INTERNATIONAL BURCH UNIVERSITY

FACULTY OF ENGINEERING AND NATURAL SCIENCES

ELECTRICAL AND ELECTRONICS ENGINEERING

POWER SYSTEM ANALYSIS

PROJECT

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1. INTRODUCTION

This project involves calculating the power flow and fault currents and voltages of a power system. It consists of two Generators, two Transformers, six Transmission Lines, eight Busses and six loads. The power flow is calculated using MATLAB's Power System Analysis Toolbox (PSAT). The values are obtained by using the Newton-Rhapson Method. Following this, a fault analysis is performed, with the Double Line-To-Ground Fault and the Three-Phase Fault.

Normal working conditions of a system can often be disturbed. This happens when extremely high currents flow through a path, because of a partial or complete insulation failure at certain points in the system. If a complete insulation failure happens, then it is called a short circuit or fault. It occurs when one or more conductors, which are energized, make a contact with ground component or other conductors. The consequence are extremely high currents flowing through the system towards the fault point. The temperature starts to rise, which can cause the equipment to burn out.

Because they carry large amounts of electricity at very high voltages, transmission lines are not covered by an insulating layer. The air around them provides insulation. However, this increases probability of faults occurring, since nothing can come close to the lines. Weather conditions, animals, humans and electric nature of the equipment are just a few examples of what can cause a fault in a power system.

Faults can be permanent or temporary, with permanent faults causing equipment damage and sometimes resulting in explosions. However, most faults on overhead transmission lines are actually temporary (transient period), allowing for restoration of services by isolating and quickly closing the faulty line segments. Fault analysis, known as short-circuit analysis, determines the maximum and minimum fault currents, alongside voltages, at different points of a system. This is performed for different types of faults. The analysis is performed so that the equipment can be properly designed. It has to withstand the currents of this transient period, where the fault occurs.

1.1. SYMMETRICAL COMPONENTS

When dealing with a single-phase three-wire electrical setup, it is considered unbalanced if the neutral current is not zero. This typically occurs when the loads connected between the line and neutral are not the same. This imbalance leads to uneven currents and voltages, resulting in a nonzero current in the neutral line. The necessary calculations can be done by using the method of symmetrical components. Any unbalanced three-phase system of phasors can be shown as three balanced systems of phasors: (1) positive-sequence system, (2) negative-sequence system, and (3) zero-sequence system, as shown in Figure 1.

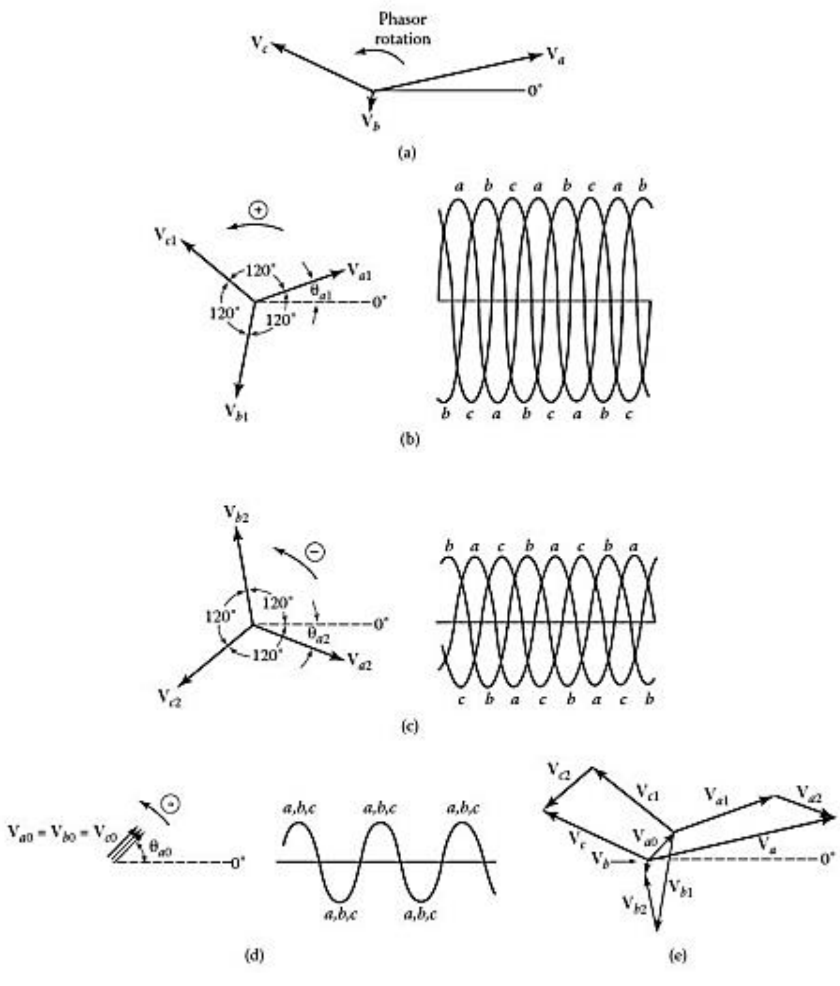


FIGURE 1. Analysis and combination of set of three unbalanced voltage phasors: (a) original system of unbalanced phasors; (b) positive-sequence components; (c) negative-sequence components; (d) zero-sequence components; (e) representation of phasors for obtaining original unbalanced phasors.

The positive-sequence system is represented by a balanced system of phasors having the same phase sequence as the original unbalanced system. The phasors of the positive-sequence system are equal in magnitude but are moved from each other by 120°.

The negative-sequence system is represented by a balanced system of phasors having the opposite phase sequence from the original system. The phasors of the negative-sequence system are equal in magnitude and moved from each other by 120°.

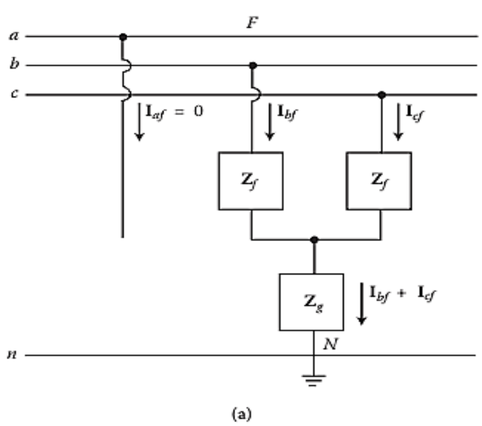
The zero-sequence system is represented by three single phasors equal in magnitude and angle. Because of the use symmetrical components theory, there is a need for a unit phasor (or operator) that will rotate another phasor by 120° in the counterclockwise direction but leave its magnitude unchanged. Such an operator is a complex number of unit magnitude with an angle of 120° and is defined by:

$$a = 1\angle 120°$$

1.2. DOUBLE LINE-TO-GROUND FAULT

A double line-to-ground fault (DLG) is a serious event in a three-phase symmetrical system that can lead to significant asymmetry. It is an unbalanced (unsymmetrical) fault type, alongside single line-to ground (SLG) and line-to-line (L-L) faults. If not addressed quickly, DLG might grow into a three-phase fault.

In Figure 2(a), there is the general representation of a double line-to-ground fault, denoted as F, with associated impedances Z_f and the impedance from line to ground, Z_g. Figure 2(b) illustrates the sequences network diagram. For the simplicity, it is assumed that phase b and phase c are the faulted phases.



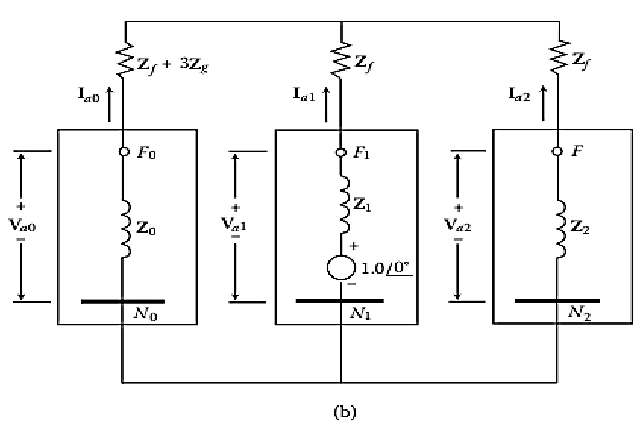


FIGURE 2. General representation of a Double Line-to-Ground Fault (a), Sequence Network Diagram of a Double Line-to-Ground Fault (b)

From observing the Figure above, it can be concluded that:

$$I_{af} = 0$$

$$V_{bf} = (Z_f + Z_g)I_{bf} + Z_g I_{cf}$$

$$V_{cf} = (Z_f + Z_g)I_{cf} + Z_g I_{bf}$$

When it comes to the positive sequence currents, they are obtained as:

$$I_{a1} = \frac{1.0\angle 0°}{(Z_1 + Z_f) + \frac{(Z_2 + Z_f)(Z_0 + Z_f + 3Z_g)}{(Z_2 + Z_f) + (Z_0 + Z_f + 3Z_g)}}$$

$$I_{a2} = -[\frac{(Z_0 + Z_f + 3Z_g)}{(Z_2 + Z_f) + (Z_0 + Z_f + 3Z_g)}]I_{a1}$$

$$I_{a0} = -[\frac{(Z_2 + Z_f)}{(Z_2 + Z_f) + (Z_0 + Z_f + 3Z_g)}]I_{a1}$$

Another way to obtain this is:

$$I_{af} = 0 = I_{a0} + I_{a1} + I_{a2} \qquad I_{a0} = -(I_{a1} + I_{a2})$$

If the two impedances, Z_f and Z_g, are both zero, then the positive-, negative-, and zero-sequences are expressed from:

$$I_{a1} = \frac{1.0\angle 0°}{(Z_1) + \frac{(Z_2)(Z_0)}{(Z_2 + Z_0)}} \qquad I_{a2} = -[\frac{(Z_0)}{(Z_2 + Z_0)}]I_{a1} \qquad I_{a0} = -[\frac{(Z_2)}{(Z_2 + Z_0)}]I_{a1}$$

The fault currents for each phase are:

$$I_{af} = 0 \qquad I_{bf} = I_{a0} + a^2 I_{a1} + aI_{a2} \qquad I_{cf} = I_{a0} + aI_{a1} + a^2 I_{a2}$$

The total fault current, flowing into the neutral, can be expressed as:

$$I_n = 3I_{a0} = I_{bf} + I_{cf}$$

Using the obtained information, phase voltages are obtained in the following form:

$$V_{af} = V_{a0} + V_{a1} + V_{a2} = 3V_{a1} \qquad V_{bf} = V_{cf} = 0$$

In the end, the line-to-line voltages have this formulation:

$$V_{abf} = V_{af} - V_{bf} = V_{af} \qquad V_{bcf} = V_{bf} - V_{cf} = 0 \qquad V_{caf} = V_{cf} - V_{af} = -V_{af}$$

1.3. THREE-PHASE FAULTS

A three-phase (3φ) fault is considered a balanced or symmetrical fault, meaning it can be analyzed using symmetrical components. Although rare, it is the most severe fault. Due to the balanced nature of the network, it is addressed on a per-phase basis. The other two phases carry identical currents, although with a phase shift. In Figure 3(a), two impedances, Z_f and Z_g are present.

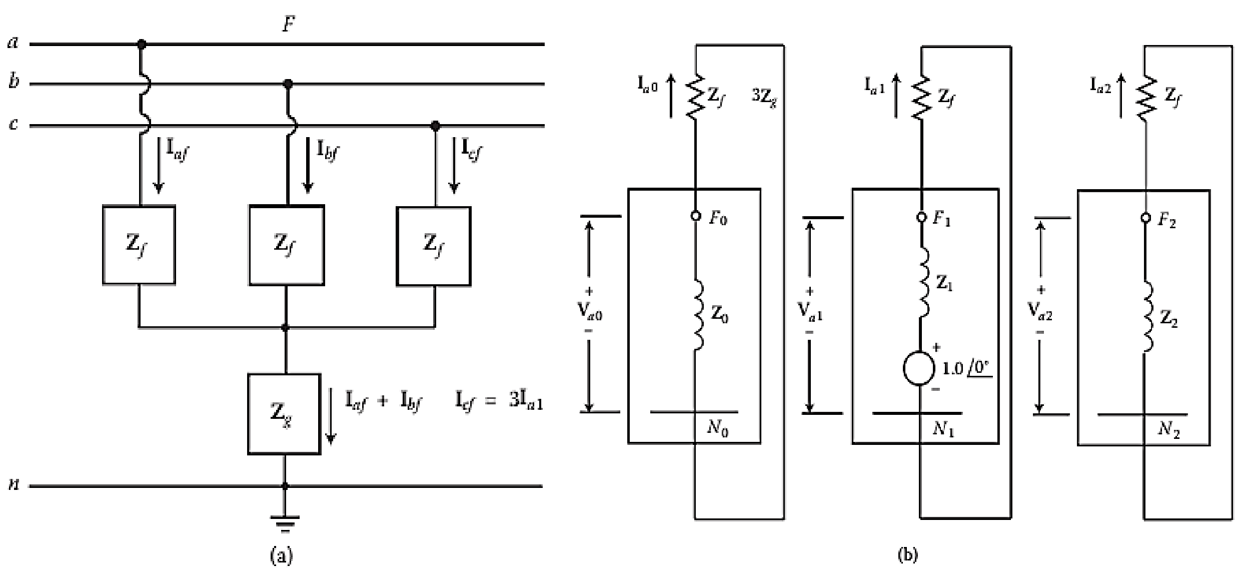


FIGURE 3. Three-phase fault: (a) general representation; (b) interconnection of sequence networks

Figure 3(b) represents the lack of interconnection of resulting sequence networks. These networks are short-circuited over their own fault impedances and thus isolated from each other. Only the positive sequence network has an internal voltage source. This means that the positive-, negative-, and zero sequence currents can be expressed as:

$$I_{a0} = 0 \qquad I_{a2} = 0 \qquad I_{a1} = \frac{1.0\angle 0°}{Z_{1+}Z_f}$$, and if $Z_f = 0$, $$I_{a1} = \frac{1.0\angle 0°}{Z_1}$$

Using the above equations, the following matrix is created:

$$\begin{bmatrix} I_{af} \\ I_{bf} \\ I_{cf} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 0 \\ I_{a1} \\ 0 \end{bmatrix}$$

From this, it is obtained that:

$$I_{af} = I_{a1} = \frac{1.0\angle 0°}{Z_{1+}Z_f} \qquad I_{bf} = a^2 I_{a1} = \frac{1.0\angle 240°}{Z_{1+}Z_f} \qquad I_{cf} = a\, I_{a1} = \frac{1.0\angle 120°}{Z_{1+}Z_f}$$

Because the sequence networks are short-circuited over their own fault impedances:

$$V_{a0} = 0 \qquad V_{a1} = Z_f I_{a1} \qquad V_{a2} = 0$$

Using these equations, the following matrix is created:

$$\begin{bmatrix} V_{af} \\ V_{bf} \\ V_{cf} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 0 \\ V_{a1} \\ 0 \end{bmatrix}$$

From here:

$$V_{af} = V_{a1} = Z_f I_{a1} \qquad V_{bf} = a^2 V_{a1} = Z_f I_{a1}\angle 240° \qquad V_{cf} = aV_{a1} = Z_f I_{a1}\angle 120°$$

The line-to-line voltages are:

$$V_{ab} = V_{af} - V_{bf} = V_{a1}(1 - a^2) = \sqrt{3} Z_f I_{a1}\angle 30°$$

$$V_{bc} = V_{bf} - V_{cf} = V_{a1}(a^2 - a) = \sqrt{3}Z_f I_{a1}\angle -90°$$

$$V_{ca} = V_{cf} - V_{af} = V_{a1}(a - 1) = \sqrt{3}Z_f I_{a1}\angle 150°$$

In case that $Z_f = 0$, I_{af}, I_{bf} and I_{cf} lose that component in their equations. On the other hand, V_{af}, V_{bf} and V_{cf} will be zero. Of course, voltages V_{a0}, V_{a1} and V_{a2} are zero as well.

The reactance of the synchronous generator under short-circuit conditions is a time-varying quantity. For the network analysis, three reactances are defined. If a circuit breaker is set up, the subtransient reactance for generators, and transient reactance for the synchronous motors are used.

The subtransient reactance X_d'' is during the first cycle after the fault occurs (0.05-0.1s). Transient reactance X_d' determines the fault current after a few cycles. In about 0.2-2s, it increases to the synchronous reactance X_d. This reactance determines the fault current after steady state conditions are reached. Three different reactances are used, since the flux across the air gap of the machine is much greater at the instant the fault occurs than it is a few cycles later.

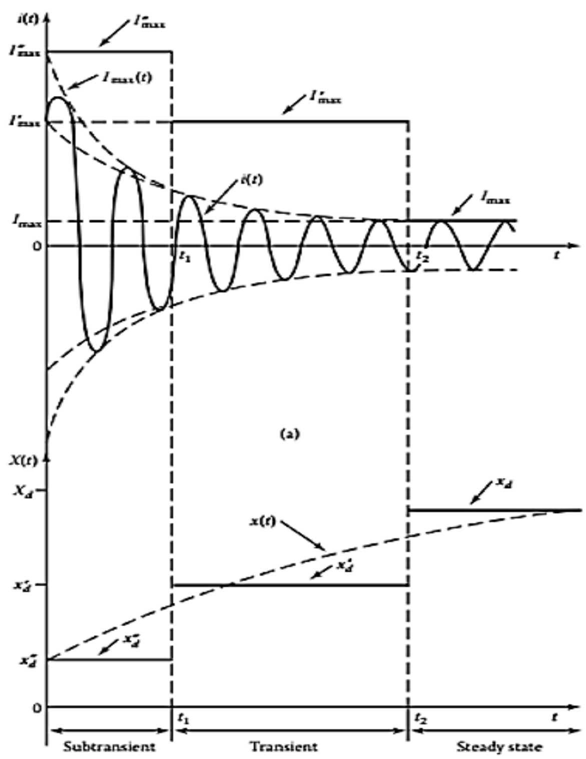


FIGURE 4. The Graphical Representation of Three Reactances

The subtransient (initial) reactance X_d'' is the leakage reactance of the stator and rotor windings of the generator, as well as the damper windings. The larger, transient reactance X_d' is the leakage reactance of the stator and excitation generator windings. Finally, the synchronous reactance X_d is the total reactance of the armature winding. That involves the leakage reactance of the stator and the armature reactance of the generator. This reactance is much larger than transient reactance X_d'.

Additionally, in the quadrature axis, the generator has reactances. These are the reactances due to the flux path between the field poles and are designated as X_q'', X_q', and X_q. In a machine with cylindrical rotor, values of X_d and X_q are practically equal. Because of this, the synchronous reactance X_s is only called, while X_d and X_q do not have to be differentiated.

