



NRI INSTITUTE OF TECHNOLOGY
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POWER SYSTEM ANALYSIS
III BTECH II SEM EEE

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**DEPARTMENT OF ELECTRICAL & ELECTRONICS
ENGINEERING**

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POWER SYSTEM ANALYSIS SYLLABUS

UNIT I:

POWER SYSTEM NETWORK MATRICES: Bus Incidence Matrix, Y-bus formation by Direct and Singular Transformation Methods, Numerical Problems.

FORMATION OF Z-BUS: Partial network, Algorithm for the Modification of Z Bus Matrix for addition element for the following cases: Addition of element from a new bus to reference, Addition of element from a new bus to an old bus, Addition of element between an old bus to reference and addition of element between two old buses (Derivations and Numerical Problems) - Modification of Z Bus for the changes in network (Numerical Problems).

UNIT II:

POWER FLOW STUDIES - I: Necessity of Power Flow Studies– Data for Power Flow Studies – Derivation of Static load flow equations. Load Flow Solutions Using Gauss Seidel Method: Acceleration Factor, Load flow solution with and without P-V buses, Algorithm and Flowchart. Numerical Load flow Solution for Simple Power Systems (Max. 3-Buses): Determination of Bus Voltages, Injected Active and Reactive Powers (Sample One Iteration only) and finding Line Flows/Losses for the given Bus Voltages.

UNIT III:

POWER FLOW STUDIES - II: Newton Raphson Method: Load Flow Solution with or without PV Buses- Derivation of Jacobian Elements, Algorithm and Flowchart. Decoupled and Fast Decoupled Methods. Comparison of Different Methods – DC load Flow.

UNIT IV:

SHORT CIRCUIT ANALYSIS - I: Per-Unit system of representation, Per-unit equivalent reactance network of a three phase power system, Numerical Problems. Symmetrical Fault Analysis: Short Circuit Current and MVA Calculations, Fault levels. Symmetrical Component Theory: Symmetrical Component Transformation, Positive, Negative and Zero sequence components: Voltages, Currents and Impedances. Sequence Networks: Positive, Negative and Zero sequence Networks, Numerical Problems

UNIT V:

SHORT CIRCUIT ANALYSIS -II: Unsymmetrical Fault Analysis: LG, LL, LLG faults with and without fault impedance, Numerical Problems.

STABILITY ANALYSIS: Derivation of Swing Equation, Determination of Transient Stability by Equal Area Criterion and its applications. Methods to improve transient Stability. **(Qualitative Treatment only)**

TEXT BOOKS:

1. Power system Analysis Operation and control, Abhijit Chakrabarthy, Sunita Halder, 3rd edition, PHI,2010.
2. Modern Power system Analysis – by I.J.Nagrath & D.P.Kothari: Tata McGraw-Hill Publishing Company, 2nd edition.
3. Electrical power systems - by C.L Wadhwa, New Age International (P) Limited, Publishers, 1998.



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REFERENCE BOOKS:

1. Computer Techniques in Power System Analysis by M.A.Pai, TMH Publications
2. Power System Analysis by Grainger and Stevenson, Tata McGraw Hill.
3. Computer techniques and models in power systems, By K.Uma rao, I.K.International
4. Power System Analysis by Hadi Saadat – TMH Edition.

COURSE OUTCOMES:

After this course, the student will be able to

- Develop the Y bus and Z bus matrices
- Develop load flow programs
- Understand the importance of short circuit studies
- Understand stability and instability power systems



UNIT-1 POWER SYSTEM NETWORK MATRICES

1. FORMATION OF Y_{BUS} AND Z_{BUS}

The bus admittance matrix, Y_{BUS} plays a very important role in computer aided power system analysis. It can be formed in practice by either of the methods as under:

1. Rule of Inspection
2. Singular Transformation
3. Non-Singular Transformation
4. Z_{BUS} Building Algorithms, etc.

The performance equations of a given power system can be considered in three different frames of reference as discussed below:

Frames of Reference:

Bus Frame of Reference: There are b independent equations (b = no. of buses) relating the bus vectors of currents and voltages through the bus impedance matrix and bus admittance matrix:

$$E_{BUS} = Z_{BUS} I_{BUS} \quad I_{BUS} = Y_{BUS} E_{BUS}$$

Branch Frame of Reference: There are b independent equations (b = no. of branches of a selected Tree sub-graph of the system Graph) relating the branch vectors of currents and voltages through the branch impedance matrix and branch admittance matrix:

$$E_{BR} = Z_{BR} I_{BR} \quad I_{BR} = Y_{BR} E_{BR}$$

Loop Frame of Reference: There are b independent equations (b = no. of branches of a selected Tree sub-graph of the system Graph) relating the branch vectors of currents and voltages through the branch impedance matrix and branch admittance matrix:

$$E_{LOOP} = Z_{LOOP} I_{LOOP} \quad I_{LOOP} = Y_{LOOP} E_{LOOP}$$

Of the various network matrices referred above, the bus admittance matrix (Y_{BUS}) and the bus impedance matrix (Z_{BUS}) are determined for a given power system by the rule of inspection as explained next.

Rule of Inspection

Consider the 3-node admittance network as shown in figure5. Using the basic branch relation: $I = (YV)$, for all the elemental currents and applying Kirchhoff's Current Law principle at the nodal points, we get the relations as under:

At node 1: $I_1 = Y_1 V_1 + Y_3 (V_1 - V_3) + Y_6 (V_1 - V_2)$ At

node 2: $I_2 = Y_2 V_2 + Y_5 (V_2 - V_3) + Y_6 (V_2 - V_1)$

At node 3: $0 = Y_3 (V_3 - V_1) + Y_4 V_3 + Y_5 (V_3 - V_2)$

(12)

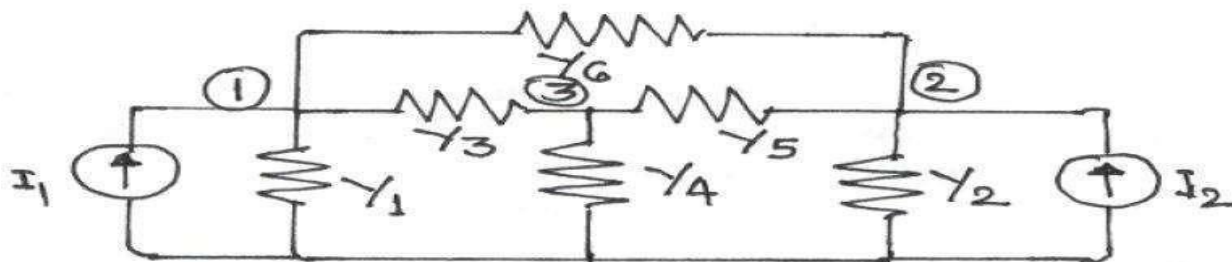


Fig. 3 Example System for finding YBUS

These are the performance equations of the given network in admittance form and they can be represented in matrix form as:

$$\begin{bmatrix} I_1 \\ I_2 \\ 0 \end{bmatrix} = \begin{bmatrix} (Y_1+Y_3+Y_6) & -Y_6 & -Y_3 \\ -Y_6 & (Y_2+Y_5+Y_6) & -Y_5 \\ -Y_3 & -Y_5 & (Y_3+Y_4+Y_5) \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (13)$$

In other words, the relation of equation (9) can be represented in the form

$$IBUS = YBUS EBUS \quad (14)$$

Where, YBUS is the bus admittance matrix, IBUS & EBUS are the bus current and bus voltage vectors respectively. By observing the elements of the bus admittance matrix, YBUS of equation (13), it is observed that the matrix elements can as well be obtained by a simple inspection of the given system diagram:

Diagonal elements: A diagonal element (Y_{ii}) of the bus admittance matrix, YBUS, is equal to the sum total of the admittance values of all the elements incident at the bus/node i,

Off Diagonal elements: An off-diagonal element (Y_{ij}) of the bus admittance matrix, YBUS, is equal to the negative of the admittance value of the connecting element present between the buses i and j, if any. This is the principle of the rule of inspection. Thus the algorithmic equations for the rule of inspection are obtained as:

$$\begin{aligned} Y_{ii} &= \sum y_{ij} \quad (j = 1, 2, \dots, n) \\ Y_{ij} &= -y_{ij} \quad (j = 1, 2, \dots, n) \end{aligned} \quad (15)$$

For $i = 1, 2, \dots, n$, n = no. of buses of the given system, y_{ij} is the admittance of element connected between buses i and j and y_{ii} is the admittance of element connected between bus i and ground (reference bus).



Bus impedance matrix

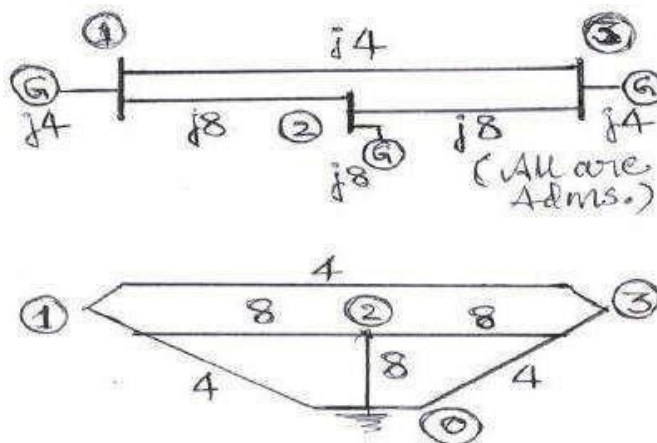
In cases where, the bus impedance matrix is also required, it cannot be formed by direct inspection of the given system diagram. However, the bus admittance matrix determined by the rule of inspection following the steps explained above, can be inverted to obtain the bus impedance matrix, since the two matrices are interinvertible.

Note: It is to be noted that the rule of inspection can be applied only to those power systems that do not have any mutually coupled elements.

Examples on Rule of Inspection:

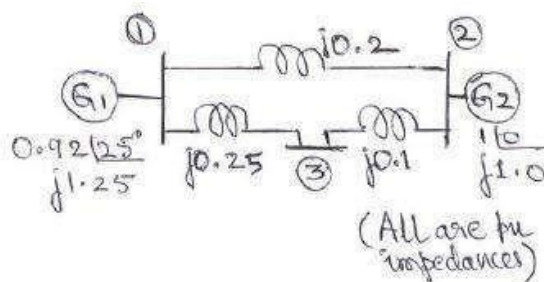
Example 6: Obtain the bus admittance matrix for the admittance network shown aside by the rule of inspection

$$Y_{BUS} = j \begin{vmatrix} 16 & -8 & -4 \\ -8 & 24 & -8 \\ -4 & -8 & 16 \end{vmatrix}$$

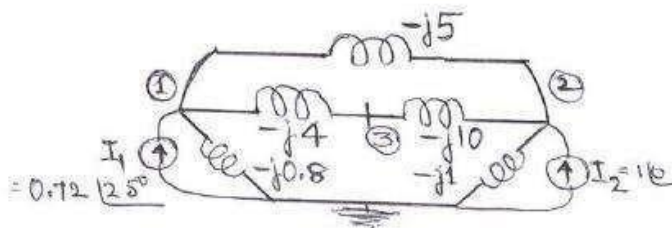


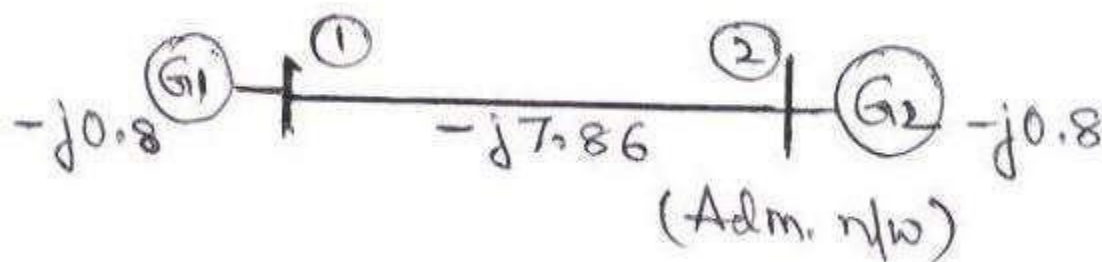
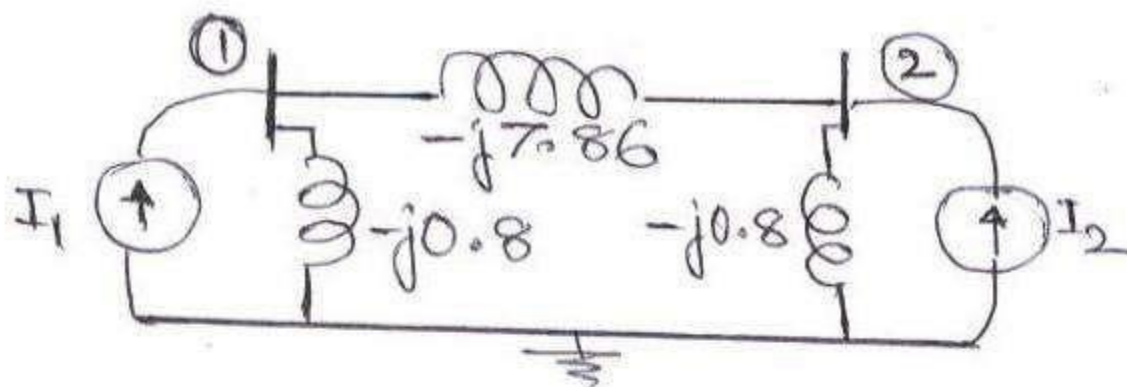
Example 7: Obtain Y_{BUS} for the impedance network shown aside by the rule of inspection. Also, determine Y_{BUS} for the reduced network after eliminating the eligible unwanted node. Draw the resulting reduced system diagram.

$$Y_{BUS} = j \begin{vmatrix} -9.8 & 5 & 4 \\ 5 & -16 & 10 \\ 4 & 10 & -14 \end{vmatrix}$$



$$Z_{BUS} = Y_{BUS}^{-1}$$





$$Y_{BUS}^{New} = Y_A - Y_B Y_D^{-1} Y_C$$

$$Y_{BUS} = j \begin{vmatrix} -8.66 & 7.86 \\ 7.86 & -8.66 \end{vmatrix}$$

SINGULAR TRANSFORMATIONS

The primitive network matrices are the most basic matrices and depend purely on the impedance or admittance of the individual elements. However, they do not contain any information about the behaviour of the interconnected network variables. Hence, it is necessary to transform the primitive matrices into more meaningful matrices which can relate variables of the interconnected network.



Bus admittance matrix, YBUS and Bus impedance matrix, ZBUS

In the bus frame of reference, the performance of the interconnected network is described by n independent nodal equations, where n is the total number of buses ($n+1$ nodes are present, out of which one of them is designated as the reference node).

For example a 5-bus system will have 5 external buses and 1 ground/ ref. bus). The performance equation relating the bus voltages to bus current injections in bus frame of reference in admittance form is given by

$$IBUS = YBUS EBUS \quad (17)$$

Where EBUS = vector of bus voltages measured with respect to reference bus IBUS

= Vector of currents injected into the bus

YBUS = bus admittance matrix

The performance equation of the primitive network in admittance form is given by $i + j = [y] v$

Pre-multiplying by A^t (transpose of A), we obtain

$$A^t i + A^t j = A^t [y] v \quad (18)$$

However, as per equation (4),

$A^t i = 0$,

since it indicates a vector whose elements are the algebraic sum of element currents incident at a bus, which by Kirchhoff's law is zero. Similarly, $A^t j$ gives the algebraic sum of all source currents incident at each bus and this is nothing but the total current injected at the bus. Hence,

$$A^t j = IBUS \quad (19)$$

$$\text{Thus from (18) we have, } IBUS = A^t [y] v \quad (20)$$

However, from (5), we have $v = A EBUS$

And hence substituting in (20) we get,

$$IBUS = A^t [y] A EBUS \quad (21)$$

Comparing (21) with (17) we obtain,

$$YBUS = A^t [y] A \quad (22)$$

The bus incidence matrix is rectangular and hence singular. Hence, (22) gives a singular transformation of the primitive admittance matrix $[y]$. The bus impedance matrix is given by ,

$$ZBUS = YBUS^{-1} \quad (23)$$

Note: This transformation can be derived using the concept of power invariance, however, since the transformations are based purely on KCL and KVL, the transformation will obviously be power invariant.



Examples on Singular Transformation:

Example 8: For the network of Fig E8, form the primitive matrices $[z]$ & $[y]$ and obtain the bus admittance matrix by singular transformation. Choose a Tree $T(1,2,3)$. The data is given in Table E8.

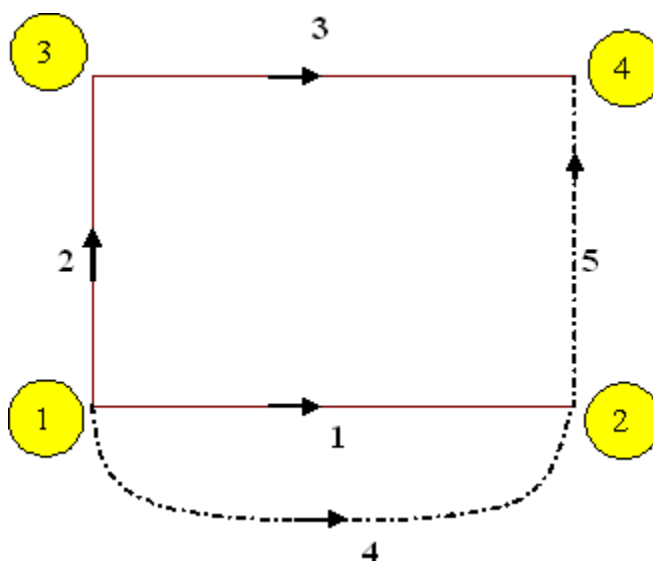


Fig E8 System for Example-8 Table

Elements	Self impedance	Mutual impedance
1	$j\ 0.6$	-
2	$j\ 0.5$	$j\ 0.1$ (with element 1)
3	$j\ 0.5$	-
4	$j\ 0.4$	$j\ 0.2$ (with element 1)
5	$j\ 0.2$	-



Solution:

The bus incidence matrix is formed taking node 1 as the reference bus.

$$A = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 0 \\ 1 & 0 & -1 \end{bmatrix}$$

The primitive incidence matrix is given by

$$[z] = \begin{bmatrix} j0.6 & j0.1 & 0.0 & j0.2 & 0.0 \\ j0.1 & j0.5 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & j0.5 & 0.0 & 0.0 \\ j0.2 & 0.0 & 0.0 & j0.4 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & j0.2 \end{bmatrix}$$

The primitive admittance matrix $[y] = [z]^{-1}$ and given by,

$$[y] = \begin{bmatrix} -j2.0833 & j0.4167 & 0.0 & j1.0417 & 0.0 \\ j0.4167 & -j2.0833 & 0.0 & -j0.2083 & 0.0 \\ 0.0 & 0.0 & -j2.0 & 0.0 & 0.0 \\ j1.0417 & -j0.2083 & 0.0 & -j3.0208 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & -j5.0 \end{bmatrix}$$

The bus admittance matrix by singular transformation is obtained as

$$Y_{BUS} = A^t [y] A = \begin{bmatrix} -j8.0208 & j0.2083 & j5.0 \\ j0.2083 & -j4.0833 & j2.0 \\ j5.0 & j2.0 & -j7.0 \end{bmatrix}$$

$$Z_{BUS} = Y_{BUS}^{-1} = \begin{bmatrix} j0.2713 & j0.1264 & j0.2299 \\ j0.1264 & j0.3437 & j0.1885 \\ j0.2299 & j0.1885 & j0.3609 \end{bmatrix}$$

SUMMARY

The formulation of the mathematical model is the first step in obtaining the solution of any electrical network. The independent variables can be either currents or voltages. Correspondingly, the elements of the coefficient matrix will be impedances or admittances.

Network equations can be formulated for solution of the network using graph theory, independent of the nature of elements. In the graph of a network, the tree-branches and links are distinctly identified. The complete information about the interconnection of the network, with the directions of the currents is contained in the bus incidence matrix.

The information on the nature of the elements which form the interconnected network is contained in the primitive impedance matrix. A primitive element can be represented in impedance form or admittance form. In the bus frame of reference, the performance of the interconnected system is described by $(n-1)$ nodal equations, where n is the number of nodes. The bus admittance matrix and the bus impedance matrix relate the bus voltages and currents. These matrices can be obtained from the primitive impedance and admittance matrices.

FORMATION OF BUS IMPEDANCE MATRIX

NODE ELIMINATION BY MATRIX ALGEBRA

Nodes can be eliminated by the matrix manipulation of the standard node equations. However, *only those nodes at which current does not enter or leave the network can be considered for such elimination*. Such nodes can be eliminated either in one group or by taking the eligible nodes one after the other for elimination, as discussed next.

CASE-A: Simultaneous Elimination of Nodes:

Consider the performance equation of the given network in bus frame of reference in admittance form for a n -bus system, given by:

$$\mathbf{IBUS} = \mathbf{YBUS} \mathbf{EBUS} \quad (1)$$

Where $\mathbf{IBUS}$ and $\mathbf{EBUS}$ are n -vectors of injected bus current and bus voltages and $\mathbf{YBUS}$ is the square, symmetric, coefficient bus admittance matrix of order n . Now, of the n buses present in the system, let p buses be considered for node elimination so that the reduced system after elimination of p nodes would be retained with m ($= n-p$) nodes only. Hence the corresponding performance equation would be similar to (1) except that the coefficient matrix would be of order m now, i.e.,

$$\mathbf{IBUS} = \mathbf{YBUS}^{\text{new}} \mathbf{EBUS} \quad (2)$$

Where $\mathbf{YBUS}^{\text{new}}$ is the bus admittance matrix of the reduced network and the vectors $\mathbf{IBUS}$ and $\mathbf{EBUS}$ are of order m . It is assumed in (1) that $\mathbf{IBUS}$ and $\mathbf{EBUS}$ are obtained with

their elements arranged such that the elements associated with p nodes to be eliminated are in the lower portion of the vectors. Then the elements of YBUS also get located accordingly so that (1) after matrix partitioning yields,

$$\begin{bmatrix} \mathbf{I}_{BUS-m} \\ \mathbf{I}_{BUS-p} \end{bmatrix} = \begin{matrix} m & p \\ \mathbf{Y}_A & \mathbf{Y}_B \\ \mathbf{Y}_C & \mathbf{Y}_D \end{matrix} \begin{bmatrix} \mathbf{E}_{BUS-m} \\ \mathbf{E}_{BUS-p} \end{bmatrix} \quad (3)$$

Where the self and mutual values of $\mathbf{Y}_A$ and $\mathbf{Y}_D$ are those identified only with the nodes to be retained and removed respectively and $\mathbf{Y}_C = \mathbf{Y}_B^T$ is composed of only the corresponding mutual admittance values, that are common to the nodes m and p.

Now, for the p nodes to be eliminated, it is necessary that, each element of the vector $\mathbf{I}_{BUS-p}$ should be zero. Thus we have from (3):

$$\begin{aligned} \mathbf{I}_{BUS-m} &= \mathbf{Y}_A \mathbf{E}_{BUS-m} + \mathbf{Y}_B \mathbf{E}_{BUS-p} \\ \mathbf{I}_{BUS-p} &= \mathbf{Y}_C \mathbf{E}_{BUS-m} + \mathbf{Y}_D \mathbf{E}_{BUS-p} = 0 \end{aligned} \quad (4)$$

Solving,

$$\mathbf{E}_{BUS-p} = -\mathbf{Y}_D^{-1} \mathbf{Y}_C \mathbf{E}_{BUS-m} \quad (5)$$

Thus, by simplification, we obtain an expression similar to (2) as,

$$\mathbf{I}_{BUS-m} = \{\mathbf{Y}_A - \mathbf{Y}_B \mathbf{Y}_D^{-1} \mathbf{Y}_C\} \mathbf{E}_{BUS-m} \quad (6)$$

Thus by comparing (2) and (6), we get an expression for the new bus admittance matrix in terms of the sub-matrices of the original bus admittance matrix as:

$$\mathbf{Y}_{BUS_{new}} = \{\mathbf{Y}_A - \mathbf{Y}_B \mathbf{Y}_D^{-1} \mathbf{Y}_C\} \quad (7)$$

This expression enables us to construct the given network with only the necessary nodes retained and all the unwanted nodes/buses eliminated. However, it can be observed from (7) that the expression involves finding the inverse of the sub-matrix $\mathbf{Y}_D$ (of order p). This would be computationally very tedious if p, the nodes to be eliminated is very large, especially for real practical systems. In such cases, it is more advantageous to eliminate the unwanted nodes from the given network by considering one node only at a time for elimination, as discussed next.

CASE-B: Separate Elimination of Nodes:

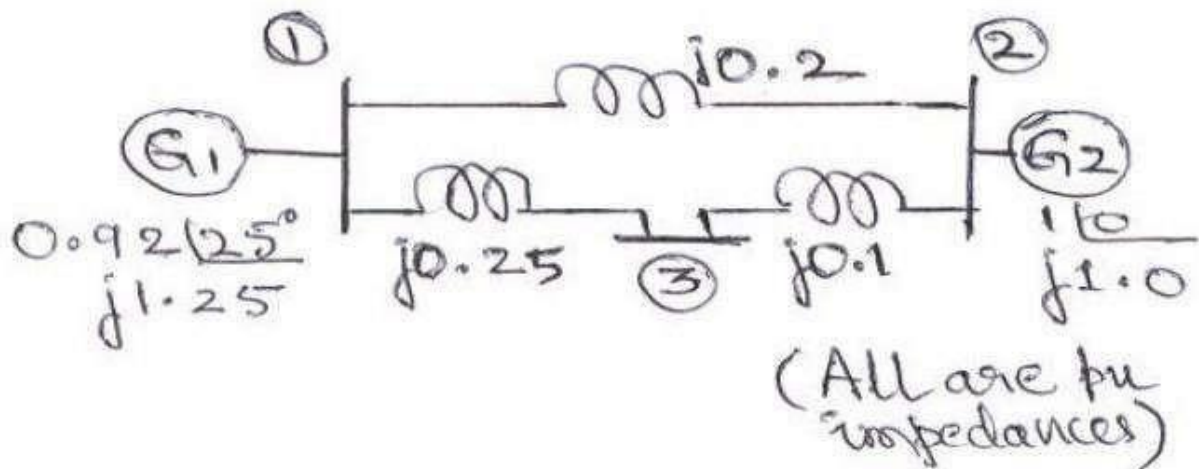
Here again, the system buses are to be renumbered, if necessary, such that the node to be removed always happens to be the last numbered one. The sub-matrix $\mathbf{Y}_D$ then would be a single element matrix and hence its inverse would be just equal to its own reciprocal value. Thus the generalized algorithmic equation for finding the elements of the new bus admittance matrix can be obtained from (6) as,

$$\mathbf{Y}_{ij}^{new} = \mathbf{Y}_{ij}^{old} - \mathbf{Y}_{in} \mathbf{Y}_{nj} / \mathbf{Y}_{nn} \quad i, j = 1, 2, \dots, n. \quad (8)$$

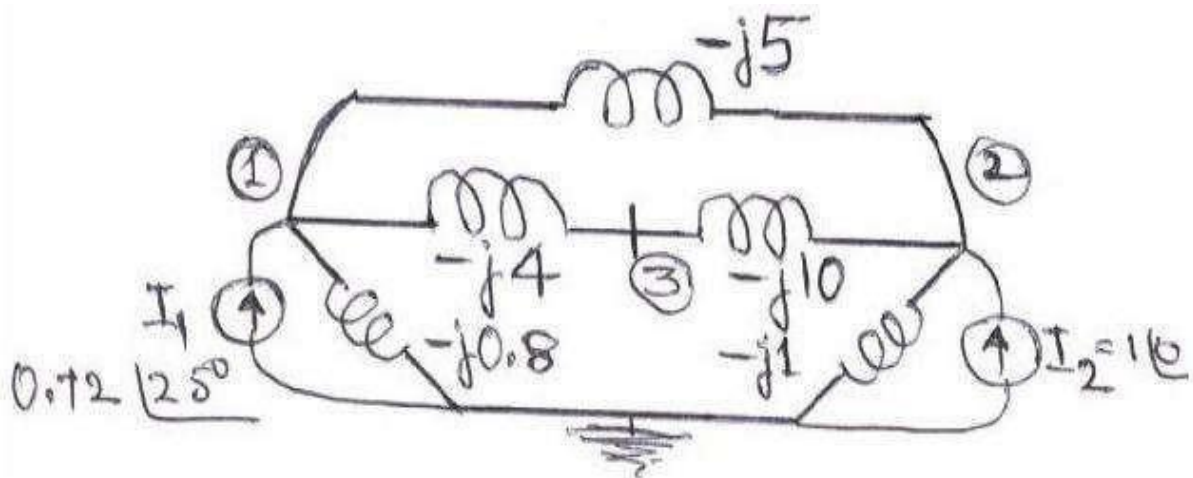
Each element of the original matrix must therefore be modified as per (7). Further, this procedure of eliminating the last numbered node from the given system of n nodes is to be iteratively repeated p times, so as to eliminate all the unnecessary p nodes from the original system.

Examples on Node elimination:

Example-1: Obtain YBUS for the impedance network shown below by the rule of inspection. Also, determine YBUS for the reduced network after eliminating the eligible unwanted node. Draw the resulting reduced system diagram.



The admittance equivalent network is as follows:



The bus admittance matrix is obtained by RoI as:

$$Y_{BUS} = j \begin{vmatrix} -9.8 & 5 & 4 \\ 5 & -16 & 10 \\ 4 & 10 & -14 \end{vmatrix}$$

The reduced matrix after elimination of node 3 from the given system is determined as per the equation:

$$Y_{BUS}^{New} = Y_A - Y_B Y_D^{-1} Y_C$$

$$Y_{BUS}^{new} = \begin{matrix} & \begin{matrix} n/n & 1 & 2 \end{matrix} \\ \begin{matrix} 1 \\ 2 \end{matrix} & \begin{bmatrix} -j8.66 & j7.86 \\ j7.86 & -j8.66 \end{bmatrix} \end{matrix}$$

Alternatively,

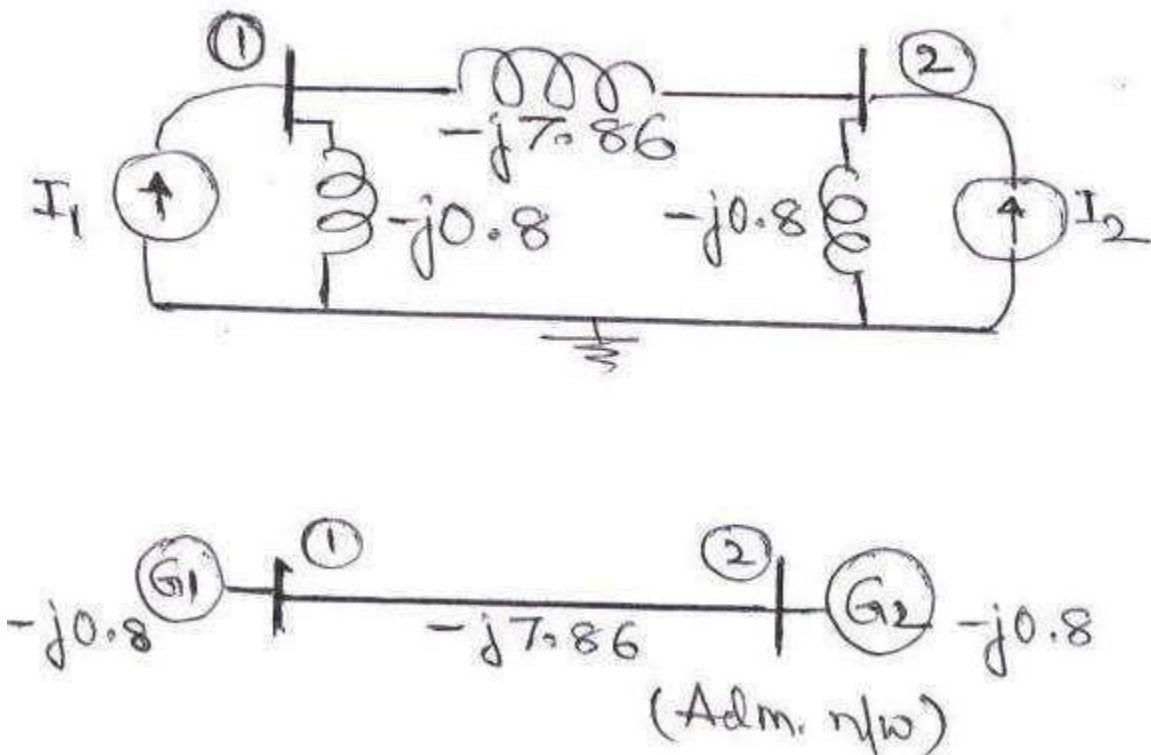
$$Y_{ij}^{new} = Y_{ij}^{old} - Y_{i3} Y_{3j} / Y_{33} \quad \forall i, j = 1, 2.$$

$$Y_{11} = Y_{11} - Y_{13} Y_{31} / Y_{33} = -j8.66$$

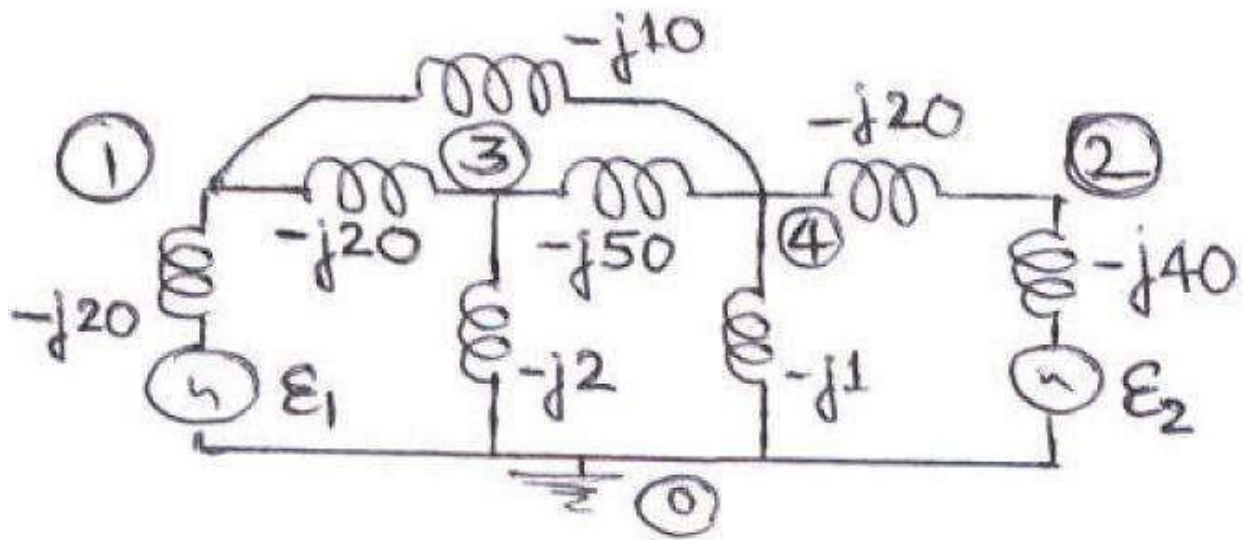
$$Y_{22} = Y_{22} - Y_{23} Y_{32} / Y_{33} = -j8.66$$

$$Y_{12} = Y_{21} = Y_{12} - Y_{13} Y_{32} / Y_{33} = j7.86$$

Thus the reduced network can be obtained again by the rule of inspection as shown below.



Example-2: Obtain YBUS for the admittance network shown below by the rule of inspection. Also, determine YBUS for the reduced network after eliminating the eligible unwanted node. Draw the resulting reduced system diagram.

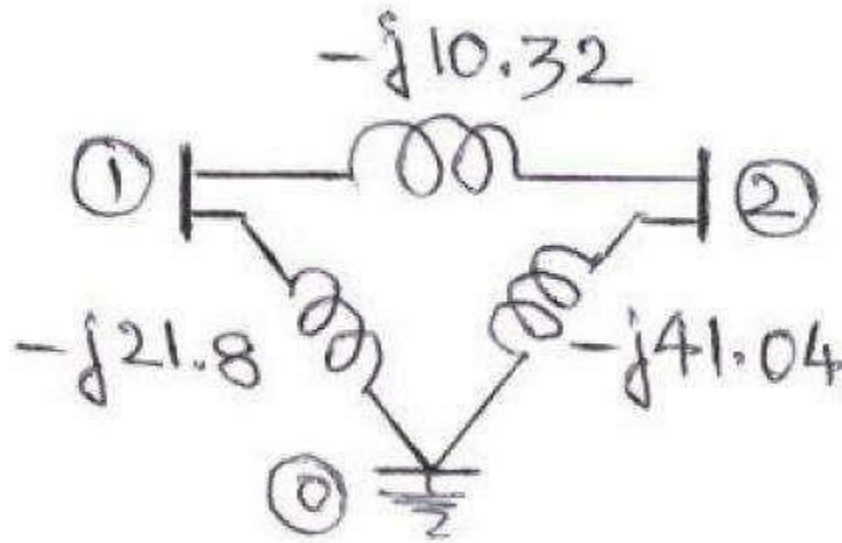


$$Y_{BUS} = \begin{array}{c|cccc} n/n & 1 & 2 & 3 & 4 \\ \hline 1 & -j50 & 0 & j20 & j10 \\ 2 & 0 & -j60 & 0 & j72 \\ 3 & j20 & 0 & -j72 & j50 \\ 4 & j10 & j72 & j50 & -j81 \end{array} = \begin{vmatrix} Y_A & Y_B \\ Y_C & Y_D \end{vmatrix}$$

$$Y_{BUS}^{New} = Y_A - Y_B Y_D^{-1} Y_C$$

$$Y_{BUS}^{new} = \begin{array}{c|cc} n/n & 1 & 2 \\ \hline 1 & -j32.12 & j10.32 \\ 2 & j10.32 & -j51.36 \end{array}$$

Thus the reduced system of two nodes can be drawn by the rule of inspection as under:



ZBUS building

FORMATION OF BUS IMPEDANCE MATRIX

The bus impedance matrix is the inverse of the bus admittance matrix. An alternative method is possible, based on an algorithm to form the bus impedance matrix directly from system parameters and the coded bus numbers. The bus impedance matrix is formed adding one element at a time to a partial network of the given system. The performance equation of the network in bus frame of reference in impedance form using the currents as independent variables is given in matrix form by

$$\bar{E}_{bus} = [Z_{bus}] \bar{I}_{bus} \quad (9)$$

When expanded so as to refer to a n bus system, (9) will be of the form

$$\begin{aligned} E_1 &= Z_{11}I_1 + Z_{12}I_2 + \dots + Z_{1k}I_k + \dots + Z_{1n}I_n \\ &\vdots \\ E_k &= Z_{k1}I_1 + Z_{k2}I_2 + \dots + Z_{kk}I_k + \dots + Z_{kn}I_n \\ &\vdots \\ E_n &= Z_{n1}I_1 + Z_{n2}I_2 + \dots + Z_{nk}I_k + \dots + Z_{nn}I_n \end{aligned} \quad (10)$$

Now assume that the bus impedance matrix Z_{bus} is known for a partial network of m buses and a known reference bus. Thus, Z_{bus} of the partial network is of dimension $m \times m$. If now a new element is added between buses p and q we have the following two possibilities:

- (i) p is an existing bus in the partial network and q is a new bus; in this case p - q is a **branch** added to the p -network as shown in Fig 1a, and

- (ii) both p and q are buses existing in the partial network; in this case p - q is a **link** added to the p-network as shown in Fig 1b.

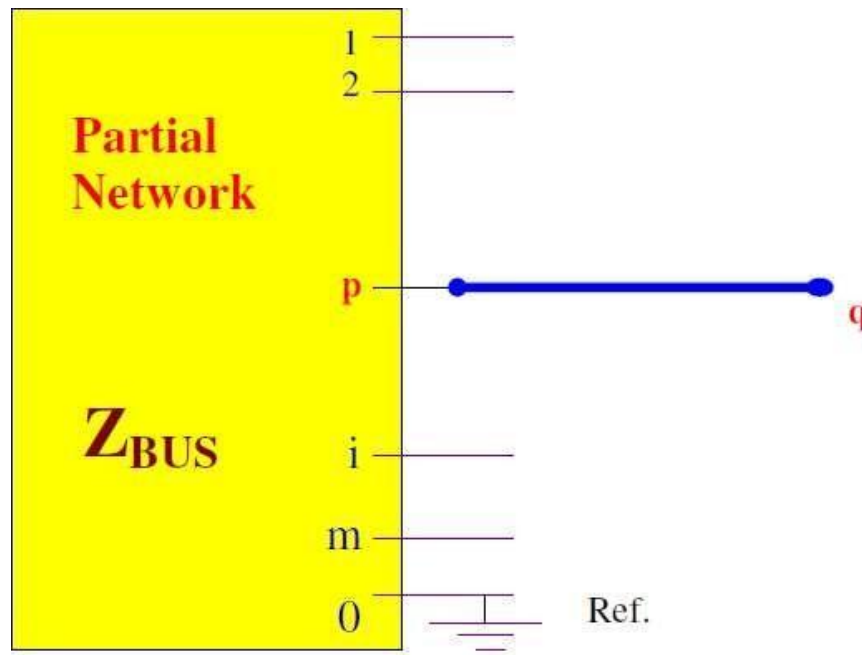


Fig 1a. Addition of branch p - q

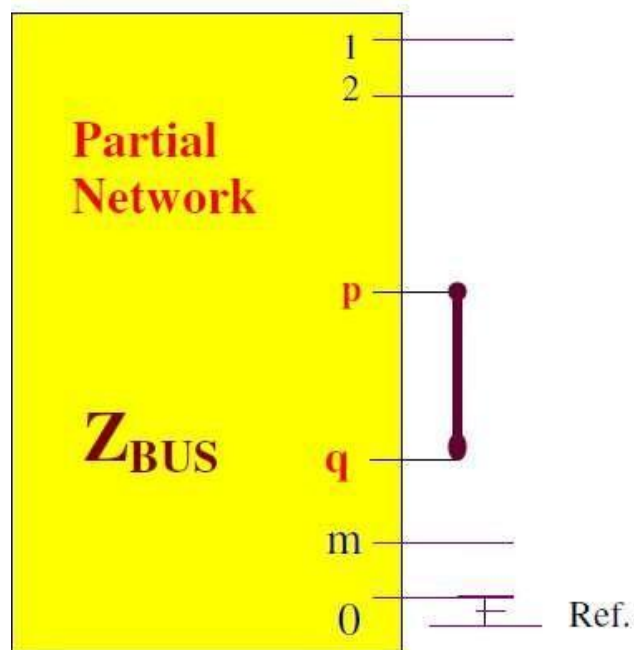


Fig 1b. Addition of link p - q

If the added element is a branch, p-q, then the new bus impedance matrix would be of order $m+1$, and the analysis is confined to finding only the elements of the new row and column (corresponding to bus-q) introduced into the original matrix. If the added element is a link, p-q, then the new bus impedance matrix will remain unaltered with regard to its order. However, all the elements of the original matrix are updated to take account of the effect of the link added.

