Manual for

A Multi-machine Transient Stability Programme

(PART-2: Unsymmetrical Fault Analysis)

(Version 1.0)

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Chapter 1

Features of the Programme

1. The programme implements the full-blown model (2.2) for synchronous generators.
2. The programme provides flexibility to use even simplified models for generators.
3. It provides an option to consider the generator saturation. IEEE Std. 1110-2002 specified procedure has been adopted to model the generator saturation.
4. The programme has options to choose six different IEEE-type exciters (as per IEEE Std. 421.5-1992):
   (a) DC type: IEEE-type DC1A
   (b) AC type: IEEE-type AC1A and IEEE-type AC4A
   (c) Static type: IEEE-type ST1A, IEEE-type ST2A and Single time-constant static exciter.
5. The programme implements three IEEE-type turbine systems with associated speed governor systems:
   (a) Speed governor systems with Hydro turbine
   (b) Speed governor systems with Non-reheat-type steam turbine
   (c) Speed governor systems with Reheat-type steam turbine
6. The programme provides option for four IEEE-type Power System Stabilizers (PSS).
   (a) Slip signal-based PSS.
   (b) Power signal-based PSS.
   (c) Bus frequency signal-based PSS.
   (d) Delta P-Omega signal-based PSS.

7. The Programme has flexibility to use any kind of exciter/PSS/turbine with a given generator.

8. Voltage and frequency dependent static load models are considered.

   The details pertaining to above items (1 to 8) have been discussed in PART-1 (Symmetrical faults) of the manual.

9. Using the programme, stability studies for Unsymmetrical faults can be carried out. Different unsymmetrical faults like LG, LL, LLG, and one/two open-conductor(s) faults can be simulated.

10. The programme provides flexibility to use different fault clearing procedures.

    The details pertaining to above items (9 and 10) have been discussed in PART-2 (Unsymmetrical faults) of the manual.

11. No restriction on the size of the system that can be handled by the programme.

Test Systems and associated folders

The main folders:
For symmetrical fault study: `symm_faults`
For unsymmetrical fault study: `unsymm_faults`
The above two folders contain the following 3 sub-folders:

1. `4_machine`: Contains files related to 4 machine, 10 bus power system (adopted from the book *'Power System Dynamics-Stability and Control'* by K.R. Padiyar).
   `gen.dat` : 2.2 model
   `gen11.dat`: 1.1 model (rename it as `gen.dat` for making it active.)
   `gen00.dat`: classical model (rename it as `gen.dat` for making it active.)

2. `smib`: Contains files related to an example 6.6 in the book *'Power System Dynamics-Stability and Control'* by K.R. Padiyar.

3. `50_machine`: Contains files related to 50 machine, 145 bus, IEEE power system.

In addition, the `unsymm_faults` -main folder contains the following examples in a sub folder `Examples` :

1. `ex9_2_soman` : Example 9.2 in the book *Computational Methods for Large Sparse Power System Analysis* by S. A. Soman, et al.

2. `ex12_1_grainger` : Example 12.1 in the book *Power System Analysis* by J. Grainger and William D. Stevenson.

3. `ex7_3_grainger` : Example 7.3 in the book *Power System Analysis* by J. Grainger and William D. Stevenson.

Manuals

The following are the manuals:

1. Manual for symmetrical faults: `manual_sym.pdf`

2. Manual for unsymmetrical faults: `manual_unsym.pdf`

Chapter 2

Stability Analysis for Unsymmetrical Faults

2.1 Introduction

In addition to performing transient stability analysis for symmetrical faults, it is desirable to study the unsymmetrical faults, in view of the practical importance of faults not involving all three phases. Though the major effect of unsymmetrical faults is to increase the apparent fault impedance, it is required to analyze a power system behaviour under unbalanced fault conditions to design and monitor system protection schemes as 95% of the faults that occur on power system are unsymmetrical faults.

A more practical approach of analyzing unsymmetrical faults is the use of symmetrical components where the three-phase voltages (and currents) which may be unbalanced are transformed into three sets (positive, negative and zero) of balanced voltages (and currents) called symmetrical components. Fault on a power system can be analyzed by appropriately interconnecting the positive-, negative- and zero-sequence networks at the fault point [1, 2, 3, 4]. The method assumes that the network is balanced except at the fault point. The solution of the resulting network gives the symmetrical components of voltages and currents throughout the system. The negative- and zero-sequence network voltages and currents throughout the system are usually not of interest in stability studies as only positive sequence voltages are generated in the system. However, the negative- and zero-sequence currents that flow during unbalanced faults are driven by the positive-sequence voltage sources only [1]. Therefore, the complete negative- and zero-sequence networks are not simulated, but their effects are represented by their equivalent (Thevenin) impedances. Depending on the type of fault, the fault impedance is modified to include the negative- and zero-sequence impedances.

For analysis of unsymmetrical faults like LG, LL, LLG, one and two open-conductor faults, the loads are modeled as constant impedance type. Further, the effect of negative sequence torque has been neglected.

2.2 Sequence Impedance of Transmission Lines

2.2.1 Positive- and Negative-Sequence Impedances

In a symmetrical three-phase static circuit, the positive- and negative-sequence impedances are identical because the impedances of such circuit is independent of the phase order of the applied voltages. Hence the positive- and negative-sequence equivalent circuits of transmission line are identical and modelling details are same as that used in load flow studies.

2.2.2 Zero-Sequence Impedance

In a positive or negative- sequence impedance network, earth return path does not play any role. However, the zero-sequence impedance of a transmission line depends upon the configuration as well as the return paths through earth, ground wire, etc. When only zero-sequence currents flow in a transmission line, the three-phase currents are identical and are in phase. Thus the magnetic field produced is very different from that produced by positive- or negative-sequence currents. The net effect is that the zero-sequence reactance of a transmission line tends to be 2 to 3 times that of the positive-sequence reactance. In case of parallel or nearby transmission lines on the same tower, the mutual coupling resulting from positive and negative sequence currents is negligible. However, for the zero sequence network it is 50-70% of the self impedance. This can have a significant effect on fault current and therefore, on protective relaying.

2.2.2.1 Zero Sequence Modeling of Transmission Lines

If in an n bus zero-sequence network, if there exists m mutually coupled lines, then, they can be represented as follows [8]:

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ . \\ \Delta V_i \\ . \\ \Delta V_m \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & . & . & Z_{1m} \\ Z_{21} & Z_{22} & . & . & Z_{2m} \\ . & . & . & . & . \\ Z_{i1} & Z_{i2} & . & . & Z_{im} \\ . & . & . & . & . \\ Z_{m1} & Z_{m2} & . & . & Z_{mm} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ . \\ I_i \\ . \\ I_m \end{bmatrix} \tag{2.1}$$

where ΔV_i is the voltage drop in the i^{th} line, and I_i is the current in the direction of voltage drop. The matrix of primitive impedances in (2.1) is represented by Z_m. The element $Z_{ii} = r_{ii} + jx_{ii}$ is the self impedance of the line and $Z_{ij} = jx_{ij}$ is the mutual reactance between the coupled lines i and j.

Writing (2.1) in vector form, we have

$$[\Delta \underline{V}] = [Z_m][\ \underline{I}\ ] \tag{2.2}$$

If the inverse of the matrix Z_m exists then, the branch currents can be computed as follows:

$$[\ \underline{I}\ ] = [Z_m]^{-1}[\Delta \underline{V}] \tag{2.3}$$

Now the voltage drop across a line can be expressed in terms of vector of node voltages as follows:

$$[\Delta \underline{V}] = [P][\ \underline{V}\ ] \tag{2.4}$$

where P is a $m \times n$ matrix such that for a line number k in the set of mutually coupled lines, connecting the nodes p_k to q_k,we have $P(k, p_k) = 1$, $P(k, q_k) =$ -1. Rest of the elements are set to zero.

Therefore, from (2.3) and (2.4), we can express line currents as a function of node voltages as follows:

$$[\ \underline{I}\ ] = [Z_m]^{-1}[P][\ \underline{V}\ ] = [Y_m][\ \underline{V}\ ] \tag{2.5}$$

where $Y_m = [Z_m]^{-1}[P]$ is the admittance matrix.

2.2.2.2 Procedure to Compute Zero Sequence Y^0_{BUS}

There are two common ways to organize computations in short circuit analysis. They are:

1. Z_{BUS} approach
2. Y_{BUS} approach

The Z_{BUS} approach of computation has been covered in [6, 7]. In this thesis the Y_{BUS} approach is implemented. The Y_{BUS} approach is preferred over Z_{BUS} in large scale computation because it is directly amenable to sparsity exploitation.

In presence of mutually coupled lines, a procedure for computing the zero sequence Y^0_{BUS} is explained below with an example [8].

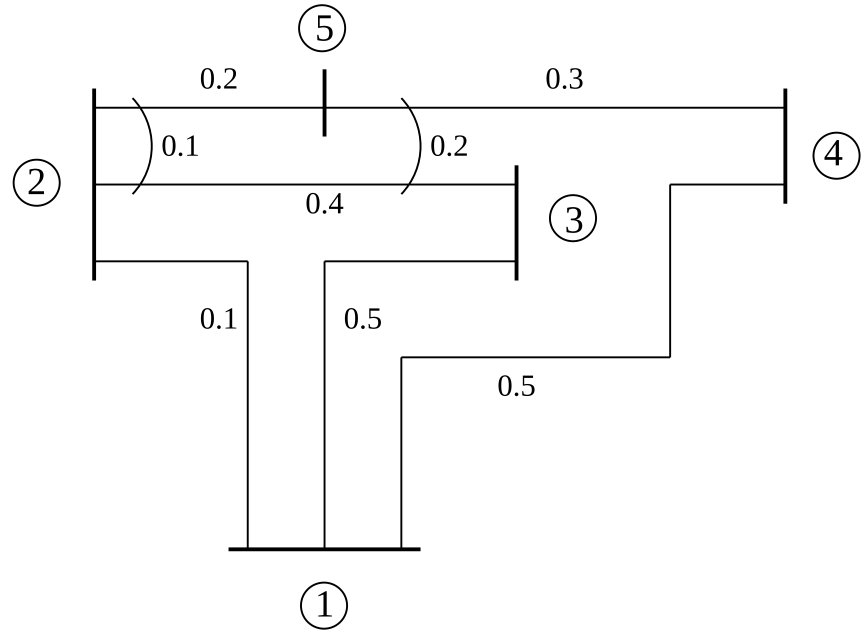

Figure 2.1: A 5-Bus Example System

1. Form $n \times n$ Y^0_{BUS} matrix without accounting for the lines that have mutual coupling, i.e., form the bus admittance matrix in a usual manner, using the self impedance of lines which are not mutually coupled with any lines.