Using the maximum voltage of the generator, the three reactances are expressed as:

$$X_d'' = \frac{E_{max}}{I_{max}''} \qquad X_d' = \frac{E_{max}}{I_{max}'} \qquad X_d = \frac{E_{max}}{I_{max}}$$

In Figure, there is a balanced three-phase fault between the points F and N:

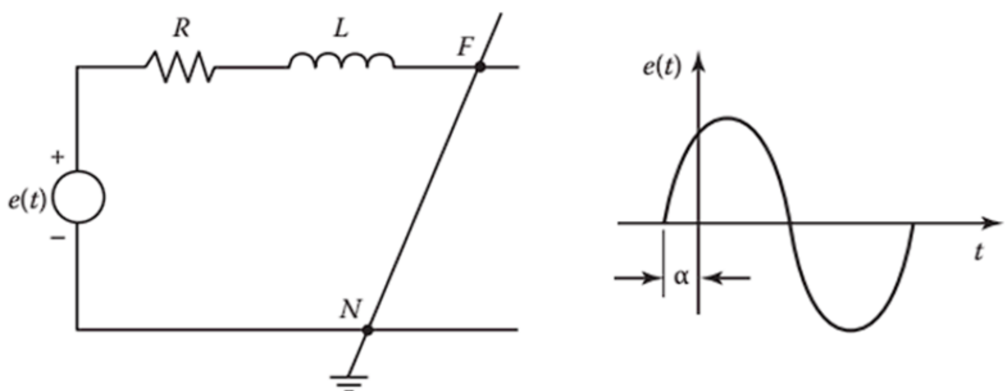


FIGURE 5. Balanced Three Phase Fault at No Load (Left), Generator Voltage (Right)

If the generator voltage is e(t) = V_m sin(ωt + α) and the fault occurs at t=0, transient current i(t) is:

$$i(t) = \frac{V_m}{Z}\left[\sin(\omega t + \alpha - \theta) - \sin(\alpha - \theta)\, e^{\frac{-Rt}{L}}\right]$$

$$Z = (R^2 + \omega^2 L^2)^{\frac{1}{2}} \qquad \theta = tan^{-1}\left(\frac{\omega L}{R}\right)$$

If the fault occurs at t = 0 when the angle α – θ = – 90°, the value of the transient current becomes twice the steady-state maximum value and can be expressed as:

$$i(t) = \frac{V_m}{2}\left[-\cos(\omega t) + e^{\frac{-Rt}{L}}\right] \qquad \tan(\alpha) = -\frac{R}{\omega L}$$

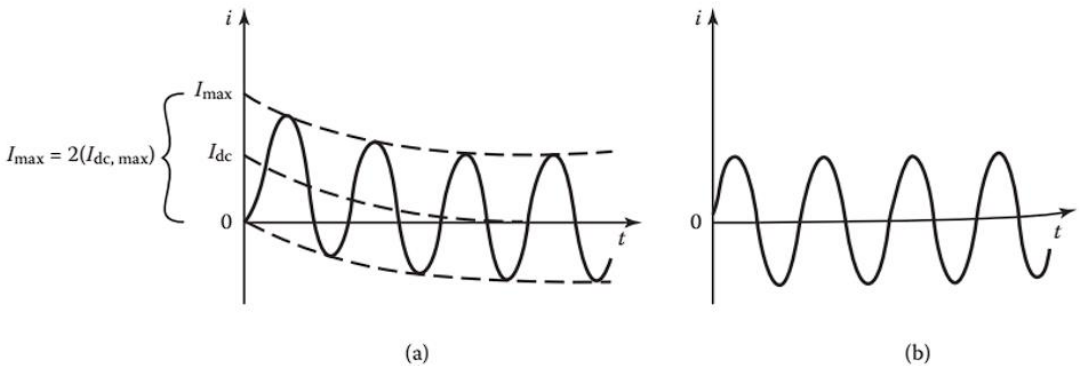


FIGURE 6. Transient Current Waveform (a), Transient Current if α=0, at t=0 (b)

As shown in Figure 6(b), if α=0, at t=0, the DC offset does not exist, and the transient current is expressed as:

$$i(t) = \frac{V_m}{Z}\sin(\omega t)$$

A fault is caused by an addition of impedance at the place of fault. If fault impedance (Z_f) is zero, it is categorized as a bolted or solid fault. This network can be solved using Thevenin's equivalent.

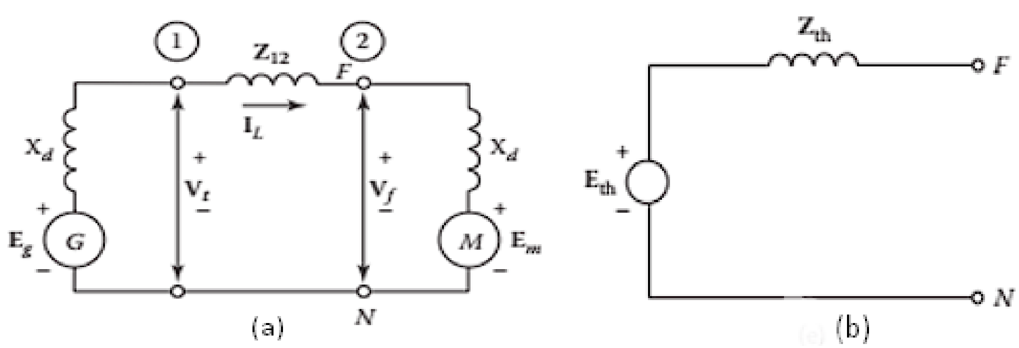


FIGURE 7. Balanced Three-Phase Fault at Full Load (a), Thevenin Equivalent of this Circuit (b)

In Figure 7(a), the load current (I_L) flows before the fault. The voltage at the fault point F is V_F. In Figure 7(b), the Thevenin voltage, E_{th}, is equivalent of V_f voltage before the fault, in Figure 7(a).

The Thevenin impedance and the subtransient fault current, at fault point F, are:

$$Z_{th} = \frac{(X''_d + X_{12})X''_d}{(X''_d + X_{12}) + X''_d} \qquad I''_f = \frac{E_{th}}{Z_{th}} = \frac{V_f}{Z_{th}}$$

1.4. POWER FLOW

Power flow (or load flow) is the solution for the balanced three-phase steady-state operating conditions of a power system. The data from power flow studies is used for the studies of normal operating mode, loss analysis, security assessment, and optimal dispatching and stability. The basic assumption is that the given power system is a balanced three-phase system operating in steady state with a constant 50/60-Hz frequency.

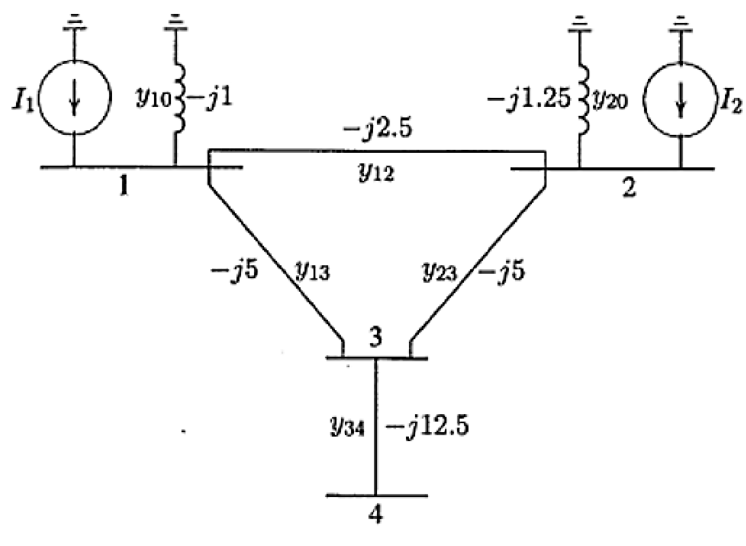


FIGURE 8. The Network for Bus Admittance Matrix

The network in Figure is represented using the bus admittance matrix (Y_{bus}) or the bus impedance matrix (Z_{bus}). Node-voltage equations are used, and the admittance is obtained from this formula:

$$y_{ij} = \frac{1}{z_{ij}} = \frac{1}{r_{ij} + jx_{ij}}$$

According to Figure, the Kirchhoff Current Law (KCL) is used at each of the four nodes:

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

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

$$0 = y_{23(}V_3 - V_2) + y_{13}(V_3 - V_1) + y_{34}(V_3 - V_4)$$

$$0 = y_{34(}V_4 - V_3)$$

The admittances are expressed as:

$$Y_{11} = y_{10} + y_{12} + y_{13} \qquad Y_{22} = y_{20} + y_{12} + y_{23} \qquad Y_{33} = y_{13} + y_{23} + y_{34}$$

$$Y_{44} = y_{34} \qquad Y_{12} = Y_{21} = -\,y_{12} \qquad Y_{13} = Y_{31} = -\,y_{13}$$

$$Y_{23} = Y_{32} = -\,y_{23} \qquad Y_{34} = Y_{43} = -\,y_{34}$$

By obtaining this, the current equations will now look like:

$$I_1 = Y_{11}V_1 + Y_{12}V_2 + Y_{13}V_3 + Y_{14}V_4 \qquad I_2 = Y_{21}V_1 + Y_{22}V_2 + Y_{23}V_3 + Y_{24}V_4$$

$$I_3 = Y_{31}V_1 + Y_{32}V_2 + Y_{33}V_3 + Y_{34}V_4 \qquad I_4 = Y_{41}V_1 + Y_{42}V_2 + Y_{43}V_3 + Y_{44}V_4$$

It is possible to define the bus power in terms of generated power, load power, and transmitted power at a given bus. The bus power of the ith bus of an n bus power system is expressed as:

$$S_i = P_i + jQ_i = (P_{Gi} - P_{Li} - P_{Ti}) + j(Q_{Gi} - Q_{Li} - Q_{Ti})$$

where:

S_i = three-phase complex bus power at ith bus

P_i = three-phase real bus power at ith bus

Q_i = three-phase reactive bus power at ith bus

P_{Gi} = three-phase real generated power flowing into ith bus

P_{Li} = three-phase real load power flowing out of ith bus

P_{Ti} = three-phase real transmitted power flowing out of ith bus

Q_{Gi} = three-phase reactive generated power flowing into ith bus

Q_{Li} = three-phase reactive load power flowing out of ith bus

Q_{Ti} = three-phase reactive transmitted power flowing out of ith bus

The system busses are categorized into three different types:

Slack Busses – one bus, taken as reference, where the magnitude and phase angle of the voltage are specified. This bus makes up for the difference between loads and generated power, caused by the losses in the network.

Load Busses – the busses where the active and reactive powers are specified. These P-Q busses have their voltage phase angle and magnitude unknown.

Regulated Busses (Generator Busses) – at these P-V busses, the real power and voltage magnitude are always specified. The voltages phase angles and reactive power have to be determined.

Due to the physical characteristics of generation and load, each bus has its conditions defined in terms of active and reactive power, rather than by bus current. Thus, the complex power, flowing into the ith bus is:

$V_i I_i^* = P_i + jQ_i$, with the bus current being: $I_i = \frac{P_i - Q_i}{V_i^*}$

When performing power flow analysis, it is crucial to know that the lagging reactive power is a positive reactive power due to the inductive current and the leading reactive power is a negative power due to the capacitive current. Additionally, the positive bus current is in the direction that flows toward the bus.

Since the generator current flows towards the bus and the load current flows away from the bus, the generator bus power sign is positive and for the load bus it is negative.

In summary, the power flow equations are summarized for a mathematical model:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \qquad I_i = \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j$$

$$P_i - jQ_i = V_i^* I_i \qquad P_i - jQ_i = |V_i| \angle - \delta_i \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j$$

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

1.4.1. Newton-Raphson Method

Initially, all power flow calculations were made by hand. However, eventually the iterative methods were developed. They were based on the Gauss–Seidel method. As the size of the networks grew, the Newton–Raphson method was developed. Newton-Raphson method is based on solving quadric equations of the network. It needs a larger time per iteration, but only a few iterations. It is also largely independent of the network size. The approximation of the initial state and use of Taylor series expansion are the basis of this method.

This method first finds the tangent line of the function at the initial guess point. Then, it is observed where the tangent line intersects the x-axis. This point is taken as the value for the new guess, known as iteration. It is performed until the difference from previous iteration becomes negligible.

Firstly, it is assumed that a single-variable equation is given as:

$$f(x) = 0$$

The given function can be expanded by Taylor series about a point x_0 as:

$$f(x) = f(x_0) + \frac{1}{1!}\frac{df(x_0)}{dx}(x - x_0) + \frac{1}{2!}\frac{df^2(x_0)}{dx^2}(x - x_0)^2 + \cdots + \frac{1}{n!}\frac{df^n(x_0)}{dx^n}(x - x_0)^n = 0$$

If it is assumed that convergence happened after the first two terms, everything after first derivative is dropped:

$$f(x) = f(x_0) + \frac{df(x_0)}{dx}(x - x_0) = 0 \qquad\qquad x_1 = x_0 - \frac{f(x_0)}{\frac{df(x_0)}{dx}}$$

For a better understanding, this expression is formulated as:

$x^{(1)} = x^{(0)} - \frac{f(x^{(0)})}{\frac{df(x^{(0)})}{dx}}$, from which a recursion formula is: $x^{(k+1)} = x^{(k)} - \frac{f(x^{(k)})}{\frac{df(x^{(k)})}{dx}}$

$x^{(0)}$ = initial approximation ; $x^{(1)}$ = first approximation

In matrix notation, if the given function is expanded by Taylor series, and terms beyond the first derivative are dropped:

$$F(x) = F\left(x^{(x)}\right) + \left[J\left(x^{(0)}\right)\right]\left[x - x^{(0)}\right] = 0$$

The coefficient matrix is called the Jacobian matrix and is expressed in the following way:

$$[J(x)] \triangleq \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots & \frac{\partial f_2}{\partial x_n} \\ \cdots & \cdots & & \cdots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \cdots & \frac{\partial f_n}{\partial x_n} \end{bmatrix}$$

1.4.2. Application of Newton Raphson Method

This fast-converging method is not sensitive to any factors that could disturb the convergence. Rectangular or polar coordinates can be used for the bus voltages. Bus admittance matrix is used. Since the magnitude and phase angle of the slack bus are known, it is not in the iteration process.

The power at bus i in a system with n-busses is formulated as:

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

The following equations are formulated, where I_i is the current flowing into bus i:

$$V_i \triangleq e_i + jf_i \qquad V_{ij} \triangleq G_{ij} - jB_{ij} \qquad I_i = \sum_{j=1}^{n} Y_{ij} V_{ij} \triangleq c_i + jd_i$$

Thus, Newton-Raphson method is expressed in rectangular coordinates:

$$P_i - jQ_i = (e_i - jf_i) \sum_{j=1}^{n} (G_{ij} - jB_{ij})(e_j + jf_j)$$

$$P_i = \sum_{j=1}^{n} [\left(e_i G_{ij} e_j + jB_{ij} f_j\right) + f_i\left(G_{ij} f_j - B_{ij} e_j\right)]$$

$$Q_i = \sum_{j=1}^{n} [\left(f_i G_{ij} e_j + jB_{ij} f_j\right) - e_i\left(G_{ij} f_j - B_{ij} e_j\right)]$$

For each PV generator bus, the bus voltage magnitude is obtained from estimated e and f values:

$$|V|_i^2 = e_i^2 + f_i^2 \qquad \Delta P_i^{(k)} = P_{i,spec} - P_{i,calc}^{(k)} \qquad \Delta Q_i^{(k)} = Q_{i,spec} - Q_{i,calc}^{(k)}$$

If Newton-Raphson method is applied to load flow equations in polar coordinates:

$$V_i \triangleq |V_i| \angle \delta_i \qquad V_i \triangleq |V_i| \angle - \theta_{ij}$$

$$\frac{\partial P_i}{\partial \delta_j} = \sum_{j=1}^{n} |V_i| \left| |V_j| |Y_{ij}| \right| \sin\left(\theta_{ij} + \delta_i - \delta_j\right), \ i \neq j \qquad \frac{\partial P_i}{\partial \delta_j} = |V|_i^2 |Y_{ii}| \sin \theta_{ii} - Q_i, \ i = j$$

$$\frac{\partial P_i}{\partial |V_i|} = \sum_{j=1}^{n} |V_j| \left| Y_{ij} \right| \cos\left(\theta_{ij} + \delta_i - \delta_j\right) + |V_i| |Y_{ii}| cos\theta_{ii}, \quad i \neq j$$

$$\frac{\partial P_i}{\partial |V_i|} = \frac{P_i}{|V_i|} + |V_i| |Y_{ii}| cos\theta_{ii}, \quad i = j$$

The reactive power is formulated as:

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{j=1}^{n} |V_j||Y_{ij}| \cos(\theta_{ij} + \delta_i - \delta_j) + |V_i||Y_{ii}| cos\theta_{ii} , \qquad i \neq j$$

$$\frac{\partial Q_i}{\partial \delta_i} = -|V|_i^2|Y_{ii}| \sin\theta_{ii} + P_i , \qquad i = j$$

$$\frac{\partial Q_i}{\partial |V_i|} = |V_i||Y_{ii}| cos\theta_{ii} + \sum_{j=1}^{n} |V_j||Y_{ij}| \cos(\theta_{ij} + \delta_i - \delta_j) , \qquad i \neq j$$

$$\frac{\partial P_i}{\partial |V_i|} = |V_i||Y_{ii}| sin\theta_{ii} + \frac{Q_i}{|V_i|} , \qquad i = j$$

1.5. SYSTEM DESCRIPTION

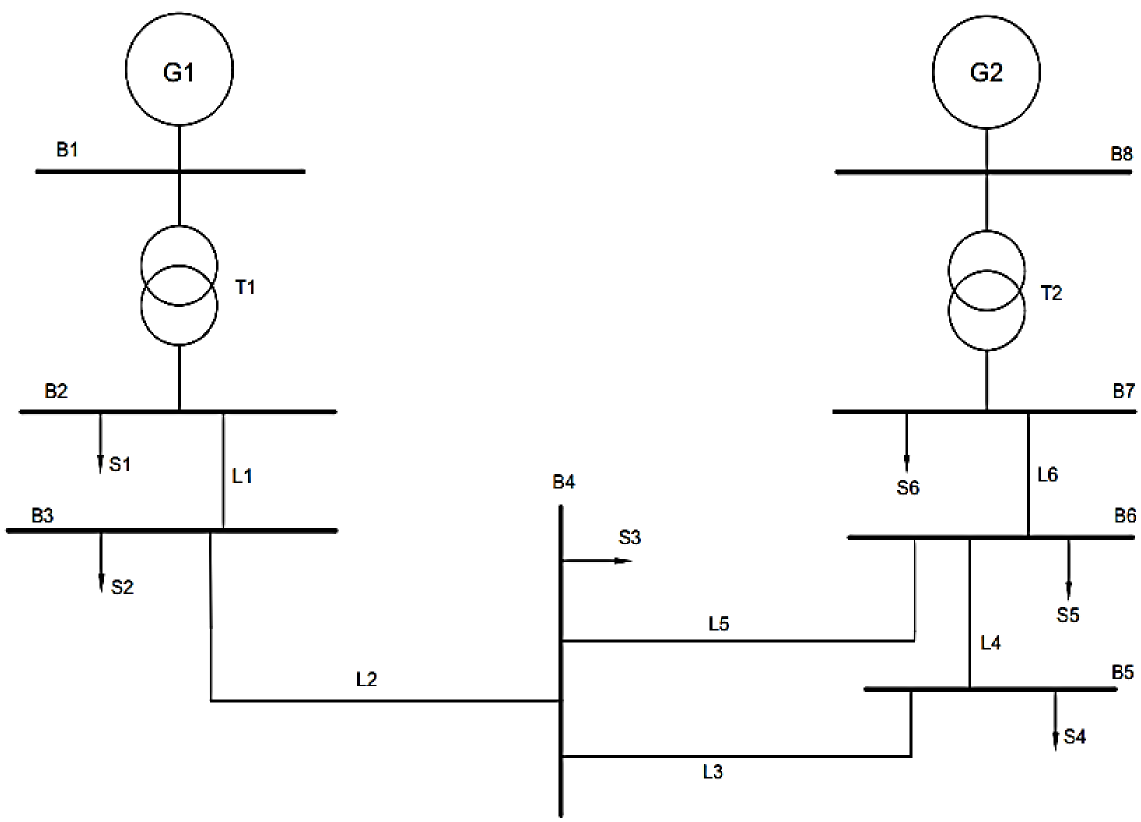


FIGURE 9. The System Model

GENERATOR INFORMATION	TRANSMISSION LINE RATINGS
G1: 100 MVA, 13.8 kV, X'' = 0.12 pu, X_2 = 0.14 pu, X_0 = 0.05 pu	$Z_1 = (0.08 + j\ 0.5)\ \Omega$/km, $Z_0 = (0.2 + j\ 1.5)\ \Omega$/km $Y_1 = 3.3(10)^{-6}$ S/km
G2: 200 MVA, 15.0 kV, X'' = 0.12 pu, X_2 = 0.14 pu, X_0 = 0.05 pu	L_1 = 15 km, L_2 = 35 km, L_3 = 40 km, L_4 =15 km, L_5 = 50 km, L_6 = 15 km
Generator neutrals are solidly grounded.	**POWER FLOW DATA**
TRANSFORMER INFORMATION	Bus 1: Slack Bus
T1: 100 MVA, 13.8-230 kV, Δ-Y, X = 0.1 pu	Bus 2, 3, 4, 5, 6, 7: Load Busses
T2: 200 MVA, 15-230 kV, Δ-Y, X = 0.1 pu	Bus 8: Generator (PV) Bus; V = 15 kV
Transformer neutrals are solidly grounded.	P = 180 MW; -87 MVAR < Q < 87 MVAR
SYSTEM BASE QUANTITIES	**LOAD DATA**
S_{base} = 100 MVA, V_{base} = 230 kV	Load = 120 MW + j 40 MVAR

TABLE 1. System Data

The system consists of two Generators, two Transformers, six Transmission Lines, eight Busses and six loads. BUS 1 is the Slack Bus, while BUS 8 is the PV Bus. The system base power is 100 MVA and the base voltage is 230 kV. BUS 2, BUS 3, BUS 4, BUS 5, BUS 6 and BUS 7 are load busses. All loads have the complex power set at 120 MW + j 40 MVAR.