ADDITION OF A BRANCH

Consider now the performance equation of the network in impedance form with the added branch p-q, given by

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_p \\ \vdots \\ E_m \\ E_q \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1p} & \cdots & Z_{1m} & Z_{1q} \\ Z_{21} & Z_{22} & \cdots & Z_{2p} & \cdots & Z_{2m} & Z_{2q} \\ \vdots & \vdots & & \vdots & & \vdots & \vdots \\ Z_{p1} & Z_{p2} & \cdots & Z_{pp} & \cdots & Z_{pm} & Z_{pq} \\ \vdots & \vdots & & \vdots & & \vdots & \vdots \\ Z_{m1} & Z_{m2} & \cdots & Z_{mp} & \cdots & Z_{mm} & Z_{mq} \\ Z_{q1} & Z_{q2} & \cdots & Z_{qp} & \cdots & Z_{qm} & Z_{qq} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_p \\ \vdots \\ I_m \\ I_q \end{bmatrix} \quad (11)$$

It is assumed that the added branch p-q is mutually coupled with some elements of the partial network and since the network has bilateral passive elements only, we have

Vector z_{pq-rs} is not equal to zero and $Z_{ij} = Z_{ji}$ " $i, j = 1, 2, \dots, m, q$
(12)

To find Z_{qi} :

The elements of last row-q and last column-q are determined by injecting a current of 1.0 pu at the bus-i and measuring the voltage of the bus-q with respect to the reference bus-0, as shown in Fig.2. Since all other bus currents are zero, we have from (11) that

$$E_k = Z_{ki} I_i = Z_{ki} \quad k = 1, 2, \dots, i, p, \dots, m, q \quad (13)$$

Hence, $E_q = Z_{qi}$; $E_p = Z_{pi}$

$$\text{Also, } E_q = E_p - v_{pq} \text{ ; so that } Z_{qi} = Z_{pi} - v_{pq} \quad i = 1, 2, \dots, i, \dots, p, \dots, m, q \quad (14)$$

To find v_{pq} :

In terms of the primitive admittances and voltages across the elements, the current through the elements is given by

$$\begin{bmatrix} i_{pq} \\ \bar{i}_{rs} \end{bmatrix} = \begin{bmatrix} y_{pq,pq} & \bar{y}_{pqrs} \\ \bar{y}_{rs,pq} & \bar{y}_{rs,rs} \end{bmatrix} \begin{bmatrix} v_{pq} \\ \bar{v}_{rs} \end{bmatrix} \quad (15)$$

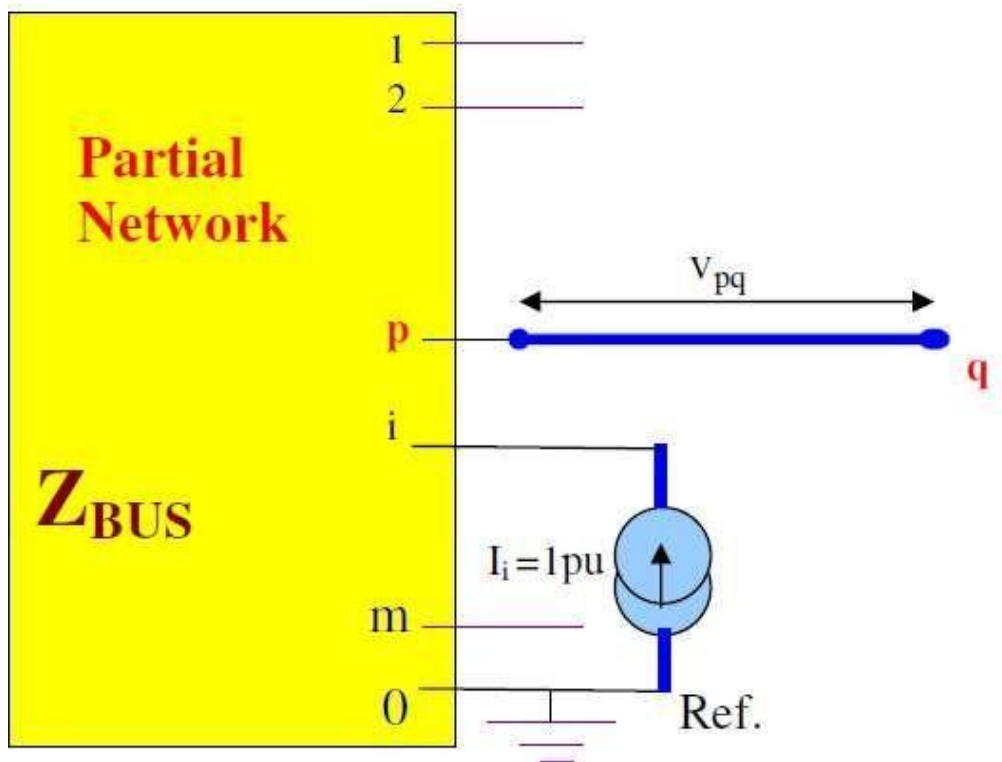


Fig.2 Calculation for Z_{qi}

where i_{pq} is current through element $p-q$

$\bar{i}_{rs}$ is vector of currents through elements of the partial network

v_{pq} is voltage across element $p-q$

$y_{pq,pq}$ is self – admittance of the added element

$\bar{y}_{pq,rs}$ is the vector of mutual admittances between the added elements $p-q$ and elements $r-s$ of the partial network.

$\bar{v}_{rs}$ is vector of voltage across elements of partial network.

$\bar{y}_{rs,pq}$ is transpose of $\bar{y}_{pq,rs}$.

$\bar{y}_{rs,rs}$ is the primitive admittance of partial network.

Since the current in the added branch $p-q$, is zero, $i_{pq} = 0$. We thus have from (15),

$$i_{pq} = y_{pq,pq} v_{pq} + \bar{y}_{pq,rs} \bar{v}_{rs} = 0 \quad (16)$$

$$\text{Solving, } v_{pq} = -\frac{\bar{y}_{pq,rs}\bar{v}_{rs}}{y_{pq,pq}} \quad \text{or}$$

$$v_{pq} = -\frac{\bar{y}_{pq,rs}(\bar{E}_r - \bar{E}_s)}{y_{pq,pq}} \quad (17)$$

Using (13) and (17) in (14), we get

$$Z_{qi} = Z_{pi} + \frac{\bar{y}_{pq,rs}(\bar{Z}_{ri} - \bar{Z}_{si})}{y_{pq,pq}} \quad i = 1, 2, \dots, m; i \neq q \quad (18)$$

To find z_{qq} :

The element Z_{qq} can be computed by injecting a current of 1pu at bus-q, $I_q = 1.0$ pu.

As before, we have the relations as under:

$$E_k = Z_{kq} I_q = Z_{kq} \quad \forall \quad k = 1, 2, \dots, i, \dots, p, \dots, m, q \quad (19)$$

$$\text{Hence, } E_q = Z_{qq}; \quad E_p = Z_{pq}; \quad \text{Also, } E_q = E_p - v_{pq}; \quad \text{so that } Z_{qq} = Z_{pq} - v_{pq} \quad (20)$$

Since now the current in the added element is $i_{pq} = -I_q = -1.0$, we have from (15)

$$i_{pq} = y_{pq,pq} v_{pq} + \bar{y}_{pq,rs} \bar{v}_{rs} = -1$$

$$\text{Solving, } v_{pq} = -1 + \frac{\bar{y}_{pq,rs} \bar{v}_{rs}}{y_{pq,pq}}$$

$$v_{pq} = -1 + \frac{\bar{y}_{pq,rs}(\bar{E}_r - \bar{E}_s)}{y_{pq,pq}} \quad (21)$$

Using (19) and (21) in (20), we get

$$Z_{qq} = Z_{pq} + \frac{1 + \bar{y}_{pq,rs}(\bar{Z}_{rq} - \bar{Z}_{sq})}{y_{pq,pq}} \quad (22)$$

Special Cases

The following special cases of analysis concerning ZBUS building can be considered with

respect to the addition of branch to a p-network.

Case (a): If there is no mutual coupling then elements of $\bar{y}_{pq,rs}$ are zero. Further, if p is the reference node, then $E_p=0$. thus,

$$\begin{aligned} & Z_{pi} = 0 \quad i = 1, 2, \dots, m; i \neq q \\ \text{And} \quad & Z_{pq} = 0. \\ \text{Hence, from (18) (22)} \quad & Z_{qi} = 0 \quad i = 1, 2, \dots, m; i \neq q \\ \text{And} \quad & Z_{qq} = z_{pq,pq} \end{aligned} \quad \forall \quad (23)$$

Case (b): If there is no mutual coupling and if p is not the ref. bus, then, from (18) and (22), we again have,

$$\begin{aligned} Z_{qi} &= Z_{pi}, \quad i = 1, 2, \dots, m; i \neq q \\ Z_{qq} &= Z_{pq} + z_{pq,pq} \end{aligned} \quad (24)$$

ADDITION OF A LINK

Consider now the performance equation of the network in impedance form with the added link $p-l$, ($p-l$ being a fictitious branch and l being a fictitious node) given by

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_p \\ \vdots \\ E_m \\ E_l \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1p} & \cdots & Z_{1m} & Z_{1q} \\ Z_{21} & Z_{22} & \cdots & Z_{2p} & \cdots & Z_{2m} & Z_{2q} \\ \vdots & \vdots & & \vdots & & \vdots & \vdots \\ Z_{p1} & Z_{p2} & \cdots & Z_{pp} & \cdots & Z_{pm} & Z_{pq} \\ \vdots & \vdots & & \vdots & & \vdots & \vdots \\ Z_{m1} & Z_{m2} & \cdots & Z_{mp} & \cdots & Z_{mm} & Z_{mq} \\ Z_{l1} & Z_{l2} & \cdots & Z_{li} & \cdots & Z_{lm} & Z_{ll} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_p \\ \vdots \\ I_m \\ I_l \end{bmatrix} \quad (25)$$

It is assumed that the added branch $p-q$ is mutually coupled with some elements of the partial network and since the network has bilateral passive elements only, we have

$$\text{Vector } y_{pq-rs} \text{ is not equal to zero and } Z_{ij} = Z_{ji} \quad \forall i, j = 1, 2, \dots, m, l. \quad (26)$$

To find Z_{li} :

The elements of last row- l and last column- l are determined by injecting a current of 1.0 pu at the bus- i and measuring the voltage of the bus- q with respect to the reference bus-0, as shown in Fig.3. Further, the current in the added element is made zero by connecting a voltage source, e_l in series with element $p-q$, as shown. Since all other bus currents are zero, we have from (25) that

$$E_k = Z_{ki} I_i = Z_{ki} \quad \forall k = 1, 2, \dots, i, \dots, p, \dots, m, l \quad (27)$$

Hence, $e_l = E_l = Z_{li}$; $E_p = Z_{pi}$; $E_p = Z_{pi}$

Also, $e_l = E_p - E_q - v_{pq}$;

$$\text{So that } Z_{li} = Z_{pi} - Z_{qi} - v_{pq} \quad \forall i = 1, 2, \dots, i, \dots, p, \dots, q, \dots, m, \neq l \quad (28)$$

To find v_{pq} :

In terms of the primitive admittances and voltages across the elements, the current through the elements is given by

$$\begin{bmatrix} \bar{i}_{pl} \\ \bar{i}_{rs} \end{bmatrix} = \begin{bmatrix} y_{pl,pl} & \bar{y}_{pl,rs} \\ \bar{y}_{rs,pl} & \bar{y}_{rs,rs} \end{bmatrix} \begin{bmatrix} v_{pl} \\ \bar{v}_{rs} \end{bmatrix} \quad (29)$$

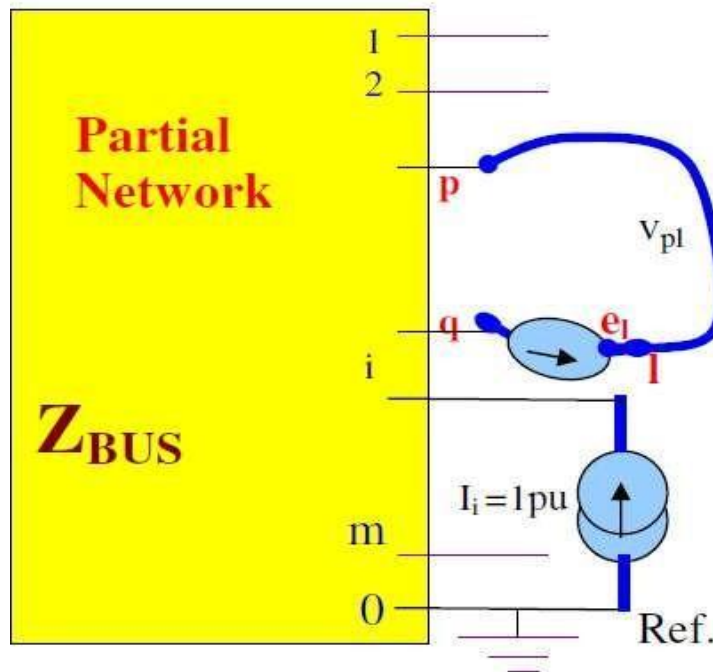


Fig.3 Calculation for Z_{li}

where i_{pl} is current through element $p-q$

$\bar{i}_{rs}$ is vector of currents through elements of the partial network

v_{pl} is voltage across element $p-q$

$y_{pl,pl}$ is self – admittance of the added element

$\bar{y}_{pl,rs}$ is the vector of mutual admittances between the added elements $p-q$ and elements $r-s$ of the partial network.

$\bar{v}_{rs}$ is vector of voltage across elements of partial network.

$\bar{y}_{rs,pl}$ is transpose of $\bar{y}_{pl,rs}$.

$\bar{y}_{rs,rs}$ is the primitive admittance of partial network.

Since the current in the added branch $p-l$, is zero, $i_{pl} = 0$. We thus have from (29),

$$i_{pl} = y_{pl,pl}v_{pl} + \bar{y}_{pl,rs}\bar{v}_{rs} = 0 \quad (30)$$

Solving, $v_{pl} = -\frac{\bar{y}_{pl,rs}\bar{v}_{rs}}{y_{pl,pl}}$ or

$$v_{pl} = -\frac{\bar{y}_{pl,rs}(\bar{E}_r - \bar{E}_s)}{y_{pl,pl}} \quad (31)$$

However,

$$\bar{y}_{pl,rs} = \bar{y}_{pq,rs}$$

And $y_{pl,pl} = y_{pq,pq}$ (32)

Using (27), (31) and (32) in (28), we get

$$Z_{li} = Z_{pi} - Z_{qi} + \frac{\bar{y}_{pq,rs}(\bar{Z}_{ri} - \bar{Z}_{si})}{y_{pq,pq}} \quad i = 1, 2, \dots, m; i \neq l \quad (33)$$

To find Z_{ll} :

The element Z_{ll} can be computed by injecting a current of 1pu at bus-1, $I_l = 1.0$ pu. As before, we have the relations as under:

$$E_k = Z_{kl} I_l = Z_{kl} \quad \forall \quad k = 1, 2, \dots, i, \dots, p, \dots, q, \dots, m, l \quad (34)$$

$$\text{Hence, } e_l = E_l = Z_{ll}; \quad E_p = Z_{pl};$$

$$\text{Also, } e_l = E_p - E_q - v_{pl};$$

$$\text{So that } Z_{ll} = Z_{pl} - Z_{ql} - v_{pl} \quad \forall \quad i=1, 2, \dots, i, \dots, p, \dots, q, \dots, m, \neq l \quad (35)$$

Since now the current in the added element is $i_{pl} = -I_l = -1.0$, we have from (29)

$$i_{pl} = y_{pl,pl} v_{pl} + \bar{y}_{pl,rs} \bar{v}_{rs} = -1$$

$$\text{Solving, } v_{pl} = -1 + \frac{\bar{y}_{pl,rs} \bar{v}_{rs}}{y_{pl,pl}}$$

$$v_{pl} = -1 + \frac{\bar{y}_{pl,rs} (\bar{E}_r - \bar{E}_s)}{y_{pl,pl}} \quad (36)$$

However,

$$\bar{y}_{pl,rs} = \bar{y}_{pq,rs}$$

$$\text{And } y_{pl,pl} = y_{pq,pq} \quad (37)$$

Using (34), (36) and (37) in (35), we get

$$Z_{ll} = Z_{pl} - Z_{ql} + \frac{1 + \bar{y}_{pq,rs} (\bar{Z}_{rl} - \bar{Z}_{sl})}{y_{pq,pq}} \quad (38)$$

Special Cases Contd....

The following special cases of analysis concerning Z_{BUS} building can be considered with respect to the addition of link to a p-network.

Case (c): If there is no mutual coupling, then elements of $\bar{y}_{pq,rs}$ are zero. Further, if p is the reference node, then $E_p=0$. thus,

$$Z_{li} = -Z_{qi}, \quad i = 1, 2, \dots, m; i \neq l$$

$$Z_{ll} = -Z_{ql} + z_{pq,pq} \quad (39)$$

From (39), it is thus observed that, when a link is added to a ref. bus, then the situation is

similar to adding a branch to a fictitious bus and hence the following steps are followed:

1. The element is added similar to addition of a branch (case-b) to obtain the new matrix of order $m+1$.
2. The extra fictitious node, l is eliminated using the node elimination algorithm.

Case (d): If there is no mutual coupling, then elements of pq rs y , are zero. Further, if p is not the reference node, then

$$Z_{li} = Z_{pi} - Z_{qi}$$

$$\begin{aligned} Z_{ll} &= Z_{pl} - Z_{ql} - Z_{pq,pq} \\ &= Z_{pp} + Z_{qq} - 2 Z_{pq} + Z_{pq,pq} \end{aligned} \quad (40)$$

MODIFICATION OF ZBUS FOR NETWORK CHANGES

An element which is not coupled to any other element can be removed easily. The Zbus is modified as explained in sections above, by adding in parallel with the element (to be removed), a link whose impedance is equal to the negative of the impedance of the element to be removed. Similarly, the impedance value of an element which is not coupled to any other element can be changed easily. The Zbus is modified again as explained in sections above, by adding in parallel with the element (whose impedance is to be changed), a link element of impedance value chosen such that the parallel equivalent impedance is equal to the desired value of impedance. When mutually coupled elements are removed, the Zbus is modified by introducing appropriate changes in the bus currents of the original network to reflect the changes introduced due to the removal of the elements.

Examples on ZBUS building

Example 1: For the positive sequence network data shown in table below, obtain ZBUS by building procedure.

Sl. No.	p-q (nodes)	Pos. seq. reactance in pu
1	0-1	0.25
2	0-3	0.20
3	1-2	0.08
4	2-3	0.06

Solution:

The given network is as shown below with the data marked on it. Assume the elements to be added as per the given sequence: 0-1, 0-3, 1-2, and 2-3.

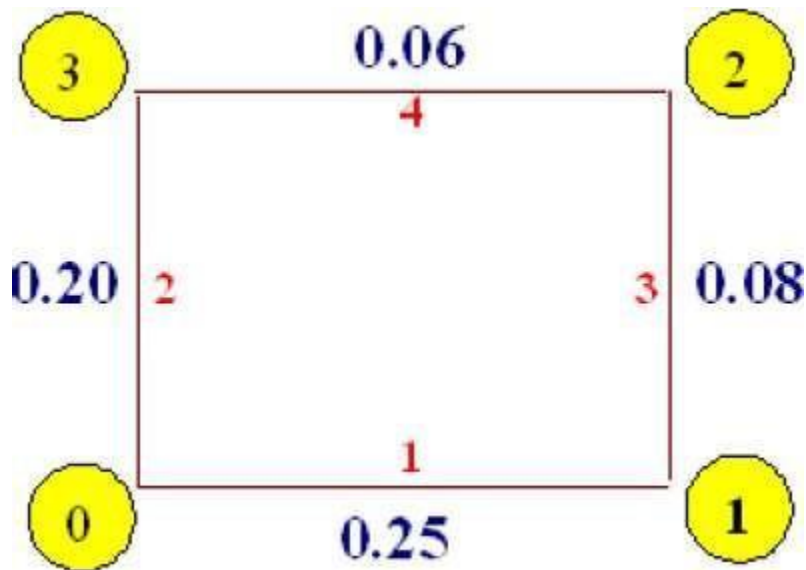
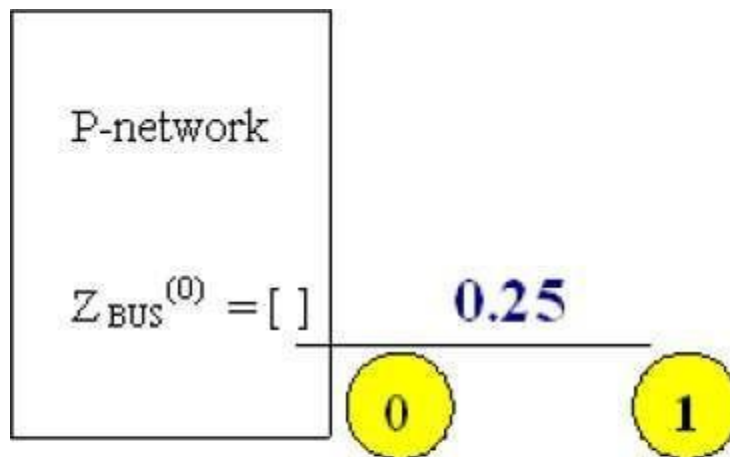


Fig. E1: Example System

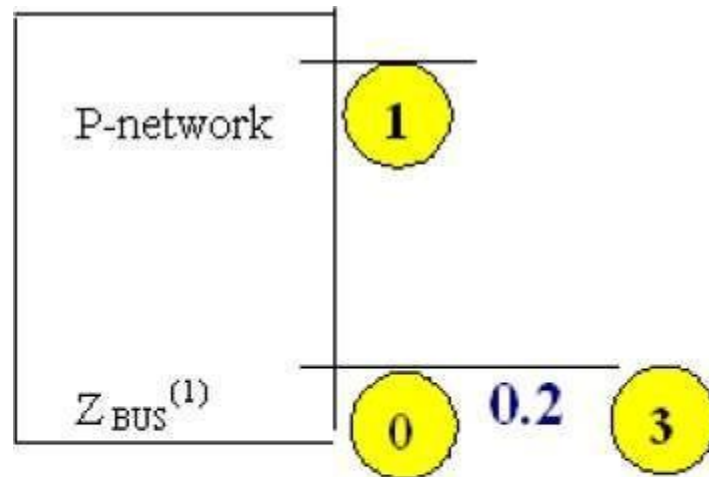
Consider building ZBUS as per the various stages of building through the consideration of the corresponding partial networks as under:

Step-1: Add element-1 of impedance 0.25 pu from the external node-1 ($q=1$) to internal ref. node-0 ($p=0$). (Case-a), as shown in the partial network;



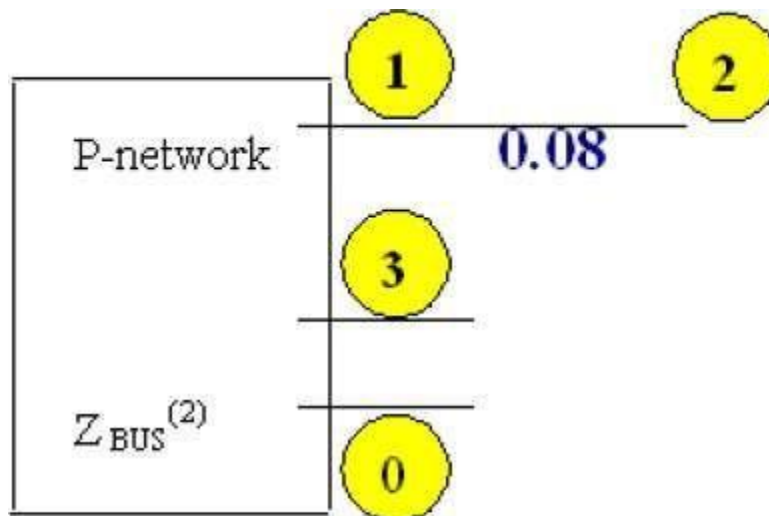
$$\mathbf{Z}_{BUS}^{(1)} = \begin{bmatrix} 1 & 0 \\ 0 & 0.25 \end{bmatrix}$$

Step-2: Add element-2 of impedance 0.2 pu from the external node-3 ($q=3$) to internal ref. node-0 ($p=0$). (Case-a), as shown in the partial network;



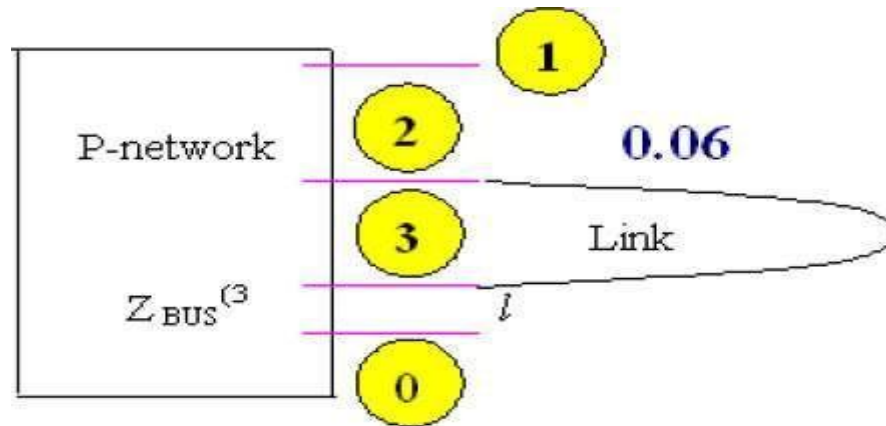
$$Z_{BUS}^{(2)} = \begin{matrix} & \begin{matrix} 1 & 3 \end{matrix} \\ \begin{matrix} 1 \\ 3 \end{matrix} & \begin{bmatrix} 0.25 & 0 \\ 0 & 0.2 \end{bmatrix} \end{matrix}$$

Step-3: Add element-3 of impedance 0.08 pu from the external node-2 (q=2) to internal node- 1 (p=1). (Case-b), as shown in the partial network;



$$Z_{BUS}^{(3)} = \begin{matrix} & \begin{matrix} 1 & 3 & 2 \end{matrix} \\ \begin{matrix} 1 \\ 3 \\ 2 \end{matrix} & \begin{bmatrix} 0.25 & 0 & 0.25 \\ 0 & 0.2 & 0 \\ 0.25 & 0 & 0.33 \end{bmatrix} \end{matrix}$$

Step-4: Add element-4 of impedance 0.06 pu between the two internal nodes, node-2 (p=2) to node-3 (q=3). (Case-d), as shown in the partial network;

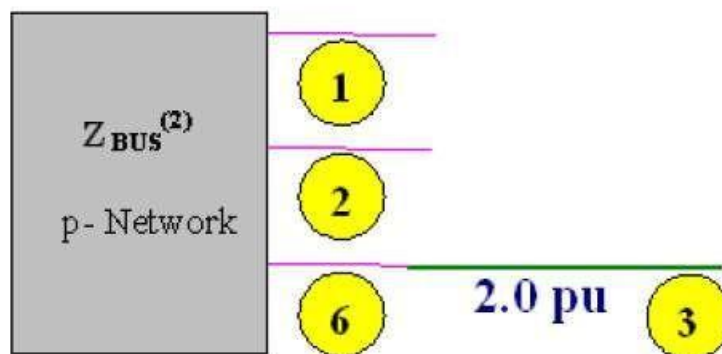
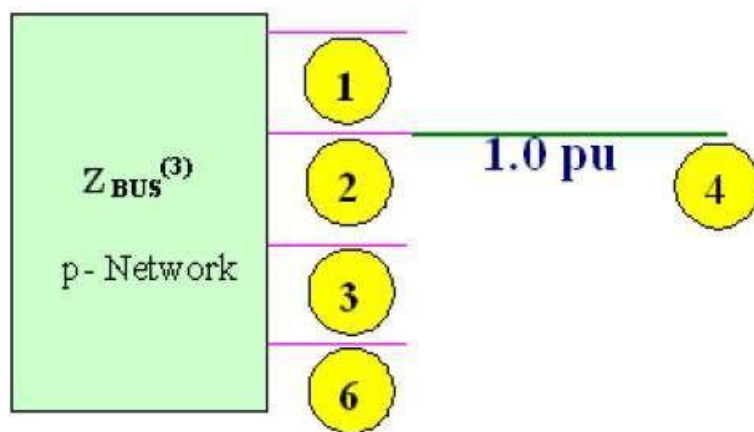
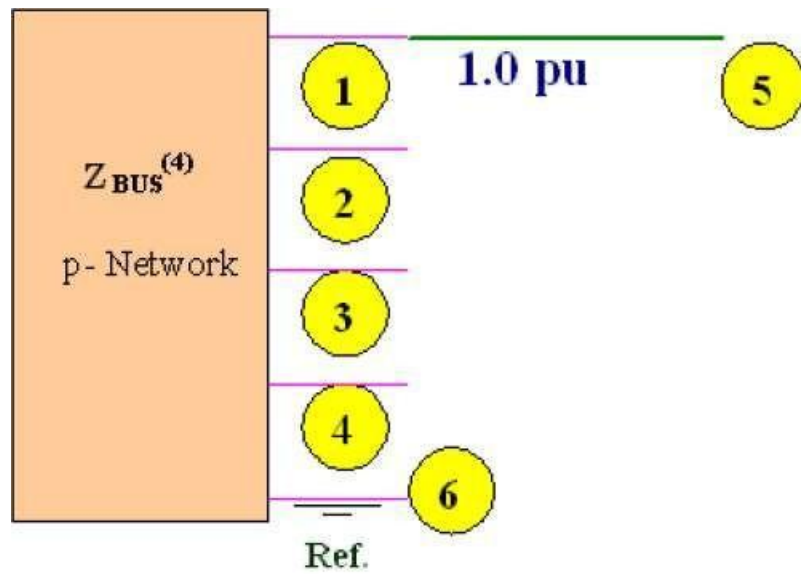


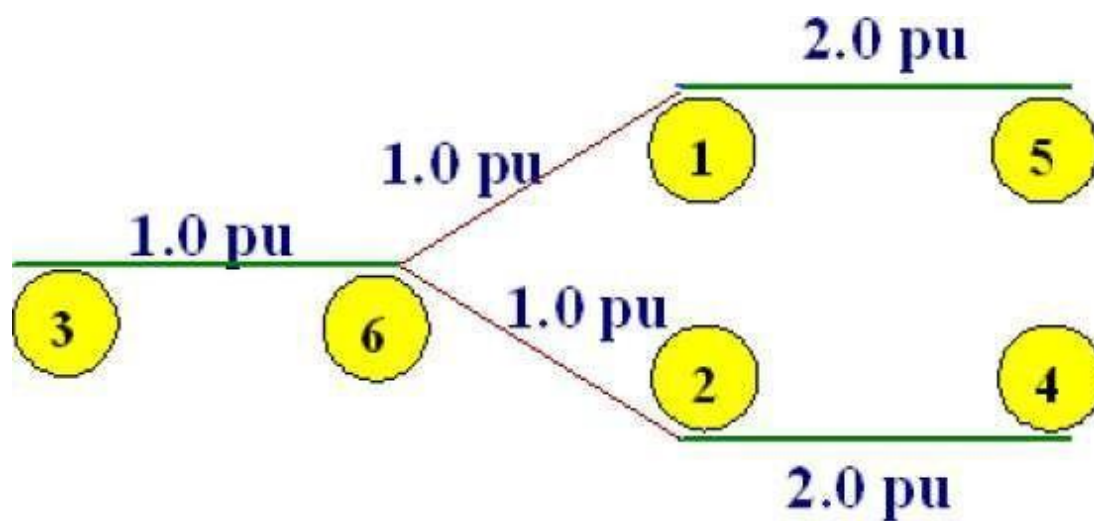
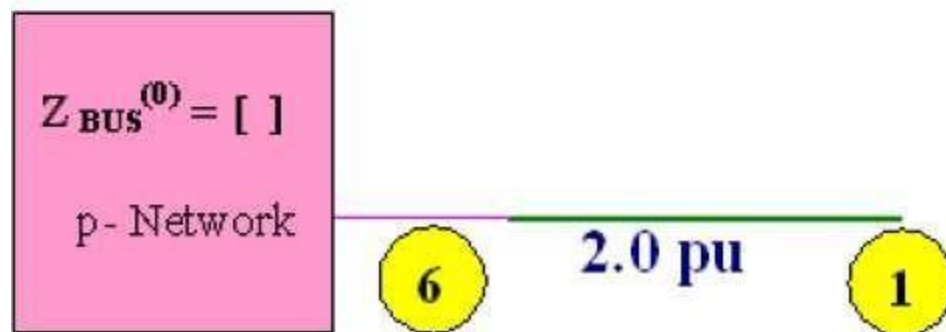
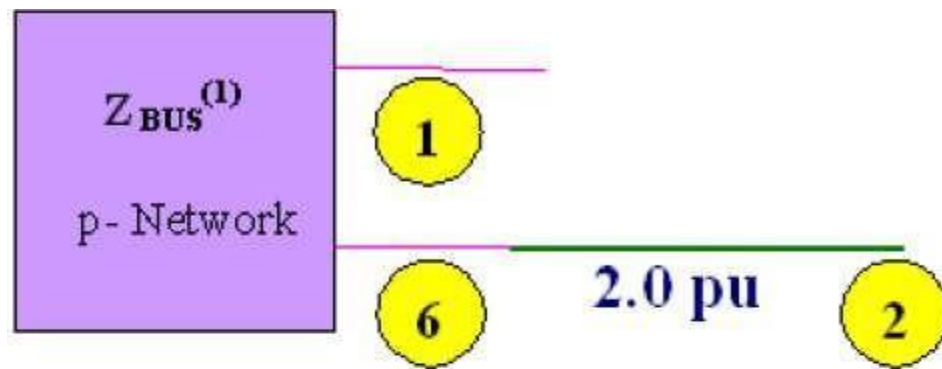
$$Z_{BUS}^{(4)} = \begin{array}{c|cccc} & 1 & 3 & 2 & l \\ \hline 1 & 0.25 & 0 & 0.25 & 0.25 \\ 3 & 0 & 0.2 & 0 & -0.2 \\ 2 & 0.25 & 0 & 0.33 & 0.33 \\ l & 0.25 & -0.2 & 0.33 & 0.59 \end{array}$$

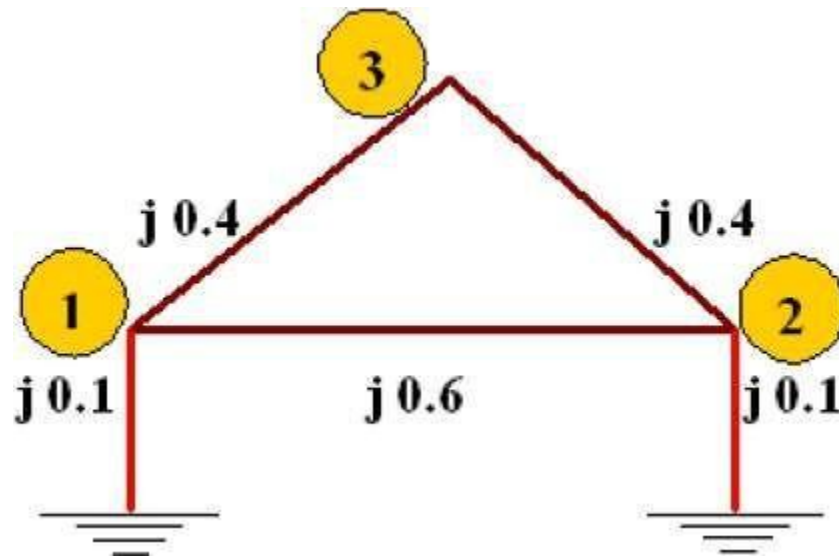
The fictitious node l is eliminated further to arrive at the final impedance matrix as under:

$$Z_{BUS}^{(final)} = \begin{array}{c|ccc} & 1 & 3 & 2 \\ \hline 1 & 0.1441 & 0.0847 & 0.1100 \\ 3 & 0.0847 & 0.1322 & 0.1120 \\ 2 & 0.1100 & 0.1120 & 0.1454 \end{array}$$

$$Z_{BUS} = \begin{array}{c|ccccc} & 1 & 2 & 3 & 4 & 5 \\ \hline 1 & 2 & 0 & 0 & 0 & 2 \\ 2 & 0 & 2 & 0 & 2 & 0 \\ 3 & 0 & 0 & 2 & 0 & 0 \\ 4 & 0 & 2 & 0 & 3 & 0 \\ 5 & 2 & 0 & 0 & 0 & 3 \end{array}$$

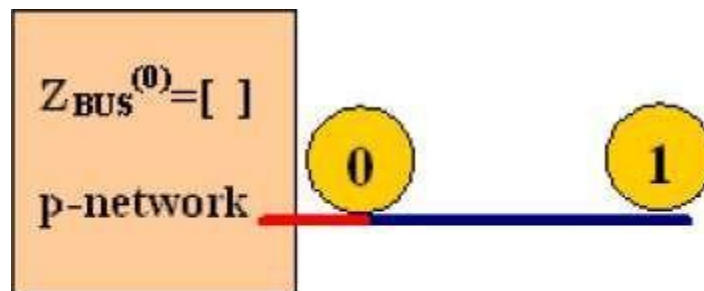






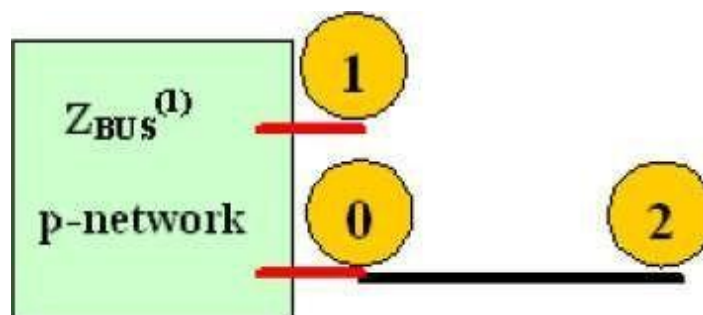
Solution: The specified system is considered with the reference node denoted by node-0. By its inspection, we can obtain the bus impedance matrix by building procedure by following the steps through the p-networks as under:

Step1: Add branch 1 between node 1 and reference node. ($q = 1, p = 0$)



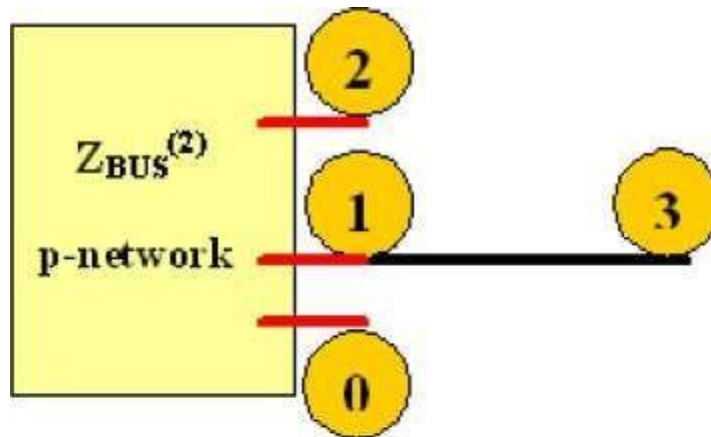
$$Z_{bus}^{(1)} = 1 \begin{bmatrix} j0.1 \end{bmatrix}$$

Step2: Add branch 2, between node 2 and reference node. ($q = 2, p = 0$).



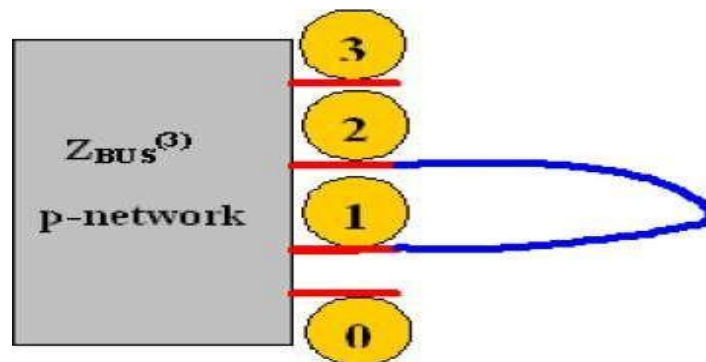
$$Z_{BUS} = \begin{matrix} & \begin{matrix} 1 & 2 \end{matrix} \\ \begin{matrix} 1 \\ 2 \end{matrix} & \begin{bmatrix} j0.1 & 0 \\ 0 & j0.15 \end{bmatrix} \end{matrix}$$

Step3: Add branch 3, between node 1 and node 3 ($p = 1, q = 3$)



$$Z_{BUS} = \begin{matrix} & \begin{matrix} 1 & 2 & 3 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} & \begin{bmatrix} j0.1 & 0 & j0.1 \\ 0 & j0.15 & 0 \\ j0.1 & 0 & j0.5 \end{bmatrix} \end{matrix}$$

Step 4: Add element 4, which is a link between node 1 and node 2. ($p = 1, q = 2$)



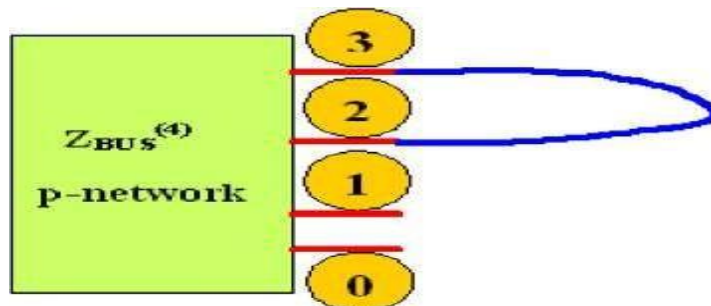
$$Z_{bus} = \begin{matrix} & \begin{matrix} 1 & 2 & 3 & l \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \\ l \end{matrix} & \begin{bmatrix} j0.1 & 0 & j0.1 & j0.1 \\ 0 & j0.15 & 0 & -j0.15 \\ j0.1 & 0 & j0.5 & j0.1 \\ j0.1 & -j0.15 & j0.1 & j0.85 \end{bmatrix} \end{matrix}$$

Now the extra node- l has to be eliminated to obtain the new matrix of step-4, using the algorithmic relation:

$$Y_{ij}^{new} = Y_{ij}^{old} - Y_{in} Y_{nj} / Y_{nn} \quad \forall i, j = 1, 2, 3.$$

$$Z_{bus} = \begin{matrix} & \begin{matrix} 1 & 2 & 3 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} & \begin{bmatrix} j0.08823 & j0.01765 & j0.08823 \\ j0.01765 & j0.12353 & j0.01765 \\ j0.08823 & j0.01765 & j0.48823 \end{bmatrix} \end{matrix}$$

Step 5: Add link between node 2 and node 3 ($p = 2, q = 3$)



$$Z_{11} = Z_{21} - Z_{31} = j0.01765 - j0.08823 = -j0.07058$$

$$Z_{12} = Z_{22} - Z_{32} = j0.12353 - j0.01765 = j0.10588$$

$$Z_{13} = Z_{23} - Z_{33} = j0.01765 - j0.48823 = -j0.47058$$

$$\begin{aligned} Z_{11} &= Z_{21} - Z_{31} + Z_{23,23} \\ &= j0.10588 - (-j0.47058) + j0.4 = j0.97646 \end{aligned}$$

Thus, the new matrix is as under:

$$Z_{bus} = \begin{matrix} & \begin{matrix} 1 & 2 & 3 & 1 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \\ 1 \end{matrix} & \begin{bmatrix} j0.08823 & j0.01765 & j0.08823 & -j0.07058 \\ j0.01765 & j0.12353 & j0.01765 & j0.10588 \\ j0.08823 & j0.01765 & j0.48823 & -j0.47058 \\ -j0.07058 & j0.10588 & -j0.47058 & j0.97646 \end{bmatrix} \end{matrix}$$

Node 1 is eliminated as shown in the previous step:

$$Z_{bus} = \begin{matrix} & \begin{matrix} 1 & 2 & 3 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} & \begin{bmatrix} j0.08313 & j0.02530 & j0.05421 \\ j0.02530 & j0.11205 & j0.06868 \\ j0.05421 & j0.06868 & j0.26145 \end{bmatrix} \end{matrix}$$

Further, the bus admittance matrix can be obtained by inverting the bus impedance matrix as under:

$$Y_{bus} = [Z_{bus}]^{-1} = \begin{matrix} & \begin{matrix} 1 & 2 & 3 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} & \begin{bmatrix} -j14.1667 & j1.6667 & j2.5 \\ j1.6667 & -j10.8334 & j2.5 \\ j2.5 & j2.5 & -j5.0 \end{bmatrix} \end{matrix}$$

As a check, it can be observed that the bus admittance matrix, Y_{BUS} can also be obtained by the rule of inspection to arrive at the same answer.

UNIT-2

LOAD FLOW STUDIES

REVIEW OF NUMERICAL SOLUTION OF EQUATIONS

The numerical analysis involving the solution of algebraic simultaneous equations forms the basis for solution of the performance equations in computer aided electrical power system analyses, such as during linear graph analysis, load flow analysis (nonlinear equations), transient stability studies (differential equations), etc. Hence, it is necessary to review the general forms of the various solution methods with respect to all forms of equations, as under:

1. Solution Linear equations:

*** Direct methods:**

- Cramer's (Determinant) Method,
- Gauss Elimination Method (only for smaller systems),
- LU Factorization (more preferred method), etc.

*** Iterative methods:**

- Gauss Method
- Gauss-Siedel Method (for diagonally dominant systems)

3. Solution of Nonlinear equations: Iterative methods only:

- Gauss-Siedel Method (for smaller systems)
- Newton-Raphson Method (if corrections for variables are small)

4. Solution of differential equations: Iterative methods only:

- Euler and Modified Euler method,
- RK IV-order method,
- Milne's predictor-corrector method, etc.

It is to be observed that the nonlinear and differential equations can be solved only by the iterative methods. The iterative methods are characterized by the various performance features as under:

- _ Selection of initial solution/ estimates
- _ Determination of fresh/ new estimates during each iteration
- _ Selection of number of iterations as per tolerance limit
- _ Time per iteration and total time of solution as per the solution method selected
- _ Convergence and divergence criteria of the iterative solution
- _ Choice of the Acceleration factor of convergence, etc.

A comparison of the above solution methods is as under:

In general, the direct methods yield exact or accurate solutions. However, they are suited for only the smaller systems, since otherwise, in large systems, the possible round-off errors make the solution process inaccurate. The iterative methods are more useful when the diagonal elements of the coefficient matrix are large in comparison with the off diagonal elements. The round-off errors in these methods are corrected at the successive steps of the iterative process. The Newton-Raphson method is very much useful for solution of non-linear equations, if all the values of the corrections for the unknowns are very small in magnitude and the initial values of unknowns are selected to be reasonably closer to the exact solution.

LOAD FLOW STUDIES

Introduction: Load flow studies are important in planning and designing future expansion of power systems. The study gives steady state solutions of the voltages at all the buses, for a particular load condition. Different steady state solutions can be obtained, for different operating conditions, to help in planning, design and operation of the power system. Generally, load flow studies are limited to the transmission system, which involves bulk power transmission. The load at the buses is assumed to be known. Load flow studies throw light on some of the important aspects of the system operation, such as: violation of voltage magnitudes at the buses, overloading of lines, overloading of generators, stability margin reduction, indicated by power angle differences between buses linked by a line, effect of contingencies like line voltages, emergency shutdown of generators, etc. Load flow studies are required for deciding the economic operation of the power system. They are also required in transient stability studies. Hence, load flow studies play a vital role in power system studies. Thus the load flow problem consists of finding the power flows (real and reactive) and voltages of a network for given bus conditions. At each bus, there are four quantities of interest to be known for further analysis: the real and reactive power, the voltage magnitude and its phase angle. Because of the nonlinearity of the algebraic equations, describing the given power system, their solutions are obviously, based on the iterative methods only. The constraints placed on the load flow solutions could be:

- _ The Kirchhoff's relations holding good,
- _ Capability limits of reactive power sources,
- _ Tap-setting range of tap-changing transformers,
- _ Specified power interchange between interconnected systems,
- _ Selection of initial values, acceleration factor, convergence limit, etc.