   For the network shown in the Figure 2.1 lines 2-1, 3-1, 4-1 are considered in the formation of bus admittance matrix. This leads to Y^0_{BUS} as shown.

$$Y^0_{BUS} = \begin{bmatrix} -j14 & j10 & j2 & j2 & 0 \\ j10 & -j10 & 0 & 0 & 0 \\ j2 & 0 & -j2 & 0 & 0 \\ j2 & 0 & 0 & -j2 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

2. Form the Z_m matrix according to (2.2) for those lines having mutual couplings.

   For the given example, the mutually coupled lines are 2-5, 5-4, 2-3. Therefore,

$$\begin{bmatrix} \Delta V_{25} \\ \Delta V_{54} \\ \Delta V_{23} \end{bmatrix} = \begin{bmatrix} j0.2 & 0 & j0.1 \\ 0 & j0.3 & j0.2 \\ j0.1 & j0.2 & j0.4 \end{bmatrix} \begin{bmatrix} \Delta I_{25} \\ \Delta I_{54} \\ \Delta I_{23} \end{bmatrix}$$

3. Compute P matrix of size $m \times n$ for all mutually coupled lines such that $P(k, p_k)$ = 1, $P(k, q_k)$ = -1, else zero.

   For the given example, m = 3, n = 5, and k varies from 1 to m. If $k = 1$ then, the line is 2-5, i.e., $p_k = 2$, $q_k = 5$. Therefore, $P(k, p_k) = P(1{,}2) = 1$ and $P(k, q_k) = P(1{,}5) = -1$. In the similar way by computing the rest of the elements of P matrix we get,

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

4. Compute $[Y_m] = [Z_m]^{-1}[P]$

$$Y_m = \begin{bmatrix} 0 & -j3.8462 & -j2.3077 & j1.5385 & j4.6154 \\ 0 & j1.5385 & -j3.0769 & j5.3846 & -j3.8462 \\ 0 & -j2.3077 & j4.6154 & -j3.0769 & j0.7692 \end{bmatrix}$$

NOTE:

In MATLAB, the computation of Y_m is done in a most efficient way by declaring Z_m as sparse matrix and using back slash command to compute Y_m as `Ym = Zm\P` instead of using inverse command: `Ym = inv(Zm)*P`.

5. For each line k in the set of mutually coupled lines, connecting node p_k to q_k, do the following steps:
   (a) Add k^{th} row of Y_m matrix to p_k^{th} row of Y_{BUS}^0.
   (b) Substract k^{th} row of Y_m matrix from q_k^{th} row of Y_{BUS}^0.
   (c) Account line charging in the usual manner.

   Therefore for the given example, for $k = 1$, add 1^{st} row of Y_m to the 2^{nd} row of Y_{BUS}^0 and substract 1^{st} row of Y_m from the 5^{th} row of Y_{BUS}^0. Thus the Y_{BUS}^0 is:

$$Y_{BUS}^0 = \begin{bmatrix} -j14 & j10 & j2 & j2 & 0 \\ j10 & -j13.8462 & -j2.3077 & j1.5385 & j4.6154 \\ j2 & 0 & -j2.0000 & 0 & 0 \\ j2 & 0 & 0 & -j2.0000 & 0 \\ 0 & j3.8462 & j2.3077 & -j1.5385 & -j4.6154 \end{bmatrix}$$

NOTE:

The ordering of nodes p_k and q_k must be consistent with the convention of voltage drops.

Repeating the above procedure for $k = 2$ and 3, we get the Y^0_{BUS} as

$$Y^0_{BUS} = \begin{bmatrix} -j14 & j10 & j2 & j2 & 0 \\ j10 & -j16.1538 & j2.3077 & -j1.5385 & j5.3846 \\ j2 & j2.3077 & -j6.6154 & j3.0769 & -j0.7692 \\ j2 & -j1.5385 & j3.0769 & -j7.3846 & j3.8462 \\ 0 & j5.3846 & -j0.7692 & j3.8462 & -j8.4615 \end{bmatrix}$$

NOTE: To get the above result run: `yzero.m`
in the folder: `\Unsymm_faults \Examples \ex9_2_soman`.

2.3 Sequence Impedance of Transformers

2.3.1 Positive- and Negative-Sequence Impedances

With the assumption that symmetry exists between different phases, the impedance to balanced three-phase currents do not depend on the phase sequence. Hence the positive- and negative-sequence equivalent circuits of transformers are identical.

2.3.2 Zero-Sequence Impedance

The impedance offered by a transformer to the flow of zero-sequence currents depends on the windings connections. The zero-sequence leakage impedance is about 85-90% of positive-sequence impedance. For zero-sequence currents to flow through the windings on one side of the transformer and into the connected lines, a return path must exist through which a completed circuit is provided. Additionally, there must be a path for the corresponding current in the coupled windings on the other side. If the windings on one side are Y-connected with neutral ungrounded, zero-sequence currents cannot flow in the windings on either side as the zero-sequence impedance viewed from either the primary or secondary side is infinite.

2.3.2.1 Zero-Sequence Modeling of Transformers

The zero-sequence model of a transformer is modeled as π-circuit [8] and is shown in Figure 2.2. The values to be assigned to the limbs depend upon the type of winding and is summarized in Table 2.1. In the table, Δ denotes a delta winding, Y a star winding, G grounding and I neutral grounding impedance. Thus, a transformer marked Δ-YGI has primary delta and secondary star connected windings with neutral grounded through an impedance Z_n. The grounding impedance Z_n can take any value between zero to infinity. If Z_n is zero the transformer winding is solidly grounded and if it is infinity the transformer is ungrounded.

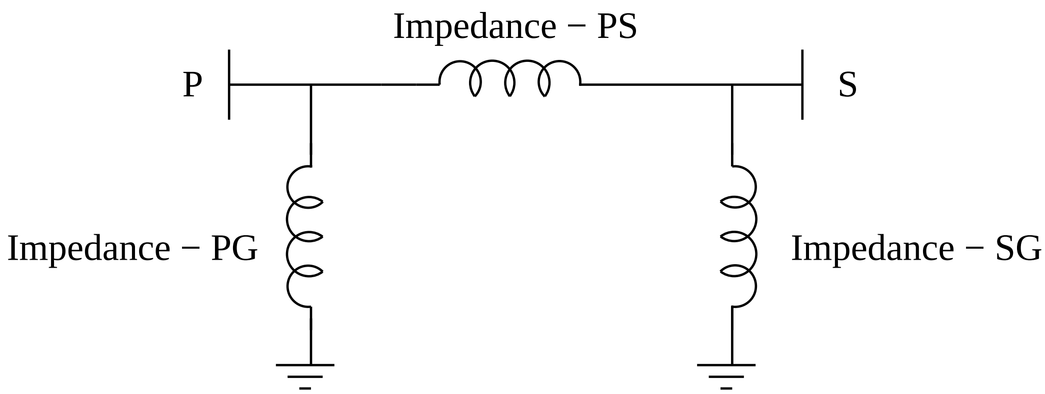

Figure 2.2: Zero-sequence transformer model

No	Transformer Type	Impedance-PG	Impedance-PS	Impedance-SG
1	Δ-YGI	∞	∞	$r_0 + jx_0 + 3Z_n$
2	YGI-Δ	$r_0 + jx_0 + 3Z_n$	∞	∞
3	YGI-YGI	∞	$r_0 + jx_0 + 3(Z_{n1} + Z_{n2})$	∞

Table 2.1: Zero sequence impedance for transformer

NOTE:

1. In the programme, the infinite impedance is approximated as 10^6 p.u. The zero-sequence and grounding resistances are neglected. Only reactances are considered.

2. The transformer configurations given in the Table 2.1 are used for the following applications:

   (a) Generator transformers: Configurations 1 and 2 are used for generator transformers, if any. One has to take care that the generator is always connected to the $\triangle$ side of the transformer. In simulating case studies, depending upon the location of the generator, one can choose configuration 1 or 2 without altering the other data files.

   (b) Inter-connecting transformers: Configuration 3 is used for inter-connecting transformers, if any.

2.4 Sequence Impedance of Synchronous Machines

2.4.1 Positive- and Negative-Sequence Impedances

For rotating machines, the positive- and negative-sequence impedances are not the same. In case of a synchronous machine, negative- sequence currents produce a rotating mmf in opposite direction to the rotor mmf. Hence, the negative-sequence reactance corresponds to the flux which rotates at twice the synchronous speed with respect to the rotor. The negative-sequence impedance is 70-90% of the subtransient reactance. For a sailent pole machine, it is taken as a mean of $x_d^{''}$ and $x_q^{''}$ values, i.e.,

$$x^{(2)} = \frac{x_d^{''} + x_q^{''}}{2} \tag{2.6}$$

In the programme, $x^{(2)}$ is calculated as per the above equation and is assumed to be uneffected by generator saturation.

2.4.2 Zero-Sequence Impedance

The zero-sequence impedance of a synchronous machine is only a small percentage (0.1-0.7 of $x_d^{''}$) of the positive-sequence impedance. If the star point of the generator is grounded through an impedance Z_g, then $3Z_g$ must be added to the zero-sequence impedance of generator before incorporating it as shunt in the Y_{BUS}^0. The effect of saturation on zero-sequence reactance is neglected.

In the programme, generator and transformer neutral are assumed to be grounded through reactances. If it is required to simulate an open neutral, set the grounding reactance to a very high value, say 10^6.

