ -y_{12} & y_{20}+y_{12} \\ +y_{23}+y_{24} & -y_{23} & -y_{24} \\ -y_{13} & -y_{23} & y_{30}+y_{13} \\ +y_{23}+y_{24} & -y_{34} \\ 0 & -y_{24} & -y_{34} & y_{40}+y_{24} \\ +y_{34} \end{bmatrix} \begin{bmatrix} v \\ v_2 \\ v_3 \\ v_4 \end{bmatrix}$$

Above matrix form can be represented as

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix}$$

where $Y_{11} = y_{10} + y_{12} + y_{13}$

$$Y_{22} = y_{20} + y_{12} + y_{23} + y_{24}$$

$$Y_{33} = y_{30} + y_{13} + y_{23} + y_{34}$$

$$Y_{44} = y_{40} + y_{24} + y_{34}$$

$$Y_{12} = Y_{21} = -y_{12}$$

$$Y_{13} = Y_{31} - y_{13}$$

$$Y_{14} = Y_{41} = -y_{14} = 0$$

$$Y_{23} = Y_{32} = -y_{23}$$

$$Y_{24} = Y_{42} = -y_{24}$$

$$Y_{34} = Y_{43} = -y_{34}$$

Each admittance Y_{ii} is called the self-admittance of node 'i' and equal to the algebraic sum of the admittances terminating on the node.

$$Y_{ii} = y_i + \sum_{\substack{K=1 \\ K \# i}}^{N} y_{iK}$$

Each off diagonal term Y_{ij} is called the mutual admittance (or transfer admittance) between nodes 'i' and 'j' and is equal to the negative of the sum off all admittances connected directly between those nodes.

$$Y_{ij} = -y_{ij}$$

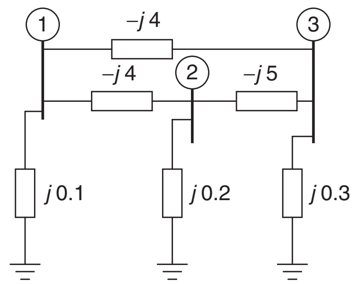
The admittance matrix is symmetric $Y_{ij} = Y_{ij}$.

Relation between bus impedance matrix and admittance matrix is given by

$$[Z_{bus}] = [Y_{bus}]^{1}$$

Solved Examples

Example 1: Three-bus admittance network of a power system is given by



(A) $\begin{bmatrix} -j7.9 & -j4 & -j4 \\ -j4 & -j8.8 & -j5 \\ -j4 & -j5 & -j8.7 \end{bmatrix}$

(B) $\begin{bmatrix} -j7.9 & +j4 & j4 \\ j4 & -j8.8 & j5 \\ j4 & j5 & -j8.7 \end{bmatrix}$

(C) $\begin{bmatrix} -j0.1 & -j4 & -j4 \\ -j4 & -j0.2 & -j5 \\ -j4 & -j5 & -j0.3 \end{bmatrix}$

(D) $\begin{bmatrix} j0.1 & -j4 & -j4 \\ -j4 & j0.2 & -j5 \\ -j4 & -j5 & j0.3 \end{bmatrix}$

Solution: (B)

Admittance matrix order is 3×3 elements of the admittance matrix are

$$Y_{11} = y_{10} + y_{12} + y_{13} = j0.1 - j4 - j4$$
$$= -7.9.$$
$$Y_{22} = y_{20} + y_{21} + y_{23} = j0.2 - j4 - j5 = -j8.8$$
$$Y_{33} = y_{30} + y_{31} + y_{32} = j0.3 - j5 - j4$$
$$= -j8.7$$
$$Y_{12} = y_{21} = j4$$
$$Y_{13} = y_{31} = j4$$
$$Y_{23} = y_{32} = j5$$

$$Y_{bus} = \begin{bmatrix} -j7.9 & j4 & j4 \\ j4 & -j8.8 & j5 \\ j4 & j5 & -j8.7 \end{bmatrix}$$

Sparsity in Y_{bus} Matrix

An element in Y_{bus} has a non-zero value, if the two buses are directly connected through a transmission line or a transformer. The non–existence of a direct connection between two buses means that the off-diagonal transfer admittances of the Y_{bus} matrix will be zero. Normally in a large interconnected power systems, each bus may be connected with a few neighbouring buses. The non-existence of a direct connection between many buses means that the vast majority of a real world Y_{bus} matrix will be zero. Thus, for a large power systems y_{bus} is highly sparse. In large systems, sparsity may be as high as 97%.

Example 2: For the Y-bus matrix of a 4-bus system given in per unit, the buses having shunt elements are

$$Y_{bus} = j\begin{bmatrix} -7 & 2 & 3 & 0 \\ 2 & -12 & 4 & 2.5 \\ 3 & 4 & -9 & 2 \\ 0 & 2.5 & 2 & -4.5 \end{bmatrix}$$

(A) 1 and 2 (B) 2 and 3
(C) 3 and 4 (D) 1, 2, and 3

Solution: (A)
In an admittance matrix, sum of elements in a row is non-zero if the corresponding node is having shunt branch.

$$\text{For bus } 1 = \sum_{j=1}^{4} y_{1j} = y_{11} + y_{12} + y_{13} + y_{14}$$
$$= -2 \neq 0$$

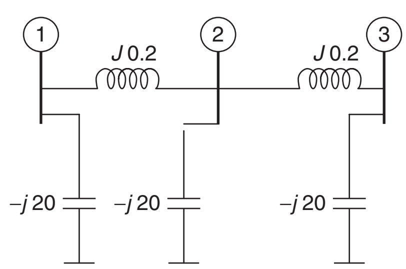
$$\text{For bus } 2 = \sum_{j=1}^{4} y_{2j} = y_{21} + y_{22} + y_{23} + y_{24}$$
$$= -3.5 \neq 0$$

$$\text{For bus } 3 = \sum_{j=1}^{4} y_{3j} = 0$$

$$\text{For bus } 4 = \sum_{j=1}^{4} y_{4j} = 0$$

Bus 1 and 2 has shunt elements.

Example 3: Impedance diagram of a network is given in the figure in per unit. The diagonal elements Y_{22} of the bus admittance matrix Y_{bus} of the network is



(A) $-j9.95$ (B) $-j19.6$ (C) $j0.4$ (D) $j20$

Solution: (A)
Diagonal element $Y_{22} = y_{20} + y_{21} + y_{23}$

$$= \frac{-1}{j20} + \frac{1}{j0.2} + \frac{1}{j0.2} = -9.95j$$

Example 4: Sparsity of a 100 bus network is given by 95%. Number of elements in the network is given by
(A) 500 (B) 4700 (C) 9500 (D) 200

Solution: (D)
Number of elements in a network

$$= \frac{N - n}{2}$$

where N = Number of non-zero elements in an admittance matrix
= 5% of total elements are non-zeros.

$$= \frac{5}{100} \times 10{,}000 = 500$$

n = order of the Y_{bus}

$$\text{Number of element} = \frac{500 - 100}{2} = 200 \text{ elements}$$

Bus Impedance Matrix

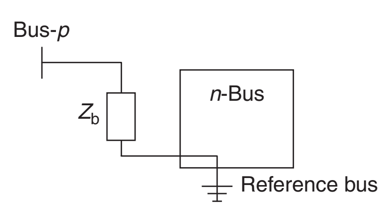
The process of building the bus impedance matrix proceeds by adding impedance one at a time till all the impedances have been included. With each addition of impedance, a new matrix is produced. The order of the matrix may or may not increase depending upon whether the addition of the impedance creates a new bus or not.

Assume that for a partial power system network with 'n' buses, a reference node 'O' and the bus impedance matrix is $Z_{original}$ is known. When an element with impedance Z_b is added to the partial network, four types of modifications are possible.

1. Addition of a tree branch, with impedance Z_b from a new bus to the reference bus.
2. Addition of a tree branch with impedance Z_b from a new bus to an existing bus.
3. Adding a co-tree link with impedance Z_b between two existing buses.
4. Adding a co-tree link with impedance Z_b between an existing bus to the reference bus.

Modification of an Existing Bus Impedance Matrix

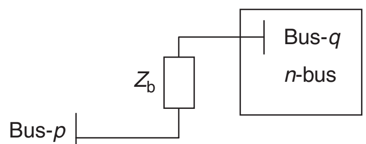
Case I: Adding Z_b from a new bus-p to reference bus



$$Z_{bus}\text{ new} = \left[\begin{array}{c|c} Z_{Original} & \begin{matrix} 0 \\ 0 \\ \vdots \end{matrix} \\ \hline 0 \quad 0 & Z_b \end{array}\right]$$

In this case, the elements of $(n + 1)^{th}$ column and rows are all zeros except the diagonal. The diagonal element is added to branch impedance Z_b. The elements of the original Z_{bus} matrix are not altered.

Case II: Adding Z_b from a new bus-p to existing bus-q



$$Z_{bus}\text{ new}\ \left(\begin{array}{c:c} Z_{\text{Original}} & \begin{matrix} Z_{1q} \\ Z_{2q} \\ \vdots \\ Z_{qq} \end{matrix} \\ \hdashline Z_{q_1}\ Z_{q_2}\ \ldots\ Z_{qn} & Z_{qq}+Z_b \end{array}\right)$$

The elements of the $(n + 1)^{th}$ column are the elements of the q^{th} column and the elements of the $(n + 1)^{th}$ row are the elements of the q^{th} row. The diagonal element is given by the sum of Z_{qq} and Z_b.

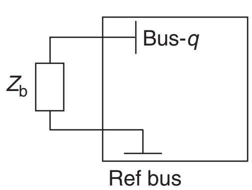
The elements of original Z_{bus} matrix are not altered.

Case III: Adding Z_b from an existing bus-q to reference bus.

It will be an addition as that of case II. The new impedance matrix of order $(n + 1)$ can be formed as that of case II.

So the bus impedance matrix has to be modified by eliminating $(n + 1)^{th}$ row and $(n + 1)^{th}$ column. This reduced bus impedance matrix is the actual new bus impedance matrix. Every element of actual new bus impedance matrix can be determined by using the equation

$$Z_{\text{jk actual}} = Z_{jk} - \frac{Z_{j(n+1)}Z_{(n+1)k}}{Z_{(n+1)(n+1)}}$$



note

$Z_{jk} = Z_{kj}$

j = row

k = column

Case IV: Adding Z_b between two existing buses 'h' and 'q'.

Hence the elements of the $(n + 1)^{th}$ row is the difference between the elements of row-h and row-q.

Here the elements of $(n + 1)^{th}$ column is the difference between the elements of column-h and column-q. The elements of $(n + 1)^{th}$ row is the difference between the elements of row-h and row-q.

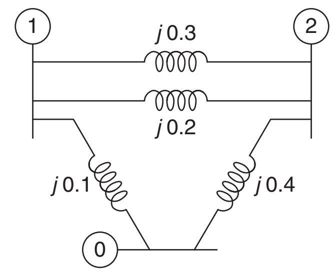
$$Z\text{ bus new} = \left(\begin{array}{c:c} Z_{\text{original}} & \begin{matrix} Z_{1h}-Z_{1q} \\ Z_{2h}-Z_{2q} \\ \\ Z_{nh}-Z_{nq} \end{matrix} \\ \hdashline Z_{h1}-Z_{q1}-Z_{hn}-\ldots & Z_{qn}-Z_{(n+1)(n-1)} \end{array}\right)$$

where $Z_{(n+1)(n+1)} = Z_b + Z_{hh} + Z_{qq} - 2Z_{hq}$

Since the modification does not involve addition of new bus, the order of new bus impedance matrix has to be reduced to $n \times n$ by eliminating the $(n + 1)^{th}$ column and $(n + 1)^{th}$ row. This reduced bus impedance matrix is the actual bus impedance matrix.

$$Z_{\text{jk actual}} = Z_{jk} - \frac{Z_{j(n+1)}Z_{(n+1)k}}{Z_{(n+1)(n+1)}}$$

Example 5: From the bus impedance matrix for the network shown in the figure.



Solution: Consider a reference bus as 'O', In this case buses 1 and 2 are connected to the reference bus. Connect bus 1 to the reference bus.

$$Z^1_{bus} = j0.1$$

Add bus 2 to the bus 1 (with $j0.2$ as impedance)

$$\begin{array}{cc} & \begin{matrix} ① & ② \\ \downarrow & \downarrow \end{matrix} \\ Z^2_{bus} = \begin{matrix} ① \\ ② \end{matrix} & \begin{bmatrix} j0.1 & j0.1 \\ j0.1 & j0.3 \end{bmatrix} \end{array}$$

Add a link between bus (2) and reference bus

$$Z^{new}_{bus} = Z^2_{bus} - \frac{1}{Z_{22}+Z_{new}}\begin{bmatrix} j0.2 \\ j0.3 \end{bmatrix}[j0.2\ \ j0.3]$$

$$= \begin{bmatrix} j0.1 & j0.1 \\ j0.1 & j0.3 \end{bmatrix} + \frac{1}{j0.3+j0.4}\begin{bmatrix} 0.04 & 0.06 \\ 0.06 & 0.09 \end{bmatrix}$$

$$= j\begin{bmatrix} 0.1 & 0.1 \\ 0.1 & 0.3 \end{bmatrix} - j\begin{bmatrix} 0.057 & 0.085 \\ 0.085 & 0.128 \end{bmatrix}$$

$$Z^{new}_{bus} = j\begin{bmatrix} 0.043 & 0.015 \\ 0.015 & 0.172 \end{bmatrix}$$

Add a link between bus (1) and (2)

$$Z^{new}_{bus} = Z^{old}_{bus} - \frac{1}{Z_{11}+Z_{22}-2Z_{12}+z_{new}}\begin{bmatrix} j0.0285 \\ -j0.157 \end{bmatrix}[j0.08 - j0.157]$$

$$= Z^{old}_{bus} - j\frac{1}{0.043+0.172-0.03+0.3}\begin{bmatrix} 7.8\times10^{-4} & -4.4\times10^{-3} \\ -4.4\times10^{-3} & 0.0246 \end{bmatrix}$$

$$= Z^{\text{old}}_{\text{bus}} - j\begin{bmatrix} 0.0016 & -0.009 \\ -0.009 & 0.0506 \end{bmatrix}$$

$$= j\begin{bmatrix} 0.043 & 0.015 \\ 0.015 & 0.172 \end{bmatrix} - j\begin{bmatrix} 0.0016 & -0.009 \\ -0.009 & 0.0506 \end{bmatrix}$$

$$Z^{\text{final}}_{\text{bus}} = j\begin{bmatrix} 0.0414 & 0.024 \\ 0.024 & 0.1214 \end{bmatrix}$$

Load Flow Analysis

A three-phase electric power system under normal steady state conditions of operation is expected to deliver the demanded real and reactive power to the consumer terminals at the rated voltage and frequency, within the specified limits of tolerance. To obtain a complete description of the behaviour of the power system, it is essential to know the voltages at various node points or buses and the power flowing through the elements of power system.

Power flow studies provide the required information regarding bus voltage and power flowing through transmission lines, transformers, and other elements of power systems for a specified load demand subjected to the regulating capabilities of generators, condensers, tap changing transformers, phase shifting transformers as well as specified net interchange of power with adjoining power systems.