Classification of buses for LFA: Different types of buses are present based on the specified and unspecified variables at a given bus as presented in the table below:

Table 1. Classification of buses for LFA

Sl. No.	Bus Types	Specified Variables	Unspecified variables	Remarks
1	Slack/ Swing Bus	$ V , \delta$	P_G, Q_G	$ V , \delta$: are assumed if not specified as 1.0 and 0°
2	Generator/ Machine/ PV Bus	$P_G, V $	Q_G, δ	A generator is present at the machine bus
3	Load/ PQ Bus	P_G, Q_G	$ V , \delta$	About 80% buses are of PQ type
4	Voltage Controlled Bus	$P_G, Q_G, V $	δ, a	'a' is the % tap change in tap-changing transformer

Importance of swing bus: The slack or swing bus is usually a PV-bus with the largest capacity generator of the given system connected to it. The generator at the swing bus supplies the power difference between the “specified power into the system at the other buses” and the “total system output plus losses”. Thus swing bus is needed to supply the additional real and reactive power to meet the losses. Both the magnitude and phase angle of voltage are specified at the swing bus, or otherwise, they are assumed to be equal to 1.0

p.u. and 0°, as per flat-start procedure of iterative

solutions. The real and reactive powers at the swing bus are found by the computer routine as part of the load flow solution process. It is to be noted that the source at the swing bus is a perfect one, called the swing machine, or slack machine. It is voltage regulated, i.e., the magnitude of voltage fixed. The phase angle is the system reference phase and hence is fixed. The generator at the swing bus has a torque angle and excitation which vary or swing as the demand changes. This variation is such as to produce fixed voltage.

Importance of YBUS based LFA:

The majority of load flow programs employ methods using the bus admittance matrix, as this method is found to be more economical. The bus admittance matrix plays a very important role in load flow analysis. It is a complex, square and symmetric matrix and hence only $n(n+1)/2$ elements of YBUS need to be stored for a n-bus system. Further, in the YBUS matrix, $Y_{ij} = 0$, if an incident element is not present in the system connecting the buses „i” and „j”. since in a large power system, each bus is connected only to a fewer buses through an incident element, (about 6-8), the coefficient matrix, YBUS of such systems would be highly sparse, i.e., it will have many zero valued elements in it. This is defined by the sparsity of the matrix, as under:

$$\text{Percentage sparsity of a given matrix of } n^{\text{th}} \text{ order:} = \frac{\text{Total no. of zero valued elements of } Y_{\text{BUS}}}{\text{Total no. of entries of } Y_{\text{BUS}}}$$

$$S = (Z / n^2) \times 100 \% \quad (1)$$

The percentage sparsity of Y_{BUS} , in practice, could be as high as 80-90%, especially for very large, practical power systems. This sparsity feature of YBUS is extensively used in reducing the load flow calculations and in minimizing the memory required to store the

coefficient matrices. This is due to the fact that only the non-zero elements YBUS can be stored during the computer based implementation of the schemes, by adopting the suitable optimal storage schemes. While YBUS is thus highly sparse, its inverse, ZBUS, the bus impedance matrix is not so. It is a FULL matrix, unless the optimal bus ordering schemes are followed before proceeding for load flow analysis.

THE LOAD FLOW PROBLEM

Here, the analysis is restricted to a balanced three-phase power system, so that the analysis can be carried out on a single phase basis. The per unit quantities are used for all quantities. The first step in the analysis is the formulation of suitable equations for the power flows in the system. The power system is a large interconnected system, where various buses are connected by transmission lines. At any bus, complex power is injected into the bus by the generators and complex power is drawn by the loads. Of course at any bus, either one of them may not be present. The power is transported from one bus to other via the transmission lines. At any bus i , the complex power S_i (injected), shown in figure 1, is defined as

$$S_i = S_{Gi} - S_{Di} \quad (2)$$

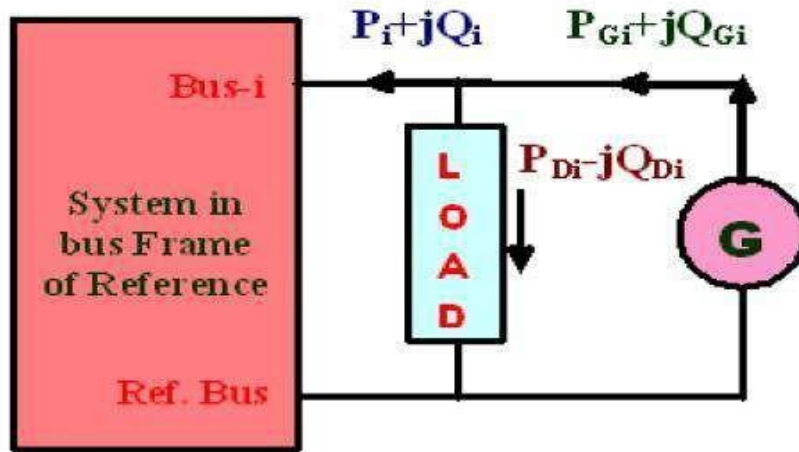


Fig.1 power flows at a bus-i

where S_i = net complex power injected into bus i , S_{Gi} = complex power injected by the generator at bus i , and S_{Di} = complex power drawn by the load at bus i . According to conservation of complex power, at any bus i , the complex power injected into the bus must be equal to the sum of complex power flows out of the bus via the transmission lines. Hence,

$$S_i = \sum_{j=1}^n S_{ij} \quad (3)$$

where S_{ij} is the sum over all lines connected to the bus and n is the number of buses in the system (excluding the ground). The bus current injected at the bus- i is defined as

$$I_i = I_{Gi} - I_{Di} \quad i = 1, 2, \dots, n \quad (4)$$

where I_{Gi} is the current injected by the generator at the bus and I_{Di} is the current drawn by the load (demand) at that bus. In the bus frame of reference

$$I_{BUS} = Y_{BUS} V_{BUS} \quad (5)$$

where

$$I_{BUS} = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} \text{ is the vector of currents injected at the buses,}$$

Y_{BUS} is the bus admittance matrix, and

$$V_{BUS} = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_n \end{bmatrix} \text{ is the vector of complex bus voltages.}$$

Equation (5) can be considered as

$$I_i = \sum_{j=1}^n Y_{ij} V_j \quad \forall i = 1, 2, \dots, n \quad (6)$$

The complex power S_i is given by

$$\begin{aligned} S_i &= V_i I_i^* \\ &= V_i \left(\sum_{j=1}^n Y_{ij} V_j \right)^* \\ &= V_i \left(\sum_{j=1}^n Y_{ij}^* V_j^* \right) \end{aligned} \quad (7)$$

Let $V_i \triangleq |V_i| \angle \delta_i = |V_i| (\cos \delta_i + j \sin \delta_i)$

$$\delta_{ij} = \delta_i - \delta_j$$

$$Y_{ij} = G_{ij} + jB_{ij}$$

Hence from (7), we get,

$$S_i = \sum_{j=1}^n |V_i| |V_j| (\cos \delta_{ij} + j \sin \delta_{ij}) (G_{ij} - j B_{ij}) \quad (8)$$

Separating real and imaginary parts in (8) we obtain,

$$P_i = \sum_{j=1}^n |V_i| |V_j| (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \quad (9)$$

$$Q_i = \sum_{j=1}^n |V_i| |V_j| (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \quad (10)$$

An alternate form of P_i and Q_i can be obtained by representing Y_{ik} also in polar form as

$$Y_{ij} = |Y_{ij}| \angle \theta_{ij} \quad (11)$$

Again, we get from (7),

$$S_i = |V_i| \angle \delta_i \sum_{j=1}^n |Y_{ij}| \angle -\theta_{ij} |V_j| \angle -\delta_j \quad (12)$$

The real part of (12) gives P_i ,

$$\begin{aligned} P_i &= |V_i| \sum_{j=1}^n |Y_{ij}| |V_j| \cos(-\theta_{ij} + \delta_i - \delta_j) \\ &= |V_i| \sum_{j=1}^n |Y_{ij}| |V_j| \cos -(\theta_{ij} - \delta_i + \delta_j) \quad \text{or} \end{aligned}$$

$$P_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad \forall i = 1, 2, \dots, n, \quad (13)$$

Similarly, Q_i is imaginary part of (12) and is given by

$$Q_i = |V_i| \sum_{j=1}^n |Y_{ij}| |V_j| \sin -(\theta_{ij} - \delta_i + \delta_j) \quad \text{or}$$

$$Q_i = -\sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad \forall i = 1, 2, \dots, n \quad (14)$$

Equations (9)-(10) and (13)-(14) are the „power flow equations“ or the „load flow equations“ in two alternative forms, corresponding to the n-bus system, where each bus- i is characterized

by four variables, P_i , Q_i , $|V_i|$, and δ_i . Thus a total of $4n$ variables are

involved in these equations. The load flow equations can be solved for any $2n$ unknowns, if the other $2n$ variables are specified. This establishes the need for classification of buses of the system for load flow analysis into: PV bus, PQ bus, etc.

DATA FOR LOAD FLOW

Irrespective of the method used for the solution, the data required is common for any load flow. All data is normally in pu. The bus admittance matrix is formulated from these data. The various data required are as under:

System data: It includes: number of buses- n , number of PV buses, number of loads, number of transmission lines, number of transformers, number of shunt elements, the slack bus number, voltage magnitude of slack bus (angle is generally taken as 0°), tolerance limit, base MVA, and maximum permissible number of iterations.

Generator bus data: For every PV bus i , the data required includes the bus number, active power generation P_{Gi} , the specified voltage magnitude V_i , minimum reactive power limit $Q_{i,min}$, and maximum reactive power limit $Q_{i,max}$.

Load data: For all loads the data required includes the bus number, active power demand P_{Di} , and the reactive power demand Q_{Di} .

Transmission line data: For every transmission line connected between buses i and k the data includes the starting bus number i , ending bus number k , resistance of the line, reactance of the line and the half line charging admittance.

Transformer data:

For every transformer connected between buses i and k the data to be given includes: the starting bus number i , ending bus number k , resistance of the transformer, reactance of the transformer, and the off nominal turns-ratio a .

Shunt element data: The data needed for the shunt element includes the bus number where element is connected, and the shunt admittance ($G_{sh} + j B_{sh}$).

GAUSS – SEIDEL (GS) METHOD

The GS method is an iterative algorithm for solving non linear algebraic equations. An initial solution vector is assumed, chosen from past experiences, statistical data or from practical considerations. At every subsequent iteration, the solution is updated till convergence is reached. The GS method applied to power flow problem is as discussed below.

Case (a): Systems with PQ buses only:

Initially assume all buses to be PQ type buses, except the slack bus. This means that $(n-1)$ complex bus voltages have to be determined. For ease of programming, the slack bus is generally numbered as bus-1. PV buses are numbered in sequence and PQ buses are ordered next in sequence. This makes programming easier, compared to random ordering of buses. Consider the expression for the complex power at bus- i , given from (7), as:

$$S_i = V_i \left(\sum_{j=1}^n Y_{ij} V_j \right)^*$$

This can be written as

$$S_i^* = V_i^* \left(\sum_{j=1}^n Y_{ij} V_j \right) \quad (15)$$

Since $S_i^* = P_i - jQ_i$, we get,

$$\frac{P_i - jQ_i}{V_i^*} = \sum_{j=1}^n Y_{ij} V_j$$

So that,

$$\frac{P_i - jQ_i}{V_i^*} = Y_{ii} V_i + \sum_{\substack{j=1 \\ j \neq i}}^n Y_{ij} V_j \quad (16)$$

Rearranging the terms, we get,

$$V_i = \frac{1}{Y_{ii}} \left[\frac{P_i - jQ_i}{V_i^*} - \sum_{\substack{j=1 \\ j \neq i}}^n Y_{ij} V_j \right] \quad \forall i = 2, 3, \dots, n \quad (17)$$

Equation (17) is an implicit equation since the unknown variable, appears on both sides of the equation. Hence, it needs to be solved by an iterative technique. Starting from an initial estimate of all bus voltages, in the RHS of (17) the most recent values of the bus voltages is substituted. One iteration of the method involves computation of all the bus voltages. In Gauss-Seidel method, the value of the updated voltages are used in the computation of subsequent voltages in the same iteration, thus speeding up convergence. Iterations are carried out till the magnitudes of all bus voltages do not change by more than the tolerance value. Thus the algorithm for GS method is as under:

Algorithm for GS method

1. Prepare data for the given system as required.
2. Formulate the bus admittance matrix YBUS. This is generally done by the rule of inspection.
3. Assume initial voltages for all buses, 2,3,...n. In practical power systems, the magnitude of the bus voltages is close to 1.0 p.u. Hence, the complex bus voltages at all (n-1) buses (except slack bus) are taken to be $1.0 \angle 0^\circ$. This is normally referred as the **flat start** solution.
4. Update the voltages. In any $(k+1)st$ iteration, from (17) the voltages are given by

$$V_i^{(k+1)} = \frac{1}{Y_{ii}} \left[\frac{P_i - jQ_i}{(V_i^{(k)})^*} - \sum_{j=1}^{i-1} Y_{ij} V_j^{(k+1)} - \sum_{j=i+1}^n Y_{ij} V_j^{(k)} \right] \quad \forall i=2,3,\dots,n \quad (18)$$

Here note that when computation is carried out for bus-i, updated values are already available for buses 2,3,...(i-1) in the current $(k+1)st$ iteration. Hence these values are used. For buses $(i+1).....n$, values from previous, kth iteration are used.

$$|\Delta V_i^{(k+1)}| = |V_i^{(k+1)} - V_i^{(k)}| < \epsilon \quad \forall i=2,3,\dots,n \quad (19)$$

Where, ϵ is the tolerance value. Generally it is customary to use a value of 0.0001 pu. Compute slack bus power after voltages have converged using (15) [assuming bus 1 is slack bus].

$$S_1^* = P_1 - jQ_1 = V_1^* \left(\sum_{j=1}^n Y_{1j} V_j \right) \quad (20)$$

7. Compute all line flows.

8. The complex power loss in the line is given by $S_{ik} + S_{ki}$. The total loss in the system is calculated by summing the loss over all the lines.

Case (b): Systems with PV buses also present:

At PV buses, the magnitude of voltage and not the reactive power is specified. Hence it is needed to first make an estimate of Q_i to be used in (18). From (15) we have

$$Q_i = -\text{Im} \left\{ V_i^* \sum_{j=1}^n Y_{ij} V_j \right\}$$

Where Im stands for the imaginary part. At any $(k+1)^{\text{st}}$ iteration, at the PV bus- i ,

$$Q_i^{(k+1)} = -\text{Im} \left\{ (V_i^{(k)})^* \sum_{j=1}^{i-1} Y_{ij} V_j^{(k+1)} + (V_i^{(k)})^* \sum_{j=i}^n Y_{ij} V_j^{(k)} \right\} \quad (21)$$

The steps for i^{th} PV bus are as follows:

1. Compute $Q_i^{(k+1)}$ using (21)
2. Calculate V_i using (18) with $Q_i = Q_i^{(k+1)}$
3. Since $|V_i|$ is specified at the PV bus, the magnitude of V_i obtained in step 2

has to be modified and set to the specified value $|V_{i,sp}|$. Therefore,

$$V_i^{(k+1)} = |V_{i,sp}| \angle \delta_i^{(k+1)} \quad (22)$$

The voltage computation for PQ buses does not change.

Case (c): Systems with PV buses with reactive power generation limits specified:

In the previous algorithm if the Q limit at the voltage controlled bus is violated during any iteration, i.e. $(k+1)$ Q computed using (21) is either less than $Q_{i,\min}$ or greater than $Q_{i,\max}$, it means that the voltage cannot be maintained at the specified value due to lack of reactive power support. This bus is then treated as a PQ bus in the $(k+1)^{\text{st}}$ iteration and the voltage is calculated with the value of Q_i set as follows:

If $Q_i < Q_{i,\min}$

If $Q_i > Q_{i,\max}$

Then $Q_i = Q_{i,\min}$.

Then $Q_i = Q_{i,\max}$.

(23)

If in the subsequent iteration, if Q_i falls within the limits, then the bus can be switched back to PV status.

Acceleration of convergence

It is found that in GS method of load flow, the number of iterations increase with increase in the size of the system. The number of iterations required can be reduced if the correction in voltage at each bus is accelerated, by multiplying with a constant α , called the acceleration factor. In the $(k+1)^{\text{st}}$ iteration we can let

$$V_i^{(k+1)}(\text{accelerate } d) = V_i^{(k)} + \alpha (V_i^{(k+1)} - V_i^{(k)}) \quad (24)$$

where α is a real number. When $\alpha = 1$, the value of $(k+1)$ is the computed value. If $1 < \alpha$

< 2 then the value computed is extrapolated. Generally α is taken between 1.2 to 1.6, for GS load flow procedure. At PQ buses (pure load buses) if the voltage magnitude violates

the limit, it simply means that the specified reactive power demand cannot be supplied, with the voltage maintained within acceptable limits.

Examples on GS load flow analysis:

Example-1: Obtain the voltage at bus 2 for the simple system shown in Fig 2, using the Gauss–Seidel method, if $V_1 = 1 \angle 0^\circ$ pu.

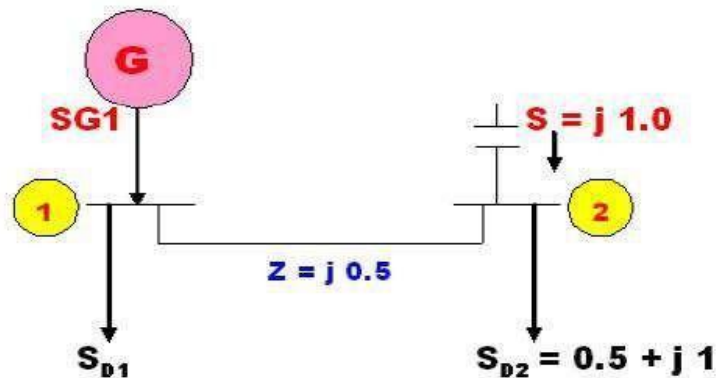


Fig : System of Example 1

Solution:

Here the capacitor at bus 2, injects a reactive power of 1.0 pu. The complex power injection at bus 2 is

$$S_2 = j1.0 - (0.5 + j 1.0) = -0.5 \text{ pu.}$$

$$V_1 = 1 \angle 0^\circ$$

$$Y_{\text{BUS}} = \begin{bmatrix} -j2 & j2 \\ j2 & -j2 \end{bmatrix}$$

$$V_2^{(k+1)} = \frac{1}{Y_{22}} \left[\frac{P_2 - jQ_2}{(V_2^{(k)})^*} - Y_{21} V_1 \right]$$

Since V_1 is specified it is a constant through all the iterations. Let the initial voltage at bus 2, $V_2^0 = 1 + j 0.0 = 1 \angle 0^\circ$ pu.

$$\begin{aligned}
 V_2^1 &= \frac{1}{-j2} \left[\frac{-0.5}{1 \angle 0^\circ} - (j2 \times 1 \angle 0^\circ) \right] \\
 &= 1.0 - j0.25 = 1.030776 \angle -14.036^\circ \\
 V_2^2 &= \frac{1}{-j2} \left[\frac{-0.5}{1.030776 \angle 14.036^\circ} - (j2 \times 1 \angle 0^\circ) \right] \\
 &= 0.94118 - j 0.23529 = 0.970145 \angle -14.036^\circ \\
 V_2^3 &= \frac{1}{-j2} \left[\frac{-0.5}{0.970145 \angle 14.036^\circ} - (j2 \times 1 \angle 0^\circ) \right] \\
 &= 0.9375 - j 0.249999 = 0.970261 \angle -14.931^\circ \\
 V_2^4 &= \frac{1}{-j2} \left[\frac{-0.5}{0.970261 \angle 14.931^\circ} - (j2 \times 1 \angle 0^\circ) \right] \\
 &= 0.933612 - j 0.248963 = 0.966237 \angle -14.931^\circ \\
 V_2^5 &= \frac{1}{-j2} \left[\frac{-0.5}{0.966237 \angle 14.931^\circ} - (j2 \times 1 \angle 0^\circ) \right] \\
 &= 0.933335 - j 0.25 = 0.966237 \angle -14.995^\circ
 \end{aligned}$$

Since the difference in the voltage magnitudes is less than 10⁻⁶ pu, the iterations can be stopped. To compute line flow

$$I_{12} = \frac{V_1 - V_2}{Z_{12}} = \frac{1 \angle 0^\circ - 0.966237 \angle -14.995^\circ}{j0.5}$$

$$= 0.517472 \angle -14.931^\circ$$

$$S_{12} = V_1 I_{12}^* = 1 \angle 0^\circ \times 0.517472 \angle 14.931^\circ$$

$$= 0.5 + j 0.133329 \text{ pu}$$

$$I_{21} = \frac{V_2 - V_1}{Z_{12}} = \frac{0.966237 \angle -14.995^\circ - 1 \angle 0^\circ}{j0.5}$$

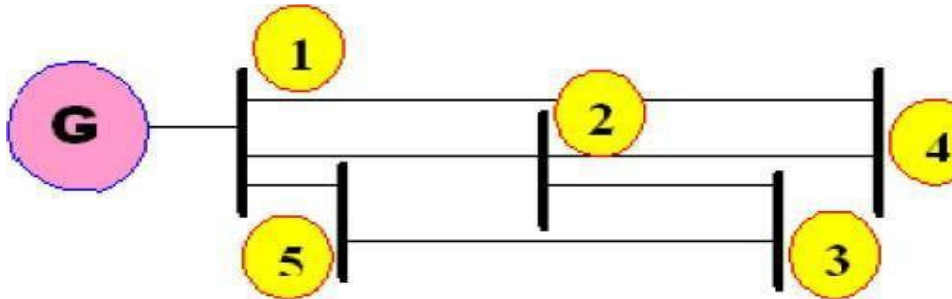
$$= 0.517472 \angle -194.93^\circ$$

$$S_{21} = V_2 I_{21}^* = -0.5 + j 0.0 \text{ pu}$$

The total loss in the line is given by $S_{12} + S_{21} = j 0.133329 \text{ pu}$. Obviously, it is observed that there is no real power loss, since the line has no resistance.

Example-2:

For the power system shown in fig. below, with the data as given in tables below, obtain the bus voltages at the end of first iteration, by applying GS method.



Power System of Example 2

Line data of example 2

SB	EB	R (pu)	X (pu)	$\frac{B_C}{2}$
1	2	0.10	0.40	-
1	4	0.15	0.60	-
1	5	0.05	0.20	-
2	3	0.05	0.20	-
2	4	0.10	0.40	-
3	5	0.05	0.20	-

Bus data of example 2

Bus No.	P_G (pu)	Q_G (pu)	P_D (pu)	Q_D (pu)	$ V_{SP} $ (pu)	δ
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Solution: In this example, we have,

- Bus 1 is slack bus, Bus 2, 4, 5 are PQ buses, and Bus 3 is PV bus
- The lines do not have half line charging admittances

$$P_2 + jQ_2 = P_{G2} + jQ_{G2} - (P_{D2} + jQ_{D2}) = -0.6 - j0.3$$

$$P_3 + jQ_3 = P_{G3} + jQ_{G3} - (P_{D3} + jQ_{D3}) = 1.0 + jQ_{G3}$$

$$\text{Similarly } P_4 + jQ_4 = -0.4 - j0.1, \quad P_5 + jQ_5 = -0.6 - j0.2$$

The Y_{bus} formed by the rule of inspection is given by:

$$Y_{bus} = \begin{bmatrix} 2.15685 & -0.58823 & 0.0+j0.0 & -0.39215 & -1.17647 \\ -j8.62744 & +j2.35294 & & +j1.56862 & +j4.70588 \\ -0.58823 & 2.35293 & -1.17647 & -0.58823 & 0.0+j0.0 \\ +j2.35294 & -j9.41176 & +j4.70588 & +j2.35294 & \\ 0.0+j0.0 & -1.17647 & 2.35294 & 0.0+j0.0 & -1.17647 \\ & +j4.70588 & -j9.41176 & & +j4.70588 \\ -0.39215 & -0.58823 & 0.0+j0.0 & 0.98038 & 0.0+j0.0 \\ +j1.56862 & +j2.35294 & & -j3.92156 & \\ -1.17647 & 0.0+j0.0 & -1.17647 & 0.0+j0.0 & 2.35294 \\ +j4.70588 & & +j4.70588 & & -j9.41176 \end{bmatrix}$$

The voltages at all PQ buses are assumed to be equal to $1+j0.0$ pu. The slack bus voltage is taken to be $V_1^0 = 1.02+j0.0$ in all iterations.

$$\begin{aligned} V_2^1 &= \frac{1}{Y_{22}} \left[\frac{P_2 - jQ_2}{V_2^{o*}} - Y_{21} V_1^o - Y_{23} V_3^0 - Y_{24} V_4^0 - Y_{25} V_5^0 \right] \\ &= \frac{1}{Y_{22}} \left[\frac{-0.6 + j0.3}{1.0 - j0.0} - \{(-0.58823 + j2.35294) \times 1.02 \angle 0^\circ\} \right. \\ &\quad \left. - \{(-1.17647 + j4.70588) \times 1.04 \angle 0^\circ\} - \{(-0.58823 + j2.35294) \times 1.0 \angle 0^\circ\} \right] \\ &= 0.98140 \angle -3.0665^\circ = 0.97999 - j0.0525 \end{aligned}$$

Bus 3 is a PV bus. Hence, we must first calculate Q_3 . This can be done as under:

$$\begin{aligned} Q_3 &= |V_3| |V_1| (G_{31} \sin \delta_{31} - B_{31} \cos \delta_{31}) + |V_3| |V_2| (G_{32} \sin \delta_{32} - B_{32} \cos \delta_{32}) \\ &\quad + |V_3|^2 (G_{33} \sin \delta_{33} - B_{33} \cos \delta_{33}) + |V_3| |V_4| (G_{34} \sin \delta_{34} - B_{34} \cos \delta_{34}) \\ &\quad + |V_3| |V_5| (G_{35} \sin \delta_{35} - B_{35} \cos \delta_{35}) \end{aligned}$$

We note that $\delta_1 = 0^\circ$; $\delta_2 = -3.0665^\circ$; $\delta_3 = 0^\circ$; $\delta_4 = 0^\circ$ and $\delta_5 = 0^\circ$

$$\therefore \delta_{31} = \delta_{33} = \delta_{34} = \delta_{35} = 0^\circ \quad (\delta_{ik} = \delta_i - \delta_k); \quad \delta_{32} = 3.0665^\circ$$

$$\begin{aligned} Q_3 &= 1.04 [1.02 (0.0+j0.0) + 0.9814 \{-1.17647 \times \sin(3.0665^\circ) - 4.70588 \\ &\quad \times \cos(3.0665^\circ)\} + 1.04 \{-9.41176 \times \cos(0^\circ)\} + 1.0 \{0.0 + j0.0\} + 1.0 \{-4.70588 \times \cos(0^\circ)\}] \\ &= 1.04 [-4.6735 + 9.78823 - 4.70588] = 0.425204 \text{ pu.} \end{aligned}$$

$$V_3^1 = \frac{1}{Y_{33}} \left[\frac{P_3 - jQ_3}{V_3^{o*}} - Y_{31} V_1^o - Y_{32} V_2^1 - Y_{34} V_4^0 - Y_{35} V_5^0 \right]$$

$$\begin{aligned}
&= \frac{1}{Y_{33}} \left[\frac{1.0 - j0.425204}{1.04 - j0.0} - \{(-1.7647 + j4.70588) \times (0.98140 \angle -3.0665^\circ)\} \right. \\
&\quad \left. - \{(-1.17647 + j4.70588) \times (1 \angle 0^\circ)\} \right] \\
&= 1.05569 \angle 3.077^\circ = 1.0541 + j0.05666 \text{ pu.}
\end{aligned}$$

Since it is a PV bus, the voltage magnitude is adjusted to specified value and V_3^1 is computed as: $V_3^1 = 1.04 \angle 3.077^\circ \text{ pu}$

$$\begin{aligned}
V_4^1 &= \frac{1}{Y_{44}} \left[\frac{P_4 - jQ_4}{V_4^{o*}} - Y_{41} V_1^o - Y_{42} V_2^1 - Y_{43} V_3^1 - Y_{45} V_5^o \right] \\
&= \frac{1}{Y_{44}} \left[\frac{-0.4 + j0.1}{1.0 - j0.0} - \{(-0.39215 + j1.56862) \times 1.02 \angle 0^\circ\} \right. \\
&\quad \left. - \{(-0.58823 + j2.35294) \times (0.98140 \angle -3.0665^\circ)\} \right] \\
&= \frac{0.45293 - j3.8366}{0.98038 - j3.92156} = 0.955715 \angle -7.303^\circ \text{ pu} = 0.94796 - j0.12149
\end{aligned}$$

$$\begin{aligned}
V_5^1 &= \frac{1}{Y_{55}} \left[\frac{P_5 - jQ_5}{V_5^{o*}} - Y_{51} V_1^o - Y_{52} V_2^1 - Y_{53} V_3^1 - Y_{54} V_4^1 \right] \\
&= \frac{1}{Y_{55}} \left[\frac{-0.6 + j0.2}{1.0 - j0.0} - \{(-1.17647 + j4.70588) \times 1.02 \angle 0^\circ\} \right. \\
&\quad \left. - \{(-1.17647 + j4.70588) \times 1.04 \angle 3.077^\circ\} \right] \\
&= 0.994618 \angle -1.56^\circ = 0.994249 - j0.027
\end{aligned}$$

Thus at end of 1st iteration, we have,

$$\begin{aligned}
V_1 &= 1.02 \angle 0^\circ \text{ pu} & V_2 &= 0.98140 \angle -3.066^\circ \text{ pu} \\
V_3 &= 1.04 \angle 3.077^\circ \text{ pu} & V_4 &= 0.955715 \angle -7.303^\circ \text{ pu} \\
\text{and} & & V_5 &= 0.994618 \angle -1.56^\circ \text{ pu}
\end{aligned}$$

Example-3:

Obtain the load flow solution at the end of first iteration of the system with data as given below. The solution is to be obtained for the following cases

- (i) All buses except bus 1 are PQ Buses
- (ii) Bus 2 is a PV bus whose voltage magnitude is specified as 1.04 pu

- (iii) Bus 2 is PV bus, with voltage magnitude specified as 1.04 and 0.25_Q2_1.0 pu.

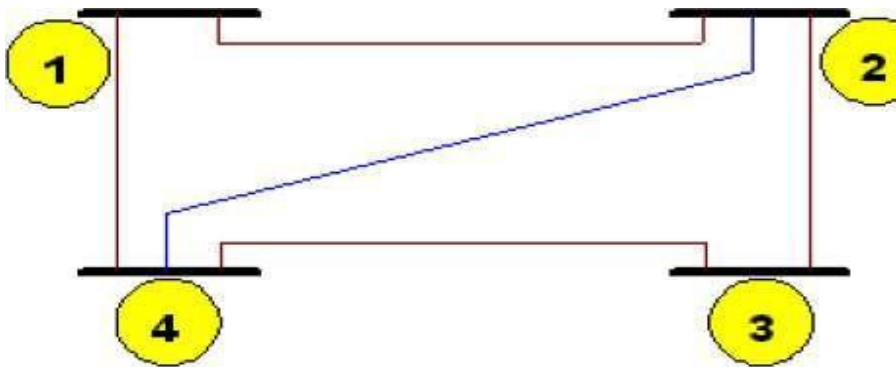


Fig. System for Example 3

Table: Line data of example 3

SB	EB	R (pu)	X (pu)
1	2	0.05	0.15
1	3	0.10	0.30
2	3	0.15	0.45
2	4	0.10	0.30
3	4	0.05	0.15

Table: Bus data of example 3

Bus No.	P_i (pu)	Q_i (pu)	V_i
1	—	—	$1.04 \angle 0^\circ$
2	0.5	- 0.2	—
3	- 1.0	0.5	—
4	- 0.3	- 0.1	—

Solution: Note that the data is directly in terms of injected powers at the buses. The bus admittance matrix is formed by inspection as under:

$$Y_{\text{BUS}} = \begin{array}{c} \begin{array}{|c|c|c|c|} \hline 3.0 - j9.0 & -2.0 + j6.0 & -1.0 + j3.0 & 0 \\ \hline -2.0 + j6.0 & 3.666 - j11.0 & -0.666 + j2.0 & -1.0 + j3.0 \\ \hline -1.0 + j3.0 & -0.666 + j2.0 & 3.666 - j11.0 & -2.0 + j6.0 \\ \hline 0 & -1.0 + j3.0 & -2.0 + j6.0 & 3.0 - j9.0 \\ \hline \end{array} \end{array}$$

Case(i): All buses except bus 1 are PQ Buses

Assume all initial voltages to be $1.0 \angle 0^\circ$ pu.

$$V_2^1 = \frac{1}{Y_{22}} \left[\frac{P_2 - jQ_2}{V_2^{o*}} - Y_{21} V_1^o - Y_{23} V_3^0 - Y_{24} V_4^0 \right]$$

$$\begin{aligned}
&= \frac{1}{Y_{22}} \left[\frac{0.5 + j0.2}{1.0 - j0.0} - \{(-2.0 + j6.0) \times (1.04 \angle 0^\circ)\} \right. \\
&\quad \left. - \{(-0.666 + j2.0) \times (1.0 \angle 0^\circ)\} - \{(-1.0 + j3.0) \times (1.0 \angle 0^\circ)\} \right] \\
&= 1.02014 \angle 2.605^\circ
\end{aligned}$$

$$\begin{aligned}
V_3^1 &= \frac{1}{Y_{33}} \left[\frac{P_3 - jQ_3}{V_3^{o*}} - Y_{31} V_1^o - Y_{32} V_2^1 - Y_{34} V_4^0 \right] \\
&= \frac{1}{Y_{33}} \left[\frac{-1.0 - j0.5}{1.0 - j0.0} - \{(-1.0 + j3.0) \times (1.04 \angle 0.0^\circ)\} \right. \\
&\quad \left. - \{(-0.666 + j2.0) \times (1.02014 \angle 2.605^\circ)\} - \{(-2.0 + j6.0) \times (1.0 \angle 0^\circ)\} \right] \\
&= 1.03108 \angle -4.831^\circ
\end{aligned}$$

$$\begin{aligned}
V_4^1 &= \frac{1}{Y_{44}} \left[\frac{P_4 - jQ_4}{V_4^{o*}} - Y_{41} V_1^o - Y_{42} V_2^1 - Y_{43} V_3^1 \right] \\
&= \frac{1}{Y_{44}} \left[\frac{0.3 + j0.1}{1.0 - j0.0} - \{(-1.0 + j3.0) \times (1.02014 \angle 2.605^\circ)\} \right. \\
&\quad \left. - \{(-2.0 + j6.0) \times (1.03108 \angle -4.831^\circ)\} \right] \\
&= 1.02467 \angle -0.51^\circ
\end{aligned}$$

Hence

$$V_1^1 = 1.04 \angle 0^\circ \text{ pu} \qquad V_2^1 = 1.02014 \angle 2.605^\circ \text{ pu}$$

$$V_3^1 = 1.03108 \angle -4.831^\circ \text{ pu} \qquad V_4^1 = 1.02467 \angle -0.51^\circ \text{ pu}$$

Case(ii): Bus 2 is a PV bus whose voltage magnitude is specified as 1.04 pu

We first compute Q_2 .

$$\begin{aligned} Q_2 &= |V_2| \left[|V_1| (G_{21} \sin \delta_{21} - B_{21} \cos \delta_{21}) + |V_2| (G_{22} \sin \delta_{22} - B_{22} \cos \delta_{22}) \right. \\ &\quad \left. + |V_3| (G_{23} \sin \delta_{23} - B_{23} \cos \delta_{23}) + |V_4| (G_{24} \sin \delta_{24} - B_{24} \cos \delta_{24}) \right] \\ &= 1.04 [1.04 \{-6.0\} + 1.04 \{11.0\} + 1.0\{-2.0\} + 1.0 \{-3.0\}] = 0.208 \text{ pu.} \end{aligned}$$

$$\begin{aligned} V_2^1 &= \frac{1}{Y_{22}} \left[\frac{0.5 - j0.208}{1.04 \angle 0^\circ} - \{(-2.0 + j6.0) \times (1.04 \angle 0^\circ)\} \right. \\ &\quad \left. - \{(-0.666 + j2.0) \times (1.0 \angle 0^\circ)\} - \{(-1.0 + j3.0) \times (1.0 \angle 0^\circ)\} \right] \\ &= 1.051288 + j0.033883 \end{aligned}$$

The voltage magnitude is adjusted to 1.04. Hence $V_2^1 = 1.04 \angle 1.846^\circ$

$$\begin{aligned} V_3^1 &= \frac{1}{Y_{33}} \left[\frac{-1.0 - j0.5}{1.0 \angle 0^\circ} - \{(-1.0 + j3.0) \times (1.04 \angle 0.0^\circ)\} \right. \\ &\quad \left. - \{(-0.666 + j2.0) \times (1.04 \angle 1.846^\circ)\} - \{(-2.0 + j6.0) \times (1.0 \angle 0^\circ)\} \right] \\ &= 1.035587 \angle -4.951^\circ \text{ pu.} \end{aligned}$$

$$\begin{aligned} V_4^1 &= \frac{1}{Y_{44}} \left[\frac{0.3 + j0.1}{1.0 - j0.0} - \{(-1.0 + j3.0) \times (1.04 \angle 1.846^\circ)\} \right. \\ &\quad \left. - \{(-2.0 + j6.0) \times (1.035587 \angle -4.951^\circ)\} \right] \\ &= 0.9985 \angle -0.178^\circ \end{aligned}$$

Hence at end of 1st iteration we have:

$$V_1^1 = 1.04 \angle 0^\circ \text{ pu}$$

$$V_2^1 = 1.04 \angle 1.846^\circ \text{ pu}$$

$$V_3^1 = 1.035587 \angle -4.951^\circ \text{ pu}$$

$$V_4^1 = 0.9985 \angle -0.178^\circ \text{ pu}$$

Case (iii): Bus 2 is PV bus, with voltage magnitude specified as 1.04 & $0.25 \leq Q_2 \leq 1$ pu. If $0.25 \leq Q_2 \leq 1.0$ pu then the computed value of $Q_2 = 0.208$ is less than the lower limit. Hence, Q_2 is set equal to 0.25 pu. Iterations are carried out with this value of Q_2 . The voltage magnitude at bus 2 can no longer be maintained at 1.04. Hence, there is no necessity to adjust for the voltage magnitude. Proceeding as before we obtain at the end of first iteration,

$$\begin{aligned} V_1^1 &= 1.04 \angle 0^\circ \text{ pu} & V_2^1 &= 1.05645 \angle 1.849^\circ \text{ pu} \\ V_3^1 &= 1.038546 \angle -4.933^\circ \text{ pu} & V_4^1 &= 1.081446 \angle 4.896^\circ \text{ pu} \end{aligned}$$

Limitations of GS load flow analysis

GS method is very useful for very small systems. It is easily adoptable, it can be generalized and it is very efficient for systems having less number of buses. However, GS LFA fails to converge in systems with one or more of the features as under:

- Systems having large number of radial lines
- Systems with short and long lines terminating on the same bus
- Systems having negative values of transfer admittances
- Systems with heavily loaded lines, etc.

GS method successfully converges in the absence of the above problems. However, convergence also depends on various other set of factors such as: selection of slack bus, initial solution, acceleration factor, tolerance limit, level of accuracy of results needed, type and quality of computer/ software used, etc.

NEWTON –RAPHSON METHOD

Newton-Raphson (NR) method is used to solve a system of non-linear algebraic equations of the form $f(x) = 0$. Consider a set of n non-linear algebraic equations given by

$$f_i(x_1, x_2, \dots, x_n) = 0 \quad i = 1, 2, \dots, n \quad (25)$$

Let $x_1^0, x_2^0, \dots, x_n^0$, be the initial guess of unknown variables and $\Delta x_1^0, \Delta x_2^0, \dots, \Delta x_n^0$ be the respective corrections. Therefore,

$$f_i(x_1^0 + \Delta x_1^0, x_2^0 + \Delta x_2^0, \dots, x_n^0 + \Delta x_n^0) = 0 \quad i = 1, 2, \dots, n \quad (26)$$

The above equation can be expanded using Taylor's series to give

$$f_i(x_1^0, x_2^0, \dots, x_n^0) + \left[\left(\frac{\partial f_i}{\partial x_1} \right)^0 \Delta x_1^0 + \left(\frac{\partial f_i}{\partial x_2} \right)^0 \Delta x_2^0 + \dots + \left(\frac{\partial f_i}{\partial x_n} \right)^0 \Delta x_n^0 \right] + \text{Higher order terms} = 0 \quad \forall i = 1, 2, \dots, n \quad (27)$$

Where, $\left(\frac{\partial f_i}{\partial x_1} \right)^0, \left(\frac{\partial f_i}{\partial x_2} \right)^0, \dots, \left(\frac{\partial f_i}{\partial x_n} \right)^0$ are the partial derivatives of f_i with respect to $x_1, x_2, \dots, x_n$ respectively, evaluated at $(x_1^0, x_2^0, \dots, x_n^0)$. If the higher order terms are neglected, then (27) can be written in matrix form as

$$\begin{bmatrix} f_1^0 \\ f_2^0 \\ \vdots \\ f_n^0 \end{bmatrix} + \begin{bmatrix} \left(\frac{\partial f_1}{\partial x_1} \right)^0 & \left(\frac{\partial f_1}{\partial x_2} \right)^0 & \dots & \left(\frac{\partial f_1}{\partial x_n} \right)^0 \\ \left(\frac{\partial f_2}{\partial x_1} \right)^0 & \left(\frac{\partial f_2}{\partial x_2} \right)^0 & \dots & \left(\frac{\partial f_2}{\partial x_n} \right)^0 \\ \vdots & \vdots & \ddots & \vdots \\ \left(\frac{\partial f_n}{\partial x_1} \right)^0 & \left(\frac{\partial f_n}{\partial x_2} \right)^0 & \dots & \left(\frac{\partial f_n}{\partial x_n} \right)^0 \end{bmatrix} \begin{bmatrix} \Delta x_1^0 \\ \Delta x_2^0 \\ \vdots \\ \Delta x_n^0 \end{bmatrix} = 0 \quad (28)$$

In vector form (28) can be written as

$$F^0 + J^0 \Delta X^0 = 0$$

$$\text{Or} \quad F^0 = -J^0 \Delta X^0$$

$$\text{Or} \quad \Delta X^0 = -[J^0]^{-1} F^0 \quad (29)$$

$$\text{And} \quad X^1 = X^0 + \Delta X^0 \quad (30)$$

Here, the matrix $[J]$ is called the **Jacobian** matrix. The vector of unknown variables is updated using (30). The process is continued till the difference between two successive iterations is less than the tolerance value.

NR method for load flow solution in polar coordinates

In application of the NR method, we have to first bring the equations to be solved, to the form $f_i(x_1, x_2, \dots, x_n) = 0$, where $x_1, x_2, \dots, x_n$ are the unknown variables to be determined. Let us assume that the power system has n_1 PV buses and n_2 PQ buses. In polar coordinates the unknown variables to be determined are:

(i) δ_i , the angle of the complex bus voltage at bus i , at all the PV and PQ buses. This gives us $n_1 + n_2$ unknown variables to be determined.

(ii) $|V_i|$, the voltage magnitude of bus i , at all the PQ buses. This gives us n_2 unknown variables to be determined.

Therefore, the total number of unknown variables to be computed is: $n_1 + 2n_2$, for which we need $n_1 + 2n_2$ consistent equations to be solved. The equations are given by,

$$\Delta P_i = P_{i,sp} - P_{i,cal} = 0 \quad (31)$$

$$\Delta Q_i = Q_{i,sp} - Q_{i,cal} = 0 \quad (32)$$

Where $P_{i,sp}$ = Specified active power at bus i
 $Q_{i,sp}$ = Specified reactive power at bus i
 $P_{i,cal}$ = Calculated value of active power using voltage estimates.
 $Q_{i,cal}$ = Calculated value of reactive power using voltage estimates
 ΔP = Active power residue
 ΔQ = Reactive power residue

The real power is specified at all the PV and PQ buses. Hence (31) is to be solved at all PV and PQ buses leading to $n_1 + n_2$ equations. Similarly the reactive power is specified at all the PQ buses. Hence, (32) is to be solved at all PQ buses leading to n_2 equations.

We thus have $n_1 + 2n_2$ equations to be solved for $n_1 + 2n_2$ unknowns. (31) and (32) are of the form $F(x) = 0$. Thus NR method can be applied to solve them. Equations (31) and (32) can be written in the form of (30) as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \quad (33)$$

Where J_1, J_2, J_3, J_4 are the negated partial derivatives of ΔP and ΔQ with respect to corresponding δ and $|V|$. The negated partial derivative of ΔP , is same as the partial derivative of P_{cal} , since P_{sp} is a constant. The various computations involved are discussed in detail next.