2.5 Representation of Faults in Stability Studies

Fault on a power system can be analyzed by appropriately interconnecting the positive-, negative-, and zero-sequence networks at the fault point. The solution of the resulting network gives the symmetrical components of voltages and currents throughout the system. Since there are no negative- and zero-sequence voltages generated in the system, the negative- and zero-sequence network voltages and currents throughout the system are not usually calculated in stability studies [1]. Therefore, the complete negative- and zero-sequence networks are not simulated but their effects are represented by their equivalent (Thevenin) impedances ($Z_{ff}^{(2)}$ and $Z_{ff}^{(0)}$) as viewed at the fault point f as shown in Figure 2.3. From this, it is clear that the net effect of unsymmetrical faults on the positive-sequence network is to increase the effective impedance of the network.

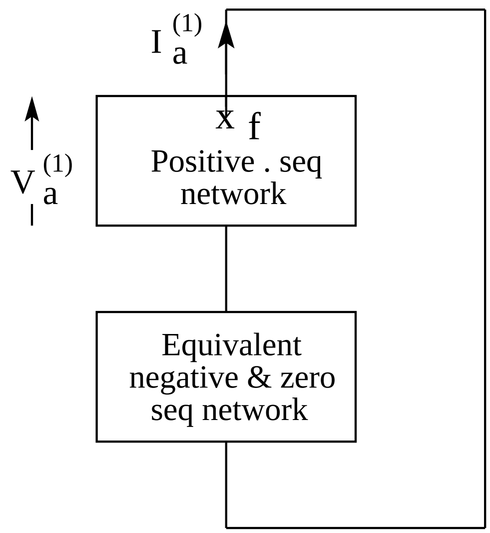

Figure 2.3: Representation of faults in stability studies

With the above representation, it is clear that the negative- and zero-sequence currents that flow during unbalanced faults are driven by the positive-sequence voltages only. In the programme, for generator torque calculations, only positive-sequence quantities are used and the effect of negative-sequence torque component has been neglected [4].

In the following sections, we consider the simulation of a power system that is essentially symmetrical but is rendered unbalanced by a fault at a particular location on the system [6].

2.6 Simulation of Unsymmetrical Short-circuit Faults

2.6.1 Single line-to-ground fault

A single line-to-ground fault through impedance Z_f on phase a is shown in Figure 2.4(a). The conditions at the fault bus f are expressed by the following equations:

$$I_b = I_c = 0 \tag{2.7}$$

$$V_a = V_a^{(0)} + V_a^{(1)} + V_a^{(2)} = I_a Z_f \tag{2.8}$$

With $I_b = I_c = 0$, the symmetrical components of the currents are given by

$$\begin{bmatrix} I_a^{(0)} \\ I_a^{(1)} \\ I_a^{(2)} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix} \tag{2.9}$$

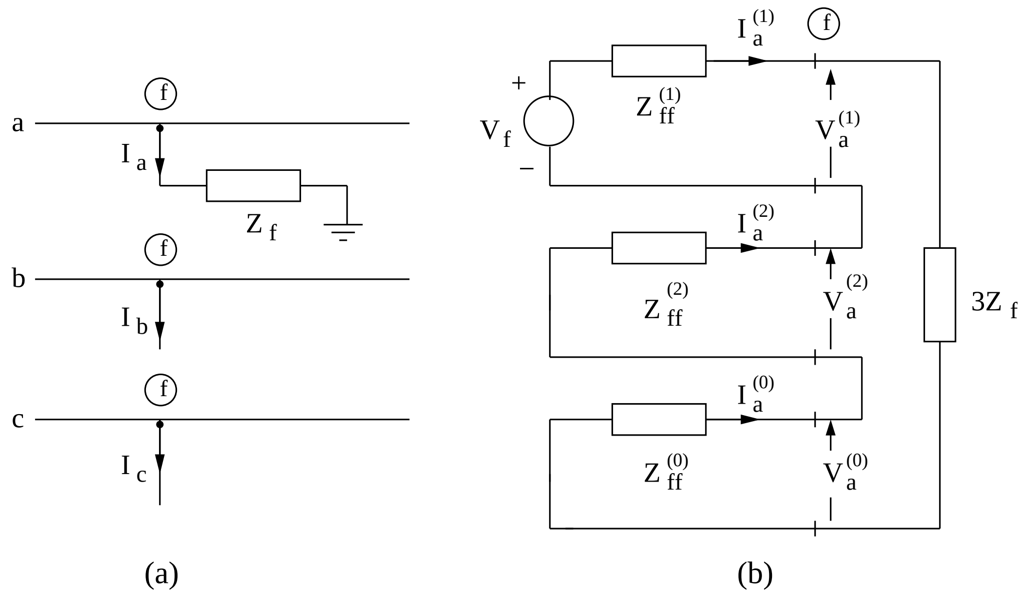

Figure 2.4: Single line-to-ground fault: (a) Fault schematic (b) Sequence network connection

and performing the multiplication yields

$$I_a^{(0)} = I_a^{(1)} = I_a^{(2)} = \frac{I_a}{3} \tag{2.10}$$

From (2.8) and (2.10)

$$V_a = -Z_{ff}^{(0)} I_a^{(0)} + V_f - Z_{ff}^{(1)} I_a^{(1)} - Z_{ff}^{(2)} I_a^{(2)} = 3Z_f I_a^{(0)} \tag{2.11}$$

where V_f is the prefault positive-sequence voltage component at fault bus f. Solving for $I_a^{(0)}$ and combining the result with (2.10), we obtain

$$I_a^{(0)} = I_a^{(1)} = I_a^{(2)} = \frac{V_f}{Z_{ff}^{(1)} + Z_{ff}^{(2)} + Z_{ff}^{(0)} + 3Z_f} \tag{2.12}$$

The sequence network connection is shown in Figure 2.4(b), which satisfy the above equations. For bolted fault, set $Z_f = 0$.

2.6.2 Line-to-line fault

Line-to-line fault through impedance Z_f, on phases b and c is shown in Figure 2.5(a). The following relations are satisfied at the fault point.

$$I_a = 0, \qquad I_b = -I_c \tag{2.13}$$

$$V_b - V_c = Z_f I_b \tag{2.14}$$

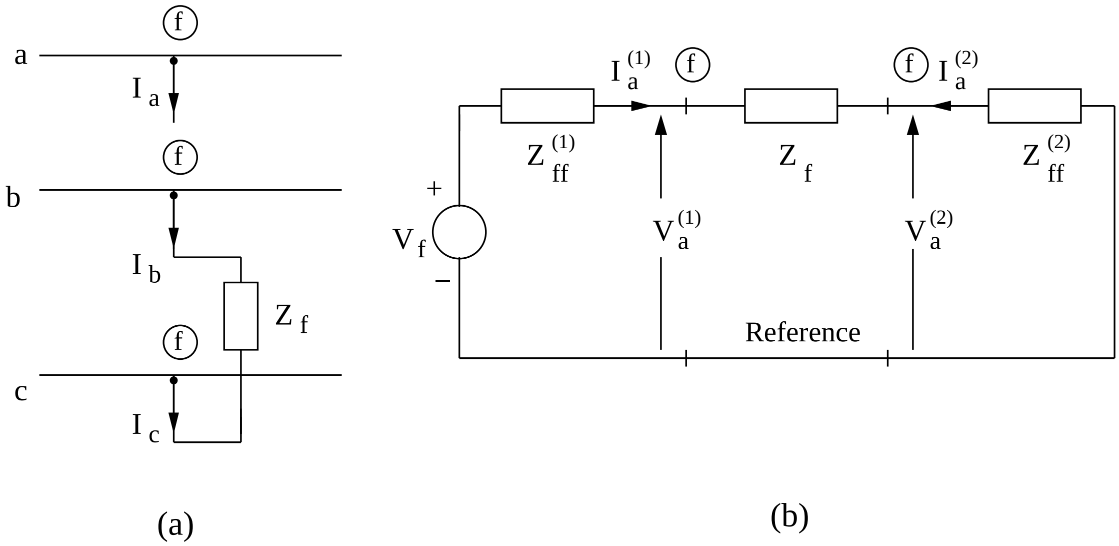

Figure 2.5: Line-to-Line fault: (a) Fault schematic (b) Sequence network connection

Transforming the line currents into symmetrical components of currents we get

$$I_a^{(0)} = 0 \tag{2.15}$$

$$I_a^{(1)} = -I_a^{(2)} \tag{2.16}$$

Using (2.14) and (2.16), it can be shown that [6]:

$$V_a^{(1)} - V_a^{(2)} = I_a^{(1)}\ Z_f \tag{2.17}$$

The sequence network connection satisfying (2.16) and (2.17) is shown in Figure 2.5(b). Since the fault does not involve ground, the zero-sequence network is absent. The equation for the positive-sequence current in the fault is given by

$$I_a^{(1)} = -I_a^{(2)} = \frac{V_f}{Z_{ff}^{(1)} + Z_{ff}^{(2)} + Z_f} \tag{2.18}$$