In the power flow analysis, the load powers are assumed as known constants. A given set of loads on the buses can be served from a given set of generators in an infinite number of power flow configurations. Power flow analysis concerns itself not only with the actual physical mechanism which controls the power flow in the network meshes but also with how a best or optimum flow configuration from among the available possibilities is selected.

1. The sum of real power injected at the generating bus must equal the sum of total system load demand plus system losses at each instant of time.
2. The power transfer capability of a transmission line is limited by the thermal loading limit and the stability limit.
3. Keep the voltage levels of certain buses with in close tolerance.
4. The power system must fulfil contractual scheduled inter change of power for neighbouring systems, via its tie lines.

Formation of Power Flow Equations

The general form of network equations for n-bus systems in the bus frame of reference in admittance form is

$$I_{\text{bus}} = Y_{\text{bus}} V_{\text{bus}}$$

where I_{bus} is the bus current vector
V_{bus} is the bus voltage vector
Y_{bus} is the bus admittance matrix

In general injected current at any bus 'I' takes the form

$$I_i = Y_{i1}V_1 + Y_{i2}V_2 + Y_{i3}V_3 + \ldots + Y_{in}V_n \text{ for } i = 1, 2, 3, \ldots, n.$$

$$I_i = \sum_{m=1}^{n} Y_{\text{IN}} V_m$$

In power systems, complex power injected at bus 'i'

$$S_i = P_i + jQ_i = V_i I_i^* \text{ for } i = 1, 2, 3, \ldots, n$$

$$\Rightarrow \quad S_i^* = P_i - JQ_i = V_i^* I_i$$

$$S_i^* = (Y_{i1}V_i + Y_{i2}V_2 + Y_{i3}V_3 + \ldots + Y_{in}V_n)V_i^*$$

$$\therefore \quad S_i^* = P_i - jQ_i = \sum_{m=1}^{n} Y_{im}V_m V_i^* \text{ for } i = 1, 2, 3, \ldots, n$$

Above equation gives the general form for static power flow equations.

Let the bus voltages and admittance be written in rectangular and polar form

$$V_i = e_i + jf_i = |V_i|\angle\delta_i$$

$$|V_i| = \sqrt{e_i^2 + f_i^2}\,;\ \delta_i = \tan^{-1}\frac{f_i}{e_i}$$

$$Y_{im} = G_{im} + jB_{im} = |Y_{im}|\angle\theta_{im}$$

$$|Y_{im}| = \sqrt{G_{im}^2 + B_{im}^2}\,;\ \theta_{im} = \tan^{-1}\frac{B_{im}}{G_{im}}$$

Substitute V_i and Y_{im} in S_i^* equation

$$P_i - jQ_i = \sum_{m=1}^{n}(G_{im} + jB_{im})(e_m + jf_m)(e_i - jf_i)$$

Equating the real and imaginary parts, we get

$$P_i = e_i\sum_{m=1}^{n}(G_{im}\,e_m - B_{im}\,f_m) + f_i\sum_{m=1}^{n}(G_{im}\,f_m + B_{im}\,e_m)$$

$$Q_i = e_i\sum_{m=1}^{n}(G_{im}\,f_m - B_{im}\,e_m) + f_i\sum_{m=1}^{n}(G_{im}\,e_m + B_{im}\,f_m)$$

for $I = 1, 2, 3, \ldots, n$.

If the polar form of bus voltage V_i and admittance Y_{im} are substituted in S_i^* expression.

$$P_i - jQ_i = |V_i|e^{-j\delta}{}_i\sum_{m=1}^{n}|Y_{im}|e^{j\theta}{}_{im}|V_m|e^{jS}{}_m$$

for $i = 1, 2, 3, \ldots n$

$$P_i = |V_i|\sum_{m=1}^{n}|Y_{im}|\,|V_m|\cos(\theta_{im} - \delta_i + \delta_m)$$

$$Q_i = |V_i|\sum_{m=1}^{n}|Y_{im}|\,|Y_m|\sin(\theta_{im} - \delta_i + \delta_m)$$

for $i = 1, 2, ,3 \ldots n$.

A typical bus of a power network is show in the figure. Each bus 'i' is associated with four variables.

- Voltage magnitude $|V_i|$
- Phase angle δ_i
- Net injected real power P_i
- Net injected reactive power Q_i

For 'n' bus system there are total number of $4n$ variables. Above mentioned '$2n$' equations in polar or rectangular form are solved for $2n$ variables provided the other '$2n$' variables are specified as input data.

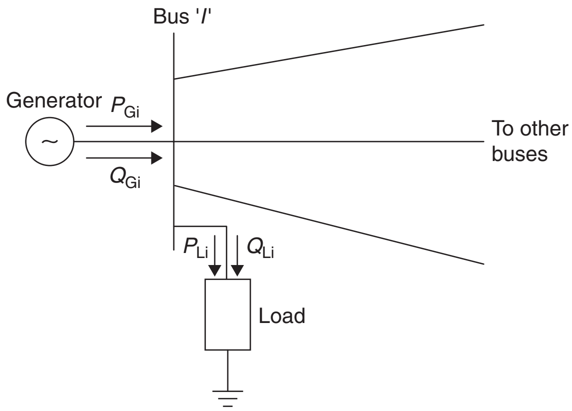


Figure 3 A typical bus of power systems

The study of various methods of solution to power system network is referred as load flow study. The solution provides the voltages at various buses, power flowing in various lines and line losses.

A load flow study of a power system generally requires the following steps

1. Representation of the system by single-line diagram.
2. Obtaining the impedance diagram using the information in single-line diagram.
3. Formulation of network equations
4. Solution of network equations

Types of Buses

The buses of power system can be classified into following three types.

1. Load bus (or PQ-bus)
2. Generator bus (or voltage controlled bus or PV bus)
3. Slack bus (or swing bus or reference bus)

Bus type	Quantities specified	Quantities to be obtained
Load bus	P, Q	$\|V\|$, d
Generator bus	P, $\|V\|$	Q, d
Slack bus	$\|V\|$, d	P, Q

Load Bus

The bus is called load bus, when real and reactive components of power are specified for the bus.

The load flow equations can be solved to find the magnitude and phase of bus voltage. In case of load bus, the voltage is allowed to vary within permissible limits.

Generator Bus

The bus is called generator bus, when real power and magnitude of bus voltage are specified for the bus. The load flow equation can be solved to find the reactive power and phase of bus voltage.

Slack Bus

The bus is called slack bus, if the magnitude and phase of bus voltage are specified for the bus.

The slack bus is the reference bus for load flow equation and usually one of the generator bus is selected as the slack bus.

Gauss–Seidel (G–S) Iterative Technique

In this Gauss–Seidel load flow, the load buses and generator busses are treated differently. In both these type of buses we use the complex power equation for updating voltages

$$V_i = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^*} - \sum_{m=1}^{n} Y_{im}\, V_m\right]$$

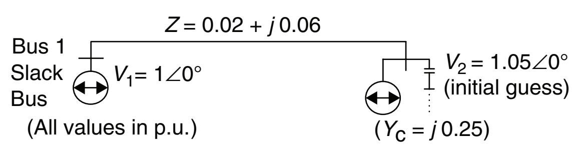
For PV buses, even though the real power is specified, its reactive power is unknown. But to update the voltage of PV buses, we must first estimate the reactive power of this bus. Reactive power expression is given by

$$Q_{i,\,inj} = -\text{Img}\left[V_i^* \sum_{m=1}^{n} Y_{im}\, V_m\right]$$

Q_i value for K^{th} iteration is given by

$$Q_i^K = -\text{Img}\left[V_i^{*(K-1)}\begin{Bmatrix} Y_{i1}V_i + Y_{i2}V_2^K + Y_{i3}V_3^K + \ldots + \\ Y_{ii}\,V_i^{(K-1)} + \ldots + Y_{IN}\,V_n^{(K-1)}\end{Bmatrix}\right]$$

Example for Gauss–Seidel Method



using Gauss–Seidel method, what should be next iteration value of V_2?

$$V_2^{(n+1)} = \frac{1}{Y_{22}}\left(\frac{S_2^{n4}}{V_2^{n4}} - \sum_{\substack{K=1\\K\#2}}^{n} Y_{2K}V_K^n\right)$$

$$= \frac{1}{Y_{22}}\left(\frac{S_2^{n4}}{V_2^{n4}} - Y_{21}V_1^n\right)$$

$$V_2^{(1)} = \frac{1}{Y_{22}}\left(\frac{S_2^{04}}{V_2^{o4}} - Y_{21}V_1^{(0)}\right) = 1.045\angle -0.83°$$

Advantages of Gauss–Seidel (G.S) Method

1. Calculations are simple, so the programming task is easier.
2. Memory requirement is less.
3. Useful for small size systems.

Disadvantages of G.S Method

1. Requires large number of iterations to reach convergence.
2. Not suitable for large systems.
3. Converge time increases with size of the system.

Newton–Raphson Method

Let us assume that an n-bus power system contains a total of n_p number of P–Q buses while the number of P–V (Generator) buses be n_g such that $n = n_p + n_g + 1$. Bus 1 is assumed to be the stack bus. We shall further use the mismatch equation ΔP_i and ΔQ_i as specified below.

$$\Delta P_i = P_{i\ \text{specified}} - P_{i\ \text{calculated}}$$

$$\Delta Q_i = Q_{i\ \text{specified}} - Q_{i\ \text{calculated}}$$

The approach to Newton–Raphson load flow is similar to that of solving a system of non-linear equations using 'Newton–Raphson' method. At each iteration, we have to form a Jacobian matrix and solve for the correction factor.

$$J\begin{bmatrix} \Delta\delta_2 \\ \Delta\delta_3 \\ \cdot \\ \cdot \\ \Delta\delta_n \\ \Delta|V_2|/V_2 \\ \cdot \\ \cdot \\ \Delta|V_i+n_p|/|V|_{1+\text{np}} \end{bmatrix} = \begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \cdot \\ \cdot \\ \Delta P_n \\ \Delta Q_2 \\ \cdot \\ \cdot \\ \Delta Q_1+n_p \end{bmatrix}$$

where 'J' is the Jacobian matrix and it is divided into submatrices as

$$J = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix}$$

Size of the Jacobian matrix is $(n + n_{p-1}) \times (n + n_{p-1})$

The dimensions of the submatrices are as follows.

$$J_{11} \to (n-1)\times(n-1)$$

$$J_{12} \to (n-1)\times n_p$$

$$J_{21} \to n_p \times (n-1)$$

$$J_{22} \to n_p \times n_p$$

Sub matrices are given by

$$J_{11} = \begin{bmatrix} \partial P_2/\partial\delta_2 & \cdot & \cdot & \partial P_2/\partial\delta_n \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \partial P_n/\partial\delta_2 & \cdot & \cdot & \partial P_n/\partial\delta_n \end{bmatrix} = \begin{bmatrix} L_{22} & \cdot & \cdot & L_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot\cdot & \cdot \\ L_{n2} & \cdot & \cdot & L_{nn} \end{bmatrix}$$

where

$$L_{ik} = \frac{\partial P_i}{\partial\delta_k} = -|Y_{ik}\,V_i\,V_k|\sin(\theta_{ik}+\delta_k-\delta_i) \text{ for } i \neq K$$

$$L_{ii} = \frac{\partial P_i}{\partial\delta_i} = \sum_{\substack{k \\ k\neq 1}}^{n} |Y_{ik}\ V_i\ V_k|\sin(\theta_{ik}+\delta_k-\delta_i)$$

$$J_{12} = \begin{bmatrix} |V_2|\dfrac{\partial P_2}{\partial|v_2|} & |V_{1+np}|\dfrac{\partial P_2}{\partial|V_{1+np}|} \\ |V_2|\dfrac{\partial P_n}{\partial|V_2|} & |V_{1+np}|\dfrac{\partial P_n}{\partial|V_{1+np}|} \end{bmatrix}$$

$$= \begin{bmatrix} N_{22} & N_{2np+1} \\ N_{n2} & N_{n\,np+1} \end{bmatrix}$$

where

$$N_{ik} = |V_K|\,.\frac{\partial P_i}{\partial|V_k|} = |Y_{ik}\,V_i\,V_{ik}|\cos(\theta_{ik}+S_k-S_i)$$

for $i \neq K$

$$N_{ii} = |V_i|\frac{\partial P_i}{\partial|V_i|} = 2|V_i|^2 G_{ii} + \sum_{\substack{k=1 \\ k\neq 1}}^{n} |Y_{ik}\ V_i\ V_k|\cos(\theta_{ik}+\delta_k-\delta_i)$$

$$J_{21} = \begin{bmatrix} \partial Q_2/\partial\delta_2 & \cdot & \cdot & \partial Q_2/\partial\delta_n \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \partial Q_n/\partial\delta_2 & \cdot & \cdot & \partial Q_n/\partial\delta_n \end{bmatrix} = \begin{bmatrix} M_{22} & \cdot & \cdot & M_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot\cdot & \cdot \\ M_{n2} & \cdot & \cdot & M_{nn} \end{bmatrix}$$

where

$$M_{ik} = \frac{\partial Q_i}{\partial\delta_k} = -|Y_{ik}\,V_i\,V_k|\cos(\theta_{ik}+\delta_k-\delta_i)\,.$$

$$M_{ii} = \frac{\partial Q_i}{\partial\delta_i} = \sum_{\substack{k=1 \\ k\neq 1}}^{n} |Y_{ik}\ V_i\ V_k|\cos(\theta_{ik}+\delta_k-\delta_i) = P_i - |V_i|^2\,Gii$$

$$J_{22} = \begin{bmatrix} |V_2|\dfrac{\partial Q_2}{\partial|V_2|} & |V_{1+np}|\dfrac{\partial Q_2}{\partial|V_{1+np}|} \\ |V_2|\dfrac{\partial Q_{1+np}}{\partial|V_2|} & |V_{1+np}|\dfrac{\partial Q_{1+np}}{\partial|V_{1+np}|} \end{bmatrix} = \begin{bmatrix} O_{22} & Q_{2np} \\ O_{np2} & O_{np\ np} \end{bmatrix}$$

where

$$O_{ik} = |V_K|\,.\frac{\partial Q_i}{\partial|V_k|} = -|V_i||Y_{ik}\,V_i\,V_{ik}|\sin(\theta_{ik}+\delta_k-\delta_i)$$

for $i \neq K$.

$$Q_{ii} = |V_i|\frac{\partial Q_i}{\partial|V_i|} = 2|V_i|2\,B_{ii} - L_{ii}$$

Load Flow Algorithm

The Newton–Raphson procedure is as follows:

Step 1: Choose initial values for the voltage magnitude $|V|^\circ$ of all n_p load buses and $(n-1)$ angles δ° of the voltages of all the buses except slack bus.

Step 2: Use the estimated voltages and phase angles to calculate $(n-1)$ number of injected real power P°_{calc} and corresponding real power mismatch ΔP° for all buses except slack bus.

Step 3: Use the estimated voltages and phase angles to calculate n_p number of injected reactive power Q°_{calc} and corresponding reactive power mismatch ΔQ° for the PQ buses.

