ELE B7 Power Systems Engineering

Balanced (Symmetrical) Faults

Fault Analysis

- Fault?

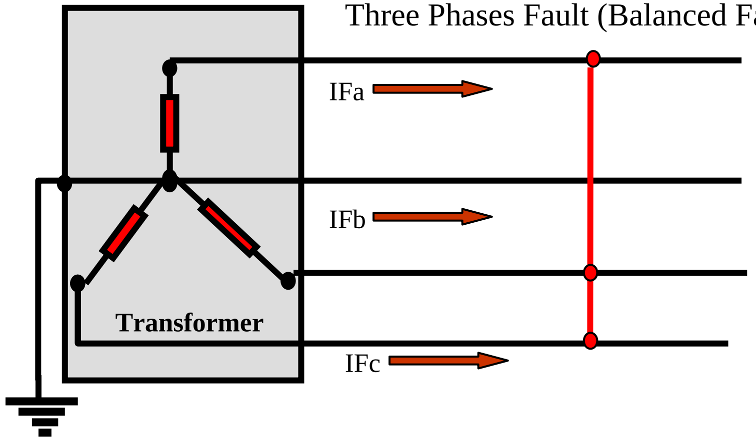
  When the insulation of the system breaks down or a conducting object comes in touch with a live point, a short circuit or a fault occurs.
- Sources?
- This breakdown can be due to a variety of different factors
  - lightning
  - wires blowing together in the wind
  - animals or plants coming in contact with the wires
  - salt spray or pollution on insulators

Fault Types

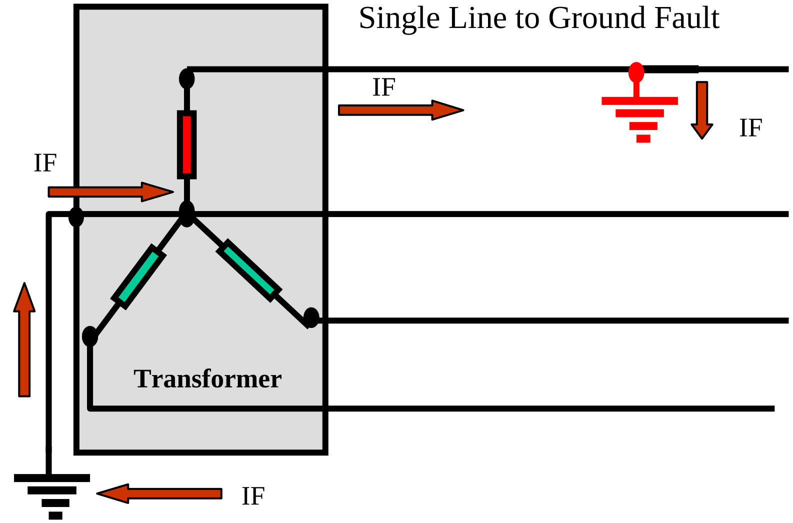
- There are two classes of faults
  - Balanced faults (symmetric faults): A Fault involving all the three phases
    - system remains balanced;
    - these faults are relatively rare, but are the easiest to analyze so we’ll consider them first.
  - Unbalanced faults (unsymmetric faults): A fault involving only one or two phases
    - The majority of the faults are unsymmetrical.
    - system is no longer balanced;
    - very common, but more difficult to analyze
- The most common type of fault on a three phase system is the single line-to-ground (SLG), followed by the line-to-line faults (LL), double line-to-ground (DLG) faults, and balanced three phase faults

Fault Types

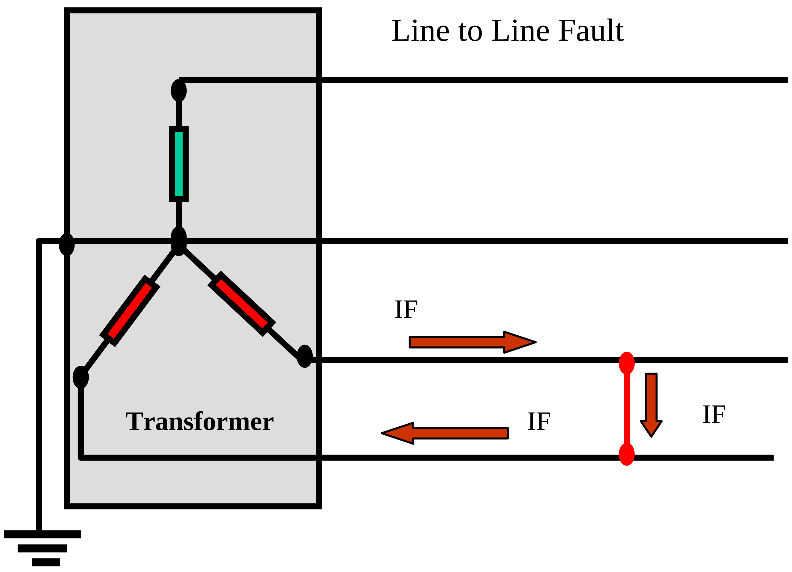
Three Phases Fault (Balanced Fault)



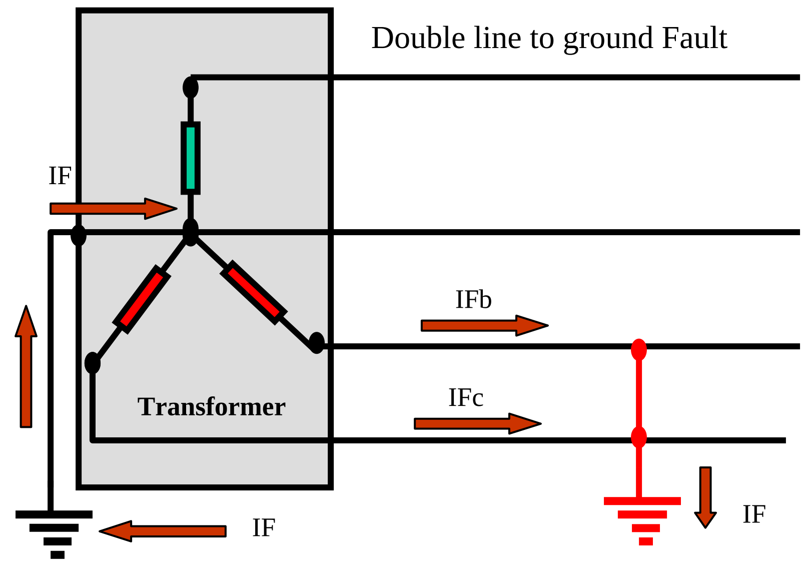
Single Line to Ground Fault



Line to Line Fault



Double line to ground Fault

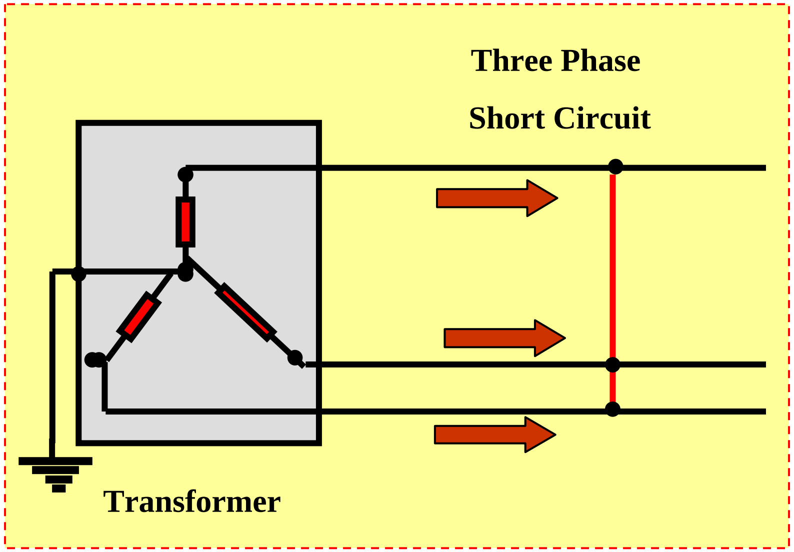


Fault Analysis

- Fault Analysis involve finding the voltage and current distribution throughout the system during fault condition.
- Fault currents cause equipment damage due to both thermal and mechanical processes
- Why do we need that?
  - To adjust and set the protective devices so we can detect any fault and isolate the faulty portion of the system.
  - To protect the human being and the equipment during the abnormal operating conditions.
  - need to determine the maximum current to insure devices can survive the fault

Symmetrical Faults (Balanced Faults)

A Fault involving all the three phases.



- It is the most severe fault but can be easily calculated
- It is an important type of fault
- The circuit breaker rated MVA breaking capacity is selected based on the three phase short circuit MVA.

Symmetrical Faults (Balanced Faults)

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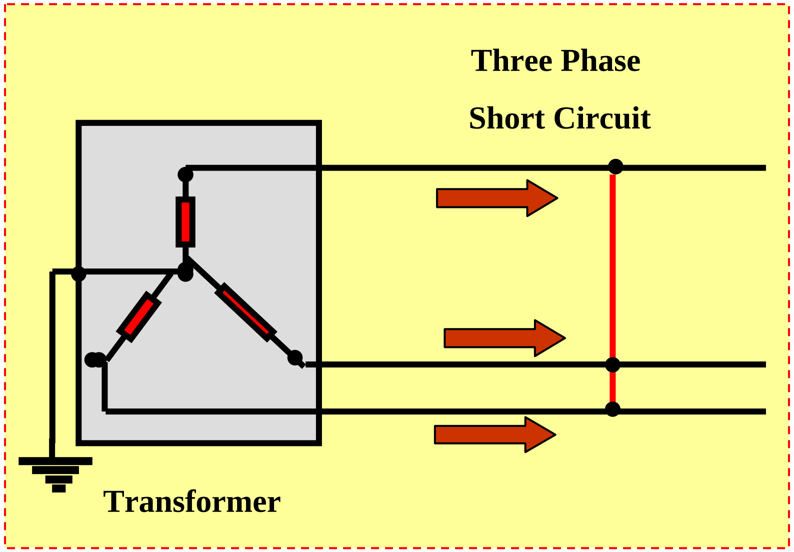


- It is the most severe fault but can be easily calculated
- It is an important type of fault
- The circuit breaker rated MVA breaking capacity is selected based on the three phase short circuit MVA.

The following assumptions are made in three phase fault calculation :

1. Synchronous machines are represented by a constant voltage sources behind subtransient reactances. The EMF of all generators are 1 per unit making zero angle.

$$\boldsymbol{V} = 1\angle 0^{o}$$

This means that the ***system voltage is at its nominal value*** and the system is operating at ***no-load conditions*** at the time of fault.

Therefore, All the generators can be replaced by a single generator since all EMFs are equal and are in phase.

