EEPS401 2025: Test 1 Report

Analysis of Symmetrical Faults in an 11 Bus Power System Network

Due Date: 11 April 2025

Student Name	Kelvin Mafurendi
Student Number	220702330
Lecturer	Mr A. Marks

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1. Introduction

This report presents a comprehensive symmetrical three-phase fault analysis performed on an 11-bus power system network, as depicted in Figure 1. Symmetrical fault analysis is fundamental to power system planning, protection design, and equipment rating, particularly for determining maximum potential fault currents that may occur during short-circuit conditions.

The significance of this analysis extends beyond academic exercise to real-world applications:

- **System Protection:** Determining appropriate relay settings to ensure selective and coordinated fault clearance.
- **Equipment Rating:** Ensuring all power system components can withstand thermal and mechanical stresses during fault conditions.
- **Operational Safety:** Predicting system behaviour during contingencies to maintain grid stability and reliability.
- **Economic Optimization:** Selecting appropriately rated equipment without excessive overdesign.

The studied network comprises a grid connection feeding a ring system with a factory load and standby generator (G4). Since G4 is not connected during normal operation, it was excluded from the fault analysis calculations. The system operates at multiple voltage levels (12 kV, 13.8 kV, 20 kV, 132 kV, 11 kV), necessitating a consistent per-unit approach based on a 100 MVA common base.

The analysis methodology follows a systematic approach:

1. Converting all impedances to a common 100 MVA base to enable system-wide comparison.
2. Constructing the bus admittance matrix (Ybus) to mathematically represent the network.
3. Deriving the bus impedance matrix (Zbus) through matrix inversion.
4. Calculating three-phase fault currents and resulting voltage profiles at each bus.
5. Determining individual generator contributions to each fault scenario.
6. Selecting appropriate circuit breaker ratings based on calculated fault currents and X/R ratios.

This comprehensive approach provides a complete picture of the network's behaviour during fault conditions, enabling informed decisions for system protection and equipment specification. The analytical results are validated through comparison with PowerWorld simulation software, ensuring confidence in the findings and recommendations presented in this report.

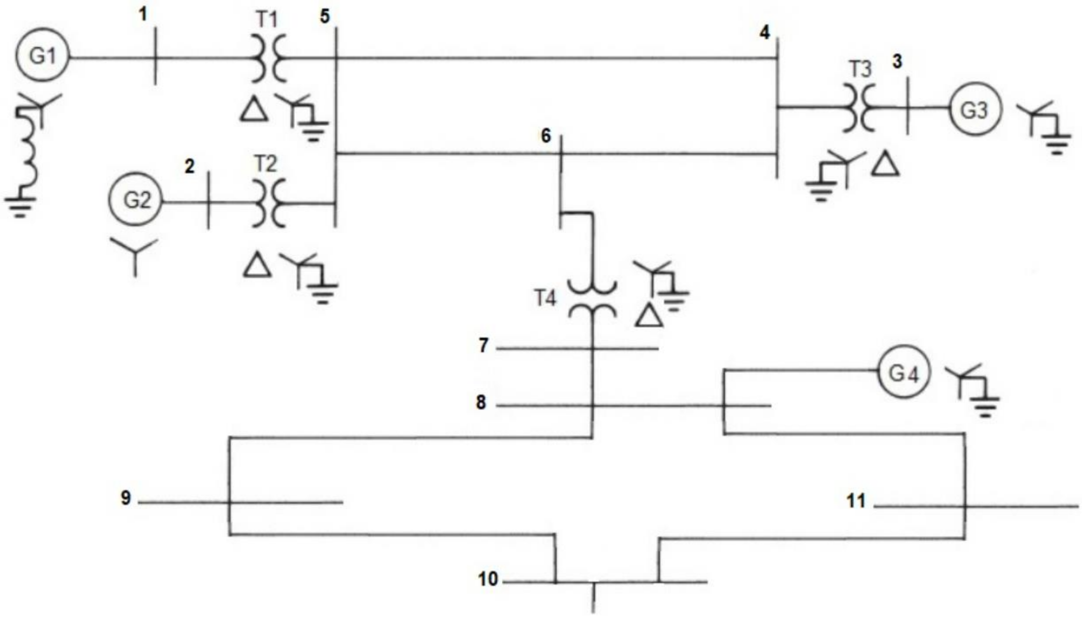


Figure 1: Network Diagram

2. Ybus and Zbus Matrices Development

The foundation of network fault analysis lies in representing the system mathematically using admittance (Ybus) and impedance (Zbus) matrices. The Ybus matrix describes the nodal connections and admittances, while the Zbus matrix (its inverse) is crucial for calculating fault currents and voltage responses.

2.1. Calculating Common Base Per Unit Impedances

Power systems typically operate at multiple voltage levels due to transformers. Direct comparison of impedance values (in ohms) is therefore not feasible. The per-unit system standardizes these values relative to common base quantities, simplifying calculations and comparisons across different voltage levels.

Base Values Selection

- **Base Apparent Power (Sbase)**: 100 MVA was chosen. This is Eskom standard and facilitates easy comparison with component ratings.
- **Base Voltage (Vbase)**: Base voltages are defined for different sections of the network, respecting the transformer turns ratios:

- $Bus\ 1\ (G1)$: $12\ kV$
- $Bus\ 2\ (G2)$: $13.8\ kV$
- $Bus\ 3\ (G3)$: $20\ kV$
- $Buses\ 4, 5, 6\ (Transmission)$: $132\ kV\ (Nominal)$
- $Buses\ 7, 8, 9, 10, 11\ (Factory\ Load)$: $11\ kV\ (Nominal)$

Based on my student number (220702330), the following MVA ratings were used for the generators and transformers:

- G1 and T1: 22 MVA (the first two non-zero digits of my student number)
- G2 and T2: 72 MVA (the next two non-zero digits of my student number)
- G3 and T3: 33 MVA (the next two non-zero digits of my student number)
- T4: 233 kVA (the last three non-zero digits of my student number)

Conversion Methodology

In this exercise, I perform symmetrical fault analysis of an 11-bus network. The network diagram is shown above in Figure 1, depicting a grid and a ring feed system/load representing a factory load with a standby generator G4. At present, G4 is on standby and not connected to the grid (therefore not included in the fault analysis calculations).

Other ratings

Item:	Voltages:	Impedances:
G1	12 kV	1+j18 %
G2	13.8 kV	2+j20 %
G3	20 kV	1.4+j25 %
T1	12/132 kV	0.7+j6.5 %
T2	13.8/132 kV	0.9+j7.5 %
T3	20/132 kV	0.5+j4.5 %
T4	132/11 kV	1,5+j10.5 %
Line 5-4	132 kV	20+j175 ohm
Line 5-6	132 kV	29+j225 ohm
Line 6-4	132 kV	8+j153 ohm
Line 7-8	11 kV	1+j4.3 ohm
Line 8-9	11 kV	3+j8.6 ohm
Line 9-10	11 kV	2+j6.2 ohm
Line 10-11	11 kV	1+j3.8 ohm
Line 8-11	11 kV	1.2+j5.1 ohm

Figure 2: Network Parameters

For Line Impedances

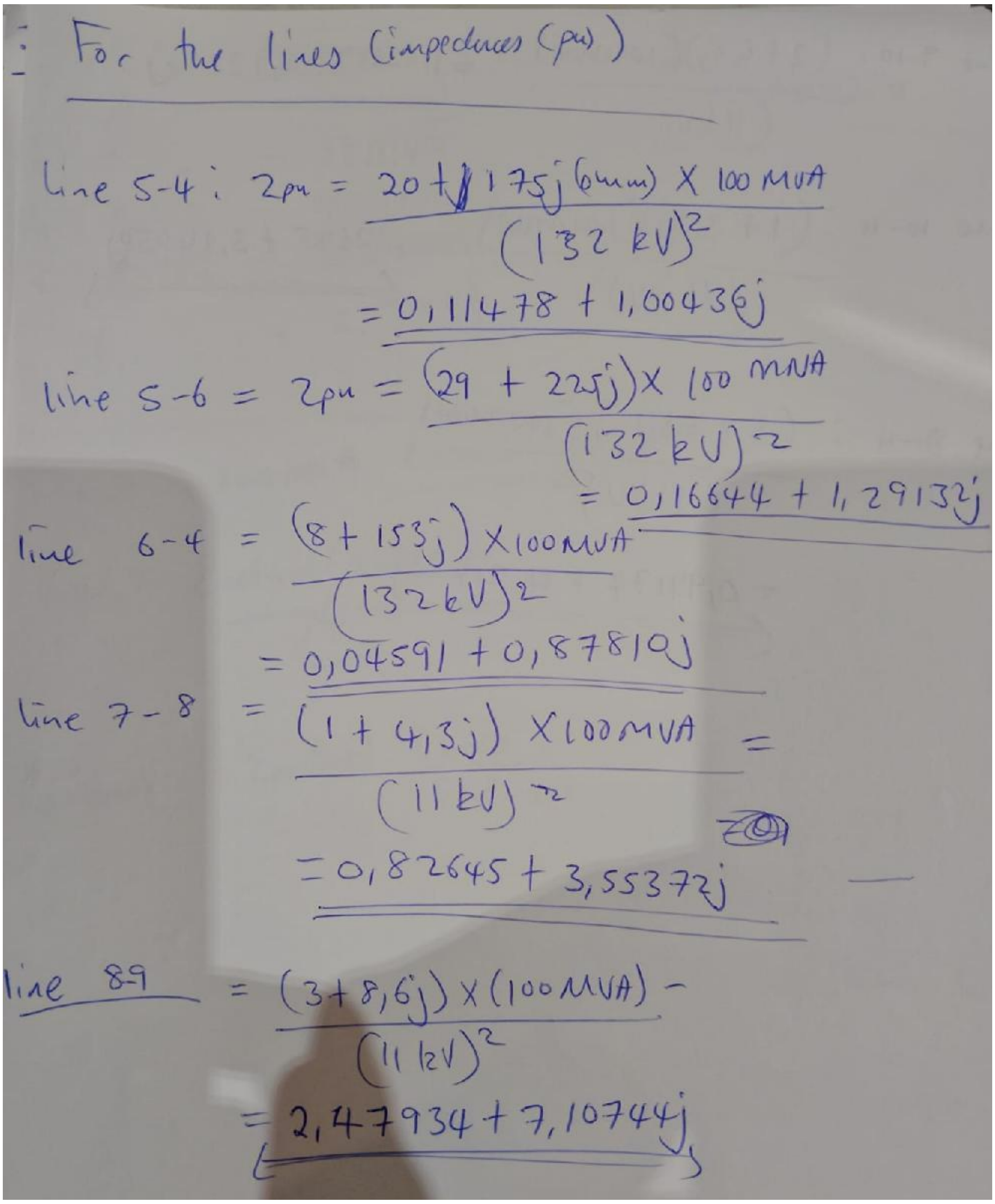
To convert line impedances from ohms to per-unit, the following equation was used:

$$Zpu = Zactual * \left(\frac{Sbase}{V_{Line}^2}\right) \ldots (1)$$

Where:

- Zpu is the calculated per-unit impedance
- $Zactual$ is the given impedance in ohms from Figure 2
- $Sbase$ is the base apparent power (100 MVA)
- V_{Line} is the line voltage at the respective line

The following figures show my calculations for these line impedances:



For the lines (impedances (pu))

Line 5-4: $Z_{pu} = \dfrac{(20 + 175j)(\Omega) \times 100\ MVA}{(132\ kV)^2}$

$= 0{,}11478 + 1{,}00436j$

line 5-6 = $Z_{pu} = \dfrac{(29 + 225j) \times 100\ MVA}{(132\ kV)^2}$

$= 0{,}16644 + 1{,}29132j$

line 6-4 = $\dfrac{(8 + 153j) \times 100MVA}{(132kV)^2}$

$= 0{,}04591 + 0{,}87810j$

line 7-8 = $\dfrac{(1 + 4{,}3j) \times 100MVA}{(11\ kV)^2} =$

$= 0{,}82645 + 3{,}55372j$

line 8-9 = $\dfrac{(3 + 8{,}6j) \times (100\ MVA)}{(11\ kV)^2}$

$= 2{,}47934 + 7{,}10744j$

Figure 3: Line Impedance Calculations 1

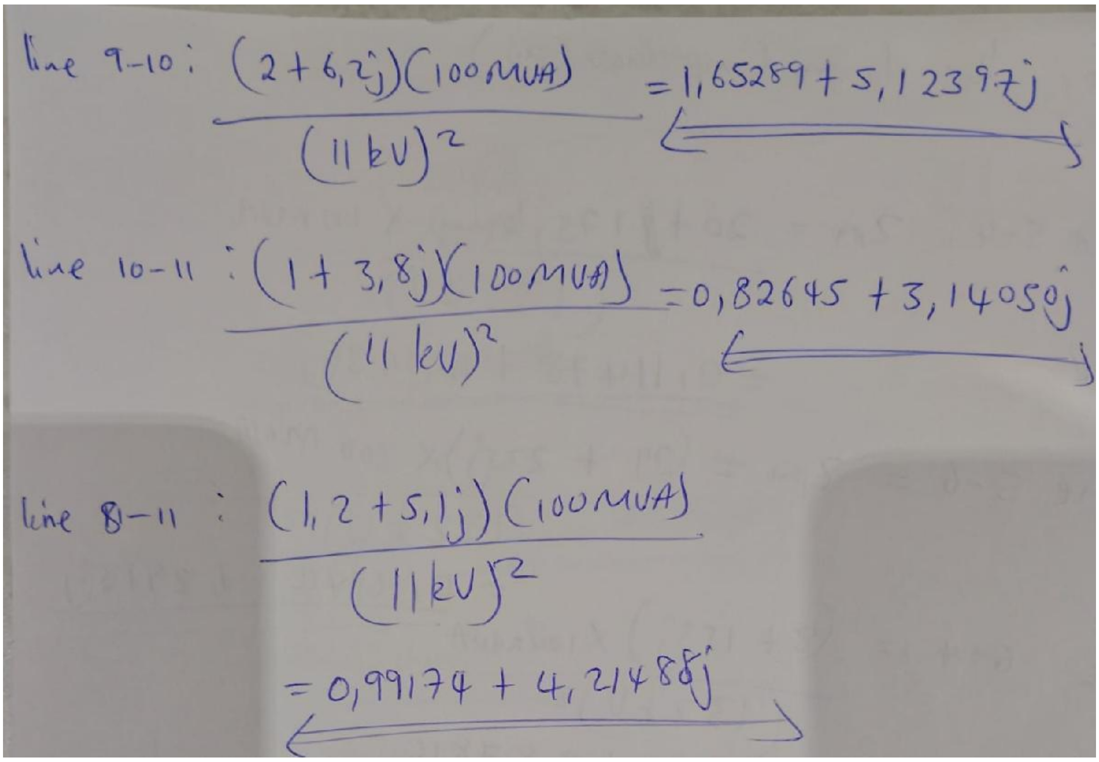


Figure 4: Line Impedance Calculations 2

For Generator and Transformer Impedances

For generators and transformers, the given percentage impedances were first divided by 100 to convert to per-unit, then adjusted to the common base using:

$$Zpu_{new} = Zpu_{rated} * \left(\frac{Sbase_{new}}{Srated}\right) \ldots (2)$$

Where:

- Zpu_{new} is the calculated common base per-unit impedance
- Zpu_{rated} is the given percentage impedance divided by 100
- $Sbase_{new}$ is the chosen base power (100 MVA)
- $Sbase_{rated}$ is the component's rated MVA value

The figures below show my calculations for these component impedances:

For the Gens & Transformers Z_{pu}

$$G_1: \frac{(1+18j)}{100} \times \frac{100\,MVA}{22\,MVA} = 0,04545 + 0,81818j$$

$$G_2: \frac{(2+20j)}{100} \times \frac{100\,MVA}{72\,MVA} = 0,02778 + 0,27778j$$

$$G_3: \frac{(1,4+25j)}{100} \times \frac{100\,MVA}{33\,MVA} = 0,04242 + 0,75758j$$

$$T_1: \frac{(0,7+6,5j)}{100} \times \frac{100\,MVA}{22\,MVA} = 0,03182 + 0,29545j$$

$$T_2: \frac{(0,9+7,5j)}{100} \times \frac{100\,MVA}{72\,MVA} = 0,01250 + 0,10417j$$

$$T_3: \frac{(0,5+4,5j)}{100} \times \frac{100\,MVA}{33\,MVA} = 0,01515 + 0,13636j$$

$$T_4: \frac{(1,5+10,5j)}{100} \times \frac{100\,MVA}{233\,kVA} = 6,43777 + 45,06438j$$

Figure 5: Generator and Transformer Impedance Calculations

With all impedances converted to a common base per-unit, I then converted the original network diagram to its per-unit equivalent admittance diagram.

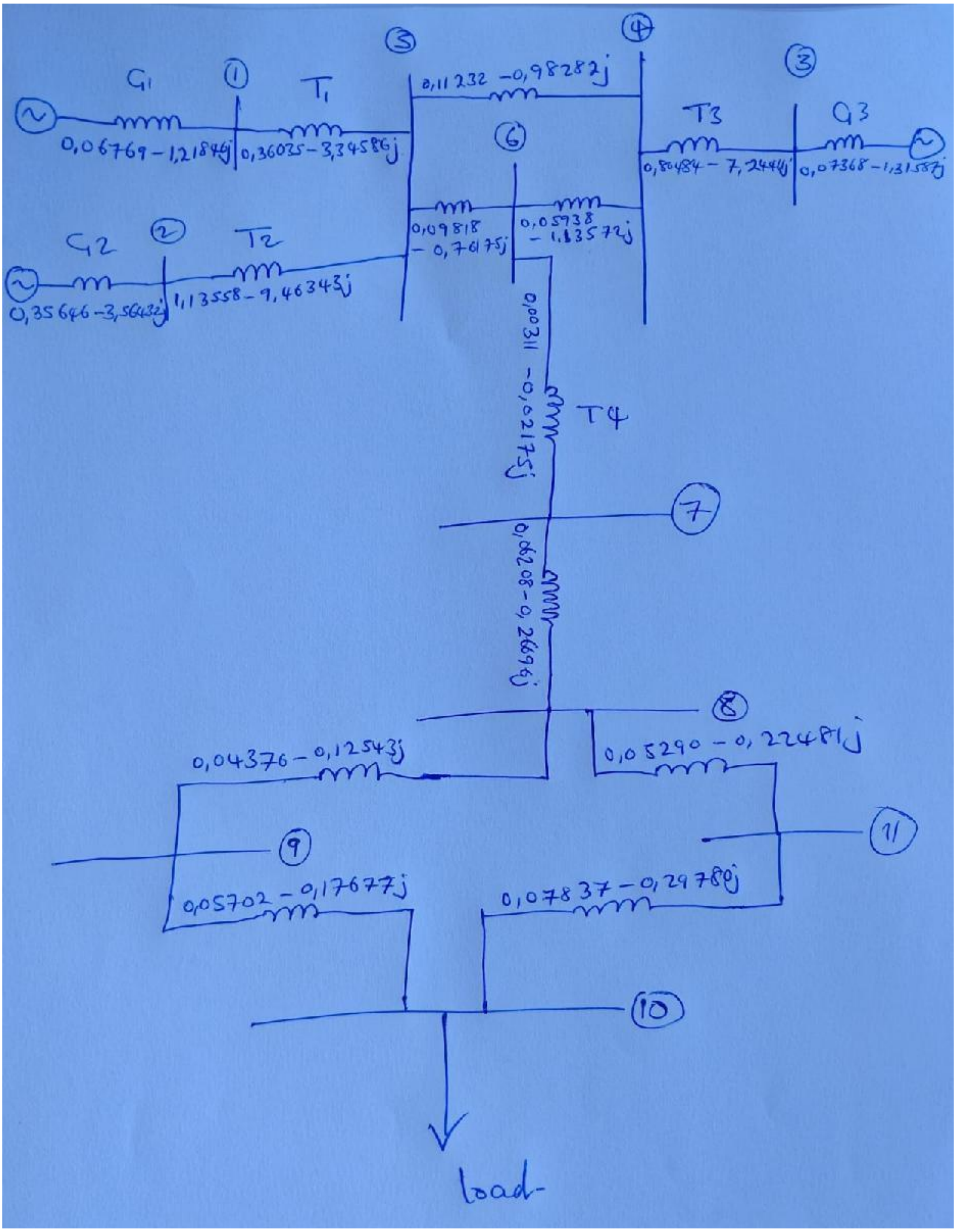


Figure 6: Resulting Admittance equivalent diagram

2.2. Developing the Admittance (Ybus) Matrix

The Ybus matrix is constructed based on the admittances of the system components. The admittance (Y) is the reciprocal of impedance (Z):

$$Y = \frac{1}{Z} \dots (3)$$

The elements of the Ybus matrix are determined as follows:

- **Diagonal Elements (Ynn):** The sum of all admittances directly connected to bus n.
- **Off-Diagonal Elements (Ynk):** The negative of the sum of all admittances connected directly between bus n and bus k. ($Ynk = Ykn$ due to symmetry). If there is no direct connection, $Ynk = 0$.

Diagonal Element Calculations

The diagonal values (Ynn) are calculated by adding all the admittances connected to bus n as shown in the figures below:

28.03.25 9:50 Calculating Ybus (Admittance) Matrix

Diagonal Values (Y_{nn})

Y_{nn} = Sum of all $\frac{1}{Z}$ values directly connected impedances to the bus (n).

$$Y_{11} = \frac{1}{(0{,}04545 + 0{,}81818j)} + \frac{1}{(0{,}03182 + 0{,}29545j)}$$

$$= 0{,}42804 - 4{,}56432j$$

$$Y_{22} = \frac{1}{(0{,}02778 + 0{,}27778j)} + \frac{1}{(0{,}01250 + 0{,}10417j)}$$

$$= 1{,}49203 - 13{,}02775j$$

$$Y_{33} = \frac{1}{(0{,}01515 + 0{,}13636j)} + \frac{1}{(0{,}04242 + 0{,}75758j)}$$

$$= 0{,}87852 - 8{,}55998j$$

$$Y_{44} = \frac{1}{(0{,}11478 + 1{,}00436j)} + \frac{1}{(0{,}04591 + 0{,}87810j)} + \frac{1}{(0{,}01515 + 0{,}13636j)}$$

$$= 0{,}97654 - 9{,}36265j$$

$$Y_{55} = \frac{1}{(0{,}03182 + 0{,}29545j)} + \frac{1}{(0{,}01250 + 0{,}10417j)} + \frac{1}{(0{,}11478 + 1{,}00436j)} + \frac{1}{(0{,}16644 + 1{,}29132j)}$$

$$= 1{,}70643 - 14{,}55386j$$

Figure 7: Diagonal Element Calculations 1

$$Y_{66} = \frac{1}{(6{,}43777 + 45{,}06438j)} + \frac{1}{(0{,}16644 + 1{,}29132j)} + \frac{1}{(0{,}04591 + 0{,}8781j)}$$

$$= 0{,}16067 - 1{,}91921j$$

$$Y_{77} = \frac{1}{(6{,}43777 + 45{,}06438j)} + \frac{1}{(0{,}82645 + 3{,}55372j)}$$

$$= 0{,}06519 - 0{,}28870j$$

$$Y_{88} = \frac{1}{(0{,}82645 + 3{,}55372j)} + \frac{1}{(2{,}47934 + 7{,}10744j)} + \frac{1}{(0{,}99174 + 4{,}21488j)}$$

$$= 0{,}15874 - 0{,}61720j$$

$$Y_{99} = \frac{1}{(2{,}47934 + 7{,}10744j)} + \frac{1}{(1{,}65289 + 5{,}12397j)}$$

$$= 0{,}10078 - 0{,}30220j$$

$$Y_{1010} = \frac{1}{(1{,}65289 + 5{,}12397j)} + \frac{1}{(0{,}82645 + 3{,}14050j)}$$

$$= 0{,}13539 - 0{,}47456j$$

$$Y_{1111} = \frac{1}{(0{,}82645 + 3{,}14050j)} + \frac{1}{(0{,}99174 + 4{,}21488j)}$$

$$= 0{,}13126 - 0{,}52261j$$

Figure 8: Diagonal Element Calculations 2

Off-Diagonal Element Calculations

The non-diagonal values (Yab) are calculated by adding the sum of all admittances between bus a and bus b, then multiplying that sum by -1. Note that Yab = Yba and Yab = 0 where there is no direct link between bus a and bus b. My calculations are shown below:

Non-Diagonals

$$Y_{nk} = -\left(\text{Sum of all } \frac{1}{Z_{nk}}\right) \text{ between 2 buses } k \text{ and } n$$

$$Y_{15} = -\left(\frac{1}{(0{,}03182 + 0{,}29545j)}\right) = -0{,}36035 + 3{,}34586j$$

$$Y_{25} = -\left(\frac{1}{(0{,}01250 + 0{,}10417j)}\right) = -1{,}13558 + 9{,}46343j$$

$$Y_{45} = -\left(\frac{1}{(0{,}11478 + 1{,}00436j)}\right) = -0{,}11232 + 0{,}98282j$$

$$Y_{56} = -\left(\frac{1}{(0{,}16644 + 1{,}29132j)}\right) = -0{,}09818 + 0{,}76175j$$

$$Y_{46} = -\left(\frac{1}{(0{,}04591 + 0{,}87810j)}\right) = -0{,}05938 + 1{,}13572j$$

$$Y_{34} = -\left(\frac{1}{(0{,}01515 + 0{,}13636j)}\right) = -0{,}80484 + 7{,}24411j$$

$$Y_{67} = -\left(\frac{1}{(6{,}43777 + 45{,}06438j)}\right) = -0{,}00311 + 0{,}02175j$$

$$Y_{78} = -\left(\frac{1}{(0{,}82645 + 3{,}55372j)}\right) = -0{,}06208 + 0{,}26696j$$

$$Y_{89} = -\left(\frac{1}{(2{,}47934 + 7{,}10744j)}\right) = -0{,}04376 + 0{,}12543j$$

$$Y_{910} = -\left(\frac{1}{(1{,}65289 + 5{,}12397j)}\right) = -0{,}05702 + 0{,}17677j$$

Figure 9: Off-Diagonal Element Calculations 1

$$Y_{10\,11} = -\left(\frac{1}{(0{,}82645 + 3{,}14050j)}\right) = -0{,}07837 + 0{,}29780j$$

$$Y_{8\,11} = -\left(\frac{1}{(0{,}99174 + 4{,}21488j)}\right) = -0{,}05290 + 0{,}22481j$$

Figure 10: Off-Diagonal Element Calculations 2

Complete Ybus Matrix

Test1_220702330.mlx | Ybus = 11×11 complex

	1	2	3	4	5	6	7	8	9	10	11
1	0.4280 - 4.5643i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	-0.3604 + 3.3459i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i
2	0.0000 + 0.0000i	1.4920 -13.0277i	0.0000 + 0.0000i	0.0000 + 0.0000i	-1.1356 + 9.4634i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i
3	0.0000 + 0.0000i	0.0000 + 0.0000i	0.8785 - 8.5600i	-0.8048 + 7.2441i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i
4	0.0000 + 0.0000i	0.0000 + 0.0000i	-0.8048 + 7.2441i	0.9765 - 9.3627i	-0.1123 + 0.9828i	-0.0594 + 1.1357i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i
5	-0.3604 + 3.3459i	-1.1356 + 9.4634i	0.0000 + 0.0000i	-0.1123 + 0.9828i	1.7064 -14.5539i	-0.0982 + 0.7618i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i
6	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	-0.0594 + 1.1357i	-0.0982 + 0.7618i	0.1607 - 1.9192i	-0.0031 + 0.0217i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i
7	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	-0.0031 + 0.0217i	0.0652 - 0.2887i	-0.0621 + 0.2670i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i
8	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	-0.0621 + 0.2670i	0.1587 - 0.6172i	-0.0438 + 0.1254i	0.0000 + 0.0000i	-0.0529 + 0.2248i
9	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	-0.0438 + 0.1254i	0.1008 - 0.3022i	-0.0570 + 0.1768i	0.0000 + 0.0000i
10	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	-0.0570 + 0.1768i	0.1354 - 0.4746i	-0.0784 + 0.2978i
11	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	0.0000 + 0.0000i	-0.0529 + 0.2248i	0.0000 + 0.0000i	-0.0784 + 0.2978i	0.1313 - 0.5226i

Figure 11: Resulting Ybus Matrix from MATLAB

With all the bus admittances calculated, they can now be fed into MATLAB for precise matrix manipulation to calculate the impedance (Zbus) matrix for the network.

2.3. PowerWorld Simulation Verification

To validate the hand and MATLAB calculations, the network was simulated using PowerWorld Simulator software.