Step 4: Use the estimated $|V|^\circ$ and δ° to formulate Jacobian matrix J°

Step 5: Solve the load flow equation for δ° and $\Delta|V|^\circ/|V|^\circ$

Step 6: Obtain the updates from.

$$\delta' = \delta^\circ + \Delta\delta^\circ$$

$$|V|^1 = |V|^\circ\left[1+\frac{|\Delta V|^\circ}{|V|^\circ}\right]$$

Step 7: Check if all the mismatches are below a small number (tolerance). Terminate process if yes. Otherwise go back to step 1 to start the next iteration with the updates given in the step '6'.

Advantages of Newton–Raphson (N.R) Method

1. The N.R method is faster, more reliable and results are more accurate.
2. Requires less number of iterations for convergence.
3. The number of iterations is independent of the size of system.
4. Suitable for large-size systems.

Disadvantages of Newton–Raphson (N.R) Method

1. The programming logic is more complex than G.S method.
2. The memory requirement is more.
3. Number of calculations per iteration is higher than G.S method.

Comparison of Gauss–Seidel and Newton–Raphson Method of Load Flow Solutions

S. No.	Gauss–Seidel method	Newton–Raphson method
1.	Variables are expressed in rectangular co-ordinates.	Variables are expressed in polar co-ordinates.
2.	Computation time per iteration is less.	Computation time per iteration is more.
3.	It has linear convergence characteristics.	It has quadratic convergence characteristics.
4.	The number of iterations required for convergence increases with size of system.	The number of iterations is independent of the size of the system.
5.	The choice of slack bus is critical.	The choice of slack bus is arbitrary.

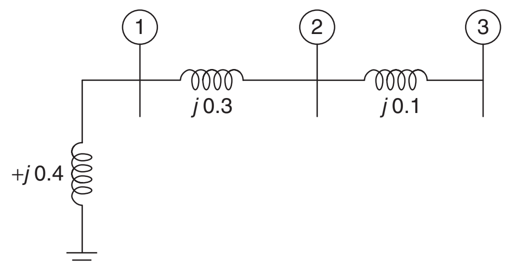
(*Continued*)

Example 7: In load flow analysis of power system,

(A) One of the bus is taken as slack bus
(B) Newton–Raphson method is preferred over Gauss–Seidel method
(C) Bus admittance matrix is a sparse matrix
(D) All the above

Solution: (D)

Example 8: Bus impedance matrix of the network given below is



(A) $j\begin{bmatrix}0.4 & 0.3 & 0\\0.3 & 0.4 & 0.1\\0 & 0.1 & 0.1\end{bmatrix}$ (B) $j\begin{bmatrix}0.4 & 0.4 & 0.4\\0.4 & 0.7 & 0.7\\0.4 & 0.7 & 0.8\end{bmatrix}$

(C) $j\begin{bmatrix}0.4 & 0 & 0\\0 & 0.7 & 0\\0 & 0 & 0.8\end{bmatrix}$ (D) $j\begin{bmatrix}0.4 & 0.4 & 0.4\\0.4 & 0.7 & 0.4\\0.4 & 0.4 & 0.8\end{bmatrix}$

Solution: (B)

Formation of bus 1

$$Z^1_{bus} = \begin{array}{cc} & ① \\ ① & [j0.4] \end{array}$$

Formation of bus 2

$$Z^2_{bus} = \begin{array}{cc} & \begin{array}{cc} ① & ② \end{array} \\ \begin{array}{c} ① \\ ② \end{array} & \begin{bmatrix} J0.4 & j0.4 \\ j0.4 & j0.7 \end{bmatrix} \end{array}$$

Formation of bus 3

$$Z^3_{bus} = \begin{array}{cc} & \begin{array}{ccc} ① & ② & ③ \end{array} \\ \begin{array}{c} ① \\ ② \\ ③ \end{array} & \begin{bmatrix} j0.4 & j0.4 & j0.4 \\ j0.4 & j0.7 & j0.7 \\ j0.4 & j0.7 & j0.8 \end{bmatrix} \end{array}$$

Example 9: A power system consist of 40 bus with 9 voltage controlled buses, the size of the Jacobian matrix is
(A) 70×70 (B) 80×80
(C) 62×62 (D) 79×79

Solution: (A)
Total number of buses (n) = 40
Voltage-controlled buses or generator buses = 9
Order of the Jacobian matrix

$$= (2 \times \text{no. of load buses}) + (\text{Number of generator buses} - 1)$$

$$= 2(40 - 9) + (9 - 1)$$

$$= 70 \times 70$$

Example 10: Voltage of a bus can be controlled by controlling
(A) Active power of the bus
(B) Reactive power of the bus
(C) Both A and B
(D) Phase angle
Solution: (B)

Example 11: The bus impedance matrix of a 4-bus power system is given by

$$Z_{\text{bus}} = \begin{bmatrix} j0.3435 & j0.2860 & j0.2723 & j0.2277 \\ j0.2860 & j0.3408 & j0.2586 & j0.2414 \\ j0.2723 & j0.2586 & j0.2791 & j0.2209 \\ j0.2277 & j0.2414 & j0.2209 & j0.2791 \end{bmatrix}$$

A branch having an impedance of $j0.2\ \Omega$ is connected between bus 2 and the reference. Then the values of $Z_{22\text{new}}$ and $Z_{23\text{new}}$ of the bus impedance matrix of the modified network are, respectively?

Solution: $Z_{\text{Bus}}(\text{new}) = Z_{\text{Bus}}(\text{old})$

$$= \frac{1}{Z_{jj} + Z_b} \begin{bmatrix} Z_{1j} \\ . \\ . \\ Z_{nj} \end{bmatrix} \left[Z_{j1 \ldots\ldots Zjn} \right]$$

New elements (Z_b) is connected between j^{th} and reference bus

Here $j = 2$, $n = 4$

$$= \frac{1}{j0.3408 + j0.2} \begin{bmatrix} j0.2860 \\ j0.3408 \\ j0.2586 \\ j0.2414 \end{bmatrix}$$

$$\times [j0.2860\ j0.3408\ j0.2586\ j0.2414]$$

We require only changes in Z_{22} and Z_{23}.

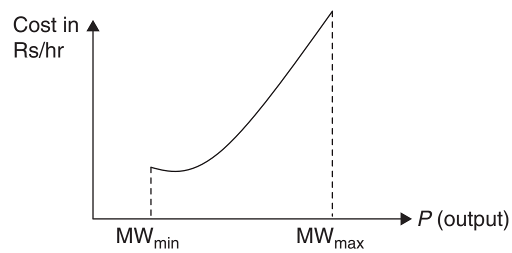
$$= \begin{bmatrix} - & - & - & - \\ - & j0.2147 & j0.16 & - \\ - & - & - & - \\ - & - & - & - \end{bmatrix}$$

$$Z_{22}\text{ new} = Z_{22}\,(\text{old}) - j0.2147 = j0.1260$$

$$Z_{23}\text{ new} = Z_{23}\,(\text{old}) - j0.16296 = j0.956$$

Optimal Operation of Generators

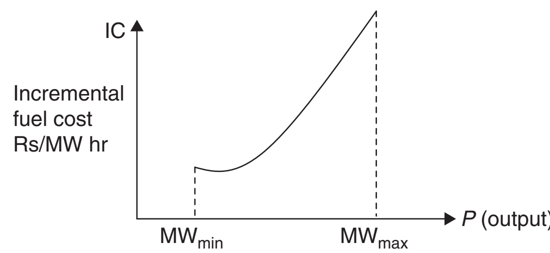
Generator operating cost: The major component of generator operating cost is the fuel input/hour, while the maintenance contributes only to a small extent. The fuel cost is most significant in case of thermal and nuclear stations. Typical cost-power output characteristics of a steam power plant are given below.



In the above characteristics, MW_{min} is the minimum loading limit below which it is uneconomical to operate the unit and MW_{max} is the maximum output limit. An analytical expression for operating cost can be written as

$$C_i = \frac{1}{2} a_i P_{\text{Gi}}^{\,2} + b_i P_{\text{Gi}} + C_i \text{ Rs/hour}$$

The slop of the curve, i.e., $\dfrac{dC_i}{dP_{\text{Gi}}}$ is called the 'incremental fuel cost' (IC) and is expressed in units of rupees per megawatt hour (Rs/MW hr). A typical plot of incremental fuel cost versus power output is given below.



When there are 'n' no. of generators present in the power system, total cost of generation is expressed as

$$C = \sum_{i=1}^{n} C_i \left(P_{\text{Gi}} \right)$$

Total cost 'C' is to be minimized under the equality constraint that $\sum_{i=1}^{n} P_{\text{Gi}} - P_{\text{Demand}} = 0$

The problem can be solved by Lagrange multipliers.

$$L = \sum_{i=1}^{n} C_1(P_{Gi}) - \lambda\left[\sum_{i=1}^{n} P_{Gi} - P_D\right]$$

where λ is the Lagrangian multiplier

Minimization of 'C' is achieved by the condition

$$\frac{\partial L}{\partial P_{Gi}} = 0 \Rightarrow \frac{\partial C_i}{\partial P_{Gi}} = \lambda \text{ for } i = 1, 2, 3....n$$

where $\frac{\partial C_i}{\partial P_{Gi}}$ is the incremental cost of the i^{th} generator

$$\therefore \quad \frac{\partial C_i}{\partial P_{Gi}} = \frac{\partial C_2}{\partial P_{G2}} = \frac{\partial C_3}{\partial P_{G3}} = ... = \frac{\partial C_n}{\partial P_{Gn}} = \lambda$$

∴ Optimal operation of generators corresponds to the equal incremental cost point of all generators.

If a particular generator loading P_{Gi} reaches the limit $P_{Gi_{max}}$ or $P_{Gi_{min}}$, its loading from now on is held fixed at this and the remaining load is then shared between the remaining generators on equal incremental cost basis.

When line losses are accounted for optimal scheduling, the equality constraint of meeting the load demand is modified as

$$\sum_{i=1}^{n} P_{Gi} - P_D - P_L = 0$$

where P_L = Total system transmission loss

Lagrangian is written as

$$L = \sum_{i=1}^{n} C_i(P_{Gi}) - \lambda\left[\sum_{i=1}^{n} P_{Gi} - P_D - P_L\right]$$

where the transmission losses are function of active power generation at all buses.

$$P_L = P_L(P_{G1}, P_{G2}, P_{G3}, ... P_{Gn})$$

For optimal power dispatch

$$\frac{\partial L}{\partial P_{Gi}} = \frac{\partial C_i}{\partial P_{Gi}} - \lambda + \lambda \frac{\partial P_L}{\partial P_{Gi}} = 0, i = 1, 2......k$$

$$\frac{\partial C_i}{\partial P_{Gi}} = \lambda\left(1 - \frac{\partial P_L}{\partial P_{Gi}}\right)$$

$$\frac{\partial C_i / \partial P_{Gi}}{(1 - \partial P_L / \partial P_{Gi})} = \lambda \qquad \text{For } i = 1, 2, 3, \dots, n$$

where $L_i = \frac{1}{\left(1 - \frac{\partial P_L}{\partial P_{Gi}}\right)}$ is called penalty factor of i^{th} plant.

The partial derivative $\frac{\partial P_L}{\partial P_{Gi}}$ is referred as the incremental transmission loss. $(ITL)_I$, associated with i^{th} generator. So, the condition for optimal generation can be given by

$$IC_i = \lambda[1 - ITL_i] \text{ for } i = 1, 2, 3.... n$$

So far optimal scheduling of plants, it is necessary to compute ITL of each plant, the functional dependence of transmission losses on real power of generating plants is given by

$$P_L = \sum_{p=1}^{n}\sum_{q=1}^{n} P_{Gp} B_{pq} P_{Gq}$$

where P_{Gp}, P_{Gq} = Real power generation at p^{th} and q^{th} plants

B_{mn} = Loss coefficients which are constants under certain assumed operating conditions.

Example 12: The fuel costs of a two-unit plant are given by

$$C_1 = 100 + 2P_1 + 0.005P_1^2$$

$$C_2 = 200 + 2P_2 + 0.01P_1^2$$

where P_1 and P_2 are in MW. The plant supplies a load of 400 MW. The economic load scheduling of two units will be?

Solution: $\frac{dC_1}{dP_1} = 2 + 0.005 \times 2P_1$

$$= 2 + 0.01P_1$$

$$\frac{dC_2}{dP_2} = 2 + 0.02P_2$$

For optimum load division, the two incremental costs should be equal.

$$\frac{dC_1}{dP_1} = \frac{dC_2}{dP_2}$$

$$2 + 0.01P_1 = 2 + 0.02P_2$$

$$P_1 = 2P_2$$

Total load is 400 MW

i.e., $P_1 + P_2 = 400$ MW

$2P_2 + P_2 = 400$ MW

$3P_2 = 400$ MW

∴ $P_2 = 133.4$ MW

$P_1 = 2P_2 = 266.6$ MW

Example 13: The power system has two generating plants and the power is being dispatched economically with P_1 = 125 MW, P_2 = 250 MW. The cost coefficients are

$$B_{11} = 0.1 \times 10^{-2} \text{ MW}^{-1}$$

$$B_{12} = -0.01 \times 10^{-2} \text{ MW}^{-1}$$

$$B_{22} = 0.13 \times 10^{-2} \text{ MW}^{-1}$$

to raise the total load on the system by 1 MW will cost an additional Rs 200 per hour. The penalty factor is ______?

Solution: $P_L = P_1^2 B_{11} + 2P_1P_2B_{12} + P_2^2 B_{22}$

$$\frac{\partial P_L}{\partial P_1} = 2P_1B_{11} + 2P_2B_{12}$$

$$= 2 \times 125 \times 0.1 \times 10^{-2} + 2 \times 250 \times (-0.01 \times 10^{-2}) = 0.2$$

Penalty factor for plant 1

$$L_1 = \frac{1}{1-\frac{\partial P_L}{\partial P_1}} = \frac{1}{1-0.2} = 1.25$$

Example 14: A generating station has two units. The incremental operating costs of the two units are as follows, G_1: $\lambda_1 = 0.1P_1 + 20$, G_2: $\lambda_2 = 0.2P_2 + 10$, where P_1, P_2 are in MW. Total loading is 200 MW. The economic loading will be

(A) $P_1 = 150, P_2 = 50$ (B) $P_1 = 100, P_2 = 100$
(C) $P_1 = 175, P_2 = 25$ (D) $P_1 = 50, P_2 = 150$

Solution: (B)

Given $P_1 + P_2 = 200$ (1)

and we know that $l_1 = l_2$, for economic load scheduling

$$0.1P_1 + 20 = 0.2P_2 + 20$$

$$\Rightarrow \quad 0.1P_1 - 0.2P_2 = -10 \tag{2}$$

Solving (1) and (2), we get

$$P_1 = 100 \text{ MW}, P_2 = 100 \text{ MW}$$

Example 15: A power system has two generating plants and the power is being dispatched economically with $P_1 = 100$ MW and $P_2 = 200$ MW. The loss coefficients are $B_{11} = 0.2 \times 10^{-2}$ MW^{-1}, $B_{12} = -0.02 \times 10^{-2}$ MW^{-1}, $B_{22} = 0.09 \times 10^{-2}$ MW^{-1}. The penalty factor for plant-1 will be

(A) 1.35 (B) 1.21 (C) 1.47 (D) 1.63

Solution: (C)

$$P_L = P_1^2 B_{11} + 2P_1P_2 B_{12} + P_2^2 B_{22}$$

$$\frac{\partial P_L}{\partial P_1} = 2P_1B_{11} + 2P_2B_{12}$$

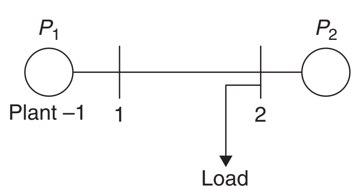
$$= [2(100)(0.2) \times 10^{-2}] + [2 \times 200 \times (-0.02) \times 10^{-2}]$$

$$= 0.4 - 0.08 = 0.32$$

Penalty factor, $L_1 = \dfrac{1}{1-\frac{\partial P_L}{\partial P_1}}$

$$= \frac{1}{1-0.32} = 1.47$$

Example 16: A system consists of two plants connected by a transmission line as shown in the fig. The load is at plant-2. If a load of 200 MW is transmitted from plant-1 to the load, there is a loss of 20 MW. Determine the loss factor B_{11}.