2. Transformers are represented by their leakage reactances

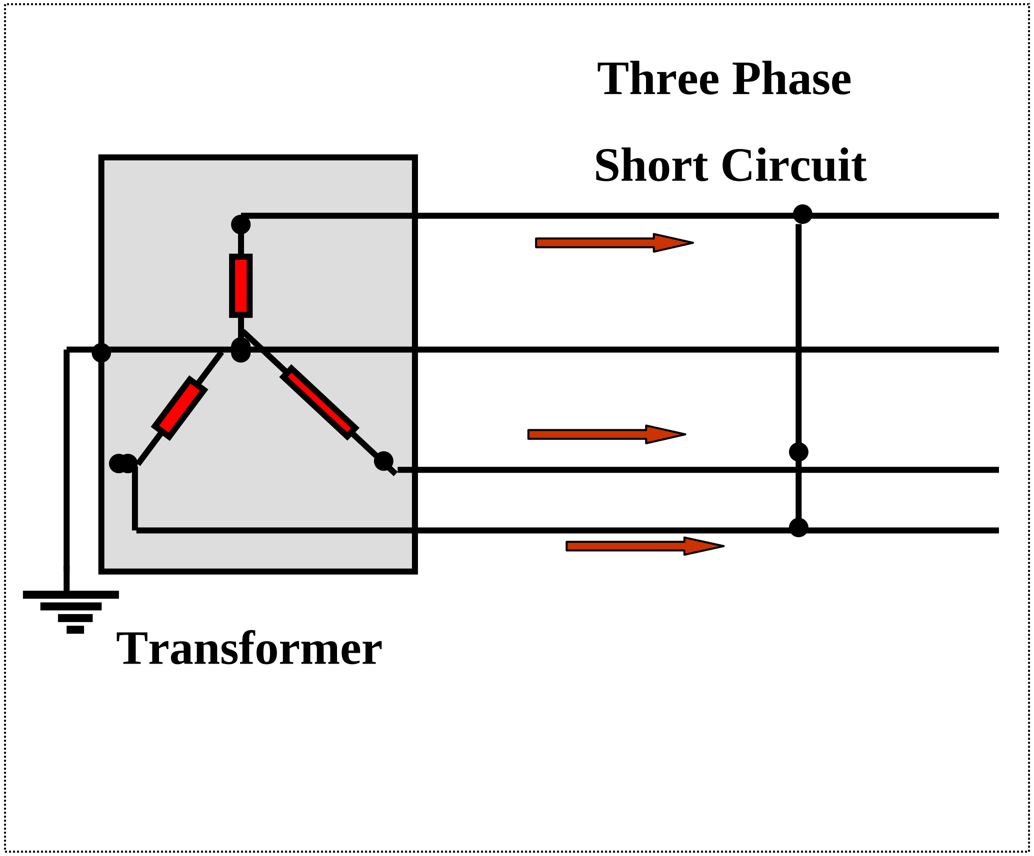
   Winding resistances, shunt admittances and Δ-Y phase shifts are neglected

3. The *shunt capacitances of the transmission Lines* are neglected.

4. The *system resistances are neglected* and ***only the inductive reactance*** of different elements are taken into account.

Symmetrical

Fault Calculation



Three Phase Fault Calculation

1. Simple Circuits
   Load Ignored
   Use Thevenin's Equivalent

2. Simple Circuits
   Load not Ignored
   Use Thevenin's Equivalent
   Find Pre-fault voltage

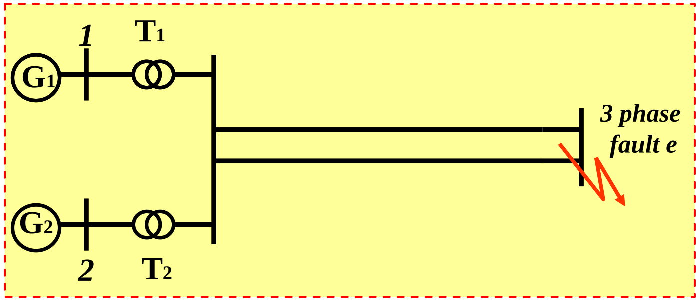
3. Large Circuits
   Construct
   The Bus Impedance Matrix

1. Simple Circuits and Load is ignored

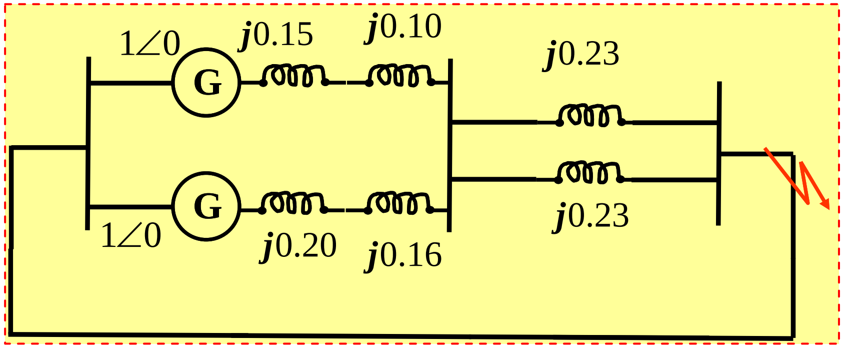
The Calculations for the three phase fault are easy because the circuit is completely symmetrical and calculations can be done for only one phase.

Steps For Calculating Symmetrical Faults:

1. Draw a single line diagram for the system.
2. Select a common base and find out the per unit reactances of all generators, transformers, transmission lines, etc.



3. From the single line diagram of the system draw a single line reactance diagram showing one phase and neutral. Indicate all the reactances, etc. on the single line reactance diagram.



4. Reduce the single line reactance diagram by using series, parallel and Delta-Why transformations *keeping the identity of the fault point intact*. Find the total reactance of the system as seen from the fault point (*Using Thevenin's Theorem*)

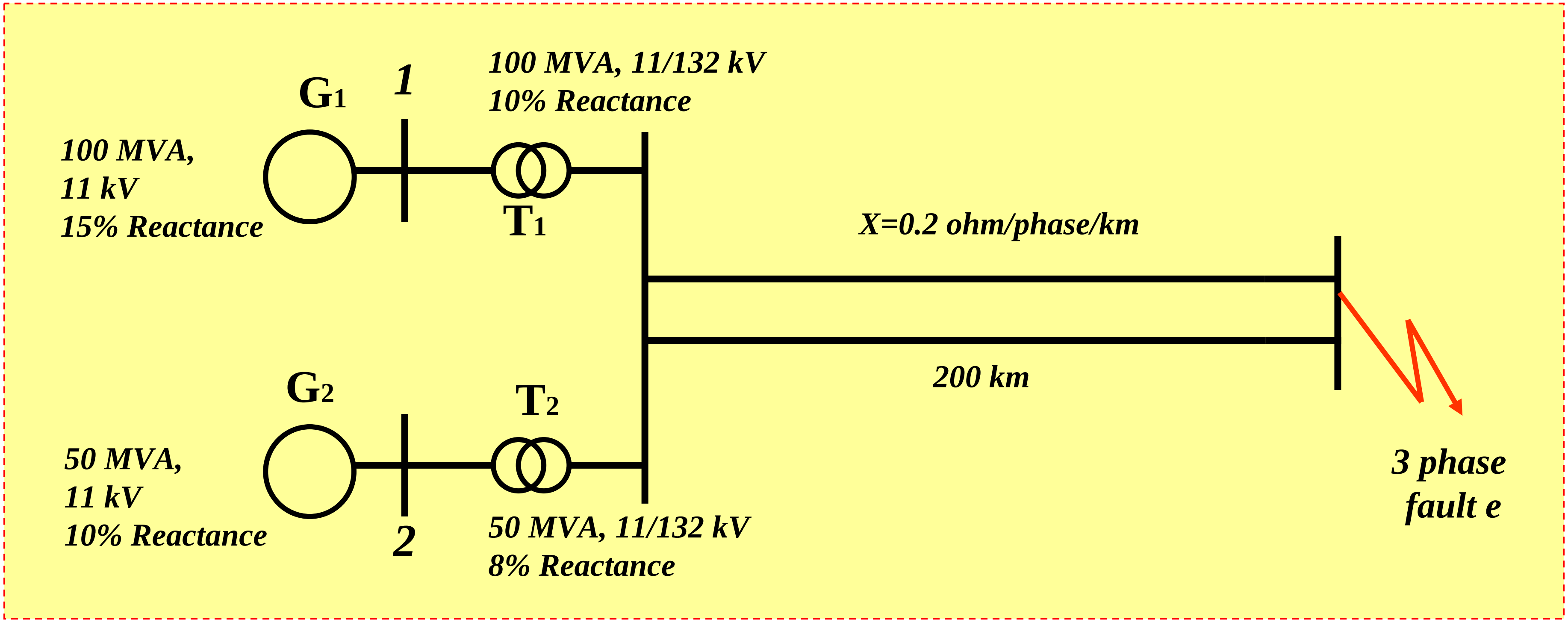
5. Find the fault current and the fault MVA in per unit.

   Convert the per unit values to actual values.

6. Retrace the steps to calculate the voltages and the currents throughout different parts of the power system

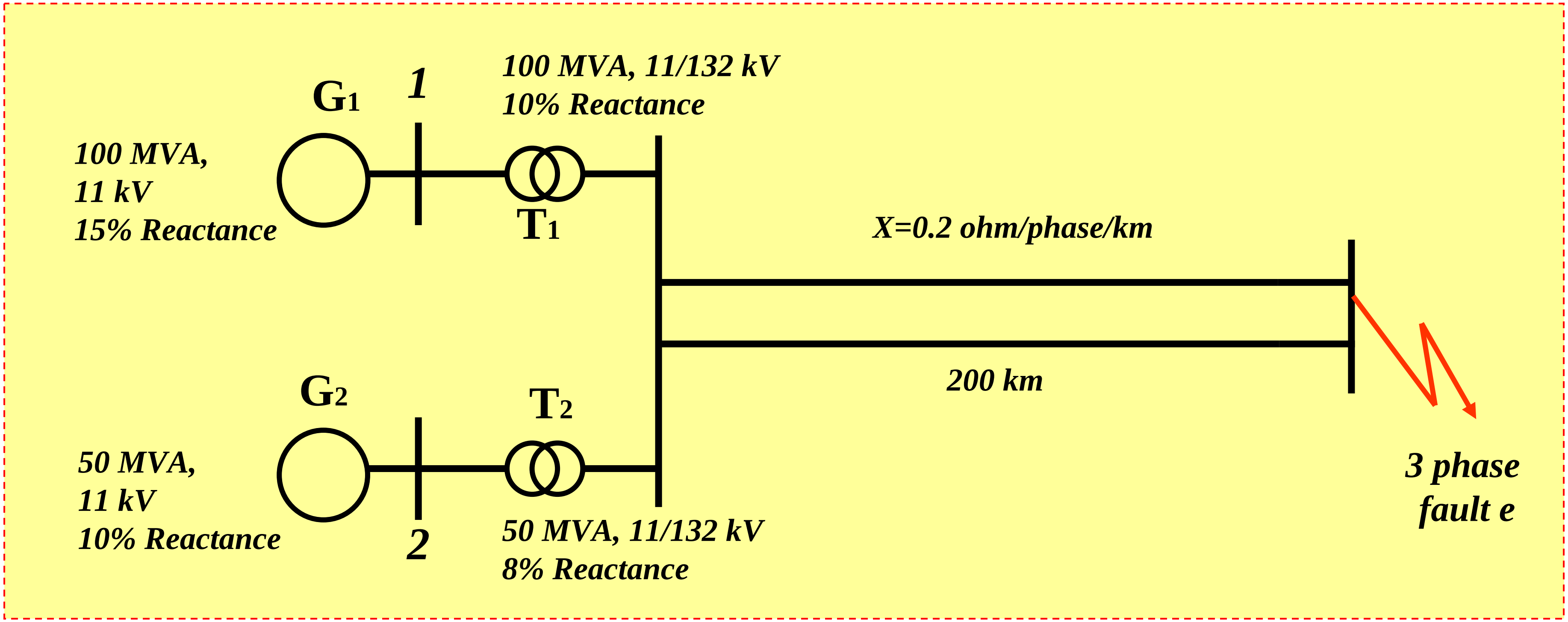
Example:

A three phase fault occurs in the system as shown in the Figure. Find the total fault current, the fault level and fault current supplied by each generator.