Generators have different nominal power and voltage values. Generator 1 has a nominal power of 100 MVA and a nominal voltage of 13.8 kV. Generator 2 has a nominal power of 200 MVA and a nominal voltage of 15 kV. The three reactances have the same values for both generators. They are X'' = 0.12 pu, X_2 = 0.14 pu and X_0 = 0.05 pu.

Transformer 1 has a nominal power of 100 MVA with a primary side voltage of 13.8 kV. Transformer 2 has a nominal power of 200 MVA with a primary side voltage of 15 kV. Transformer 1 has a secondary side voltage of 230 kV and a reactance of X = 0.1 pu, while Transformer 2 has a secondary side voltage of 230 kV and a reactance of X = 0.1 pu.

Transmission lines differ in length. Line 1 is 15 km long, Line 2 is 35 km, while Line 3 is 40 km. Line 4 is 40 km long, Line 5 is 50 km, while Line 6 is set at 15 km.

2. PROCEDURES

In order to analyze the power flow and the effect of double line-to-ground and three-phase faults on the system, the given system was modelled in MATLAB using Simulink and PSAT (Power System Analysis Toolbox). The Simulink model allows us to investigate the effects of these faults on BUS 4, on the rest of the system. In order to calculate a precise power flow of the system, the PSA Toolbox is used.

2.1. SIMULINK MODEL

The main elements, used to model the system in MATLAB Simulink, are shown in Figure 10. The model consists of two generators, two transformers, six pi-section lines, nine busses and six loads.

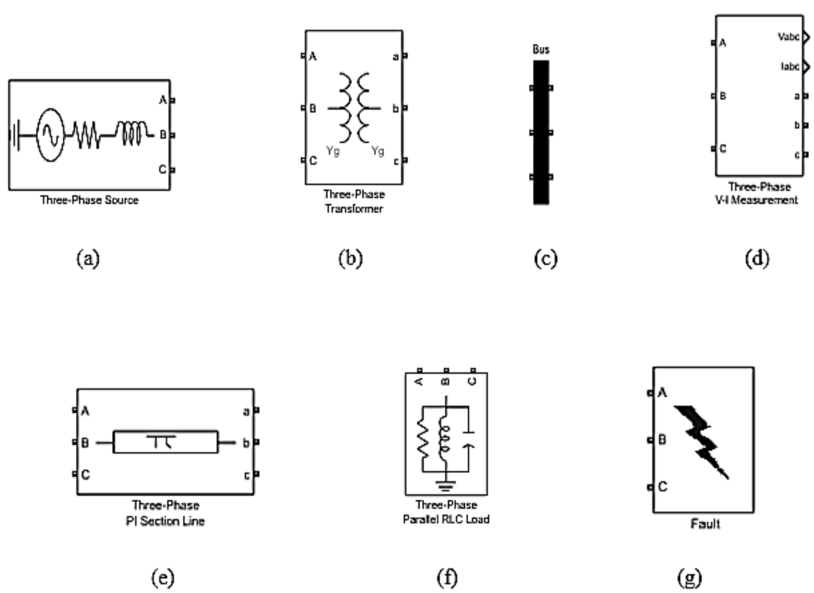


FIGURE 10. Elements used in Simulink Model: (a) Three-Phase Source; (b) Transformer; (c) Bus; (d) Three-Phase V-I Measurement; (e) Three-Phase Pi Section Line; (f)Three-Phase Parallel RLC Load; (g) Fault

Additionally, in Simulink, BUS 4 and BUS 6 required more than three ports on one of its sides. Because of this, a subsystem is created using two Three-Phase V-I Measurement blocks. The subsystem is the same for both busses.

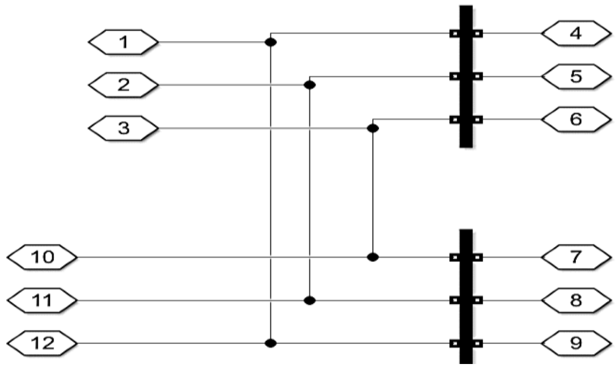


FIGURE 11. The Subsystem used for creating BUS 4 and BUS 6

Since the faults occur on BUS 4, the voltage and current are measured at the fault point. The measurements are also performed at the other side of BUS 4, before Line 3. However, fault effects on the nearby busses are analyzed as well. Thus, the voltages and currents are measured.

After connecting all the elements, the final Simulink model looks as shown in Figure 12, below:

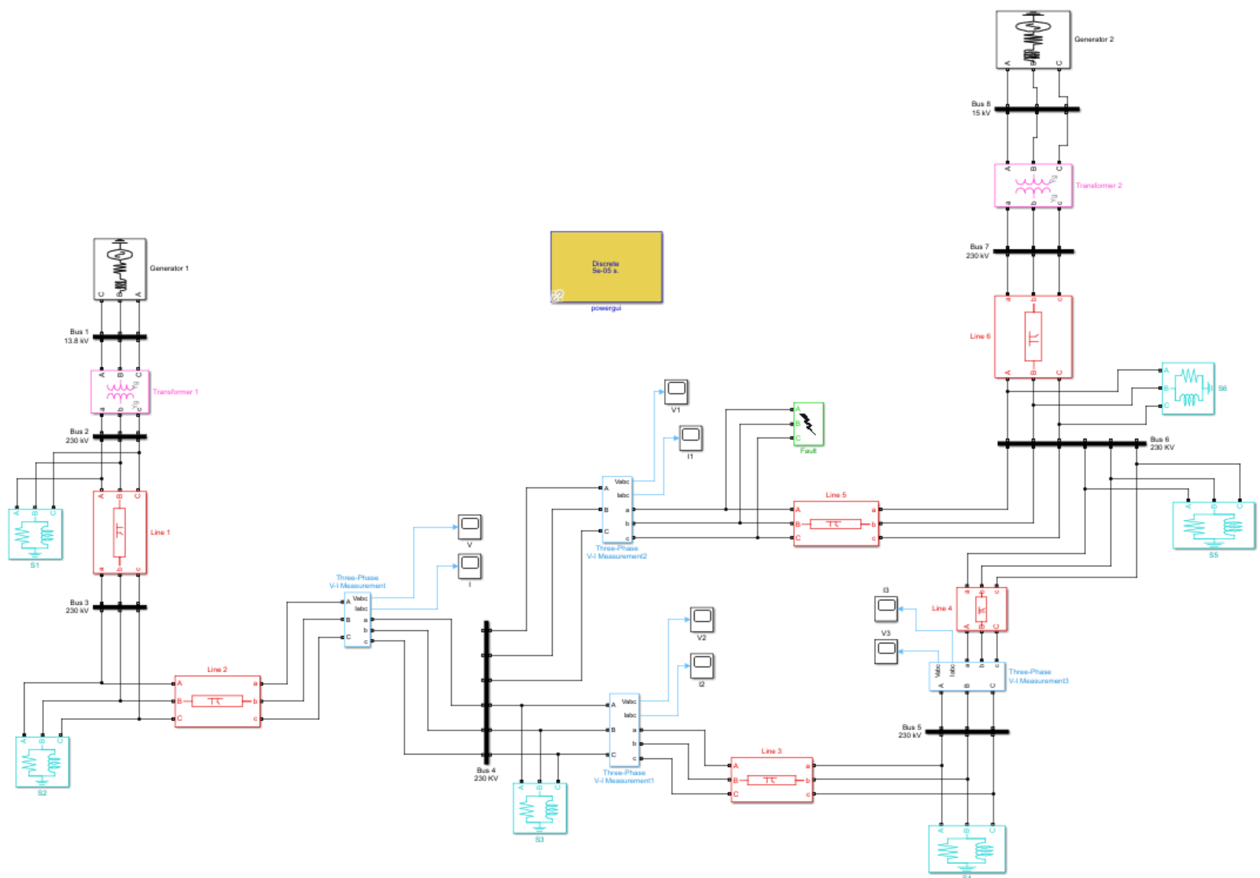


FIGURE 12. The Simulink Model for the given System

Following this, the parameters for each element are entered. For the generators, under Source section, the phase-to-phase rms voltage is set, alongside the frequency of 50 Hz. Under Impedance section, Base voltage is defined, alongside the 3-phase base VA. Impedance is defined as internal, with the short-circuit parameters are specified. When it comes to Load Flow, the Active Power Generation is set at 180 MW, while the Minimum and Maximum Reactive Powers are set at -87 MVAR and 87 MVAR, respectively.

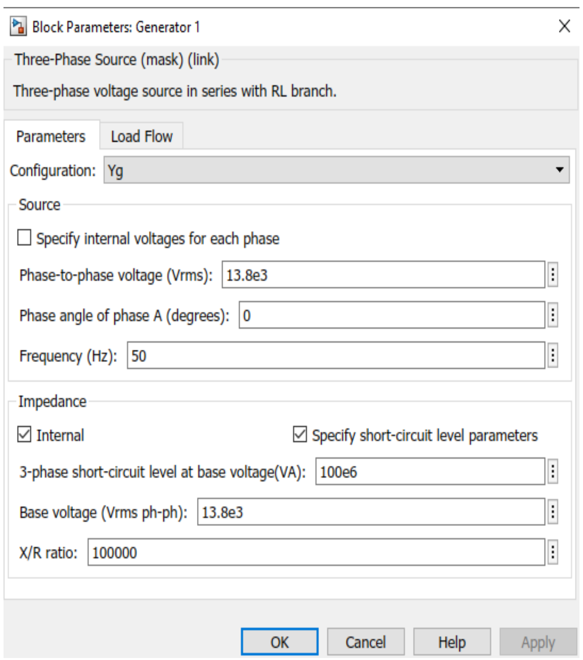


FIGURE 13. Generator 1 Parameters

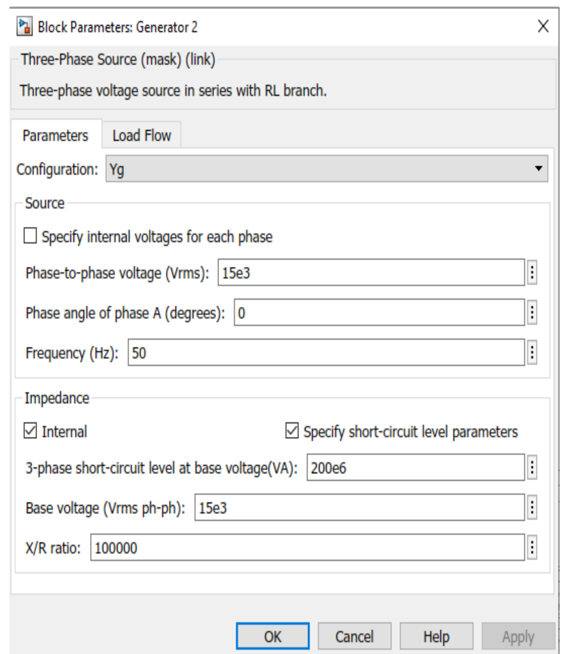


FIGURE 14. Generator 2 Parameters

Next, the transformer elements are configured. Both transformers have a Yg connection at both windings. They consist of Three single-phase transformers. The frequency is 50 Hz, like in the rest of the system. The nominal power is 100 MVA for Transformer 1 and 200 MVA for Transformer 2. The inductance is specified for both windings and the values are the same for both transformers. Voltages are set in phase-to-phase rms. They are in accordance to the generators, and later to the base voltage of 230 kV, at which the system operates.

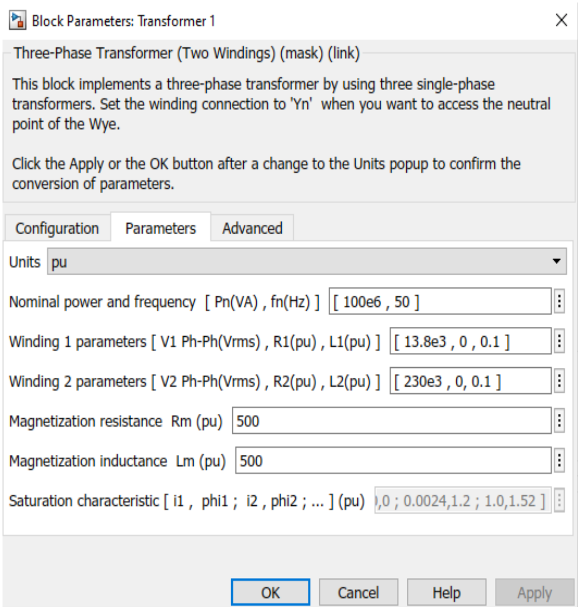


FIGURE 15. Transformer 1 Parameters

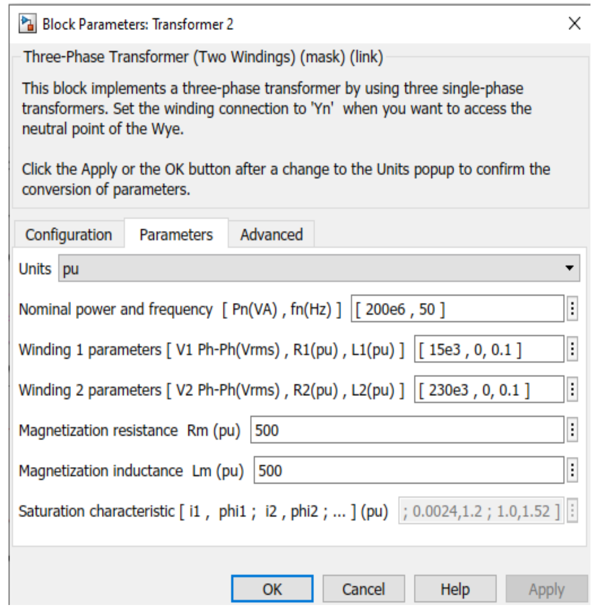


FIGURE 16. Transformer 2 Parameters

The Line parameters are entered, according to the values from Table 1. Firstly, line length and line frequency are entered. After this, the positive and zero-sequence values for resistance, inductance and capacitance are entered. These values are the same for every line and the only thing that differs in each line configuration is the Line length, as specified in Table 1.

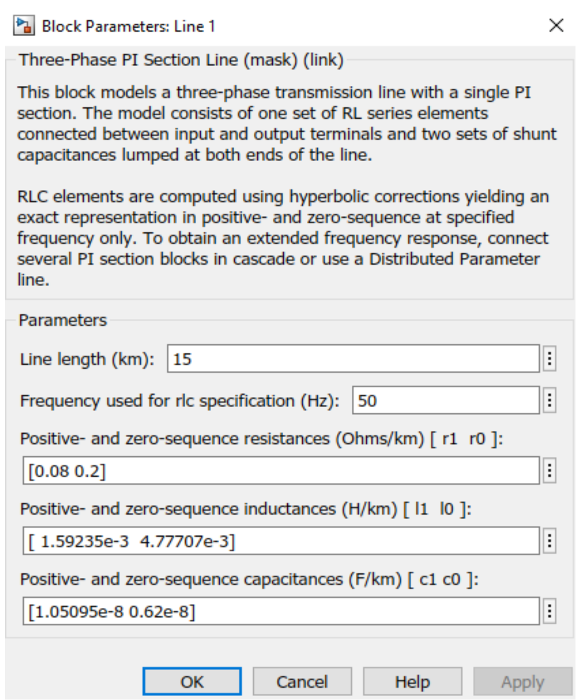


FIGURE 17. Block Parameters Example for Pi-Section Lines

The loads are at BUS 2, BUS 3, BUS 4, BUS 5, BUS 6 and BUS 7. Each of the six loads has exactly the same block parameters. These block parameters implement a three-phase parallel RLC load. They are Y (grounded). The nominal phase-to-phase voltage (in rms) is 230 kV. This the system's base voltage. The nominal frequency is, once again 50 Hz. They have active power of 120 MW and reactive power of 40 MVAR. All of the reactive power is inductive, that is, positive. None of it is capacitive, or negative.

Each of the Three-Phase Parallel RLC Loads are denoted with the letter S and the associated number. That is, S_1, S_2, S_3, S_4, S_5 and S_6.