(A) 5×10^{-4} MW^{-1} (B) 10×10^{-4} MW^{-1}
(C) 15×10^{-4} MW^{-1} (D) 20×15^{-4} MW^{-1}

Solution: (A)

$$P_L = P_1^2B_{11} + 2P_1P_2B_{12} + P_2^2B_{22}$$

$\therefore$ The load is at plant-2 bus

$$B_{12} = B_{21} = 0 \text{ and } B_{22} = 0$$

$$\therefore \quad P_L = P_1^2B_{11}$$

$$\Rightarrow \quad B_{11} = \frac{P_L}{P_1^2} = \frac{20}{(200)^2}$$

$$\therefore \quad B_{11} = 5 \times 10^{-4} \text{ MW}^{-1}$$

Example 17: A power system has two generating plants and the power is being dispatched economically with $P_1 = 100$ MW and $P_2 = 200$ MW. The loss coefficients are $B_{11} = 0.5 \times 10^{-2}$ MW^{-1}, $B_{12} = -0.02 \times 10^{-2}$ MW^{-1}, $B_{22} = 0.15 \times 10^{-2}$ MW^{-1}. To raise the total load on the system by 1 MW will cost an additional Rs 300 per hour. The penalty factor for plant-1 will be

(A) 10 (B) 11.5 (C) 12.5 (D) 15

Solution: (C)

$$P_L = P_1^2B_{11} + 2P_1P_2B_{12} + P_2^2B_{22}$$

$$\frac{\partial P_L}{\partial P_1} = 2P_1B_{11} + 2P_2B_{12}$$

$$= 2(100)(0.5 \times 10^{-2}) + 2(200)(-0.02 \times 10^{-2})$$

$$= 1 - 0.08 = 0.92$$

Penalty factor $L_1 = \dfrac{1}{1-\frac{\partial P_L}{\partial P_1}}$

$$= \frac{1}{1-0.92} = 12.5$$

Example 18: The fuel costs of two unit plants are given by

$$C_1 = 50 + 5P_1 + 0.5P_1^2,$$

$$C_2 = 10 + 15P_2 + P_2^2$$

where P_1, P_2 are in MW. The plant supplies load of 100 MW. The economic load scheduling of the two units will be

(A) $P_1 = 70, P_2 = 30$ (B) $P_1 = 30, P_2 = 70$
(C) $P_1 = 50, P_2 = 50$ (D) $P_1 = 60, P_2 = 40$

Solution: (A)

$$\frac{dC_1}{dP_1} = \frac{dC}{dP_2}$$

$$5 + P_1 = 15 + 2P_2 \tag{3}$$

$$P_1 - 2P_2 = 10 \tag{3}$$

Given, $P_1 + P_2 = 100$ (4)

Solving (3) and (4), we get

$$P_1 = 70 \text{ MW}, P_2 = 30 \text{ MW}$$

Power System Protection

Undesirable effects of faults in power system are given by

1. Power system components carrying abnormal currents get overheated.
2. Operating voltages can go above or below their acceptable values.
3. Power flow is restricted or completely blocked due to short circuit.
4. Power system areas can lose synchronism.
5. Arcing faults can vaporize equipment in the vicinity leading to possibility of fire and explosion.
6. Open-circuit faults will lead to abnormal system operation and danger to personnel.

So, the faults should be instantly detected from the faulty section. Isolated from the rest of the system in the shortest possible time. Faults are detected automatically be means of relay and the fault section isolated by means of circuit breakers. The functional characteristics of the protection system are enumerated as follows.

1. **Reliability:** Reliability of a relay is a basic requirement. It must operate when it is required. Every component and circuit which is involved in operation of relay must be found in healthy operating condition when called up on to act.
2. **Speed:** A protective relay must operate at the required speed. It should neither be too slow which may results in damage to the equipment nor should it be too fast which may result in undesired operation during transient faults. The time is in the order of 30–100 ms depending upon the fault level of the section involved
3. **Selectivity:** Relaying equipment must clearly discriminate between normal and abnormal system conditions, so it never operates un necessarily
4. **Sensitivity:** A relay should be sufficiently sensitive so that it operates reliably when required under the actual conditions in the system which produces the least tendency for operation.

Basic Definitions in Protection

Pick-up Level

The value of the actuating quantity which is on the threshold above which the relay operates.

Reset Level

The value of the actuating quantity below which a relay opens its contacts and comes to original position.

Reset Time

The time which elapses between the instant when the actuating quantity becomes less than the reset value to the instant when the relay contact return to its normal position.

Operating Time

The time which elapses between the instant when the actuating quantity exceeds the pick-up value to the instant when the relay contacts close.

Primary Relays

The relay which are directly connected in the circuit to be protected.

Secondary Relays

The relays which are connected in the circuit to be protected through current and potential transformers.

Auxiliary Relays

Relays which operate in response to the opening or closing of its operating circuit to assist another relay.

Reach

A distance relay operates whenever the impendence seen by the relay is less than a pre-specified value. The impedance or the corresponding distance is known as the reach of the relay.

Over Reach

The tendency of the relay to operate at impedance more than its setting.

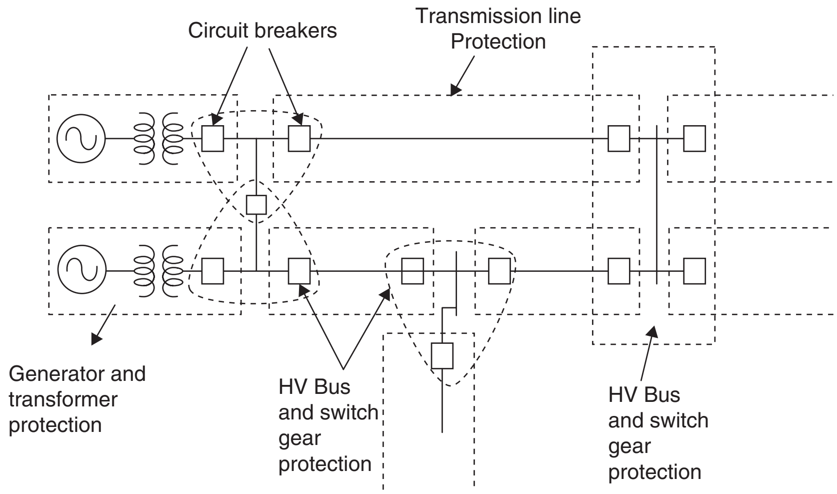
Under Reach

The tendency of the relay to operate at impedance less than its setting.

Protective Zones

In order to limit the number of elements disconnected by the protective system during a fault, the protective system is divided into number of zones. Protective zones of a power system are as shown in the figure below.

Each protective zone has the primary responsibility to disconnect the element or elements in the zone in the event of fault. The protection provided by each zone to its elements is known as ‘primary protection’ in the event of primary protection failure, backup protection is provided.



Classification of Relays

Based on the Time of Operation

1. Instantaneous relay
2. Definite minimum time relay
3. Inverse time relay
4. Inverse definite minimum time relay.

Based on the Construction

1. Electromagnetic relay
2. Induction relay
3. Static relay

Based upon Application

1. Overcurrent relay
2. Overvoltage relay
3. Differential relay
4. Distance relay

Essential Characteristics of Relay

1. Sensitivity
2. Selectivity
3. Speed
4. Reliability
5. Economy
6. Simplicity

Pick-up Value

The minimum value of operating quantity at which the relay is at wedge of operation is called 'pickup value', i.e. ready to operate.

Reset Value

The maximum value of operating quantity at which the relay is at wedge of reset is called 'reset value'.

Time Multiplier Setting (TMS)

$$\text{TMS} = \frac{\text{Actual time of operation required}}{\text{Required time of operation when TMS} = 1}$$

Plug Setting Multiplier (PSM)

It is the ratio of CT secondary fault current to relay operating current.

$$\text{Relay operating current} = \text{Current setting} \times \text{CT secondary rated current}$$

$$\text{PSM} = \frac{\text{CT secondary faulty current}}{\text{Current setting}\ \ \text{CT secondary rated current}}$$

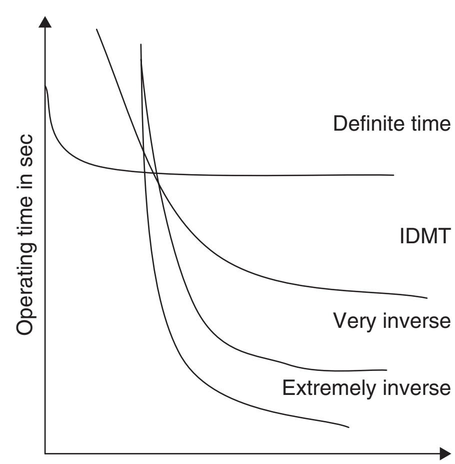
(or)

$$\text{PSM} = \frac{\text{Fault current (primary)}}{\text{Current setting} \times \text{CT secondary current} \times \text{CT ratio}}$$

Overcurrent Relays

Depending upon the time of operation, the relays are categorized as follows.

Characteristics of Various Overcurrent Relays



Instantaneous Overcurrent Relay

- In which no intentional time delay is provided for the operation.
- The time of operation of such relay is approximately 0.1 s.

Inverse Time–current Relay

- In which the operating time reduces as the activating quantity increases in magnitude.

Inverse Definite Minimum Time Current Relay (IDMT)

- In which the operating time is approximately inversely proportional to the fault current near pick-up value and becomes substantially constant slightly above the pickup value of the relay.

Very Inverse Relay

- In which the saturation of the core occurs at a later stage.

Extremely Inverse Relay

- In which the saturation of the core occurs at a still later stage.

Overcurrent (OC) Relay

The relay operates when current through it satisfies the condition

$$Q = K_1 |I|^2 - K_4 > 0$$

$$I > \sqrt{\frac{K_4}{K_1}} = |I_p|$$

where I_p = pick up value of the relay, K_1 and K_4 are constants.

The above condition for relay operation can also be written as.

$$|I| > |I_p| \text{ trip (Relay trips CB)}$$

$$|I| < |I_p| \text{ block (Relay does not trip CB)}$$

The value of the pickup current can be easily adjusted by altering the constant K_1 by means of plug setting.

For co-ordination of overcurrent relays, it is essential that these must have inverse-time characteristics where operating time decreases as relay current increases these relays are called as 'Inverse definite minimum time lag relays'. Characteristics of an IDMTL relay are expressed mathematically as

$$T_{op} = f(|I_{p.u.}| - 1) \text{ for } |I_{p.u.}| > 1$$

$$|I_{p.u.}| = {}^{|I|}/_{|P|}$$

- The inverse time current relays are non-directional relays and are used for the protection of feeders, transmission lines, transformers, machines and other numerous applications.

Directional Relays

At a certain points in power system, current is flowing in one direction (specified direction), if due to any changes in the circuit condition, the current flows in opposite direction, the relay will develop positive torque and will operate.

In a directional relay

$$Q = K_3 |V| |I| \cos(\theta - \tau) - K_4$$

where θ = Angle by which $|I$ leads $|V|$

τ = Adjustable angle parameter

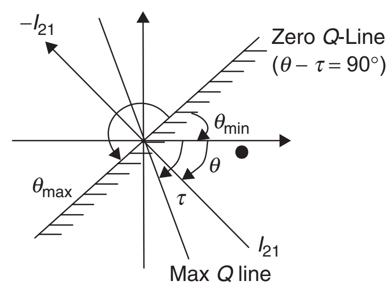
The relay operator when

$$Q = K_3 |V| |I| \cos(\theta - \tau) > 0$$

or
$$\cos(\theta - \tau) > 0 \text{ trip}$$

$$\cos(\theta - \tau) < 0 \text{ block}$$

The operating characteristics of directional relay are shown in figure below.



In a directional relay, V is taken as the reference phasor, under fault, it undergoes only a small change in phase angle, This phase is called as the 'polarizing quantity' of the relay. The relay characteristics also can be expressed as

$$\theta_{min} > \theta > \theta_{max} \text{ trip}$$

$$\theta_{min} < \theta < \theta_{max} \text{ block}$$

Impedance Relay

From the general relay equation we have a special case

$$Q = K_1 |I|^2 + K_2 |I|^2 - K_4$$

If effect of K_4 is neglected, the relay operates when

$$K_1 |I|^2 + K_2 |V|^2 > 0$$

Or

$$\frac{|V|}{|I|} = |Z| < \left(\frac{K_1}{-K_2}\right)^{1/2} = |Z_{rs}|$$

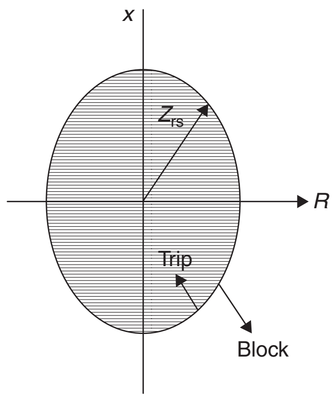
If K_2 is negative, such a relay senses impendence magnitude, and operates if the magnitude of impendence seen from its location is less than a specified value. Since $|V|$ prevents relay operation and $|I|$ tries to operate it, voltage in the restraining quantity and current is operating quantity of the relay.

The characteristics impendence can be generally expressed as

$$|Z| < |Z_{rs}| \text{ trip}$$

$$|Z| > |Z_{rs}| \text{ Block}$$

where $|Z_{rs}|$ = impendence setting of the relay. RX-plane of the impendence characteristics is given by



Mho Relay

A modified impendence relay called 'Mho relay' in case of Mho relay

$$Q = K_3\,|V|\,|I| \cos(\theta - \tau) - (-K_1)\,|V|^2 - K_4$$

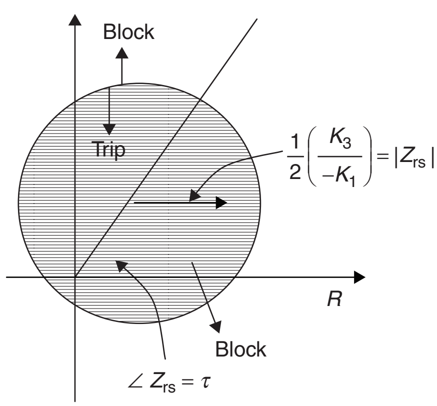
For relay operation neglecting K_4

$$K_3\,|V|\,|I| \cos(\theta - \tau) - (-K_1)\,|V|^2 > 0$$

$$\frac{|V|}{|I|} = |Z| < \frac{K_3}{-K_1}\cos(\theta - \tau)$$

$$|Z - Z_{rs}| < |Z_{rs}| \text{ trip}$$

$$|Z - Z_{rs}| > |Z_{rs}| \text{ block}$$



Rx–diagram of a Mho relay

Reactance Relay

A reactance relay is an overcurrent relay with directional restraint the direction element is arranged to yield maximum Q-contribution when its current lags its voltage by 90°

$$Q = K_1\,|I| \cos(\theta - \tau) - (-K_1)\,|V|^2 - K_4$$

For relay operation neglecting K_4

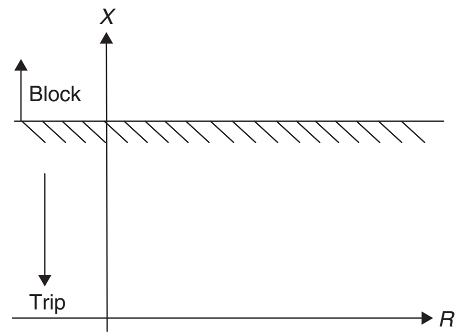
$$K_1\,|I|^2 - (K_2)\,|V|\,|I| \sin\theta > 0$$

$$\frac{|V|}{|I|}\sin\theta < \frac{K_1}{-K_2}$$

$$|Z|\sin\theta < \frac{K_1}{-K_2}$$

$$x < \frac{K_1}{-K_2}$$

These characteristics are represented in R-x-plane as shown below.