Solution:

Step 1: Draw a single line diagram for the system.



The single line diagram for the system is given in the example as shown.

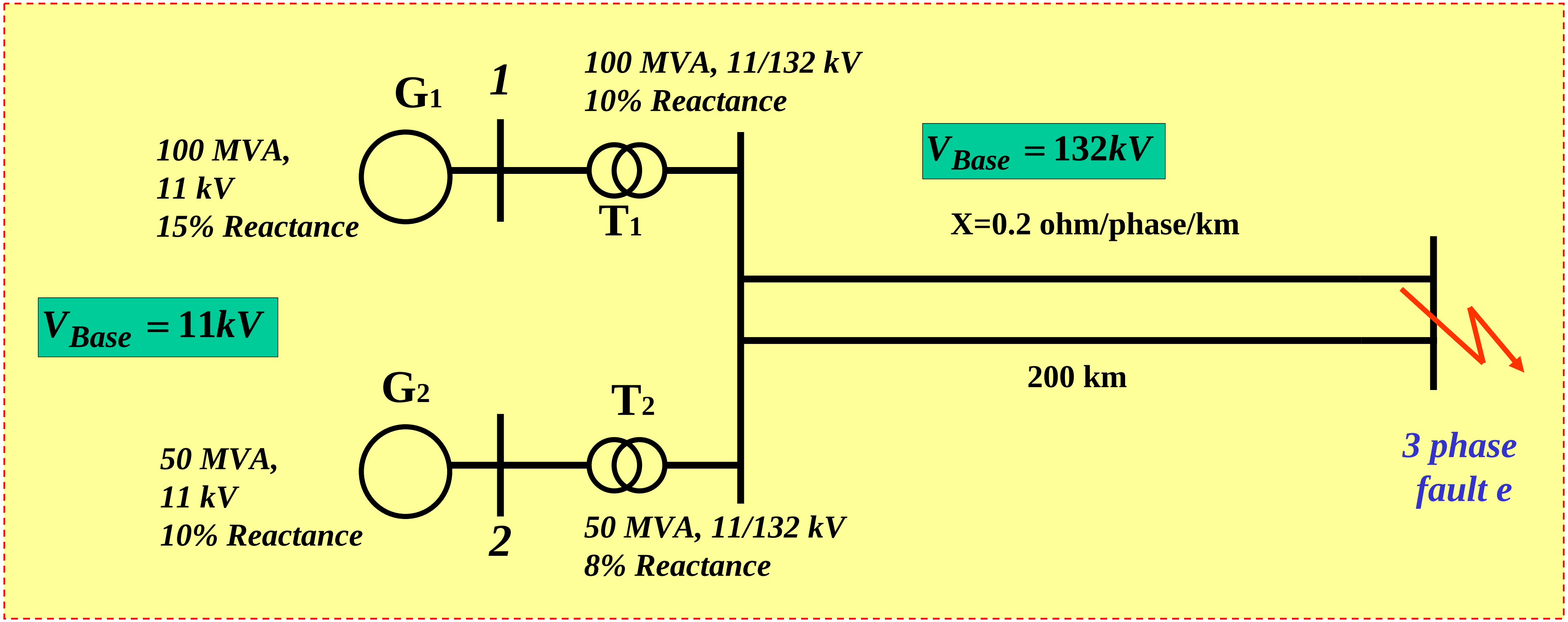
Step 2: Select a common base and *find the per unit reactances* of all generators, transformers, etc.

<u>Select the common base as</u>:

100 MVA (100,000 kVA)

11 kV for Transformer low voltage side (LV)

132 kV for Transformer high voltage side (HV)



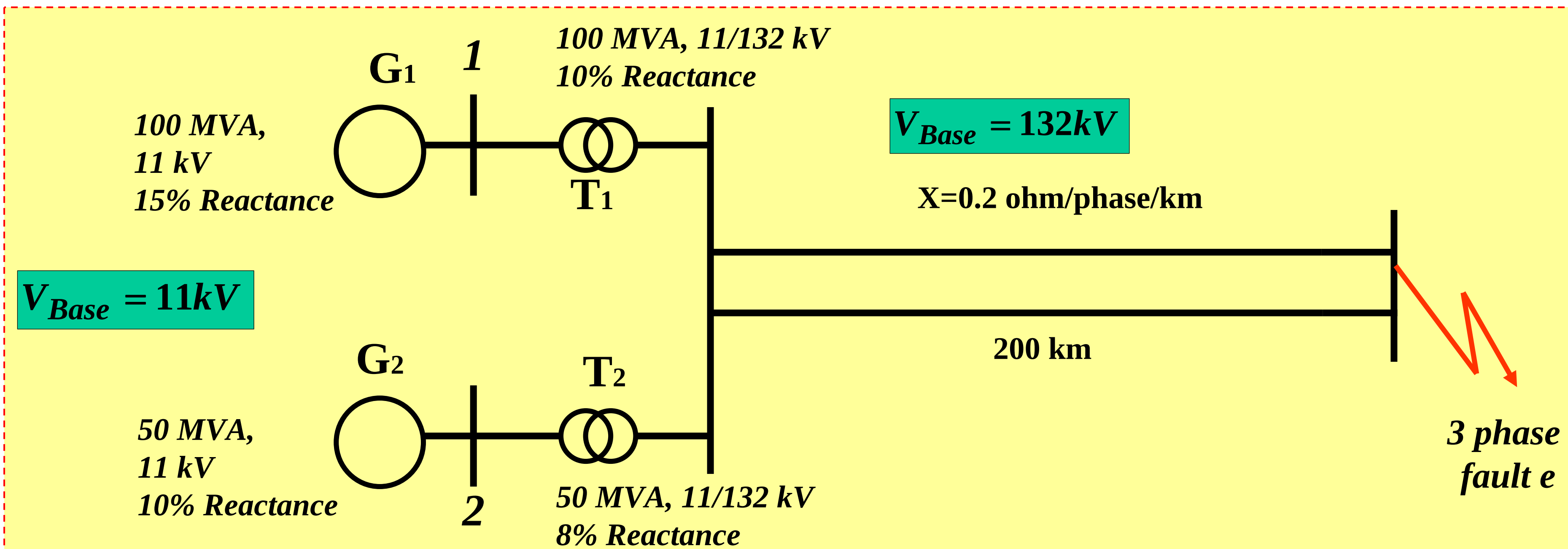
G1 The per unit reactance $XG_1 = j0.15$

G2 The per unit reactance $XG_2 = j0.1 * \frac{100}{50} = j0.2$

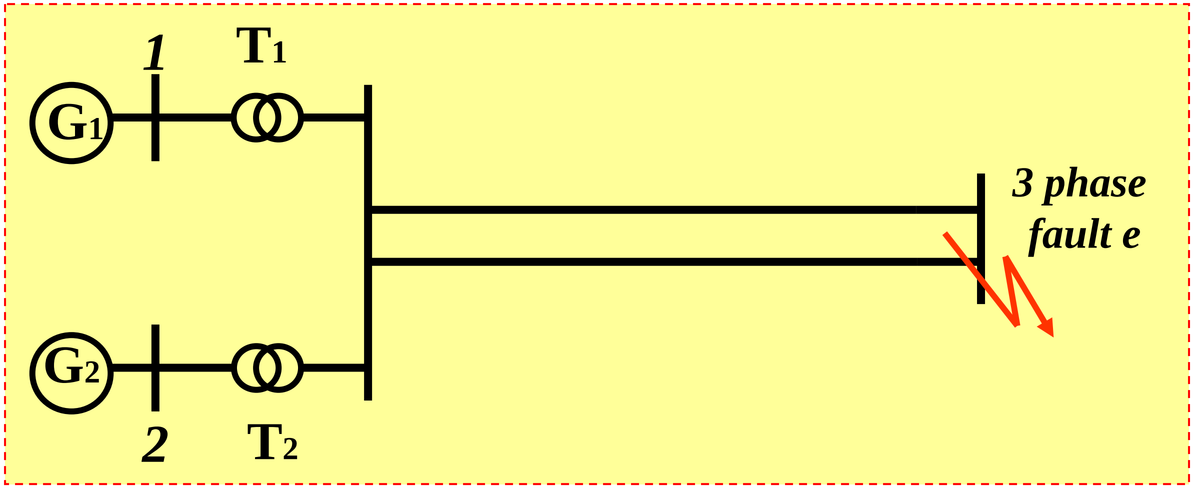
T1 The per unit reactance $XT_1 = j0.1$

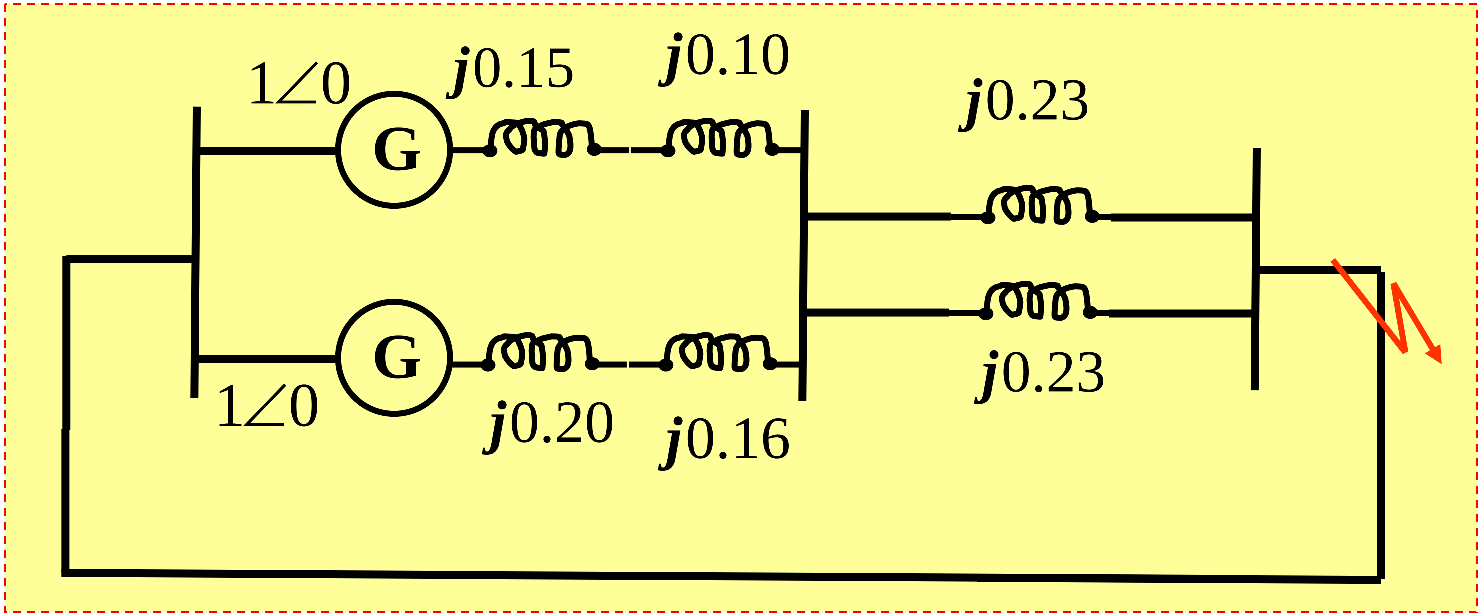
T2 The per unit reactance $XT_2 = j0.08 * \frac{100}{50} = j0.16$