2.6.3 Double line-to-ground fault

The fault schematic for double line-to-ground fault through impedance Z_f, on phases b and c is shown in Figure 2.6(a). The relations now existing at the fault bus f are

$$I_a = I_a^{(0)} + I_a^{(1)} + I_a^{(2)} = 0 \tag{2.19}$$

$$V_b = V_c = (I_b + I_c)Z_f \tag{2.20}$$

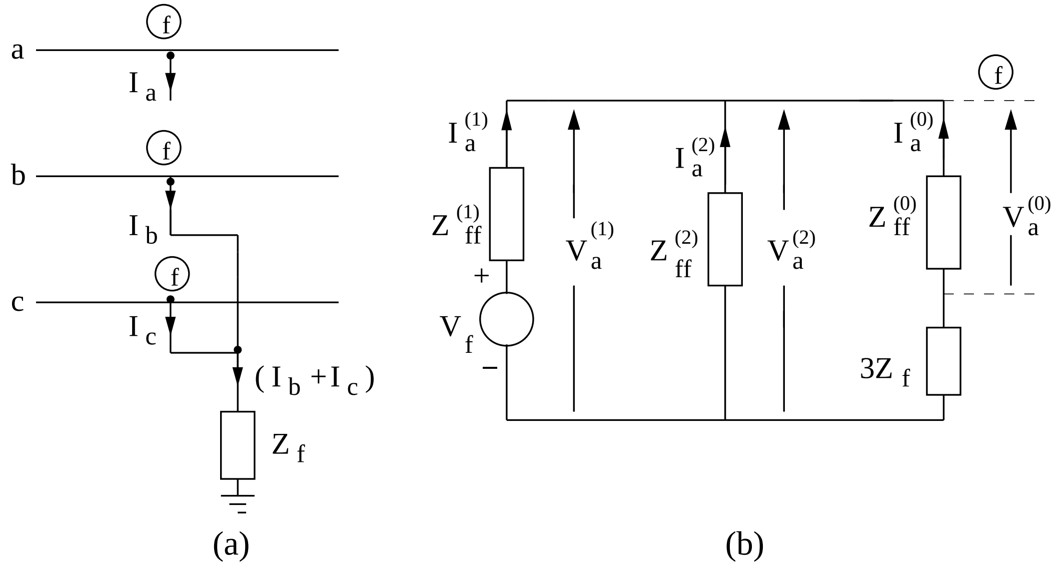

Figure 2.6: Double line-to-ground fault: (a) Fault schematic (b) Sequence network connection

Transforming the line currents and voltages into symmetrical components we get

$$V_a^{(1)} = V_a^{(2)} = V_a^{(0)} - 3Z_f I_a^{(0)} \tag{2.21}$$

The sequence network connections satisfying the (2.19) and (2.21) is shows in Figure 2.6(b). From the sequence network the positive-sequence current is given by

$$I_a^{(1)} = \frac{V_f}{Z_{ff}^{(1)} + \dfrac{Z_{ff}^{(2)}(Z_{ff}^{(0)} + 3Z_f)}{Z_{ff}^{(2)} + Z_{ff}^{(0)} + 3Z_f}} \tag{2.22}$$

In general, for any unsymmetrical short-circuit faults, the positive-sequence component of fault current, $I_a^{(1)}$ is given by

$$I_a^{(1)} = \frac{V_f}{Z_{sc-eq}} \tag{2.23}$$

where Z_{sc-eq} is short-circuit equivalent impedance. Its expression for different types of faults with and without fault impedance Z_f is tabulated in Table 2.2.

The change in the positive-sequence component of bus voltages is obtained as

$$\triangle V_i^{(1)} = -Z_{if}^{(1)}\ I_a^{(1)} \qquad \text{for } i = 1, 2, .., n \tag{2.24}$$

where n is the number of buses in the network and the suffix f represents the fault bus number.

Fault Type	Equivalent Impedance of Sequence Network, Z_{sc-eq}	
	Without Fault Impedance	With Fault Impedance Z_f
LG	$Z_{ff}^{(1)} + Z_{ff}^{(2)} + Z_{ff}^{(0)}$	$Z_{ff}^{(1)} + Z_{ff}^{(2)} + Z_{ff}^{(0)} + 3Z_f$
LL	$Z_{ff}^{(1)} + Z_{ff}^{(2)}$	$Z_{ff}^{(1)} + Z_{ff}^{(2)} + Z_f$
LLG	$Z_{ff}^{(1)} + \dfrac{Z_{ff}^{(2)} Z_{ff}^{(0)}}{Z_{ff}^{(2)} + Z_{ff}^{(0)}}$	$Z_{ff}^{(1)} + \dfrac{Z_{ff}^{(2)}(Z_{ff}^{(0)} + 3Z_f)}{Z_{ff}^{(2)} + Z_{ff}^{(0)} + 3Z_f}$
LLL	$Z_{ff}^{(1)}$	$Z_{ff}^{(1)} + Z_f$

Table 2.2: Equivalent impedance of sequence network for different short-circuit faults

2.7 Simulation of Unsymmetrical Open-conductor Faults

When one or two phases of a balanced three-phase circuit opens as shown in Figure 2.7, an unbalance is created and asymmetrical currents flow. Such open-conductor faults can be analyzed by means of the bus impedance matrices of the sequence networks, as demonstrated below [6]. This method assumes that the line shunt suceptance is negligibly small.

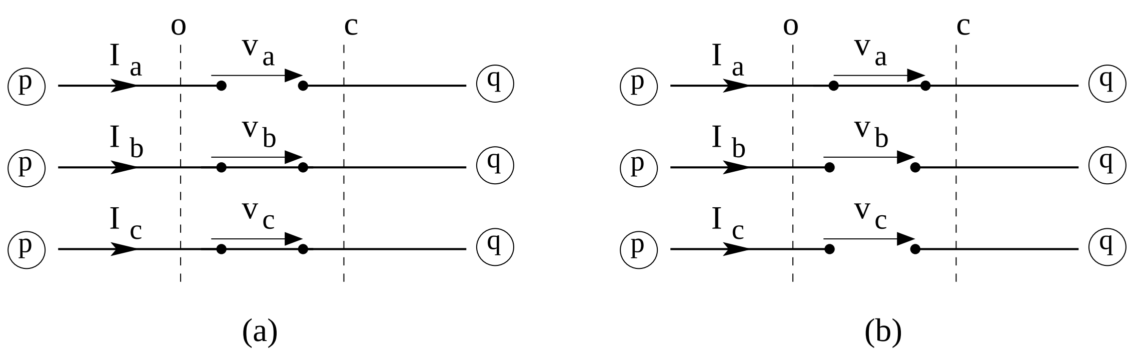

Figure 2.7: Open conductor faults: (a) One open conductor, (b) Two open conductors

If the line p-q has the sequence impedances Z_0, Z_1, and Z_2, we can simulate the opening of the three phase conductors by adding the negative impedances $-Z_0$, $-Z_1$, and $-Z_2$, between buses p and q in the corresponding Thevenin equivalents of the three sequence networks of the intact system. Figure 2.8 shows the connection of $-Z_1$ to the positive-sequence Thevenin equivalent between buses p and q.

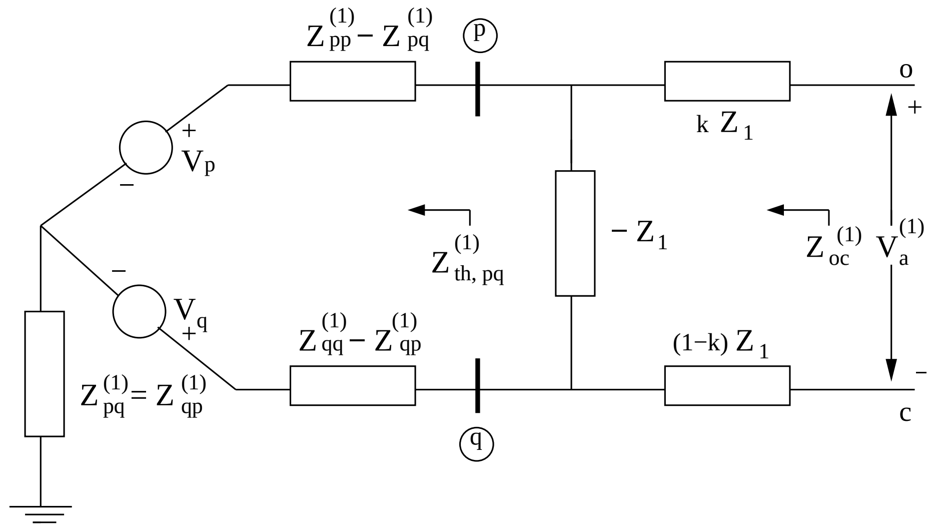

Figure 2.8: Connections to positive-sequence Thevenin equivalent of the network

The impedances shown are the elements $Z_{pp}^{(1)}, Z_{qq}^{(1)}$, and $Z_{pq}^{(1)} = Z_{qp}^{(1)}$ of the positive-sequence bus impedance matrix $Z_{bus}^{(1)}$ of the intact system, and $Z_{th,pq}^{(1)} = Z_{pp}^{(1)} + Z_{qq}^{(1)} - 2Z_{pq}^{(1)}$ is the corresponding Thevenin impedance between buses p and q. Voltages V_p and V_q are the normal (positive-sequence) voltages of phase a at buses p and q before the open-conductor fault occur. The positive-sequence impedances kZ_1 and (1-k)Z_1, where $0 \leq k \leq 1$, are added as shown to represent the fractional lengths of the broken line p-q.

By source transformation we can replace the phase-a positive-sequence voltage drop $V_a^{(1)}$ in series with the impedance [kZ_1 + (1-k)Z_1] in Figure (2.8) by the current $V_a^{(1)}/Z_1$ in parallel with the impedance Z_1. The parallel combination of Z_1 and $-Z_1$ can be canceled as shown in Figure (2.9).

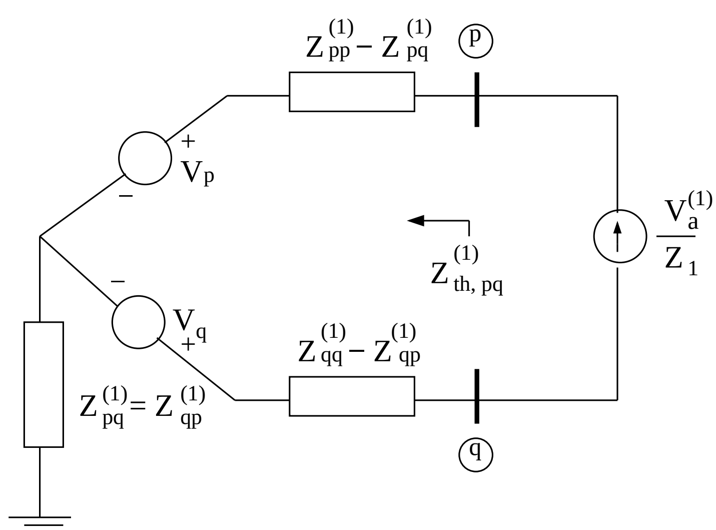

Figure 2.9: Resultant equivalent circuit

The above considerations for the positive-sequence network also apply to the negative- and zero-sequence networks, but they do not contain any internal sources of their own. The voltage drops across the fault points o and c for each type of open conductor fault can be regarded as giving rise to a set of injection currents which are given in Table 2.3, into the sequence networks of the normal system configuration.