Computation of P_{cal} and Q_{cal} :

The real and reactive powers can be computed from the load flow equations as:

$$\begin{aligned} P_{i,Cal} &= P_i = \sum_{k=1}^n |V_i| |V_k| (G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik}) \\ &= G_{ii} |V_i|^2 + \sum_{\substack{k=1 \\ k \neq i}}^n |V_i| |V_k| (G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik}) \end{aligned} \quad (34)$$

$$\begin{aligned} Q_{i,Cal} &= Q_i = \sum_{k=1}^n |V_i| |V_k| (G_{ik} \sin \delta_{ik} - B_{ik} \cos \delta_{ik}) \\ &= -B_{ii} |V_i|^2 + \sum_{\substack{k=1 \\ k \neq i}}^n |V_i| |V_k| (G_{ik} \sin \delta_{ik} - B_{ik} \cos \delta_{ik}) \end{aligned} \quad (35)$$

The powers are computed at any $(r+1)^{st}$ iteration by using the voltages available from previous iteration. The elements of the Jacobian are found using the above equations as:

Elements of J_1

$$\begin{aligned} \frac{\partial P_i}{\partial \delta_i} &= \sum_{\substack{k=1 \\ k \neq i}}^n |V_i| |V_k| \{G_{ik} (-\sin \delta_{ik}) + B_{ik} \cos \delta_{ik}\} \\ &= -Q_i - B_{ii} |V_i|^2 \\ \frac{\partial P_i}{\partial \delta_k} &= |V_i| |V_k| (G_{ik} (-\sin \delta_{ik})(-1) + B_{ik} (\cos \delta_{ik})(-1)) \end{aligned}$$

Elements of J_3

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{\substack{k=1 \\ k \neq i}}^n |V_i| |V_k| (G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik}) = P_i - G_{ii} |V_i|^2$$

$$\frac{\partial Q_i}{\partial \delta_k} = -|V_i| |V_k| (G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik})$$

Elements of J_2

$$\frac{\partial P_i}{\partial |V_i|} |V_i| = 2|V_i|^2 G_{ii} + |V_i| \sum_{\substack{k=1 \\ k \neq i}}^n |V_k| (G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik}) = P_i + |V_i|^2 G$$

$$\frac{\partial P_i}{\partial |V_k|} |V_k| = |V_i| |V_k| (G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik})$$

Elements of J_4

$$\frac{\partial P_i}{\partial |V_i|} |V_i| = -2|V_i|^2 B_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^n |V_i| |V_k| (G_{ik} \sin \delta_{ik} - B_{ik} \cos \delta_{ik}) = Q_i - |V_i|^2 G$$

$$\frac{\partial Q_i}{\partial |V_k|} |V_k| = |V_i| |V_k| (G_{ik} \sin \delta_{ik} - B_{ik} \cos \delta_{ik})$$

Thus, the linearized form of the equation could be considered again

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \frac{\Delta \delta}{|V|} \end{bmatrix}$$

The elements are summarized below:

$$(i) \quad H_{ii} = \frac{\partial P_i}{\partial \delta_i} = -Q_i - B_{ii} |V_i|^2$$

$$(ii) \quad H_{ik} = \frac{\partial P_i}{\partial \delta_k} = a_k f_i - b_k e_i = |V_i| |V_k| (G_{ik} \sin \delta_{ik} - B_{ik} \cos \delta_{ik})$$

$$(iii) \quad N_{ii} = \frac{\partial P_i}{\partial |V_i|} |V_i| = P_i + G_{ii} |V_i|^2$$

$$(iv) \quad N_{ik} = \frac{\partial P_i}{\partial |V_k|} |V_k| = a_k e_i + b_k f_i = |V_i| |V_k| (G_{ik} \cos \delta_{ik} + B_{ik} \sin \delta_{ik})$$

$$(v) \quad M_{ii} = \frac{\partial Q_i}{\partial \delta_i} = P_i - G_{ii} |V_i|^2$$

DECOUPLED LOAD FLOW

In the NR method, the inverse of the Jacobian has to be computed at every iteration. When solving large interconnected power systems, alternative solution methods are possible, taking into account certain observations made of practical systems. These are,

- Change in voltage magnitude $|V_i|$ at a bus primarily affects the flow of reactive power Q in the lines and leaves the real power P unchanged. This observation implies that $\frac{\partial Q_i}{\partial |V_j|}$ is much larger than $\frac{\partial P_i}{\partial |V_j|}$. Hence, in the Jacobian, the elements of the sub-matrix $[N]$, which contains terms that are partial derivatives of real power with respect to voltage magnitudes can be made zero.
- Change in voltage phase angle at a bus, primarily affects the real power flow P over the lines and the flow of Q is relatively unchanged. This observation implies that $\frac{\partial P_i}{\partial \delta_j}$ is much larger than $\frac{\partial Q_i}{\partial \delta_j}$. Hence, in the Jacobian the elements of the sub-matrix $[M]$, which contains terms that are partial derivatives of reactive power with respect to voltage phase angles can be made zero.

These observations reduce the NRLF linearised form of equation to

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \frac{\Delta |V|}{|V|} \end{bmatrix} \quad (37)$$

From (37) it is obvious that the voltage angle corrections $\Delta \delta$ are obtained using real power residues ΔP and the voltage magnitude corrections $\frac{\Delta |V|}{|V|}$ are obtained from reactive power residues ΔQ . This equation can be solved through two alternate strategies as under:

Strategy-1

- (i) Calculate $\Delta P^{(r)}, \Delta Q^{(r)}$ and $J^{(r)}$
- (ii) Compute
$$\begin{bmatrix} \Delta \delta^{(r)} \\ \Delta |V^{(r)}| \\ |V^{(r)}| \end{bmatrix} = [J^{(r)}]^{-1} \begin{bmatrix} \Delta P^{(r)} \\ \Delta Q^{(r)} \end{bmatrix}$$
- (iii) Update δ and $|V|$.
- (iv) Go to step (i) and iterate till convergence is reached.

Strategy-2

- (i) Compute $\Delta P^{(r)}$ and Sub-matrix $H^{(r)}$. From (37) find $\Delta \delta^{(r)} = [H^{(r)}]^{-1} \Delta P^{(r)}$
- (ii) Up date δ using $\delta^{(r+1)} = \delta^{(r)} + \Delta \delta^{(r)}$.
- (iii) Use $\delta^{(r+1)}$ to calculate $\Delta Q^{(r)}$ and $L^{(r)}$
- (iv) Compute
$$\frac{\Delta |V^{(r)}|}{|V^{(r)}|} = [L^{(r)}]^{-1} \Delta Q^{(r)}$$
- (v) Update, $|V^{(r+1)}| = |V^{(r)}| + \Delta |V^{(r)}|$
- (vi) Go to step (i) and iterate till convergence is reached.

In the first strategy, the variables are solved simultaneously. In the second strategy the iteration is conducted by first solving for $\Delta \delta$ and using updated values of δ to calculate $\Delta |V|$. Hence, the second strategy results in faster convergence, compared to the first strategy.

FAST DECOUPLED LOAD FLOW

If the coefficient matrices are constant, the need to update the Jacobian at every iteration is eliminated. This has resulted in development of fast decoupled load Flow (FDLF). Here, certain assumptions are made based on the observations of practical power systems as under:

- $B_{ij} \gg G_{ij}$ (Since the X/R ratio of transmission lines is high in well designed systems)

- The voltage angle difference $(\delta_i - \delta_j)$ between two buses in the system is very small. This means $\cos(\delta_i - \delta_j) \cong 1$ and $\sin(\delta_i - \delta_j) = 0.0$
- $Q_i \ll B_{ii}|V_i|^2$

With these assumptions the elements of the Jacobian become

$$H_{ik} = L_{ik} = -|V_i||V_k|B_{ik} \quad (i \neq k)$$

$$H_{ii} = L_{ii} = -B_{ii}|V_i|^2$$

The matrix (37) reduces to

$$\begin{aligned} [\Delta P] &= [|V_i||V_j|B'_{ij}] [\Delta \delta] \\ [\Delta Q] &= [|V_i||V_j|B''_{ij}] \left[\frac{\Delta |V|}{|V|} \right] \end{aligned} \quad (38)$$

Where B'_{ij} and B''_{ij} are negative of the susceptances of respective elements of the bus admittance matrix. In (38) if we divide LHS and RHS by $|V_i|$ and assume $|V_j| \cong 1$, we get,

$$\begin{aligned} \left[\frac{\Delta P}{|V|} \right] &= [B'_{ij}] [\Delta \delta] \\ \left[\frac{\Delta Q}{|V|} \right] &= [B''_{ij}] \left[\frac{\Delta |V|}{|V|} \right] \end{aligned} \quad (39)$$

Equations (39) constitute the Fast Decoupled load flow equations. Further simplification is possible by:

- Omitting effect of phase shifting transformers
- Setting off-nominal turns ratio of transformers to 1.0
- In forming B'_{ij} , omitting the effect of shunt reactors and capacitors which mainly affect reactive power
- Ignoring series resistance of lines in forming the Y_{bus} .

With these assumptions we obtain a loss-less network. In the FDLF method, the matrices $[B']$ and $[B'']$ are constants and need to be inverted only once at the beginning of the iterations.

REPRESENTATION OF TAP CHANGING TRANSFORMERS

Consider a tap changing transformer represented by its admittance connected in series with an ideal autotransformer as shown (a = turns ratio of transformer)

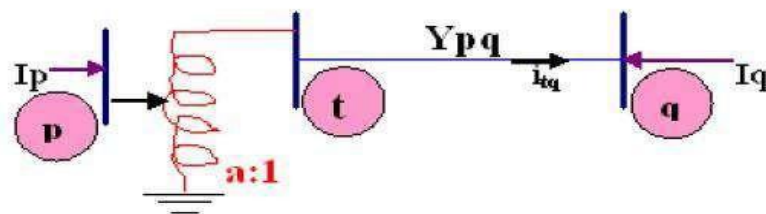


Fig. 2. Equivalent circuit of a tap setting transformer

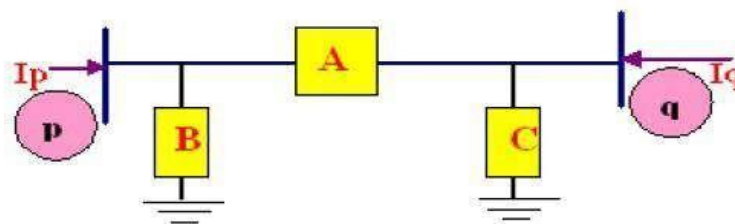


Fig. 3. π -Equivalent circuit of Fig.2 above.

By equating the bus currents in both the mutually equivalent circuits as above, it can be shown that the π -equivalent circuit parameters are given by the expressions as under:

(i) **Fixed tap setting transformers (on no load)**

$$A = Y_{pq} / a$$

$$B = 1/a (1/a - 1) Y_{pq}$$

$$C = (1 - 1/a) Y_{pq}$$

(i) Tap changing under load (TCUL) transformers (on load)

$$A = Y_{pq}$$

$$B = (1/a - 1) (1/a + 1 - E_q/E_p) Y_{pq}$$

$$C = (1 - 1/a) (E_p/E_q) Y_{pq}$$

Thus, here, in the case of TCUL transformers, the shunt admittance values are observed to be a function of the bus voltages.

COMPARISON OF LOAD FLOW METHODS

The comparison of the methods should take into account the computing time required for preparation of data in proper format and data processing, programming ease, storage requirements, computation time per iteration, number of iterations, ease and time required for modifying network data when operating conditions change, etc. Since all the methods presented are in the bus frame of reference in admittance form, the data preparation is same for all the methods and the bus admittance matrix can be formed using a simple algorithm, by the rule of inspection. Due to simplicity of the equations, Gauss-Seidel method is relatively easy to program. Programming of NR method is more involved and becomes more complicated if the buses are randomly numbered. It is easier to program, if the PV buses are ordered in sequence and PQ buses are also ordered in sequence.

The storage requirements are more for the NR method, since the Jacobian elements have to be stored. The memory is further increased for NR method using rectangular coordinates. The storage requirement can be drastically reduced by using sparse matrix techniques, since both the admittance matrix and the Jacobian are sparse matrices. The time taken for a single iteration depends on the number of arithmetic and logical operations required to be performed in a full iteration. The Gauss –Seidel method requires the fewest number of operations to complete iteration. In the NR method, the computation of the Jacobian is necessary in every iteration. Further, the inverse of the Jacobian also has to be computed. Hence, the time per iteration is larger than in the GS method and is roughly about 7 times that of the GS method, in large systems, as depicted graphically in figure below. Computation time can be reduced if

the Jacobian is updated once in two or three iterations. In FDLF method, the Jacobian is constant and needs to be computed only once. In both NR and FDLF methods, the time per iteration increases directly as the number of buses.

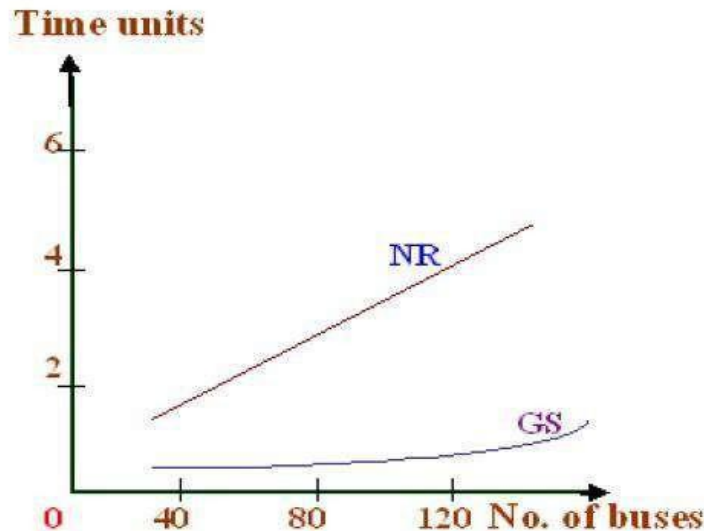


Figure 4. Time per Iteration in GS and NR methods

The number of iterations is determined by the convergence characteristic of the method. The GS method exhibits a linear convergence characteristic as compared to the NR method which has a quadratic convergence. Hence, the GS method requires more number of iterations to get a converged solution as compared to the NR method. In the GS method, the number of iterations increases directly as the size of the system increases. In contrast, the number of iterations is relatively constant in NR and FDLF methods. They require about 5-8 iterations for convergence in large systems. A significant increase in rate of convergence can be obtained in the GS method if an acceleration factor is used. All these variations are shown graphically in figure below. The number of iterations also depends on the required accuracy of the solution. Generally, a voltage tolerance of 0.0001 pu is used to obtain acceptable accuracy and the real power mismatch and reactive power mismatch can be taken as 0.001 pu. Due to these reasons, the NR method is faster and more reliable for large systems. The convergence of FDLF method is geometric and its speed is nearly 4-5 times that of NR method.

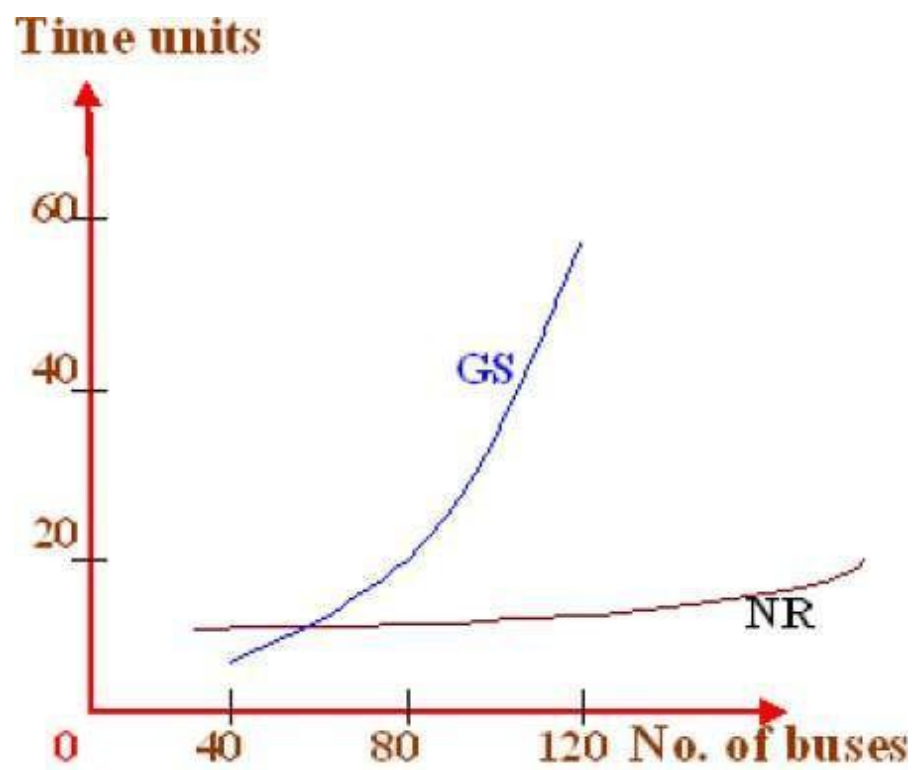
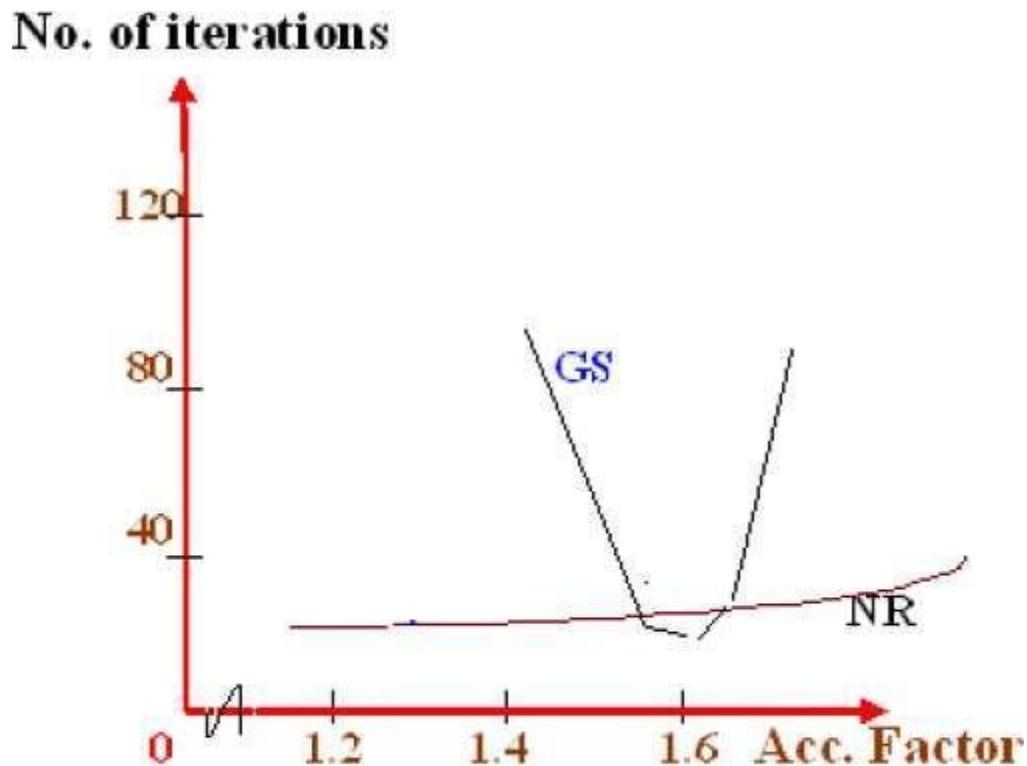


Figure 5. Total time of Iteration in GS and NR methods



**Figure 6. Influence of acceleration factor
on load flow methods**

FINAL WORD

In this chapter, the load flow problem, also called as the power flow problem, has been considered in detail. The load flow solution gives the complex voltages at all the buses and the complex power flows in the lines. Though, algorithms are available using the impedance form of the equations, the sparsity of the bus admittance matrix and the ease of building the bus admittance matrix, have made algorithms using the admittance form of equations more popular. The most popular methods are the Gauss-Seidel method, the Newton-Raphson method and the Fast Decoupled Load Flow method. These methods have been discussed in detail with illustrative examples. In smaller systems, the ease of programming and the memory requirements, make GS method attractive. However, the computation time increases with increase in the size of the system. Hence, in large systems NR and FDLF methods are more popular. There is a trade off between various requirements like speed, storage, reliability, computation time, convergence characteristics etc. No single method has all the desirable features. However, NR method is most popular because of its versatility, reliability and accuracy.

UNIT-3

ECONOMIC OPERATION OF POWER SYSTEM

INTRODUCTION

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

- i) Problem of *economic dispatch*, which deals with determining the power output of each plant to meet the specified load, such that the overall fuel cost is minimized.
- ii) Problem of *optimal power flow*, which deals with minimum – loss delivery, where in the power flow, is optimized to minimize losses in the system. In this chapter we consider the problem of economic dispatch.

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

- i) Base supply without regulation: the output is a constant.
- ii) Base supply with regulation: output power is regulated based on system load.
- iii) Automatic non-economic regulation: output level changes around a base setting as area control error changes.
- iv) Automatic economic regulation: output level is adjusted, with the area load and area control error, while tracking an economic setting.

Regardless of the units operating state, it has a contribution to the economic operation, even though its output is changed for different reasons. The factors influencing the cost of generation are the generator efficiency, fuel cost and transmission losses. The most efficient generator may not give minimum cost, since it may be located in a place where fuel cost is high. Further, if the plant is located far from the load centers, transmission losses may be high and running the plant may become uneconomical. The economic dispatch problem basically determines the generation of different plants to minimize total operating cost.

Modern generating plants like nuclear plants, geo-thermal plants etc, may require capital investment of millions of rupees. The economic dispatch is however determined in terms of fuel cost per unit power generated and does not include capital investment, maintenance, depreciation, start-up and shut down costs etc.

PERFORMANCE CURVES**INPUT-OUTPUT CURVE**

This is the fundamental curve for a thermal plant and is a plot of the input in British thermal units (Btu) per hour versus the power output of the plant in MW as shown in Fig1.

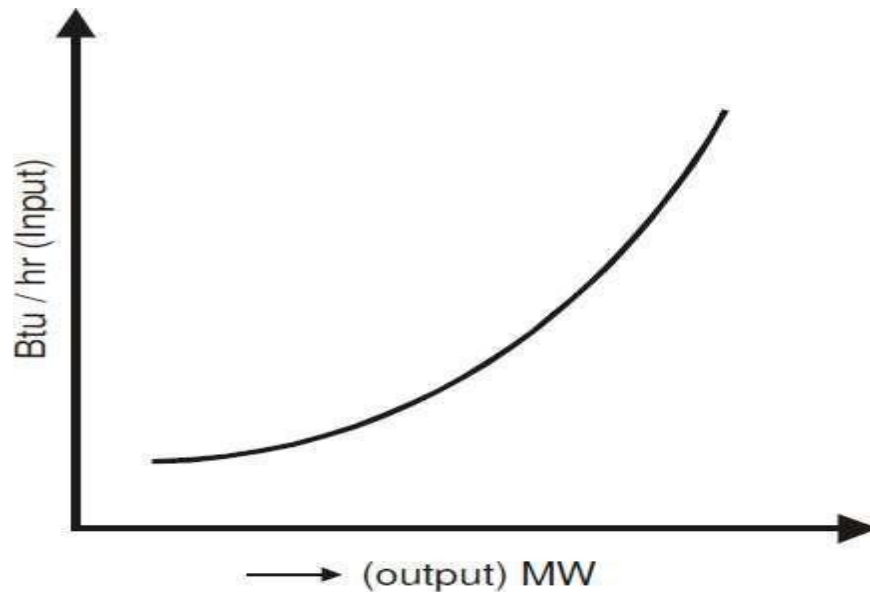


Fig 1: Input – output curve

HEAT RATE CURVE

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

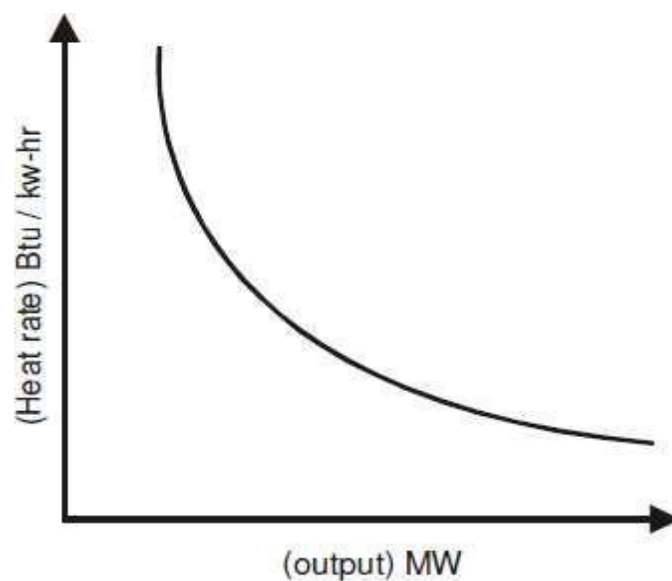


Fig .2 Heat rate curve.

INCREMENTAL FUEL RATE CURVE

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

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

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

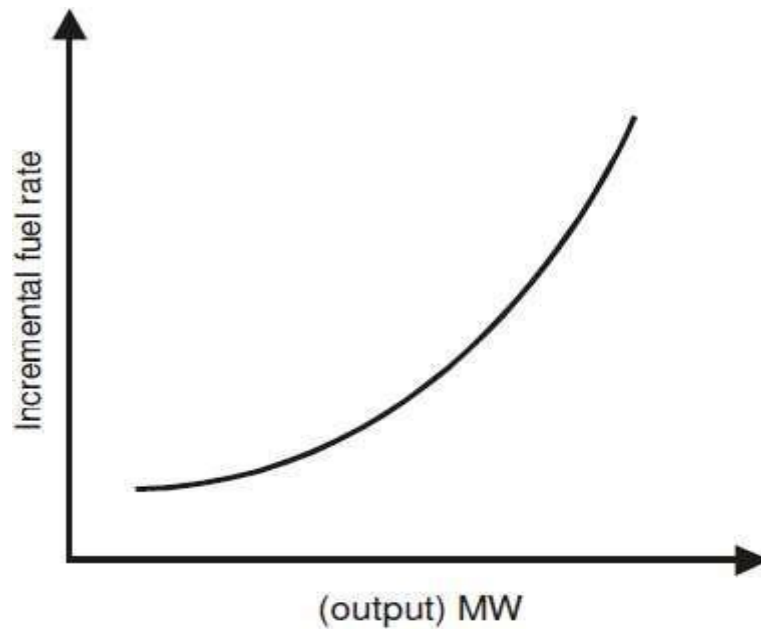


Fig 3: Incremental fuel rate curve

Incremental cost curve

The incremental cost is the product of incremental fuel rate and fuel cost (Rs / Btu or \$ / Btu). The curve is shown in Fig. 4. The unit of the incremental fuel cost is Rs / MWh or \$ / MWh.

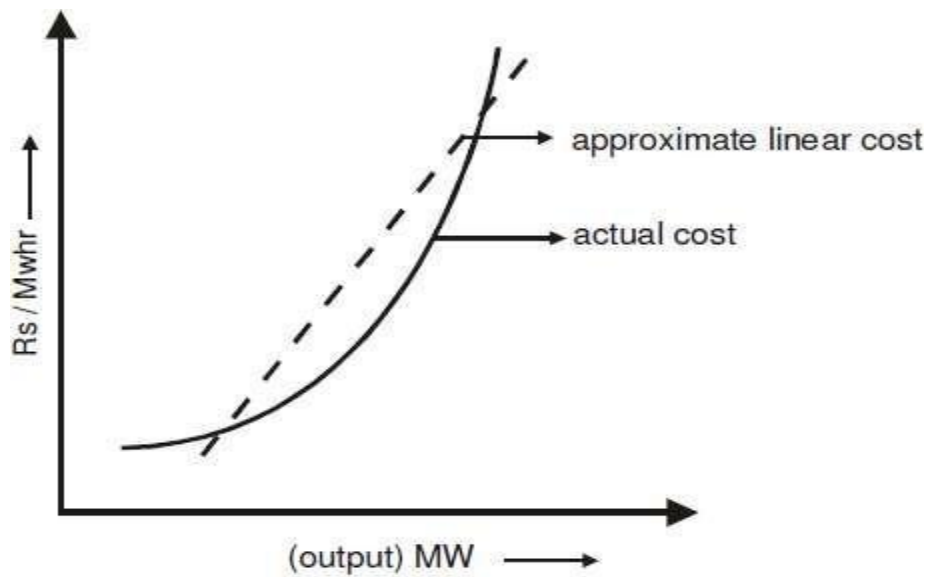


Fig 4: Incremental cost curve

In general, the fuel cost F_i for a plant, is approximated as a quadratic function of the generated output P_{Gi} .

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

The incremental fuel cost is given by

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

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

ECONOMIC GENERATION SCHEDULING NEGLECTING LOSSES AND GENERATOR LIMITS

The simplest case of economic dispatch is the case when transmission losses are neglected. The model does not consider the system configuration or line impedances. Since losses are neglected, the total generation is equal to the total demand P_D . Consider a system with n_g number of generating plants supplying the total demand P_D . If F_i is the

cost of plant i in Rs/h, the mathematical formulation of the problem of economic scheduling can be stated as follows:

$$\begin{aligned} \text{Minimize} \quad & F_T = \sum_{i=1}^{n_g} F_i \\ \text{Such that} \quad & \sum_{i=1}^{n_g} P_{Gi} = P_D \end{aligned}$$

where F_T = total cost.
 P_{Gi} = generation of plant i .
 P_D = total demand.

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

LAGRANGE METHOD FOR SOLUTION OF ECONOMIC SCHEDULE

The problem is restated below:

$$\begin{aligned} \text{Minimize} \quad & F_T = \sum_{i=1}^{n_g} F_i \\ \text{Such that} \quad & P_D = \sum_{i=1}^{n_g} P_{Gi} = 0 \end{aligned}$$

The augmented cost function is given by

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

The minimum is obtained when

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

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

$$\frac{\partial \mathcal{L}}{\partial \lambda} = P_D - \sum_{i=1}^{n_g} P_{Gi} = 0$$

The second equation is simply the original constraint of the problem. The cost of a plant

F_i depends only on its own output P_{Gi} , hence

$$\frac{\partial F_T}{\partial P_{Gi}} = \frac{\partial F_i}{\partial P_{Gi}} = \frac{dF_i}{dP_{Gi}}$$

Using the above,

$$\frac{\partial F_i}{\partial P_{Gi}} = \frac{dF_i}{dP_{Gi}} = \lambda ; \quad i = 1 \dots n_g$$

We can write

$$b_i + 2c_i P_{Gi} = \lambda \quad i = 1 \dots n_g$$

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

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

We know in a loss less system

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

Substituting (8.16) we get

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

An analytical solution of λ is obtained from (8.17) as

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

It can be seen that λ is dependent on the demand and the coefficients of the cost function.

Example 1.

The fuel costs of two units are given by

$$F_1 = 1.5 + 20 P_{G1} + 0.1 P_{G1}^2 \text{ Rs/h}$$

$$F_2 = 1.9 + 30 P_{G2} + 0.1 P_{G2}^2 \text{ Rs/h}$$

P_{G1} , P_{G2} are in MW. Find the optimal schedule neglecting losses, when the demand is 200 MW.

Solution:

$$\frac{dF_1}{dP_{G1}} = 20 + 0.2 P_{G1} \text{ Rs / MWh}$$

$$\frac{dF_2}{dP_{G2}} = 30 + 0.2 P_{G2} \text{ Rs / MWh}$$

$$P_D = P_{G1} + P_{G2} = 200 \text{ MW}$$

For economic schedule

$$\frac{dF_1}{dP_{G1}} = \frac{dF_2}{dP_{G2}} = \lambda$$

$$20 + 0.2 P_{G1} = 30 + 0.2 (200 - P_{G1})$$

Solving we get,

$$P_{G1} = 125 \text{ MW}$$

$$P_{G2} = 75 \text{ MW}$$

$$\lambda = 20 + 0.2 (125) = 45 \text{ Rs / MWh}$$

Example 2

The fuel cost in \$ / h for two 800 MW plants is given by

$$F_1 = 400 + 6.0 P_{G1} + 0.004 P_{G1}^2$$

$$F_2 = 500 + b_2 P_{G2} + c_2 P_{G2}^2$$

where P_{G1} , P_{G2} are in MW

(a) The incremental cost of power, λ is \$8 / MWh when total demand is 550MW.

Determine optimal generation schedule neglecting losses.

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

Determine optimal schedule neglecting losses.

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

Solution:

$$a) \quad P_{G1} = \frac{\lambda - b_1}{2c_1} = \frac{8.0 - 6.0}{2 \times 0.004} = 250 \text{ MW}$$

$$P_{G2} = P_D - P_{G1} = 550 - 250 = 300 \text{ MW}$$

$$b) \quad P_{G1} = \frac{\lambda - b_1}{2C_1} = \frac{10 - 6}{2 \times 0.004} = 500 \text{ MW}$$

$$P_{G2} = P_D - P_{G1} = 1300 - 500 = 800 \text{ MW}$$

$$c) \quad P_{G2} = \frac{\lambda - b_2}{2c_2}$$

$$\text{From (a)} \quad 300 = \frac{8.0 - b_2}{2c_2}$$

$$\text{From (b)} \quad 800 = \frac{10.0 - b_2}{2c_2}$$

$$\begin{aligned} \text{Solving we get} \quad b_2 &= 6.8 \\ c_2 &= 0.002 \end{aligned}$$

ECONOMIC SCHEDULE INCLUDING LIMITS ON GENERATOR (NEGLECTING LOSSES)

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

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

and the inequality constraint

$$P_{Gi \text{ (min)}} \leq P_{Gi} \leq P_{Gi \text{ (max)}}; i = 1, \dots, n_g$$

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

Example 3

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

$$\frac{dF_1}{dP_{G1}} = 0.01P_{G1} + 2.0 \text{ $ / MWh}$$

$$\frac{dF_2}{dP_{G2}} = 0.012P_{G2} + 1.6 \text{ $ / MWh}$$

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

Solution:

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

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

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

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

At $P_{G(\max)} = 125 \text{ MW}$.

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

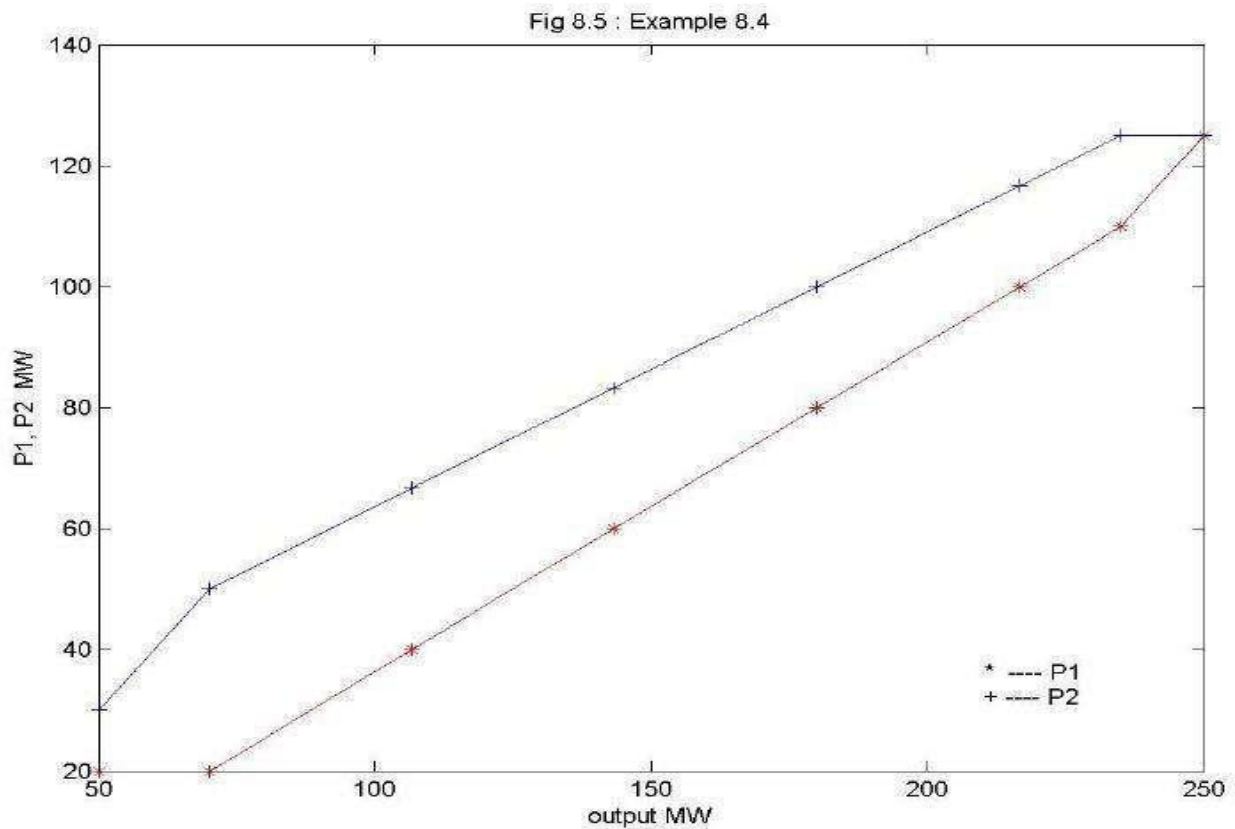
$$\lambda_{2(\max)} = 0.012 \times 125 + 1.6 = 3.1 \text{ $ / MWh}$$

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

Table Plant output and output of the two units

$\frac{dF_1}{dP_{G1}}$ \$/MWh	$\frac{dF_2}{dP_{G2}}$ \$/MWh	Plant λ \$/MWh	P_{G1} MW	P_{G2} MW	Plant Output MW
2.2	1.96	1.96	20 ⁺	30	50
2.2	2.2	2.2	20 ⁺	50	70
2.4	2.4	2.4	40	66.7	106.7
2.6	2.6	2.6	60	83.3	143.3
2.8	2.8	2.8	80	100	180
3.0	3.0	3.0	100	116.7	216.7
3.1	3.1	3.1	110	125*	235

For a particular value of λ , P_{G1} and P_{G2} are calculated using (8.16). Fig 8.5 Shows plot of each unit output versus the total plant output.



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

Example 4.

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

Solution:

From Table it is seen that for a load of 180 MW, the economic schedule is $P_{G1} = 80$ MW and $P_{G2} = 100$ MW. When load is shared equally $P_{G1} = P_{G2} = 90$ MW. Hence, the generation of unit 1 increases from 80 MW to 90 MW and that of unit 2 decreases from 100 MW to 90 MW, when the load is shared equally. There is an increase in cost of unit 1 since P_{G1} increases and decrease in cost of unit 2 since P_{G2} decreases.

$$\begin{aligned} \text{Increase in cost of unit 1} &= \int_{80}^{90} \left(\frac{dF_1}{dP_{G1}} \right) dP_{G1} \\ &= \int_{80}^{90} (0.01P_{G1} + 2.0) dP_{G1} = 28.5 \$ / \text{h} \end{aligned}$$

$$\begin{aligned} \text{Decrease in cost of unit 2} &= \int_{100}^{90} \left(\frac{dF_2}{dP_{G2}} \right) dP_{G2} \\ &= \int_{100}^{90} (0.012P_{G2} + 1.6) dP_{G2} = -27.4 \$ / \text{h} \end{aligned}$$

Total increase in cost if load is shared equally = $28.5 - 27.4 = 1.1 \$ / \text{h}$

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

ECONOMIC DISPATCH INCLUDING TRANSMISSION LOSSES

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

Minimize

$$F_T = \sum_{i=1}^{n_g} F_i$$

Such That

$$\sum_{i=1}^{n_g} P_{Gi} = P_D + P_L$$

where P_L is the total loss.

The Lagrange function is now written as

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

The minimum point is obtained when

$$\frac{\partial \mathcal{L}}{\partial P_{Gi}} = \frac{\partial F_T}{\partial P_{Gi}} - \lambda \left(1 - \frac{\partial P_L}{\partial P_{Gi}} \right) = 0; \quad i = 1, \dots, n_g$$

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

Since

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

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

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

The term $\frac{1}{1 - \frac{\partial P_L}{\partial P_{Gi}}}$ is called the penalty factor of plant i , L_i . The coordination

equations including losses are given by

$$\lambda = \frac{dF_i}{dP_{Gi}} L_i; \quad i = 1, \dots, n_g$$

The minimum operation cost is obtained when the product of the incremental fuel cost and the penalty factor of all units is the same, when losses are considered. A rigorous general expression for the loss P_L is given by

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

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

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

The expression assumes that all load currents vary together as a constant complex fraction of the total load current. Experiences with large systems has shown that the loss of accuracy is not significant if this approximation is used. An average set of loss coefficients may be used over the complete daily cycle in the coordination of incremental production costs and incremental transmission losses. In general, $B_{mn} = B_{nm}$ and can be expanded for a two plant system as

$$P_L = B_{11} P_{G1}^2 + 2 B_{12} P_{G1} P_{G2} + B_{22} P_{G2}^2$$

Example 5

A generator is supplying a load. An incremental change in load of 4 MW requires generation to be increased by 6 MW. The incremental cost at the plant bus is Rs 30 /MWh. What is the incremental cost at the receiving end?

Solution:

$$\frac{dF_1}{dP_{G1}} = 30$$

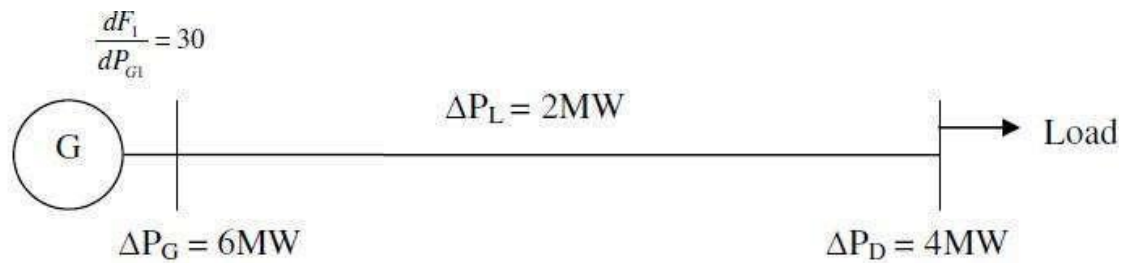


Fig ; One line diagram of example 5

$$\Delta P_L = \Delta P_G - \Delta P_D = 2 \text{ MW}$$

λ at receiving end is given by

$$\lambda = \frac{dF_1}{dP_{G1}} \times \frac{\Delta P_G}{\Delta P_D} = 30 \times \frac{6}{4} = 45 \text{ Rs / MWh}$$

$$\text{or } \lambda = \frac{dF_1}{dP_{G1}} \times \frac{1}{1 - \frac{\Delta P_L}{\Delta P_G}} = 30 \times \frac{1}{1 - \frac{2}{6}} = 45 \text{ Rs / MWh}$$

Example 6

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

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

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

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

If $\frac{\partial P_L}{\partial P_{G2}} = 0.2$, find the plant penalty factors and $\frac{\partial P_L}{\partial P_{G1}}$.

Solution:

For economic schedule,

$$\frac{dF_i}{dP_{Gi}} L_i = \lambda ; \quad L_i = \frac{1}{1 - \frac{\partial P_L}{\partial P_{Gi}}}$$

For plant 2, $P_{G2} = 100 \text{ MW}$

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

Solving, $\lambda = 30 \text{ Rs / MWh}$

$$L_2 = \frac{1}{1 - 0.2} = 1.25$$

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

$$L_1 = 1.428$$

$$L_1 = \frac{1}{1 - \frac{\partial P_L}{\partial P_{G1}}}$$

$$1.428 = \frac{1}{1 - \frac{\partial P_L}{\partial P_{G1}}} ; \text{ Solving } \frac{\partial P_L}{\partial P_{G1}} = 0.3$$

Example 7

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

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

$$\frac{dF_2}{dP_{G2}} = 0.04P_{G2} + 20.0 \text{ Rs / MWh}$$

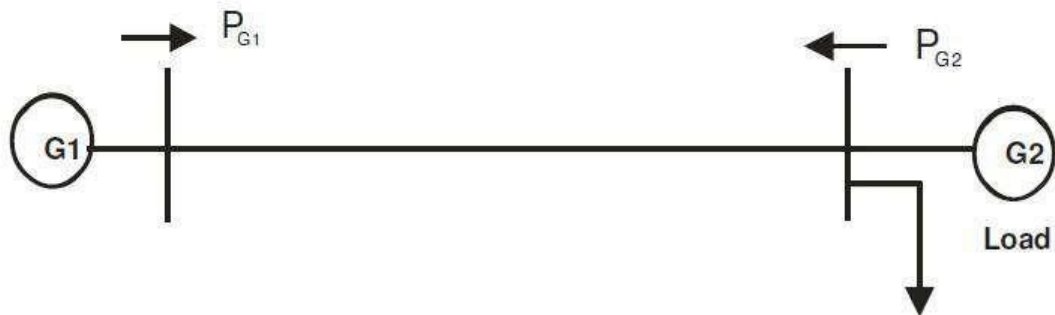


Fig One line diagram of example 7**Solution:**

Since the load is connected at bus 2 , no loss is incurred when plant two supplies the load.

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

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

From data we have $P_L = 10$ MW, if $P_{G1} = 100$ MW

$$10 = B_{11} (100)^2$$

$$B_{11} = 0.001 \text{ MW}^{-1}$$

Coordination equation with loss is

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

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

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

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

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

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

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

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

DERIVATION OF TRANSMISSION LOSS FORMULA

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

- (i) All load currents have same phase angle with respect to a common reference
- (ii) The ratio X / R is the same for all the network branches.