TL The per unit reactance $X_{LINE} = \frac{X_{LINE}}{Z_{Base}} = (j0.2 * 200\Omega)\frac{100\,MVA}{(132kV)^2} = j0.23$

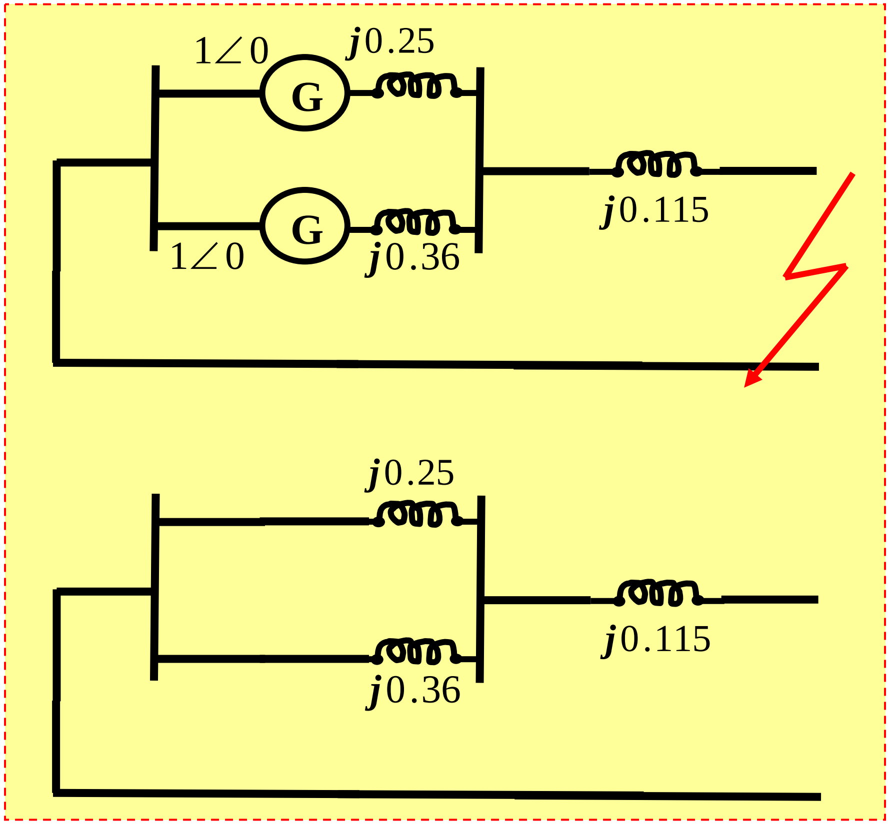


From the single line diagram of the system ***draw a single line reactance diagram*** **showing one phase and neutral. Indicate all the reactances, etc. on the single line reactance diagram.**



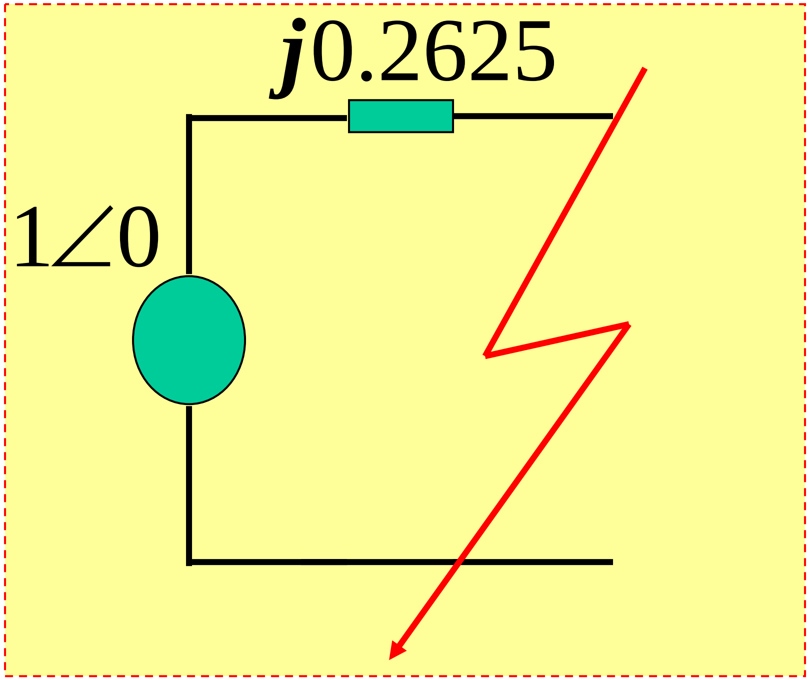


Find the *total impedance* (reactance) of the system as seen from the fault side.



$$X_{Total} = \frac{j0.25 * j0.36}{j0.25 + j0.36} + j0.115$$

$$X_{Total} = j0.2625 pu$$



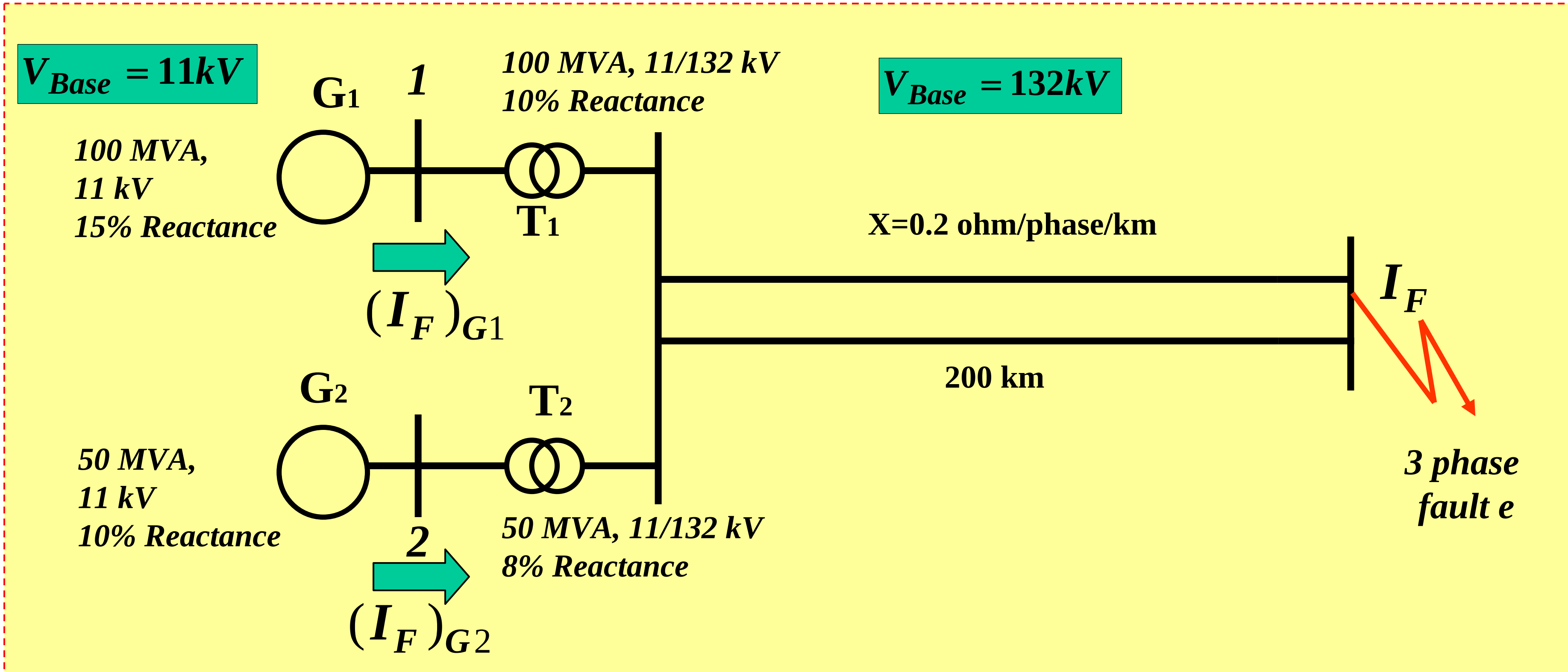
$$I_F = \frac{1\angle 0}{j0.2625} = -j3.8095\,pu$$

$$|I_{base}|_L = \frac{|S_{Base}|_{3\phi}}{\sqrt{3}\,|V_{Base}|_{LL}}$$

$$(I_{Base})_{132kV-side} = \frac{100*1000}{\sqrt{3}*132} = 437.4\,A$$

$$(I_F)_{Actual} = (I_F)_{pu} * I_{Base}$$

$$(I_F)_{Actual} = -j3.8095*437.4 = 1666.27\angle -90^o\,A$$

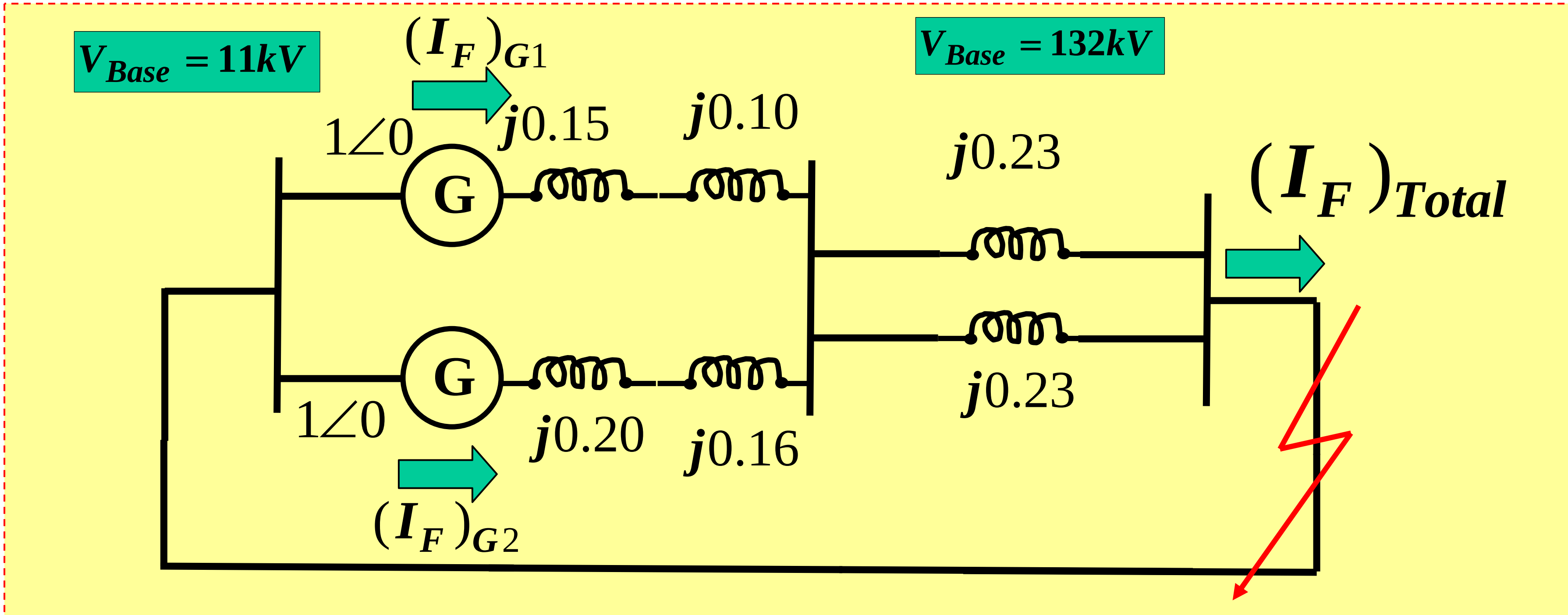


The Fault Level is:

$$(MVA)_{Level} = 3.8095\, pu$$

$$(MVA)_{Base} = 100$$

$$(MVA)_{Actual\ Level} = 3.8095 * 100 = 380.95$$

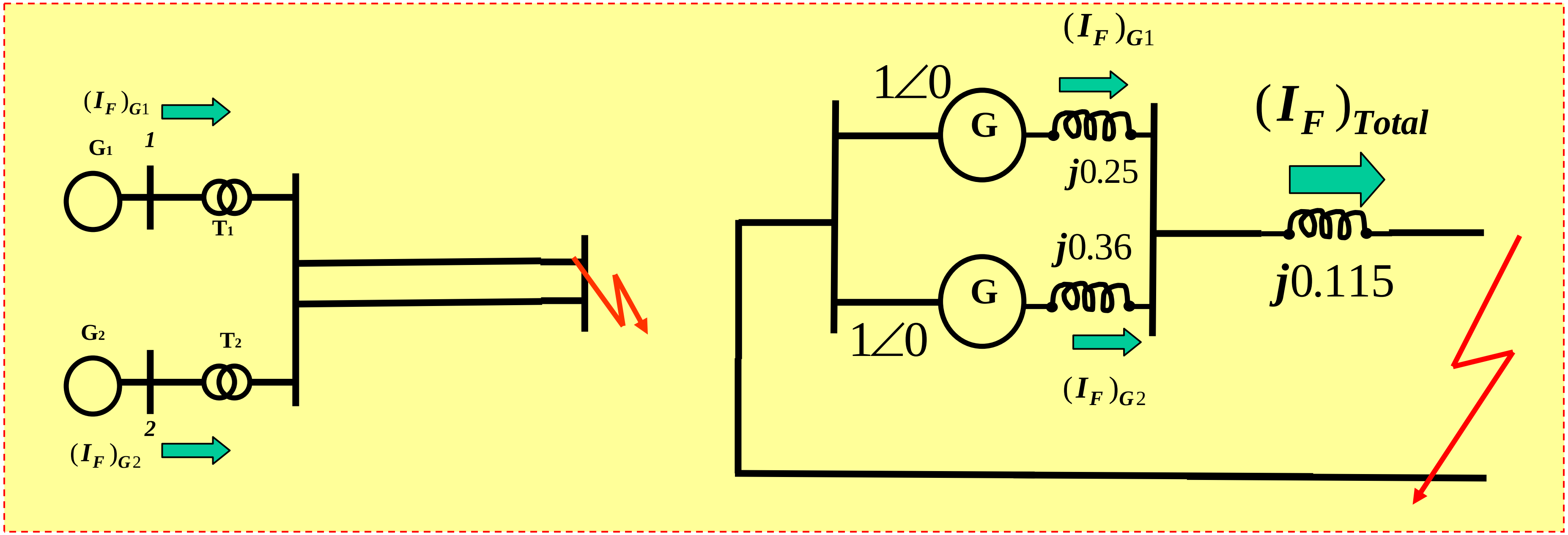


At 11 kV Side:

$$(I_{Base})_{11kV-side} = \frac{100*1000}{\sqrt{3}*11} = 5248.8A$$

The Fault Current at 11 kV side supplied by the two generators is:

$$(I_F)_{Actual} = -j3.8095*5248.8 = 19995\angle -90^o\ A$$



$$(I_F)_{G1} = (I_F)_{T,11kV}\,\frac{j0.36}{j0.36 + j0.25} = 11800.3\angle -90A$$

$$(I_F)_{G1} = (19995\angle -90)\frac{j0.36}{j0.36 + j0.25} = 11800.3\angle -90A$$

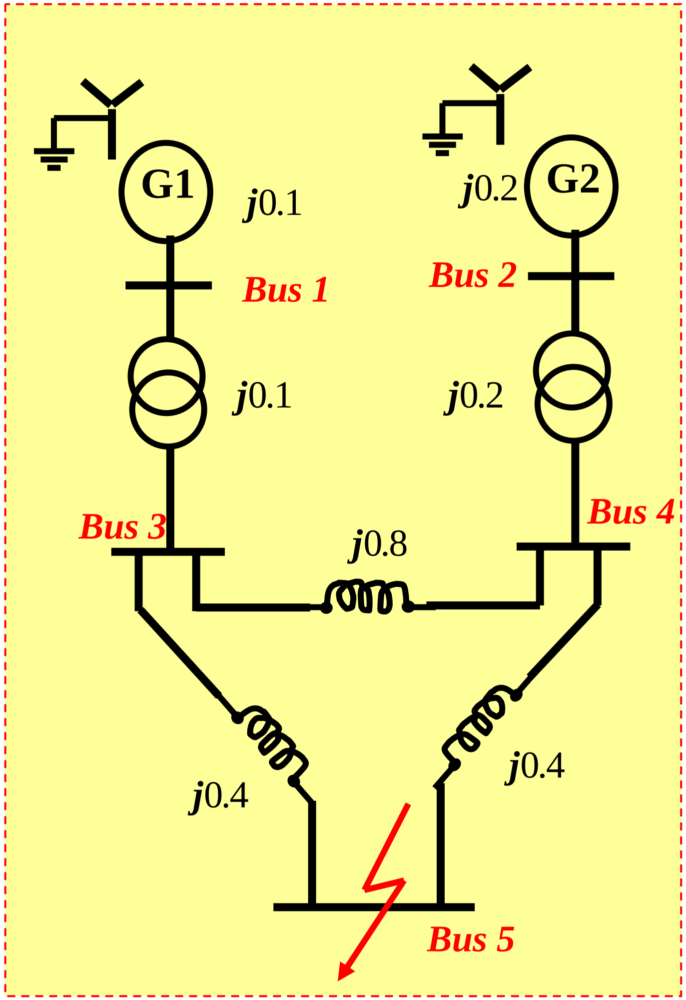
$$(I_F)_{G2} = (I_F)_{T,11kV} - (I_F)_{G1}$$