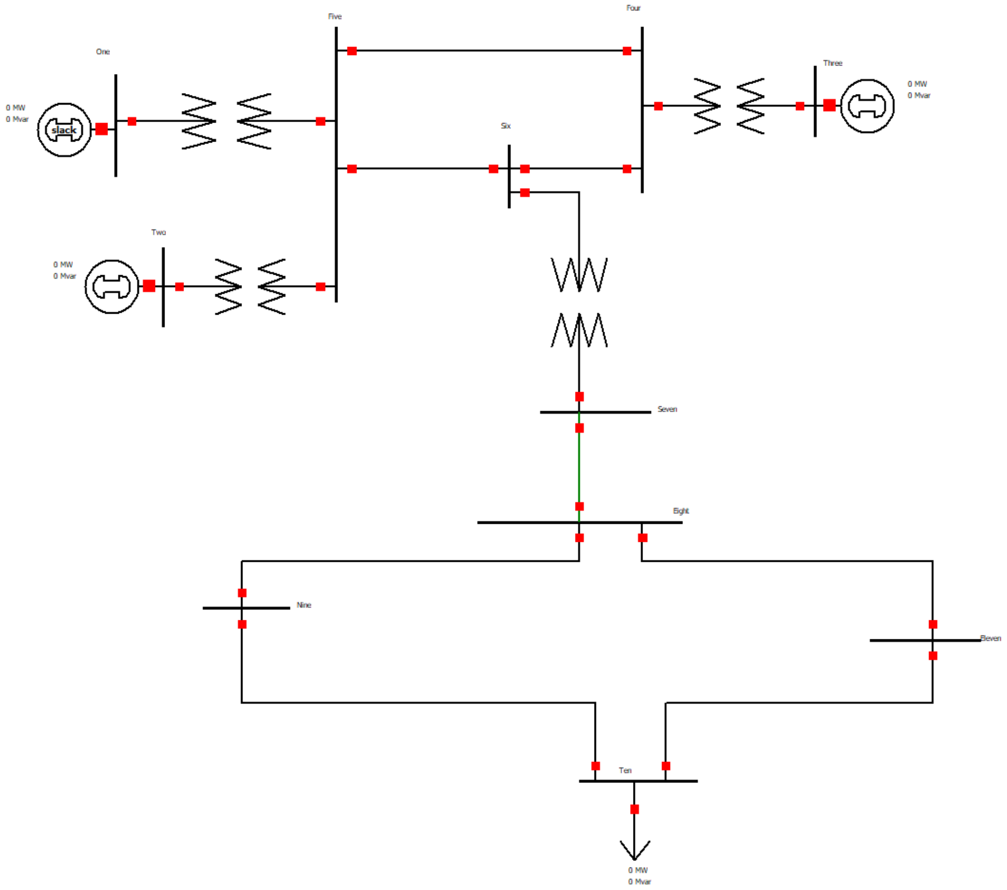


Figure 12: PowerWorld Simulator Network Diagram

The Ybus matrix generated by PowerWorld is shown below:

	Number	Name	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11
1	1	One	0,43 - j4,56				-0,36 + j3,35						
2	2	Two		1,49 - j13,03			-1,14 + j9,46						
3	3	Three			0,88 - j8,56	-0,80 + j7,24							
4	4	Four			-0,80 + j7,24	0,98 - j9,36	-0,11 + j0,98	-0,06 + j1,14					
5	5	Five	-0,36 + j3,35	-1,14 + j9,46		-0,11 + j0,98	1,71 - j14,55	-0,10 + j0,76					
6	6	Six				-0,06 + j1,14	-0,10 + j0,76	0,16 - j1,92	-0,00 + j0,02				
7	7	Seven						-0,00 + j0,02	0,07 - j0,29	-0,06 + j0,27			
8	8	Eight							-0,06 + j0,27	0,16 - j0,62	-0,04 + j0,13		-0,05 + j0,22
9	9	Nine								-0,04 + j0,13	0,10 - j0,30	-0,06 + j0,18	
10	10	Ten									-0,06 + j0,18	0,14 - j0,47	-0,08 + j0,30
11	11	Eleven								-0,05 + j0,22		-0,08 + j0,30	0,13 - j0,52

Figure 13: PowerWorld Simulator Ybus Matrix Output

Comparing the PowerWorld Ybus matrix with the one calculated by hand and implemented in MATLAB reveals strong conformity. Minor differences in the representation (e.g. Numerical precision) are negligible and likely due to software tolerances or display formatting. The close match provides confidence in the calculated per-unit values and the structure of the Ybus matrix used for subsequent analysis. PowerWorld serves as an effective tool for verifying network parameters before proceeding to fault calculations.

2.2. Developing the Impedance (Zbus) Matrix

The bus impedance matrix (Zbus) is essential for fault analysis, as it directly relates the pre-fault voltage to the fault current ($Ifault\ = \frac{Vpre_{fault}}{Znn}$) and allows calculation of voltages at all other buses during a fault. Zbus is obtained by inverting the Ybus matrix:

$$Zbus \;=\; inv(Ybus)$$

This inversion was performed using MATLAB. And resulted in Figure below:

Test1_220702330.mlx | Zbus = 11×11 complex

	1	2	3	4	5	6	7	8	9	10	11
1	0.0290 + 0.3474i	0.0097 + 0.1288i	0.0045 + 0.0849i	0.0061 + 0.1002i	0.0142 + 0.1772i	0.0080 + 0.1314i	0.0080 + 0.1315i	0.0079 + 0.1315i	0.0079 + 0.1315i	0.0079 + 0.1315i	0.0079 + 0.1315i
2	0.0097 + 0.1288i	0.0193 + 0.2033i	0.0051 + 0.0841i	0.0069 + 0.0992i	0.0156 + 0.1753i	0.0090 + 0.1300i	0.0090 + 0.1302i	0.0090 + 0.1302i	0.0090 + 0.1302i	0.0090 + 0.1302i	0.0090 + 0.1302i
3	0.0045 + 0.0849i	0.0051 + 0.0841i	0.0343 + 0.4501i	0.0298 + 0.3947i	0.0077 + 0.1156i	0.0260 + 0.2818i	0.0259 + 0.2821i	0.0259 + 0.2821i	0.0259 + 0.2821i	0.0259 + 0.2821i	0.0259 + 0.2821i
4	0.0061 + 0.1002i	0.0069 + 0.0992i	0.0298 + 0.3947i	0.0391 + 0.4656i	0.0102 + 0.1364i	0.0335 + 0.3324i	0.0334 + 0.3328i	0.0334 + 0.3328i	0.0334 + 0.3328i	0.0334 + 0.3328i	0.0334 + 0.3328i
5	0.0142 + 0.1772i	0.0156 + 0.1753i	0.0077 + 0.1156i	0.0102 + 0.1364i	0.0227 + 0.2411i	0.0133 + 0.1788i	0.0133 + 0.1790i	0.0133 + 0.1790i	0.0133 + 0.1790i	0.0133 + 0.1790i	0.0133 + 0.1790i
6	0.0080 + 0.1314i	0.0090 + 0.1300i	0.0260 + 0.2818i	0.0335 + 0.3324i	0.0133 + 0.1788i	0.0716 + 0.7936i	0.0714 + 0.7944i	0.0714 + 0.7944i	0.0714 + 0.7944i	0.0714 + 0.7945i	0.0714 + 0.7944i
7	0.0080 + 0.1315i	0.0090 + 0.1302i	0.0259 + 0.2821i	0.0334 + 0.3328i	0.0133 + 0.1790i	0.0714 + 0.7944i	6.5054 +45.8966i	6.5045 +45.8988i	6.5043 +45.9003i	6.5042 +45.9013i	6.5035 +45.9006i
8	0.0079 + 0.1315i	0.0090 + 0.1302i	0.0259 + 0.2821i	0.0334 + 0.3328i	0.0133 + 0.1790i	0.0714 + 0.7944i	6.5045 +45.8988i	7.3298 +49.4549i	7.3297 +49.4564i	7.3295 +49.4576i	7.3288 +49.4568i
9	0.0079 + 0.1315i	0.0090 + 0.1302i	0.0259 + 0.2821i	0.0334 + 0.3328i	0.0133 + 0.1790i	0.0714 + 0.7944i	6.5043 +45.9003i	7.3297 +49.4564i	8.7917 +53.9913i	8.1076 +52.1346i	7.7561 +50.9922i
10	0.0079 + 0.1315i	0.0090 + 0.1302i	0.0259 + 0.2821i	0.0334 + 0.3328i	0.0133 + 0.1790i	0.0714 + 0.7945i	6.5042 +45.9013i	7.3295 +49.4576i	8.1076 +52.1346i	8.6187 +54.0618i	8.0357 +52.0973i
11	0.0079 + 0.1315i	0.0090 + 0.1302i	0.0259 + 0.2821i	0.0334 + 0.3328i	0.0133 + 0.1790i	0.0714 + 0.7944i	6.5035 +45.9006i	7.3288 +49.4568i	7.7561 +50.9922i	8.0357 +52.0973i	8.1670 +52.7705i

Figure 14: Network Zbus matrix as calculated in MATLAB

The Zbus matrix provides the driving point (diagonal) and transfer (off-diagonal) impedances necessary for fault calculations.

3. Calculating Fault Currents and Fault Voltages

Calculating fault currents and the resulting bus voltages across the network during a fault is the primary objective of this analysis. These values dictate the requirements for protective devices and assess the voltage stability of the system under fault conditions. A bolted three-phase symmetrical fault is assumed at each bus, one at a time. Pre-fault currents are neglected, and the pre-fault voltage (Vf) at all buses is assumed to be 1.0 pu at an angle of 0 degrees.

3.1. Fault Current Calculations & Results

The symmetrical fault current (Ifault) at the faulted bus 'n' is calculated using the diagonal element of the Zbus matrix (Znn, the driving point impedance at bus n) and the pre-fault voltage (Vf):

$$Ifault(n) = \frac{Vf}{Zbus(n,n)} \ldots (pu)$$

To obtain the actual fault current in Amperes (A), the per-unit value is multiplied by the base current for the faulted bus 'n' (Ibase_n):

$$Ibase_n = \frac{Sbase}{\sqrt{3} * Vbase_n} \ldots (A)$$

$$Ifault_{actual(n)} = Ifault(n)_{pu} * Ibase_n \dots (A)$$

These calculations were performed in MATLAB for faults at each bus (1 through 11).