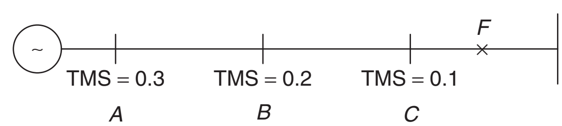
Protection of Feeders

Radial Feeders

Overcurrent protection for radial feeder is done by the following methods.

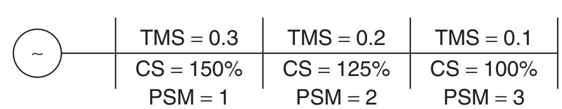
Time-graded System

The time of operation of the relays at various locations is so adjusted that the relay farthest from the source will have minimum time of operation and as it is approached towards the source the operating time increases.



Current Graded Method

In this method for the relay farthest from the source the current setting (cs) is kept minimum. As we go towards the source, the current setting gradually increases.



$$\text{Current setting} \propto \frac{1}{\text{PSM}}$$

$$\text{PSM} \propto \frac{1}{\text{TMS}}$$

Time Current Graded System

According to this system the TMS and current setting for the relay farther from the source is kept minimum and as we go towards the source both these values increase.

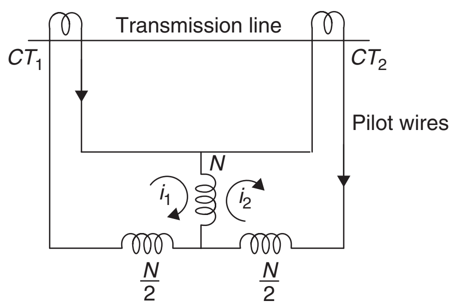
Parallel Feeders

- In this protection scheme, directional as well as non-directional overcurrent relays are used.
- Non directional relays are provided near the source and directional relays are provided near the load.

Ring Main Feeders

- The ring main considered two radial feeders.
- Non-directional relays must be placed near the source.
- Directional relays are placed near the load.

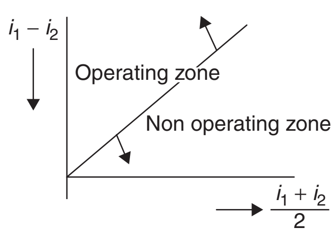
Differential Relays



$$\text{Operating coil} \propto (i_1 - i_2)\, N$$

$$\text{Restraining force} \propto \frac{i_1 N}{2} + \frac{i_1 N}{2}$$

$$\propto \frac{(i_1 + i_2)N}{2}$$



- Operating zone and non-operating zone is fixed by percentage differential relay.
- A differential protection using percentage differential relay is called as merz-price circulating current coil.
- A differential relay will not operate for inter turn fault in the generator winding. For inter turn fault protection of generator winding, split phase relay is used.
- For short circuits, normally percentage differential protection is recommended for transformers rated more than 1 MVA. For low rating, overcurrent relaying is used.

Neutral Grounding

The process of connecting neutral point of three-phase system to Earth (i.e. soil), either directly or through some circuit element (E.g. resistance, reactance, etc.) is called neutral grounding.

Methods of Neutral Grounding

Solid or Effective Grounding

Neutral point of a 3-ϕ system is directly connected to earth through a wire of negligible resistance and reactance.

This type of grounding is used for voltages up to 33 kV with total power capacity not exceeding 5000 kVA.

Resistance Grounding

When the neutral point of a three-phase system is connected to earth through a resistor, it is called resistance grounding.

It is used for voltages between 2.2 kV and 33 kV when power capacity is more than 5000 kVA.

Reactance Grounding

- A reactance is inserted between the neutral and ground.
- High transient voltage appears under fault condition.

Resonant Grounding

Capacitance currents are responsible for producing arcing grounds. These capacitive currents flow because capacitance exists between each line and Earth.

When the value of 'L' for arc suppression coil is such that the fault current, I_f exactly balances the capacitive current I_c, it is called resonant grounding (or Peterson coil grounding).

For resonant grounding,

$$I_L = I_C$$

$$\frac{V_{Ph}}{X_L} = \frac{3V_{Ph}}{X_C}$$

$$X_L = \frac{X_C}{3}$$

$$\omega L = \frac{1}{3\omega C}$$

$$\therefore \quad L = \frac{1}{3\omega^2 C}$$

Solid State Relay

A solid state relay (SSR) is an electronic switching device in which a small control signal controls a larger load current or voltage. It comprises a voltage or current sensor which responds to appropriate input (control signal), a solid state electronic switching device of some kind which switches power to the load circuitry either on or off, and some coupling mechanism to control signal to activate this switch without mechanical parts. It serves same functions as an electromechanical relay, but has no moving parts.

Many SSRs use optical coupling. The control voltage energizes an LED which illuminates and switches on a photo sensitive diode (photo-voltaic). The diode current turns on a back to back thyristor, silicon control rectifier, or MOSFET to switch the load.

Advantages of SSRs

- SSRs are faster
- Increased life time
- Clean, bounce less operation
- No sparking, silent operation
- Identically smaller than electromagnetic relay

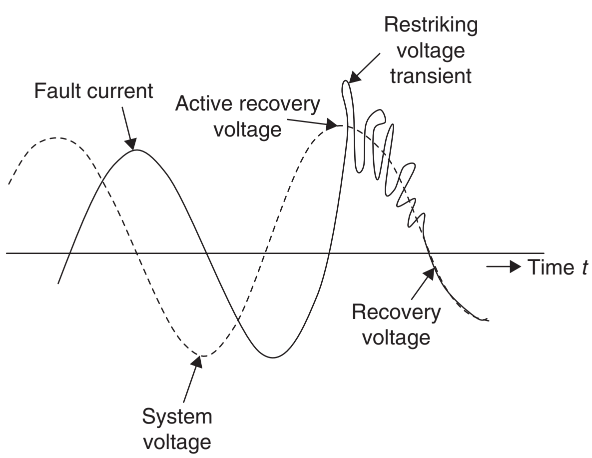
Disadvantages of SSRs

- Isolated bias supply is required for gate charge circuit.
- SSRs have higher transient reverse recovery time due to the presence of diode.

CIRCUIT BREAKER

Circuit breakers can be used for opening and closing of electrical circuit under normal and abnormal conditions. Generally circuit breaker consist of both moving and fixed contacts, when the circuit under normal (or) healthy conditions the contacts are closed and when the circuit under abnormal (or) fault condition the contacts are separated.

Consider a circuit operated under normal conditions and after some time interval fault occurs on the system. Then the variation of voltage and currents is as shown below.



When the circuit is interrupted by a circuit breaker under fault condition an arc is formed between the two contacts of the circuit breaker. This arc can be extinguished by two methods.

1. Low resistance (or) current zero method
2. High resistance method

Arc Voltage

The voltage appeared across the contacts of the circuit breaker during arcing period is known as arc voltage.

Restriking Voltage

The transient voltage appears across the circuit breaker contacts at current zero point is known as restriking voltage.

Average Rate of Rise of Restriking Voltage (RRRV)

It is the ratio of peak value of restriking voltage to the time taken to reach peak value voltage.

The average RRRV

$$= \frac{\text{Peak value of restriking voltage}}{\text{Time taken in attaining peak value}}$$

$$= \frac{2V_{\text{max}}}{\pi\sqrt{LC}}$$

Insertion P_6

Ratings of Circuit Breaker

The circuit Breaker performance is analysed by the following terms.

1. Breaking capacity
2. Making capacity
3. Short time capacity

Breaking Capacity

It is the product of rated breaking current in terms of kA and rated voltage in terms of kV.

For three-phase, the Breaking capacity = $\sqrt{3}VI$

Making Capacity

The making capacity of circuit breaker is the ability of the circuit breaker to withstand the electromagnetic force under short-circuit condition. Generally making capacity is 2.55 times of breaking capacity.

Making capacity = 2.55 × Breaking capacity.

Short Time Capacity

It is the capacity of the circuit Breaker which can safely applied to the circuit Breaker under its normal condition for 3 seconds time period.

Types of Circuit Breakers

1. Air-break circuit breakers
2. Oil circuit breakers (OCB)
3. Vacuum circuit breakers (VCB)
4. Air-blast circuit breakers (ABCB)
5. SF_6 circuit Breakers

Air Break Circuit Breakers

Air Break circuit Breakers are generally indoor type. These are used for DC circuit up to 12 kV and for medium- and low-voltage AC circuits up to 6.6 kV, 400–200 A.

The constructional details of an ABCB are shown in figure. The arc is lengthened in the breakers by the magnetic field and are runners and is finally extinguished by are splitters. There are two sets of contacts:

– Main contacts
– Arcing contacts

The main contacts are first to dislodge, while the arcing contacts are still closed under spring pressure. Thus the min contacts do not open any current and have long life. Arcing contacts made of hard copper alloy are easily replicable.

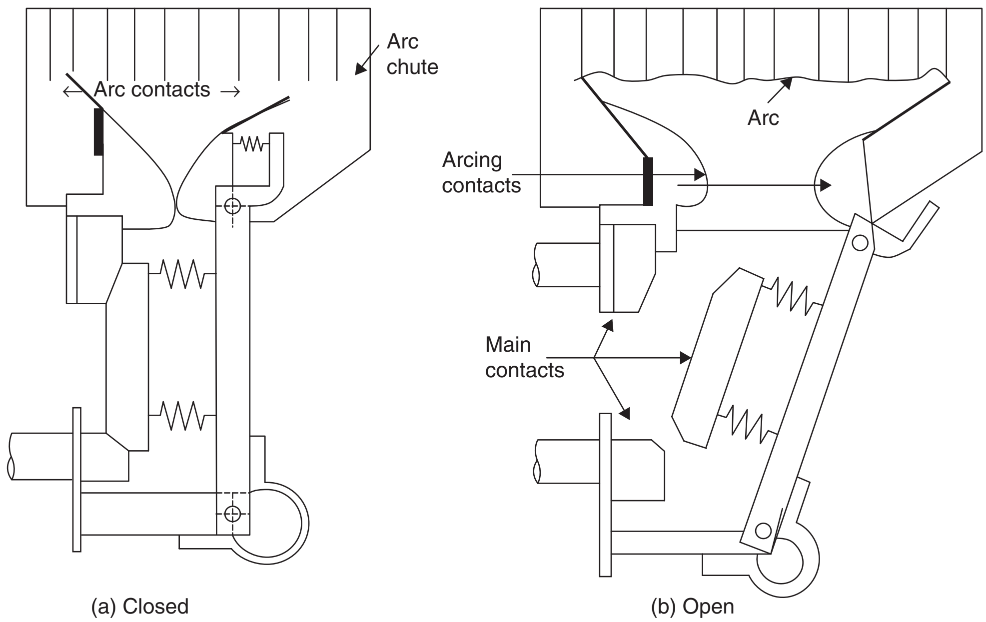
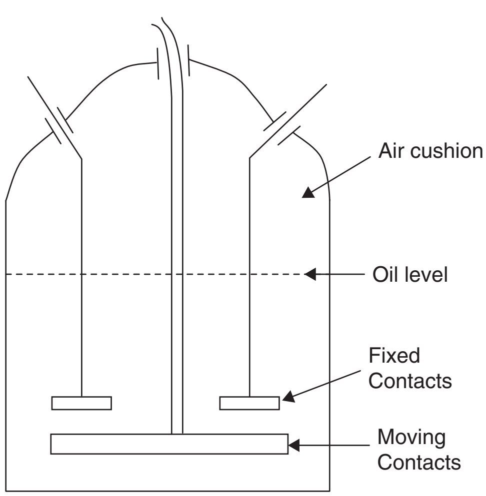


Figure 4 Air break circuit breakers

Oil Circuit Breakers (OCB)

Oil is used as the arc-quenching medium. These CB's have been developed for the voltage levels of 3.6 kV, 7.2 kV, 12 kV, 36 kV, 72.5 kV, 145 kV and 245 kV. The arc control devices are based on axial-flow and /or cross-flow principle. For higher current ratings, cross flow principle is preferred. The technique of arc quenching in oil circuit breakers is shown below.



In oil circuit breakers, as the contacts separate, the heat of the arc causes the oil to decompose in to hydrogen (70%) acetylene, etc. The gaseous formation causes the pressure inside the arc control device to rise and as a result, the arc is pushed across the side vents, there by elongating it. As the contacts move farther apart lengthening of arc occurs and hence the arc will be extinguished. For a specific design and speed of contracts, the gas pressure generated is a function of arc current and arcing time.

Disadvantages of OCB:

1. Arc products are inflammable.
2. Oil is hygroscopic, and must be sealed air-tight in chamber.
3. Dielectric strength of oil is reduced by carbonization during the arcing process.

Vacuum Circuit Breakers

The separation of current carrying contacts comes the metal vapour to the released from the contacts giving rise to plasma – electrons and positive arc. The vapour density depends up on the current in the arc. In the decreasing phase of the current the rate of release of metal vapour quickly disperses and the medium regains its dielectric strength the arc is thus extinguished in just half a cycle. The contact separation needed is of the order of a few millimetres—least among all circuit Breaker types. VCBs have been employed at voltages up to 72.5 kV.

Air Blast Circuit Breakers (ABCB)

Blast of air at high speeds directed at the arc is very effective in cooing it, and in removing the products of ionization after current zero with consequent arc extinction with in a cycle. The high speed pressure is produced by externally generated pressure. The breaker in designated to direct a jet of air derived from the high pressure source to the contact space at the instant of contact separation. Various possible alternative arrangements for achieving this are shown below.