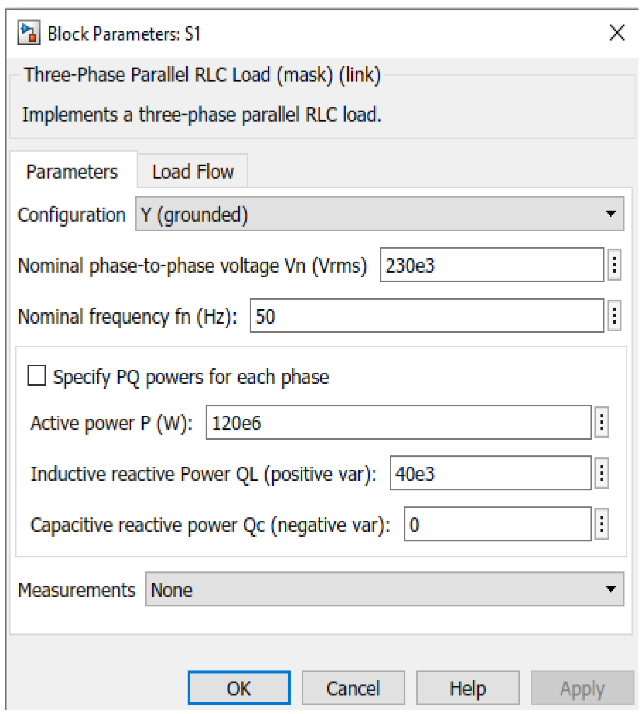


FIGURE 18. Block Parameters for the Loads, at BUS 2, BUS 3, BUS 4, BUS 5, BUS 6 and BUS 7

2.2. PSAT MODEL

In order to model the given system in MATLAB's Simulink, it is required to use PSAT (Power System Analysis Toolbox). Blocks from this library are required for system modelling. PSAT Toolbox is utilized in order to calculate the precise power flow of the system. The PSAT model is a single-line model, made from the elements in Figure 19:

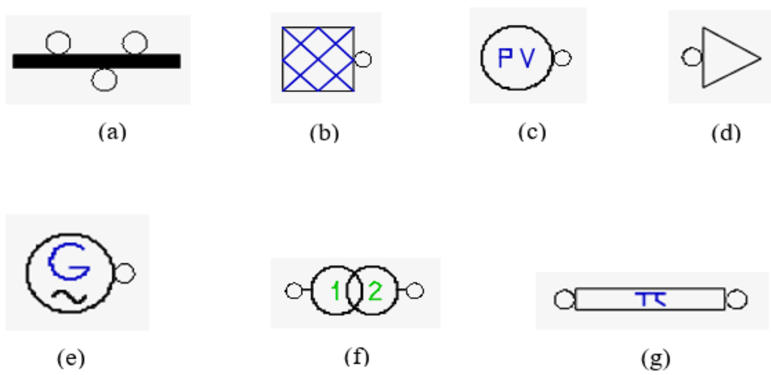


FIGURE 19. The Elements used in this PSAT model: (a) Bus; (b) Slack Bus; (c) PV Bus; (d) Load; (e) Generator; (f) Transformer; (g) Pi Section Line;

(a) A Bus is any node in the single-line diagram at which voltage, current, power flow, or other quantities are set to be evaluated.

(b) The Slack Bus, also referred to as the Reference Bus or the Swing Bus, plays a crucial role in maintaining the balance of active and reactive power within the system. It is the angular reference point for all the other buses in the system, being set at 0 degrees. Additionally, the voltage magnitude at the slack bus is assumed to be 1 per unit (p.u.).

(c) PV is also known as the Generator Bus. Power and voltage ratings need to be specified. This block also requires active power and voltage magnitude to be entered in p.u. values. Minimum and maximum values for both voltage and reactive power are included in PV block as well.

(d) An electrical load refers to a component or a circuit section that consumes active electric power. The PQ bus, also known as the Load Bus, has specified values for real power P and reactive power Q. Typically, in a PQ bus, the generated real and reactive power are assumed to be zero.

(e) Synchronous generator is a synchronous machine. It converts mechanical energy into electric energy (AC electric energy). The principle of operation relies on electromagnetic induction.

(f) Transformer is a device used in the transmission of electric energy. The transmission current is AC. It transfers electric energy from one alternating-current circuit to one or more other circuits. The voltage get either increased (stepped up) or decreased (stepped down).

(g) Transmission line is a part of the power system which carries electric energy from one point to another. A transmission line with a pi-section configuration is called this way because the arrangement of its impedance elements resembles Greek letter "π" (pi).

After connecting all of the elements, the final PSAT Model looks as shown in Figure 20:

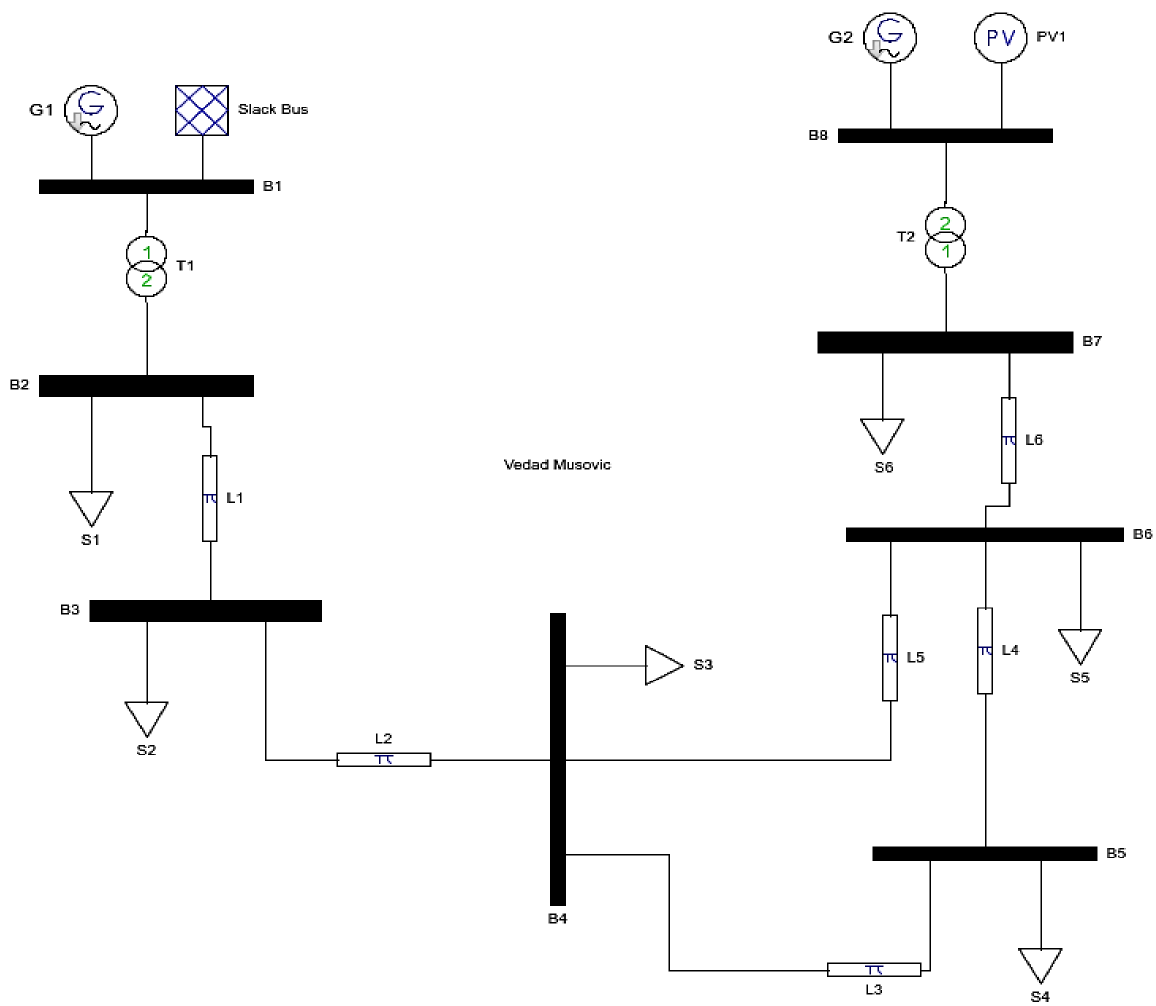


FIGURE 20. The PSAT Model

This PSAT Model is obtained, when all the components are connected. All of the block are assigned a specific name for easier navigation and system analysis. The Generators are named with letter G, Transformers with letter T, Loads with S, Pi Section Lines with L and the Busses are named with B. The next step was to enter the parameters for each element. The parameters for them are shown in the following figures. Firstly, there are parameters for both generators.

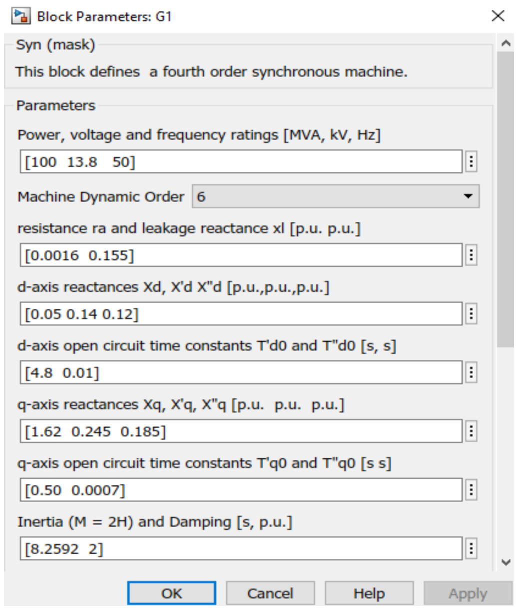


FIGURE 21. Generator 1 Parameters

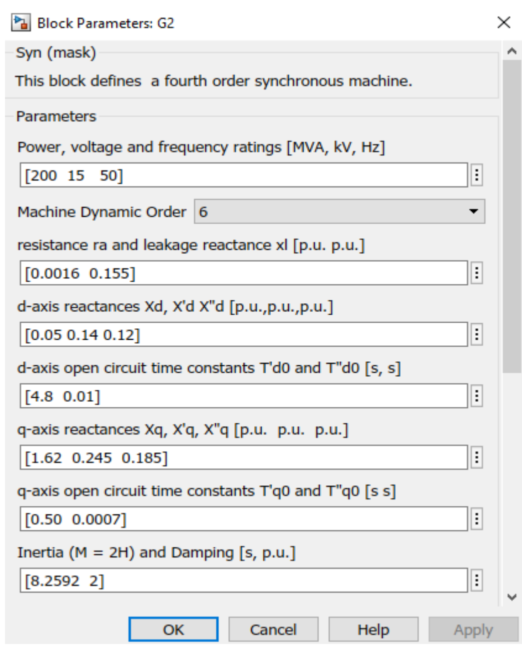


FIGURE 22. Generator 2 Parameters

Generator 1 is connected to the Slack Bus at BUS 1. Thus, we need to set up its parameters:

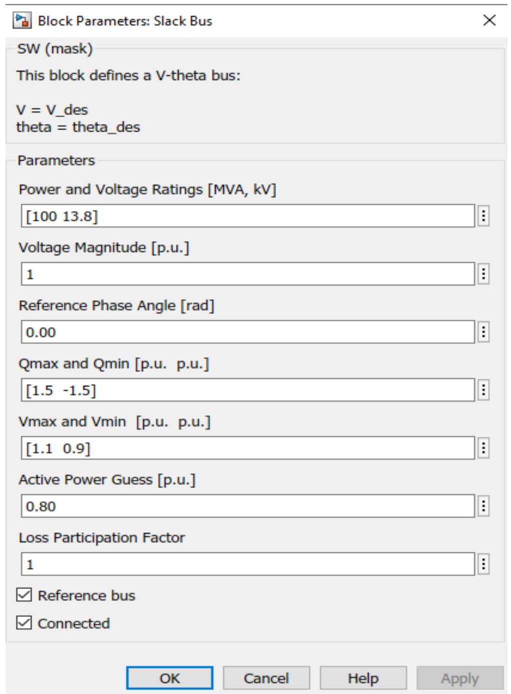


FIGURE 23. Slack Bus Parameters

Generator 2 is connected to PV element at BUS 8. This block contains the following parameters:

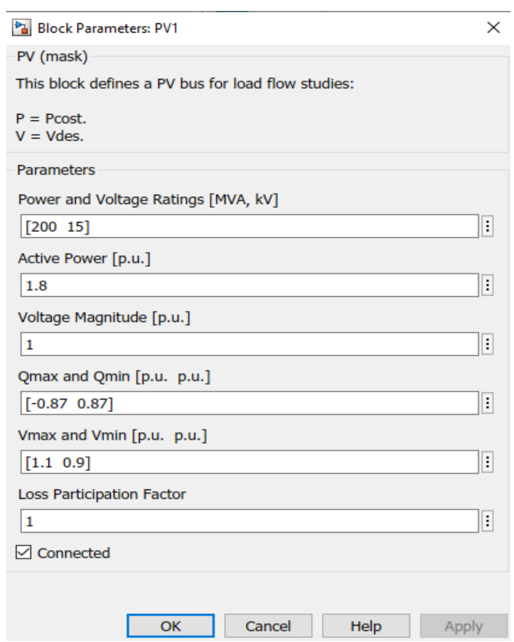


FIGURE 24. PV Parameters

The parameters for the Transformers are adjusted in the following way:

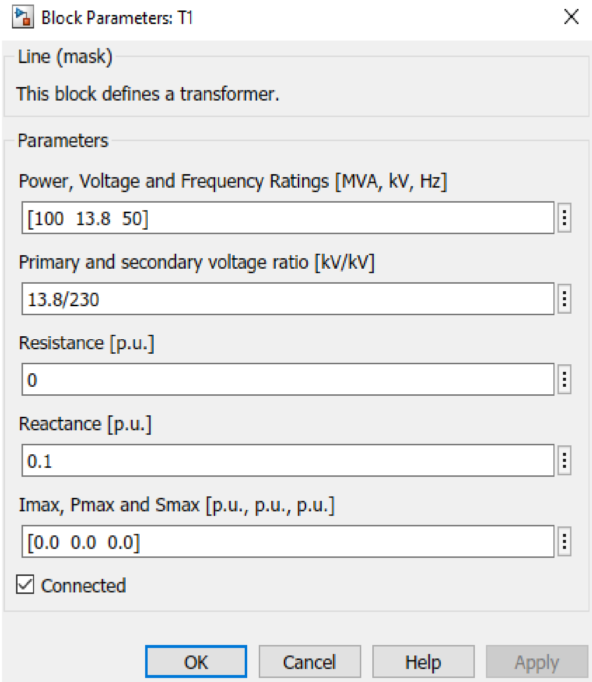


FIGURE 25. Transformer 1

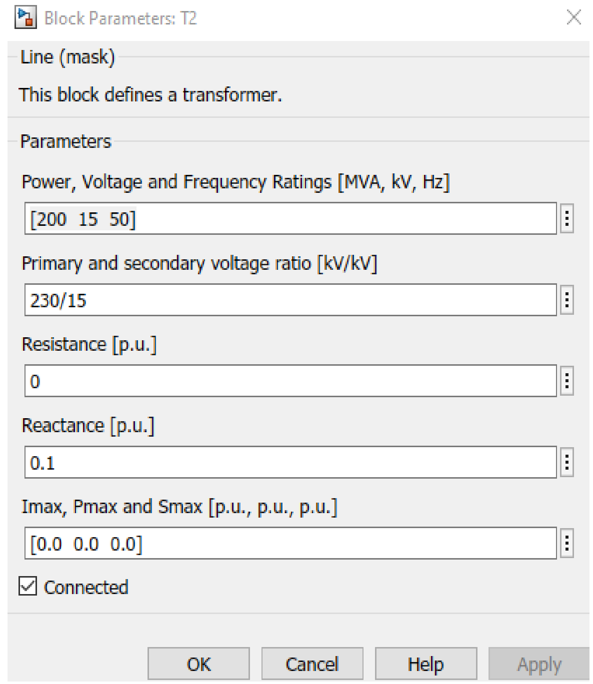


FIGURE 26. Transformer 2

In order to set the parameters for each line, the values, given in the system description, needed to be converted into the p.u. values of resistance, reactance and admittance. The first step is to find the system base impedance. It is the ratio of base voltage (squared) and the base complex power:

$$Z_{base} = \frac{V_{base}^2}{S_{base}}$$

The per-unit values for can then be obtained from the following expressions:

$$R_{pu} = \frac{R}{Z_{base}} * L \qquad X_{pu} = \frac{X}{Z_{base}} * L \qquad Y_{pu} = Y * Z_{base} * L$$

L is the transmission line length, R is the resistance, X is the reactance and Y is the admittance.