Table 1: Symmetrical Fault Currents (Per Unit)

Fault Currents (pu):

Faulted_Bus	Magnitude_pu	Angle_deg
1	2.8687	-85.222
2	4.8977	-84.572
3	2.2152	-85.642
4	2.14	-85.202
5	4.1295	-84.613
6	1.255	-84.843
7	0.021572	-81.933
8	0.020002	-81.569
9	0.018281	-80.751
10	0.018267	-80.942
11	0.018727	-81.202

Table 2: Symmetrical Fault Currents (Actual, kA)

Fault Currents (Actual, kA):

Faulted_Bus	Fault_Current_kA	Fault_Current_Angle
1	13.802	-85.222
2	20.49	-84.572
3	6.3949	-85.642
4	0.93602	-85.202
5	1.8062	-84.613
6	0.54892	-84.843
7	0.11323	-81.933
8	0.10498	-81.569
9	0.095949	-80.751
10	0.095875	-80.942
11	0.098291	-81.202

3.2. Fault Voltage Calculations & Results

During a fault at bus 'n', the voltage at any bus 'k' (E(k)) can be calculated using the Zbus matrix elements (Zkn, the transfer impedance between k and n, and Znn) and the pre-fault voltage (Vf):

$$E(k) = Vf * \left[1 - \frac{Zbus(k,n)}{Zbus(n,n)}\right] \dots (pu)$$

The actual voltage at bus 'k' during the fault at bus 'n' is then:

$$E_{actual(k)} = E(k)_{pu} * Vbase_k \dots (kV)$$

These calculations were performed in MATLAB for faults at each bus, determining the resulting voltages at all other buses.

Table 3: Fault Voltages (Per Unit Magnitude | Angle in Degrees)

```
disp(voltTable_pu);
```

Faulted_Bus	Bus1_Mag	Bus1_Ang	Bus2_Mag	Bus2_Ang	Bus3_Mag	Bus3_Ang	Bus4_Mag	Bus4_Ang	Bus5_Mag	Bus5_Ang	Bus6_Mag	Bus6_Ang
1	0	90	0.6294	-0.29	0.7562	-0.57	0.7121	-0.52	0.4901	-0.19	0.6226	-0.79
2	0.3675	-1.96	0	0	0.588	-1.36	0.5134	-1.38	0.138	-2.18	0.3622	-2.59
3	0.8117	-0.31	0.8135	-0.2	0	0	0.1232	-0.29	0.7434	-0.19	0.3733	1.53
4	0.7852	-0.36	0.7873	-0.22	0.1532	-2.65	0	0	0.7073	-0.21	0.2853	2.38
5	0.2662	-2.18	0.2732	-0.82	0.5219	-1.45	0.4354	-1.43	0	0	0.2601	-3.19
6	0.8349	-0.33	0.8365	-0.23	0.6448	0.06	0.5807	0.43	0.775	-0.26	0	0
7	0.9972	-0.01	0.9972	-0.01	0.9939	-0.02	0.9928	-0.02	0.9961	-0.01	0.9828	-0.05
8	0.9974	-0.01	0.9974	-0.01	0.9943	-0.02	0.9933	-0.02	0.9964	-0.02	0.9841	-0.05
9	0.9976	-0.01	0.9976	-0.01	0.9948	-0.02	0.9939	-0.02	0.9967	-0.02	0.9855	-0.06
10	0.9976	-0.01	0.9976	-0.01	0.9948	-0.02	0.9939	-0.02	0.9967	-0.02	0.9855	-0.06
11	0.9975	-0.01	0.9976	-0.01	0.9947	-0.02	0.9937	-0.02	0.9966	-0.02	0.9851	-0.06

Faulted_Bus	Bus7_Mag	Bus7_Ang	Bus8_Mag	Bus8_Ang	Bus9_Mag	Bus9_Ang	Bus10_Mag	Bus10_Ang	Bus11_Mag	Bus11_Ang
1	0.6222	-0.8	0.6222	-0.8	0.6222	-0.8	0.6222	-0.8	0.6222	-0.8
2	0.3616	-2.63	0.3616	-2.63	0.3616	-2.63	0.3616	-2.63	0.3616	-2.64
3	0.3727	1.5	0.3726	1.5	0.3726	1.5	0.3726	1.5	0.3726	1.5
4	0.2846	2.35	0.2846	2.34	0.2846	2.34	0.2845	2.34	0.2846	2.34
5	0.2594	-3.25	0.2594	-3.26	0.2593	-3.26	0.2593	-3.26	0.2593	-3.26
6	0.001	-161.55	0.0011	-160.91	0.0011	-161.06	0.0011	-161.14	0.0011	-160.22
7	0	0	0.0001	-148.09	0.0001	-155.04	0.0001	-157.18	0.0001	-145.84
8	0.073	-4.64	0	0	0	-166.31	0.0001	-165.75	0	-143.16
9	0.1537	-6.54	0.0871	-8.62	0	0	0.0362	-10.98	0.058	-9.8
10	0.154	-5.47	0.0873	-6.58	0.0364	-5.79	0	0	0.0374	-7.47
11	0.1324	-4.81	0.064	-5.4	0.0342	-4.21	0.0128	-2.24	0	0

Table 4: Fault Voltages (kV Magnitude | Angle in Degrees)

```
disp(voltTable_kV);
```

Faulted_Bus	Bus1_Mag	Bus1_Ang	Bus2_Mag	Bus2_Ang	Bus3_Mag	Bus3_Ang	Bus4_Mag	Bus4_Ang	Bus5_Mag	Bus5_Ang	Bus6_Mag	Bus6_Ang
1	0	90	8.6852	-0.29	15.124	-0.57	93.996	-0.52	64.689	-0.19	82.179	-0.79
2	4.4103	-1.96	0	0	11.76	-1.36	67.77	-1.38	18.222	-2.18	47.816	-2.59
3	9.7401	-0.31	11.226	-0.2	0	0	16.262	-0.29	98.126	-0.19	49.272	1.53
4	9.4226	-0.36	10.864	-0.22	3.0632	-2.65	0	0	93.366	-0.21	37.661	2.38
5	3.1944	-2.18	3.7698	-0.82	10.439	-1.45	57.478	-1.43	0	0	34.331	-3.19
6	10.019	-0.33	11.543	-0.23	12.896	0.06	76.654	0.43	102.3	-0.26	0	0
7	11.966	-0.01	13.761	-0.01	19.878	-0.02	131.05	-0.02	131.49	-0.01	129.73	-0.05
8	11.969	-0.01	13.764	-0.01	19.887	-0.02	131.12	-0.02	131.53	-0.02	129.9	-0.05
9	11.971	-0.01	13.767	-0.01	19.897	-0.02	131.19	-0.02	131.57	-0.02	130.08	-0.06
10	11.971	-0.01	13.767	-0.01	19.897	-0.02	131.19	-0.02	131.57	-0.02	130.08	-0.06
11	11.97	-0.01	13.766	-0.01	19.894	-0.02	131.17	-0.02	131.56	-0.02	130.03	-0.06

Faulted_Bus	Bus7_Mag	Bus7_Ang	Bus8_Mag	Bus8_Ang	Bus9_Mag	Bus9_Ang	Bus10_Mag	Bus10_Ang	Bus11_Mag	Bus11_Ang
1	6.8443	-0.8	6.8441	-0.8	6.8439	-0.8	6.8439	-0.8	6.8439	-0.8
2	3.9781	-2.63	3.9778	-2.63	3.9776	-2.63	3.9774	-2.63	3.9776	-2.64
3	4.0992	1.5	4.0989	1.5	4.0987	1.5	4.0986	1.5	4.0987	1.5
4	3.1307	2.35	3.1304	2.34	3.1301	2.34	3.1299	2.34	3.1301	2.34
5	2.8532	-3.25	2.8529	-3.26	2.8526	-3.26	2.8525	-3.26	2.8526	-3.26
6	0.0112	-161.55	0.0118	-160.91	0.0121	-161.06	0.0124	-161.14	0.0122	-160.22
7	0	0	0.0006	-148.09	0.0009	-155.04	0.0012	-157.18	0.001	-145.84
8	0.8032	-4.64	0	0	0.0004	-166.31	0.0006	-165.75	0.0005	-143.16
9	1.6908	-6.54	0.9581	-8.62	0	0	0.3979	-10.98	0.638	-9.8
10	1.6939	-5.47	0.9607	-6.58	0.4006	-5.79	0	0	0.4117	-7.47
11	1.4561	-4.81	0.7041	-5.4	0.376	-4.21	0.1413	-2.24	0	0

To better understand the system's response to faults, the calculated data are visualized graphically. This approach (of visualizing results through graphs) has been applied throughout the assignment. [1]

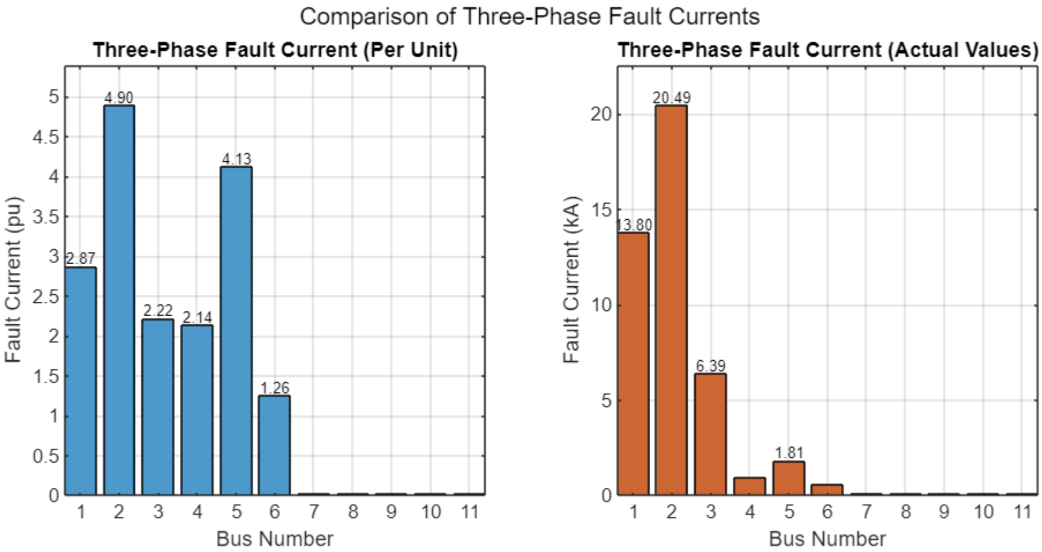


Figure 15: Comparison of Three-Phase Fault Currents (pu and kA)