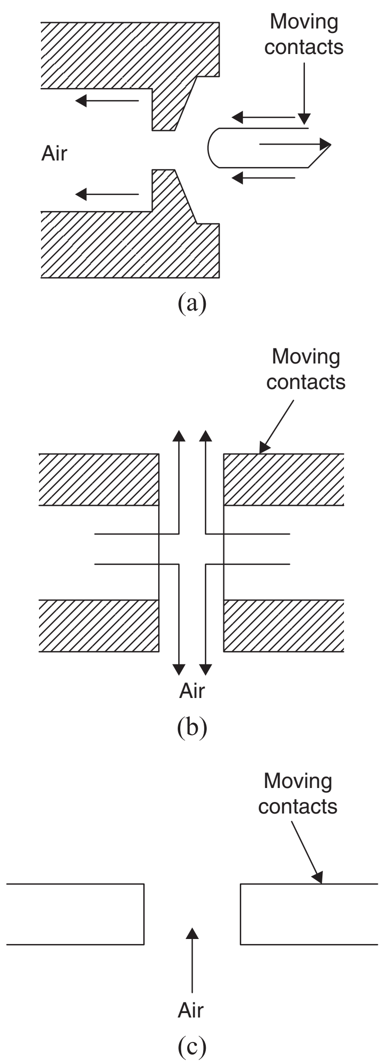


Figure 5 (a) Axial blast with hollow fixed contact; (b) Radial blast; (c) Cross blast

Advantages

- Reliable because an external source is used for arc extinction.
- clean, non-compassable, and non-inflammable.
- Fresh medium is used every time.
- Faster contact travel.
- Small contact travel is involved.

Disadvantages

- High air noise while operating
- Chopping possibility
- Independent pressure system is needed for ABCB.

Sulphur Hexafluoride (SF_6)CB

The attachment of the electron with the natural gas molecules may occur in two ways

$$SF_6 + e^- \rightarrow SF_6^-$$

$$SF_6 + e^- \rightarrow SF_5 + f$$

The negative ions formed are relatively heavier than free electrons and therefore under a given field the ions do not attain sufficient energy to lead cumulative ionization in the gas. This property gives rise to very high dielectric strength of SF_6. The property of SF_6 makes it very effective in quenching arcs.

Advantages

- Current-chopping tendency is minimized.
- There is no exhaust of high-pressure gas to atmosphere.
- There is short time arc, low-contact erosion and no contact replacement.
- No carbon deposition takes place.
- The smaller size of conductors and clearness lead to small overall breaker size.
- They are non-inflammable.

Example 19: Which of the following protection relay is inherently directional?

(A) Reactance relay (B) Impedance relay
(C) OHM relay (D) MHO relay

Solution: (D)

Example 20: Purpose of harmonic restraint in protection transformers is to protect against

(A) Lightning
(B) Unbalanced operation
(C) Switching overvoltages
(D) Magnetizing inrush current

Solution: (D)

Example 21: Reactance relay is mainly used for

(A) Earth faults (B) Open-circuit faults
(C) Phase faults (D) None of the above

Solution: (A)

Example 22: A negative sequence relay is commonly used to protect

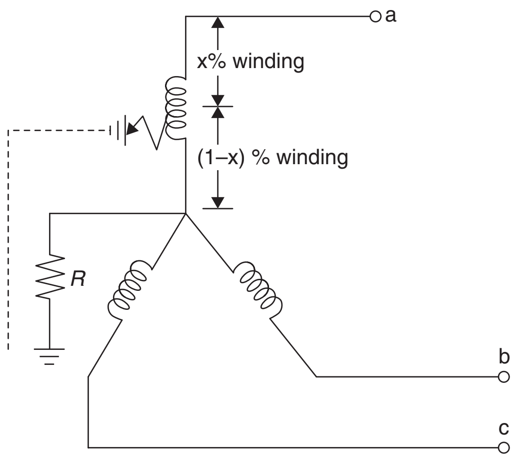
(A) A transformer (B) An alternator
(C) A transmission line (D) A bus bar

Solution: (B)

Example 23: The neutral of 10 MVA, 11 kV, alternator is earthed through a resistance of 5 Ω. The earth fault relay is set to operate at 0.65 A. The CTs have a ratio of 1000/5. What percentage of the alternator winding is protected?

(A) 89.7% (B) 98.3%
(C) 10.3% (D) 1.7%

Solution: Fault current $(I_f) = (1-x)\dfrac{V_{ph}}{R}$



$\therefore$ Primary fault setting current $(I_p) = (1-x)\dfrac{V_{ph}}{R}$

Earthing resistor current setting $(I_s) = \dfrac{V_{ph}}{R}$

$$\therefore \quad I_P = (1-X)I_s$$

$$\Rightarrow \quad x = \left(1 - \frac{I_{ph}}{I_s}\right)$$

$\therefore$ Given that the earth fault relay set current = 0.65 A.

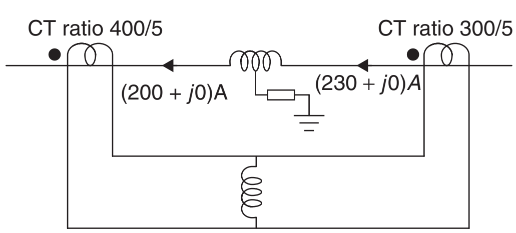
Primary fault setting current $(I_p) = 0.65 \times \dfrac{1000}{5} = 130$ A

Earth resistor current setting I_R

$$= \frac{V_{ph}}{R} = \frac{11000}{\sqrt{3}} \times \frac{1}{5} = 1270.17 \text{ A}$$

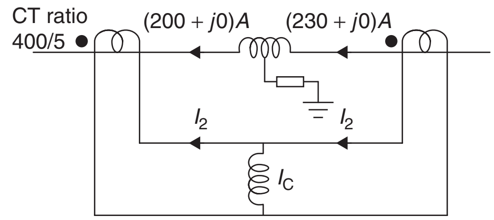
$$\% \text{ of winding protected} = = \left(1 - \frac{130}{1270.17}\right) \times 100 = 89.7\%$$

Example 24: Consider a stator winding of an alternator with an internal high resistance ground fault. The currents under the fault condition are shown in the figure the winding is protected using differential current scheme with current transformer of ratio 300/5 A as shown. The current through the operating coil is



(A) 3.83 A
(B) 3.33 A
(C) 1.33 A
(D) 0.369 A

Solution: (C)



$$I_1 = 200 \times \frac{5}{400} = 2.5 \text{ A}$$

$$I_2 = 230 \times \frac{5}{300} = 3.83$$

$$I_c = I_2 - I_1 = 1.33 \text{ A}$$

Example 25: A 3-ϕ, 33 kV oil-circuit breaker is rated 1100 A, 2000 MVA, 2.5 s. The symmetrical braking current is

(A) 35 kA
(B) 3600 A
(C) 1200 A
(D) 105 A

Solution: (A)

Symmetrical breaking current $= \dfrac{P}{\sqrt{3}V_L}$

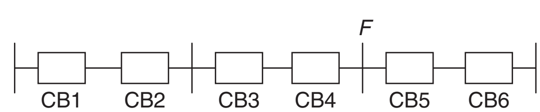
$$= \frac{2000 \times 10^6}{\sqrt{3} \times 33 \times 10^3} = 35 \text{ kA}$$

Example 26: The interrupting time of a circuit breaker is the time period between

(A) Initiation of short circuit and the parting of primary arc contacts.
(B) Energizing of the trip circuit and the parting of primary arc contacts.
(C) Energizing of the trip circuit and the arc extinction on an opening operation.
(D) Initiation of short circuit and the arc extinction on an opening operation.

Solution: (C)

Example 27: Three sections of a feeder are provided with circuit breaker: CB1, CB2, CB3, CB4, CB5, CB6, for a fault 'F' as indicated in the following figure.



(A) CB5 must be set to trip before CB1, CB2, CB3 and CB4 trip.
(B) CB5 must be set to trip after CB1 trip
(C) CB5 must be set to trip after CB2 trips
(D) CB5 must be set to trip after CB2, and CB4 trips

Solution: (A)

Example 28: Resistance switching is normally employed in
(A) Bulk oil breakers
(B) Minimum oil breakers
(C) Air blast circuit breakers
(D) All breakers

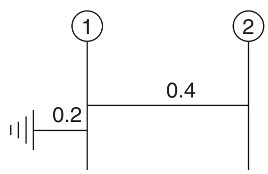
Solution: (D)

Exercises

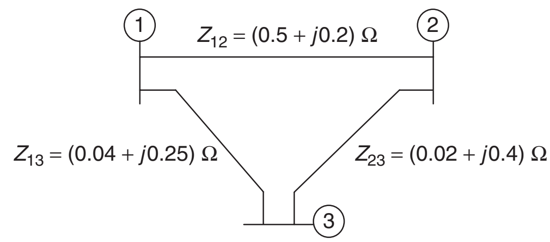
Practice Problems I

Directions for questions 1 to 22: Select the correct alternative from the given choices.

1. In power flow analysis, a load connected at a bus acts as
   (A) Constant impedance connected at the bus
   (B) Voltage and frequency dependent source at the bus.
   (C) Constant real and reactive power drawn from the bus
   (D) Constant current drawn from the bus
2. A system has two buses marked 1 and 2. The per unit impedances are also marked. The bus admittance matrix is



   (A) $\begin{bmatrix} 0.6 & 0.4 \\ 0.4 & 0.4 \end{bmatrix}$ (B) $\begin{bmatrix} 7.5 & 2.5 \\ 2.5 & 2.5 \end{bmatrix}$
   (C) $\begin{bmatrix} 0.6 & -0.4 \\ -0.4 & 0.4 \end{bmatrix}$ (D) $\begin{bmatrix} 7.5 & -2.5 \\ -2.5 & 7.5 \end{bmatrix}$
3. The load flow studies is performed using Y bus matrix rather than Z bus matrix. This is because
   (A) Y bus is a square matrix
   (B) Y bus is a sparse matrix
   (C) Z bus is a sparse matrix
   (D) Z bus is a singular matrix
4. The number of iterations required for solving load flow problems in Gauss Seidel and Newton–Raphson methods is
   (A) Both directly proportional to number of buses
   (B) Directly proportional to number of buses and independent of number of buses, respectively
   (C) Independent of number of buses and directly proportional to number of buses, respectively
   (D) both independent of the number of system
5. The value of $\boldsymbol{Y}11$ of the bus admittance matrix of the network is



   (A) $1.8 - j8.6$ (B) $1.3 - j7.2$
   (C) $1.8 + j8.6$ (D) $1.3 + j7.2$
6. Two alternators in parallel supplying a total load of 75 MW have the following data:
   Machine 1: 50 MVA with 4% speed regulation
   Machine 2: 70 MVA with 5% speed regulation
   The load shared between machines 1 and 2 is
   (A) $P_1 = 50$ MW, $P_2 = 25$ MW
   (B) $P_1 = 25$ MW, $P_2 = 50$ MW
   (C) $P_1 = 40$ MW, $P_2 = 35$ MW
   (D) $P_1 = 35$ MW, $P_2 = 40$ MW
7. Two generators delivering a total of 220 MW have their incremental cost characteristics as follows
   $$\frac{dF_1}{dP_1} = 1 + 0.15P_1$$
   $$\frac{dF_2}{dP_2} = 4.0 + 0.1P_2$$
   For economic operation P_1 and P_2 should be
   (A) $P_1 = 120$ MW, $P_2 = 100$ MW
   (B) $P_1 = 100$ MW, $P_2 = 120$ MW
   (C) $P_1 = 80$ MW, $P_2 = 140$ MW
   (D) $P_1 = 140$ MW, $P_2 = 80$ MW
8. The most inappropriate among the disadvantages of Gauss–Seidel method of load flow solution is
   (A) Slow convergence
   (B) Unreliable convergence
   (C) A good initial guess is essential for convergence.
   (D) Choice of slack bus affects convergence
9. For the Y bus matrix of a 4-bus system given in per unit, the buses having shunt elements are,
   $$Y_{BUS} = j\begin{bmatrix} -5 & 2 & 2.5 & 0 \\ 2 & -10 & 2.5 & 4 \\ 2.5 & 2.5 & -9 & 4 \\ 0 & 4 & 4 & -8 \end{bmatrix}$$

(A) 3 and 4 (B) 2 and 3
(C) 1 and 2 (D) 1, 2 and 4

10. If the equation $x^2 - 500 = 0$ is to be solved using Newton–Raphson method, the iterative steps involved is

(A) $x_{R+1} = x_R + \dfrac{500}{x_R}$ (B) $x_{R+1} = \dfrac{1}{2}\left(x_R + \dfrac{500}{x_R}\right)$

(C) $x_{R+1} = \dfrac{1}{2}\left(x_R - \dfrac{500}{x_R}\right)$ (D) $x_{R+1} = x_R - \dfrac{500}{x_R}$

11. The equation $e^x - 1 = 0$ is to be solved using Newton–Raphson method with initial guess $x_0 = 1$ After one step, estimate x of solution is given by
(A) 0.36788 (B) 0.71828
(C) 0.20587 (D) 0.0000

12. The specified variables in a slack bus are
(A) Active power demand and reactive power demand at the bus
(B) Active power demand and magnitude of voltage at the bus
(C) Reactive power demand and phase angle of the voltage
(D) Magnitude of the voltage and phase angle of the voltage

Common Data for Questions 13 and 14:
The fuel cost of a system having two plants are given by

$$C_1 = (100 + 2P_1 + 0.005P_1^2) \text{ Rupees}$$
$$C_2 = (100 + 2P_2 + 0.01P_2^2) \text{ Rupees}$$

where P_1 and P_2 are in MW.

The loss coefficients are

$$B_{11} = 0.1 \times 10^{-2} \text{ MW}^{-1}$$
$$B_{12} = -0.09 \times 10^{-2} \text{ MW}^{-1}$$
$$B_{22} = 0.09 \times 10^{-2} \text{ MW}^{-1}$$

13. If the system supplies a load of 600 MW, the scheduling of two plants will be
(A) $P_1 = 266.7$ MW, $P_2 = 333.3$ MW
(B) $P_1 = 333.3$ MW, $P_2 = 266.7$ MW
(C) $P_1 = 400$ MW, $P_2 = 200$ MW
(D) $P_1 = 200$ MW, $P_2 = 400$ MW

14. The penalty factor of plant 1 is
(A) 1.79 (B) 1.92 (C) 1.25 (D) 1.36

15. The instantaneous value of current interrupted is 8 A. If the inductance and capacitance of a system are 2.0 H and 0.025 μF, voltage across the breaker contacts will be
(A) 71.55 V (B) 71.55 kV
(C) 5.155 kV (D) 715.5 kV

16. A10 A, 3 second overcurrent relay having a current setting of 125% and a time setting multiplier of 0.4 is connected to supply circuit through a 400/10 current transformer. When the circuit carries a fault current of 4000 A, operating time is?
Given

PSM	4	6	8	1	0
TSM	2.8	3.2	3.5	1.2	0.8

(A) 1.4 s (B) 2.2 s (C) 3.6 s (D) 4.25 s

17. A percentage differential relay is employed for protecting a 80 MVA, 110/66 kV, Δ/Y, three-phase power transformer.
The ratios of primary and secondary currents in the CT's located in delta and wye side of power transformer are 400/10 A and 1100/10 A, respectively. The relay current at full load is
(A) −0.5219 A (B) 0.12 A
(C) 0.68 A (D) 6.5 A

18. The bus bars of a power station are in two sections P and Q separated by a reactor. Section P has a 20 MVA generator of 10% reactance and Q has two generators; one is 25MVA with 13% reactance and other 10 MVA with 8% reactance. Feeders are connected to bus bars through transformers, each rated 10 MVA and 6% reactance. Maximum short-circuit MVA with which the circuit breakers on the outgoing side of the transformers have to deal [The reactor is rated at 15MVA and 16% reactance] is
(A) 150 MVA (B) 163 MVA
(C) 180 MVA (D) 100 MVA

19. For a 132 kV system, the inductive reactance and capacitance up to the location of circuit breaker is 10 Ω and 0.06 μF.
A resistance of 300 Ω is connected across the contacts. The value of resistance which will give damped frequency of oscillation of 1/4th natural frequency
(A) 128.65 Ω (B) 363.37 Ω
(C) 280.56 Ω (D) 500.08 Ω

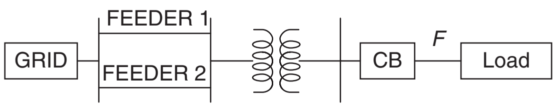
20. A 50 Hz three-phase alternator with grounded neutral has an inductance of 1.4 mH per phase and is connected to the bus bars through a circuit breaker. The capacitance to earth of the circuit between the alternator and CB is 0.00165 μF per phase. Time to attain maximum RRRV is
(A) 1.85 (B) 2.38 μs
(C) 1.75 μs (D) 3.55 μs

21. Consider grid as infinite bus. Choose 10 MVA as base
Transformer: Three-phase 66/33 kV, 10 MVA,

$$0.02 + j0.06 \text{ p.u. impedance}$$

Load: Three-phase, 11 kV, 6000 kVA, 0.8 lag, $j0.6$ p.u. impedance.
Impedance of each feeder $= 8 + j16$ Ω.