After this, the parameters can be entered for every single line. The following figures show this:

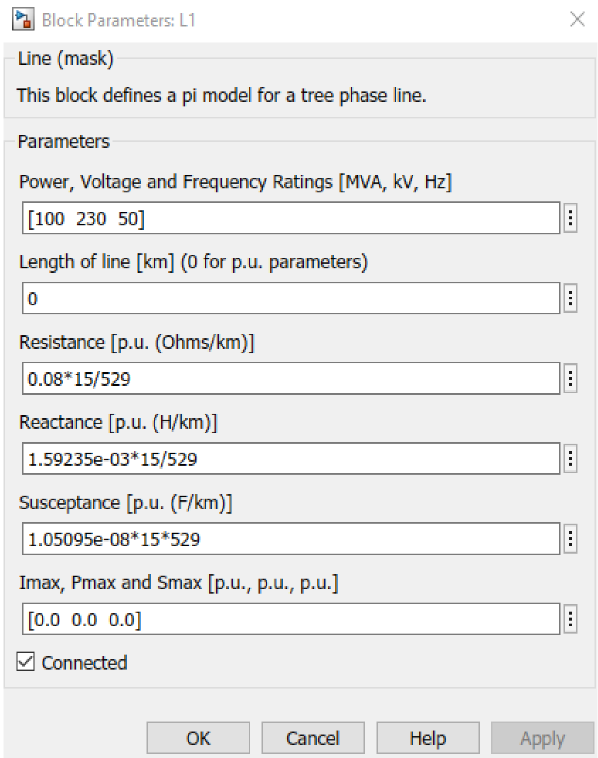


FIGURE 27. Line 1 (BUS 2 – BUS 3)

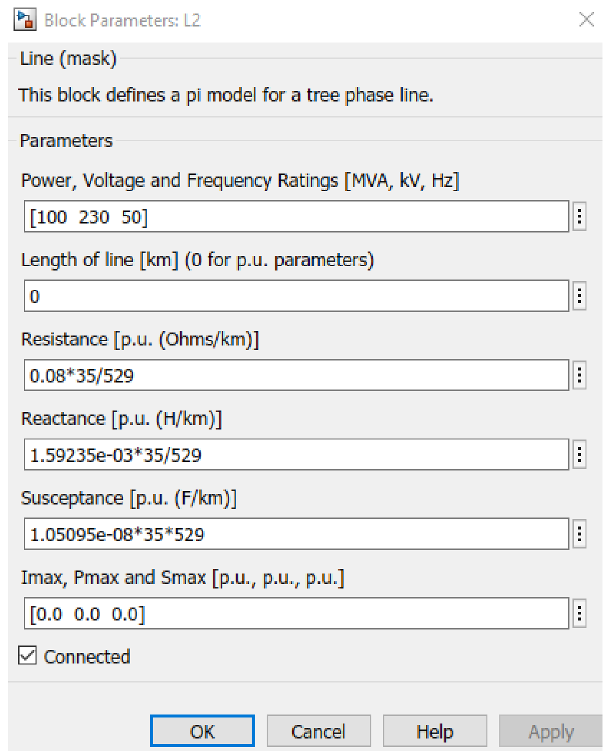


FIGURE 28. Line 2 (BUS 3 – BUS 4)

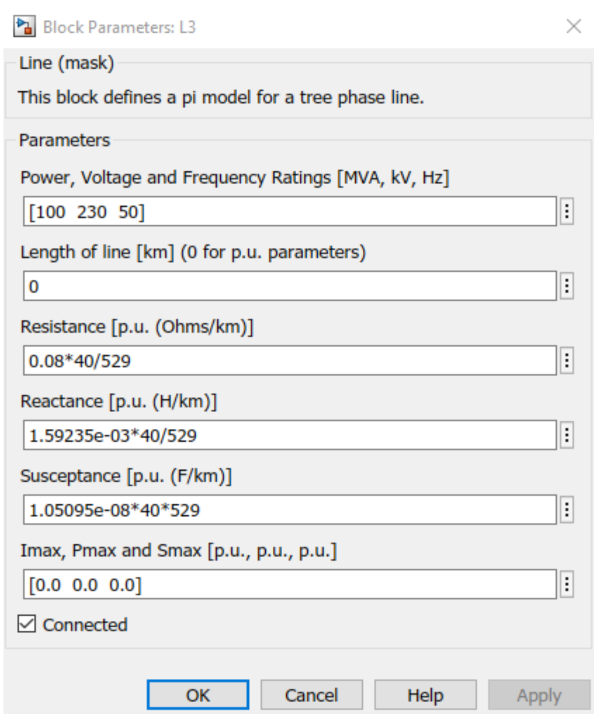


FIGURE 29. Line 3 (BUS 4 – BUS 5)

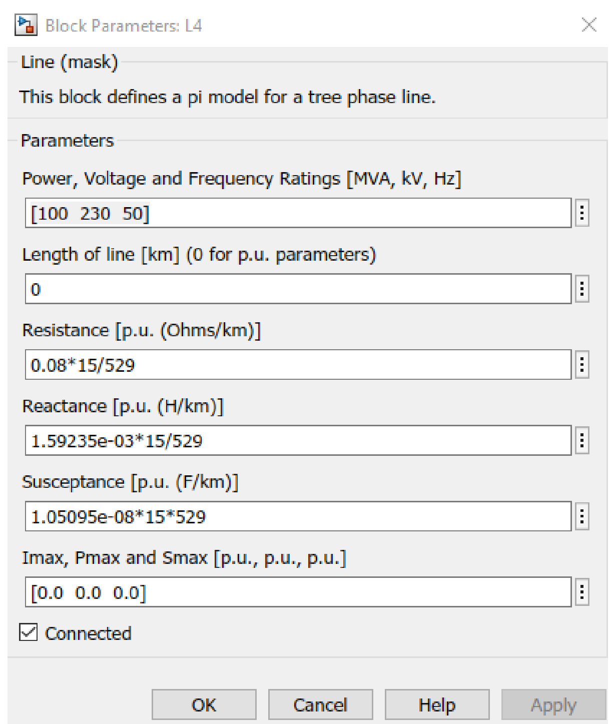


FIGURE 30. Line 4 (BUS 5 – BUS 6)

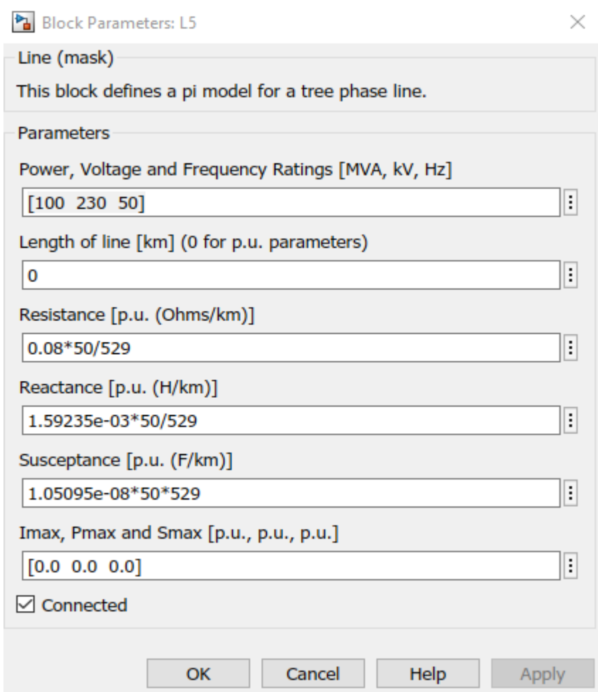


FIGURE 31. Line 5 (BUS 4 – BUS 6)

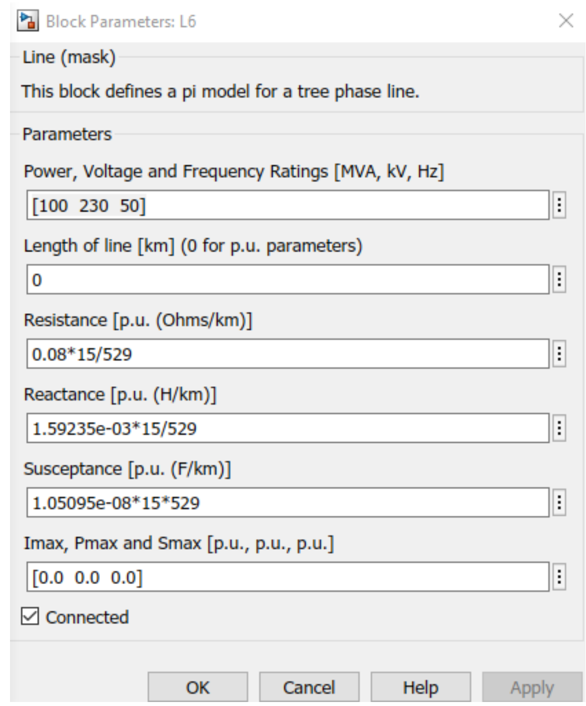


FIGURE 32. Line 6 (BUS 6 – BUS 7)

Finally, the loads remain. In order to model them, the values for their power and voltage ratings need to be entered, as well as their active and reactive power values.

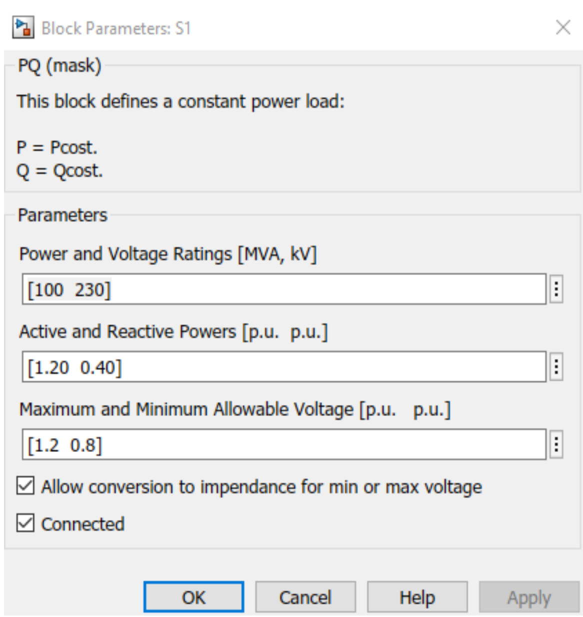


FIGURE 33. The Load at Bus 2

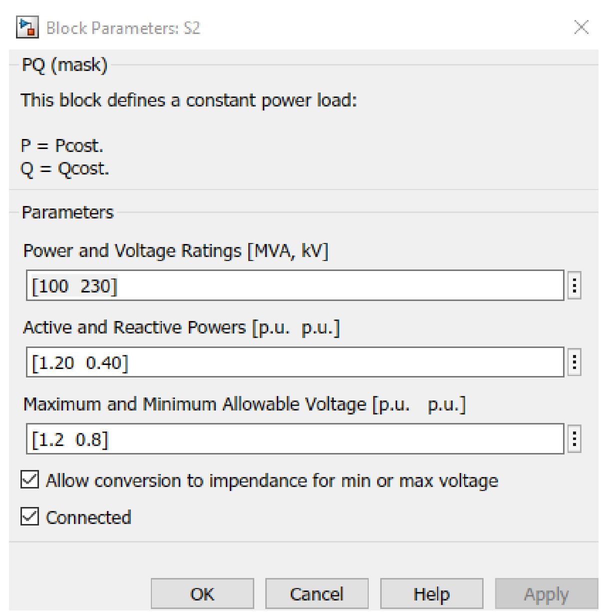


FIGURE 34. The Load at Bus 3

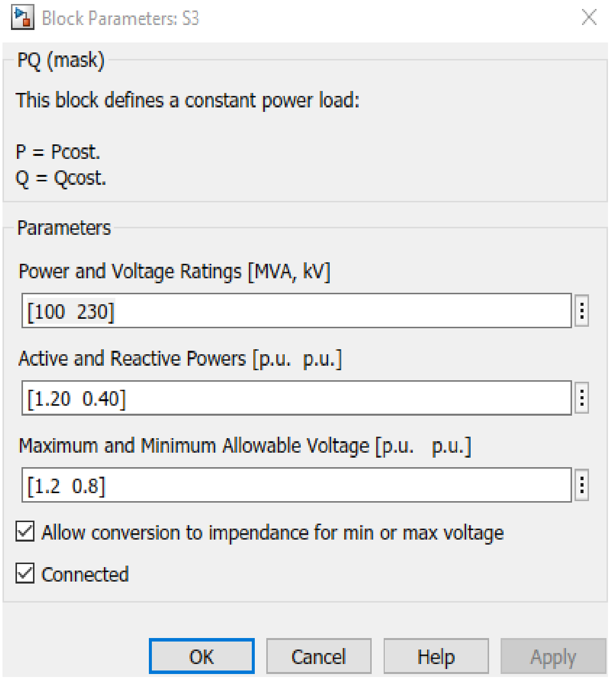


FIGURE 35. The Load at Bus 4

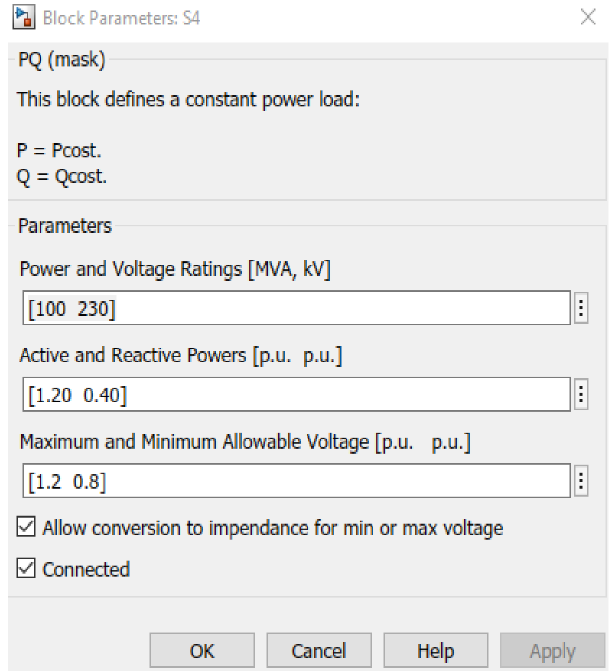


FIGURE 36. The Load at Bus 5

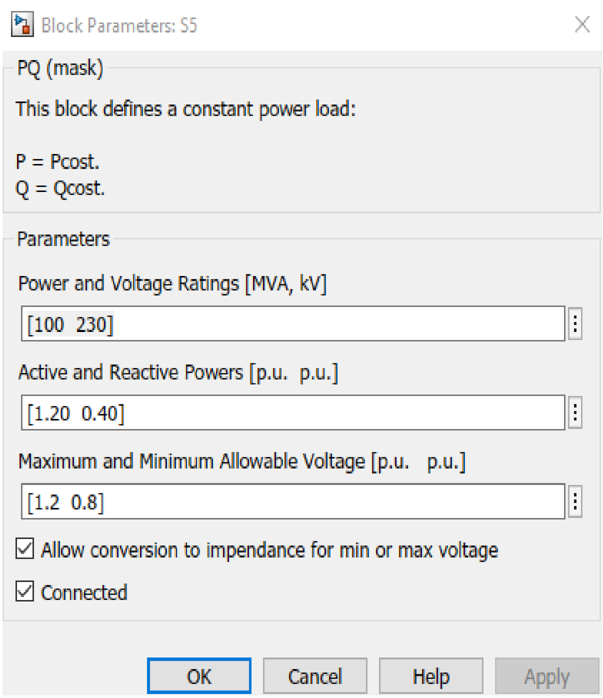


FIGURE 37. The Load at Bus 6

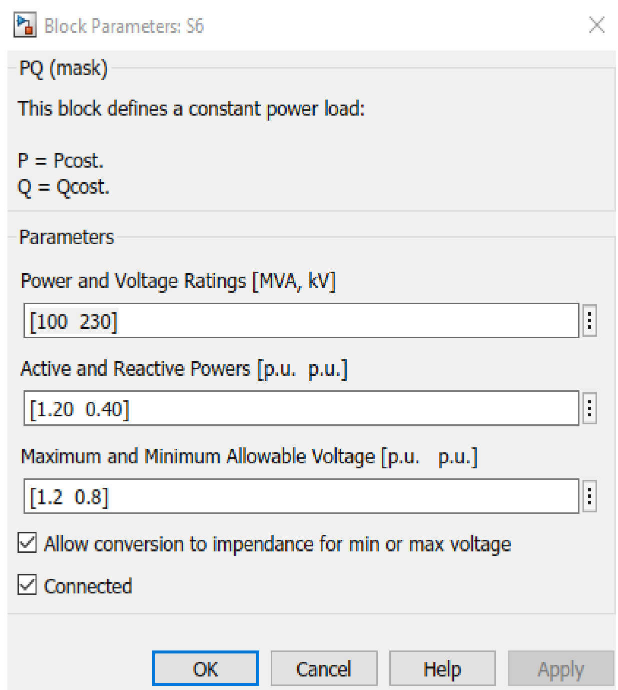


FIGURE 38. The Load at Bus 7

3. RESULTS

3.1. POWER FLOW RESULTS

In order to perform system analysis, we need to type ‘psat’ in MATLAB command window. It is required to select the path where the PSAT toolbox is located. Now, when the PSAT window opens, in the top left corner, we select ‘Open Data File’ icon. In the new window, PSAT Simulink (.mdl) is selected under ‘Filters’ section. Next, in the ‘Current path’ section, the location where PSAT model is saved (as .mdl file) is chosen.

Then, the system gets loaded for analysis. After this, the ‘Power Flow’ button is pressed and the power flow of our system is calculated. It is performed using the Newton-Rhapson Method.

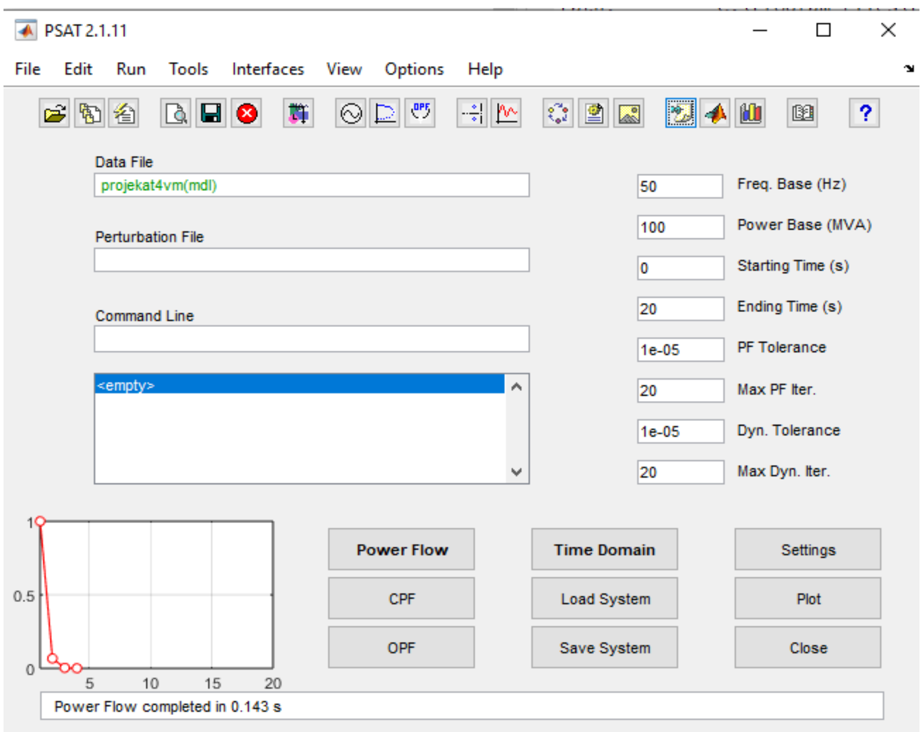


FIGURE 39. PSAT Window with the model, loaded as .mdl file

In order to view the results, we should click on the ‘Static Report’ icon. A new window with all the necessary values opens up. The results are in p.u. However, there is an option to view the results in actual values.