Consider the simple case of two generating plants connected to an arbitrary number of loads through a transmission network as shown in Fig a

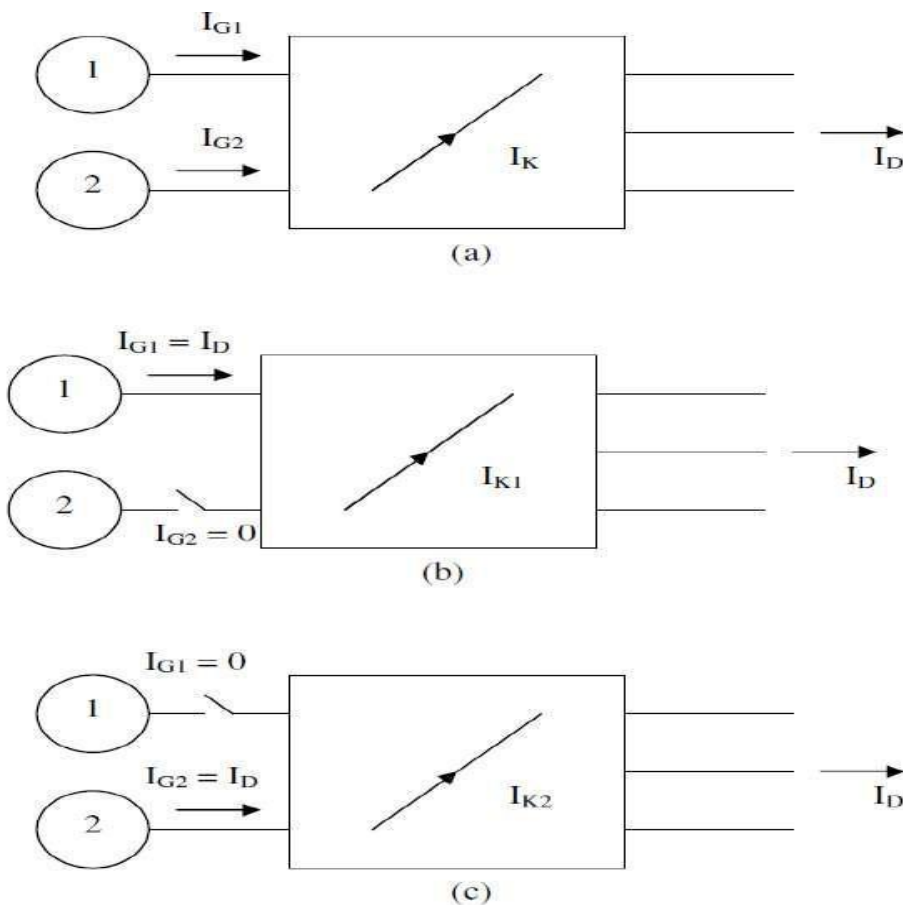


Fig Two plants connected to a number of loads through a transmission network

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

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

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

$$N_{K2} = \frac{I_{K2}}{I_D}$$

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

$$I_K = N_{K1} I_{G1} + N_{K2} I_{G2}$$

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

$$I_{G1} = |I_{G1}| \angle \sigma_1 \text{ and } I_{G2} = |I_{G2}| \angle \sigma_2.$$

where σ_1 and σ_2 are phase angles of I_{G1} and I_{G2} with respect to a common reference. We can write

$$\begin{aligned} |I_K|^2 &= (N_{K1}|I_{G1}|\cos\sigma_1 + N_{K2}|I_{G2}|\cos\sigma_2)^2 + (N_{K1}|I_{G1}|\sin\sigma_1 + N_{K2}|I_{G2}|\sin\sigma_2)^2 \\ &= N_{K1}^2|I_{G1}|^2[\cos^2\sigma_1 + \sin^2\sigma_1] + N_{K2}^2|I_{G2}|^2[\cos^2\sigma_2 + \sin^2\sigma_2] \\ &\quad + 2[N_{K1}|I_{G1}|\cos\sigma_1 N_{K2}|I_{G2}|\cos\sigma_2 + N_{K1}|I_{G1}|\sin\sigma_1 N_{K2}|I_{G2}|\sin\sigma_2] \\ &= N_{K1}^2|I_{G1}|^2 + N_{K2}^2|I_{G2}|^2 + 2N_{K1}N_{K2}|I_{G1}||I_{G2}|\cos(\sigma_1 - \sigma_2) \end{aligned}$$

$$\text{Now } |I_{G1}| = \frac{P_{G1}}{\sqrt{3}|V_1|\cos\phi_1} \text{ and } |I_{G2}| = \frac{P_{G2}}{\sqrt{3}|V_2|\cos\phi_2}$$

where P_{G1} , P_{G2} are three phase real power outputs of plant1 and plant 2; V_1 , V_2 are the line to line bus voltages of the plants and ϕ_1 , ϕ_2 are the power factor angles.

The total transmission loss in the system is given by

$$P_L = \sum_K 3|I_K|^2 R_K$$

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

$$\begin{aligned} P_L &= \frac{P_{G1}^2}{|V_1|^2(\cos\phi_1)^2} \sum_K N_{K1}^2 R_K + \frac{2P_{G1}P_{G2}\cos(\sigma_1 - \sigma_2)}{|V_1||V_2|\cos\phi_1\cos\phi_2} \sum_K N_{K1}N_{K2}R_K \\ &\quad + \frac{P_{G2}^2}{|V_2|^2(\cos\phi_2)^2} \sum_K N_{K2}^2 R_K \end{aligned}$$

$$P_L = P_{G1}^2 B_{11} + 2P_{G1}P_{G2}B_{12} + P_{G2}^2 B_{22}$$

where

$$B_{11} = \frac{1}{|V_1|^2(\cos\phi_1)^2} \sum_K N_{K1}^2 R_K$$

$$B_{12} = \frac{\cos(\sigma_1 - \sigma_2)}{|V_1||V_2|\cos\phi_1\cos\phi_2} \sum_K N_{K1}N_{K2}R_K$$

$$B_{22} = \frac{1}{|V_2|^2(\cos\phi_2)^2} \sum_K N_{K2}^2 R_K$$

The loss – coefficients are called the B – coefficients and have unit MW^{-1} .

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

$$P_L = \frac{P_{G1}^2}{|V_1|^2(\cos\phi_1)^2} \sum_K N_{K1}^2 + \dots + \frac{P_{Gn}^2}{|V_n|^2(\cos\phi_n)^2} \sum_K N_{Kn}^2 R_K$$

$$+ 2 \sum_{\substack{p,q=1 \\ p \neq q}}^n \frac{P_{Gp}P_{Gq}\cos(\sigma_p - \sigma_q)}{|V_p||V_q|\cos\phi_p\cos\phi_q} \sum_K N_{Kp}N_{Kq}R_K$$

In a compact form

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

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

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

Example 8

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

$I_a = 1.2 - j 0.4 \text{ pu}$	$Z_a = 0.02 + j 0.08 \text{ pu}$
$I_b = 0.4 - j 0.2 \text{ pu}$	$Z_b = 0.08 + j 0.32 \text{ pu}$
$I_c = 0.8 - j 0.1 \text{ pu}$	$Z_c = 0.02 + j 0.08 \text{ pu}$
$I_d = 0.8 - j 0.2 \text{ pu}$	$Z_d = 0.03 + j 0.12 \text{ pu}$
$I_e = 1.2 - j 0.3 \text{ pu}$	$Z_e = 0.03 + j 0.12 \text{ pu}$

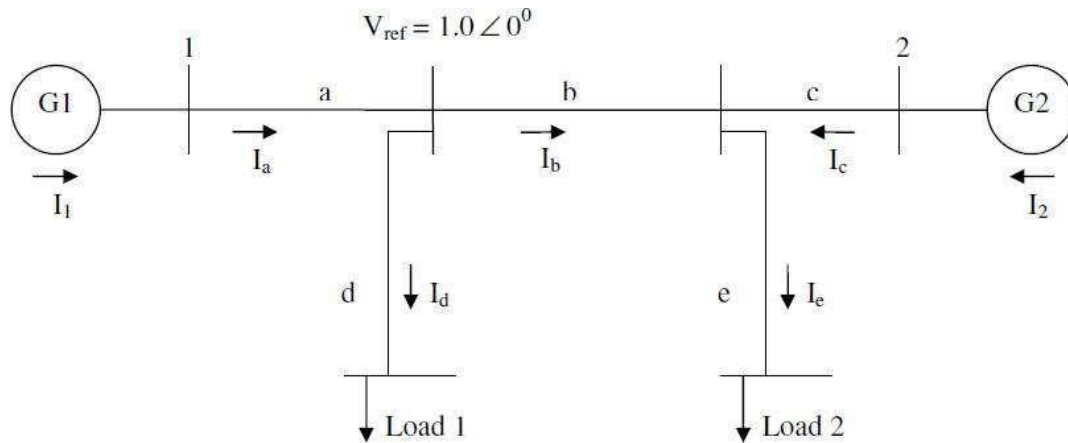


Fig : Example 8

Solution:

Total load current

$$I_L = I_d + I_e = 2.0 - j 0.5 = 2.061 \angle -14.03^\circ \text{ A}$$

$$I_{L1} = I_d = 0.8 - j 0.2 = 0.8246 \angle -14.03^\circ \text{ A}$$

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

If generator 1, supplies the load then $I_1 = I_L$. The current distribution is shown in Fig a.

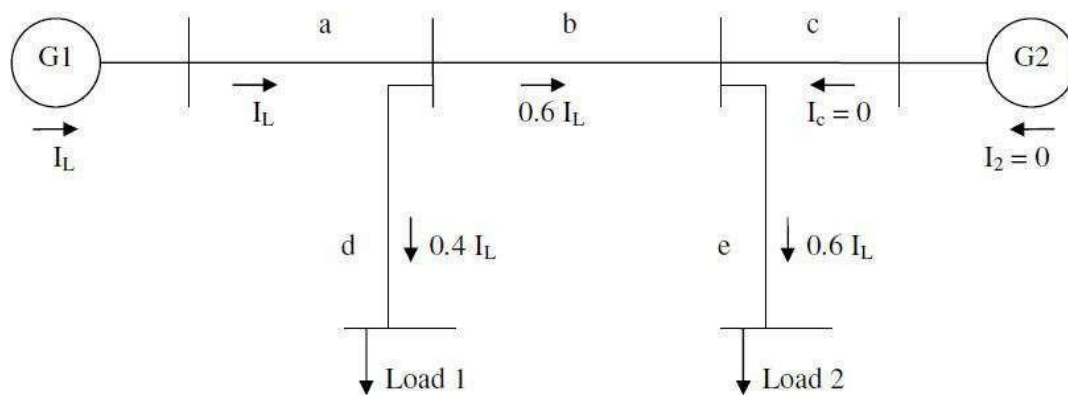


Fig a : Generator 1 supplying the total load

$$N_{a1} = \frac{I_a}{I_L} = 1.0; \quad N_{b1} = \frac{I_b}{I_L} = 0.6; \quad N_{c1} = 0; \quad N_{d1} = 0.4; \quad N_{e1} = 0.6.$$

Similarly the current distribution when only generator 2 supplies the load is shown in Fig b.

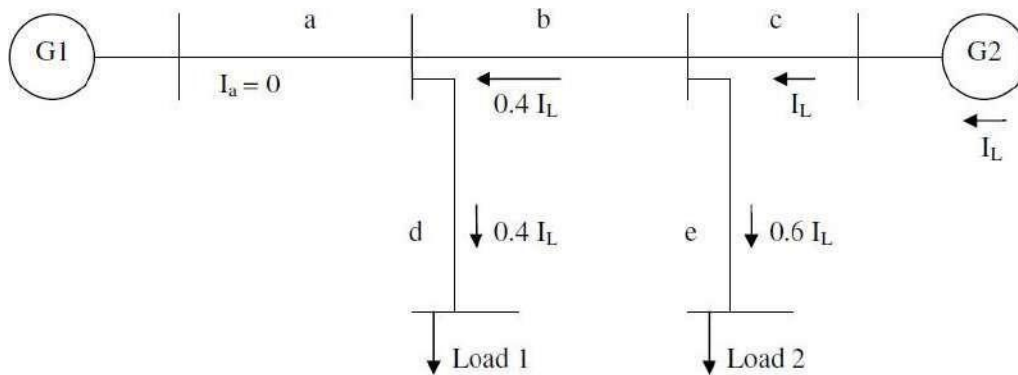


Fig b: Generator 2 supplying the total load

$$N_{a2}=0; N_{b2}=-0.4; N_{c2}=1.0; N_{d2}=0.4; N_{e2}=0.6$$

From Fig 8.10, $V_1 = V_{ref} + Z_a I_a$

$$\begin{aligned} &= 1 \angle 0^\circ + (1.2 - j 0.4) (0.02 + j 0.08) \\ &= 1.06 \angle 4.78^\circ = 1.056 + j 0.088 \text{ pu.} \end{aligned}$$

$$V_2 = V_{ref} - I_b Z_b + I_c Z_c$$

$$\begin{aligned} &= 1.0 \angle 0^\circ - (0.4 - j 0.2) (0.08 + j 0.32) + (0.8 - j 0.1) (0.02 + j 0.08) \\ &= 0.928 - j 0.05 = 0.93 \angle -3.10^\circ \text{ pu.} \end{aligned}$$

Current Phase angles

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

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

$$\cos(\sigma_1 - \sigma_2) = 0.98$$

Power factor angles

$$\phi_1 = 4.78^\circ + 18.43^\circ = 23.21^\circ; \cos \phi_1 = 0.92$$

$$\phi_2 = 7.13^\circ - 3.10^\circ = 4.03^\circ; \cos \phi_2 = 0.998$$

$$B_{11} = \frac{\sum_K N_{K1}^2 R_K}{|V_1|^2 (\cos \phi_1)^2} = \frac{1.0^2 \times 0.02 + 0.6^2 \times 0.08 + 0.4^2 \times 0.03 + 0.6^2 \times 0.03}{(1.06)^2 (0.920)^2}$$

$$= 0.0677 \text{ pu}$$

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

$$B_{12} = \frac{\cos(\sigma_1 - \sigma_2)}{|V_1||V_2|(\cos \phi_1)(\cos \phi_2)} \sum_K N_{K1} N_{K2} R_K$$

$$\begin{aligned} &= \frac{0.98}{(1.06)(0.93)(0.998)(0.92)} [-0.4 \times 0.6 \times 0.08 + 0.4 \times 0.4 \times 0.03 + 0.6 \times 0.6 \times 0.03] \\ &= -0.00389 \text{ pu} \\ &= -0.0078 \times 10^{-2} \text{ MW}^{-1} \end{aligned}$$

$$\begin{aligned} B_{22} &= \frac{\sum_K N_{K2}^2 R_K}{|V_2|^2 (\cos \phi_2)^2} \\ &= \frac{(-0.4)^2 0.08 + 1.0^2 \times 0.02 + 0.4^2 \times 0.03 + 0.6^2 \times 0.03}{(0.93)^2 (0.998)^2} \\ &= 0.056 \text{ pu} = 0.112 \times 10^{-2} \text{ MW}^{-1} \end{aligned}$$

UNIT 4

FAULT ANALYSIS

1.01 INTRODUCTION

A fault is any abnormal condition in a power system. The steady state operating mode of a power system is balanced 3-phase a.c. .However, due to sudden external or internal changes in the system, this condition is disrupted.

When the insulation of the system fails at one or more points or a conducting object comes into contact with a live point, a short circuit or a fault occurs.

CAUSES OF POWER SYSTEM FAULTS

The causes of faults are numerous, e.g.

- Lightning
- Heavy winds
- Trees falling across lines
- Vehicles colliding with towers or poles
- Birds shorting lines
- Aircraft colliding with lines
- Vandalism
- Small animals entering switchgear
- Line breaks due to excessive loading

COMMON POWER SYSTEM FAULTS

Power system faults may be categorised as one of four types; in order of frequency of occurrence, they are:

- Single line to ground fault
- Line to line fault
- Double line to ground fault
- Balanced three phase fault

The first three types constitutes severe unbalanced operating conditions which involves only one or two phases hence referred to as unsymmetrical faults. In the fourth type, a fault involving all the three phases occurs therefore referred to as symmetrical (balanced) fault.

1.04 EFFECTS OF POWER SYSTEM FAULTS

Faults may lead to fire breakout that consequently results into loss of property, loss of life and destruction of a power system network. Faults also leads to cut of supply in areas beyond the fault point in a transmission and distribution network leading to power blackouts; this interferes with industrial and commercial activities that supports economic growth, stalls learning activities in institutions, work in offices, domestic applications and creates insecurity at night.

All the above results into retarded development due to low gross domestic product realised.

It is important therefore to determine the values of system voltages and currents during faulted conditions, so that protective devices may be set to detect and minimize the harmful effects of such contingencies

THEVENIN'S EQUIVALENT CIRCUIT

Thevenin's theorem states that any linear network containing any number of voltage sources and impedances can be replaced by a single emf and an impedance.

The emf is the open circuit voltage as seen from the terminals under consideration and the impedance is the network impedance as seen from these terminals.

This circuit consisting of a single emf and impedance is known as Thevenin's equivalent circuit.

The calculation of fault current can then be very easily done by applying this theorem after obtaining the open circuit emf and network impedance as seen from the fault point.

SYMMETRICAL COMPONENTS

The majority of faults in power systems are asymmetrical. To analyse an asymmetrical fault, an unbalanced 3-phase circuit has to be solved. Since the direct solution of such a circuit is very difficult, the solution can be more easily obtained by using symmetrical components since this yields three (fictitious) single phase networks, only one of which contains a driving emf.

Since the system reactances are balanced the three fictitious networks have no mutual coupling between them, a fact that is making this method of analysis quite simple.

1.21 General principles

Any set of unbalanced 3-phase voltages (or current) can be transformed into 3 balanced sets. These are:

1. A positive sequence set of three symmetrical voltages (i.e. all numerically equal and all displaced from each other by 120°) having the same phase sequence abc as the original set and denoted by V_{a1}, V_{b1}, V_{c1} as shown in the fig(1a)

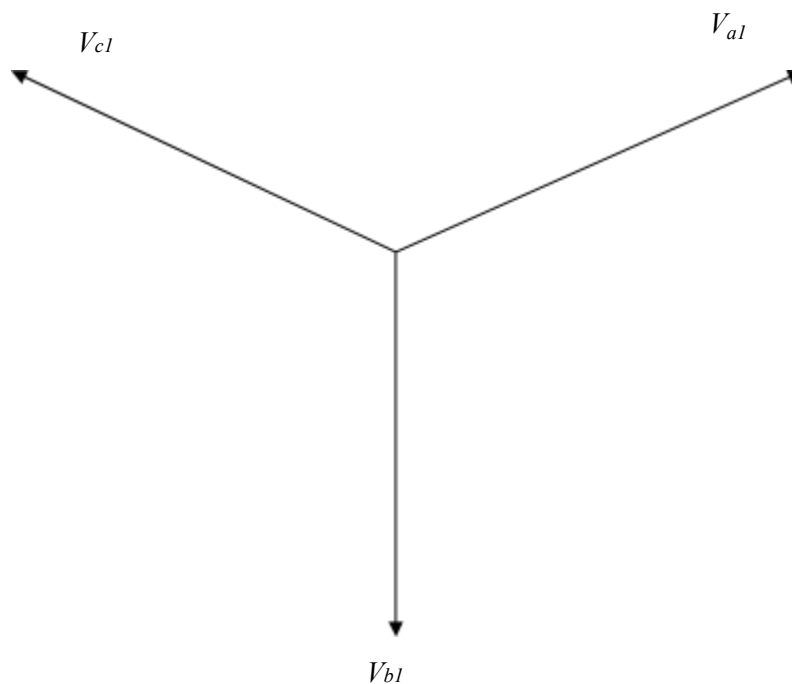


Fig. (a)

2. A negative sequence set of three symmetrical voltages having the phase sequence opposite to that of the original set and denoted by V_{a2} , V_{b2} , V_{c2} as shown in fig(1b)

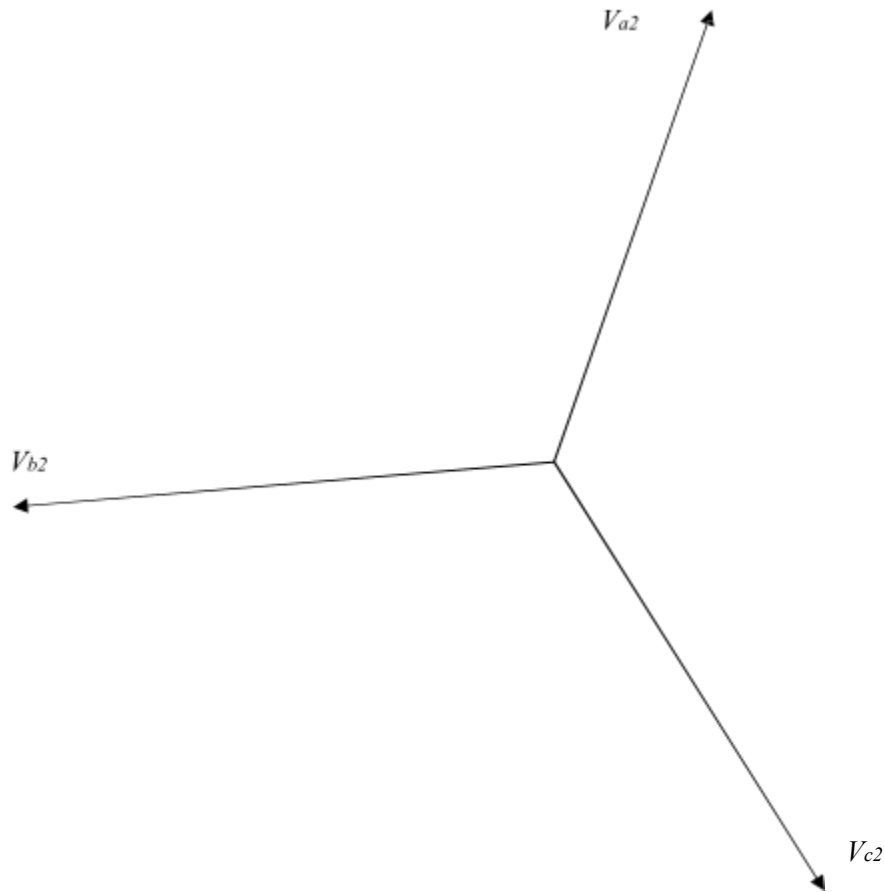


Fig. 1 (b)

3. A zero sequence set of three voltages, all equal in magnitude and in phase with each other and denoted by V_{a0} , V_{b0} , V_{c0} as shown in fig (1c) below:

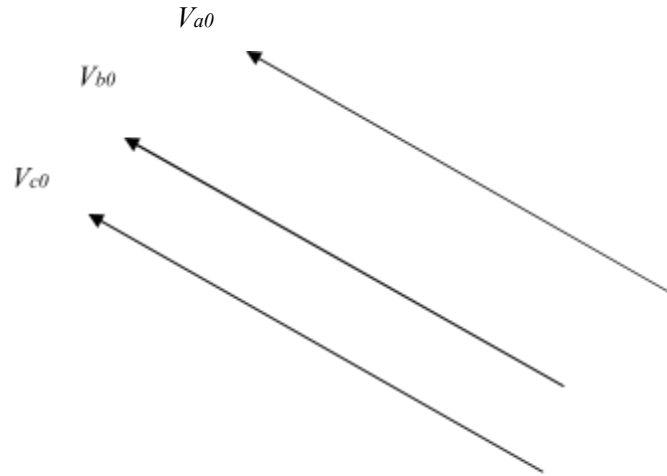


Fig. 1 (c)

The positive, negative and zero sequence sets above are known as symmetrical components. Thus we have,

$$V_a = V_{a1} + V_{a2} + V_{a0}$$

$$V_b = V_{b1} + V_{b2} + V_{b0}$$

$$V_c = V_{c1} + V_{c2} + V_{c0}$$

The symmetrical components application to power system analysis is of fundamental importance since it can be used to transform arbitrarily unbalanced condition into symmetrical components, compute the system response by straightforward circuit analysis on simple circuit models and transform the results back to the original phase variables.

Generally the subscripts 1, 2 and 0 are used to indicate positive sequence, negative sequence and zero sequence respectively.

The symmetrical components do not have separate existence; they are just mathematical components of unbalanced currents (or voltages) which actually flow in the system.

1.2.2 The “a” operator

The operator “a” as used in symmetrical components is one in which when multiplied to a vector, rotates the vector through 120° in a positive (anticlockwise) direction without changing the magnitude.

The operator “a” is defined as $1 \angle 120^\circ$

THREE-SEQUENCE IMPEDANCES AND SEQUENCE NETWORKS

Positive sequence currents give rise to only positive sequence voltages, the negative sequence currents give rise to only negative sequence voltages and zero sequence currents give rise to only zero sequence voltages, hence each network can be regarded as flowing within in its own network through impedances of its own sequence only.

In any part of the circuit, the voltage drop caused by current of a certain sequence depends on the impedance of that part of the circuit to current of that sequence.

The impedance of any section of a balanced network to current of one sequence may be different from impedance to current of another sequence.

The impedance of a circuit when positive sequence currents are flowing is called impedance,

When only negative sequence currents are flowing the impedance is termed as negative sequence impedance.

With only zero sequence currents flowing the impedance is termed as zero sequence impedance.

The analysis of unsymmetrical faults in power systems is carried out by finding the symmetrical components of the unbalanced currents. Since each sequence current causes a voltage drop of that sequence only, each sequence current can be considered to flow in an independent network composed of impedances to current of that sequence only.

The single phase equivalent circuit composed of the impedances to current of any one sequence only is called the sequence network of that particular sequence.

The sequence networks contain the generated emfs and impedances of like sequence.

Therefore for every power system we can form three- sequence network s. These sequence networks, carrying current I_{a1} , I_{a2} and I_{a0} are then inter-connected to represent the different fault conditions.

PHYSICAL SIGNIFICANCE OF SEQUENCE COMPONENTS

This is achieved by considering the fields which results when these sequence voltages are applied to the stator of a 3-phase machine e.g. an induction motor.

If a positive sequence set of voltages is applied to the terminals a, b, c of the machine, a magnetic field revolving in a certain direction will be set up. If now the voltages to the terminals b and c are changed by interchanging the leads to terminals b and c, it is known from induction motor theory that the direction of magnetic field would be reversed.

It is noted that for this condition, the relative phase positions of the voltages applied to the motor are the same as for the negative sequence set.

Hence, a negative sequence set of voltages produces a rotating field rotating in an opposite direction to that of positive sequence.

For both positive and negative sequence components, the standard convention of counter clockwise rotation is followed.

The application of zero sequence voltages does not produce any field because these voltages are in phase and the three -phase windings are displaced by 120° . The positive and the negative sequence set are the balanced one. Thus, if only positive and negative sequence currents are flowing, the phasor sum of each will be zero and there will be no residual current. However, the zero sequence components of currents in the three phases are in phase and the residual current will be three times the zero sequence current of one phase. In the case of a fault involving ground, the positive and negative sequence currents are in equilibrium while the zero sequence currents flow through the ground and overhead ground wires.

CHAPTER TWO

SEQUENCE NETWORKS OF SYNCHRONOUS MACHINES

An unloaded synchronous machine having its neutral earthed through impedance, z_n , is shown in fig. 2(a) below.

A fault at its terminals causes currents I_a , I_b and I_c to flow in the lines. If fault involves earth, a current I_n flows into the neutral from the earth. This current flows through the neutral impedance Z_n .

Thus depending on the type of fault, one or more of the line currents may be zero.

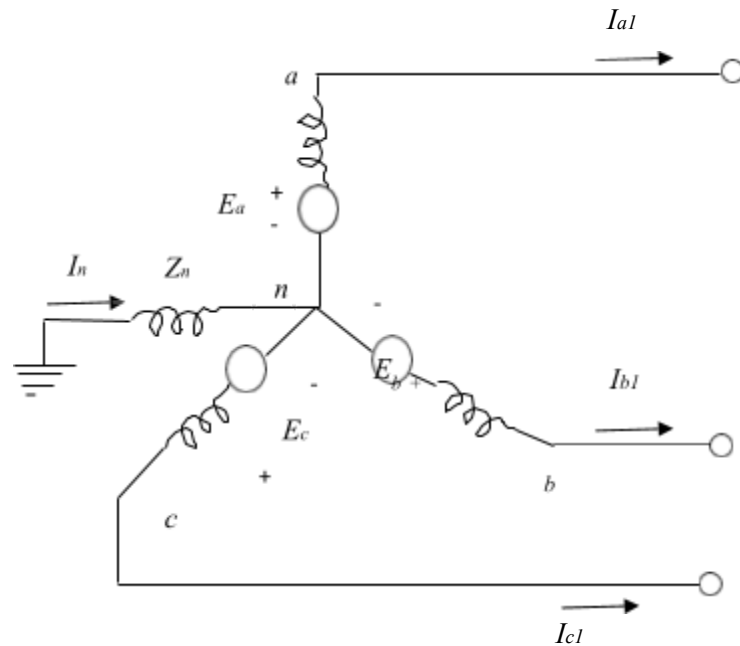


Fig.2 (a)

Positive sequence network

The generated voltages of a synchronous machine are of positive sequence only since the windings of a synchronous machine are symmetrical.

The positive sequence network consists of an emf equal to no load terminal voltages and is in series with the positive sequence impedance Z_1 of the machine. Fig.2 (b) and fig.2(c) shows the paths for positive sequence currents and positive sequence network respectively on a single phase basis in the synchronous machine. The neutral impedance Z_n does not appear in the circuit because the phasor sum of I_{a1} , I_{b1} and I_{c1} is zero and no positive sequence current can flow through Z_n . Since its a balanced circuit, the positive sequence N

The reference bus for the positive sequence network is the neutral of the generator.

The positive sequence impedance Z_1 consists of winding resistance and direct axis reactance. The reactance is the sub-transient reactance X''_d or transient reactance X'_d or synchronous reactance X_d depending on whether sub-transient, transient or steady state conditions are being studied.

From fig.2 (b) , the positive sequence voltage of terminal a with respect to the reference bus is given by:

$$V_{a1} = E_a - Z_1 I_{a1}$$

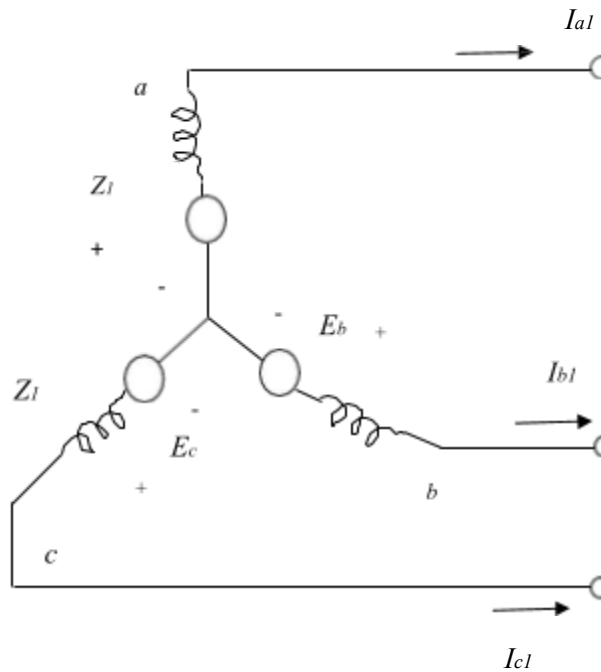


Fig.2 (b)

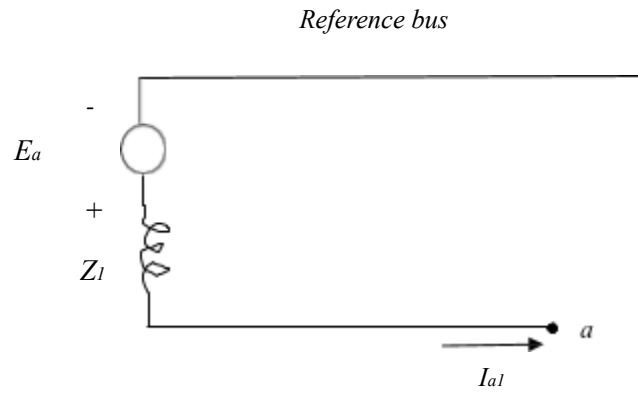


Fig.2(c)

2.02 Negative sequence network

A synchronous machine does not generate any negative sequence voltage. The flow of negative sequence currents in the stator windings creates an mmf which rotates at synchronous speed in a direction opposite to the direction of rotor, i.e., at twice the synchronous speed with respect to rotor.

Thus the negative sequence mmf alternates past the direct and quadrature axis and sets up a varying armature reaction effect. Thus, the negative sequence reactance is taken as the average of direct axis and quadrature axis sub-transient reactance, i.e.,

$$X_2 = 0.5 (X''_d + X''_q).$$

It not necessary to consider any time variation of X_2 during transient conditions because there is no normal constant armature reaction to be effected. For more accurate calculations, the negative sequence resistance should be considered to account for power dissipated in the rotor poles or damper winding by double supply frequency induced currents.

The fig.2 (d) and fig.2 (e) shows the negative sequence currents paths and the negative sequence network respectively on a single phase basis of a synchronous machine.

The reference bus for the negative sequence network is the neutral of the machine. Thus, the negative sequence voltage of terminal a with respect to the reference bus is given by:

$$V_{a2} = -Z_2 I_{a2}$$

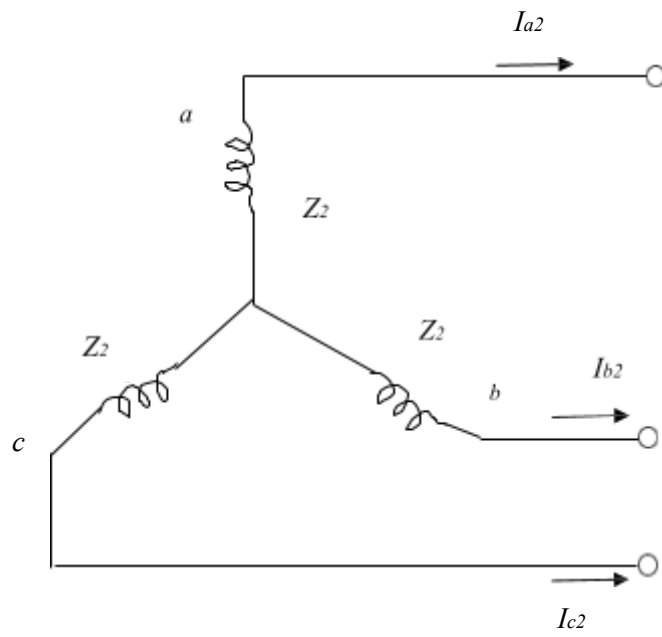


Fig.2 (d)

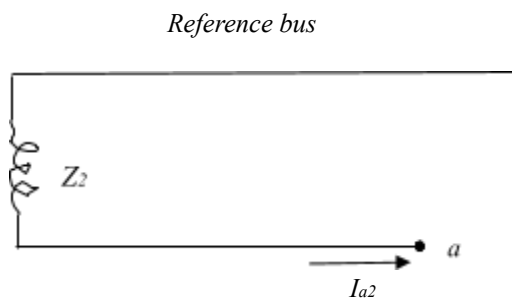


Fig.2 (e)

2.0.3 Zero sequence network

No zero sequence voltage is induced in a synchronous machine. The flow of zero sequence currents in the stator windings produces three mmf which are in time phase. If each phase winding produced a sinusoidal space mmf, then with the rotor removed, the flux at a point on the axis of the stator due to zero sequence current would be zero at every instant.

When the flux in the air gap or the leakage flux around slots or end connections is considered, no point in these regions is equidistant from all the three –phase windings of the stator.

The mmf produced by a phase winding departs from a sine wave, by amounts which depend upon the arrangement of the winding.

The zero sequence currents flow through the neutral impedance Z_n and the current flowing through this impedance is $3I_{a0}$.

Fig.2(f) and fig.2(g) shows the zero sequence current paths and zero sequence network respectively, and as can be seen, the zero sequence voltage drop from point a to ground is $-3I_{a0}Z_n - I_{a0}Z_{g0}$ where Z_{g0} is the zero sequence impedance per phase of the generator.

Since the current in the zero sequence network is I_{a0} this network must have an impedance of $3Z_n + Z_{g0}$. Thus,

$$Z_0 = 3Z_n + Z_{g0}$$

The zero sequence voltage of terminal a with respect to the reference bus is thus:

$$V_{a0} = -I_{a0}Z_0$$

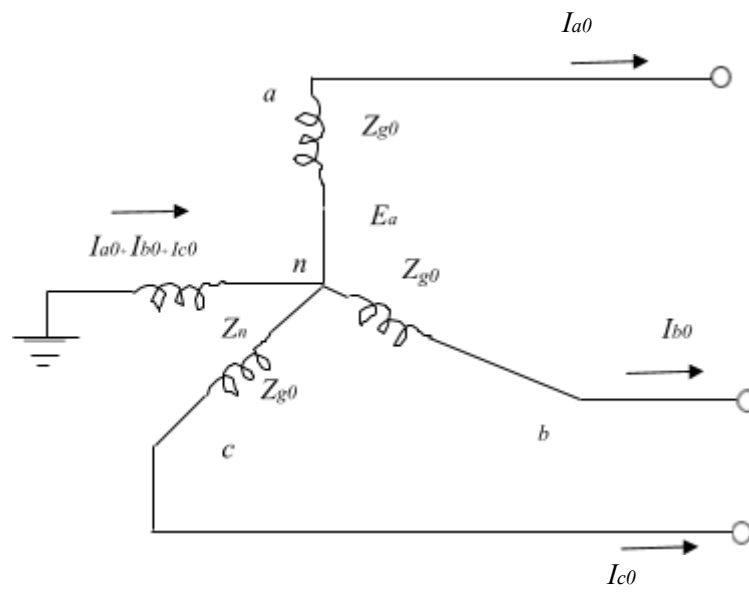


Fig.2 (f)

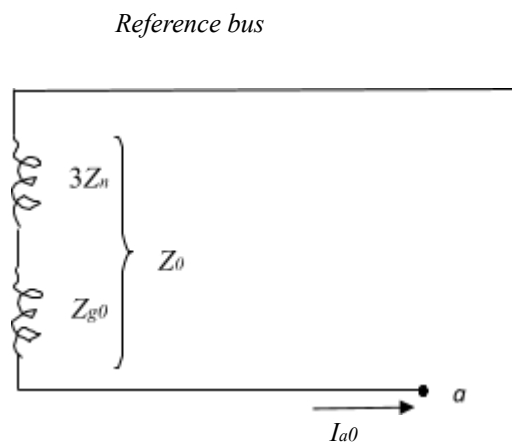


Fig.2 (g)

SEQUENCE IMPEDANCES OF TRANSMISSION LINE

The positive and negative sequence impedances of linear symmetrical static circuits do not depend on the phase sequence and are, therefore equal. When only zero sequence currents flow in the lines, the currents in all the phases are identical. These currents return partly through the ground and partly through overhead ground wires.

The magnetic field due to the flow of zero sequence currents through line, ground and round wires is very different from the magnetic field due to positive sequence currents. The zero sequence reactance of lines is about 2 to 4 times the positive sequence reactance.

SEQUENCE IMPEDANCES OF TRANSFORMERS

A power system network has a number of transformers for stepping up and stepping down the voltage levels.

A transformer for a 3-phase circuit may consist of three single phase transformers with windings suitably connected in star or delta or it may be a 3-phase unit.

Modern transformers are invariably three-phase units because of their lower cost, lesser space requirements and higher efficiency. The positive sequence impedance of a transformer equals its leakage impedance. The resistance of the windings is usually small as compared to leakage reactance.

For transformers above 1 MVA rating, the reactance and impedance are almost equal. Since the transformer is a static device, the negative sequence impedance is equal to the positive sequence impedance.

The zero sequence impedance of 3-phase units is slightly different from positive sequence impedance. However the difference is very slight and the zero sequence impedance is also assumed to be the same as the positive sequence impedance.

The flow of zero sequence currents through a transformer and hence in the system depends greatly on the winding connections. The zero sequence currents can flow through the winding

connected in star only if the star point is grounded. If the star point isolated zero sequence currents cannot flow in the winding.

The zero sequence currents cannot flow in the lines connected to a delta connected winding because no return path is available for these zero sequence currents. However, the zero sequence currents caused by the presence of zero sequence voltages can circulate through the delta connected windings.

FORMATION OF SEQUENCE NETWORKS

A power system network consists of synchronous machines, transmission lines and transformers.

The positive sequence network is the same as the single line reactance diagram used for the calculation of symmetrical fault current. The reference bus for positive sequence network is the system neutral.

The negative sequence network is similar to the positive sequence network except that the negative sequence network does not contain any voltage source. The negative sequence impedances for transmission line and transformers are the same as the positive sequence impedances. But the negative sequence impedance of a synchronous machine may be different from its positive sequence impedance.

Any impedance connected between a neutral and ground is not included in the positive and negative sequence networks because the positive and the negative sequence currents cannot flow through such impedance.

The zero sequence network also does not contain any voltage source. Any impedance included between neutral and ground becomes three times its value in a zero sequence network.

The following are the summary of the rules for the formation of sequence networks:-

- The positive sequence network is the same as single line impedance or reactance diagram used in symmetrical fault analysis. The reference bus for this network is the system neutral.

- The generators in power system produce balanced voltages. Therefore only positive sequence network has voltage source. There are no voltage sources in negative and zero sequence networks.
- The positive sequence current can cause only positive sequence voltage drop. Similarly negative sequence current can cause only negative sequence voltage drop and zero sequence current can cause only zero sequence voltage drop.
- The reference for negative sequence network is the system neutral. However, the reference for zero sequence network is the ground. Zero sequence current can flow only if the neutral is grounded.
- The neutral grounding impedance Z_n appears as $3Z_n$ in the zero sequence network.
- The three sequence networks are independent and are interconnected suitably depending on the type of fault.

UNSYMMETRICAL FAULTS

The basic approach to the analysis of unsymmetrical faults is to consider the general situation shown in the fig.3.0 which shows the three lines of the three- phase power system at the point of fault.

The general terminals brought out are for purposes of external connections which simulate the fault. Appropriate connections of the three stubs represent the different faults, e.g., connecting stub 'a' to ground produces a single line to ground fault, through zero impedance, on phase 'a'. The currents in stubs b and c are then zero and I_a is the fault current.

Similarly, the connection of stubs b and c produces a line to line fault, through zero impedance, between phases b and c , the current in stub a is then zero and I_b is equal to I_c . The positive assignment of phase quantities is important. It is seen that the currents flow out of the system.

The three general sequence circuits are shown in fig.3.1 (a). The ports indicated correspond to the general 3- phase entry port of fig.3.1. A suitable inter- connection of the three- sequence networks depending on the type fault yields the solution to the problem.

The sequence networks of fig.3.1 (a) can be replaced by equivalent sequence networks of fig.3.1 (b) . Z_0 , Z_1 and Z_2 indicate the sequence impedances of the network looking into the fault

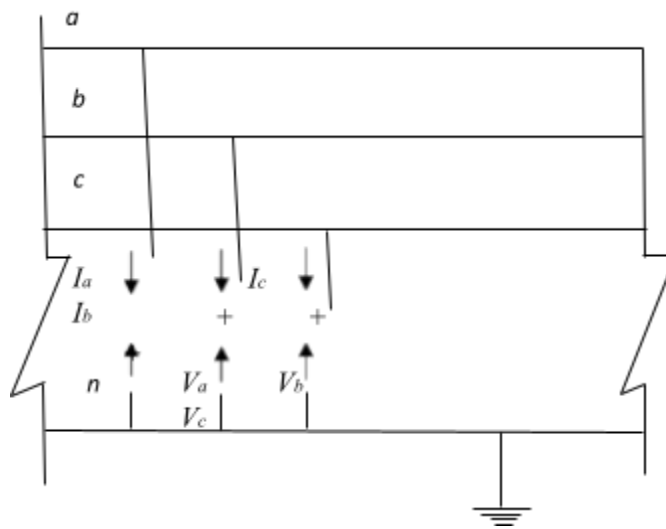


Fig.3.0 General 3- phase access port

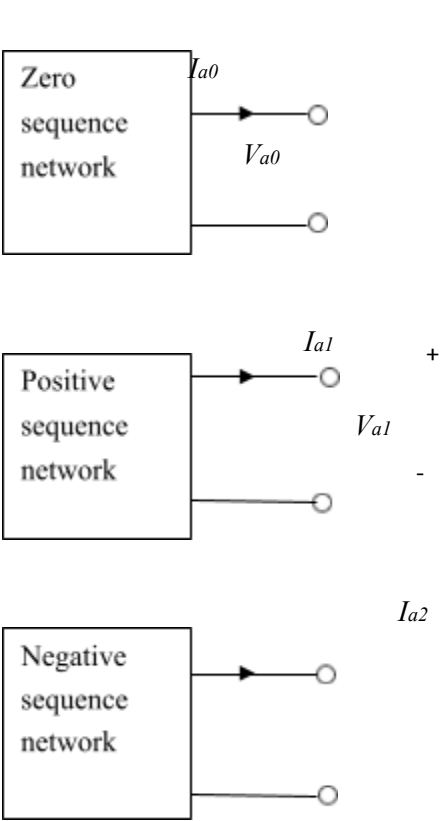


Fig.3.1 (a)

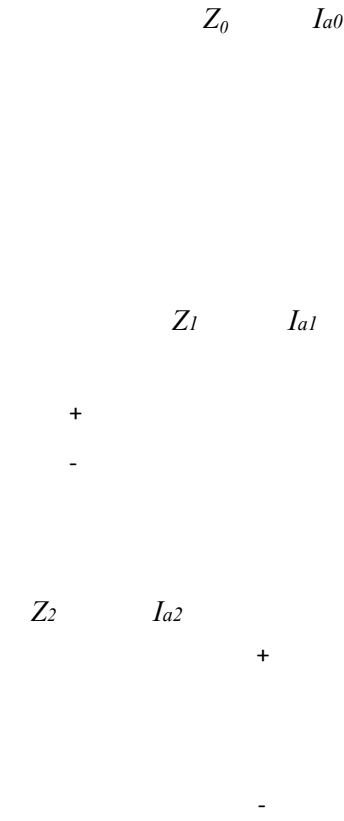


Fig.3.1 (b)

SINGLE LINE TO GROUND FAULT

The termination of the three- phase access port as shown in fig. 3.2 brings about a condition of single line to ground fault through a fault impedance Z_f .