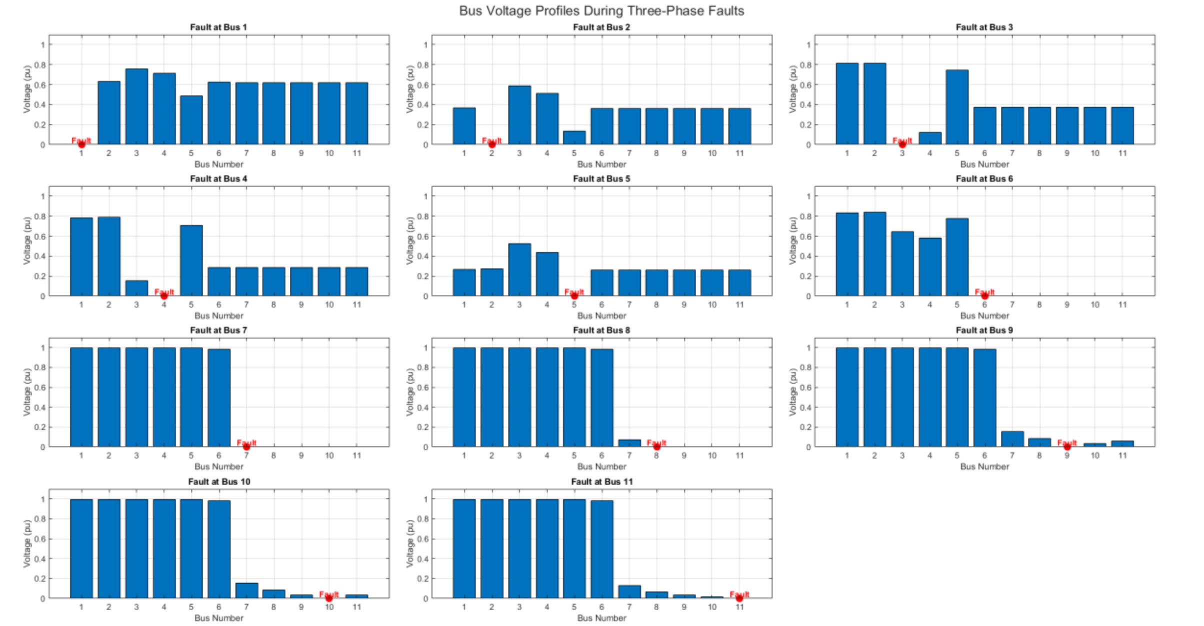


Figure 16: Bus Voltage Profiles During Three-Phase Faults at Each Bus

3.3. Analysis of Fault Currents and Voltages

- **Fault Currents:** As observed in Table 2 and Figure 15, the highest fault current occurs for a fault at Bus 2 (20.49 kA), followed closely by Bus 1 (13.80 kA) and Bus 3 (6.39 kA). These buses are directly connected to the main generators (G1, G2, G3) via their step-up transformers, providing low impedance paths for fault current contribution. The lowest fault currents are seen at the buses electrically furthest from the generation sources, within the 11 kV factory load ring (Buses 7-11), with magnitudes around 0.1 kA. The fault current magnitude generally decreases as the electrical distance (impedance) from the generation sources to the faulted bus increases.
- **Fault Voltages:** Figure 16 clearly shows that during a fault at any given bus, the voltage at that bus collapses to zero (as expected for a bolted fault). The voltages at adjacent buses also decrease significantly, while buses further away experience less severe voltage drops. For example, a fault at Bus 1 (generator bus) causes significant voltage drops across the transmission system (Buses 4, 5, 6) and the load buses (7-11), though less severe than the drop at the faulted bus itself. Conversely, a fault at a load bus like Bus 9 causes a severe drop at Bus 9 and its neighbours (8, 10, 11) but results in only a minor voltage dip at the generator buses (1, 2, 3) and the high-voltage transmission buses (4, 5, 6). This illustrates the principle of fault current limiting by system impedance. The voltage angles (Tables 3 & 4) also shift during faults, reflecting the change in power flow patterns, but the magnitudes are generally the primary concern for protection and voltage stability analysis.

The results obtained conform with the PowerWorld simulation results as well as calculated for each bus in the “single faults” tab in PowerWorld Simulator.

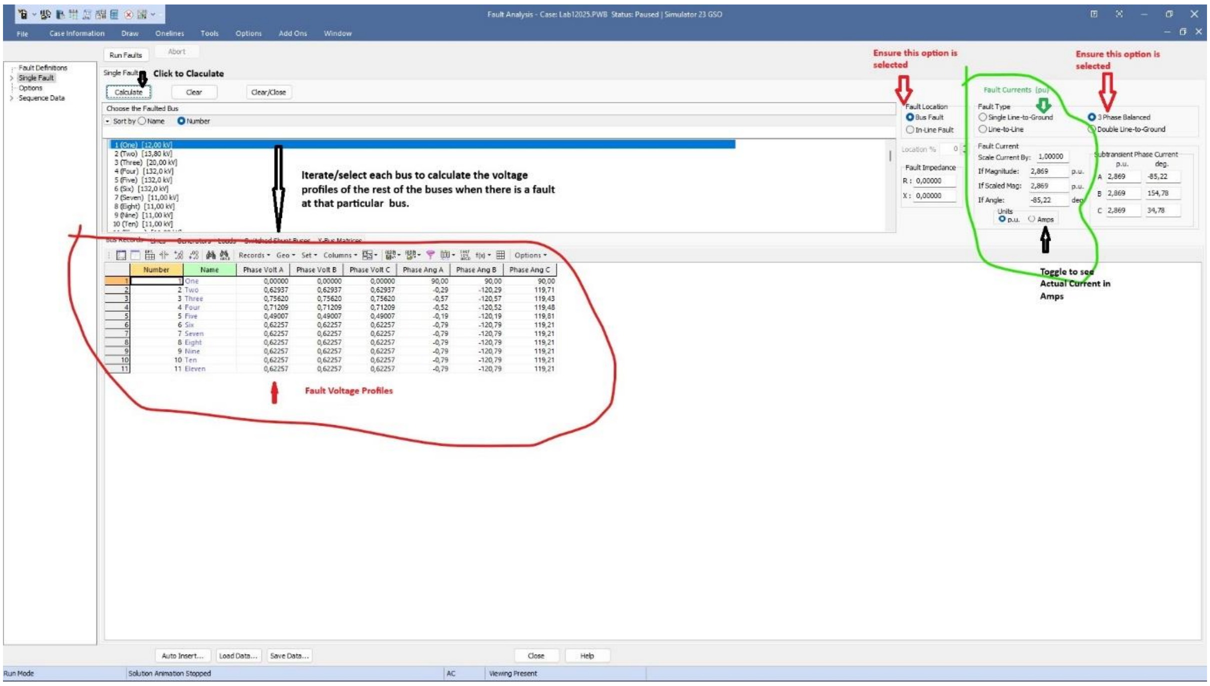


Figure 17: Confirming results in PowerWorld Simulator

4. Investigating Generator Contribution to Faults

During a fault, multiple generators connected to the network contribute current to the fault point. Understanding the magnitude of each generator's contribution is important for coordinating protection schemes, particularly differential protection.

4.1. Methodology

The contribution of each generator 'g' (connected at bus 'gen_bus') to a fault at bus 'n' can be calculated using the voltage difference across the generator's internal impedance $(Zgen\_pu)$ during the fault. The voltage at the generator's bus during the fault is $E(fault\_bus, gen\_bus)$ (calculated previously). The pre-fault voltage behind the generator impedance is Vf (assumed 1.0 pu).

$$I_{contribution} = \frac{Vf\ -\ E(fault_{bus}, gen_{bus})}{Zgen_{pu(g)}} \ldots (pu)$$

The total fault current is the phasor sum of contributions from all sources (in this case, neglecting pre-fault load currents, it's primarily the sum of generator contributions feeding into the fault through the network). The percentage contribution of each generator is calculated relative to the *total* fault current (sum of absolute contributions for simplicity in this analysis):

$$\% \; Contribution \; = \left[\frac{\left| I_{contribution(g)} \right|}{\Sigma \left| I_{contribution(all)} \right|} \right] * \; 100\%$$

Alternatively:

$$\% \; Contribution \; = \left[\frac{gen_{contributions_{pu(f,g)}}}{total_{fault_{current_{pu(f)}}}} \right] * \; 100\%$$

where $total\_fault\_current\_pu(f)$ is the sum of the *absolute* values of individual generator pu contributions for a fault at bus f.

4.2. Generator Contribution Results

The contributions of G1, G2, and G3 to faults at each of the 11 buses were calculated in pu, actual Amperes (using the generator's specific Ibase), and as a percentage of the total fault current.