	Positive Sequence	Negative Sequence	Zero Sequence
At bus p	$\frac{V_a^{(1)}}{Z_1}$	$\frac{V_a^{(2)}}{Z_2}$	$\frac{V_a^{(0)}}{Z_0}$
At bus q	$\frac{-V_a^{(1)}}{Z_1}$	$\frac{-V_a^{(2)}}{Z_2}$	$\frac{-V_a^{(0)}}{Z_0}$

Table 2.3: Currents to be injected at buses p and q

By multiplying the bus impedance matrices $Z_{bus}^{(0)}$, $Z_{bus}^{(1)}$ and $Z_{bus}^{(2)}$ by current vectors containing only these current injections, we obtain the following changes in the symmetrical components of the phase-a voltage of each bus i:

$$\begin{aligned} \Delta V_i^{(0)} &= \frac{Z_{ip}^{(0)} - Z_{iq}^{(0)}}{Z_0}\ V_a^{(0)} \\ \Delta V_i^{(1)} &= \frac{Z_{ip}^{(1)} - Z_{iq}^{(1)}}{Z_1}\ V_a^{(1)} \qquad \text{for } i = 1, 2, .., n \\ \Delta V_i^{(2)} &= \frac{Z_{ip}^{(2)} - Z_{iq}^{(2)}}{Z_2}\ V_a^{(2)} \end{aligned} \tag{2.25}$$

where $V_a^{(0)}$, $V_a^{(1)}$ and $V_a^{(2)}$ are the sequence components of the voltage drop across the fault points o and c.

Looking into the positive-sequence network of Figure 2.8 between o and c, we see the impedance $Z_{oc}^{(1)}$ given by

$$Z_{oc}^{(1)} = \frac{-Z_1^2}{Z_{th,\ pq}^{(1)} - Z_1} \tag{2.26}$$

Similarly, the negative- and zero-sequence impedances are given by

$$Z_{oc}^{(2)} = \frac{-Z_2^2}{Z_{th,\ pq}^{(2)} - Z_2} \tag{2.27}$$

$$Z_{oc}^{(0)} = \frac{-Z_0^2}{Z_{th,\ pq}^{(0)} - Z_0} \tag{2.28}$$

The open-circuit voltage from o to $c = Z_{oc}^{(1)} I_{pq}$
where I_{pq} is the prefault current in phase-a before any conductor opens and is given by

$$I_{pq} = \frac{V_p - V_q}{Z_1} \tag{2.29}$$

2.7.1 One open-conductor

Consider one open conductor as in Figure 2.7(a). Owing to open circuit in phase a, the current $I_a = 0$, and so

$$I_a^{(0)} + I_a^{(1)} + I_a^{(2)} = 0 \tag{2.30}$$

Since phases b and c are closed, we also have the voltage drops $V_{oc,\ b} = 0$ and $V_{oc,\ c} = 0$. Resolving the series voltage drops across the fault point into their symmetrical components we obtain

$$V_a^{(0)} = V_a^{(1)} = V_a^{(2)} = \frac{V_{oc,\ a}}{3} \tag{2.31}$$

The connection of the sequence networks of the system satisfying the above equations is shown in Figure 2.10.

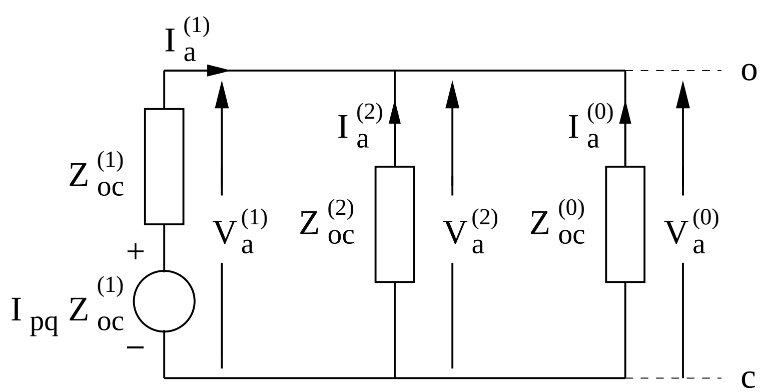

Figure 2.10: One open-conductor fault: Connection of sequence networks

The expression for the positive-sequence current $I_a^{(1)}$ is

$$I_a^{(1)} = \frac{Z_{oc}^{(1)}\ I_{pq}}{Z_{oc}^{(1)} + \dfrac{Z_{oc}^{(2)} Z_{oc}^{(0)}}{Z_{oc}^{(2)} + Z_{oc}^{(0)}}} \tag{2.32}$$

The sequence voltage drops are given by

$$V_a^{(0)} = V_a^{(1)} = V_a^{(2)} = \frac{Z_{oc}^{(2)} Z_{oc}^{(0)}}{Z_{oc}^{(2)} + Z_{oc}^{(0)}} \; I_a^{(1)} \tag{2.33}$$

From (2.32) and (2.33) we can write the positive-sequence voltage as

$$V_a^{(1)} = \frac{Z_{oc}^{(0)} Z_{oc}^{(1)} Z_{oc}^{(2)}}{Z_{oc}^{(0)} Z_{oc}^{(1)} + Z_{oc}^{(1)} Z_{oc}^{(2)} + Z_{oc}^{(2)} Z_{oc}^{(0)}} \; I_{pq} \tag{2.34}$$

2.7.2 Two open-conductors

Consider two open conductor as in Figure 2.7(b). Owing to open circuit in phases b and c, the currents $I_b = 0$ and $I_c = 0$. Since phase a is closed, we have the voltage drop

$$V_{oc,\ a} = V_a^{(0)} + V_a^{(1)} + V_a^{(2)} = 0 \tag{2.35}$$

Resolving the line currents into their symmetrical components gives

$$I_a^{(0)} = I_a^{(1)} = I_a^{(2)} = \frac{I_a}{3} \tag{2.36}$$

Equations (2.35) and (2.36) are both satisfied by connecting the sequence networks as shown in Figure 2.11.

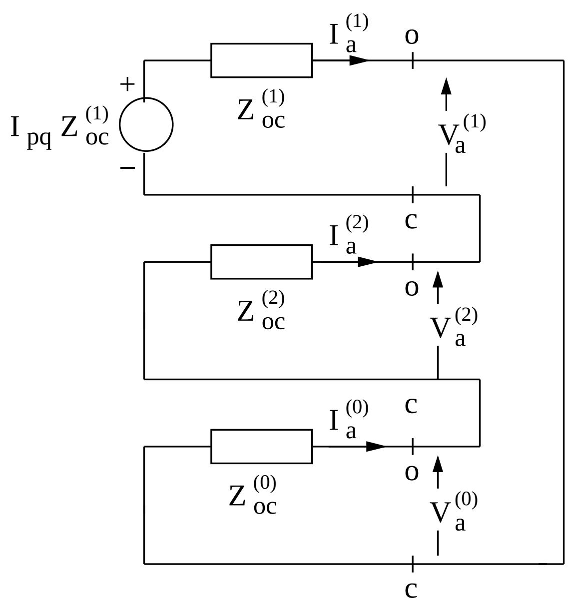

Figure 2.11: Two open-conductors fault: Connection of sequence networks

The expression for the sequence currents are given by

$$I_a^{(0)} = I_a^{(1)} = I_a^{(2)} = \frac{Z_{oc}^{(1)}\ I_{pq}}{Z_{oc}^{(1)} + Z_{oc}^{(2)} + Z_{oc}^{(0)}} \tag{2.37}$$

where I_{pq} is again the prefault current in phase a of line p-q before the open circuits occur in phases b and c. The sequence voltage component are given by

$$\begin{aligned} V_a^{(1)} &= \frac{Z_{oc}^{(1)}(Z_{oc}^{(2)} + Z_{oc}^{(0)})}{Z_{oc}^{(1)} + Z_{oc}^{(2)} + Z_{oc}^{(0)}}\ I_{pq} \\ V_a^{(2)} &= \frac{-Z_{oc}^{(1)} Z_{oc}^{(2)}}{Z_{oc}^{(1)} + Z_{oc}^{(2)} + Z_{oc}^{(0)}}\ I_{pq} \\ V_a^{(0)} &= \frac{-Z_{oc}^{(1)} Z_{oc}^{(0)}}{Z_{oc}^{(1)} + Z_{oc}^{(2)} + Z_{oc}^{(0)}}\ I_{pq} \end{aligned} \tag{2.38}$$

In general, for open-conductor faults, the positive-sequence component of series voltage drop across the fault points is given by

$$V_a^{(1)} = I_{pq}\ Z_{oc-eq} \tag{2.39}$$

where Z_{oc-eq} is the equivalent open-circuit impedance and it takes the expression depending on the type of fault as given in Table 2.4.

Fault Type	Equivalent Impedance of Sequence Network, Z_{oc-eq}
One Open Conductor	$\dfrac{Z_{oc}^{(0)} Z_{oc}^{(1)} Z_{oc}^{(2)}}{Z_{oc}^{(0)} Z_{oc}^{(1)} + Z_{oc}^{(1)} Z_{oc}^{(2)} + Z_{oc}^{(2)} Z_{oc}^{(0)}}$
Two Open Conductors	$\dfrac{Z_{oc}^{(1)}(Z_{oc}^{(2)} + Z_{oc}^{(0)})}{Z_{oc}^{(1)} + Z_{oc}^{(2)} + Z_{oc}^{(0)}}$

Table 2.4: Equivalent impedance of sequence network for different open-conductor faults

The change in the positive-sequence component of bus voltages $\triangle V^{(1)}$, is obtained from (2.25). The net effect of the open conductors on the positive-sequence network is to increase the transfer impedance across the line in which the open-conductor fault occurs.