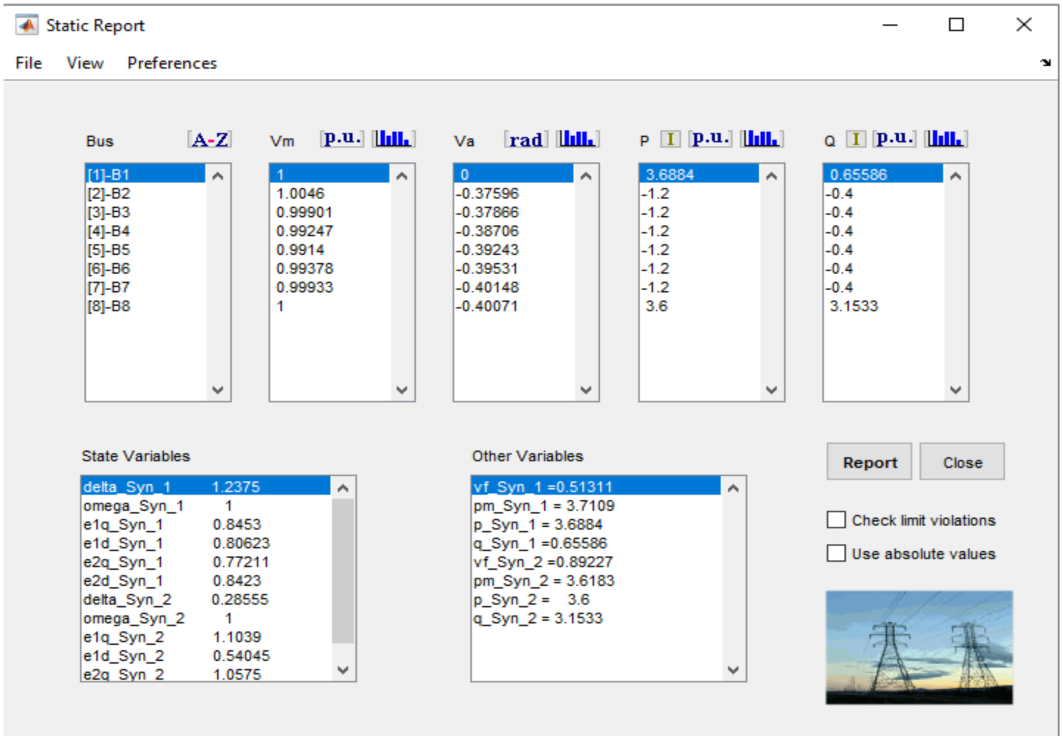


FIGURE 40. Static Report Window (in p.u. values)

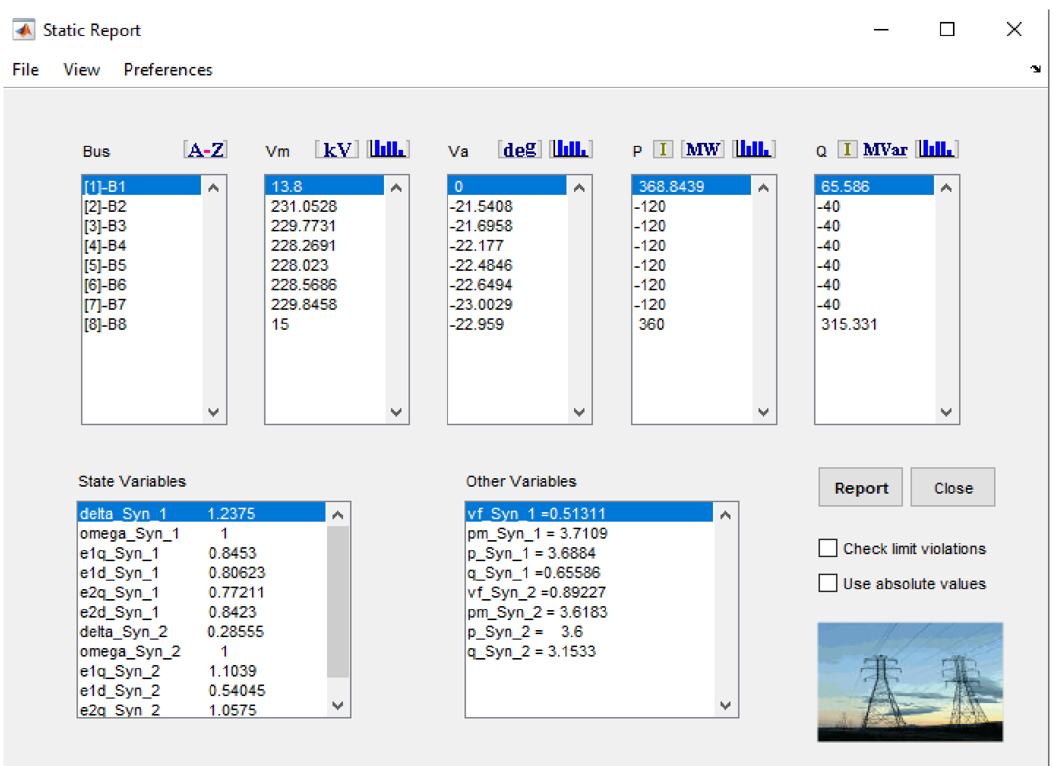


FIGURE 41. Static Report Window (in real values)

Static Report Window offers an option to view the results in graphical form as well.

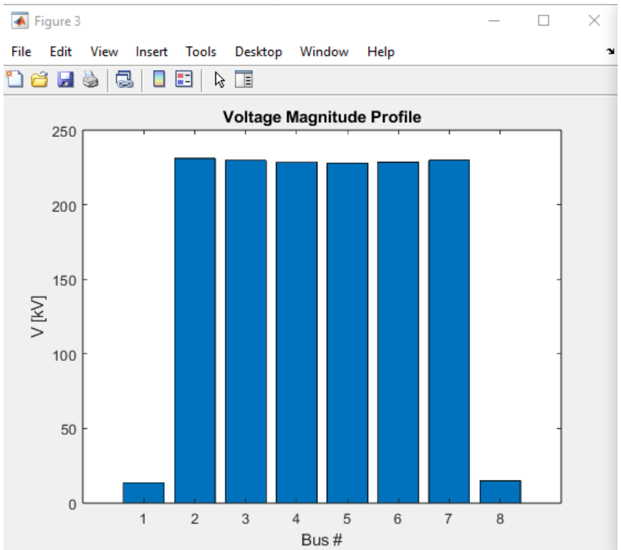


FIGURE 42. Voltage Magnitude Profile

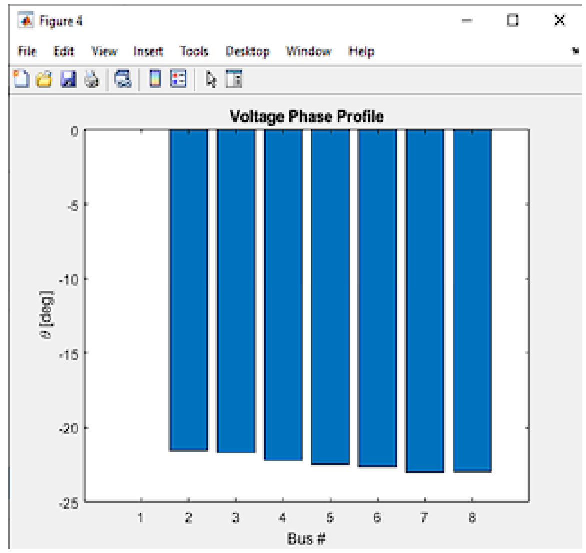


FIGURE 43. Voltage Phase Profile

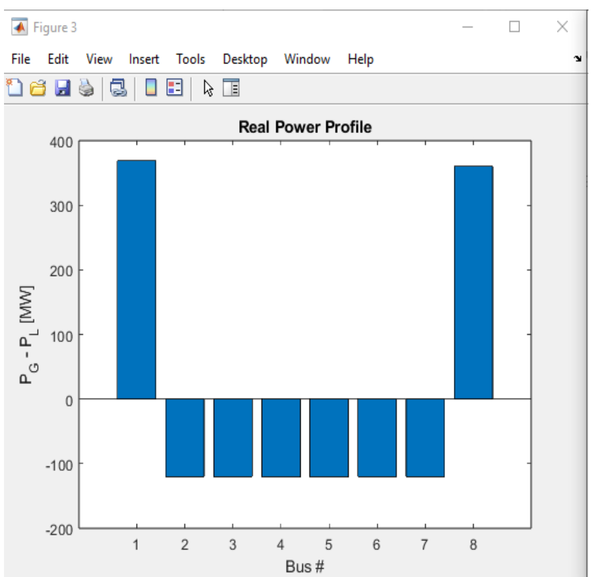


FIGURE 44. Real Power Profile

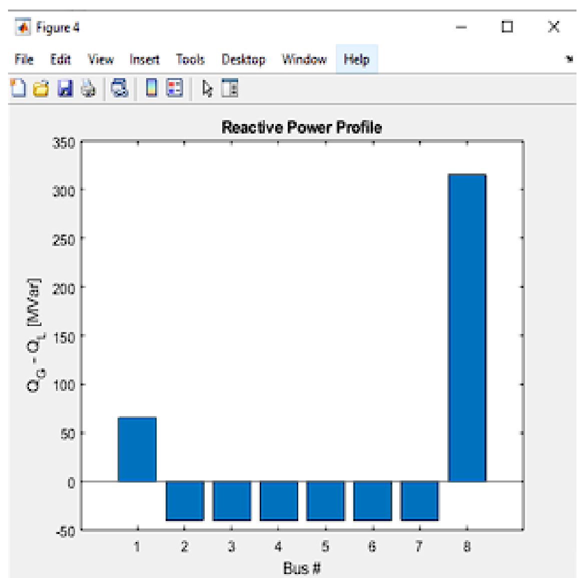


FIGURE 45. Reactive Power Profile

Finally, in order to obtain the detailed Power Flow Report, we simply click on the 'Report' button in the Static Report Window.

3.1.1. Power Flow Report

P S A T 2.1.11

Author: Federico Milano, (c) 2002-2019

e-mail: federico.milano@ucd.ie

website: faraday1.ucd.ie/psat.html

File: C:\Users\pc\Desktop\projekat4vm.mdl

Date: 25-Dec-2023 01:49:30

NETWORK STATISTICS

Buses:	8
Lines:	6
Transformers:	2
Generators:	2
Loads:	6

SOLUTION STATISTICS

Number of Iterations:	4
Maximum P mismatch [p.u.]	0
Maximum Q mismatch [p.u.]	0
Power rate [MVA]	100

POWER FLOW RESULTS

Bus	V	phase	P gen	Q gen	P load	Q load
	[p.u.]	[deg]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
B1	1	0	3.6884	0.65586	0	0
B2	1.0046	-21.5408	0	0	1.2	0.4
B3	0.99901	-21.6958	0	0	1.2	0.4
B4	0.99247	-22.177	0	0	1.2	0.4
B5	0.9914	-22.4846	0	0	1.2	0.4
B6	0.99378	-22.6494	0	0	1.2	0.4
B7	0.99933	-23.0029	0	0	1.2	0.4
B8	1	-22.959	3.6	3.1533	0	0

STATE VARIABLES

delta_Syn_1	1.2375
omega_Syn_1	1
e1q_Syn_1	0.8453
e1d_Syn_1	0.80623
e2q_Syn_1	0.77211
e2d_Syn_1	0.8423
delta_Syn_2	0.28555
omega_Syn_2	1
e1q_Syn_2	1.1039
e1d_Syn_2	0.54045
e2q_Syn_2	1.0575

e2d_Syn_2	0.56463

OTHER ALGEBRAIC VARIABLES

vf_Syn_1	0.51311
pm_Syn_1	3.7109
p_Syn_1	3.6884
q_Syn_1	0.65586
vf_Syn_2	0.89227
pm_Syn_2	3.6183
p_Syn_2	3.6
q_Syn_2	3.1533

LINE FLOWS

From Bus	To Bus	Line	P Flow [p.u.]	Q Flow [p.u.]	P Loss [p.u.]	Q Loss [p.u.]
B2	B3	1	2.4884	-1.1476	0.01688	0.00025
B4	B3	2	-1.2503	1.5481	0.02128	0.00023
B5	B4	3	-0.19037	0.86943	0.00488	-0.00012
B5	B6	4	-1.0096	-1.2694	0.00607	4e-05
B4	B6	5	-0.14497	-1.0785	0.00909	-9e-05
B6	B7	6	-2.3698	-2.7479	0.03024	0.00052
B1	B2	7	3.6884	0.65586	0	1.4035
B7	B8	8	-3.6	-3.1484	0	0.00487

LINE FLOWS

From Bus	To Bus	Line	P Flow [p.u.]	Q Flow [p.u.]	P Loss [p.u.]	Q Loss [p.u.]
B3	B2	1	-2.4716	1.1479	0.01688	0.00025
B3	B4	2	1.2716	-1.5479	0.02128	0.00023
B4	B5	3	0.19525	-0.86955	0.00488	-0.00012
B6	B5	4	1.0157	1.2695	0.00607	4e-05
B6	B4	5	0.15406	1.0785	0.00909	-9e-05
B7	B6	6	2.4	2.7484	0.03024	0.00052
B2	B1	7	-3.6884	0.74761	0	1.4035
B8	B7	8	3.6	3.1533	0	0.00487

GLOBAL SUMMARY REPORT

TOTAL GENERATION

REAL POWER [p.u.] 7.2884

REACTIVE POWER [p.u.] 3.8092

TOTAL LOAD

REAL POWER [p.u.] 7.2

REACTIVE POWER [p.u.] 2.4

TOTAL LOSSES

REAL POWER [p.u.] 0.08844

REACTIVE POWER [p.u.] 1.4092

3.2. FAULT EFFECTS

Since the faults occur on BUS 4, the voltage and current are measured at the fault point. The measurements are also performed at the other side of BUS 4, before Line 3. However, fault effects on the nearby busses are analyzed as well. Thus, the voltages and currents are measured. Three-Phase V-I Measurement blocks are used, alongside scopes, to represent voltage and current.

The Fault block is used to measure these faults. Double line-to-ground and three-phase fault are the two faults that occur, respectively. The block parameters for Fault block have a few important things. The switching time, where the fault effects will be clearly visible is defined between 0.90 and 0.91 seconds. The fault resistance is 0.001 Ω and the ground resistance is also 0.001 Ω. The fault between phases is set up according to the particular fault.

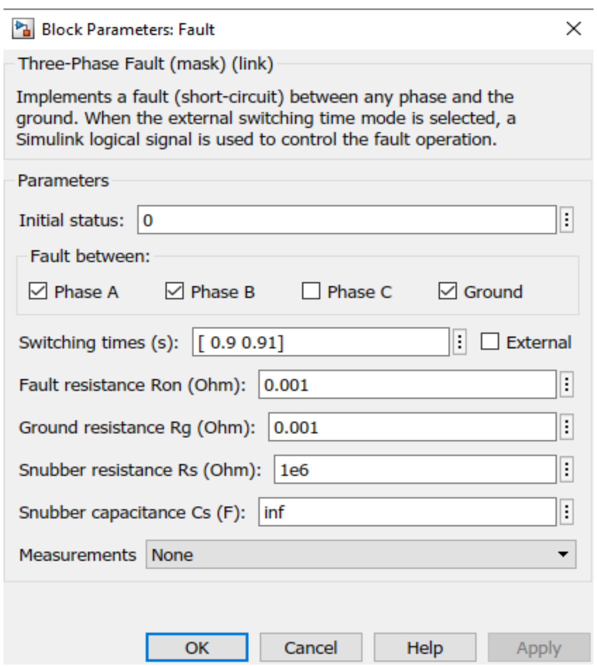


FIGURE 46. Fault Parameters for DLG Fault

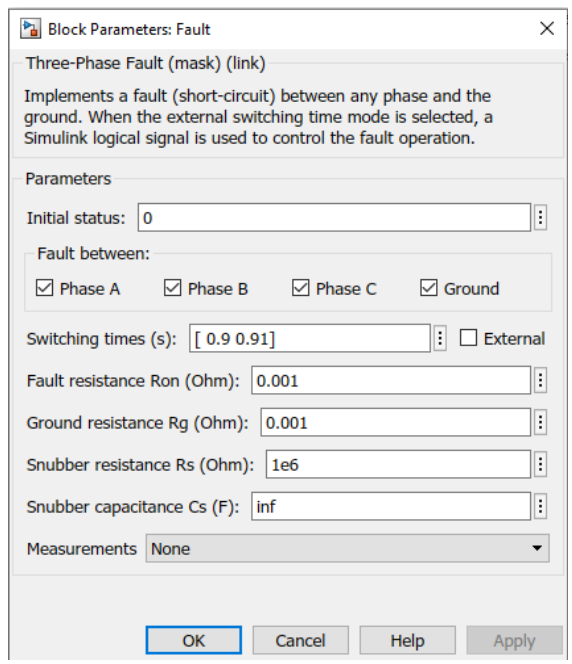


FIGURE 47. Fault Parameters for 3φ Fault

Additionally, the Simulink Model requires a Powergui block. It should be of simulation type Discrete, with Sample Time: 5e-05 s. Inside Simulink, the Stop Time is specified at 1s, since it needs to be in accordance to the Switching Times of the Fault blocks.

3.2.1. Double Line-To-Ground (DLG) Fault Results

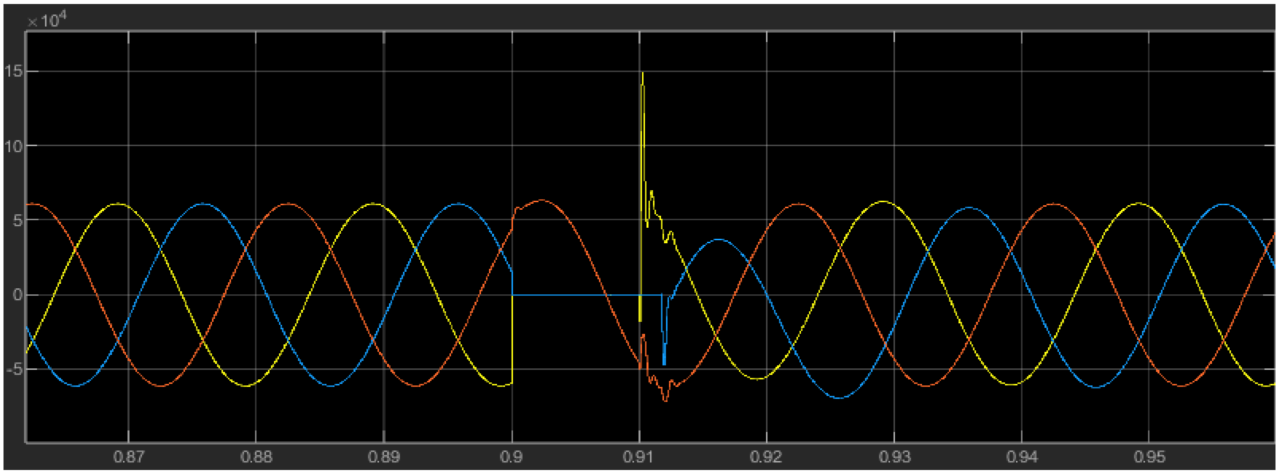


FIGURE 48. Fault Voltages for DLG Fault, at Bus 4, Line 5

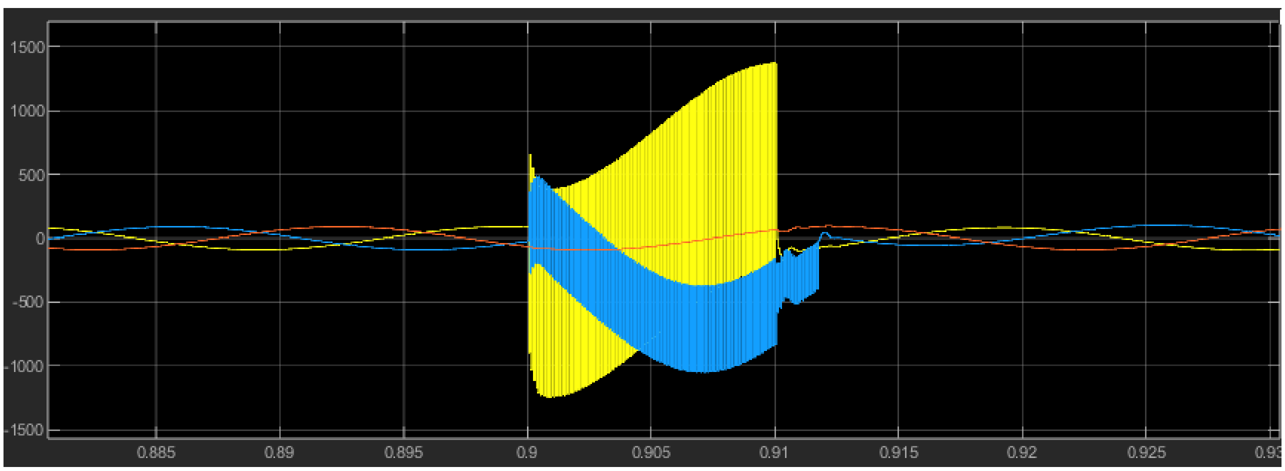


FIGURE 49. Fault Currents for DLG Fault, at Bus 4, Line 5

Figure 48 and Figure 49 represent the fault voltage and current respectively. Since this is a Double Line-To-Ground Fault, phase a and phase b have their voltage values go to zero, during the fault occurring. The voltage values will need certain time, even after the fault, to go back to their regular values and state. Since the fault has no effect on phase c, the voltage graph will maintain its regular path during the switching time and will only experience slight deviation from it, at the end of the fault. The currents will rise to extremely high values, for phases a and b, during the fault. Again, they will need a certain amount of time to go back to their regular values and state. The current for phase c will not rise during the fault and it maintains its path.