Table 5: Generator Contributions (Percentage of Total Fault Current)

```
disp(genContribTable);
```

Faulted_Bus	G1_Percent	G2_Percent	G3_Percent
1	42.527	46.269	11.204
2	15.767	73.136	11.097
3	10.374	30.153	59.473
4	12.249	35.601	52.15
5	21.69	63.043	15.266
6	16.055	46.664	37.281
7	16.055	46.664	37.281
8	16.055	46.664	37.281
9	16.055	46.664	37.281
10	16.055	46.664	37.281
11	16.055	46.664	37.281

4.3. Graphical Visualization of Contributions

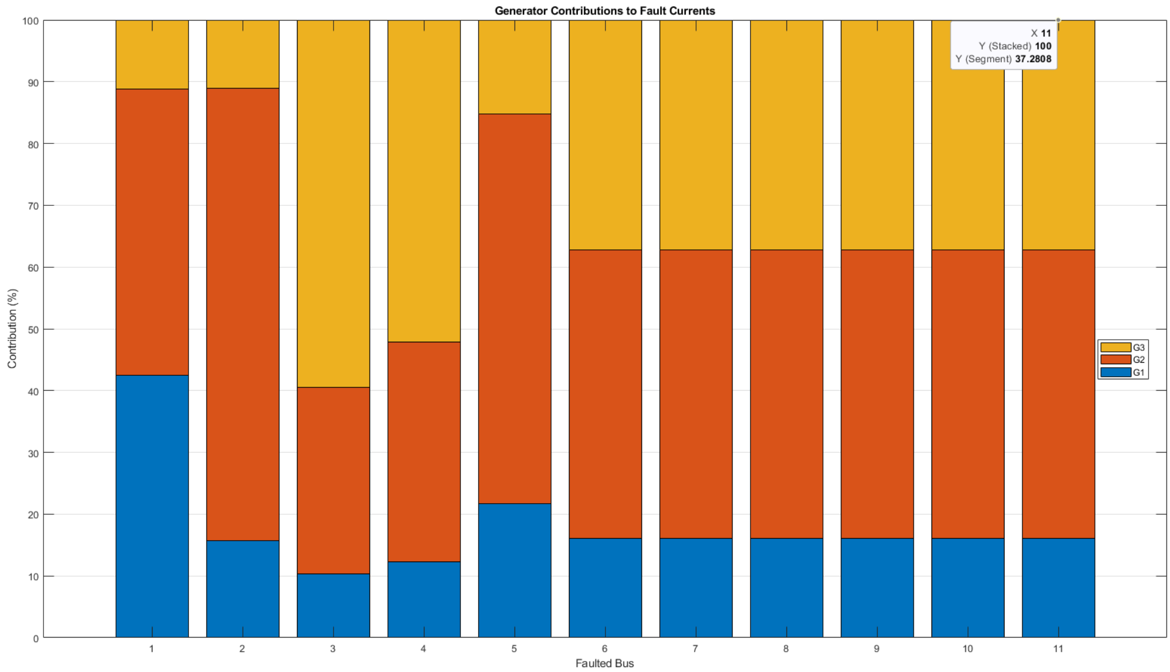


Figure 18:Generator Contributions to Fault Currents at Each Bus (%)

These results were also confirmed in PowerWorld, as exemplified in Figure 19:

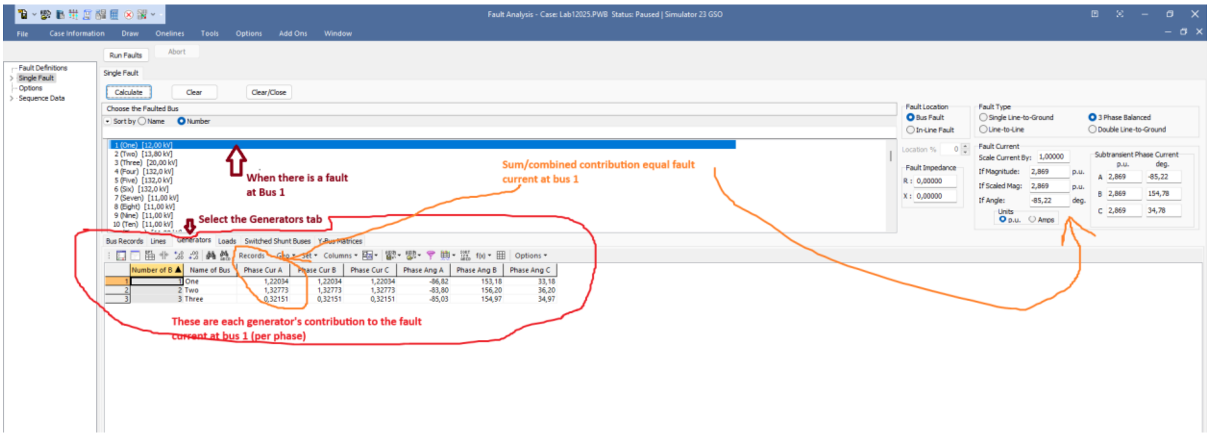


Figure 19: Generator contributions to fault current at bus 1, in PowerWorld Simulator

4.4. Analysis of Generator Contributions

Figure 18 and Table 5 clearly show how generator contributions vary depending on the fault location:

- **Faults near Generators:** When a fault occurs electrically close to a generator, that generator provides the largest contribution(with the exception of Bus 1 where G1 contributes slightly below G2). For example, for a fault at Bus 1, G1 contributes 42.5% and G2 contributes 46.3%, while the more distant G3 contributes only 11.2%. For a fault at Bus 2, G2 dominates with 73.1%. For a fault at Bus 3, G3 provides the largest share at 59.5%.

- **Faults on Transmission System (Buses 4, 5, 6):** Contributions are more distributed. For a fault at Bus 5 (central transmission bus), G2 is still dominant (63.0%) due to its large MVA rating (72 MVA) and lower impedance path compared to G1 (22 MVA) and G3 (33 MVA). G1 (21.7%) and G3 (15.3%) contribute less.
- **Faults on Load System (Buses 7-11):** For faults on the 11 kV ring system, the percentage contributions from the generators stabilize. This indicates that from the perspective of these buses, the impedance back to the equivalent source (dominated by the generators and the 132/11kV transformer T4) becomes the primary factor determining current distribution, rather than the exact location within the ring itself. G2 contributes the most (~46.7%), followed by G3 (~37.3%) and G1 (~16.1%). The very high impedance of T4 significantly limits the total fault current magnitudes at these buses, but the relative contributions are dictated by the effective source impedances behind T4.

This analysis is crucial for setting protective relays, ensuring they operate correctly based on the expected contribution from different sources during various fault scenarios. [2]

5. Circuit Breaker Selection

The final step is to select appropriately rated circuit breakers (CBs) for each bus. The primary function of a CB is to interrupt the flow of current when a fault occurs, protecting downstream equipment and isolating the faulted section. Therefore, the breaker must be rated to handle the maximum symmetrical fault current it is expected to interrupt, considering the system's X/R ratio which influences the potential DC offset.

5.1. Methodology (E/X Simplified Method)

The selection process follows the E/X Simplified Method, utilizing the calculated fault currents and system X/R ratios. [2] This method involves:

1. Calculating the maximum symmetrical three-phase fault current at the bus (Ifault_actual).
2. Determining the X/R ratio at the bus.
3. Calculating the minimum required symmetrical interrupting capability ($Min\_Required\_Rating\_kA$).

4. Selecting a standard CB rating that meets or exceeds this minimum requirement, considering the system voltage.

5.2. Calculation of X/R Ratios

The X/R ratio at each bus 'n' is calculated from the diagonal element of the Zbus matrix ($Znn = Rnn + jXnn$):

$$XR_{ratio(n)} = \frac{Xnn}{Rnn} = \frac{imag\big(Zbus(n,n)\big)}{real\big(Zbus(n,n)\big)}$$

These ratios were calculated using MATLAB.

5.3. Circuit Breaker Rating Selection

The minimum required symmetrical interrupting capability depends on the X/R ratio:

- **If $\boldsymbol{X/R < 17}$:** The DC component decays relatively quickly. The required symmetrical rating is taken as the maximum of the three-phase fault current and the single-line-to-ground (SLG) fault current. For this analysis, lacking SLG fault data, we approximate by using the calculated three-phase fault current (as implemented in the MATLAB script where $max(three\_phase\_fault\_kA, 0.9 * three\_phase\_fault\_kA)$ simplifies to $three\_phase\_fault\_kA$).
- **If $\boldsymbol{X/R \geq 17}$:** The DC component decays more slowly, potentially leading to a higher asymmetrical interrupting duty. A multiplying factor is applied to the symmetrical fault current:
  $Multiplier = 1 + 0.02 * (XR\_ratio(n) - 17)$
  $$Min_{Required_{Rating_{kA}}} = Fault_{Current_{kA(n)}} * Multiplier$$

Based on the calculated $Min_{Required_{Rating_{kA}}}$, the next highest standard CB rating (kA) is selected from the standard values provided in Table 8.10 of the reference book (e.g.. $31.5, 40, 50, 63, 80, 100\ kA$).

Line No.	Rated Maximum Voltage U_r kV, rms	Rated Continuous Current A, rms	Rated Short-Circuit and Short-Time Current kA, rms	Rated Interrupt-ing Time ms	Maximum Permissible Tripping Time Delay Y, s	Rated Closing and Latching Current kA, peak
	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6
1	123	1200,2000	31.5	50	1	82
2	123	2000, 3000, 4000	40	50	1	104
3	123	2000, 3000, 4000	50	50	1	130
4	123	2000, 3000, 4000	63	50	1	164
5	145	1200, 2000	31.5	33 or 50	1	82
6	145	1600, 2000, 3000	40	33 or 50	1	104
7	145	2000, 3000	50	33 or 50	1	130
8	145	2000, 3000	63	33 or 50	1	164
9	145	2000, 3000, 4000	80	33 or 50	1	208
10	170	1600, 2000	31.5	33 or 50	1	82
11	170	2000, 3000	40	33 or 50	1	104
12	170	2000, 3000, 4000, 5000	50	33 or 50	1	130
13	170	2000, 3000, 4000, 5000	63	33 or 50	1	164
14	170	3000, 4000, 5000	80	33 or 50	1	208
15	170	4000, 5000	100	33 or 50	1	260
16	245	1600, 2000, 3000	31.5	33 or 50	1	82
17	245	2000, 3000	40	33 or 50	1	104
18	245	2000, 3000	50	33 or 50	1	130
19	245	2000, 3000, 4000, 5000	63	33 or 50	1	164
20	245	3000, 4000, 5000	80	33 or 50	1	208
21	362	2000, 3000	40	33 or 50	1	104
22	362	2000, 3000	50	33 or 50	1	130
23	362	2000, 3000, 4000	63	33 or 50	1	164
24	550	2000, 3000	40	33	1	104
25	550	3000, 4000	50	33	1	130
26	550	3000, 4000	63	33	1	164
27	800	2000, 3000	40	33	1	104
28	800	3000, 4000	50	33	1	130
29	800	3000, 4000	63	33	1	164

TABLE 8.10

Preferred ratings for outdoor circuit breakers rated 100 kV and above, including circuit breakers applied in gas-insulated substations (symmetrical current basis of rating)

Figure 20: Standard Circuit breaker list

If the calculated minimum exceeds the highest standard rating, the highest standard rating is chosen. The voltage class of the breaker must also match the system voltage at the bus.