In the following section calculation of positive-sequence bus voltages is explained.

2.8 Calculation of Positive-Sequence Bus Voltages

The positive-sequence bus voltages $V_{bus}^{(1)}$ is calculated by computing the change in bus voltages $\triangle V^{(1)}$ and adding it to the prefault positive-sequence bus voltages as shown in Figure 2.12.

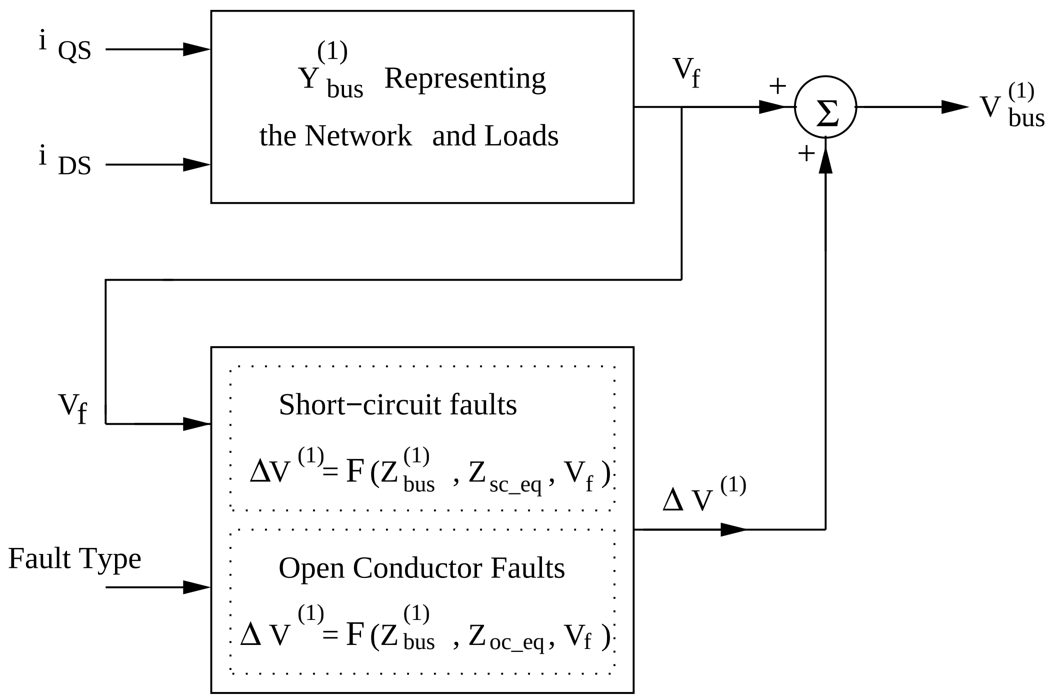

Figure 2.12: Calculation of positive-sequence bus voltages

Note that the loads are modelled as constant impedance type and are included in the positive-sequence bus admittance matrix, $Y_{bus}^{(1)}$. The change in bus voltages $\triangle V^{(1)}$ is computed as a function of $Z_{bus}^{(1)}$, V_f and equivalent impedances as given below:
For short-circuit faults:

$$\triangle V^{(1)} = F(Z_{bus}^{(1)}, Z_{sc-eq}, V_f) \tag{2.40}$$

For open-conductor faults:

$$\triangle V^{(1)} = F(Z_{bus}^{(1)}, Z_{oc-eq}, V_f) \tag{2.41}$$

In (2.41), V_f is used to compute the prefault current I_{pq}.
NOTE:
In the above functions, the entire $Z_{bus}^{(1)}$ elements are not computed by taking the inverse of $Y_{bus}^{(1)}$ as the function requires only the f^{th} column of $Z_{bus}^{(1)}$. These f^{th} column elements

are computed in MATLAB as follows:

```
E_f = zeros(n,1);
E_f(f) = 1;
Zbus_f = Ybus\E_f;
```

where n is the number of buses, f is the fault the bus number, and `Ybus` represents $Y_{bus}^{(1)}$ and `Zbus_f` represents the f^{th} column of $Z_{bus}^{(1)}$.

2.9 Conductors/Lines Tripping and Reclosing Procedures

The fault on the system can be cleared in different ways depending upon the intensity and type of the fault. In general, the faults can be cleared with/without tripping a lines/conductor/transformer. For any fault on the system, T_{fault} is the time at which fault occurs wrt time $t = 0$ s and the fault is cleared at $t = T_{clr}$ after a time interval T_{clear} wrt T_{fault} as shown in Figure 2.13.

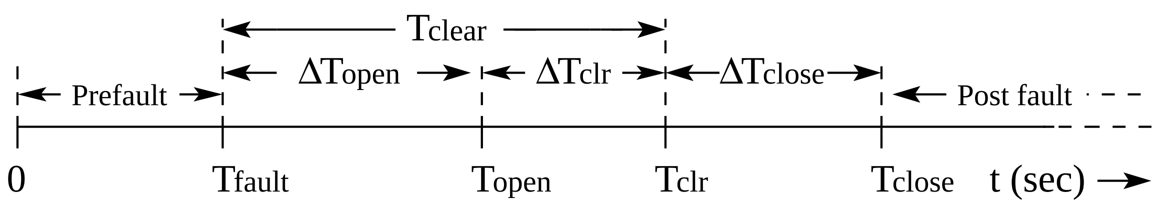

Figure 2.13: Time of occurrence of fault and fault clearing instants

The different methods of tripping and reclosing procedures provided in the programme are given below:

1. For any fault, either symmetrical or unsymmetrical, the fault can be cleared by employing the following procedures:

    (a) Self clearing of faults: Here a fault is assumed to be removed without tripping any line/transformer. In this case, the post fault system is identical to the prefault system from $t = T_{clr}$ onwards.

    (b) Fault is cleared by tripping the line/transformer: Here a fault is cleared by tripping a line/transformer at $t = T_{clr}$. In this case, the following two options are possible:

        (i) A line/transformer is tripped permanently at $t = T_{clr}$. The post fault system becomes different from the prefault system from $t = T_{clr}$ onwards.

(ii) A line/transformer is tripped temporarily for a duration of $\triangle T_{close}$, i.e., a line opened at $t = T_{clr}$ is reclosed at $t = T_{close}$. The post fault system is identical to prefault system from $t = T_{close}$ onwards.

2. For unsymmetrical short-circuit faults, the faulted conductor(s) can be opened without tripping the entire line, i.e., short-circuit faults followed by open-conductor faults. This involves tripping the faulted conductor(s) after a time interval of ΔT_{open} wrt T_{fault}. During the time interval (ΔT_{open}) between T_{fault} and T_{open}, the system experiences short-circuit fault and during the time interval (ΔT_{clr}) between T_{open} and T_{clr}, the system experiences open-conductor fault. Later the fault can be cleared with/without line tripping at time $t = T_{clr}$. If a line is tripped, the above procedure can be applied to reclose the line.
   NOTE: The time interval ΔT_{open} must be less than T_{clear}.

3. For unsymmetrical open-conductor faults, the conductor(s) are tripped at $t = T_{fault}$. The fault can be cleared with/without tripping the line at time $t = T_{clr}$ after a time interval of T_{clear} wrt T_{fault}. If a line is tripped, the procedure explained above can be applied to reclose the line.
   NOTE: Open conductors faults are not allowed on transformers.

Chapter 3

Case Studies with Test Systems

3.1 4 Generator, 10-Bus System

The single line diagram of a 4 machine power system is shown in Figure 3.1. The system details are adopted from [5].

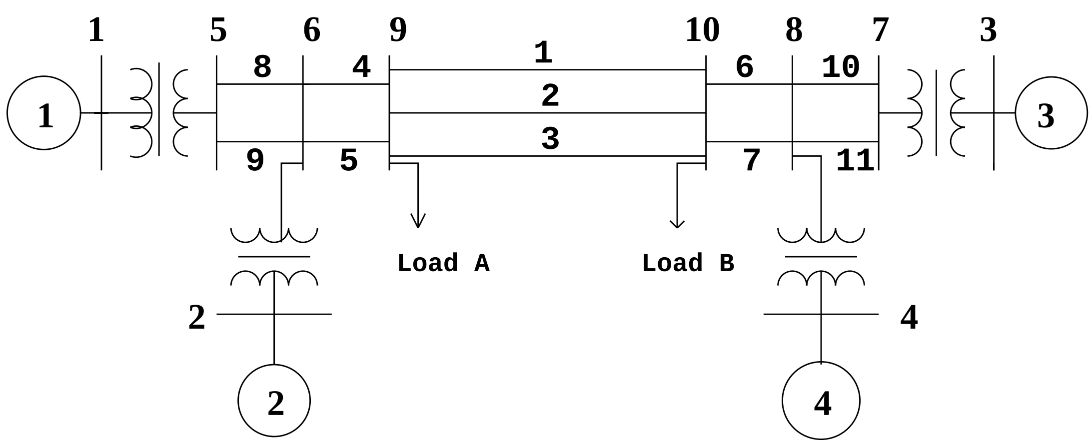

Figure 3.1: Four machine power system.

To run the transient stability programme, the steps to be followed are :

1. Perform the power flow studies by running: `fdlf_loadflow.m` file. It requires the following `.m` and data files:
   (a) `B_bus_form.m`, `fdlf_jacob_form.m`, `powerflow.m` and `lfl_result.m`.
   (b) `busno.dat` : System details- number of lines, buses, transformers, etc
   (c) `nt.dat` : Transmission line and transformer data
   (d) `pvpq.dat` : Generation data and load data.
   (e) `shunt.dat` : Shunt data

On successful run, it generates two output files: `lfl.dat` and `report.dat`. The converged loadflow results are available in `lfl.dat`.

2. Execute the main file: `simpre.m` . This file in turn calls the following four files:

   (a) `initcond.m` : It calculates the initial conditions.