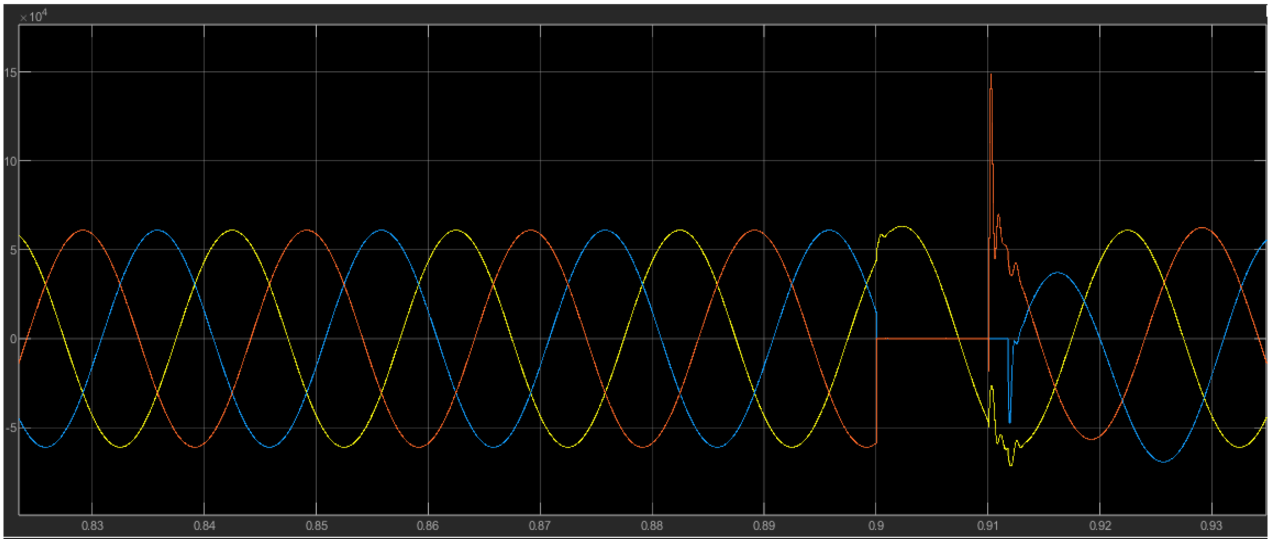


FIGURE 50. Voltages for DLG Fault, at Bus 4, Line 3

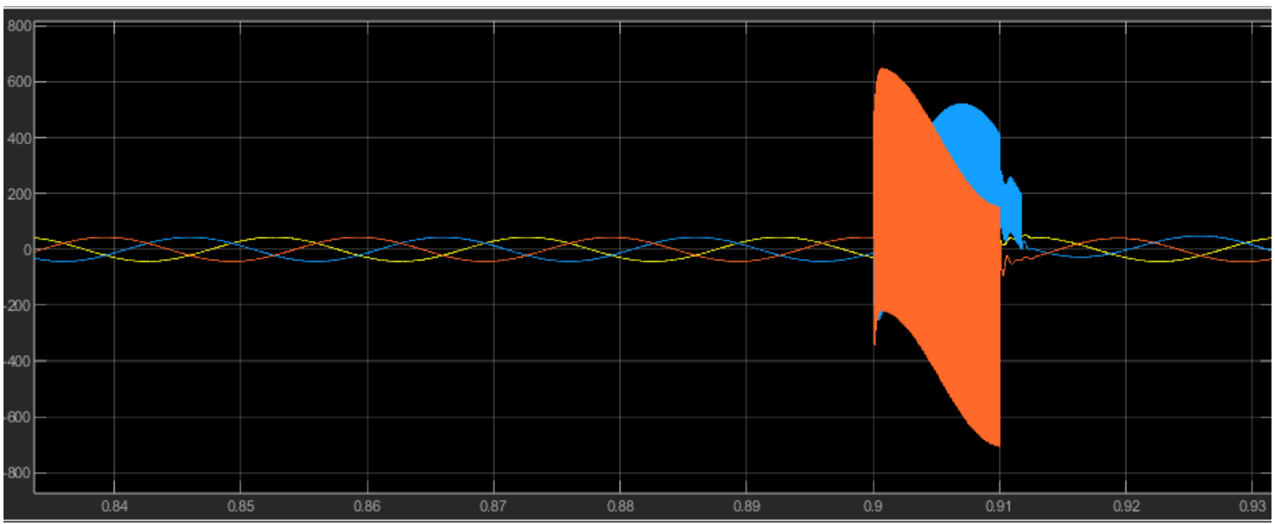


FIGURE 51. Currents for DLG Fault, at Bus 4, Line 3

At BUS 4, Line 3, the Double Line-To-Ground Fault shows its effects. Once again, the voltages drop during the fault occurring. The currents rise to abnormal values during fault period. Fault effects can be transferred to the phase, which is not a fault. During switching time (0.90-0.91 s), alongside phase b, the voltage and current changes also happen to phase c. The voltages drop to zero, while currents rise abnormally, although smaller than at fault point (at Line 5), expectedly. The voltages and currents require time to go back to normal. As seen, the fault effects are still clearly visible. This is because we are still at BUS 4, still close to the fault.

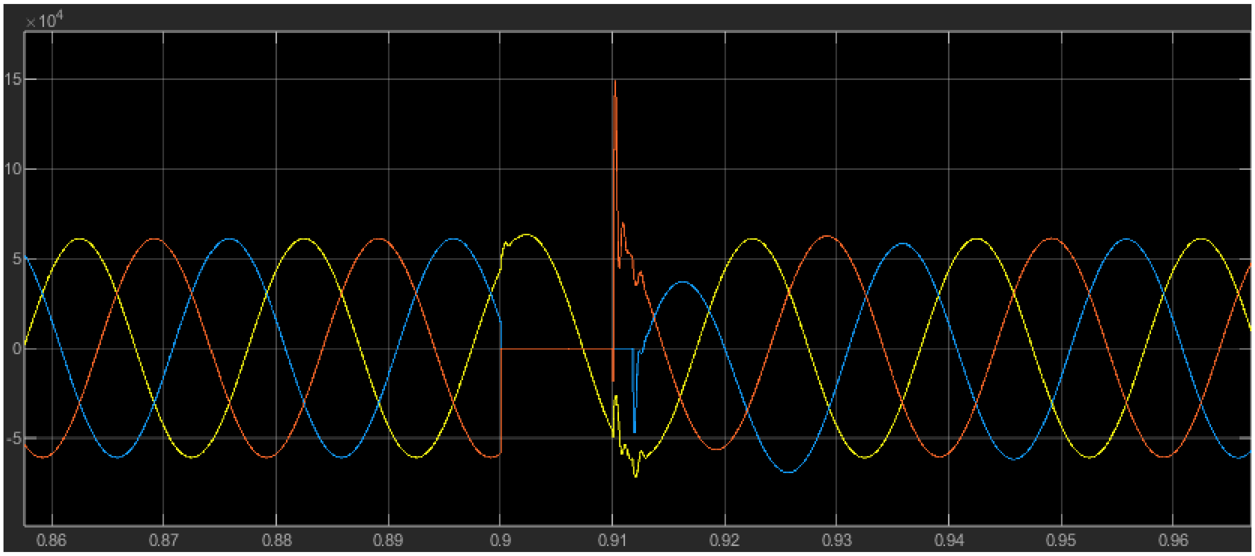


FIGURE 52. Voltages for DLG Fault, at Bus 3, Line 2

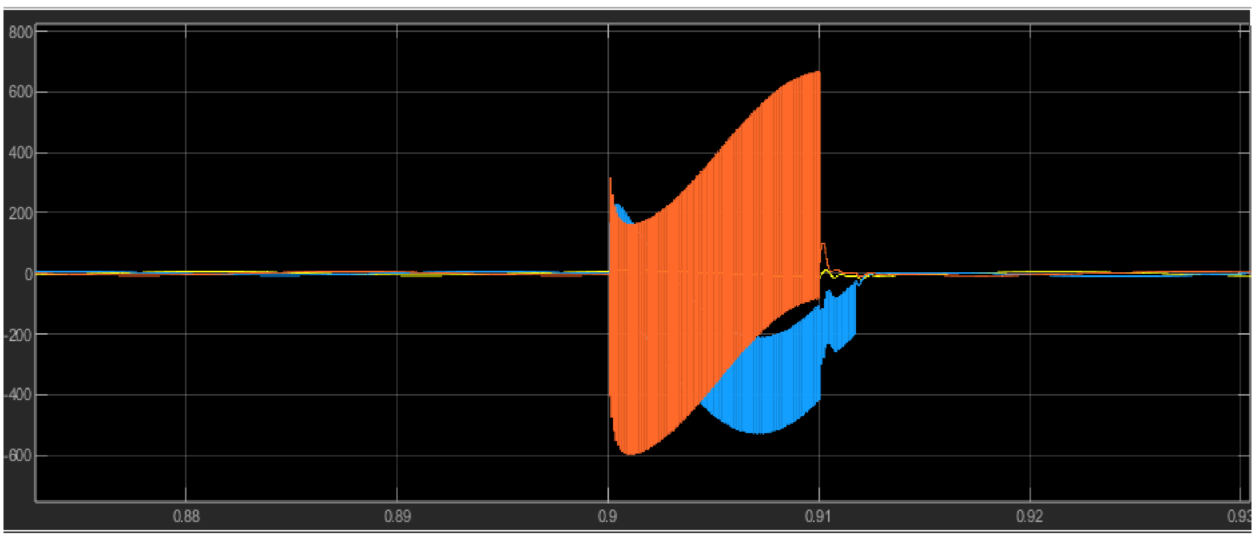


FIGURE 53. Currents for DLG Fault, at Bus 3, Line 2

At BUS 3, Line 2, once again, the voltages drop during the fault occurring. The currents rise to extremely high values during fault period. Fault effects can be transferred to the phase, which is not at fault. During switching time (0.90-0.91 s), alongside phase b, the voltage and current changes also happen to phase c. The currents are smaller at this position in the system since this is before the fault occurs. The voltages drop to zero, while currents rise abnormally, although smaller than at fault point (at Line 5), expectedly. The voltages and currents need some time to go back to normal. The fault effects are still clearly visible.

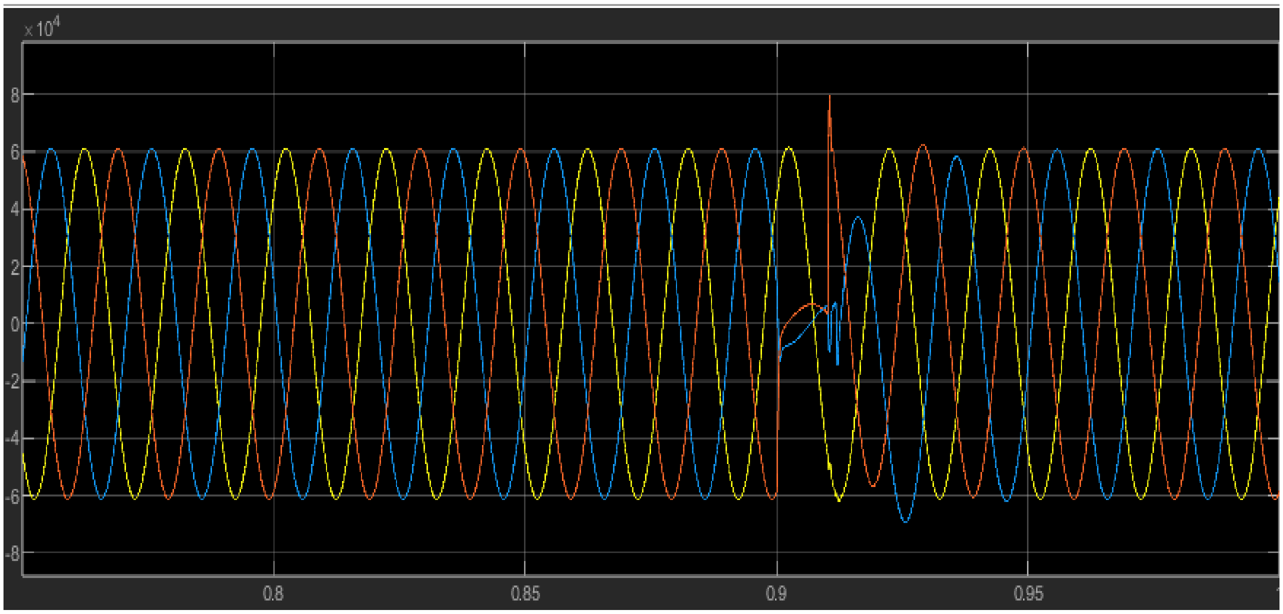


FIGURE 54. Voltages for DLG Fault, at Bus 5, Line 4

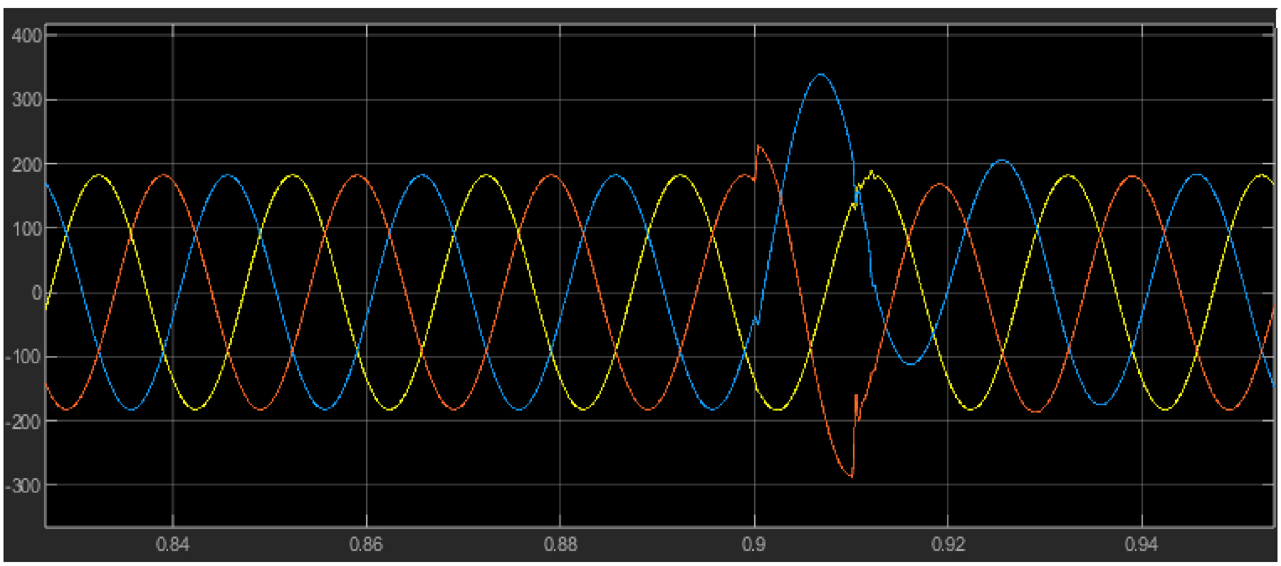


FIGURE 55. Currents for DLG Fault, at Bus 5, Line 4

At BUS 5, Line 4, the voltage drops at the fault time, although not all the way to zero. After that, they will, after some time, return back to normal. The currents will naturally, as a consequence of the fault, be all at a higher value. During switching time, the values will exhibit only a slight change, which is not that significant. The currents will go back to normal values after some time. Finally, this shows how the fault effects are still present to a certain extent, as we move further away from the point where the fault occurs.

3.2.2. Three-Phase (3φ) Fault Results

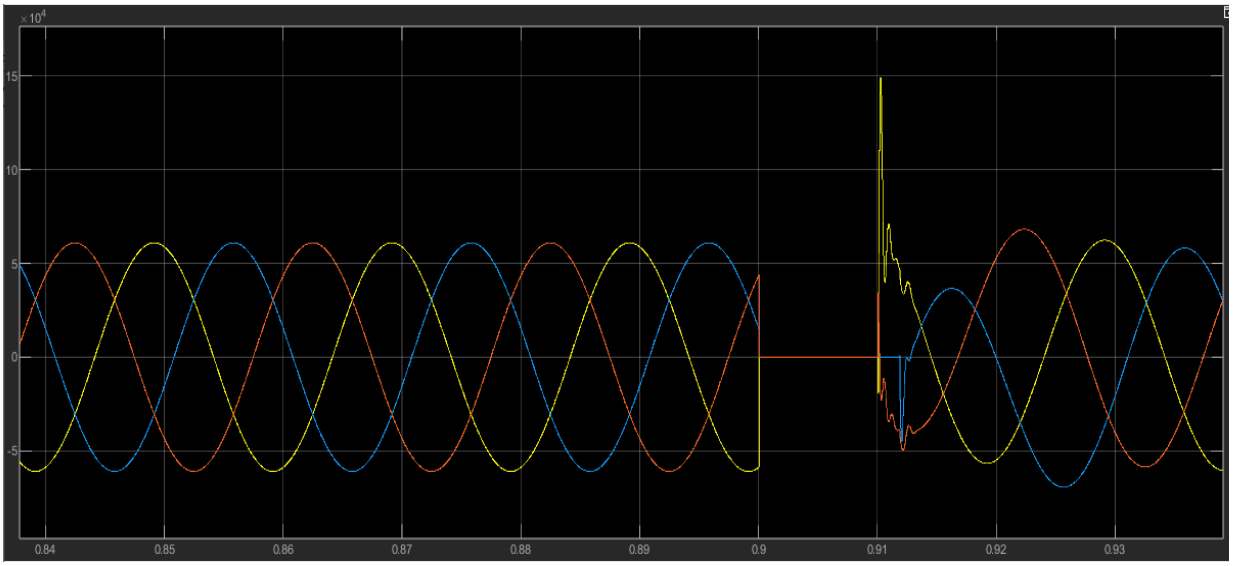


FIGURE 56. Fault Voltages for 3φ Fault, at Bus 4, Line 5

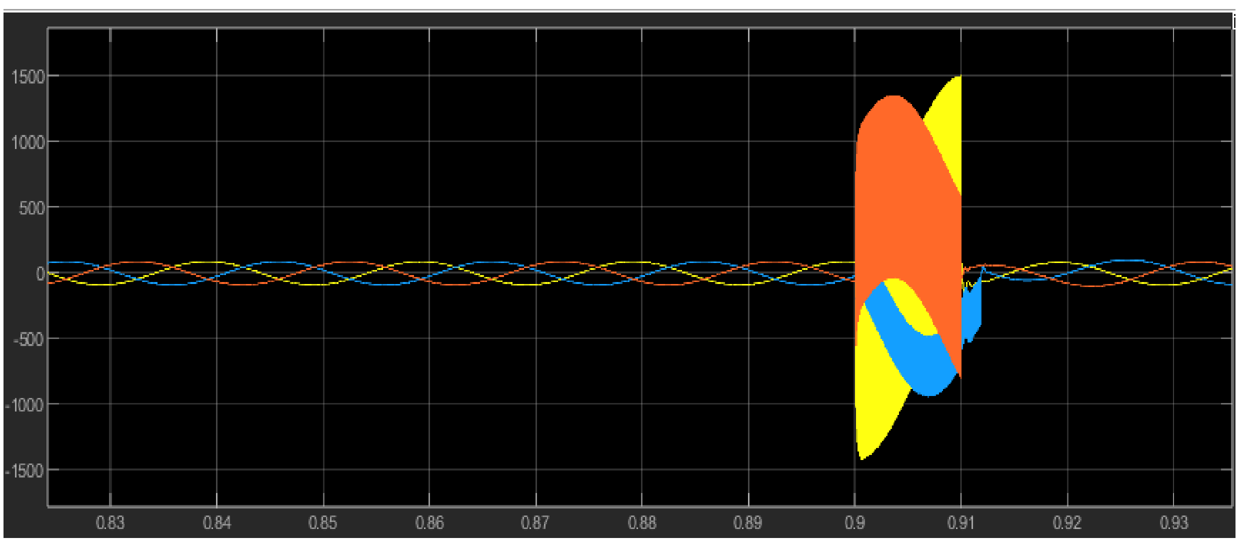


FIGURE 57. Fault Currents for 3φ Fault, at Bus 4, Line 5

Since this is a Three-Phase Fault (with ground included), fault voltage and current are observed at the Fault point, respectively. All three voltages drop to zero during the switching time (0.90-0.91 s). Following this period, they will require certain time to return to their normal path and values. The three currents flow regularly, until the switching time, when they have abnormal values. They will return to their normal path and values, a few moments after the fault.