Typically Z_f is set to zero in all fault studies. I include Z_f in the analysis for the sake of generality. The terminal conditions at the fault point give the following equations:

$$I_b = 0$$

$$I_c = 0$$

$$V_a = I_a Z_f$$

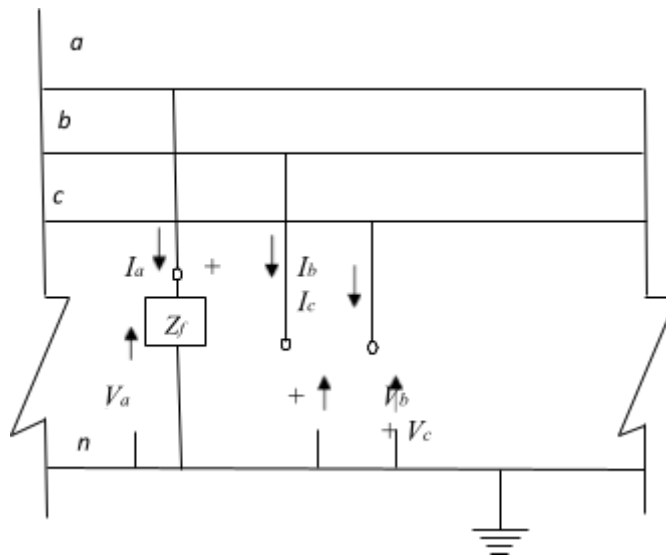


Fig. 3.2

Connections of sequence networks for a single line to ground fault and its simplified equivalent circuit are shown in the fig. 3.3(a) and fig. 3.3 (b) below:

General sequence networks

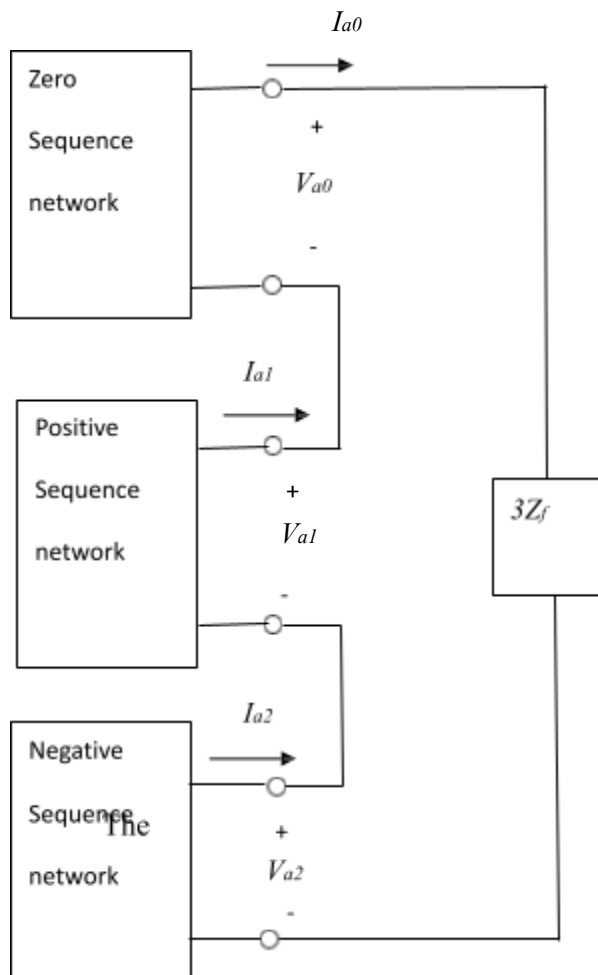


Fig.3.3 (a)

Equivalent sequence networks

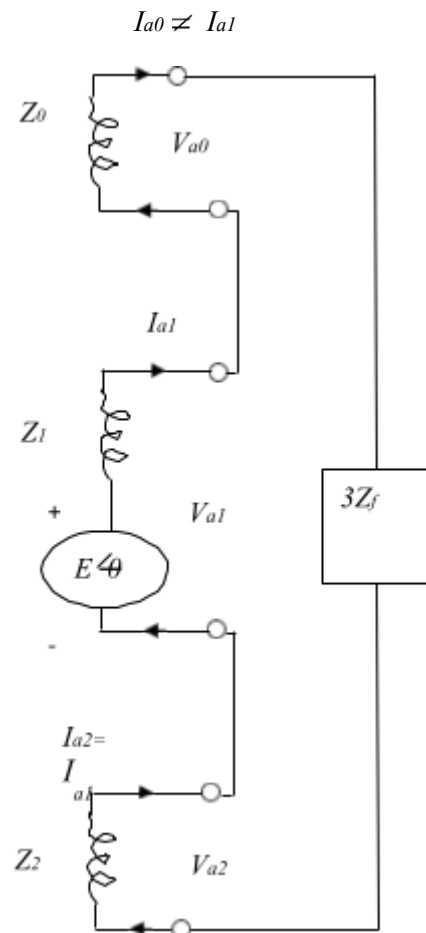


Fig.3.3 (b)

LINE TO LINE FAULT

The termination of the three- phase access port as in the fig.3.4 below simulates a line to line fault through a fault impedance Z_f .

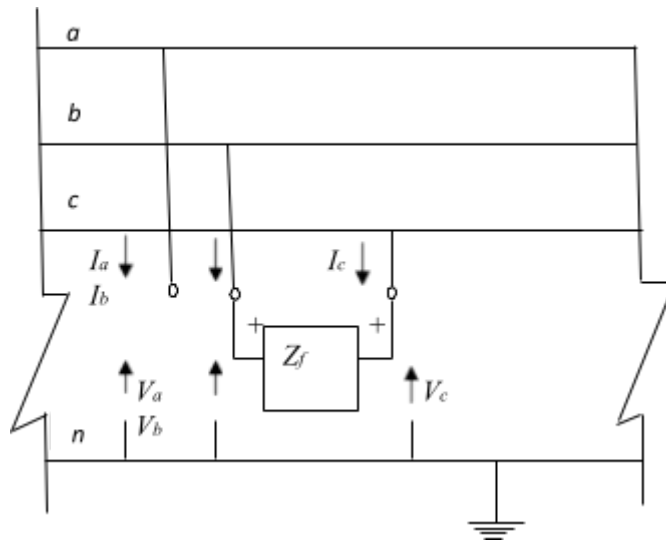


Fig. 3.4

The terminal conditions at the fault point give the following equations,

$$I_a = 0$$

$$I_b = -I_c$$

$$V_b = V_c + Z_f I_b$$

$$I_b = -I_c = I_{a0} + a^2 I_{a1} + a I_{a2}$$

Connection of sequence networks for a line to line fault and its simplified equivalent circuit are shown in the fig.3.5 (a) and fig.(b) below.

General sequence networks

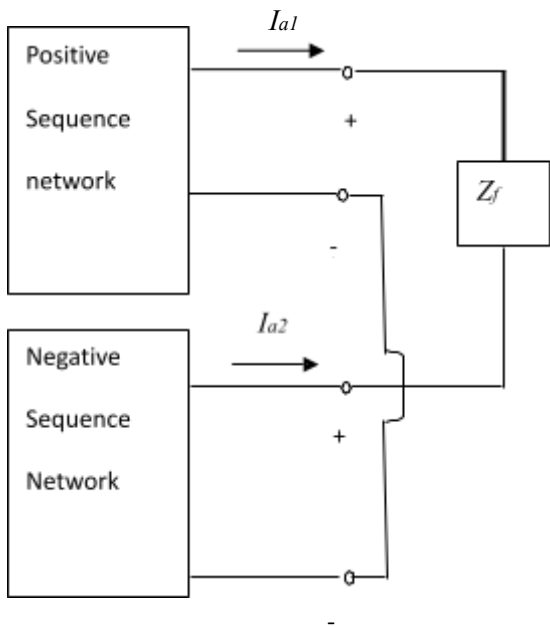
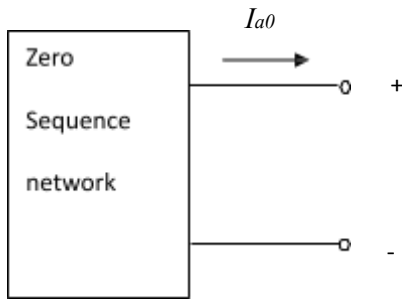


Fig. 3.5 (a)

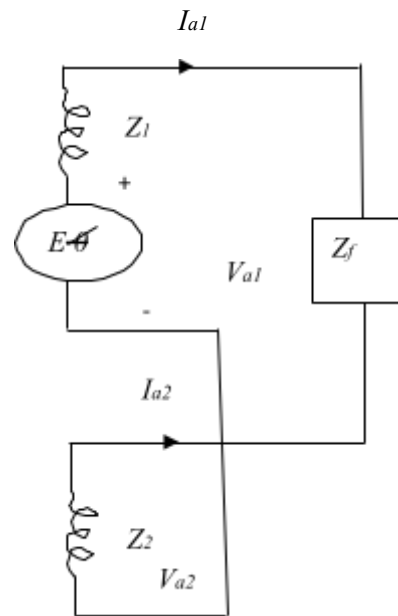


Fig.3.5 (b)

DOUBLE LINE TO GROUND FAULT

The termination of the three- phase access port as shown in fig.3.6 simulates a double line to ground fault through fault impedance Z_f .

The terminal conditions at the fault point give the following equations,

$$I_a = 0$$

$$V_b = V_c = (I_b + I_c) Z_f$$

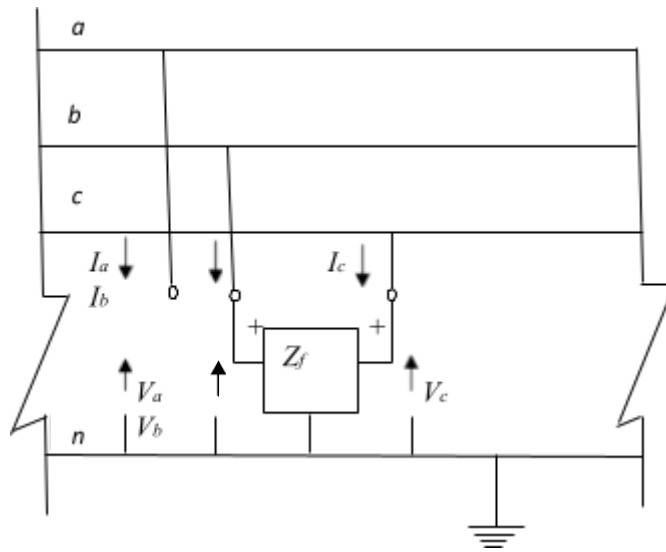


Fig. 3.6

The sequence networks and the equivalent circuit are shown by the Fig.3.7 (a) and Fig. 3.7 (b) below

General sequencenetworks

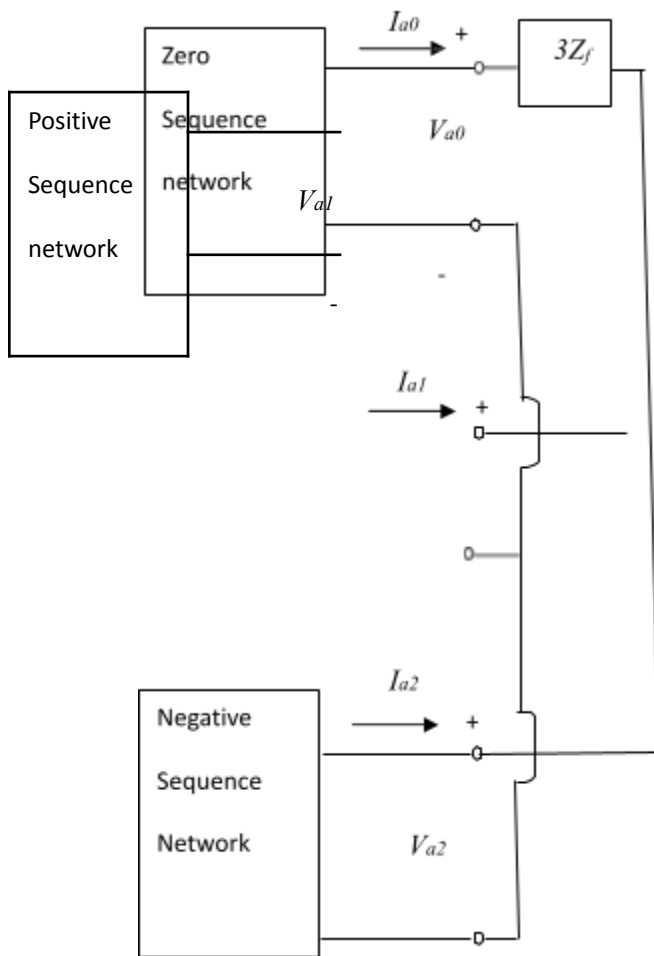


Fig. 3.7(a)

Equivalent sequence networks

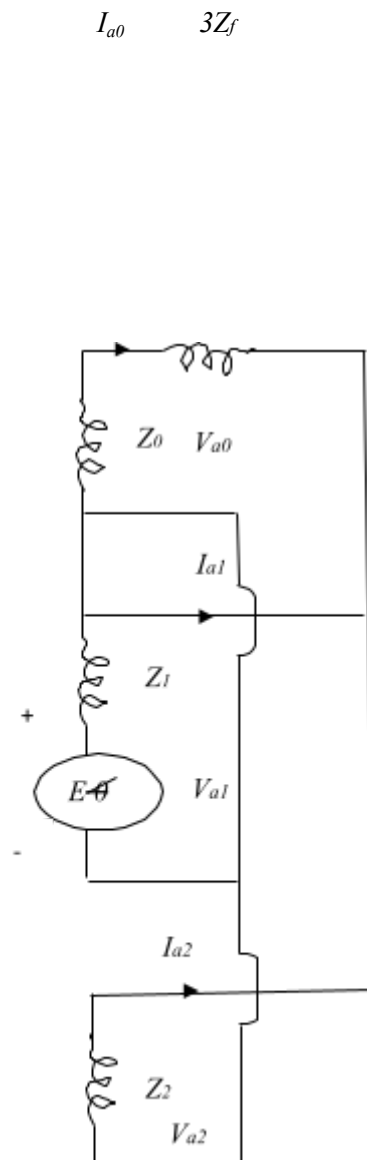


Fig.3.7 (b)

BALANCED THREE PHASE FAULT

This type of fault occurs infrequently, as for example, when a line, which has been made safe for maintenance by clamping all the three phases to earth, is accidentally made alive or when, due to slow fault clearance, an earth fault spreads across to the other two phases or when a mechanical excavator cuts quickly through a whole cable.

It is an important type of fault in that it results in an easy calculation and generally, a pessimistic answer.

The circuit breaker rated MVA breaking capacity is based on 3- phase fault MVA. Since circuit breakers are manufactured in preferred standard sizes e.g. 250, 500, 750 MVA high precision is not necessary when calculating the 3- phase fault level at a point in a power system.

The system impedances are also never known accurately in three phase faults.

CHAPTER THREE

THE BUS IMPEDANCE MATRIX

INTRODUCTION

Since the actual power systems are very large, network reduction method can only be used to solve very small systems. Therefore a systematic procedure suitable for digital computer calculations is necessary.

System studies can be carried out using Y_{bus} or Z_{bus} . Y_{bus} is used for load flow computations, but for fault calculations (short circuit studies) , the use of Z_{bus} is preferable.

THE ALGORITHM FOR FORMULATING THE COMPLEX Z_{bus} IMPEDANCE MATRIX

This is described in terms of modifying an existing bus impedance matrix designated as $[Z_{bus}]_{old}$. The new modified matrix is designated as $[Z_{bus}]_{new}$.

The network consists of a reference bus and a number of other buses. When a new element having self impedance z_s is added, a new bus may be created if the new element is a tree branch or a new bus may not be created if the new element is a link.

Each of these two cases can be subdivided into two cases so that z_s may be added in the following ways:

1. Adding z_s from a new bus to reference.
2. Adding z_s from a new bus to an old bus.
3. Adding z_s from an old bus to reference.
4. Adding z_s between two old buses.

The case of addition of z_s to create two new buses simultaneously has been carefully avoided by properly selecting the order in which the elements are added.

Therefore, for my case, bus zero was taken as the reference bus and then the following procedure was adhered to:

1. A branch was added from a new bus to a reference bus zero.
2. A branch was then added from a new bus to an existing bus.
3. A link was finally added between two old buses to generate the complex bus impedance matrix by method of building algorithms.

A THREE BUS POWER SYSTEM NETWORK

A 3-bus system characterised by the following parameter values was used for the analysis:

Input data (Impedances in per- unit)

BUS CODE		Z0		Z1	
0	1	0.0	0.40	0.0	0.25
0	2	0.0	0.10	0.0	0.25
1	2	0.0	0.30	0.0	0.125
1	3	0.0	0.35	0.0	0.15
2	3	0.0	0.7125	0.0	0.25

CHAPTERT FOUR

ANALYSIS

Fault analysis was done by technical computer method using the theory of symmetrical components. The fault impedance Z_f was taken as zero.

The following describes how the program codes that were developed for each type of fault were executed using a Matlab environment to generate results for the analysis:

LINE-GROUND FAULT

The program prompts the user to enter the faulted bus number and the fault impedance Z_f . The prefault bus voltages are defined by the reserved Vector V . The array V may be defined or it is returned from the power flow programs *lfgauss*, *lfnewton*, *decouple* or *perturb*. If V does not exist the prefault bus voltages are automatically set to 1.0 per unit. The program obtains the total fault current, bus voltages and line currents during the fault.

LINE-LINE FAULT

The program prompts the user to enter the faulted bus number and the fault impedance Z_f . The prefault bus voltages are defined by the reserved Vector V . The array V may be defined or it is returned from the power flow programs *lfgauss*, *lfnewton*, *decouple* or *perturb*. If V does not exist the prefault bus voltages are automatically set to 1.0 per unit. The program obtains the total fault current, bus voltages and line currents during the fault.

DOUBLE-LINE-GROUND FAULT

The program prompts the user to enter the faulted bus number and the fault impedance Z_f . The prefault bus voltages are defined by the reserved Vector V . The array V may be defined or it is returned from the power flow programs lfgauss, lfnewton, decouple or perturb. If V does not exist the prefault bus voltages are automatically set to 1.0 per unit. The program obtains the total fault current, bus voltages and line currents during the fault.

SYMMETRICAL FAULT (BALANCED THREE - PHASE FAULT)

The program prompts the user to enter the faulted bus number and the fault impedance Z_f . The prefault bus voltages are defined by the reserved Vector V . The array V may be defined or it is returned from the power flow programs lfgauss, lfnewton, decouple or perturb. If V does not exist the prefault bus voltages are automatically set to 1.0 per unit. The program obtains the total fault current, the postfault bus voltages and line currents.

Z BUILD CODE

The zero sequence impedances and the positive sequence impedances for the network were computed using the zbuild code where the positive and the negative sequence impedances were treated to be the same as indicated by the programs specifications. The network data for the various sequence impedances i.e the sequence network of its thevenin's equivalent was obtained as below:

The above sequence network was run using the zbuild code to form the complex bus impedance matrix by the method of building algorithm.

RESULTS

The following results were obtained after simulation of the codes using a matlab environment:

The complex bus impedance matrix

Z_{bus1} =

$$\begin{bmatrix} 0 + 0.1450i & 0 + 0.1050i & 0 + 0.1300i \\ 0 + 0.1050i & 0 + 0.1450i & 0 + 0.1200i \\ 0 + 0.1300i & 0 + 0.1200i & 0 + 0.2200i \end{bmatrix}$$

Z_{bus0} =

$$\begin{bmatrix} 0 + 0.1820i & 0 + 0.0545i & 0 + 0.1400i \\ 0 + 0.0545i & 0 + 0.0864i & 0 + 0.0650i \\ 0 + 0.1400i & 0 + 0.0650i & 0 + 0.3500i \end{bmatrix}$$

Line-to-ground fault analysis

Single line to-ground fault at bus No. 1

Total fault current = 6.3559 per unit

Bus Voltages during the fault in per unit

Bus -----Voltage Magnitude-----

No.	Phase a	Phase b	Phase c
1	0.0000	1.0414	1.0414
2	0.4396	0.9510	0.9510
3	0.1525	1.0108	1.0108

Line currents for fault at bus No. 1

From	To	-----Line Current Magnitude----		
Bus	Bus	Phase a	Phase b	Phase c
1	F	6.3559	0.0000	0.0000
2	1	2.2564	0.2225	0.2225
2	3	0.6780	0.0424	0.0424
3	1	0.6780	0.0424	0.0424

Single line to-ground fault at bus No. 2

Total fault current = 7.9708 per unit

Bus Voltages during the fault in per unit

Bus	-----Voltage Magnitude-----		
No.	Phase a	Phase b	Phase c
1	0.2972	0.9401	0.9401
2	0.0000	0.9319	0.9319
3	0.1896	0.9355	0.9355

Line currents for fault at bus No. 2

From	To	-----Line Current Magnitude----		
Bus	Bus	Phase a	Phase b	Phase c
1	2	1.9827	0.5679	0.5679
1	3	0.6111	0.1860	0.1860
2	F	7.9708	0.0000	0.0000
3	2	0.6111	0.1860	0.1860

Single line to-ground fault at bus No. 3

Total fault current = 3.7975 per unit

Bus Voltages during the fault in per unit

Bus	-----Voltage Magnitude-----		
No.	Phase a	Phase b	Phase c
1	0.4937	1.0064	1.0064
2	0.6139	0.9671	0.9671
3	0.0000	1.0916	1.0916

Line currents for fault at bus No. 3

Bus	Bus	Phase a	Phase b	Phase c
1	3	2.2785	0.0000	0.0000
2	1	0.5190	0.2152	0.2152
2	3	1.5190	0.0000	0.0000
3	F	3.7975	0.0000	0.0000

Line-to-line fault analysis

Line-to-line fault at bus No. 1

Total fault current = 5.9726 per unit

Bus Voltages during the fault in per unit

Bus -----Voltage Magnitude-----

No.	Phase a	Phase b	Phase c
1	1.0000	0.5000	0.5000
2	1.0000	0.5541	0.5541
3	1.0000	0.5080	0.5080

From	To	-----Line Current Magnitude----		
Bus	Bus	Phase a	Phase b	Phase c
1	F	0.0000	5.9726	5.9726
2	1	0.0000	1.9112	1.9112
2	3	0.0000	0.5973	0.5973
3	1	0.0000	0.5973	0.5973

Line-to-line fault at bus No. 2

Total fault current = 5.9726 per unit

Bus Voltages during the fault in per unit

Bus	-----Voltage Magnitude-----		
No.	Phase a	Phase b	Phase c
1	1.0000	0.5541	0.5541
2	1.0000	0.5000	0.5000
3	1.0000	0.5218	0.5218

Line currents for fault at bus No. 2

From	To	-----Line Current Magnitude----		
Bus	Bus	Phase a	Phase b	Phase c
1	2	0.0000	1.9112	1.9112
1	3	0.0000	0.5973	0.5973

2	F	0.0000	5.9726	5.9726
3	2	0.0000	0.5973	0.5973

Line-to-line fault at bus No. 3

Total fault current = 3.9365 per unit

Bus Voltages during the fault in per unit

Bus -----Voltage Magnitude-----

No.	Phase a	Phase b	Phase c
1	1.0000	0.6128	0.6128
2	1.0000	0.6364	0.6364
3	1.0000	0.5000	0.5000

Line currents for fault at bus No. 3

From To -----Line Current Magnitude----

Bus	Bus	Phase a	Phase b	Phase c
1	3	0.0000	2.3619	2.3619
2	1	0.0000	0.3149	0.3149
2	3	0.0000	1.5746	1.5746
3	F	0.0000	3.9365	3.9365

Double line-to-ground fault analysis

Double line-to-ground fault at bus No.

1 Total fault current = 5.8939 per unit

Bus Voltages during the fault in per unit

Bus -----Voltage Magnitude-----

No.	Phase a	Phase b	Phase c
1	1.0727	0.0000	0.0000
2	0.9008	0.3756	0.3756
3	1.0196	0.1322	0.1322

Line currents for fault at bus No. 1

From To -----Line Current Magnitude----

Bus	Bus	Phase a	Phase b	Phase c
1	F	0.0000	6.6601	6.6601
2	1	0.2063	2.2302	2.2302
2	3	0.0393	0.6843	0.6843
3	1	0.0393	0.6843	0.6843

Total fault current = 9.4414 per unit

Bus Voltages during the fault in per unit

Bus -----Voltage Magnitude-----

No.	Phase a	Phase b	Phase c
1	0.8411	0.2894	0.2894
2	0.8155	0.0000	0.0000
3	0.8269	0.1835	0.1835

Line currents for fault at bus No. 2

From To -----Line Current Magnitude----

Bus	Bus	Phase a	Phase b	Phase c
1	2	0.6727	2.0868	2.0868
1	3	0.2203	0.6482	0.6482
2	F	0.0000	7.6129	7.6129
3	2	0.2203	0.6482	0.6482

Double line-to-ground fault at bus No.

3 Total fault current = 3.2609 per unit

Bus Voltage
Magnitude

No.	Phase a	Phase b	Phase c
1	1.0109	0.4498	0.4498
2	0.9402	0.5362	0.5362
3	1.1413	0.0000	0.0000

Line currents for fault at bus No. 3

From	To	-----Line Current Magnitude----		
Bus	Bus	Phase a	Phase b	Phase c
1	3	0.0000	2.5565	2.5565
2	1	0.1848	0.4456	0.4456
2	3	0.0000	1.7043	1.7043
3	F	0.0000	4.2608	4.2608

Balanced three-phase fault analysis

Balanced three-phase fault at bus No. 1

Total fault current = 6.8966 per unit

Bus Voltages during fault in per unit

Bus	Voltage	Angle
No.	Magnitude	degrees
1	0.0000	0.0000

2	0.2759	0.0000
3	0.1034	0.0000

Line currents for fault at bus No. 1

From	To	Current	Angle
Bus	Bus	Magnitude	degrees
G	1	4.0000	-90.0000
1	F	6.8966	-90.0000
G	2	2.8966	-90.0000
2	1	2.2069	-90.0000
2	3	0.6897	-90.0000
3	1	0.6897	-90.0000

Balanced three-phase fault at bus No. 2

Total fault current = 6.8966 per unit

Bus Voltages during fault in per unit

Bus	Voltage	Angle
No.	Magnitude	degrees
1	0.2759	0.0000
2	0.0000	0.0000
3	0.1724	0.0000

Line currents for fault at bus No. 2

From	To	Current	Angle
Bus	Bus	Magnitude	
degrees			
G	1	2.8966	-90.0000
1	2	2.2069	-90.0000
1	3	0.6897	-90.0000
G	2	4.0000	-90.0000
2	F	6.8966	-90.0000
3	2	0.6897	-90.0000

Balanced three-phase fault at bus No. 3

Total fault current = 4.5455 per unit

Bus Voltages during fault in per unit

Bus	Voltage	Angle
No.	Magnitude	degrees
1	0.4091	0.0000
2	0.4545	0.0000
3	0.0000	0.0000

Line currents for fault at bus No. 3

From	To	Current	Angle
Bus	Bus	Magnitude	degrees
G	1	2.3636	-90.0000
1	3	2.7273	-90.0000
G	2	2.1818	-90.0000
2	1	0.3636	-90.0000
2	3	1.8182	-90.0000
3	F	4.5455	-90.0000

DISCUSSION

Computation of fault currents in power system is best done by computer. Computer formulation of the impedance matrix was accomplished by programming the four modifications presented in chapter three. Care was taken to avoid the new- bus to new-bus modification, which requires infinite entries into $[Z]$. This situation was avoided in two ways; the buses were numbered to avoid the problem; a fictitious large impedance was inserted from one of the new busses to reference that was taken as bus zero, to change its status to an old bus in the next step. Complete modification was done using the old-bus- to new- bus method.

The procedure was followed in duplicate for the sequences since same values were used for positive- and negative- sequence impedances.

In most fault calculation techniques, prefault, or load, component of current is neglected usually on the assumption that currents throughout the system are zero prior to the fault, this is almost never strictly true; however the error produced is small, since the fault currents are generally much larger than the load currents. The load currents and the fault currents are almost 90° displaced in phase from each other, making their sum more closely equal to the large component than would have been the case if the currents were in phase. Besides, selecting precise values for all prefault currents is somewhat speculative, since there is no way of predicting what the loaded state of the system is when a fault occurs.

CONCLUSION

The fault analysis codes were able to generate accurate results based on the input data defined by the theory of symmetrical components. It was noted that only symmetrical fault analysis can reveal the post fault bus voltages while the unbalanced faults analysis can only generate results for total fault current, bus voltages and line currents during the fault. Therefore the project can be regarded as successfully done.

RECOMMENDATIONS

The local power generating companies e.g. KenGen and power transmission and distribution companies e.g. KPLC should establish a fully - fledged faults analysis department in their institutions to entrench and implement modern computerised methods of electrical power systems fault analysis that would provide more accurate data that can be used to size and set protective devices adequately.

For purposes of future work, the following should be given due attention:

1. Incorporate computer monitoring software for fault detection
2. More work to be done on the analysis so that it can reflect the post fault security of a system.
3. Computerised technique on interfacing of fault detection application and protection systems e.g. circuit breakers needs to be studied to improve the switching speed of our protective devices.
4. There is need to focus on the relevance of the fibre optics technology to fault studies so as to have our fault analysis softwares embedded in the communication link for efficient customer notification services by KPLC on fault occurrences.

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9. Stevenson series "*Elements of power systems*"

APPENDIX A

MATLAB CODES

Z_{bus} IMPEDANCE MATRIX

% This program forms the complex bus impedance matrix by the method
% of building algorithm. Bus zero is taken as reference.

```
function [Zbus] = zbuild(linedata)
nl = linedata(:,1); nr = linedata(:,2); R = linedata(:,3);
X = linedata(:,4);
nbr=length(linedata(:,1)); nbus = max(max(nl), max(nr));
for k=1:nbr
    if R(k) == inf | X(k) == inf
        R(k) = 99999999; X(k) = 99999999;
    else,
end end

ZB = R + j*X;
Zbus = zeros(nbus, nbus);
tree=0; %%%%new
% Adding a branch from a new bus to reference bus 0
for I = 1:nbr
    ntree(I) = 1;
    if nl(I) == 0 | nr(I) == 0
        if nl(I) == 0 n = nr(I);
        elseif nr(I) == 0 n =
            nl(I); end
        if abs(Zbus(n,n)) == 0 Zbus(n,n) = ZB(I); tree=tree+1; %%%new
        else Zbus(n,n) = Zbus(n,n)*ZB(I)/(Zbus(n,n) + ZB(I));
        end
        ntree(I) = 2;
    else,end
end

% Adding a branch from new bus to an existing bus
while tree < nbus %%%% new

for n = 1:nbus
    nadd = 1;
    if abs(Zbus(n,n)) == 0
        for I = 1:nbr
            if nadd == 1;
                if nl(I) == n | nr(I) == n
```

```

        if nl(I) == n k = nr(I);
        elseif nr(I) == n k =
nl(I); end
        if abs(Zbus(k,k)) ~=
0 for m = 1:nbus
            if m ~= n
                Zbus(m,n) = Zbus(m,k);
                Zbus(n,m) = Zbus(m,k);
            else, end
        end
        Zbus(n,n) = Zbus(k,k) + ZB(I); tree=tree+1; %%%new
        nadd = 2; ntree(I) = 2;
    else,
end else,
end
else,
end end
else, end
end

```

```

end %%%%%%%%%new

```

```

% Adding a link between two old buses
for n = 1:nbus
    for I = 1:nbr
        if ntree(I) == 1
            if nl(I) == n | nr(I) == n
                if nl(I) == n k = nr(I);
                elseif nr(I) == n k =
nl(I); end
            DM = Zbus(n,n) + Zbus(k,k) + ZB(I) - 2*Zbus(n,k);
            for jj = 1:nbus
                AP = Zbus(jj,n) - Zbus(jj,k);
                for kk = 1:nbus
                    AT = Zbus(n,kk) - Zbus(k, kk);
                    DELZ(jj,kk) = AP*AT/DM;
                end
            end
            Zbus = Zbus - DELZ;
            ntree(I) = 2;
        else,en
        d else,end
    end
end
end

```

Double- Line- Ground fault

% The program dlfault is designed for the double line-to-ground
% fault analysis of a power system network. The program requires

```

% the positive-, negative- or zero-sequence bus impedance matrices,
% Zbus1 Zbus2, and Zbus0. The bus impedances matrices may be defined
% by the user, obtained by the inversion of Ybus or it may be
% determined either from the function Zbus = zbuild(zdata)
% or the function Zbus = zbuildpi(linedata, gendata, yload).
% The program prompts the user to enter the faulted bus number
% and the fault impedance Zf. The prefault bus voltages are
% defined by the reserved Vector V. The array V may be defined or
% it is returned from the power flow programs lfgauss, lfnewton,
% decouple or perturb. If V does not exist the prefault bus voltages
% are automatically set to 1.0 per unit. The program obtains the
% total fault current, bus voltages and line currents during the fault.

```

```

function dlglfault(zdata0, Zbus0, zdata1, Zbus1, zdata2, Zbus2, V)
if exist('zdata2') ~= 1
zdata2=zdata1;
else, end
if exist('Zbus2') ~= 1
Zbus2=Zbus1;
else, end

nl = zdata1(:,1); nr = zdata1(:,2);
nl0 = zdata0(:,1); nr0 = zdata0(:,2);
nbr=length(zdata1(:,1)); nbus = max(max(nl), max(nr));
nbr0=length(zdata0(:,1));
R0 = zdata0(:,3); X0 = zdata0(:,4);
R1 = zdata1(:,3); X1 = zdata1(:,4);
R2 = zdata2(:,3); X2 = zdata2(:,4);

for k = 1:nbr0
    if R0(k) == inf | X0(k) == inf
        R0(k) = 99999999; X0(k) = 999999999;
    else,
end end
ZB1 = R1 + j*X1; ZB0 = R0 + j*X0;
ZB2 = R2 + j*X2;

if exist('V') == 1
    if length(V) == nbus
        V0 = V;
    else, end
else, V0 = ones(nbus, 1) + j*zeros(nbus, 1);
end

fprintf('\nDouble line-to-ground fault analysis \n')
ff = 999;

```

```

while ff > 0
nf = input('Enter Faulted Bus No. -> ');
while nf <= 0 | nf > nbus
    fprintf('Faulted bus No. must be between 1 & %g \n', nbus)
    nf = input('Enter Faulted Bus No. -> ');
end
fprintf('\nEnter Fault Impedance Zf = R + j*X in ')
Zf = input('complex form (for bolted fault enter 0). Zf = ');
fprintf(' \n')
fprintf('Double line-to-ground fault at bus No. %g\n', nf)
a = cos(2*pi/3) + j*sin(2*pi/3);
sctm = [1 1 1; 1 a^2 a; 1 a a^2];

Z11 = Zbus2(nf, nf)*(Zbus0(nf, nf) + 3*Zf)/(Zbus2(nf, nf) + Zbus0(nf, nf) + 3*Zf);
Ia1 = V0(nf)/(Zbus1(nf, nf) + Z11);
Ia2 = -(V0(nf) - Zbus1(nf, nf)*Ia1)/Zbus2(nf, nf);
Ia0 = -(V0(nf) - Zbus1(nf, nf)*Ia1)/(Zbus0(nf, nf) + 3*Zf);
I012 = [Ia0; Ia1; Ia2];
Ifabc = sctm*I012; Ifabcm = abs(Ifabc);
Ift = Ifabc(2) + Ifabc(3);
Iftm = abs(Ift);

fprintf('Total fault current = %9.4f per unit\n\n', Iftm)
fprintf('Bus Voltages during the fault in per unit \n\n')
fprintf(' Bus -----Voltage Magnitude          \n')
fprintf(' No. Phase a Phase b Phase c \n')

for n = 1:nbus
Vf0(n) = 0 - Zbus0(n, nf)*Ia0;
Vf1(n) = V0(n) - Zbus1(n, nf)*Ia1;
Vf2(n) = 0 - Zbus2(n, nf)*Ia2;
Vabc = sctm*[Vf0(n); Vf1(n); Vf2(n)];
Va(n) = Vabc(1); Vb(n) = Vabc(2); Vc(n) = Vabc(3);
fprintf(' %5g', n)
fprintf(' %11.4f, abs(Va(n))'), fprintf(' %11.4f, abs(Vb(n))')
fprintf(' %11.4f\n', abs(Vc(n)))
end
fprintf(' \n')
fprintf('Line currents for fault at bus No. %g\n', nf)
fprintf(' From To -----Line Current Magnitude \n')
fprintf(' Bus Bus Phase a Phase b Phase c \n')
for n = 1:nbus
for I = 1:nbr
if nl(I) == n | nr(I) == n
if nl(I) == n k = nr(I);
elseif nr(I) == n k = nl(I);
end
if k ~= 0
Ink1(n, k) = (Vf1(n) - Vf1(k))/ZB1(I);
Ink2(n, k) = (Vf2(n) - Vf2(k))/ZB2(I);

```

```

        else,
    end else,
    end
end
for I = 1:nbr0
    if nl0(I) == n | nr0(I) == n
        if nl0(I) == n k = nr0(I);
        elseif nr0(I) == n k = nl0(I);
        end
        if k ~= 0
            Ink0(n, k) = (Vf0(n) - Vf0(k))/ZB0(I);
        else,
        end else,
        end
    end
    for I = 1:nbr
        if nl(I) == n | nr(I) == n
            if nl(I) == n k = nr(I);
            elseif nr(I) == n k = nl(I);
            end
            if k ~= 0
                Inkabc = sctm*[Ink0(n, k); Ink1(n, k); Ink2(n,
                k)]; Inkabcm = abs(Inkabc); th=angle(Inkabc);
                if real(Inkabc(2)) < 0
                    fprintf('%7g', n), fprintf('%10g', k),
                    fprintf(' %11.4f', abs(Inkabc(1))), fprintf(' %11.4f', abs(Inkabc(2)))
                    fprintf(' %11.4f\n', abs(Inkabc(3)))
                    elseif real(Inkabc(2)) == 0 & imag(Inkabc(2)) > 0
                        fprintf('%7g', n), fprintf('%10g', k),
                        fprintf(' %11.4f', abs(Inkabc(1))), fprintf(' %11.4f', abs(Inkabc(2)))
                        fprintf(' %11.4f\n', abs(Inkabc(3)))
                        else,
                    end else,
                    end
                else, end
            end
            if n==nf
                fprintf('%7g',n), fprintf('      F'),
                fprintf(' %11.4f', Ifabcm(1)), fprintf(' %11.4f', Ifabcm(2))
                fprintf(' %11.4f\n', Ifabcm(3))
            else,
            end end
        resp=0;
        while strcmp(resp, 'n')~=1 & strcmp(resp, 'N')~=1 & strcmp(resp, 'y')~=1 & strcmp(resp,
        'Y')~=1
            resp = input('Another fault location? Enter "y" or "n" within single quote -> ');
            if strcmp(resp, 'n')~=1 & strcmp(resp, 'N')~=1 & strcmp(resp, 'y')~=1 & strcmp(resp,
            'Y')~=1
                fprintf('\n Incorrect reply, try again \n\n'), end
            end
            if resp == 'y' | resp == 'Y'
                nf = 999;
            else ff = 0; end
        end
    end
end

```

```
end % end for while
```

Line- Ground fault

% The program lgfault is designed for the single line-to-ground
% fault analysis of a power system network. The program requires
% the positive-, negative- and zero-sequence bus impedance matrices,
% Zbus1 Zbus2, and Zbus0. The bus impedances matrices may be defined
% by the user, obtained by the inversion of Ybus or it may be
% determined either from the function Zbus = zbuild(zdata)
% or the function Zbus = zbuildpi(linedata, gendata, yload).
% The program prompts the user to enter the faulted bus number
% and the fault impedance Zf. The prefault bus voltages are
% defined by the reserved Vector V. The array V may be defined or
% it is returned from the power flow programs lfgauss, lfnewton,
% decouple or perturb. If V does not exist the prefault bus voltages
% are automatically set to 1.0 per unit. The program obtains the
% total fault current, bus voltages and line currents during the fault.

```
function lgfault(zdata0, Zbus0, zdata1, Zbus1, zdata2, Zbus2, V)
if exist('zdata2') ~= 1
zdata2=zdata1;
else, end
if exist('Zbus2') ~= 1
Zbus2=Zbus1;
else, end
nl = zdata1(:,1); nr = zdata1(:,2);
nl0 = zdata0(:,1); nr0 = zdata0(:,2);
nbr=length(zdata1(:,1)); nbus = max(max(nl), max(nr));
nbr0=length(zdata0(:,1));
R0 = zdata0(:,3); X0 = zdata0(:,4);
R1 = zdata1(:,3); X1 = zdata1(:,4);
```

```

R2 = zdata1(:,3); X2 = zdata1(:,4);

for k=1:nbr0
    if R0(k)==inf | X0(k)==inf
        R0(k) = 99999999; X0(k) = 99999999;
    else,
    end end
ZB1 = R1 + j*X1; ZB0 = R0 + j*X0;
ZB2 = R2 + j*X2;

if exist('V') == 1
    if length(V) == nbus
        V0 = V;
    else, end
else, V0 = ones(nbus, 1) + j*zeros(nbus, 1);
end
fprintf('\nLine-to-ground fault analysis \n')
ff = 999;
while ff > 0
    nf = input('Enter Faulted Bus No. -> ');
    while nf <= 0 | nf > nbus
        fprintf('Faulted bus No. must be between 1 & %g \n', nbus)
        nf = input('Enter Faulted Bus No. -> ');
    end
    fprintf('\nEnter Fault Impedance Zf = R + j*X in ')
    Zf = input('complex form (for bolted fault enter 0). Zf = ');
    fprintf(' \n')
    fprintf('Single line to-ground fault at bus No. %g\n', nf)
    a = cos(2*pi/3) + j*sin(2*pi/3);
    sctm = [1 1 1; 1 a^2 a; 1 a a^2];
    Ia0 = V0(nf)/(Zbus1(nf,nf)+Zbus2(nf, nf)+ Zbus0(nf, nf)+3*Zf); Ia1=Ia0; Ia2=Ia0;
    I012=[Ia0; Ia1; Ia2];
    Ifabc = sctm*I012;
    Ifabcm = abs(Ifabc);
    fprintf('Total fault current = %9.4f per unit\n\n', Ifabcm(1))
    fprintf('Bus Voltages during the fault in per unit \n\n')
    fprintf('    Bus    -----Voltage Magnitude        \n')
    fprintf('    No.   Phase a   Phase b   Phase c \n')

    for n = 1:nbus
        Vf0(n)= 0 - Zbus0(n, nf)*Ia0;
        Vf1(n)= V0(n) - Zbus1(n, nf)*Ia1;
        Vf2(n)= 0 - Zbus2(n, nf)*Ia2;
        Vabc = sctm*[Vf0(n); Vf1(n); Vf2(n)];
        Va(n)=Vabc(1); Vb(n)=Vabc(2); Vc(n)=Vabc(3);
        fprintf(' %5g',n)
        fprintf(' %11.4f', abs(Va(n))),fprintf(' %11.4f', abs(Vb(n)))
        fprintf(' %11.4f\n', abs(Vc(n)))
    end
    fprintf(' \n')

```

```
fprintf('Line currents for fault at bus No. %g\n', nf)
```

```
fprintf(' From To -----Line Current Magnitude \n')
fprintf(' Bus Bus Phase a Phase b Phase c \n')
for n= 1:nbus
    for I =
        1:nbr
        if nl(I) == n | nr(I) == n
            if nl(I) == n k = nr(I);
            elseif nr(I) == n k = nl(I);
            end
            if k ~= 0
                Ink1(n, k) = (Vf1(n) - Vf1(k))/ZB1(I);
                Ink2(n, k) = (Vf2(n) - Vf2(k))/ZB2(I);
            else,
            end else,
            end
        end
        for I = 1:nbr0
            if nl0(I) == n | nr0(I) == n
                if nl0(I) == n k = nr0(I);
                elseif nr0(I) == n k = nl0(I);
                end
                if k ~= 0
                    Ink0(n, k) = (Vf0(n) - Vf0(k))/ZB0(I);
                else,
                end else,
                end
            end
            for I = 1:nbr
                if nl(I) == n | nr(I) == n
                    if nl(I) == n k = nr(I);
                    elseif nr(I) == n k = nl(I);
                    end
                    if k ~= 0
                        Inkabc = setm*[Ink0(n, k); Ink1(n, k); Ink2(n,
                        k)]; Inkabcm = abs(Inkabc); th=angle(Inkabc);
                        if real(Inkabc(1)) > 0
                            fprintf('%7g', n), fprintf('%10g', k),
                            fprintf(' %11.4f', abs(Inkabc(1))),fprintf(' %11.4f', abs(Inkabc(2)))
                            fprintf(' %11.4f\n', abs(Inkabc(3)))
                        elseif real(Inkabc(1)) ==0 & imag(Inkabc(1)) < 0
                            fprintf('%7g', n), fprintf('%10g', k),
                            fprintf(' %11.4f', abs(Inkabc(1))),fprintf(' %11.4f', abs(Inkabc(2)))
                            fprintf(' %11.4f\n', abs(Inkabc(3)))
                        else,
                        end else,
                        end
                    end
                else, end
            end
        end
        if n==nf
            fprintf('%7g',n), fprintf(' F'),
            fprintf(' %11.4f', Ifabcm(1)),fprintf(' %11.4f', Ifabcm(2))
            fprintf(' %11.4f\n', Ifabcm(3))
        else, end
    end
end
```

```

end
resp=0;
while strcmp(resp, 'n')~=1 & strcmp(resp, 'N')~=1 & strcmp(resp, 'y')~=1 & strcmp(resp,
'Y')~=1
    resp = input('Another fault location? Enter "y" or "n" within single quote -> ');
    if strcmp(resp, 'n')~=1 & strcmp(resp, 'N')~=1 & strcmp(resp, 'y')~=1 & strcmp(resp,
'Y')~=1
        fprintf('\n Incorrect reply, try again \n\n'), end
    end
    if resp == 'y' | resp == 'Y'
        nf = 999;
    else ff = 0; end
end % end for while
%Ink0
%Ink1
%Ink2