   (b) `yform.m`: It constructs the positive- and negative-sequence Y_{BUS}.

   (c) `yzero.m`: It constructs zero-sequence Y_{BUS}

   (d) `fault.m`: It calculates different fault parameters depending upon the type of fault.

   The above files require the following data files:

   (i) `lfl.dat` : Converged loadflow results.

   (ii) `ld.dat` : Load data.

   (iii) `shunt.dat` : Shunt data.

   (iv) `gen.dat` : Generator data.

   (v) `sat.dat` : Generator saturation data.

   (vi) `nt_line.dat` : Transmission line data.

   (vii) `nt_trans.dat` : Transformer data.

   (viii) `busno.dat` : System details- number of lines, buses, transformers, etc.

   (ix) `exc_static.dat` : Single-time constant static exciter data .

   (x) `exc_ST1A.dat` : IEEE ST1A type static exciter data.

   (xi) `exc_ST2A.dat` : IEEE ST2A type static exciter data.

   (xii) `exc_AC4A.dat` : IEEE AC4A type AC exciter data.

   (xiii) `exc_AC1A.dat` : IEEE AC1A type AC exciter data.

   (xiv) `exc_DC1A.dat` : IEEE DC1A type DC commutator exciter data.

   (xv) `turb_hydro.dat` : Simplified hydro-turbine data.

   (xvi) `turb_nrst.dat` : Non-reheat type steam turbine data.

   (xvii) `turb_rhst.dat` : Reheat type steam turbine data.

   (xviii) `slip_pss.dat` : Slip signal based PSS data.

   (xix) `power_pss.dat` : Power signal based PSS data.

   (xx) `freq_pss.dat` : Bus frequency signal based PSS data

   (xxi) `delPw_pss.dat` : Delta-P-Omega type PSS data.

3. Then run `transtability.mdl` to perform the transient stability simulation.

3.1.1 Format of Data Files

In the following lines the format of each of the data file has been given using 4 machine power system data:

The format of files: `busno.dat`, `nt.dat`, `pvpq.dat`, `shunt.dat` , and `lfl.dat` has been indicated in PART-1 of the manual.

Preparation of data for running `transtability.mdl` :

Load data:

`File name: ld.dat` See PART-1 of the manual.

Generator data (2.2 model):

```
File name: gen.dat
--------------------------------------------------------------------------------
Gen.No xd  xdd   xddd Td0d Td0dd  xq   xqd  xqdd Tq0d Tq0dd  H D  xl    x0   xg
--------------------------------------------------------------------------------
  1   0.2 0.033 0.0264 8.0  0.05 0.19 0.061 0.03  0.4  0.04 54 0 0.022 0.0132 0
  2   0.2 0.033 0.0264 8.0  0.05 0.19 0.061 0.03  0.4  0.04 54 0 0.022 0.0132 0
  3   0.2 0.033 0.0264 8.0  0.05 0.19 0.061 0.03  0.4  0.04 63 0 0.022 0.0132 0
  4   0.2 0.033 0.0264 8.0  0.05 0.19 0.061 0.03  0.4  0.04 63 0 0.022 0.0132 0
--------------------------------------------------------------------------------
```

NOTE:
Armature resistance, R_a is neglected. Generators are identified by their bus numbers to which they are connected. `xg` represents neutral grounding reactance.

Generator saturation data:

```
File name: sat.dat
------------------------------------------------------------------------
      |<-- d axis saturation data -->|<-- q axis saturation data -->|
Gen.No siTd  siaT1 siaTu1 siaT2 siaTu2  siTq  siaT1 siaTu1 siaT2 siaTu2
------------------------------------------------------------------------
   1    0.8   1.2   1.7    1.3   2.3    0.45  1.0   1.5    1.2   2.25
   2    0.8   1.2   1.7    1.3   2.3    0.45  1.0   1.5    1.2   2.25
   3    0.8   1.2   1.7    1.3   2.3    0.45  1.0   1.5    1.2   2.25
   4    0.8   1.2   1.7    1.3   2.3    0.45  1.0   1.5    1.2   2.25
------------------------------------------------------------------------
```

Transmission lines data:

File name: `nt_line.dat`

Ele.No	From	To	R	X	X0	M.Ele	Xm	B	B0
1	9	10	0.022	0.22	0.66	0	0	0.330	0.2310
2	9	10	0.022	0.22	0.66	0	0	0.330	0.2310
3	9	10	0.022	0.22	0.66	0	0	0.330	0.2310
4	9	6	0.002	0.02	0.06	0	0	0.030	0.0210
5	9	6	0.002	0.02	0.06	0	0	0.030	0.0210
6	10	8	0.002	0.02	0.06	0	0	0.030	0.0210
7	10	8	0.002	0.02	0.06	0	0	0.030	0.0210
8	5	6	0.005	0.05	0.15	0	0	0.075	0.0525
9	5	6	0.005	0.05	0.15	0	0	0.075	0.0525
10	7	8	0.005	0.05	0.15	0	0	0.075	0.0525
11	7	8	0.005	0.05	0.15	0	0	0.075	0.0525

NOTE:

1. `M.Ele` - Mutual coupling element: If i^{th} element (`Ele.No` $= i$) is coupled with j^{th} element (`Ele.No` $= j$), then in i^{th} row, in `M.Ele` column, enter j. Note that one should not enter i once again in the `M.Ele` column pertaining to j^{th} row. If there is no mutual coupling enter 0.

2. `Xm` - Mutual reactance: If mutual coupling element is there, enter the mutual reactance value, else 0.

3. For transmission lines, only zero-sequence *reactance* is considered and is approximated as 3 times the positive-sequence reactance.

4. The value of zero-sequence line charging,`B0`, is taken as 70% of positive-sequence line charging, `B`.

Transmission lines data for the example explained under section 2.2.2.2 is given below. This data file is available in folder `\unsymm_faults\Examples\ex9_2_soman`.

File name: `nt_line.dat`

Ele.No	From	To	R	X	X0	M.Ele	Xm	B	B0
1	1	2	0	0.0333	0.1	0	0	0	0
2	1	3	0	0.1667	0.5	0	0	0	0
3	1	4	0	0.1667	0.5	0	0	0	0
4	2	5	0	0.0666	0.2	6	0.1	0	0
5	5	4	0	0.1000	0.3	6	0.2	0	0
6	2	3	0	0.1334	0.4	0	0	0	0

Transformers data:

File name: `nt_trans.dat`

Ele.No	From	To	R	X	X0	Tap	T/F.con	Xgds	Xssp	Xsss
1	1	5	0.001	0.012	0.0102	1.0	1	0	0	0
2	2	6	0.001	0.012	0.0102	1.0	1	0	0	0
3	3	7	0.001	0.012	0.0102	1.0	1	0	0	0
4	4	8	0.001	0.012	0.0102	1.0	1	0	0	0

NOTE:

1. `T/F.con` - Type of transformer connection. It is equal to 1 for Δ-Y type connection, 2 for Y-Δ type connection and 3 for Y-Y type connection.

2. `Xgds` - Grounding reactance of Y - winding of Δ-Y or Y-Δ type transformers.

3. `Xssp` and `Xsss` - Primary and secondary grounding reactance of Y-Y type transformers.

For data file formats for exciters, turbines and PSS, please refer to PART-1 of the manual.

3.1.2 Component Selectors:

Please refer to PART-1 of the manual.

3.1.3 Load Modeling

All the loads are modeled as constant impedance type. This is achieved by setting the power (`p1` and `r1`) and current (`p2` and `r2`) fractions for both real and reactive components of loads to zero in `load_zip_model.m` as shown below:

```
Real component of load:

  p1=0;    Please do not tamper this settings.
  p2=0;
  p3=1;

Reactive component of load:

  r1=0;    Please do not tamper this settings.
  r2=0;
  r3=1;
```

NOTE: The frequency dependency of loads is not considered.

3.1.4 A Sample Run

Consider the following case: A LLG fault is applied at time $t = T_{fault} = 0.5$ s at bus 9. This fault is cleared by tripping and reclosing the faulted conductors of line 1 without tripping the entire line. For this case, $T_{clear} = 0.7$ s and $\triangle T_{open} = 0.6$ s (LLG fault duration) such that $\triangle T_{clr} = 0.1$ s (two open-conductor fault duration) . This case is simulated by performing the following steps:

1. Prepare the data files as indicated in the PART-1 of the manual.
2. Initialize the Main and Individual Selectors in file `initcond.m`
3. Execute `simpre.m`. The statements displayed in the MATLAB Command Window and the respective inputs are shown below:

```
Choose the type of fault from the menu:
  1. LG
  2. LL
  3. LLG
  4. LLL
  5. One conductor OC
  6. Two conductor OC
  7. Sample run without any fault

Enter the type of fault: 3

Fault initiation time (seconds), Tfault: 0.5
Enter the fault duration time (seconds), Tclear: 0.7
Enter the fault impedance Zf= 0
Enter the fault bus number: 9

Open the respective conductor(s)?  y / n : y

Enter the line number= 1
Enter time duration dTopen w.r.t Tfault, such that dTopen<Tclear: 0.6

Clear the fault by  tripping line 1 ? y / n : n
```

4. Open `transtability.mdl` and start the simulation.

After the simulation stops, the following variables are available in the Command Window for plotting:

```
delta_COI   ---> Rotor angles wrt to COI reference.
Efd_out     ---> Variation of Efd.
Vbus        ---> Positive-sequence bus voltages.
PSS_out     ---> PSS output.
Tm_out      ---> Turbine output.
Te_out      ---> Electrical power output.
time        ---> Time coordinates.
```

Figure 3.2 displays the variation of rotor angles. The figure also shows the rotor angle plots when the saturation is not considered.