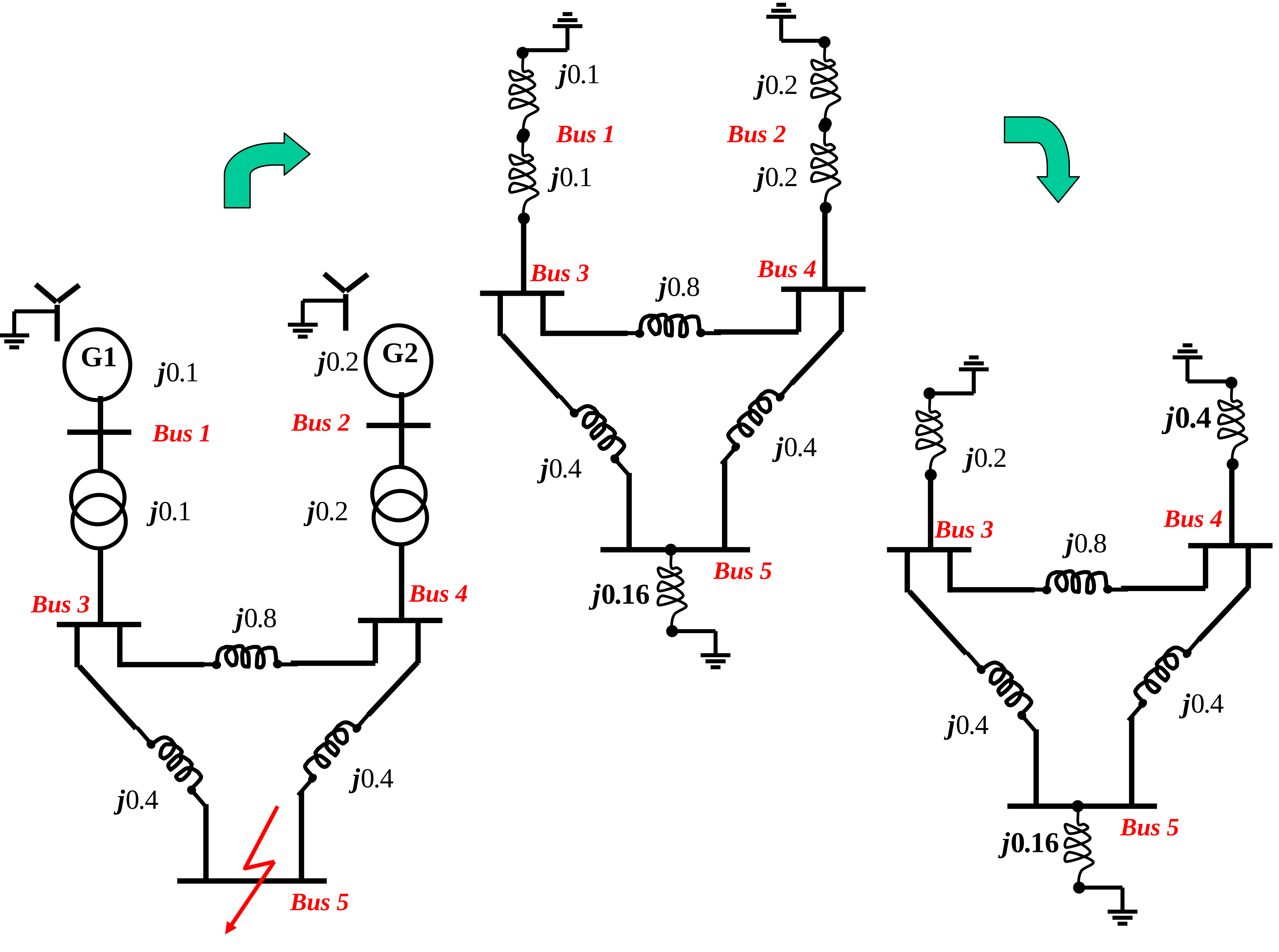
$$(I_F)_{G2} = 8194.7\angle -90A$$

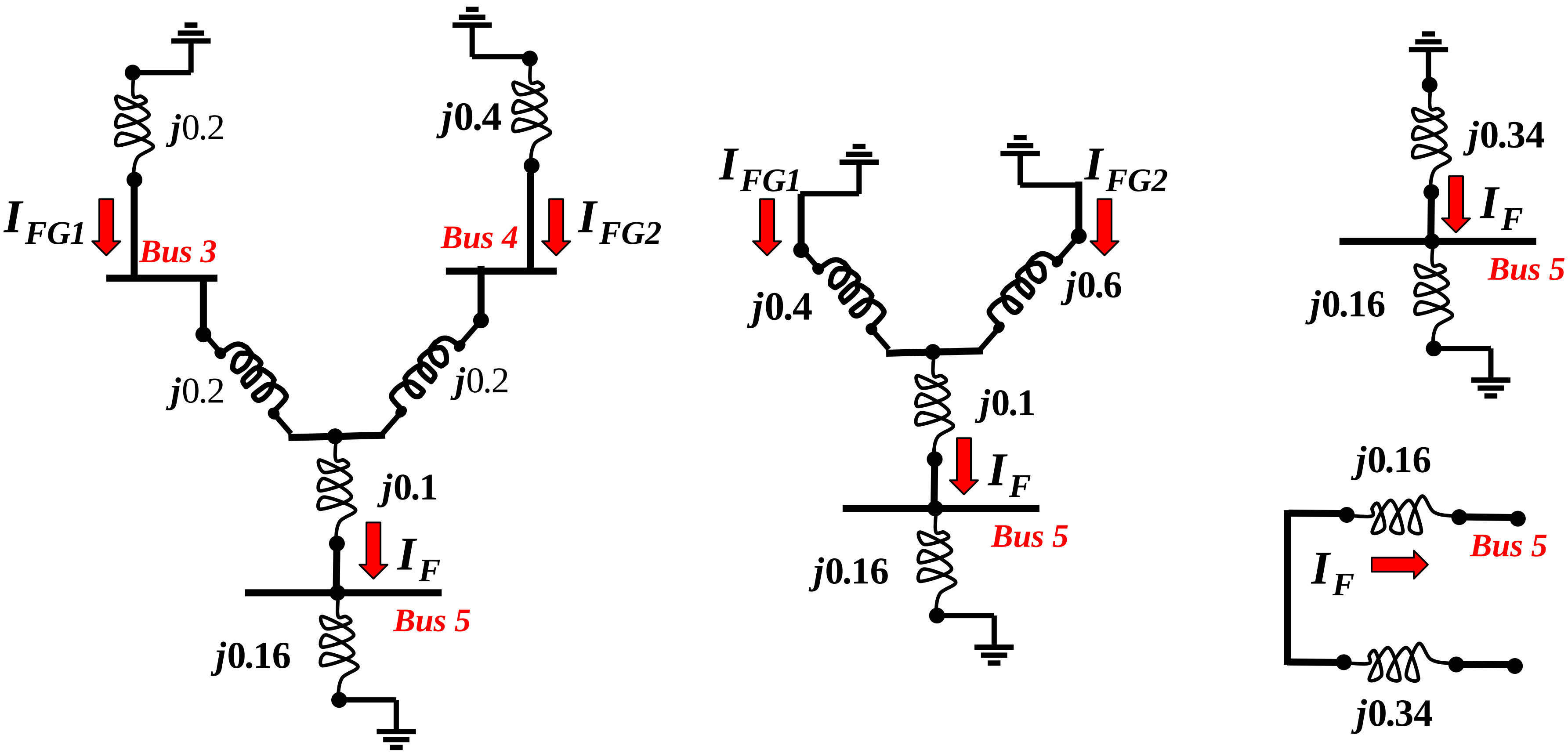
Example:

Consider the single-line diagram of a power system shown below. The transient reactance of each part of the system is as shown and expressed in pu on a common 100 MVA base.

Assuming that all generators are working on the rated voltages, when a three-phase fault with impedance of **j0.16** pu occurs at bus 5. *Find: The fault currents and buses voltages*.




G1
G2
j0.1
j0.2
Bus 1
Bus 2
j0.1
j0.2
Bus 3
Bus 4
j0.8
j0.4
j0.4
Bus 5
j0.1
j0.1
j0.2
j0.2
Bus 1
Bus 2
Bus 3
Bus 4
j0.8
j0.4
j0.4
Bus 5
j0.16
j0.2
j0.4
Bus 3
Bus 4
j0.8
j0.4
j0.4
Bus 5
j0.16

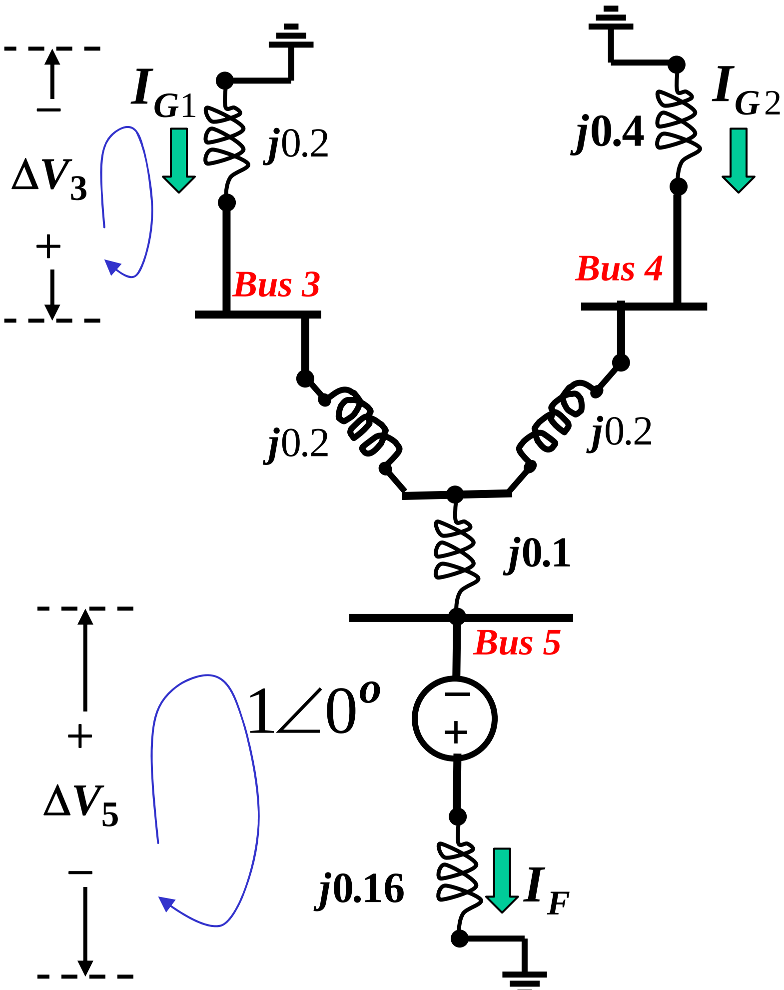


$$Z_{TH} = j0.34 + j0.16 = j0.5$$

$$(I_F)_{G1} = I_F \frac{j0.6}{j0.6 + j0.4} = -j1.2\,pu$$

$$(I_F)_{Bus5} = \frac{1^{\angle 0}}{j0.5} = -j2.0\,pu$$

$$(I_F)_{G2} = I_F \frac{j0.4}{j0.6 + j0.4} = -j0.8\,pu$$



Prefault Voltages :

$$V_{BUS} = 1\angle 0^o \quad \& \quad V_{Ground} = 0$$

Voltage Variation During Fault is :

$$\Delta V_3 = 0 - I_{G1}(j0.2)$$
$$= 0 - (j0.2)(-j1.2)$$
$$= -0.24\,pu$$

Fault Voltage :

$$V_3 = prefault + \Delta V_3$$
$$= 1\angle 0^o - 0.24 = 0.76\,pu$$

Voltage Variation during Fault :

$$\Delta V_5 = -1\angle 0^o + (j0.16)(-j2.0)$$
$$= -0.68$$

Fault Voltage :

$$V_5 = prefault + \Delta V_5$$
$$= 1\angle 0^o - 0.68 = 0.32\,pu$$

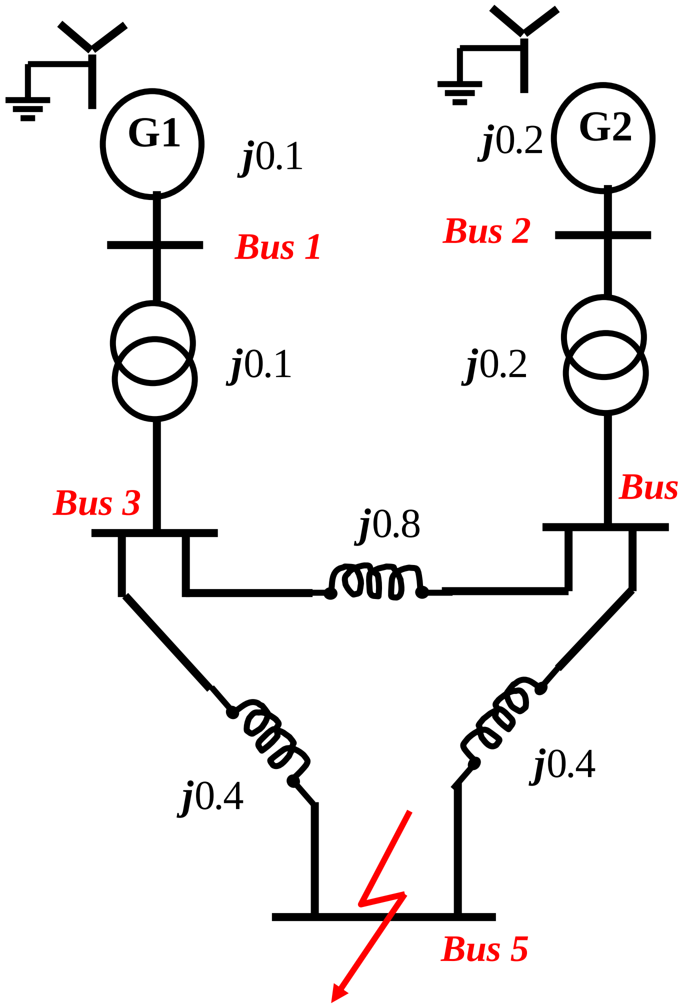
NOTE: If the fault impedance is zero.