```

Line- line fault

% The program llfault is designed for the line-to-line
 % fault analysis of a power system network. The program requires
 % the positive- and negative-sequence bus impedance matrices,
 % Zbus function Zbus = zbuildpi(linedata, gendata, yload).
 % The program prompts the user to enter the faulted bus number
 % and the fault impedance Zf. The prefault bus voltages are
 % defined by the reserved Vector V. The array V may be defined or
 % it is returned from the power flow programs lfgauss, lfnewton,
 % decouple or perturb. If V does not exist the prefault bus voltages
 % are automatically set to 1.0 per unit. The program obtains the
 % total fault current, bus voltages and line currents during the fault.

```

function llfault(zdata1, Zbus1, zdata2, Zbus2, V)
if exist('zdata2') ~= 1
    zdata2=zdata1;
else, end
if exist('Zbus2') ~= 1
    Zbus2=Zbus1;
else, end

nl = zdata1(:,1); nr = zdata1(:,2);
R1 = zdata1(:,3); X1 = zdata1(:,4);
R2 = zdata2(:,3); X2 = zdata2(:,4);
ZB1 = R1 + j*X1; ZB2 = R2 + j*X2;
nbr=length(zdata1(:,1)); nbus = max(max(nl), max(nr));

```

```

if exist('V') == 1
    if length(V) == nbus
        V0 = V;
    else, end
else, V0 = ones(nbus, 1) + j*zeros(nbus, 1);
end
fprintf('\nLine-to-line fault analysis \n')
ff = 999;
while ff > 0
    nf = input('Enter Faulted Bus No. -> ');
    while nf <= 0 | nf > nbus
        fprintf('Faulted bus No. must be between 1 & %g \n', nbus)
        nf = input('Enter Faulted Bus No. -> ');
    end
    fprintf('\nEnter Fault Impedance Zf = R + j*X in ')
    Zf = input('complex form (for bolted fault enter 0). Zf = ');
    fprintf(' \n')
    fprintf('Line-to-line fault at bus No. %g\n', nf)
    a = cos(2*pi/3) + j*sin(2*pi/3);
    sctm = [1 1 1; 1 a^2 a; 1 a a^2];
    Ia0 = 0;
    Ia1 = V0(nf)/(Zbus1(nf,nf)+Zbus2(nf, nf)+Zf); Ia2 = -Ia1;
    I012 = [Ia0; Ia1; Ia2];
    Ifabc = sctm*I012;
    Ifabcm = abs(Ifabc);
    fprintf('Total fault current = %9.4f per unit\n\n', Ifabcm(2))
    fprintf('Bus Voltages during the fault in per unit \n\n')
    fprintf('   Bus   -----Voltage Magnitude      \n')
    fprintf('   No.   Phase a   Phase b   Phase c \n')

    for n = 1:nbus
        Vf0(n) = 0;
        Vf1(n) = V0(n) - Zbus1(n, nf)*Ia1;
        Vf2(n) = 0 - Zbus2(n, nf)*Ia2;
        Vabc = sctm*[Vf0(n); Vf1(n); Vf2(n)];
        Va(n) = Vabc(1); Vb(n) = Vabc(2); Vc(n) = Vabc(3);
        fprintf(' %5g', n)
        fprintf(' %11.4f', abs(Va(n))), fprintf(' %11.4f', abs(Vb(n)))
        fprintf(' %11.4f\n', abs(Vc(n)))
    end
    fprintf(' \n')
    fprintf('Line currents for fault at bus No. %g\n\n', nf)
    fprintf('   From   To   -----Line Current Magnitude   \n')
    fprintf('   Bus    Bus   Phase a   Phase b   Phase c \n')

    for n = 1:nbus
        for I = 1:nbr
            if nl(I) == n | nr(I) == n
                if nl(I) == n      k = nr(I);
                elseif nr(I) == n k = nl(I);
            end
        end
    end

```

```

end
if k ~= 0
Ink0(n, k) = 0;
Ink1(n, k) = (Vf1(n) - Vf1(k))/ZB1(I);
Ink2(n, k) = (Vf2(n) - Vf2(k))/ZB2(I);

Inkabc = setm*[Ink0(n, k); Ink1(n, k); Ink2(n, k)];
Inkabcm = abs(Inkabc); th=angle(Inkabc);
if real(Inkabcm(2)) < 0

fprintf('%7g', n), fprintf('%10g', k),
fprintf(' %11.4f', abs(Inkabcm(1))),fprintf(' %11.4f', abs(Inkabcm(2)))
fprintf(' %11.4f\n', abs(Inkabcm(3)))
elseif real(Inkabcm(2)) ==0 & imag(Inkabcm(2)) > 0
fprintf('%7g', n), fprintf('%10g', k),
fprintf(' %11.4f', abs(Inkabcm(1))),fprintf(' %11.4f', abs(Inkabcm(2)))
fprintf(' %11.4f\n', abs(Inkabcm(3)))
else,
end else,
end
else, end
end
if n==nf
fprintf('%7g',n), fprintf('      F'),
fprintf(' %11.4f', Ifabcm(1)),fprintf(' %11.4f', Ifabcm(2))
fprintf(' %11.4f\n', Ifabcm(3))
else,
end end
resp=0;
while strcmp(resp, 'n')~=1 & strcmp(resp, 'N')~=1 & strcmp(resp, 'y')~=1 & strcmp(resp,
'Y')~=1
resp = input('Another fault location? Enter "y" or "n" within single quote -> ');
if strcmp(resp, 'n')~=1 & strcmp(resp, 'N')~=1 & strcmp(resp, 'y')~=1 & strcmp(resp,
'Y')~=1
fprintf('\n Incorrect reply, try again \n\n'), end
end
if resp == 'y' | resp == 'Y'
nf = 999;
else ff = 0; end
end % end for while

```

Balanced Three- phase fault

% The program symfault is designed for the balanced three-phase
 % fault analysis of a power system network. The program requires
 % the bus impedance matrix Zbus. Zbus may be defined by the
 % user, obtained by the inversion of Ybus or it may be
 % determined either from the function Zbus =zbuild(zdata)
 % or the function Zbus = zbuildpi(linedata, gendata, yload).

```
% The program prompts the user to enter the faulted bus number
% and the fault impedance Zf. The prefault bus voltages are
% defined by the reserved Vector V. The array V may be defined or
% it is returned from the power flow programs lfgauss, lfnewton,
% decouple or perturb. If V does not exist the prefault bus voltages
% are automatically set to 1.0 per unit. The program obtains the
% total fault current, the postfault bus voltages and line currents.function symfault(zdata,
Zbus, V)
```

```
nl = zdata(:,1); nr = zdata(:,2); R = zdata(:,3);
X = zdata(:,4);
nc = length(zdata(1,:));
if nc > 4
    BC = zdata(:,5);
elseif nc ==4, BC = zeros(length(zdata(:,1)), 1);
end
ZB = R + j*X;
nbr=length(zdata(:,1)); nbus = max(max(nl), max(nr));
if exist('V') == 1
    if length(V) == nbus
        V0 = V;
    else, end
else, V0 = ones(nbus, 1) + j*zeros(nbus, 1);
end
fprintf('\nThree-phase balanced fault analysis \n')
ff = 999;
while ff > 0
    nf = input('Enter Faulted Bus No. -> ');
    while nf <= 0 | nf > nbus
        fprintf('Faulted bus No. must be between 1 & %g \n', nbus)
        nf = input('Enter Faulted Bus No. -> ');
    end
    fprintf('\nEnter Fault Impedance Zf = R + j*X in ')
    Zf = input('complex form (for bolted fault enter 0). Zf = ');
    fprintf(' \n')
    fprintf('Balanced three-phase fault at bus No. %g\n', nf)

    If = V0(nf)/(Zf + Zbus(nf, nf));
    Ifm = abs(If); Ifmang=angle(If)*180/pi; fprintf('Total
    fault current = %8.4f per unit \n\n', Ifm)
    %fprintf(' p.u. \n\n', Ifm)
    fprintf('Bus Voltages during fault in per unit \n\n')
    fprintf('   Bus   Voltage   Angle\n')
    fprintf('   No.   Magnitude   degrees\n')

    for n = 1:nbus
        if n==nf
            Vf(nf) = V0(nf)*Zf/(Zf + Zbus(nf,nf)); Vf = abs(Vf(nf)); angv=angle(Vf(nf))*180/pi;
        else, Vf(n) = V0(n) - V0(n)*Zbus(n,nf)/(Zf + Zbus(nf,nf));
            Vf = abs(Vf(n)); angv=angle(Vf(n))*180/pi;
```

```

end
fprintf('%4g', n), fprintf('%13.4f', Vfm), fprintf('%13.4f\n', angv)

end

fprintf('\n')

fprintf('Line currents for fault at bus No. %g\n\n', nf)
fprintf('  From    To    Current    Angle\n')
fprintf('  Bus      Bus    Magnitude degrees\n')

for n= 1:nbus
    %Ign=0;
    for I = 1:nbr
        if nl(I) == n | nr(I) == n
            if nl(I) == n k = nr(I);
            elseif nr(I) == n k = nl(I);
            end
            if k==0
                Ink = (V0(n) - Vf(n))/ZB(I);
                Inkm = abs(Ink); th=angle(Ink);
                %if th <= 0
                if real(Ink) > 0
                    fprintf('      G '), fprintf('%7g',n), fprintf('%12.4f',
                    Inkm) fprintf('%12.4f\n', th*180/pi)
                elseif real(Ink) ==0 & imag(Ink) < 0
                    fprintf('      G '), fprintf('%7g',n), fprintf('%12.4f',
                    Inkm) fprintf('%12.4f\n', th*180/pi)
                else, end
                Ign=Ink;
            elseif k ~= 0
                Ink = (Vf(n) - Vf(k))/ZB(I)+BC(I)*Vf(n);
                %Ink = (Vf(n) - Vf(k))/ZB(I);
                Inkm = abs(Ink); th=angle(Ink);
                %Ign=Ign+Ink;
                %if th <= 0
                if real(Ink) > 0
                    fprintf('%7g', n), fprintf('%10g', k),
                    fprintf('%12.4f', Inkm), fprintf('%12.4f\n', th*180/pi)
                elseif real(Ink) ==0 & imag(Ink) < 0
                    fprintf('%7g', n), fprintf('%10g', k),
                    fprintf('%12.4f', Inkm), fprintf('%12.4f\n', th*180/pi)
                else, end
            else, end
        else, end
    end

    if n==nf
        fprintf('%7g',n), fprintf('      F'), fprintf('%12.4f',
        Ifm) fprintf('%12.4f\n', Ifmang)
    end
end

```

```

else, end
end
resp=0;
while strcmp(resp, 'n')~=1 & strcmp(resp, 'N')~=1 & strcmp(resp, 'y')~=1 & strcmp(resp,
'Y')~=1
    resp = input('Another fault location? Enter "y" or "n" within single quote -> ');
    if strcmp(resp, 'n')~=1 & strcmp(resp, 'N')~=1 & strcmp(resp, 'y')~=1 & strcmp(resp,
'Y')~=1
        fprintf('\n Incorrect reply, try again \n\n'), end
    end
    if resp == 'y' | resp == 'Y'
        nf = 999;
    else ff = 0; end
end % end for while

```

NETWORK CODE

```

zdata1=[0    1    0    0.25
         0    2    0    0.25
         1    2    0    0.125
         1    3    0    0.15
         2    3    0    0.25];

```

```

zdata0=[0    1    0    0.40
         0    2    0    0.1
         1    2    0    0.3
         1    3    0    0.35
         2    3    0    0.7125];

```

```

zdata2=zdata1;
Zbus1=zbuild(zdata1)
Zbus0=zbuild(zdata0)
Zbus2=Zbus1;
symfault(zdata1,Zbus1)
lgfault(zdata0, Zbus0, zdata1, Zbus1, zdata2, Zbus2)
llfault(zdata1, Zbus1, zdata2, Zbus2)
dlgfault(zdata0,Zbus0,zdata1,Zbus1,zdata2,Zbus2)

```

UNIT-5

STABILITY ANALYSIS

INTRODUCTION

Power system stability of modern large inter-connected systems is a major problem for secure operation of the system. Recent major black-outs across the globe caused by system instability, even in very sophisticated and secure systems, illustrate the problems facing secure operation of power systems. Earlier, stability was defined as the ability of a system to return to normal or stable operation after having been subjected to some form of disturbance. This fundamentally refers to the ability of the system to remain in synchronism. However, modern power systems operate under complex interconnections, controls and extremely stressed conditions. Further, with increased automation and use of electronic equipment, the quality of power has gained utmost importance, shifting focus on to concepts of voltage stability, frequency stability, inter-area oscillations etc.

The IEEE/CIGRE Joint Task Force on stability terms and conditions have proposed the following definition in 2004: “*Power System stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded, so that practically the entire system remains intact*”. The Power System is an extremely non-linear and dynamic system, with operating parameters continuously varying. Stability is hence, a function of the initial operating condition and the nature of the disturbance. Power systems are continually subjected to small disturbances in the form of load changes. The system must be in a position to be able to adjust to the changing conditions and operate satisfactorily. The system must also withstand large disturbances, which may even cause structural changes due to isolation of some faulted elements. A power system may be stable for a particular (large) disturbance and unstable for another disturbance. It is impossible to design a system which is stable under all disturbances. The power system is generally designed to be stable under those disturbances which have a high degree of occurrence. The response to a disturbance is extremely complex and involves practically all the equipment of the power system. For example, a short circuit leading to a line isolation by circuit breakers will cause variations in the power flows, network bus voltages and generators rotor speeds. The voltage variations will actuate the voltage regulators in the system and generator speed variations will actuate the prime mover governors; voltage and frequency variations will affect the system loads. In stable systems, practically all generators and loads remain connected, even though parts of the system may be isolated to preserve bulk operations. On the other hand, an unstable system condition could lead to cascading outages and a shutdown of a major portion of the power system.

ROTOR ANGLE STABILITY

Rotor angle stability refers to the ability of the synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance. Instability results in some generators accelerating (decelerating) and losing synchronism with other generators. Rotor angle stability depends on the ability of each synchronous machine to maintain equilibrium between electromagnetic torque and mechanical torque. Under steady state, there is equilibrium between the input mechanical torque and output electromagnetic torque of each generator, and its speed remains a constant. Under a disturbance, this equilibrium is upset and the generators accelerate/decelerate according to the mechanics of a rotating body. Rotor angle stability is further categorized as follows:

Small single (or small disturbance) rotor angle stability

It is the ability of the power system to maintain synchronism under small disturbances. In this case, the system equation can be linearized around the initial operating point and the stability depends only on the operating point and not on the disturbance. Instability may result in

- (i) A non oscillatory or a periodic increase of rotor angle
- (ii) Increasing amplitude of rotor oscillations due to insufficient damping.

The first form of instability is largely eliminated by modern fast acting voltage regulators and the second form of instability is more common. The time frame of small signal stability is of the order of 10-20 seconds after a disturbance.

Large-signal rotor angle stability or transient stability

This refers to the ability of the power system to maintain synchronism under large disturbances, such as short circuit, line outages etc. The system response involves large excursions of the generator rotor angles. Transient stability depends on both the initial operating point and the disturbance parameters like location, type, magnitude etc. Instability is normally in the form of a periodic angular separation. The time frame of interest is 3-5 seconds after disturbance. The term dynamic stability was earlier used to denote the steady-state stability in the presence of automatic controls (especially excitation controls) as opposed to manual controls. Since all generators are equipped with automatic controllers today, dynamic stability has lost relevance and the Task Force has recommended against its usage.

MECHANICS OF ROTATORY MOTION

Since a synchronous machine is a rotating body, the laws of mechanics of rotating bodies are applicable to it. In rotation we first define the fundamental quantities. The angle θ is defined, with respect to a circular arc with its center at the vertex of the angle, as the ratio of the arc length s to radius r .

$$\theta_m = \frac{s}{r} \quad (1)$$

The unit is radian. Angular velocity ω_m is defined as

$$\omega_m = \frac{d\theta_m}{dt} \quad (2)$$

and angular acceleration as

$$\alpha = \frac{d\omega_m}{dt} = \frac{d^2\theta_m}{dt^2} \quad (3)$$

The torque on a body due to a tangential force F at a distance r from axis of rotation is given by

$$T = r F \quad (4)$$

The total torque is the summation of infinitesimal forces, given by

$$T = \int r dF \quad (5)$$

The unit of torque is N-m. When torque is applied to a body, the body experiences angular acceleration. Each particle experiences a tangential acceleration $a = r\alpha$, where r is the distance of the particle from axis of rotation. The tangential force required to accelerate a particle of mass dm is

$$dF = a dm = r \alpha dm \quad (6)$$

The torque required for the particle is

$$dT = r dF = r^2 \alpha dm \quad (7)$$

and that required for the whole body is given by

$$T = \alpha \int r^2 dm = I \alpha \quad (8)$$

Here

$$I = \int r^2 dm \quad (9)$$

is called the moment of inertia of the body. The unit is $\text{Kg} - \text{m}^2$. If the torque is assumed to be the result of a number of tangential forces F , which act at different points of the body

$$T = \sum r F$$

Now each force acts through a distance

$$ds = r d\theta_m$$

The work done is $\sum F \cdot ds$

$$dW = \sum F r d\theta_m = d\theta_m T$$

$$W = \int T d\theta_m \quad (10)$$

$$\text{and} \quad T = \frac{dW}{d\theta_m} \quad (11)$$

Thus the unit of torque may also be Joule per radian.

The power is defined as rate of doing work. Using (11)

$$P = \frac{dW}{dt} = \frac{T d\theta_m}{dt} = T \omega_m \quad (12)$$

The angular momentum M is defined as

$$M = I \omega_m \quad (13)$$

and the kinetic energy is given by

$$KE = \frac{1}{2} I \omega_m^2 = \frac{1}{2} M \omega_m \quad (14)$$

From (14) we can see that the unit of M is seen to be J-sec/rad.

SWING EQUATION:

From (8)

$$I \alpha = T$$

or $\frac{I d^2 \theta_m}{dt^2} = T \quad (15)$

Here T is the net torque of all torques acting on the machine, which includes the shaft torque (due to prime mover of a generator or load on a motor), torque due to rotational losses (friction, windage and core loss) and electromagnetic torque.

Let T_m = shaft torque or mechanical torque corrected for rotational losses

T_e = Electromagnetic or electrical torque

For a generator T_m tends to accelerate the rotor in positive direction of rotation and for a motor retards the rotor.

The accelerating torque for a generator

$$T_a = T_m - T_e \quad (16)$$

Under steady-state operation of the generator, T_m is equal to T_e and the accelerating torque is zero. There is no acceleration or deceleration of the rotor masses and the machines run at a constant synchronous speed. In the stability analysis in the following sections, T_m is assumed to be a constant since the prime movers (steam turbines or hydro turbines) do not act during the short time period in which rotor dynamics are of interest in the stability studies.

Now (15) has to be solved to determine θ_m as a function of time. Since θ_m is measured with respect to a stationary reference axis on the stator, it is the measure of the absolute rotor angle and increases continuously with time even at constant synchronous speed. Since machine acceleration /deceleration is always measured relative to synchronous speed, the rotor angle is measured with respect to a synchronously rotating reference axis. Let

$$\delta_m = \theta_m - \omega_{sm} t \quad (17)$$

where ω_{sm} is the synchronous speed in mechanical rad/s and δ_m is the angular displacement in mechanical radians.

Taking the derivative of (17) we get

$$\begin{aligned} \frac{d\delta_m}{dt} &= \frac{d\theta_m}{dt} - \omega_{sm} \\ \frac{d^2\delta_m}{dt^2} &= \frac{d^2\theta_m}{dt^2} \end{aligned} \quad (18)$$

Substituting (18) in (15) we get

$$I \frac{d^2\delta_m}{dt^2} = T_a = T_m - T_e \quad \text{N-m} \quad (19)$$

Multiplying by ω_m on both sides we get

$$\omega_m I \frac{d^2\delta_m}{dt^2} = \omega_m (T_m - T_e) \quad \text{N-m} \quad (20)$$

From (12) and (13), we can write

$$M \frac{d^2\delta_m}{dt^2} = P_m - P_a \quad \text{W} \quad (21)$$

where M is the angular momentum, also called inertia constant

P_m = shaft power input less rotational losses

P_e = Electrical power output corrected for losses

P_a = acceleration power

M depends on the angular velocity ω_m , and hence is strictly not a constant, because ω_m deviates from the synchronous speed during and after a disturbance. However, under stable conditions ω_m does not vary considerably and M can be treated as a constant. (21) is called the “*Swing equation*”. The constant M depends on the rating of the machine and varies widely with the size and type of the machine. Another constant called H constant (also referred to as inertia constant) is defined as

$$H = \frac{\text{stored kinetic energy in mega joules at synchronous speed}}{\text{Machine rating in MVA}} \text{ MJ / MVA} \quad (22)$$

H falls within a narrow range and typical values are given in Table 9.1.

If the rating of the machine is G MVA, from (22) the stored kinetic energy is GH Mega Joules. From (14)

$$GH = \frac{1}{2} M \omega_{sm} \text{ MJ} \quad (23)$$

or

$$M = \frac{2GH}{\omega_{sm}} \text{ MJ-s/mech rad} \quad (24)$$

The swing equation (21) is written as

$$\frac{2H}{\omega_{sm}} \frac{d^2 \delta_m}{dt^2} = \frac{P_a}{G} = \frac{P_m - P_e}{G} \quad (25)$$

In (.25) δ_m is expressed in mechanical radians and ω_{sm} in mechanical radians per second (the subscript *m* indicates mechanical units). If δ and ω have consistent units then mec

$$\frac{2H}{\omega_s} \frac{d^2 \delta}{dt^2} = P_a = P_m - P_e \text{ pu} \quad (26)$$

Here ω_s is the synchronous speed in electrical rad/s ($\omega_s = \left(\frac{p}{2}\right) \omega_{sm}$) and P_a is acceleration power in per unit on same base as H. For a system with an electrical frequency *f* Hz, (26) becomes

$$\frac{H}{\pi f} \frac{d^2 \delta}{dt^2} = P_a = P_m - P_e \text{ pu} \quad (27)$$

when δ is in electrical radians and

$$\frac{H}{180f} \frac{d^2\delta}{dt^2} = P_a = P_m - P_e \quad \text{pu} \quad (28)$$

when δ is in electrical degrees.

(27) and (28) also represent the swing equation. It can be seen that the swing equation is a second order differential equation which can be written as two first order differential equations:

$$\frac{2H}{\omega_s} \frac{d\omega}{dt} = P_m - P_e \quad \text{pu} \quad (29)$$

$$\frac{d\delta}{dt} = \omega - \omega_s \quad (30)$$

in which ω , ω_s and δ are in electrical units. In deriving the swing equation, damping has been neglected.

Table 1 : H constants of synchronous machines

Type of machine	H (MJ/MVA)
Turbine generator condensing 1800 rpm	9 – 6
3600 rpm	7 – 4
Non condensing 3600 rpm	4 – 3
Water wheel generator	
Slow speed < 200 rpm	2 – 3
High speed > 200 rpm	2 – 4
Synchronous condenser	
Large	1.25
Small	1.0
} 25% less for hydrogen cooled	
Synchronous motor with load varying from 1.0 to 5.0	2.0

In defining the inertia constant H, the MVA base used is the rating of the machine. In a multi machine system, swing equation has to be solved for each machine, in which case, a common MVA base for the system has to be chosen. The constant H of each machine must be consistent with the system base.

Let

G_{mach} = Machine MVA rating (base)

G_{system} = System MVA base

In (9.25), H is computed on the machine rating $G = G_{mach}$

Multiplying (9.25) by $\frac{G_{mach}}{G_{system}}$ on both sides we get

$$\left(\frac{G_{mach}}{G_{system}} \right) \frac{2H}{\omega_{sm}} \frac{d^2 \delta_m}{dt^2} = \frac{P_m - P_e}{G_{mach}} \left(\frac{G_{mach}}{G_{system}} \right) \quad (31)$$

$$\frac{2H_{system}}{\omega_{sm}} \frac{d^2 \delta_m}{dt^2} = P_m - P_e \text{ pu (on system base)}$$

$$\text{where } H_{system} = H \frac{G_{mach}}{G_{system}} \quad (32)$$

In the stability analysis of a multi machine system, computation is considerably reduced if the number of swing equations to be solved is reduced. Machines within a plant normally swing together after a disturbance. Such machines are called coherent machines and can be replaced by a single equivalent machine, whose dynamics reflects the dynamics of the plant.

Example 1:

A 50Hz, 4 pole turbo alternator rated 150 MVA, 11 kV has an inertia constant of 9 MJ / MVA. Find the (a) stored energy at synchronous speed (b) the rotor acceleration if the input mechanical power is raised to 100 MW when the electrical load is 75 MW, (c) the speed at the end of 10 cycles if acceleration is assumed constant at the initial value.

Solution:

(a) Stored energy = $GH = 150 \times 9 = 1350 \text{ MJ}$

(b) $P_a = P_m - P_e = 100 - 75 = 25 \text{ MW}$

$$M = \frac{GH}{180f} = \frac{1350}{180 \times 50} = 0.15 \text{ MJ} - \text{s /}^\circ\text{e}$$

$$0.15 \frac{d^2 \delta}{dt^2} = 25$$

$$\begin{aligned}
 \text{Acceleration } \alpha &= \frac{d^2\delta}{dt^2} = \frac{25}{0.15} = 166.6 \text{ }^\circ\text{e/s}^2 \\
 &= 166.6 \times \frac{2}{P} \text{ }^\circ\text{m/s}^2 \\
 &= 166.6 \times \frac{2}{P} \times \frac{1}{360} \text{ rps/s} \\
 &= 166.6 \times \frac{2}{P} \times \frac{1}{360} \times 60 \text{ rpm/s} \\
 &= 13.88 \text{ rpm/s}
 \end{aligned}$$

* Note $^\circ\text{e}$ = electrical degree; $^\circ\text{m}$ = mechanical degree; P=number of poles.

$$(c) 10 \text{ cycles} = \frac{10}{50} = 0.2 \text{ s}$$

$$N_s = \text{Synchronous speed} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

$$\begin{aligned}
 \text{Rotor speed at end of 10 cycles} &= N_s + \alpha \times 0.2 \\
 &= 1500 + 13.88 \times 0.2 = 1502.776 \text{ rpm}
 \end{aligned}$$

Example 2:

Two 50 Hz generating units operate in parallel within the same plant, with the following ratings:

Unit 1: 500 MVA, 0.8 pf, 13.2 kV, 3600 rpm: $H = 4 \text{ MJ/MVA}$

Unit 2: 1000 MVA, 0.9 pf, 13.8 kV, 1800 rpm: $H = 5 \text{ MJ/MVA}$

Calculate the equivalent H constant on a base of 100 MVA.

Solution:

$$\begin{aligned}
 H_{1\text{system}} &= H_{1\text{mach}} \times \frac{G_{1\text{mach}}}{G_{\text{system}}} \\
 &= 4 \times \frac{500}{100} = 20 \text{ MJ/MVA}
 \end{aligned}$$

$$\begin{aligned}
 H_{2\text{system}} &= H_{2\text{mach}} \times \frac{G_{2\text{mach}}}{G_{\text{system}}} \\
 &= 5 \times \frac{1000}{100} = 50 \text{ MJ/MVA}
 \end{aligned}$$

$$H_{eq} = H_1 + H_2 = 20 + 50 = 70 \text{ MJ/MVA}$$

This is the equivalent inertia constant on a base of 100 MVA and can be used when the two machines swing coherently.

POWER-ANGLE EQUATION:

In solving the swing equation, certain assumptions are normally made (i) Mechanical power input P_m is a constant during the period of interest, immediately after the disturbance (ii) Rotor speed changes are insignificant. (iii) Effect of voltage regulating loop during the transient is neglected i.e the excitation is assumed to be a constant. As discussed in section 9.4, the power-angle relationship plays a vital role in the solution of the swing equation.

POWER-ANGLE EQUATION FOR A NON-SALIENT POLE MACHINE:

The simplest model for the synchronous generator is that of a constant voltage behind an impedance. This model is called the classical model and can be used for cylindrical rotor (non-salient pole) machines. Practically all high-speed turbo alternators are of cylindrical rotor construction, where the physical air gap around the periphery of the rotor is uniform. This type of generator has approximately equal magnetic reluctance, regardless of the angular position of the rotor, with respect to the armature mmf.

The power output of the generator is given by the real part of $E_g I_a^*$.

$$I_a = \frac{E_g \angle \delta - V_t \angle 0^\circ}{R_a + jx_d} \quad (38)$$

$$\text{Neglecting } R_a, I_a = \frac{E_g \angle \delta - V_t \angle 0^\circ}{jx_d}$$

$$\begin{aligned} P &= \Re \left\{ (E_g \angle \delta) \left(\frac{E_g \angle 90^\circ - \delta}{x_d} - \frac{V_t \angle 90^\circ}{x_d} \right)^* \right\} \\ &= \frac{E_g^2 \cos 90^\circ}{x_d} - \frac{E_g V_t \cos (90^\circ + \delta)}{x_d} \\ &= \frac{E_g V_t \sin \delta}{x_d} \end{aligned} \quad (39)$$

(Note- $\Re$ stands for real part of)

The maximum power that can be transferred for a particular excitation is given by $\frac{E_g V_t}{x_d}$ at $\delta = 90^\circ$.

POWER ANGLE EQUATION FOR A SALIENT POLE MACHINE:

Here because of the salient poles, the reluctance of the magnetic circuit in which flows the flux produced by an armature mmf in line with the quadrature axis is higher than that of the magnetic circuit in which flows the flux produced by the armature mmf in line with the direct axis. These two components of armature mmf are proportional to the corresponding components of armature current. The component of armature current producing an mmf acting in line with direct axis is called the direct component, I_d . The component of armature current producing an mmf acting in line with the quadrature axis is called the quadrature axis component, I_q .

$$\begin{aligned} \text{Power output } P &= V_t I_a \cos \theta \\ &= E_d I_d + E_q I_q \end{aligned} \quad (40)$$

$$E_d = V_t \sin \delta \quad (41a)$$

$$E_q = V_t \cos \delta \quad (41b)$$

$$I_d = \frac{E_g - E_q}{x_d} = I_a \sin(\delta + \theta) \quad (41c)$$

$$I_q = \frac{E_d}{x_q} = I_a \cos(\delta + \theta) \quad (41d)$$

Substituting (9.41c) and (9.41d) in (9.40), we obtain

$$P = \frac{E_g V_t \sin \delta}{x_d} + \frac{V_t^2 (x_d - x_q) \sin 2\delta}{2 x_d x_q} \quad (42)$$

(9.42) gives the steady state power angle relationship for a salient pole machine. The second term does not depend on the excitation and is called the reluctance power component. This component makes the maximum power greater than in the classical model. However, the angle at which the maximum power occurs is less than 90° .

TRANSIENT STABILITY:

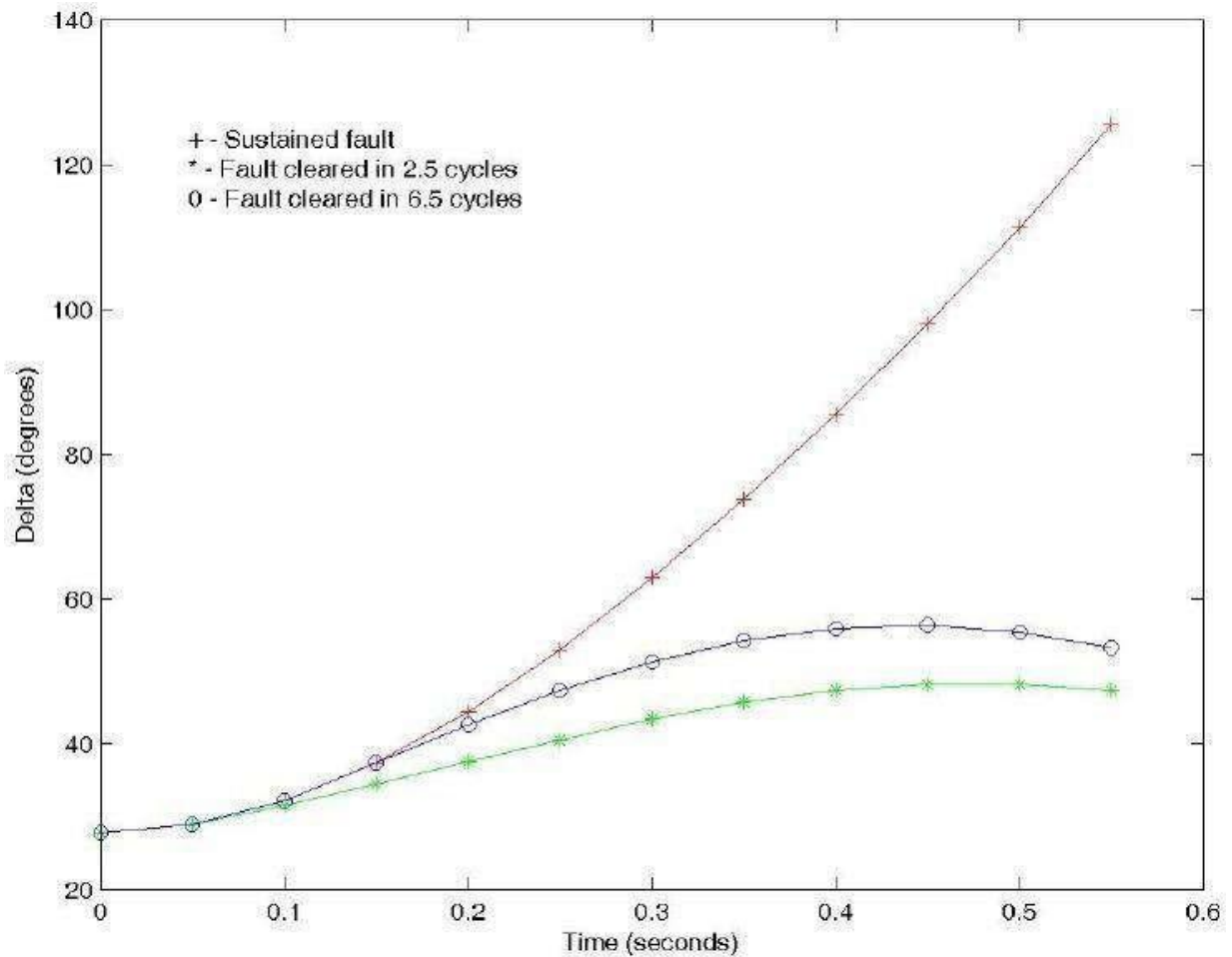
As defined earlier, transient stability is the ability of the system to remain stable under large disturbances like short circuits, line outages, generation or load loss etc. The evaluation of the transient stability is required offline for planning, design etc. and online for load management, emergency control and security assessment. Transient stability analysis deals with actual solution of the nonlinear differential equations describing the dynamics of the machines and their controls and interfacing it with the algebraic equations describing the

interconnections through the transmission network. Since the disturbance is large, linearized analysis of the swing equation (which describes the rotor dynamics) is not possible. Further, the fault may cause structural changes in the network, because of which the power angle curve prior to fault, during the fault and post fault may be different. Due to these reasons, a general stability criteria for transient stability cannot be established, as was done in the case of steady state stability (namely $PS > 0$). Stability can be established, for a given fault, by actual solution of the swing equation. The time taken for the fault to be cleared (by the circuit breakers) is called the *clearing time*. If the fault is cleared fast enough, the probability of the system remaining stable after the clearance is more. If the fault persists for a longer time, likelihood of instability is increased. *Critical clearing time* is the maximum time available for clearing the fault, before the system loses stability. Modern circuit breakers are equipped with auto reclosure facility, wherein the breaker automatically recloses after two sequential openings. If the fault still persists, the breakers open permanently. Since most faults are transient, the first reclosure is in general successful. Hence, transient stability has been greatly enhanced by auto closure breakers.

Some common assumptions made during transient stability studies are as follows:

1. Transmission line and synchronous machine resistances are neglected. Since resistance introduces a damping term in the swing equation, this gives pessimistic results.
2. Effect of damper windings is neglected which again gives pessimistic results.
3. Variations in rotor speed are neglected.
4. Mechanical input to the generator is assumed constant. The governor control loop is neglected. This also leads to pessimistic results.
5. The generator is modeled as a constant voltage source behind a transient reactance, neglecting the voltage regulator action.
6. Loads are modeled as constant admittances and absorbed into the bus admittance matrix.

The above assumptions, vastly simplify the equations. A digital computer program for transient stability analysis can easily include more detailed generator models and effect of controls, the discussion of which is beyond the scope of present treatment. Studies on the transient stability of an SMIB system, can shed light on some important aspects of stability of larger systems. The figure below shows an example of how the clearing time has an effect on the swing curve of the machine.



Modified Euler's method:

Euler's method is one of the easiest methods to program for solution of differential equations using a digital computer. It uses the Taylor's series expansion, discarding all second-order and higher-order terms. Modified Euler's algorithm uses the derivatives at the beginning of a time step, to predict the values of the dependent variables at the end of the step ($t_1 = t_0 + \Delta t$). Using the predicted values, the derivatives at the end of the interval are computed. The average of the two derivatives is used in updating the variables.

Consider two simultaneous differential equations:

$$\frac{dx}{dt} = f_x(x, y, t)$$

$$\frac{dy}{dt} = f_y(x, y, t)$$

Starting from initial values x_0, y_0, t_0 at the beginning of a time step and a step size h we solve as follows:

Let

$$D_x = f_x(x_0, y_0, t_0) = \left. \frac{dx}{dt} \right|_0$$

$$D_y = f_y(x_0, y_0, t_0) = \left. \frac{dy}{dt} \right|_0$$

$$\left. \begin{aligned} x^P &= x_0 + D_x h \\ y^P &= y_0 + D_y h \end{aligned} \right\} \quad \text{Predicted values}$$

$$D_{xP} = \left. \frac{dx}{dt} \right|_P = f_x(x^P, y^P, t_1)$$

$$D_{yP} = \left. \frac{dy}{dt} \right|_P = f_y(x^P, y^P, t_1)$$

$$x_1 = x_0 + \left(\frac{D_x + D_{xP}}{2} \right) h$$

$$y_1 = y_0 + \left(\frac{D_y + D_{yP}}{2} \right) h$$

x_1 and y_1 are used in the next iteration. To solve the swing equation by Modified Euler's method, it is written as two first order differential equations:

$$\frac{d\delta}{dt} = \omega$$

$$\frac{d\omega}{dt} = \frac{P_a}{M} = \frac{P_m - P_{\max} \sin \delta}{M}$$

Starting from an initial value δ_0, ω_0 at the beginning of any time step, and choosing a step size Δt , the equations to be solved in modified Euler's are as follows:

$$\left. \frac{d\delta}{dt} \right|_0 = D_1 = \omega_0$$

$$\left. \frac{d\omega}{dt} \right|_0 = D_2 = \frac{P_m - P_{\max} \sin \delta_0}{M}$$

$$\delta^P = \delta_0 + D_1 \Delta t$$

$$\omega^P = \omega_0 + D_2 \Delta t$$

$$\left. \frac{d\delta}{dt} \right|_P = D_{1P} = \omega^P$$

$$\left. \frac{d\omega}{dt} \right|_P = D_{2P} = \frac{P_m - P_{\max} \sin \delta^P}{M}$$

$$\delta_1 = \delta_0 + \left(\frac{D_1 + D_{1P}}{2} \right) \Delta t$$

$$\omega_1 = \omega_0 + \left(\frac{D_2 + D_{2P}}{2} \right) \Delta t$$

δ_1 and ω_1 are used as initial values for the successive time step. Numerical errors are introduced because of discarding higher-order terms in Taylor's expansion. Errors can be decreased by choosing smaller values of step size. Too small a step size, will increase computation, which can lead to large errors due to rounding off. The Runge- Kutta method which uses higher-order terms is more popular.

Example :A 50 Hz, synchronous generator having inertia constant $H = 5.2$ MJ/MVA and $x_d' = 0.3$ pu is connected to an infinite bus through a double circuit line as shown in Fig. 9.21. The reactance of the connecting HT transformer is 0.2 pu and reactance of each line is 0.4 pu. $|E_g| = 1.2$ pu and $|V| = 1.0$ pu and $P_e = 0.8$ pu. Obtain the swing curve using modified Eulers method for a three phase fault occurs at the middle of one of the transmission lines and is cleared by isolating the faulted line.

Solution:

Before fault transfer reactance between generator and infinite bus

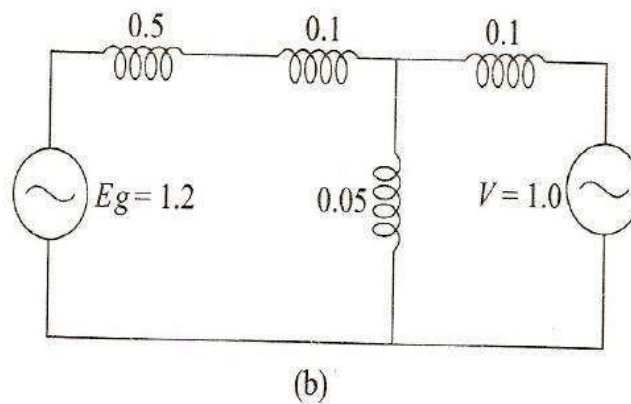
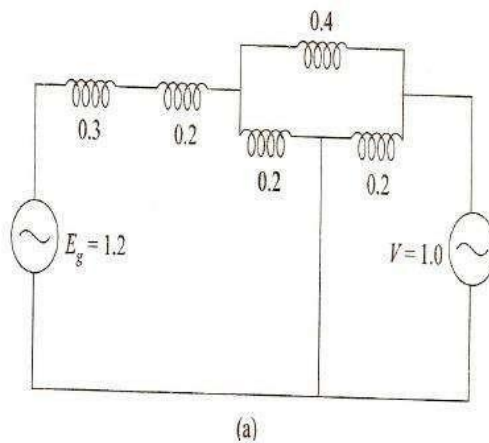
$$X_1 = 0.3 + 0.2 + \frac{0.4}{2} = 0.7 \text{ pu}$$

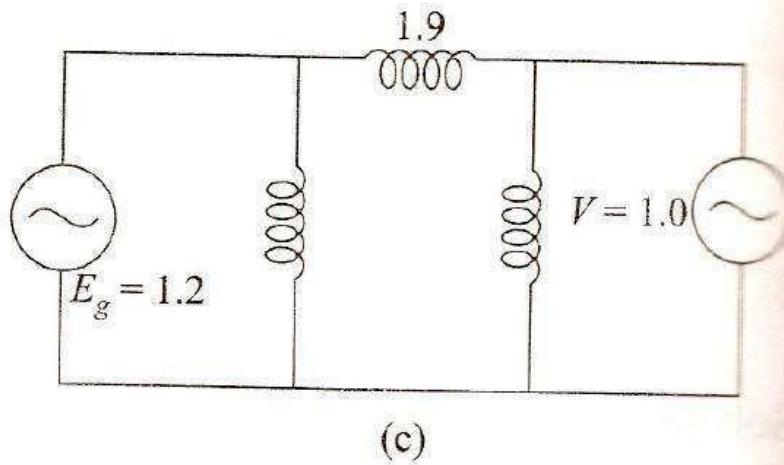
$$P_{\max 1} = \frac{1.2 \times 1.0}{0.7} = 1.714 \text{ pu.}$$

$$\text{Initial } P_e = 0.8 \text{ pu} = P_m$$

$$\text{Initial operating angle } \delta_o = \sin^{-1} \frac{0.8}{1.714} = 27.82^\circ = 0.485 \text{ rad.}$$

When fault occurs at middle of one of the transmission lines, the network and its reduction is as shown in Fig a to Fig c.