The required MVA rating of CB is



(A) 35.714 MVA (B) 25.65 MVA
(C) 10.5 MVA (D) 8.82 MVA

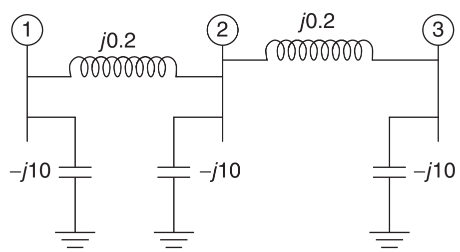
22. In a short-circuit test on a circuit breaker, time to reach the peak restriking voltage is 85 ms and the peak restriking voltage is 150 kV. The average rate of rise of restriking voltage is
(A) 1.76 kV/μS (B) 2.08 kV/μS
(C) 0.82 kV/μS (D) 5.04 kV/μS

Practice Problems 2

Directions for questions 1 to 15: Select the correct alternative from the given choices.

1. The power generated by two plants are $P_1 = 80$ MW and $P_2 = 100$ MW
If the loss coefficients are $B_{11} = 0.002$, $B_{22} = 0.004$ and $B_{12} = -0.0008$
The power loss is
(A) 12.0 MW (B) 16.4 MW
(C) 15.4 MW (D) 10.0 MW

2. The network shown in the figure has impedances in p.u. as indicated. The diagonal element Y_{22} of the bus admittance matrix Y bus of the network is

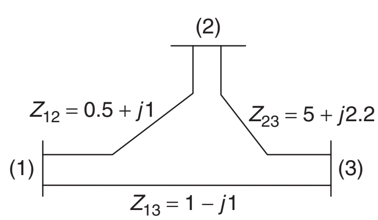


(A) $-j9.6$ (B) $+j0.104$
(C) $+j9.9$ (D) $-j9.9$

3. If X is the reactance of a line and R is the resistance of the line, the power transferred is maximum when
(A) $X = R$ (B) $X = 2R$
(C) $X = \sqrt{3}R$ (D) $X = \sqrt{2}R$

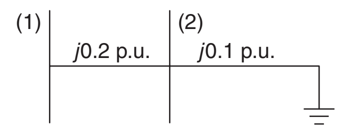
4. The fuel cost of two or more plants operating in parallel is minimum when
(A) The penalty factor of each plant is the same.
(B) Incremental fuel cost of each plant is the same.
(C) The incremental fuel cost multiplied by its penalty factor for each plant is the same.
(D) Ratio of incremental fuel cost to penalty factor of each plant is the same.

5. The value of Y_{11} of the bus admittance matrix for the network shown is



(A) $0.9 - j0.3$ (B) $0.1 - j0.3$
(C) $1 - j0.3$ (D) $0.9 - j0.8$

6. The bus admittance matrix for the network shown below is



(A) $\begin{bmatrix} j5 & j5 \\ j5 & -j13 \end{bmatrix}^{-1}$ (B) $\begin{bmatrix} j5 & j5 \\ j5 & -j15 \end{bmatrix}$

(C) $\begin{bmatrix} j0.2 & j0.1 \\ -j0.2 & -j0.1 \end{bmatrix}$ (D) $\begin{bmatrix} j10 & -j15 \\ j5 & j15 \end{bmatrix}$

7. For a generator rated at 30 MVA, 22 kV, 3-cycle circuit breaker is employed. The interrupting current is [Take $X_d' = 30\%$, $E_g = 1$ p.u.]
(A) 4.8 kA (B) 3.15 kA
(C) 5.6 A (D) None of these

8. For a relay, the operating speed depends upon,
(A) Spring tension
(B) Armature core air gap
(C) Rate of flux build-up
(D) All of these

9. For a system, the normal line current is 120 A. The circuit is designed to operate at 125% of normal line current and the trip coil is connected through a CT of ratio of 100:1. The trip mechanism should be set to operate at
(A) 1.5 A (B) 2.5 A
(C) 1.2 A (D) 2 A

10. For universal relays, the torque equation is
(A) $K_3 VI\cos(\theta - \delta)$ (B) $K_1 I^2 - K_2 V^2$
(C) $\dfrac{V}{I} = \sqrt{\dfrac{K_1}{K_2}}$ (D) None of these

11. The relay which is operated depending on the ratio of applied voltage to current is
(A) Distance relay
(B) Impedance relay
(C) Induction type overcurrent relay
(D) Both (B) and (A)

12. The shunt resistance connected across the breaker contacts

(1) Modifies the oscillatory restriking voltage to a periodic wave.

(2) Should have a value of $\frac{1}{2}\sqrt{\frac{L}{C}}$ for critical damping.

(3) RRRV will be increased

(4) Results in increase in rupturing capacity

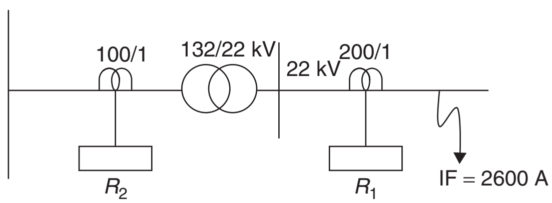
Which of the statements is correct?

(A) 1, 2 (B) 1, 2 and 3
(C) 1, 2 and 4 (D) 1, 2, 3 and 4

13. Maximum value of restriking voltage for a 132 kV system with 3 Ω reactance is

(A) 126.5 V (B) 180.5 kV
(C) 215.55 kV (D) 208.56 kV

14. Fault current level at 22 kV side is 2600 A; CT ratio at 22 kV side is 200:1 and 132 kV side is 100:1. Two relays shown in the figure are set at 125% plug setting. The time of operation of relay R_1 when the time grading margin is 0.6 s and TMs for relay 1150.15 is



Given: relay characteristic curve

PSM:	1.3	2	4	8	10	20
TSM:	30	10	5	3.3	3	2.2

(A) 0.68 s (B) 0.25 s
(C) 1.8 s (D) 0.39 s

15. Which of the following are correct?

(1) Relay time is the interval between the occurrence of the fault and up to the activated signal given to circuit breaker.

(2) Time interval between closure of trip circuit and final arc extinction is called breaker time.

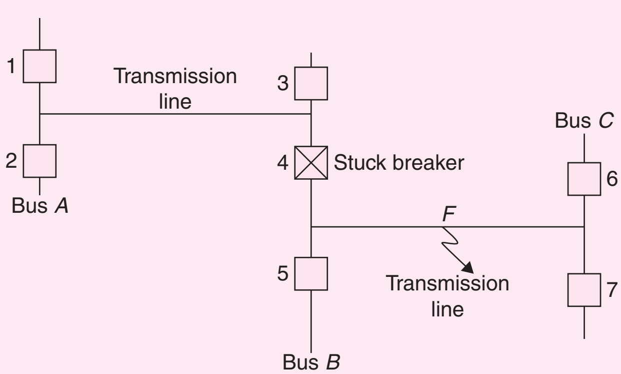
(3) Time elapsed between the instant of occurrence of fault and final arc extinction is called fault clearing time.

(4) Time during which stored energy is dissipated after the characteristic quantity has beensuddenly restored is reset time

(A) 1, 2
(B) 1, 2 and 3
(C) 1 and 3
(D) 1, 2 and 4

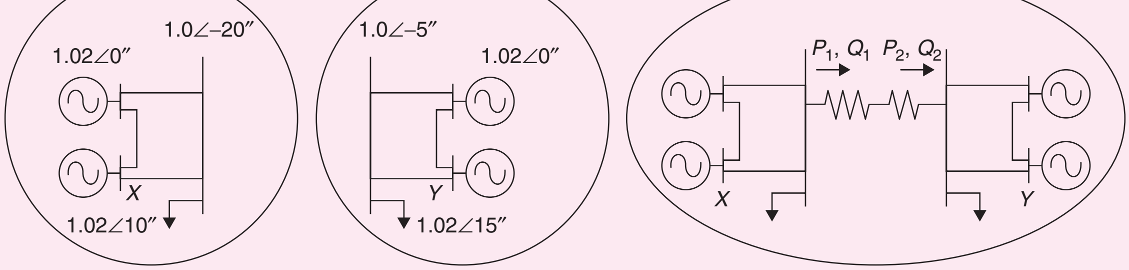
Previous Years' Questions

1. Consider the protection system shown in the figure below. The circuit breakers, numbered from 1 to 7 are of identical type. A single line to ground fault with zero fault impedance occurs at the midpoint of the line (at point F), but circuit breaker 4 fails to operate ('stuck breaker'). If the relays are coordinated correctly, a valid sequence of circuit breaker operations is **[2007]**



(A) 1, 2, 6, 7, 3, 5
(B) 1, 2, 5, 6, 7, 3
(C) 5, 6, 7, 3, 1, 2
(D) 5, 1, 2, 3, 6, 7

2. Consider the two power systems shown in figure A below, which are initially not interconnected, and are operating in steady state at the same frequency. Separate load flow solutions are computed individually for the two systems, corresponding to the scenario. The bus voltage phasors so obtained are indicated on figure A. These two isolated systems are now interconnected by a short transmission line as shown in figure B, and it is found that $P_1 = P_2 = Q_1 = Q_2 = 0$: **[2007]**



The bus voltage phase angular difference between generator bus X and generator bus Y after the inter-connection is

(A) 10° (B) 25° (C) –30° (D) 30°

3. A lossless power system has to serve a load of 250 MW. There are two generators (G_1 and G_2) in the system with cost curves C_1 and C_2, respectively, defined as follows

$C_1(P_{G1}) = P_{G1} + 0.055 \times P_{G1}^2$

$C_2(P_{G2}) = 3P_{G2} + 0.03 \times P_{G2}^2$

where P_{G1} and P_{G2} are the MW injections from generator G_1 and G_2, respectively. Then the minimum cost dispatch will be **[2008]**

(A) $P_{G1} = 250$ MW; $P_{G2} = 0$ MW
(B) $P_{G1} = 150$ MW; $P_{G2} = 100$ MW
(C) $P_{G1} = 100$ MW; $P_{G2} = 150$ MW
(D) $P_{G1} = 0$ MW; $P_{G2} = 250$ MW

4. For the Y-bus matrix of a 4-bus system given in per unit, the buses having shunt elements are Y_{BUS} =

$$j\begin{bmatrix} -5 & 2 & 2.5 & 0 \\ 2 & -10 & 2.5 & 4 \\ 2.5 & 2.5 & -9 & 4 \\ 0 & 4 & 4 & -8 \end{bmatrix}$$ **[2009]**

(A) 3 and 4 (B) 2 and 3
(C) 1 and 2 (D) 1,2 and 4

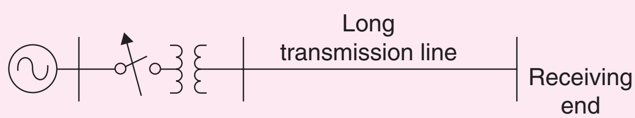
5. A 500 MW, 21 kV, 50 Hz, three-phase, 2-pole synchronous generator having a rated p.f. = 0.9, has a moment of inertia of 27.5×10^3 kg-m^2. The inertia constant (H) will be **[2009]**

(A) 2.44 s (B) 2.71 s
(C) 4.88 s (D) 5.42 s

6. Voltage phasors at the two terminals of a transmission line of length 70 km have a magnitude of 1.0 per unit but are 180 degrees out of phase. Assuming that the maximum load current in the line is $\frac{1}{5}$ th of minimum three-phase fault current, which one of the following transmission line protection schemes will NOT pick up for this condition? **[2008]**

(A) Distance protection using mho relays with zone-1 set to 80% of the line impedance
(B) Directional overcurrent protection set to pick up at 1.25 times the maximum load current
(C) Pilot relaying system with directional comparison scheme
(D) Pilot relaying system with segregated phase comparison scheme

7. A 50 Hz synchronous generator is initially connected to a long lossless transmission line which is open-circuited at the receiving end. With the field voltage held constant, the generator is disconnected from the transmission line. Which of the following may be said about the steady state terminal voltage and field current of the generator? **[2010]**



(A) The magnitude of terminal voltage decreases, and the field current does not change.
(B) The magnitude of terminal voltage increases, and the field current does not change.
(C) The magnitude of terminal voltage increases, and the field current increases.
(D) The magnitude of terminal voltage does not change, and the field current decreases.