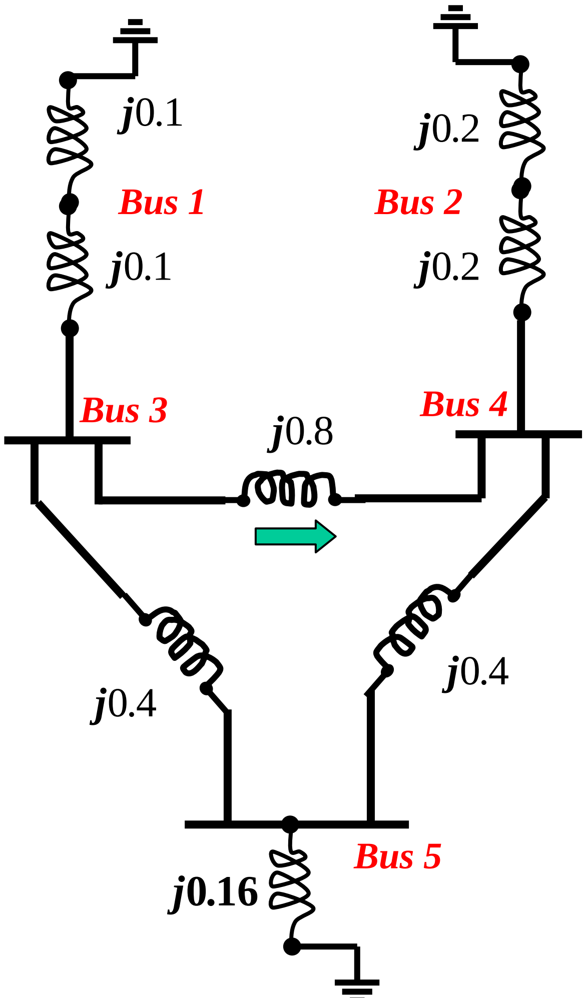
Voltage Variation during Fault :

$\Delta V_5 = -1\angle 0^o + (j0.0)(I_F) = -1.0$ ***and*** $V_5 = prefault + \Delta V_5 = 1\angle 0^o - 1.0 = 0.0\,pu$

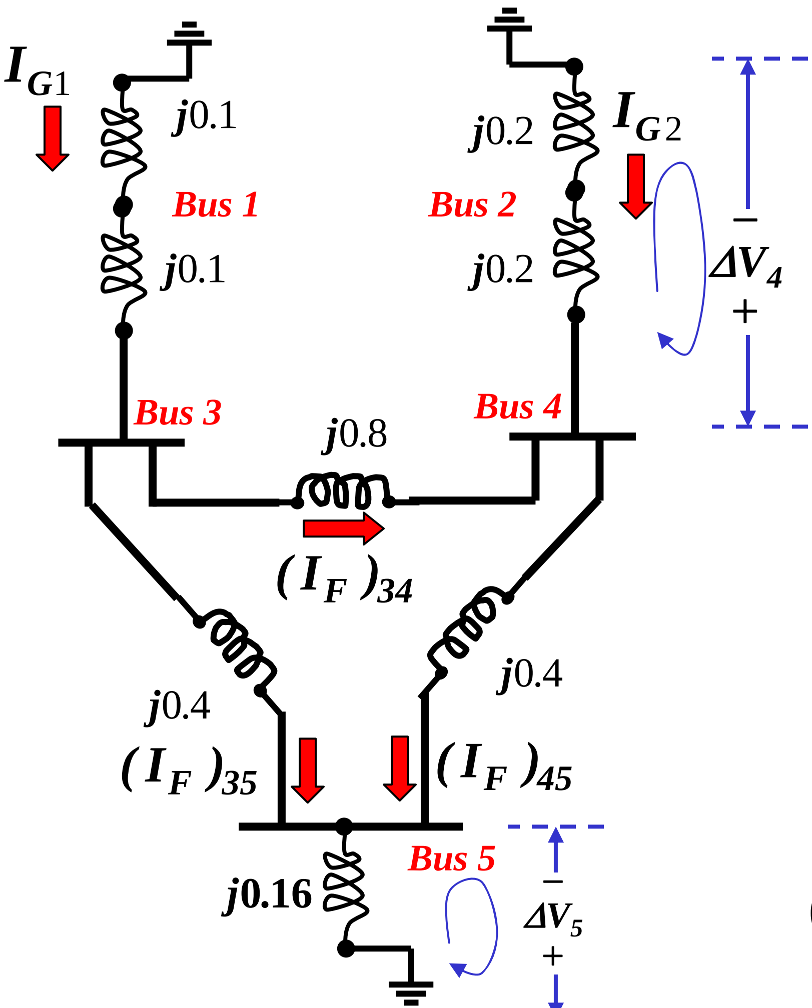
Problem:

For the network shown in the figure, find the current flowing between buses 3 and 4 during symmetrical three phase fault at bus 5 as in the previous example.





$$(I_F)_{G1} = I_F \frac{j0.6}{j0.6 + j0.4} = -j1.2\,pu \qquad (I_F)_{G2} = I_F \frac{j0.4}{j0.6 + j0.4} = -j0.8\,pu$$



During Fault Voltage :

$$V_3 = prefault + \Delta V_3$$
$$= 1\angle 0^o - 0.24 = 0.76\,pu$$

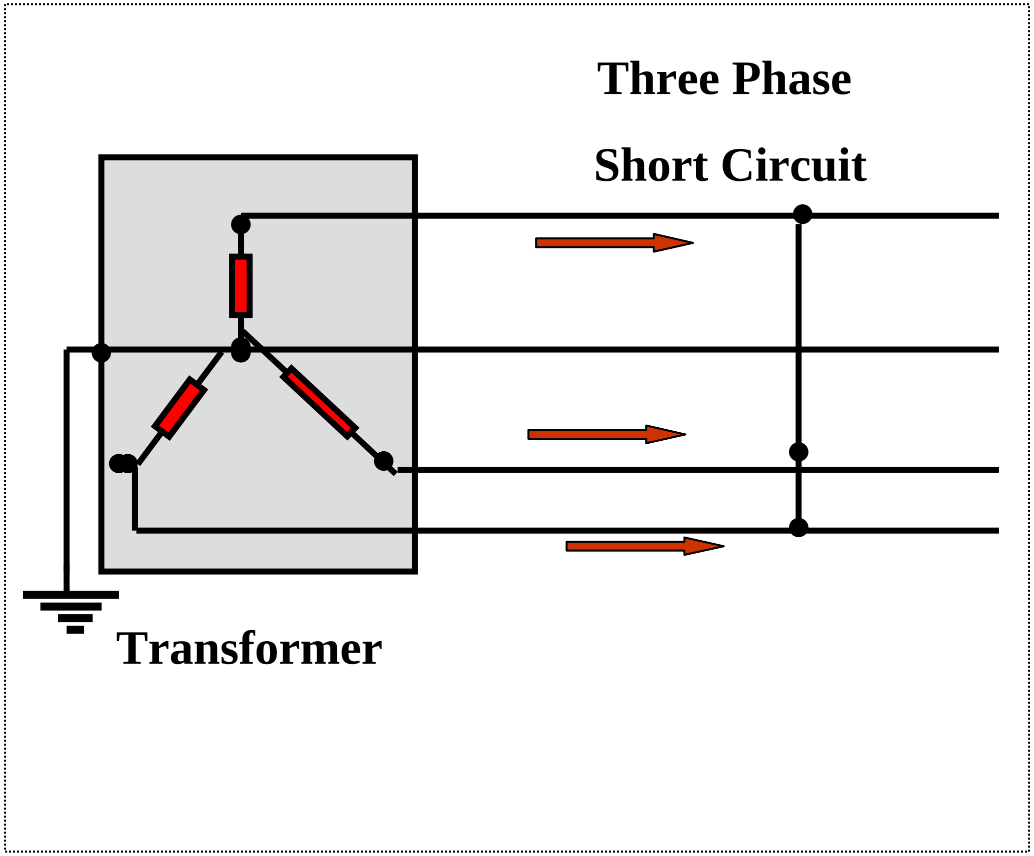
$$V_4 = prefault + \Delta V_4$$
$$= prefault + 0 - (j0.4)(-j0.8)$$
$$= 1\angle 0^o - 0.32 = 0.68\,pu$$

$$(I_F)_{34} = \frac{V_3 - V_4}{j0.8} = -j0.1\,pu$$

$$(I_F)_{35} = \frac{V_3 - V_5}{j0.4} \quad \text{and} \quad (I_F)_{45} = \frac{V_4 - V_5}{j0.4}$$

Symmetrical

Fault Calculation



Three Phase Fault Calculation

Simple Circuits
Load Ignored
Use Thevenin's Equivalent

2

Simple Circuits
Load not Ignored
Use Thevenin's Equivalent
Find Pre-fault voltage

Large Circuits
Construct
The Bus Impedance Matrix

2. Symmetrical Faults Considering the load current

Generally, the fault currents are much larger than the load currents. Therefore, the *load current can be neglected during fault calculations*.

There are some cases where ***considering the load current is an essential factor*** in fault calculations. Superposition technique is proposed for such cases to compute the fault current.

Connecting the load to the system causes the current to flow in the network. Voltage drop due to system impedance cause the *voltage magnitude at different buses to be deviated from 1.0 pu*.

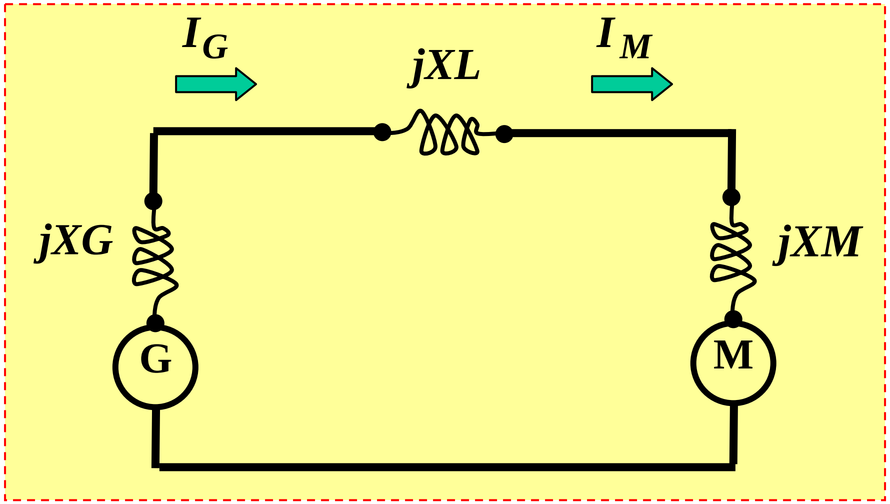
For such case, ***it is necessary to compute the terminal voltage*** at fault location before fault takes place. This terminal voltage is known as the ***pre-fault voltage***.

The ***pre-fault voltage*** and the $\boldsymbol{Z_{TH}}$ are used in calculating the fault current.

The ***fault current represents two components***:

1. ***The Load Current***
2. ***The Short Circuit Current***

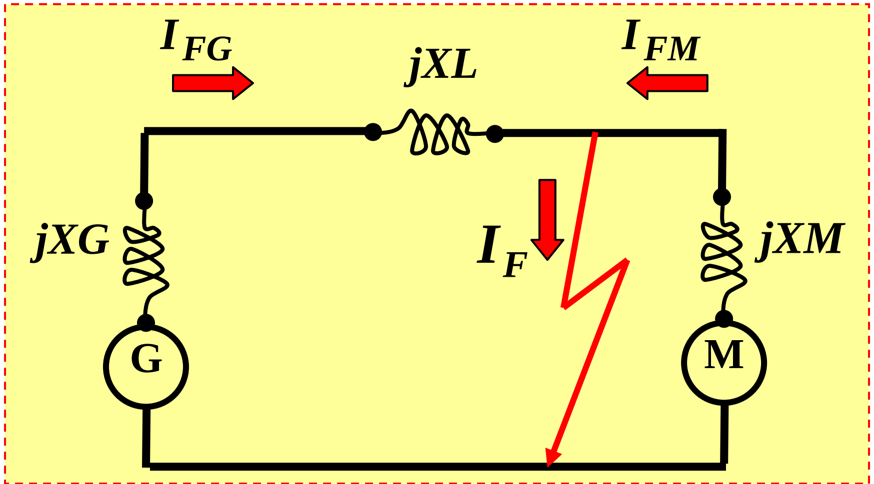
Consider a load (synchronous Motor) connected to a synchronous generator through a transmission line. The circuit model of the network could be represented as shown in the Figure



Normal Operation Condition:

$$I_G = I_M = I_L$$

During fault condition in the system, the generator as well as the load (synchronous motor) will supply the faulted terminals with power from the energy stored in their windings.