The transfer reactance is 1.9 pu.

$$P_{\max II} = \frac{1.2 \times 1.0}{1.9} = 0.63 \text{ pu}$$

Since there is no outage, $P_{\max III} = P_{\max I} = 1.714$

$$\delta_{\max} = \pi - \sin^{-1} \left(\frac{P_m}{P_{\max III}} \right) = \pi - \sin^{-1} \left(\frac{0.8}{1.714} \right) = 2.656 \text{ rad}$$

$$\begin{aligned} \cos \delta_{cr} &= \frac{P_m (\delta_{\max} - \delta_o) - P_{\max II} \cos \delta_o + P_{\max III} \cos \delta_{\max}}{P_{\max III} - P_{\max II}} \\ &= \frac{0.8(2.656 - 0.485) - 0.63 \cos(0.485) + 1.714 \cos(2.656)}{1.714 - 0.63} \\ &= \frac{1.7368 - 0.5573 - 1.5158}{1.084} = -0.3102 \end{aligned}$$

$$\delta_{cr} = \cos^{-1}(-0.3102) = 1.886 \text{ rad} = 108.07^\circ$$

with line outage

$$X_{III} = 0.3 + 0.2 + 0.4 = 0.9 \text{ pu}$$

$$P_{\max III} = \frac{1.2 \times 1.0}{0.9} = 1.333 \text{ pu}$$

$$\delta_{\max} = \pi - \sin^{-1} \frac{0.8}{1.333} = 2.498 \text{ rad}$$

7.7

Modified Eulers method

$$\delta_0 = 27.82^\circ = 0.485 \text{ rad}$$

$$\omega_0 = 0.0 \text{ rad / sec (at } t = 0^0)$$

Choosing a step size of 0.05 s, the swing is computed. Table a gives the values of the derivatives and predicted values. Table b gives the initial values δ_0 , ω_0 and the values at the end of the interval δ_1 , ω_1 . Calculations are illustrated for the time step $t = 0.2$ s.

$$\delta_0 = 0.761$$

$$\omega_0 = 2.072$$

$$P_m = 0.8$$

$$M = \left[\frac{5.2}{\pi \times 50} \right] = 0.0331 \text{ s}^2 / \text{rad}$$

$$P_{\max} \text{ (after fault clearance)} = 1.333 \text{ pu}$$

$$D_1 = 2.072$$

$$D_2 = \frac{0.8 - 1.333 \sin(0.761)}{0.0331} = -3.604$$

$$\delta^P = 0.761 + (2.072 \times 0.05) = 0.865$$

$$\omega^P = 2.072 + (-3.604 \times 0.05) = 1.892$$

$$D_{1P} = 1.892$$

$$D_{2P} = \frac{0.8 - 1.333 \sin(0.865)}{0.0331} = -6.482$$

$$\delta_1 = 0.761 + \left(\frac{2.072 + 1.892}{2} \right) 0.05 = 0.860$$

$$\omega_1 = 2.072 + \left(\frac{-3.604 - 6.482}{2} \right) 0.05 = 1.82$$

δ_1 , ω_1 are used as initial values in next time step.

Table a : Calculation of derivatives in modified Euler's method

t	D ₁	D ₂	δ^P	ω^P	D _{1P}	D _{2P}
0 ⁺	0.0	15.296	0.485	0.765	0.765	15.296
0.05	0.765	14.977	0.542	1.514	1.514	14.350
0.10	1.498	14.043	0.636	2.200	2.200	12.860
0.15	2.17	- 0.299	0.761	2.155	2.155	- 3.600
0.20	2.072	- 3.604	0.865	1.892	1.892	- 6.482
0.25	1.820	- 6.350	0.951	1.502	1.502	- 8.612
0.30	1.446	- 8.424	1.015	1.025	1.025	- 10.041
0.35	0.984	- 9.827	1.054	0.493	0.493	- 10.843
0.40	0.467	- 10.602	1.065	- 0.063	- 0.063	- 11.060
0.45	- 0.074	- 10.803	1.048	- 0.614	- 0.614	- 10.720
0.50	- 0.612	- 10.46	1.004	- 1.135	- 1.135	- 9.800

Table b : calculations of δ_0 , ω_0 and δ_1 , ω_1 in modified Euler's method

T	$P_{\max}$ (pu)	δ_0 rad	ω_0 rad / sec	δ_1 rad	ω_1 rad / sec	δ_1 deg
0^-	1.714	0.485	0.0	—	—	-
0^+	0.630	0.485	0.0	0.504	0.765	28.87
0.05	0.630	0.504	0.765	0.561	1.498	32.14
0.10	0.630	0.561	1.498	0.653	2.170	37.41
0.15	1.333	0.653	2.170	0.761	2.072	43.60
0.20	1.333	0.761	2.072	0.860	1.820	49.27
0.25	1.333	0.860	1.820	0.943	1.446	54.03
0.30	1.333	0.943	1.446	1.005	0.984	57.58
0.35	1.333	1.005	0.984	1.042	0.467	59.70
0.40	1.333	1.042	0.467	1.052	- 0.074	60.27
0.45	1.333	1.052	- 0.074	1.035	- 0.612	59.30
0.50	1.333	1.035	- 0.612	0.991	- 1.118	56.78

7.8

Runge - Kutta method

In Runge - Kutta method, the changes in dependent variables are calculated from a given set of formulae, derived by using an approximation, to replace a truncated Taylor's series expansion. The formulae for the Runge - Kutta fourth order approximation, for solution of two simultaneous differential equations are given below;

$$\text{Given } \frac{dx}{dt} = f_x(x, y, t)$$

$$\frac{dy}{dt} = f_y(x, y, t)$$

Starting from initial values x_0, y_0, t_0 and step size h , the updated values are

$$x_1 = x_0 + \frac{1}{6} (k_1 + 2k_2 + 2k_3 + k_4)$$

$$y_1 = y_0 + \frac{1}{6} (l_1 + 2l_2 + 2l_3 + l_4)$$

where $k_1 = f_x(x_0, y_0, t_0) h$

$$k_2 = f_x \left(x_0 + \frac{k_1}{2}, y_0 + \frac{l_1}{2}, t_0 + \frac{h}{2} \right) h$$

$$k_3 = f_x \left(x_0 + \frac{k_2}{2}, y_0 + \frac{l_2}{2}, t_0 + \frac{h}{2} \right) h$$

$$k_4 = f_x(x_0 + k_3, y_0 + l_3, t_0 + h) h$$

$$l_1 = f_y(x_0, y_0, t_0) h$$

$$l_2 = f_y \left(x_0 + \frac{k_1}{2}, y_0 + \frac{l_1}{2}, t_0 + \frac{h}{2} \right) h$$

$$l_3 = f_y \left(x_0 + \frac{k_2}{2}, y_0 + \frac{l_2}{2}, t_0 + \frac{h}{2} \right) h$$

$$l_4 = f_y(x_0 + k_3, y_0 + l_3, t_0 + h) h$$

The two first order differential equations to be solved to obtain solution for the swing equation are:

$$\frac{d\delta}{dt} = \omega$$

$$\frac{d\omega}{dt} = \frac{P_a}{M} = \frac{P_m - P_{\max} \sin \delta}{M}$$

Starting from initial value δ_0, ω_0, t_0 and a step size of Δt the formulae are as follows

$$k_1 = \omega_0 \Delta t$$

$$l_1 = \left[\frac{P_m - P_{\max} \sin \delta_0}{M} \right] \Delta t$$

$$k_2 = \left(\omega_0 + \frac{l_1}{2} \right) \Delta t$$

$$l_2 = \left[\frac{P_m - P_{\max} \sin \left(\delta_0 + \frac{k_1}{2} \right)}{M} \right] \Delta t$$

$$k_3 = \left(\omega_0 + \frac{l_2}{2} \right) \Delta t$$

$$l_3 = \left[\frac{P_m - P_{\max} \sin \left(\delta_0 + \frac{k_2}{2} \right)}{M} \right] \Delta t$$

$$k_4 = (\omega_0 + l_3) \Delta t$$

$$l_4 = \left[\frac{P_m - P_{\max} \sin (\delta_0 + k_3)}{M} \right] \Delta t$$

$$\delta_1 = \delta_0 + \frac{1}{6} [k_1 + 2k_2 + 2k_3 + k_4]$$

$$\omega_1 = \omega_0 + \frac{1}{6} [l_1 + 2l_2 + 2l_3 + l_4]$$

Example

Obtain the swing curve for previous example using Runge - Kutta method.

Solution:

$$\delta_0 = 27.82^\circ = 0.485 \text{ rad.}$$

$$\omega_0 = 0.0 \text{ rad / sec. (at } t = 0 \text{)}$$

Choosing a step size of 0.05 s, the coefficient k_1, k_2, k_3, k_4 and l_1, l_2, l_3 , and l_4 are calculated for each time step. The values of δ and ω are then updated. Table a gives the coefficient for different time steps. Table b gives the starting values δ_0, ω_0 for a time step and the updated values δ_1, ω_1 obtained by Runge - Kutta method. The updated values are used as initial values for the next time step and process continued. Calculations are illustrated for the time step $t = 0.2$ s.

$$\delta_0 = 0.756$$

$$M = 0.0331 \text{ s}^2 / \text{rad}$$

$$\omega_0 = 2.067$$

$$P_m = 0.8$$

$$P_{\max} = 1.333 \text{ (after fault is cleared)}$$

$$k_1 = 2.067 \times 0.05 = 0.103$$

$$l_1 = \left[\frac{0.8 - 1.333 \sin(0.756)}{0.0331} \right] \times 0.05 = -0.173$$

$$k_2 = \left[2.067 - \frac{0.173}{2} \right] 0.05 = 0.099$$

$$l_2 = \left[\frac{0.8 - 1.333 \sin\left(0.756 + \frac{0.103}{2}\right)}{0.0331} \right] \times 0.05 = -0.246$$

$$k_3 = \left[2.067 - \frac{0.246}{2} \right] 0.05 = 0.097$$

$$l_3 = \left[\frac{0.8 - 1.333 \sin\left(0.756 + \frac{0.099}{2}\right)}{0.0331} \right] \times 0.05 = -0.244$$

$$k_4 = (2.067 - 0.244) 0.05 = 0.091$$

$$l_4 = \left[\frac{0.8 - 1.333 \sin(0.756 + 0.097)}{0.0331} \right] \times 0.05 = -0.308$$

$$\delta_1 = 0.756 + \frac{1}{6} [0.103 + 2 \times 0.099 + 2 \times 0.097 + 0.091] = 0.854$$

$$\omega_1 = 2.067 + \frac{1}{6} [-0.173 + 2 \times -0.246 + 2 \times -0.244 - 0.308] = 1.823$$

Now $\delta = 0.854$ and $\omega = 1.823$ are used as initial values for the next time step. The computations have been rounded off to three digits. Greater accuracy is obtained by reducing the step size.

Table a : Coefficients in Runge - Kutta method

T	k ₁	l ₁	k ₂	l ₂	k ₃	l ₃	K ₄	l ₄
0.0	0.0	0.764	0.019	0.764	0.019	0.757	0.038	0.749
0.05	0.031	0.749	0.056	0.736	0.056	0.736	0.075	0.703
0.10	0.075	0.704	0.092	0.674	0.091	0.667	0.108	0.632
0.15	0.108	-0.010	0.108	-0.094	0.106	-0.095	0.103	-0.173
0.20	0.103	-0.173	0.099	-0.246	0.097	-0.244	0.091	-0.308
0.25	0.091	-0.309	0.083	-0.368	0.082	-0.363	0.073	-0.413
0.30	0.073	-0.413	0.063	-0.455	0.061	-0.450	0.050	-0.480
0.35	0.050	-0.483	0.038	-0.510	0.037	-0.504	0.025	-0.523
0.40	0.025	-0.523	0.012	-0.536	0.011	-0.529	-0.001	-0.534
0.45	-0.001	-0.534	-0.015	-0.533	-0.015	-0.526	-0.027	-0.519
0.50	-0.028	-0.519	-0.040	-0.504	-0.040	-0.498	-0.053	-0.476

Table b: δ , ω computations by Runge - Kutta method

t (sec)	P _{max} (pu)	δ_0 (rad)	ω_0 rad/sec	δ_1 rad	ω_1 rad/sec	δ_1 deg
0 ⁻	1.714	0.485	0.0			
0 ⁺	0.630	0.485	0.0	0.504	0.759	28.87
0.05	0.630	0.504	0.756	0.559	1.492	32.03
0.10	0.630	0.559	1.492	0.650	2.161	37.24
0.15	1.333	0.650	2.161	0.756	2.067	43.32
0.20	1.333	0.756	2.067	0.854	1.823	48.93

0.25	1.333	0.854	1.823	0.936	1.459	53.63
0.30	1.333	0.936	1.459	0.998	1.008	57.18
0.35	1.333	0.998	1.008	1.035	0.502	59.30
0.40	1.333	1.035	0.502	1.046	-0.029	59.93
0.45	1.333	1.046	-0.029	1.031	-0.557	59.07
0.50	1.333	1.031	-0.557	0.990	-1.057	56.72

Note: δ_0, ω_0 indicate values at beginning of interval and δ_1, ω_1 at end of interval. The fault is cleared at 0.125 seconds. $\therefore P_{\max} = 0.63$ at $t = 0.1$ sec and $P_{\max} = 1.333$ at $t = 0.15$ sec, since fault is already cleared at that time. The swing curves obtained from modified Euler's method and Runge - Kutta method are shown in Fig. It can be seen that the two methods yield very close results.

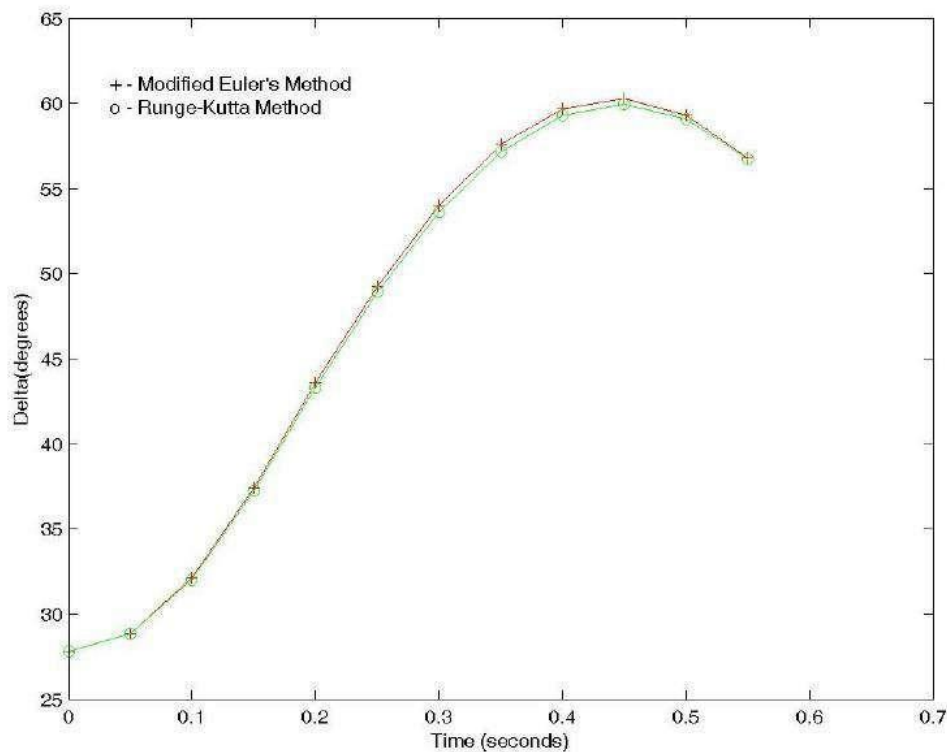


Fig: : Swing curves with Modified Euler' and Runge-Kutta methods

Milne's Predictor Corrector method:

The Milne's formulae for solving two simultaneous differential equations are given below.

$$\text{Consider } \frac{dx}{dt} = f_x(x, y, t)$$

$$\frac{dy}{dt} = f_y(x, y, t)$$

With values of x and y known for four consecutive previous times, the predicted value for $n + 1^{\text{th}}$ time step is given by

$$x_{n+1}^p = x_{n-3} + \frac{4h}{3} [2x'_{n-2} - x'_{n-1} + 2x'_n]$$

$$y_{n+1}^p = y_{n-3} + \frac{4h}{3} [2y'_{n-2} - y'_{n-1} + 2y'_n]$$

Where x' and y' are derivatives at the corresponding time step. The corrected values are

$$x_{n+1} = x_{n-1} + \frac{h}{3} [x'_{n-1} + 4x'_n + x'_{n+1}]$$

$$y_{n+1} = y_{n-1} + \frac{h}{3} [y'_{n-1} + 4y'_n + y'_{n+1}]$$

$$\text{where } x'_{n+1} = f_x(x_{n+1}^p, y_{n+1}^p, t_{n+1})$$

$$y'_{n+1} = f_y(x_{n+1}^p, y_{n+1}^p, t_{n+1})$$

To start the computations we need four initial values which may be obtained by modified Euler's method, Runge - Kutta method or any other numerical method which is self starting, before applying Milne's method. The method is applied to the solution of swing equation as follows:

$$\text{Define } \delta'_n = \left. \frac{d\delta}{dt} \right|_n = \omega_n$$

$$\omega'_n = \left. \frac{d\omega}{dt} \right|_n = \frac{P_m - P_{\max} \sin \delta_n}{M}$$

$$\delta_{n+1}^p = \delta_{n-3} + \frac{4\Delta t}{3} [2\delta'_{n-2} - \delta'_{n-1} + 2\delta'_n]$$

$$\omega_{n+1}^p = \omega_{n-3} + \frac{4\Delta t}{3} [2\omega'_{n-2} - \omega'_{n-1} + 2\omega'_n]$$

$$\delta_{n+1} = \delta_{n-1} + \frac{\Delta t}{3} [\delta'_{n-1} + 4\delta'_n + \delta'_{n+1}]$$

$$\omega_{n+1} = \omega_{n-1} + \frac{\Delta t}{3} [\omega'_{n-1} + 4\omega'_n + \omega'_{n+1}]$$

where $\delta'_{n+1} = \omega_{n+1}^p$

$$\omega'_{n+1} = \frac{P_m - P_{\max} \sin \delta_{n+1}^p}{M}$$

Example

Solve example using Milne's method.

Solution:

To start the process, we take the first four computations from Range Kutta method

$$t = 0.0 \text{ s} \quad \delta_1 = 0.504 \quad \omega_1 = 0.759$$

$$t = 0.05 \text{ s} \quad \delta_2 = 0.559 \quad \omega_2 = 1.492$$

$$t = 0.10 \text{ s} \quad \delta_3 = 0.650 \quad \omega_3 = 2.161$$

$$t = 0.15 \text{ s} \quad \delta_4 = 0.756 \quad \omega_4 = 2.067$$

The corresponding derivatives are calculated using the formulae for δ'_n and ω'_n . We get

$$\delta'_1 = 0.759 \quad \omega'_1 = 14.97$$

$$\delta'_2 = 1.492 \quad \omega'_2 = 14.075$$

$$\delta'_3 = 2.161 \quad \omega'_3 = 12.65$$

$$\delta'_4 = 2.067 \quad \omega'_4 = -3.46$$

We now compute δ_5 and ω_5 , at the next time step i.e $t = 0.2 \text{ s}$.

$$\begin{aligned} \delta_5^p &= \delta_1 + \frac{4\Delta t}{3} [2\delta'_2 - \delta'_3 + 2\delta'_4] \\ &= 0.504 + \frac{4 \times 0.05}{3} [2 \times 1.492 - 2.161 + 2 \times 2.067] = 0.834 \end{aligned}$$

$$\omega_5^p = \omega_1 + \frac{4\Delta t}{3} [2\omega'_2 - \omega'_3 + 2\omega'_4]$$

$$= 0.759 + \frac{4 \times 0.05}{3} [2 \times 14.075 - 12.65 + 2 \times (-3.46)] = 1.331$$

$$\delta'_5 = 1.331$$

$$\omega'_5 = \frac{0.8 - 1.333 \sin(0.834)}{0.0331} = -5.657$$

$$\delta_5 = \delta_3 + \frac{\Delta t}{3} [\delta'_3 + 4\delta'_4 + \delta'_5]$$

$$= 0.65 + \frac{0.05}{3} [2.161 + 4 \times 2.067 + 1.331] = 0.846$$

$$\omega_5 = \omega_3 + \frac{\Delta t}{3} [\omega'_3 + 4\omega'_4 + \omega'_5]$$

$$= 2.161 + \frac{0.05}{3} [12.65 - 4 \times 3.46 - 5.657] = 2.047$$

$$\delta'_5 = \omega_5 = 2.047$$

$$\omega'_5 = \frac{0.8 - 1.333 \sin(0.846)}{0.0331} = -5.98$$

The computations are continued for the next time step in a similar manner.

MULTI MACHINE TRANSIENT STABILITY ANALYSIS

A typical modern power system consists of a few thousands of nodes with heavy interconnections. Computation simplification and memory reduction have been two major issues in the development of mathematical models and algorithms for digital computation of transient stability. In its simplest form, the problem of a multi machine power system under going a disturbance can be mathematically stated as follows:

$$\dot{x}(t) = f_I(x(t)) \quad -\infty \leq t \leq 0$$

$$\dot{x}(t) = f_{II}(x(t)) \quad 0 < t \leq t_{ce}$$

$$\dot{x}(t) = f_{III}(x(t)) \quad t_{ce} < t < \infty$$

$x(t)$ is the vector of state variables to describe the differential equations governing the generator rotor dynamics, dynamics of flux decay and associated generator

controller dynamics (like excitation control, PSS, governor control etc). The function f_I describes the dynamics prior to the fault. Since the system is assumed to be in steady state, all the state variable are constant. If the fault occurs at $t = 0$, f_{II} describes the dynamics during fault, till the fault is cleared at time t_{cl} . The post-fault dynamics is governed by f_{III} . The state of the system x_{cl} at the end of the fault-on period (at $t = t_{cl}$) provides the initial condition for the post-fault network described which determines whether a system is stable or not after the fault is cleared. Some methods are presented in the following sections to evaluate multi machine transient stability. However, a detailed exposition is beyond the scope of the present book.

REDUCED ORDER MODEL

This is the simplest model used in stability analysis and requires minimum data. The following assumptions are made:

- Mechanical power input to each synchronous machine is assumed to be constant.
- Damping is neglected.
- Synchronous machines are modeled as constant voltage sources behind transient reactance.
- Loads are represented as constant impedances.

With these assumptions, the multi machine system is represented as in Fig. 9.26.

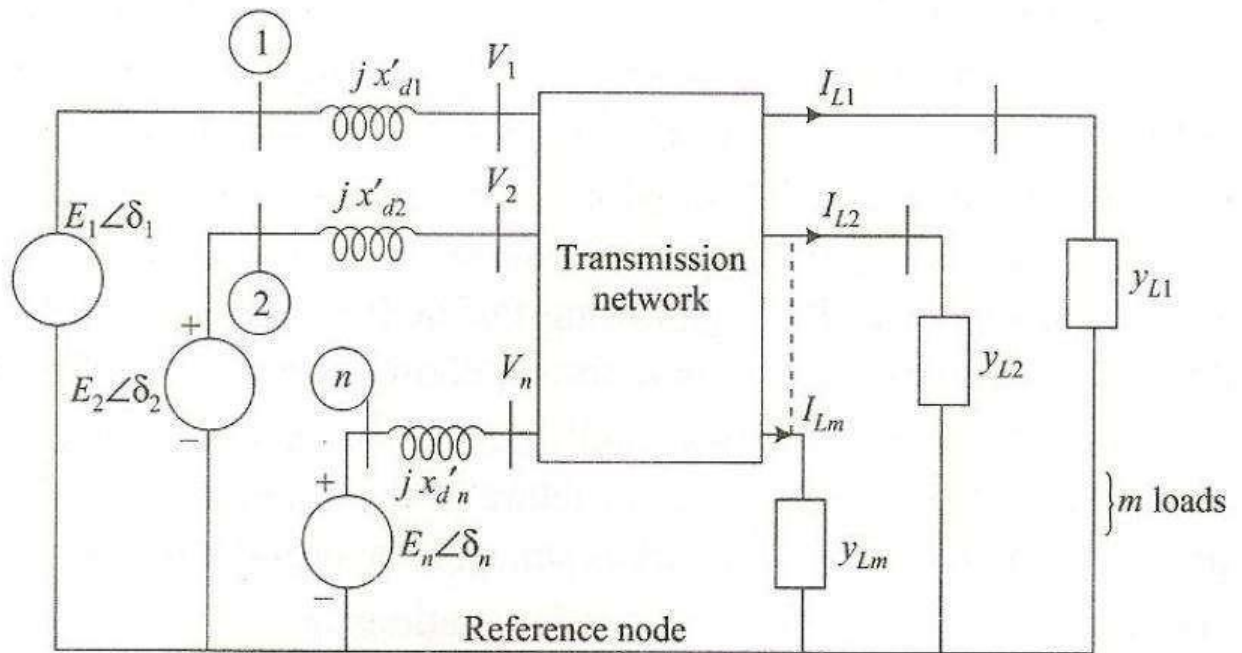


Fig 9.26 Multi machine system

Nodes 1, 2 n are introduced in the model and are called internal nodes (the terminal node is the external node connected to the transmission network). The swing equations are formed for the various generators using the following steps:

Step 1: All system data is converted to a common base.

Step 2: A prefault load flow is performed, to determine the prefault steady state voltages, at all the external buses. Using the prefault voltages, the loads are converted into equivalent shunt admittance, connected between the respective bus and the reference node. If the complex load at bus i is given by

$$S_i = P_{Li} + jQ_{Li}$$

the equivalent admittance is given by

$$Y_{Li} = \frac{S_{Li}^*}{|V_{Li}|^2} = \frac{P_{Li} - jQ_{Li}}{|V_{Li}|^2}$$

Step 3: The internal voltages are calculated from the terminal voltages, using

$$\begin{aligned}
|E_i| \angle \delta'_i &= |V_i| + jx'_{di} I_i \\
&= |V_i| + jx'_{di} \frac{S_{Gi}^*}{|V_i|} \\
&= |V_i| + jx'_{di} \frac{(P_{Gi} - jQ_{Gi})}{|V_i|}
\end{aligned}$$

δ'_i is the angle of E_i with respect to V_i . If the angle of V_i is β_i , then the angle of E_i , with respect to common reference is given by $\delta_i = \delta'_i + \beta_i$. P_{Gi} and Q_{Gi} are obtained from load flow solution.

Step4: The bus admittance matrix Y_{bus} formed to run the load flow is modified to include the following.

- (i) The equivalent shunt load admittance given by, connected between the respective load bus and the reference node.
- (ii) Additional nodes are introduced to represent the generator internal nodes. Appropriate values of admittances corresponding to x'_d , connected between the internal nodes and terminal nodes are used to update the Y_{bus} .
- (iii) Y_{bus} corresponding to the faulted network is formed. Generally transient stability analysis is performed, considering three phase faults, since they are the most severe. The Y_{bus} during the fault is obtained by setting the elements of the row and column corresponding to the faulted bus to zero.
- (iv) Y_{bus} corresponding to the post-fault network is obtained, taking into account line outages if any. If the structure of the network does not change, the Y_{bus} of the post-fault network is same as the prefault network.

Step 5: The admittance form of the network equations is

$$I = Y_{bus} V$$

Since loads are all converted into passive admittances, current injections are present only at the n generator internal nodes. The injections at all other nodes are zero. Therefore, the current vector I can be partitioned as

$$I = \begin{bmatrix} I_n \\ 0 \end{bmatrix}$$

where I_n is the vector of current injections corresponding to the n generator internal nodes. Y_{bus} and V are also partitioned appropriately, so that

$$\begin{bmatrix} I_n \\ 0 \end{bmatrix} = \begin{bmatrix} Y_1 & Y_2 \\ Y_3 & Y_4 \end{bmatrix} \begin{bmatrix} E_n \\ V_t \end{bmatrix}$$

where E_n is the vector of internal emfs of the generators and V_t is the vector of external bus voltages. From (9.91) we can write

$$I_n = Y_1 E_n + Y_2 V_t$$

$$0 = Y_3 E_n + Y_4 V_t$$

we get

$$V_t = -Y_4^{-1} Y_3 E_n$$

$$I_n = (Y_1 - Y_2 Y_4^{-1} Y_3) E_n = \hat{Y} E_n$$

where $\hat{Y} = Y_1 - Y_2 Y_4^{-1} Y_3$ is called the reduced admittance matrix and has dimension $n \times n$. $\hat{Y}$ gives the relationship between the injected currents and the internal generator voltages. It is to be noted we have eliminated all nodes except the n internal nodes.

Step 6: The electric power output of the generators are given by

$$P_{Gi} = \Re [E_i I_i^*]$$

Substituting for I_i from (9.94) we get

$$P_{Gi} = |E_i|^2 \hat{G}_{ii} + \sum_{j=1 \neq i}^n |E_i| |E_j| (\hat{B}_{ij} \sin(\delta_i - \delta_j) + \hat{G}_{ij} \cos(\delta_i - \delta_j))$$

(This equation is derived in chapter on load flows)

Step 7: The rotor dynamics representing the swing is now given by

$$M_i \frac{d^2 \delta_i}{dt^2} = P_{Mi} - P_{Gi} \quad i = 1, \dots, n$$

The mechanical power P_{Mi} is equal to the pre-fault electrical power output, obtained from pre-fault load flow solution.

Step 8: The n second order differential equations can be decomposed into $2n$ first order differential equations which can be solved by any numerical method.

Though reduced order models, also called classical models, require less computation and memory, their results are not reliable. Further, the interconnections of the physical network of the system is lost.

FACTORS AFFECTING TRANSIENT STABILITY:

The relative swing of a machine and the critical clearing time are a measure of the stability of a generating unit. From the swing equation, it is obvious that the generating units with smaller H , have larger angular swings at any time interval. The maximum power transfer $P_{\max} = \frac{E_g V}{x'_d}$, where V is the terminal voltage of the generators. Therefore an increase in x'_d , would reduce $P_{\max}$. Hence, to transfer a given power P_e , the angle δ would increase since $P_e = P_{\max} \sin \delta$, for a machine with larger x'_d . This would reduce the critical clearing time, thus, increasing the probability of losing stability.

Generating units of present day have lower values of H , due to advanced cooling techniques, which have made it possible to increase the rating of the machines without significant increase in the size. Modern control schemes like generator excitation control, Turbine valve control, single-pole operation of circuit breakers and fast-acting circuit breakers with auto re-closure facility have helped in enhancing overall system stability.

Factors which can improve transient stability are

- (i) Reduction of transfer reactance by using parallel lines.
- (ii) Reducing transmission line reactance by reducing conductor spacing and increasing conductor diameter, by using hollow cores.
- (iii) Use of bundled conductors.
- (iv) Series compensation of the transmission lines with series capacitors. This also increases the steady state stability limit. However it can lead to problem of sub-synchronous resonance.
- (v) Since most faults are transient, fast acting circuit breakers with rapid re-closure facility can aid stability.
- (vi) The most common type of fault being the single-line-to-ground fault, selective single pole opening and re-closing can improve stability.
- (vii) Use of braking resistors at generator buses. During a fault, there is a sudden decrease in electric power output of generator. A large resistor, connected at the generator bus, would partially compensate for the load loss and help in decreasing the acceleration of the generator. The braking resistors are switched during a fault through circuit breakers and remain for a few cycles after fault is cleared till system voltage is restored.
- (viii) Short circuit current limiters, which can be used to increase transfer impedance during fault, thereby reducing short circuit currents.
- (ix) A recent method is fast valving of the turbine where in the mechanical power is lowered quickly during the fault, and restored once fault is cleared.

Hall Ticket Number:

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III B. Tech. II Semester Regular/Supplementary Examinations, March-2023

POWER SYSTEM ANALYSIS

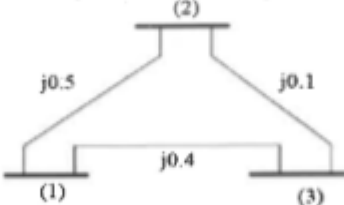
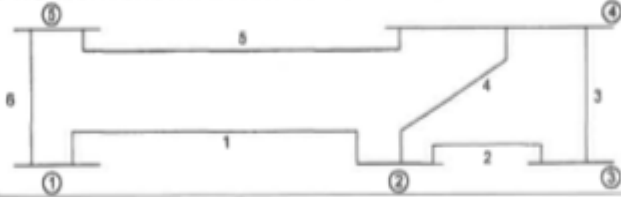
(Electrical and Electronics Engineering)

Time: 3 Hours

Max. Marks: 70

- Question paper contains **FIVE** units
Answer one question from each unit

Unit-I

1. a)	For the system shown below, make use of direct inspection method to obtain Y_{bus} . Take bus (1) as reference. The element impedances are indicated in p.u.	8M	1	III
				
b)	Explain the importance of primitive network representation in power systems?	6M	1	II
OR				
2. a)	A 100 MVA, 13.8 kV, 3- Φ generator has a reactance of 20%. The generator is connected to a 3-phase transformer T_1 rated 100 MVA 12.5 kV/ 110 kV with 10% reactance. The H.V. side of the transformer is connected to a transmission line of reactance 100 Ω . The far end of the line is connected to a step down transformer T_2 made of three single-phase transformers each rated 30 MVA, 60 kV/ 10 kV with 10% reactance. The generator supplies two motors connected on the L.V. side T_2 . The motors are rated at 25 MVA and 50 MVA both at 10 kV with 15% reactance. Show the reactance diagram with all values in per unit. Take generator rating as base.	8M	1	IV
b)	For the network shown below solve the bus incidence matrix?	7M	1	III
				

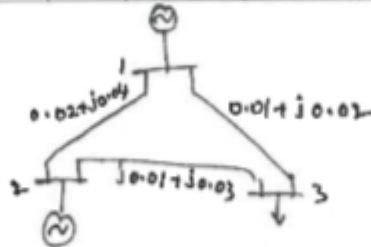
Unit-II

3. a)	Develop load flow equations suitable for solution by Newton Raphson method using rectangular when only PQ buses are present.	8M	2	V
b)	Compare Gauss-Seidel, Newton Raphson, Decoupled and Fast decoupled methods with respect to i) Number of iterations and ii) Convergence characteristics.	6M	2	II

OR

4. For the power system network shown below, determine V_3 using Gauss-Seidel method after first iteration? The impedance values in p.u. indicated in the network.

Bus code	V	Generation		Load	
		MW	MVAR	MW	MVAR
1	1.05	-	-	-	-
2	1.02	10	-	7.5	7
3	1.0	0	0	30	15



14M

2

V

Unit-III

5. A 3-phase line operating at 11 kV and having a resistance of 1.5Ω and reactance of 6Ω is connected to a generating station bus bars through a 5 MVA step-up transformer having reactance of 5%. The bus bars are supplied by a 12 MVA generator having 25% of reactance. Calculate the short circuit kVA fed into a symmetric fault at the (i) load end of the transformer and (ii) H.V. terminals of the transformer.

14M

3

V

OR

6. a) Explain how a synchronous generator is represented in short circuit analysis?
b) Illustrate the modification of Z_{bus} matrix for addition of an element from an old bus to reference.

7M

3

IV

7M

3

IV

Unit-IV

7. Derive an expression for fault current with necessary conditions for a double-line fault as an unloaded generator. Also draw sequence diagrams. What is the severity of fault current compared to other type of faults?

14M

4

IV

OR

8. a) Determine the symmetrical components for the following 3-phase currents.
 $I_R = 15 \angle 0^\circ \text{ A}$, $I_Y = 15 \angle 230^\circ \text{ A}$ and $I_B = 15 \angle 130^\circ \text{ A}$.
b) What is sequence impedance? Explain the sequence network of an unloaded generator?

7M

4

IV

7M

4

III

Unit-V

9. Explain equal area criterion in detail? Elaborate its use for predicting system stability and write its limitations.

14M

5

V

OR

10. a) Explain about the various factors affecting the transient stability of the system?
b) Explain Transfer reactance and Inertia constant related to power system stability studies?

8M

5

IV

6M

5

II

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Sno						
100	105	1	1	Edit	Delete	A graph that can be drawing without crossover of edges is termed Planar graph Non-planar graph Tree Graph
	106	1	2	Edit	Delete	Base impedance in ohms is mathematically expressed as: [Base voltage in kV (line to line)] * 1000 / Base kVA [Base voltage in kV (line to line)]^2 * 1000 / Base kVA [Base voltage in kV (line to line)]^3 * 1000 / Base kVA None of these
101	107	1	2	Edit	Delete	Which of the following statements is correct about Per unit system Transformer connections affect the per unit values Referring electrical quantities from one side of the transformer to Very often per unit impedances expand to very narrow range None of these
	108	1	3	Edit	Delete	Which of the following statement is false about Graph theory in P An element of a graph is called an edge For n number of nodes the rank of graph is n-1 Each current source is replaced by a short circuit in a graph Planar graph is the one can be drawing without edges cross-over
102	109	1	1	Edit	Delete	The number of edges connected to a vertex or node is called: Degree Rank Path Sub graph
	110	1	2	Edit	Delete	Certain graph has 4 nodes and 7 elements, the number of links is: 3 4 11 28

111	1	4	Edit	Delete	At a slack bus the quantities specified are: P and Q P and IVI P and δ IVI and δ
112	1	1	Edit	Delete	If E is number of elements and N is number of nodes then dimensions of the following are: $E \times N$ E/N $E+N$ $E-N$
113	1	3	Edit	Delete	Which of the following is correct about Z bus matrix: $Z_{bus} = Y_{bus}$ $Z_{bus} = 2.Y_{bus}$ $Z_{bus} = Y_{bus}^{-1}$ $Z_{bus} = Y_{bus}^3$
114	1	1	Edit	Delete	In element node incidence matrix if the pth element is incident to node q, then the value of a_{pq} is: $a_{pq} = 1$ $a_{pq} = -1$ $a_{pq} = 0$ $a_{pq} = 2$
115	1	1	Edit	Delete	If e is number of elements and n is number of nodes in graph, then the dimensions of the following are: $e \times n$ e/n $e+n$ $e-n$
116	1	2	Edit	Delete	Susceptance is _____ part of _____: Real, Admittance Imaginary, Admittance Real, Conductance Imaginary, Conductance

Susceptance is _____ part of _____:

116

1

2

Edit

Delete

Real, Admittance
Imaginary, Admittance
Real, Conductance
Imaginary, Conductance

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POWER SYSTEM

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The dimension of bus incidence matrix is:

117

1

2

Edit

Delete

exn
 $ex(n-1)$
 $ex(n+1)$
 $ex(n+2)$

Single line diagram of which of the following power system is pos

118

1

2

Edit

Delete

a) Power system with LG fault
b) Balanced power system
c) Power system with LL fault
d) Power system with LLG fault

Single line diagram does not represents:

119

1

2

Edit

Delete

a) Ratings of machines
b) Neutral wire of transmission lines
c) Delta connection of transformer winding
d) Star connection of transformer winding

Sno Mid Con
Ans

100

2

2

120

1

1

Edit

Delete

In impedance diagram different power system elements are repre
a) False
b) True

101

2

1

121

1

3

Edit

Delete

In impedance diagram different power system elements are repre
a) False
b) True

Power System Analysis					Page 10 of 15
102	2	4	Edit	Delete	_____ are designed on the basis of swing curve: 1) Rotor windings 2) Stator windings 3) Transformer windings 4) Protection devices

Sno	Mid	Correct Answer			
103	2	3	Edit	Delete	The major cause of voltage instability is: 1) Transformer 2) Generator 3) Load 4) Transmission lines
104	2	3	Edit	Delete	Which of the following is a sparse matrix: 1) Jacobian matrix 2) Y bus matrix 3) Both of these 4) None of these
105	2	2	Edit	Delete	Which type of convergence takes place in Newton Raphson method: 1) Linear convergence 2) Quadratic convergence 3) Cubic convergence 4) None of these
106	2	1	Edit	Delete	Equal area criterion is applicable to: 1) Single machine connected to infinite bus 2) Two machines connected to infinite bus 3) Multi machine system connected to infinite bus 4) All of these

Power System Analysis					Page 10 of 15
107	2	3	Edit	Delete	The quantity H in swing equation is: 1) Kelvin constant 2) Motion of synchronous motor/3.55 3) Inertia constant 4) None of these
108	2	3	Edit	Delete	With respect to Graph theory in Power System Analysis for n number of nodes the rank of graph is: 1) $n+2$ 2) n 3) $n-1$ 4) None

Sno	Mid	Correct Answer			
109	2	3	Edit	Delete	The approximate number of iteration required for n-bus system in Newton-Raphson method is: 1) 1 2) n 3) 3 4) n^2
110	2	2	Edit	Delete	1. Single line diagram of which of the following power system is possible? a) Power system with LG fault b) Balanced power system c) Power system with LL fault d) Power system with LLG fault
111	2	2	Edit	Delete	A power system will have greater flexibility of operation if they have _____ a) Only Base load plants operating in combination b) Various types of power plants operating in combination c) Only Peak load plants operating in combination d) Only thermal power plants operating in combination

Power System Analysis					Page 1015
112	2	2	Edit	Delete	Single line diagram does not represents: a) Ratings of machines b) Neutral wire of transmission lines c) Delta connection of transformer winding d) Star connection of transformer winding
113	2	1	Edit	Delete	In impedance diagram different power system elements are represented by symbols. a) False b) True c) None
114	2	2	Edit	Delete	In combined operation of several power plants the reserve capacity requirement is reduced. a) False b) True c) none

Sno	Mid	Correct Answer			
115	2	1	Edit	Delete	For a given power system, its zero and maximum regulation will occur at the impedance angle of a) 45 b) 60 c) 35 d) 50
116	2	1	Edit	Delete	A 200 bus power system has 160 PQ bus. For achieving a load flow solution by N-R in polar coordinates, the minimum number of simultaneous equation to be solved is _____ a) 359 b) 334 c) 357 d) 345

Power System Analysis					Page No.
117	2	1	Edit	Delete	A 50 bus power system Ybus has 80% sparsity. The total number of transmission lines will be _____ a) 225 b) 563 c) 345 d) 456
118	2	2	Edit	Delete	The given graph is the depiction of _____ on a large power system network. a) Three phase motor getting short b) L-G fault c) Ratings of machines d) Any of the mentioned
119	2	4	Edit	Delete	A protection system engineer is planning to provide the complete protection, he can achieve this by _____ a) a two phase fault relays and three earth fault relays b) a two phase fault relays and two earth fault relays c) two phase fault relays and three earth fault relays d) three phase fault relays and two earth fault relays
120	2	1	Edit	Delete	A power system has a maximum load of 15 MW. Annual load factor is 50%. The reserve capacity of plant is _____ if the plant capacity factor is 40%. a) 3.75 MW b) 7.75 MW c) 46.75 MW d) 8.75 MW

Sno	Mid	Correct Answer			
121	2	4	Edit	Delete	The area under the load curve represents _____ a) maximum demand b) load factor c) the average load on power system d) number of units generated

Power System Analysis					
122	2	1	Edit	Delete	If all the sequence voltages at the fault point in a power system are equal, then fault is _____ a) LLG fault b) Line to Line fault c) Three phase to ground fault d) LG fault
123	2	1	Edit	Delete	If the power system network is at $V_s \angle \delta$ and receiving end voltage is $V_r \angle 0$ consisting of the impedance of TL as $(R+j5)\Omega$. For maximum power transfer to the load, the most appropriate value of resistance R should be _____ a) 1.732 b) 3.45 c) 5.2 d) 0.33
124	2	3	Edit	Delete	Voltage regulation in the power system is _____ a) dip in voltage at sending end b) rise in voltage at sending end c) rise in voltage at receiving end d) dip in voltage at receiving end
125	2	1	Edit	Delete	Which of the following is not neglected during formation of reactance diagram from impedance diagram? a) Shunt component of Transformers b) Static loads c) Resistance of various power system components d) Reactance of alternators
126	2	3	Edit	Delete	Which of the following is not a requirement for site selection of hydroelectric power plant? a) Large catchment area b) Rocky land c) Sedimentation d) Availability of water
Sno	Mid	Correct Answer			

Power System Analysis					Page 1 of 1
127	2	2	Edit	Delete	Which of the following is not an advantage of hydroelectric power plant? a) no fuel requirement b) continuous power source c) low running cost d) no standby losses
128	2	1	Edit	Delete	Which of the following element of hydroelectric power plant prevents the penstock from water hammer phenomenon? a) Surge Tank b) Draft tubes c) Spillway d) Valves and Gates
129	2	4	Edit	Delete	Which of the following part of thermal power plant causes maximum energy losses? a) Alternator b) Ash and unburnt carbon c) Boiler d) Condenser
130	2	4	Edit	Delete	Which of the following are the most widely used condensers in modern thermal power plants? a) Low level counter flow type jet condenser b) Parallel flow type jet condenser c) High level counter flow type jet condenser d) Surface condensers
131	2	1	Edit	Delete	Which of the following is most suitable fuel for thermal power plant? a) Bituminous coal b) Lignite coal c) Anthracite coal d) Peat coal
132	2	2	Edit	Delete	Which of the following is most advantageous and most widely method of solid fuel firing? a) Spreader stoker firing b) Pulverised fuel firing c) Underfeed firing d) Stoker firing

Sno	Mid	Correct Answer			
133	2	4	Edit	Delete	Which of the following method is used in large modern thermal power plants to heat feed water? a) Open type heatre is used b) Surface type heater is used c) Close type heater is used d) Steam is directly taken from main turbine and used to heat it feed water
134	2	2	Edit	Delete	Which of the following pollutant causes acid rain? a) NO2 b) SO2 c) CO2 d) NO
135	2	4	Edit	Delete	What of the below mentioned statements are incorrect as compared to the HVDC system? a) Distance limitation b) Back to back connection is possible c) Extra reactive power compensation d) More corona losses
136	2	2	Edit	Delete	When the ozone gas is produced as a by product of corona, that causes _____ a) increase of power factor b) corrosion of wires c) improvement of regulation d) reduction of power factor
137	2	1	Edit	Delete	Which component of gas turbine power plant is main cause of its low efficiency? a) Compressor b) Starting motor c) Gas turbine d) Combustion chambe
138	2	2	Edit	Delete	Which of the following power plants can be profitably employed for supplying base loads as well as peak loads? a) Diesel power plant b) Hydroelectric power plant c) Thermal power plant d) Nuclear power plant