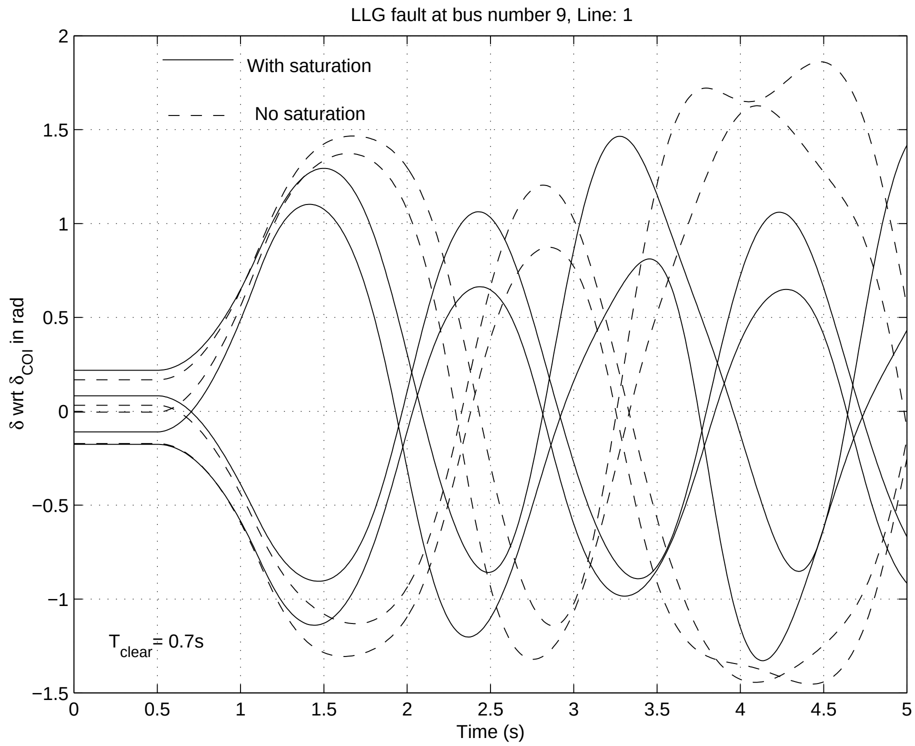

Figure 3.2: Variation of rotor angles with respect to COI reference for LLG fault (4 m/c system).

3.2 Single Machine Infinite Bus System

The single line diagram of SMIB power system is shown in Figure 3.3. The system details are given in PART-1 of the manual.

A two-open conductors fault is applied at time $t = T_{fault} = 0.5$ s on line 3. The fault is cleared after a duration of 0.1 s without tripping the line. Under this case, the following two conditions are studied:

1. The generator-transformer neutral is grounded: use `nt_trans.dat`.

2. The generator-transformer neutral is ungrounded: Make the file `nt_trans_ungn.dat` active by renaming it as `nt_trans.dat`.

After preparing the data files as explained for 4 machine systems, execute `simpre.m`. The statements displayed in the MATLAB Command Window and the respective inputs are shown below:

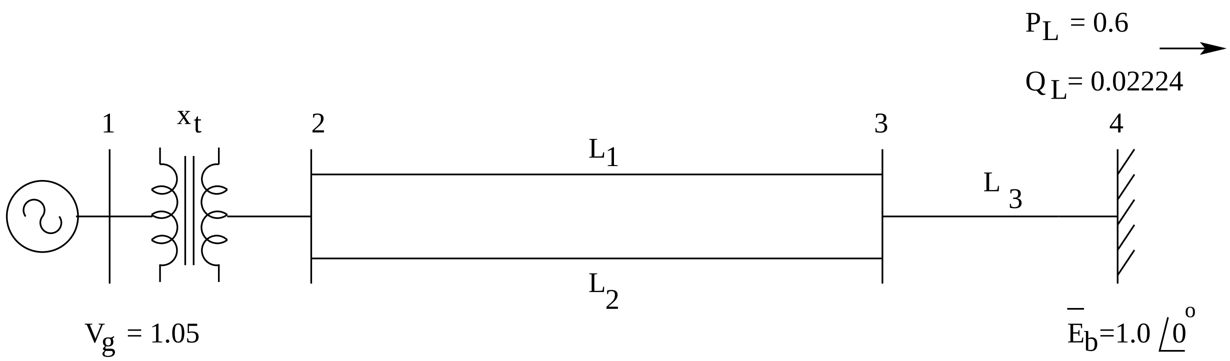

Figure 3.3: SMIB power system.

```
Choose the type of fault from the menu:
  1. LG
  2. LL
  3. LLG
  4. LLL
  5. One conductor OC
  6. Two conductor OC
  7. Sample run without any fault

Enter the type of fault: 6

Fault initiation time (seconds), Tfault: 0.5
Enter the fault duration time (seconds), Tclear: 0.1
Open conductor fault on line number: 3
Clear the fault by  tripping line 3 ? y / n : n
```

Figure 3.4 shows that when the transformer neutral is ungrounded, the power supplied to the load reduces to zero during the fault. The figure also displays the plot of power transfer when the transformer neutral is solidly grounded.

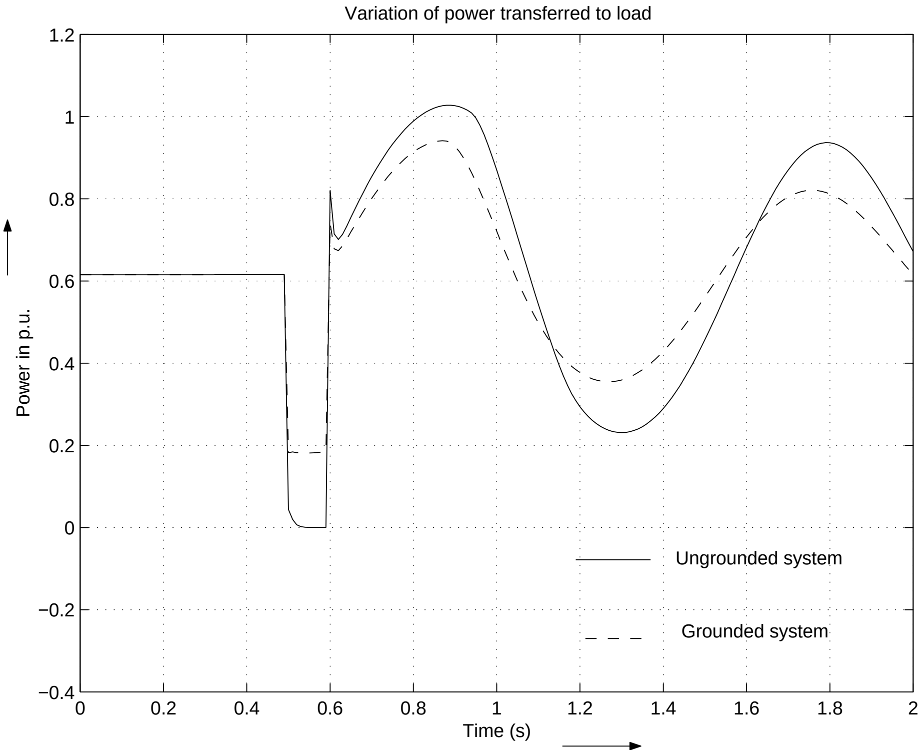

Figure 3.4: Variation of electrical power output of the generator (SMIB system).

3.3 50 Generator, 145-Bus IEEE Transient Stability Test System

The data for a 50 machine IEEE system has been obtained following the web link [11]. This system has 145 buses, 401 lines, 52 transformers, 64 loads and 97 shunts. Out of 50 generators, 44 generators are with classical model and the rest 6 generators are with 1.1 model. These 6 generators are provided with IEEE type AC4A exciters.

A LG fault is applied at bus 7 at $t = T_{fault} = 0.5$ s. The faulted conductor of line 8 is tripped at $t = T_{open}$ such that $\triangle T_{open} = 0.4$ s. The line is tripped with $T_{clear} = 0.6$ s. The tripped line is reclosed after some time duration $\triangle T_{close} = 0.1$ s. In this case, the saturation on all the machines is considered.

After preparing the data files as explained before, execute `simpre.m`. The statements displayed in the MATLAB Command Window and the respective inputs are shown below:

```
Choose the type of fault from the menu:
  1. LG
  2. LL
  3. LLG
  4. LLL
```

```
  5. One conductor OC
  6. Two conductor OC
  7. Sample run without any fault

Enter the type of fault: 1

Fault initiation time (seconds), Tfault: 0.5
Enter the fault duration time (seconds), Tclear: 0.6
Enter the fault impedance Zf= 0
Enter the fault bus number: 7

Open the respective conductor(s)?  y / n : y

Enter the line number= 8
Enter time duration dTopen w.r.t Tfault, such that dTopen<Tclear: 0.4

Clear the fault by  tripping line 8 ? y / n : y

Reclose the tripped Line ?  y / n : y

Enter time duration dTclose such that, Tclose = Tfault + Tclear + dTclose: 0.1
```

Figure 3.5 displays the variation of rotor angles for the above fault condition.

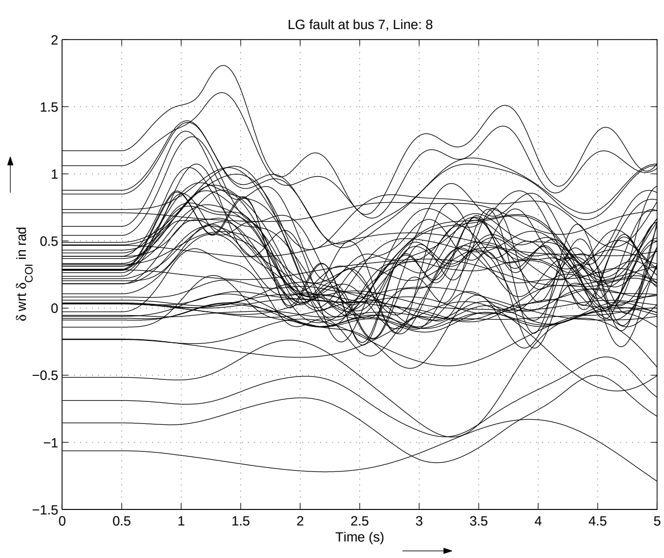

Figure 3.5: The plot of rotor angles for 50 m/c system for LG fault.

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