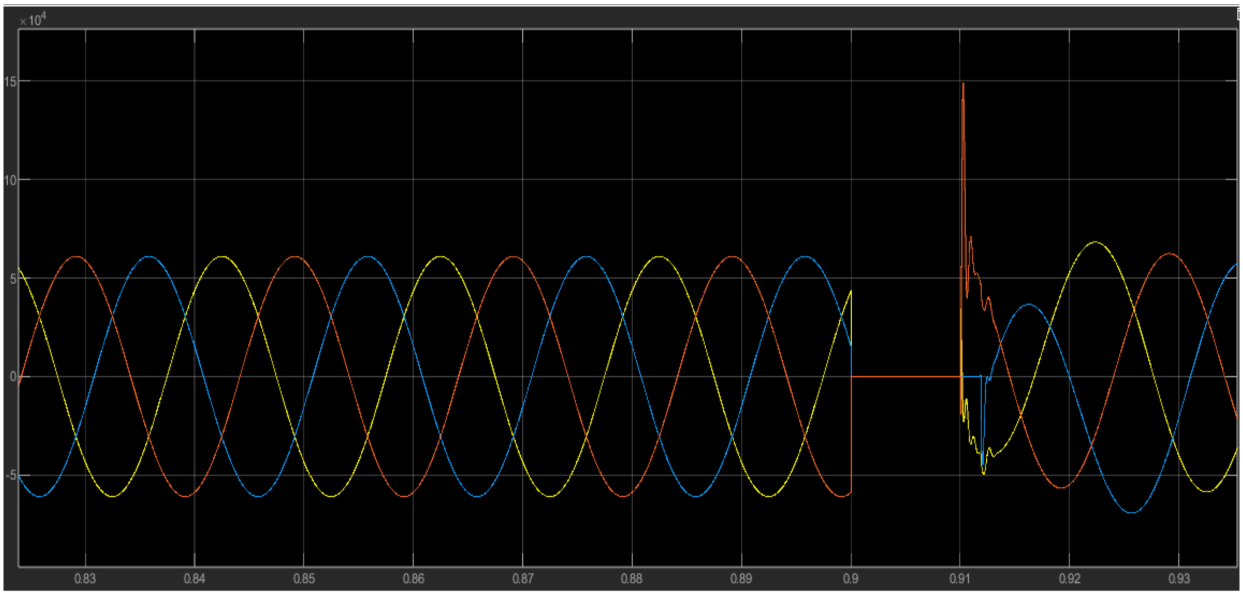


FIGURE 58. Voltages for 3φ Fault, at Bus 4, Line 3

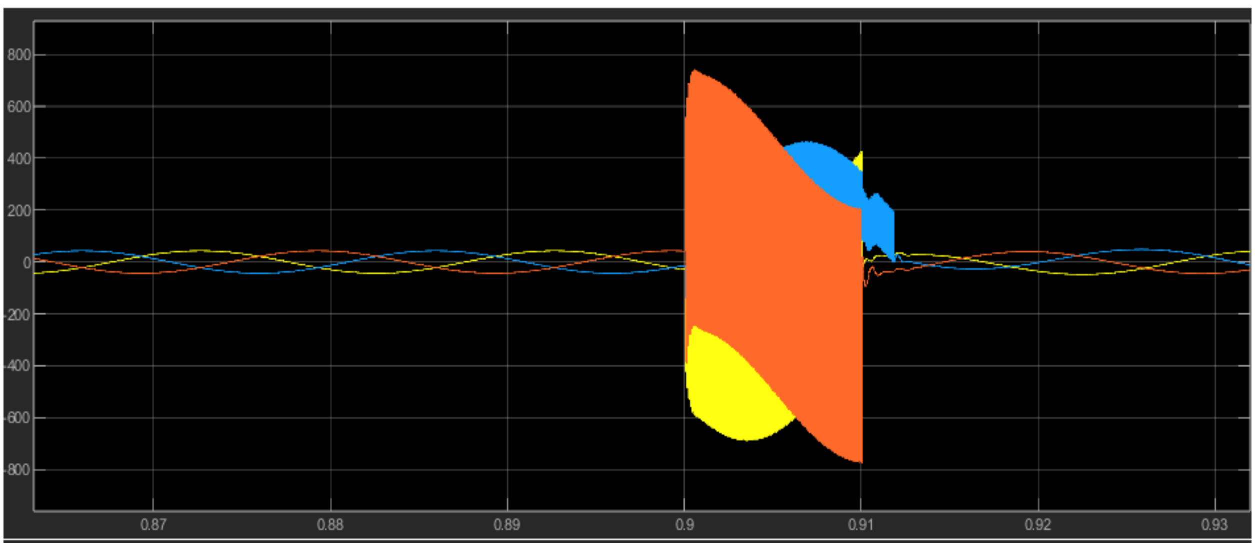


FIGURE 59. Currents for 3φ Fault, at Bus 4, Line 3

When it comes to voltages and currents at BUS 4, Line 3, the following paths are observed. The voltages drop to zero at the period where the fault occurs, as expected. This is because we are still at BUS 4. The current values are lower than the ones at BUS 4, Line 5. The currents have a regular path, until the fault period, when they have abnormal values. Since the current values are lower, they also rise to lower values. Both voltages and currents eventually return to their regular paths after the switching time ends at 0.91 s. In conclusion, fault effect are still clearly visible.

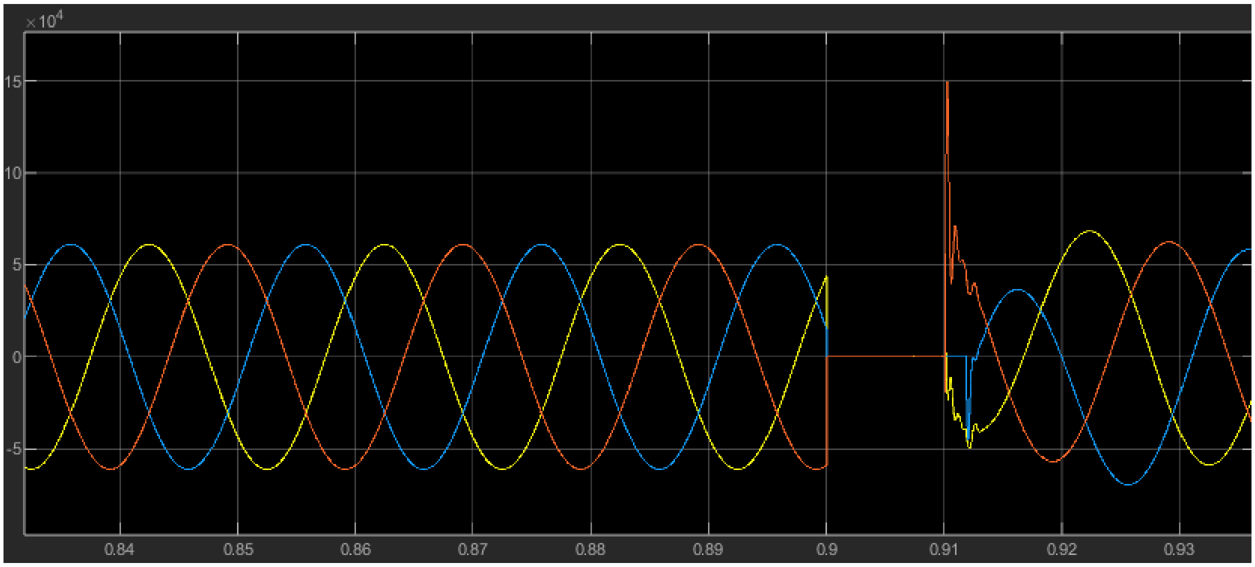


FIGURE 60. Voltages for 3φ Fault, at Bus 3, Line 2

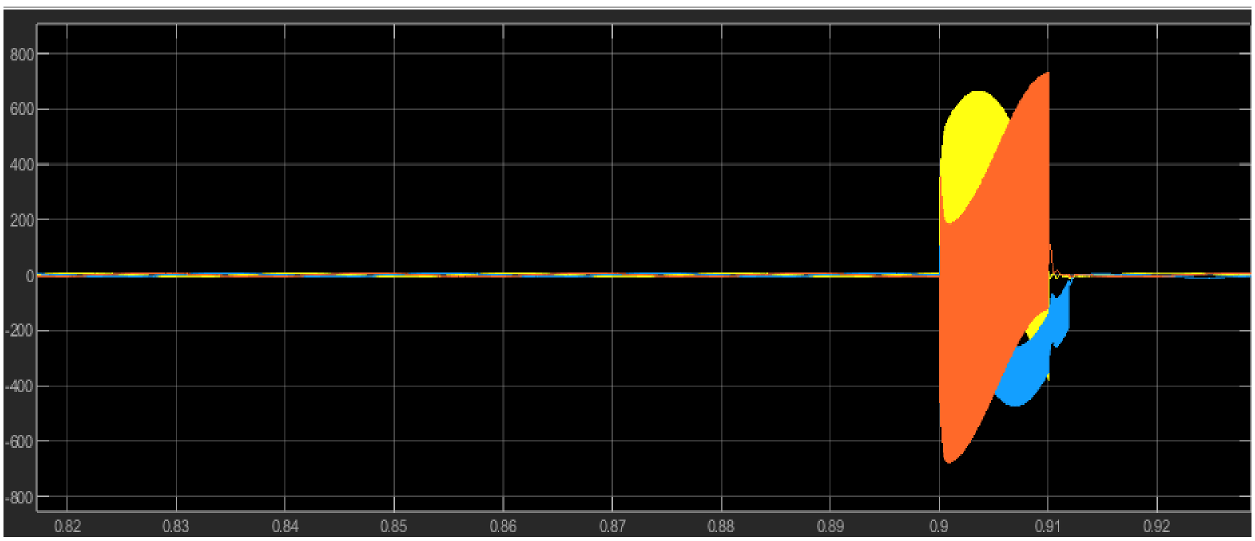


FIGURE 61. Currents for 3φ Fault, at Bus 3, Line 2

In analysis of voltages and currents at BUS 3, Line 2, patterns similar to the ones at BUS 4 are observed. Firstly, the voltages will once again drop to zero at the switching time (0.90-0.91 s). A few moments after the fault, they return to their normal path and values. When it comes to the currents, they will naturally be smaller, since this is the Bus before the fault occurs. The currents will still rise to abnormal values when the fault occurs. These values, to which the currents rises to, are lower than the values for BUS 4, Line 5 currents. The fault effects are visible in here, with the current values clearly indicating the position of this bus.

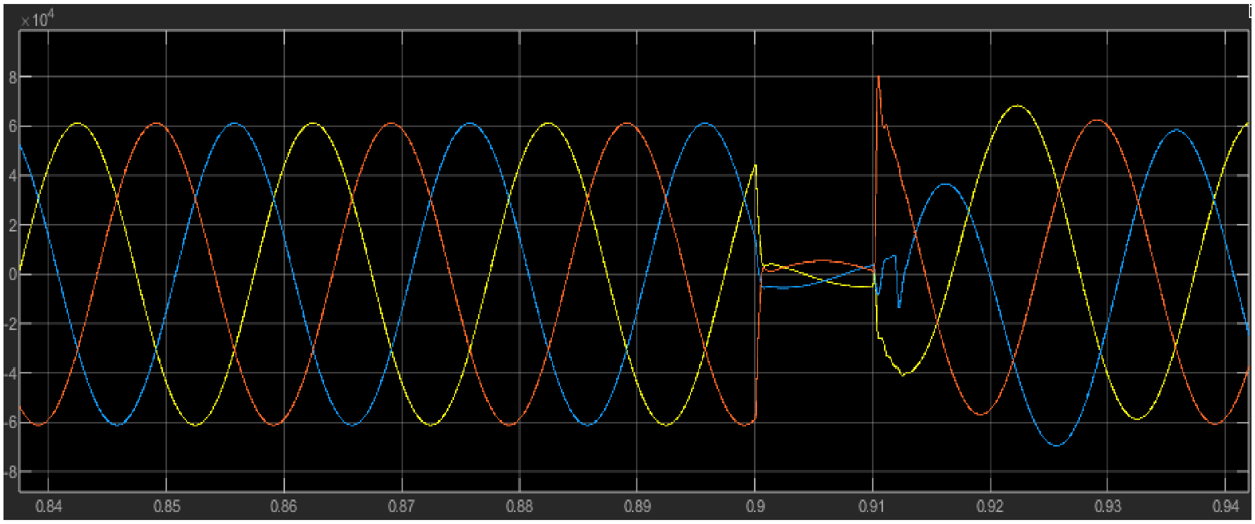


FIGURE 62. Voltages for 3φ Fault, at Bus 5, Line 4

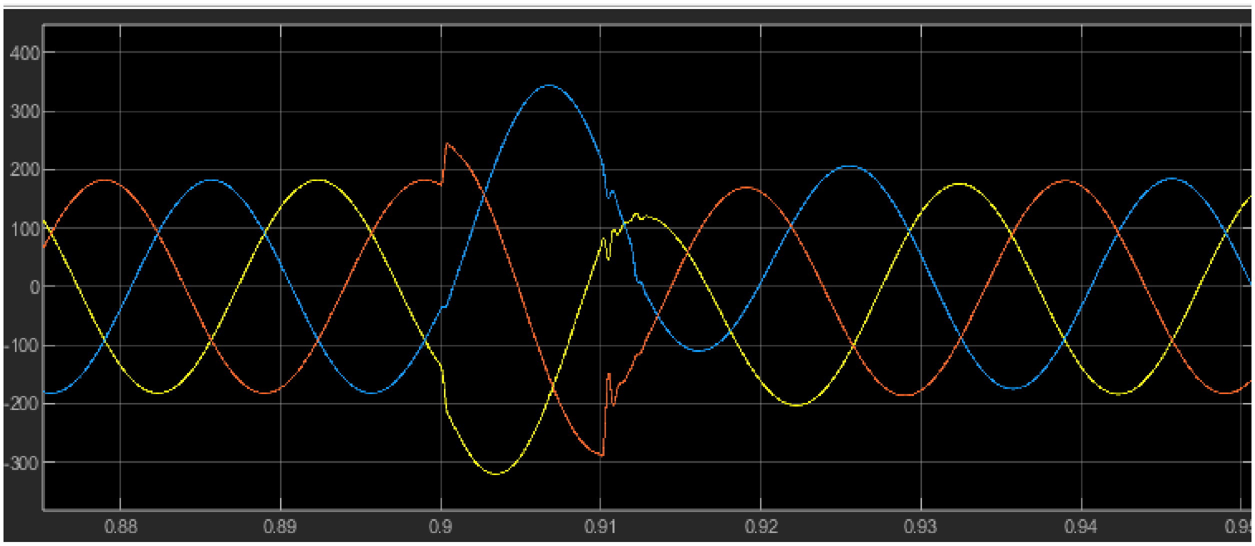


FIGURE 63. Currents for 3φ Fault, at Bus 5, Line 4

This Three-Phase Fault has certain effects on BUS 5, Line 4 as well. Naturally, voltage values will drop close to zero, but not all the way to zero, during the switching time. After that, the voltage takes some to return to its normal value. Since this is after the fault occurs, the currents will, of course, have larger values than the ones at BUS 3, before the fault occurring. The currents will experience certain deviations during the fault period. They are, of course, present in all three phases. After the fault period ends, the currents will return to their normal path after some time. The presented graphs represent how the fault effects are still present to a certain extent, as we move further away from the point where the fault occurs.

4. CONCLUSION

A detailed analysis of a power system was conducted, focusing on both operation during normal conditions and fault scenarios. The power flow results reveal that bus voltages were in the acceptable range, from 0.95 p.u to 1.05 p.u, indicating that the system functions properly. However, during fault conditions, abnormally high current levels were observed, as expected. The fault effects were examined at various buses and lines, showing the impact on voltage and current profiles. Fault analysis is performed for Double Line-To-Ground Fault (DLG) and a Three-Phase Fault (3φ), respectively.

The DLG fault at BUS 4, Line 5, had significant voltage drops and a big rise in current, with effects extending to neighboring buses, demonstrating that the system is sensitive to faults. However, the voltage and current graphs return to their normal path after switching time, when the fault occurs. This represents the system’s ability to gradually recover from a fault. The same logic can be applied for a Three-Phase (3φ) fault, highlighting the consequences of faults on different buses and lines within the given system. Simulations were conducted using Simulink, incorporating fault blocks with specific parameters such as switching time and resistance values. The results show the transient behavior of the system during faults.

To perform power flow analysis, the PSAT toolbox in MATLAB was employed, utilizing the Newton-Rhapson Method for power flow calculations. The Static Report Window provided a detailed overview of the system's performance, allowing for reading of results in both per-unit (p.u.) and real values.

The dynamic behavior of a power system under fault conditions was successfully investigated, providing valuable insights into voltage and current responses at different locations. Power flow analysis was made to ensure that the overall system functions properly. The use of simulation tools like Simulink and PSAT was crucial in understanding the system resilience and sensitivity during abnormal conditions. It contributes to the improving of power system reliability and safety.

REFERENCES

[1] Short, T.A. (2004). *Electric Power Distribution Handbook*. CRC Press LLC. Leo L. Grigsby (Ed.), The Electric Power Engineering Series.

[2] Gonen, T. (2014). *Electric Power Distribution Engineering* (3rd ed.). CRC Press. https://doi.org/10.1201/b16455

[3] Gonen, T. (2013). *Modern Power System Analysis* (2nd ed.). CRC Press. https://doi.org/10.1201/b14796

LIST OF FIGURES