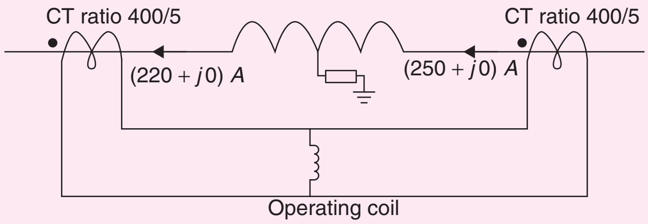
8. Consider two buses connected by an impedance of $(0 + j5)\ \Omega$. The bus 1 voltage is $100\angle 30°$ V, and bus 2 voltage is $100\angle 0°$ V. The real and reactive powers supplied by bus 1, respectively, are **[2010]**

(A) 1000 W, 268 VAr (B) –1000 W, –134 Var
(C) 276.9 W, –56.7 Var (D) –276.9 W, 56.7 Var

9. A three-phase, 33 kV oil-circuit breaker is rated 1200 A, 2000 MVA, 3 s. The symmetrical breaking current is **[2010]**

(A) 1200 A (B) 3600 A
(C) 35 kA (D) 104.8 kA

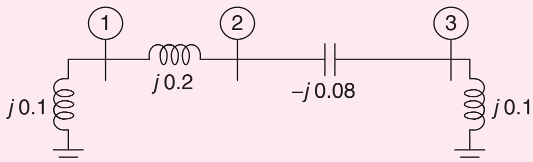
10. Consider a stator winding of an alternator with an internal high-resistance ground fault. The currents under the fault condition are as shown in the figure. The winding is protected using a differential current scheme with current transformers of ratio 400/5 A as shown. The current through the operating coil is **[2010]**



(A) 0.17875 A (B) 0.2 A
(C) 0.375 A (D) 60 KA

11. A negative sequence relay is commonly used to protect **[2011]**
(A) An alternator (B) A transformer
(C) A transmission line (D) A busbar

12. A three-bus network is shown in the figure below indicating the p.u. impedances of each element. **[2011]**



The bus admittance matrix, Y-bus of the network is

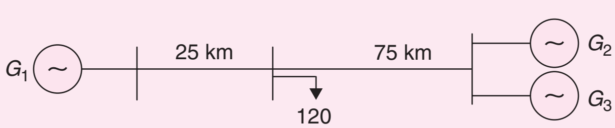
(A) $j\begin{bmatrix} 0.3 & 0.2 & 0 \\ -0.2 & 0.12 & 0.08 \\ 0 & 0.08 & 0.02 \end{bmatrix}$

(B) $j\begin{bmatrix} -15 & 5 & 0 \\ 5 & 7.5 & -12.5 \\ 0 & 12.5 & 2.5 \end{bmatrix}$

(C) $j\begin{bmatrix} 0.1 & 0.2 & 0 \\ 0.2 & 0.12 & -0.08 \\ 0 & -0.08 & 0.10 \end{bmatrix}$

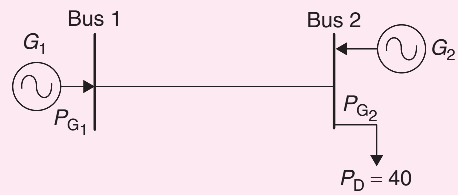
(D) $j\begin{bmatrix} 10 & 5 & 0 \\ 5 & 7.5 & 12.5 \\ 0 & 12.5 & -10 \end{bmatrix}$

13. A load centre of 120 MW derives power from two power stations connected by 220 kV transmission lines of 25 km and 75 km as shown in the figure below. The three generators G_1, G_2 and G_3 are of 100 MW capacity each and have identical fuel cost characteristics. The minimum loss generation schedule for supplying the 120 MW load is **[2011]**



(A) P_1 = 80 MW + losses
P_2 = 20 MW
P_3 = 20 MW
(B) P_1 = 60 MW
P_2 = 30 MW + losses
P_3 = 30 MW
(C) P_1 = 40 MW
P_2 = 40 MW
P_3 = 40 MW + losses
(D) P_1 = 30 MW + losses
P_2 = 45 MW
P_3 = 45 MW

14. The figure shows a two-generator system supplying a load of P_D = 40 MW, connected at bus 2.



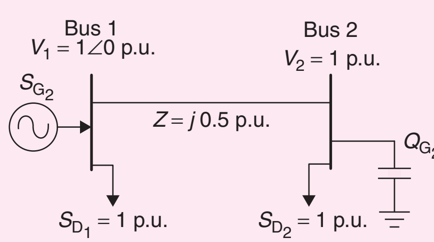
The fuel cost of generators G_1 and G_2 are:
$C_1(P_{G1})$ = 10,000 Rs/MWh and $C_2(P_{G2})$ = 12,500 Rs/MWh and the loss in the line is $P_{loss(p.u.)} = 0.5\,P^2_{G1(p.u.)}$, where the loss coefficient is specified in p.u. on a 100 MVA base. The most economic power generation schedule in MW is **[2012]**
(A) $P_{G1} = 20$, $P_{G2} = 22$
(B) $P_{G1} = 22$, $P_{G2} = 20$
(C) $P_{G1} = 20$, $P_{G2} = 20$
(D) $P_{G1} = 0$, $P_{G2} = 40$

15. The bus admittance matrix of a three-bus-line system is

$$Y = j\begin{bmatrix} -13 & 10 & 5 \\ 10 & -18 & 10 \\ 5 & 10 & -13 \end{bmatrix}$$

If each transmission line between the two buses is represented by an equivalent π-network, the magnitude of the shunt susceptance of the line connecting bus 1 and 2 is **[2012]**
(A) 4 (B) 2
(C) 1 (D) 0

16. For the system shown below, S_{D1} and S_{D2} are complex power demands at bus 1 and bus 2, respectively. If $|V_2| = 1$ p.u., the VAR rating of the capacitor (Q_{G2}) connected at bus 2 is **[2012]**



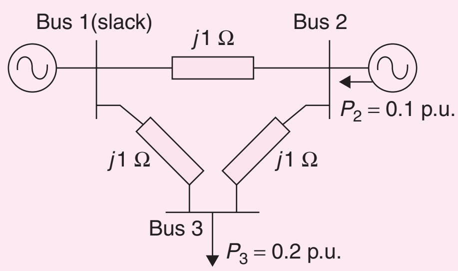
(A) 0.2 p.u. (B) 0.268 p.u.
(C) 0.312 p.u. (D) 0.4 p.u.

17. For a power system network with n nodes, Z_{33} of its bus impedance matrix is $j0.5$ per unit. The voltage at node 3 is $1.3\ \angle -10^{\circ}$ per unit. If a capacitor having reactance of $-j3.5$ per unit is now added to the network between node 3 and the reference node, the current drawn by the capacitor per unit is **[2013]**

(A) $0.325\ \angle -100^{\circ}$ (B) $0.325\angle 80^{\circ}$
(C) $0.371\ \angle -100^{\circ}$ (D) $0.433\angle 80^{\circ}$

Common Data for Questions 18 and 19:

In the following network, the voltage magnitudes at all buses are equal to 1 p.u., the voltage phase angles are very small, and the line resistance are negligible. All the line reactances are equal to $j1\ \Omega$.



18. The voltage-phase angles in radians at buses 2 and 3 are **[2013]**

(A) $\theta_2 = -0.1,\ \theta_3 = -0.2$ (B) $\theta_2 = 0,\ \theta_3 = -0.1$
(C) $\theta_2 = 0.1,\ \theta_3 = 0.1$ (D) $\theta_2 = 0.1,\ \theta_3 = 0.2$

19. If the base impedance and the line-to-line base voltage are 100 Ω and 100 kV, respectively, then the real power in MW delivered by the generator connected at the slack bus is **[2013]**

(A) −10 (B) 0 (C) 10 (D) 20

20. The fuel cost functions of two power plants are

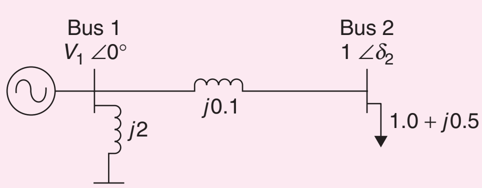
Plant P_1: $C_1 = 0.05\ P_{g_1}^2 + AP_{g1} + B$

Plant P_2: $C_2 = 0.10\ P_{g_2}^2 + 3AP_{g2} + 2B$

where P_{g1} and P_{g2} are the generated powers of two plants, and A and B are the constants. If the two plants optimally share 1000 MW load at incremental fuel cost of 100 Rs/MWh, the ratio of load shared by plants P_1 and P_2 is **[2014]**

(A) 1:4 (B) 2:3
(C) 3:2 (D) 4:1

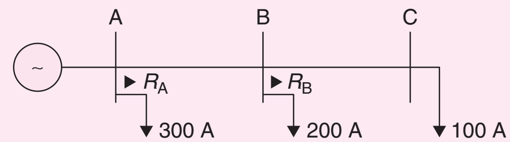
21. A two-bus power system shown in the figure supplies load of $1.0 + j0.5$ p.u.



The values of V_1 in p.u. and δ_2, respectively, are **[2014]**

(A) 0.95 and 6.00° (B) 1.05 and −5.44°
(C) 1.1 and −6.00° (D) 1.1 and −27.12°

22. The overcurrent relays for the line protection and loads connected at the buses are shown in the figure.



The relays are IDMT in nature having the characteristic

$$t_{op} = \frac{0.14 \times \text{Time Multiplier Setting}}{(\text{Plug Setting Multiplier})^{0.02} - 1}$$

The maximum and minimum fault currents at bus B are 2000 A and 500 A, respectively. Assuming the time multiplier setting and plug setting for relay R_B to be 0.1 and 5 A, respectively, the operating time of R_B (in seconds) is______ **[2014]**

23. A 183-bus power system has 150 PQ buses and 32 PV buses. In the general case, to obtain the load flow solution using Newton–Raphson method in polar coordinates, the minimum number of simultaneous equations to be solved is _______. **[2014]**

24. Consider the economic dispatch problem for a power plant having two generating units. The fuel costs in Rs/MWh along with the generation limits for the two units are given below: **[2015]**

$C_1(P_1) = 0.01\ P_1^2 + 30P_1 + 10;\ 100\text{ MW} \le P_1 \le 150$ MW

$C_2(P_2) = 0.05\ P_2^2 + 10P_2 + 10;\ 100\text{ MW} \le P_2 \le 180$ mW

The incremental cost (in Rs/MWh) of the power plant when it supplies 200 MW is _______.

24. Determine the correctness or otherwise of the following Assertion [*a*] and the Reason [*r*].

Assertion: Fast decouples load flow method gives approximate load flow solution because it uses several assumptions.

Reason: Accuracy depends on the power mismatch vector tolerance. **[2015]**

(A) Both [*a*] and [*r*] are true and [*r*] is the correct reason for [*a*].
(B) Both [*a*] and [*r*] are true but [*r*] is not the correct reason for [*a*].
(C) Both [*a*] and [*r*] are false.
(D) [*a*] is false and [*r*] is true.

26. A 3-bus power system network consists of 3 transmission lines. The bus admittance matrix of the uncompensated system is

$$\begin{bmatrix} -j6 & j3 & j4 \\ j3 & -j7 & j5 \\ j4 & j5 & -j8 \end{bmatrix} \text{pu.}$$

If the shunt capacitance of all transmission lines is 50% compensated, the imaginary part of the 3rd row 3rd column element (in pu) of the bus admittance matrix after compensation is **[2015]**

(A) $-j7.0$ (B) $-j8.5$
(C) $-j7.5$ (D) $-j9.0$

27. The incremental costs (in Rupees/MWh) of operating two generating units are functions of their positive powers P_1 and P_2 in MW, and are given by

$$\frac{dC_1}{dP_1} = 0.2P_1 + 50$$

$$\frac{dC_2}{dP_2} = 0.24P_2 + 40$$

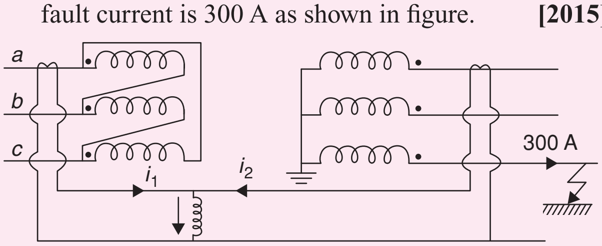
Where

$20 \text{ MW} \le P_1 \le 150 \text{ MW}$

$20 \text{ MW} \le P_2 \le 150 \text{ MW}.$

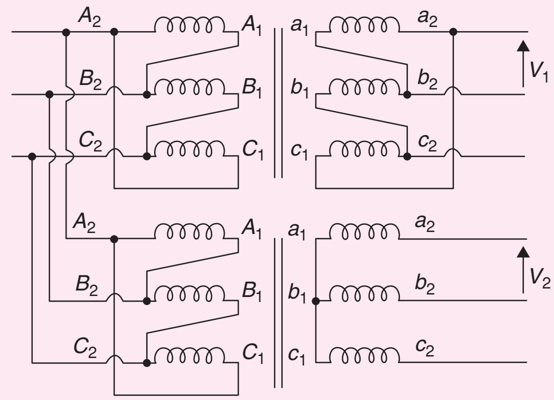
For a certain load demand, P_1 and P_2 have been chosen such that dC_1/dP_1 = 76 Rs/MWh and dC_2/dP_2 = 68.8 ₹/MWh. If the generations are rescheduled to minimize the total cost, then P_2 is ______. **[2015]**

28. A 3-kphase transformer rated for 33 kV/11 kV is connected in delta/star as shown in figure. The current transformers (CTs) on low and high voltage sides have a ratio of 500/5. Find the currents i_1 and i_2, if the fault current is 300 A as shown in figure. **[2015]**



(A) $i_1 = 1/\sqrt{3}$ A, $i_2 = 0$ A
(B) $i_1 = 0$ A, $i_2 = 0$ A
(C) $i_1 = 0$ A, $i_2 = 1/\sqrt{3}$ A
(D) $i_1 = 1\sqrt{3}$ A, $i_2 = 1/\sqrt{3}$ A

29. Two three-phase transformers are realized using single-phase transformers as shown in the figure.

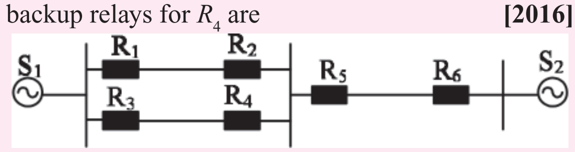


The phase difference (in degree) between voltages V_1 and V_2 is ______. **[2015]**

30. In a 100 bus power system, there are 10 generators. In a particular iteration of Newton Raphson load flow technique (in polar coordinates), two of the PV buses are converted to PQ type. In this iteration, **[2016]**

(A) the number of unknown voltage angles increases by two and the number of unknown voltage magnitudes increases by two.
(B) the number of unknown voltage angles remains unchanged and the number of unknown voltage magnitudes increases by two.
(C) the number of unknown voltage angles increases by two and the number of unknown voltage magnitudes decreases by two.
(D) the number of unknown voltage angles remains unchanged and the number of unknown voltage magnitudes decreases by two.

31. A power system with two generators is shown in the figure below. The system (generators, buses and transmission lines) is protected by six over current relays R_1 to R_6. Assuming a mix of directional and non directional relays at appropriate locations, the remote backup relays for R_4 are **[2016]**



(A) R_1, R_2 (B) R_2, R_6
(C) R_2, R_5 (D) R_1, R_6

32. A power system has 100 buses including 10 generator buses, for the load flow analysis using Newton – Raphson, method in polar coordinates, the size of the Jacobian is **[2016]**

(A) 189×189 (B) 100×100
(C) 90×90 (D) 180×180

Answer Keys

Exercises

Practice Problems 1

1. C	**2.** D	**3.** B	**4.** B	**5.** A	**6.** B	**7.** B	**8.** C	**9.** C	**10.** B
11. A	**12.** D	**13.** C	**14.** A	**15.** B	**16.** A	**17.** A	**18.** B	**19.** B	**20.** B
21. A	**22.** A								

Practice Problems 2

1. D	**2.** D	**3.** C	**4.** C	**5.** A	**6.** B	**7.** B	**8.** D	**9.** A	**10.** A
11. D	**12.** C	**13.** C	**14.** C	**15.** B					

Previous Years' Questions

1. C	**2.** A	**3.** C	**4.** C	**5.** A	**6.** A	**7.** B	**8.** A	**9.** C	**10.** C
11. A	**12.** B	**13.** A	**14.** A	**15.** B	**16.** B	**17.** D	**18.** B	**19.** C	**20.** D
21. B	**22.** 0.23	**23.** 332	**24.** 20	**25** D	**26.** B	**27.** 135 to 137		**28.** A	**29.** 30
30. B	**31.** D	**32.** A							