Table 6: Circuit Breaker Selection Table

Circuit Breaker Selection (Based on Known X/R Ratios):

==

Bus	X_R_Ratio	Fault_Current_kA	Min_Required_Rating_kA	Selected_CB_Rating_kA	Selected_Available_CB_Rating_kA	Min_Voltage_kV
1	11.965	13.802	13.802	16	31.5	12
2	10.524	20.49	20.49	25	31.5	13.8
3	13.12	6.3949	6.3949	8	31.5	20
4	11.914	0.93602	0.93602	6.3	31.5	132
5	10.604	1.8062	1.8062	6.3	31.5	132
6	11.079	0.54892	0.54892	6.3	31.5	132
7	7.0551	0.11323	0.11323	6.3	31.5	11
8	6.7471	0.10498	0.10498	6.3	31.5	11
9	6.1412	0.095949	0.095949	6.3	31.5	11
10	6.2726	0.095875	0.095875	6.3	31.5	11
11	6.4614	0.098291	0.098291	6.3	31.5	11

5.4. Graphical Visualization of CB Selection

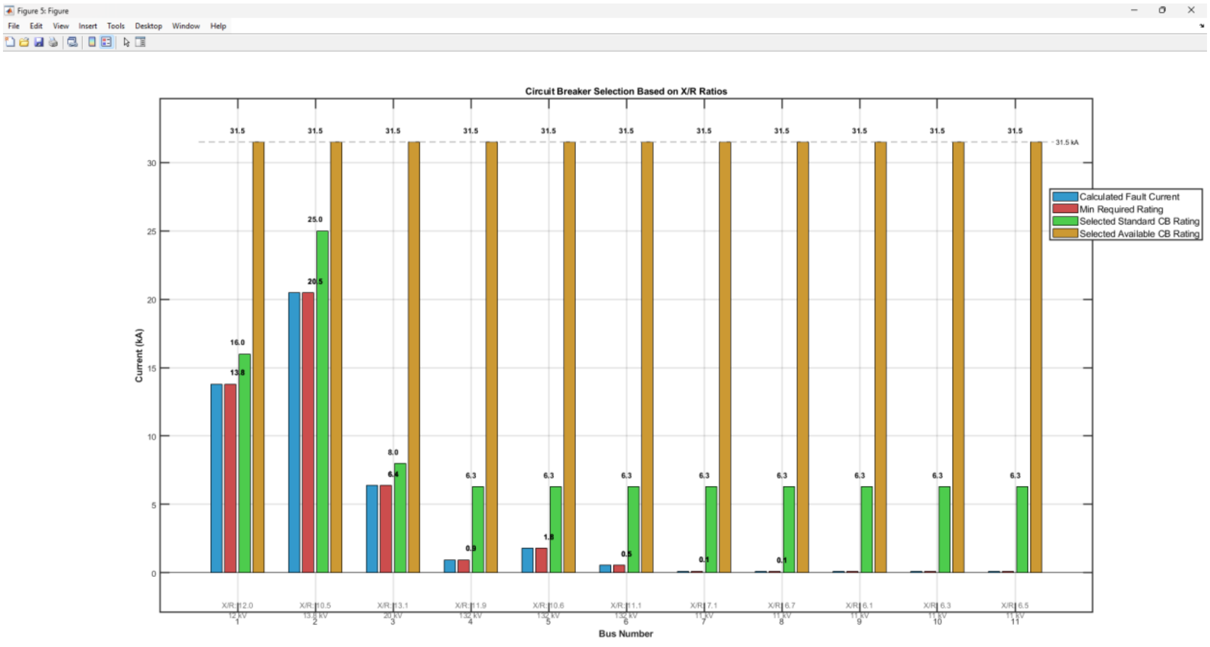


Figure 21: Circuit Breaker Selection Based on X/R Ratios

5.5 Analysis of Circuit Breaker Selection

Table 6 and Figure 21 summarize the CB selection process calculations done in MATLAB. The CB selection analysis reveals several important considerations:

- **X/R Ratios**: All calculated X/R ratios are below 17, so no correction factor was needed.
- **Significant Overrating**: When restricting our selection to the circuit breaker ratings provided in Table 8.10 of the reference (which only lists 31.5, 40, 50, 63, 80, and 100 kA for higher voltage applications), we would be significantly overrating the breakers for most buses. This is particularly evident for buses

7-11, where the required rating is only about 0.11-0.12 kA, yet we would need to select a 31.5 kA breaker—over 250 times the required capacity.

- **Alternative Standards**: It's important to note that Table 8.10 primarily focuses on high-voltage circuit breakers (100 kV and above). In practice, for our system with various voltage levels (11kV, 12kV, 13.8kV, 20kV, and 132kV), we would consult additional standards like IEC 62271-100 or IEEE C37.04/C37.09 that include lower-rated circuit breakers. Industry standards typically offer more appropriate ratings such as 6.3, 8, 12.5, 16, 20, and 25 kA for distribution and medium voltage systems.
- **Economic and Practical Considerations**: Using the oversized breakers from Table 8.10 would be economically impractical, especially for the lower voltage buses. A more cost-effective approach would involve selecting from other standard CB ratings not included in the reference table, which would still provide adequate protection without excessive overrating.

The significant disparity between the "selected_available_CB_rating_kA" and "selected_CB_rating_kA" columns clearly illustrates the practical implications of using appropriate industry standards. The practical selections would still provide adequate protection margins while optimizing cost-effectiveness.

This comparative analysis demonstrates that while adhering strictly to Table 8.10 ensures safety margins are met, it introduces substantial economic inefficiencies (refer to the orange bar in Figure 21).

In actual industry practice, circuit breaker selection would be based on:

1. The calculated fault current at the bus
2. Standard safety margins (typically 25-50% above the calculated fault current)
3. Future system expansion considerations
4. Economic feasibility and optimization
5. Compliance with appropriate voltage class standards

For this power system, the “Selected Available CB Rating" (green bar) selection provides a more balanced approach, ensuring both adequate protection and economic sensibility.

- Therefore, a Line No. 1 Circuit breaker would be more than sufficient for buses 1-3 and 7-11 where the voltage is way below 123kV, and the short circuit fault current is 31.5kA (which is way above the minimum required for all the buses.)
- For bus 4,5 and 6, where the Line voltage is 132kV, a Line No. 5 Circuit breaker would be most suitable as it has a 145kV (greater than 132kV) and also the 31.5kA is still way above the minimum required.

These choices are the most economically reasonable, and they also provide more than sufficient safety to the network.

6. Conclusion

This analysis has successfully characterized the symmetrical fault behaviour of the 11-bus power system, providing crucial data for system protection design and equipment rating. The methodical approach using per-unit calculations, matrix methods, and computational tools has yielded several important findings:

- **Impedance Modeling**: All system components were accurately represented in a common 100 MVA base, enabling consistent network analysis across multiple voltage levels (12 kV to 132 kV).
- **Fault Current Distribution**: The highest fault currents occur at buses electrically closest to generating sources, with Bus 2 experiencing the maximum fault current (20.49 kA) due to its proximity to generator G2 with its significant 72 MVA capacity. Conversely, the electrically distant 11 kV factory load buses experience substantially lower fault currents (approximately 0.11-0.12 kA) due to the limiting effect of transformer and line impedances.
- **Voltage Profiles**: During fault conditions, pronounced voltage drops were observed not only at faulted buses but also at electrically adjacent buses. This voltage profile data is essential for assessing the stability of critical loads and the coordination of voltage-sensitive protection devices.
- **Generator Contributions**: The analysis revealed distinct patterns in how generators contribute to fault currents based on electrical proximity and capacity. G2 consistently provides the highest contribution across most fault scenarios (up to 73.1% for faults at Bus 2), highlighting its dominance in the system's dynamic response.
- **Circuit Breaker Selection**: The X/R ratio analysis demonstrated that all buses have ratios below 17, simplifying the circuit breaker selection process. The significant disparity between theoretically required ratings and standard available ratings (particularly for buses 7-11) underscores the importance of balancing technical requirements with economic feasibility when specifying equipment.

The validation of these results through PowerWorld simulation confirms the accuracy of the mathematical models and calculations employed. This comprehensive fault analysis provides power system operators and protection engineers with the necessary data to:

1. Configure protective relays with appropriate settings for selective fault isolation
2. Specify circuit breakers with adequate interrupting capacity
3. Identify potential weak points in the network where reinforcement may be necessary
4. Ensure equipment ratings are sufficient to withstand maximum fault conditions

This information forms the foundation for reliable power system operation, protecting both equipment and personnel while maintaining continuity of supply to critical loads.

7. References

[1] MathWorks, “Types of Bar Graphs,” MathWorks, 9 April 2025. [Online]. Available: https://www.mathworks.com/help/matlab/creating_plots/types-of-bar-graphs.html. [Accessed 9 April 2025].

[2] J. Duncan, Glover, T. J and Overbye, Power System Analysis and Design SI Edition (Seventh Edition), Boston: Cengage Learning, Inc., 2023.