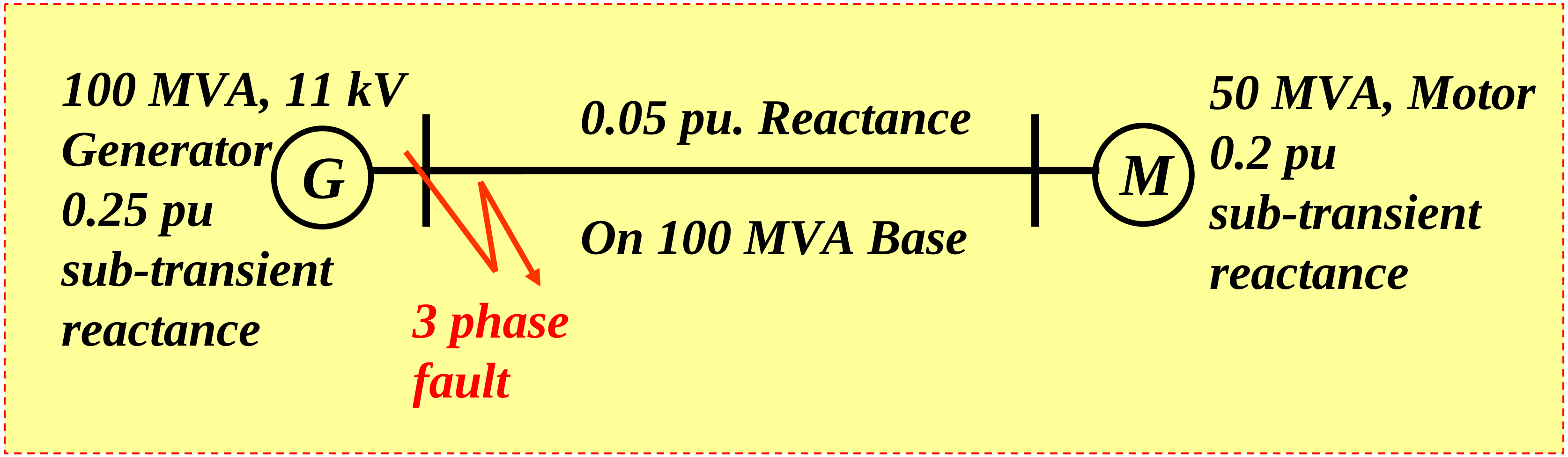
Fault condition at Load terminal:

$$I_G = (I_F)_G + I_L$$

$$I_M = -(I_F)_M + I_L$$

$$I_F = (I_F)_G + (I_F)_M$$

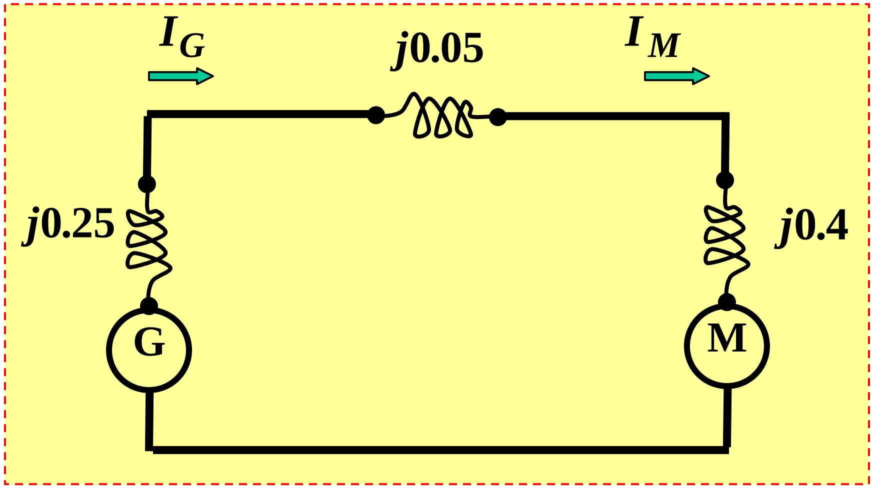
Example



The Motor is drawing 40 MW at 0.8 pf. Leading with terminal voltage of 10.95 kV.

Calculate the total current in the generator and motor during 3 phase s.c.

Solution:
The network could be represented as shown in the Fig.



$$Base\ \ MVA = 100\,MVA$$

$$Base\ \ kV\ = 11kV$$

$$Base\,Curret = \frac{100\,MVA}{\sqrt{3}(11kV)} = 5248.88\,A$$

Under Normal Operation Condition (Prefault condition)

$$The\ Load\ \ Curret = \frac{40\,MW}{\sqrt{3}(10.95kV\ )(0.8\ )} = 2636.4\,A$$

$$(I_L)_{pu} = \frac{2636.4}{5248.88} = 0.502\,pu$$

$$The\ power\ \ factor\ is\ 0.8\ leading$$

$$I_L = 0.502\angle\cos^{-1}(0.8)$$

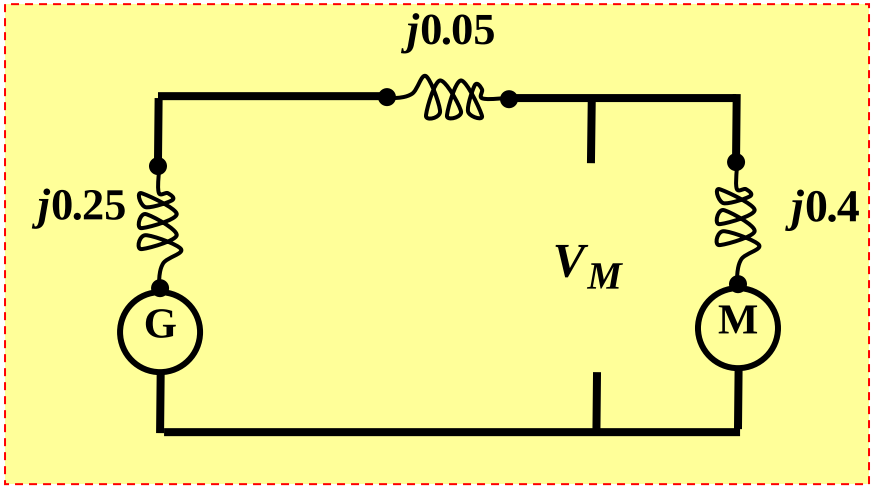
$$I_L = 0.502(0.8 + j0.6)$$

$$I_L = (0.402 + j0.301)\ \ pu$$

Consider the motor terminal voltage as a reference.

$$(\textit{Motor terminal voltage})_{pu} = \frac{10.95}{11} = 0.995 \ pu$$

$$(V_M)_{pu} = 0.995\angle 0^o \ pu$$

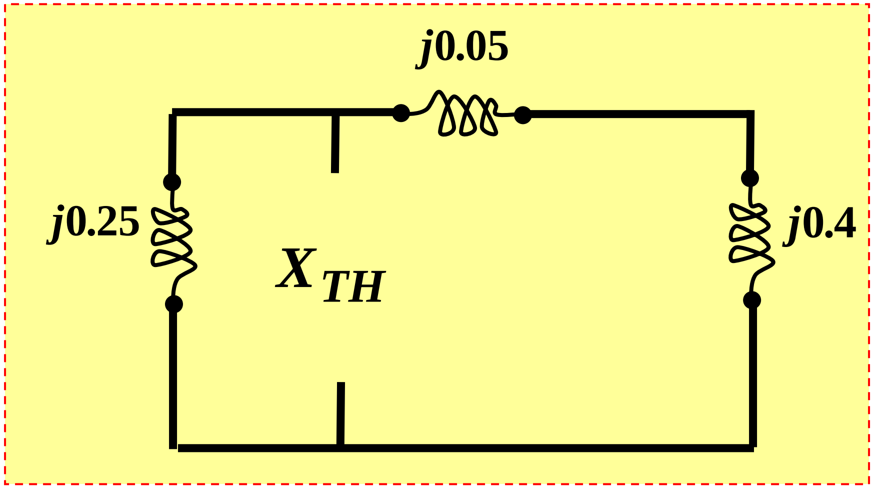


Using KVL, calculate the *pre-fault voltage* at the generator terminal.

$$V_G = I_L(j0.050) + V_M$$

$$V_G = (0.402 + j0.301)(j0.050) + 0.995$$

$$V_G = (0.9799 + j0.0201)\,pu$$

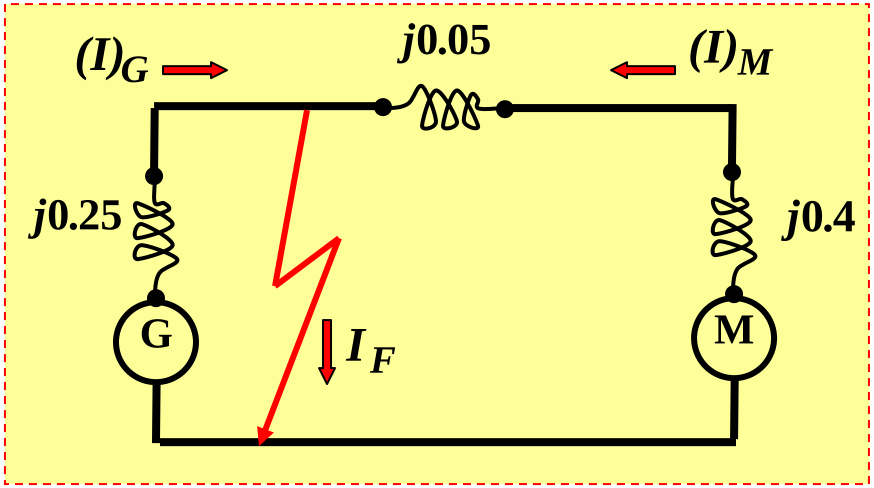


Find the *equivalent reactance* as seen from the fault terminals.

$$X_{TH} = \frac{(j0.25)(j0.45)}{(j0.25) + (j0.45)}$$

$$X_{TH} = j0.1607 \ pu$$

Calculate the fault current



$$(I_F)_{pu} = \frac{pre - fault\ Voltaege}{X_{TH}}$$

$$(I_F)_{pu} = \frac{0.9799 + j0.0201}{j0.1607}$$

$$(I_F)_{pu} = (0.125 - j6.09)\,pu$$

Fault Current from *Generator Side*

$$(I_F)_G = (I_F)_{pu}\frac{j0.45}{j0.45 + j0.25}$$

$$(I_F)_G = (0.08 - j3.91)\,pu$$

Current from *Generator Side*:

$$(I)_G = (I_F)_G + I_L$$

$$(I)_G = (0.08 - j3.91) + (0.402 + j0.301)$$

$$(I)_G = (0.482 - j3.609)\,pu$$

$$(I)_G = 3.64\angle -82.4^o\ pu$$

Fault Current from *Motor Side*

$$(I_F)_M = (I_F)_{pu} - (I_F)_G$$

$$(I_F)_M = (0.125 - j6.09) - (0.08 - j3.91)\,pu$$

$$(I_F)_M = (0.045 - j2.18)\,pu$$

Current from *Motor Side*:

$$(I)_M = (I_F)_M - I_L$$

$$(I)_M = (0.045 - j2.18) - (0.402 + j0.301)$$

$$(I)_M = (-0.357 - j2.48)\,pu$$

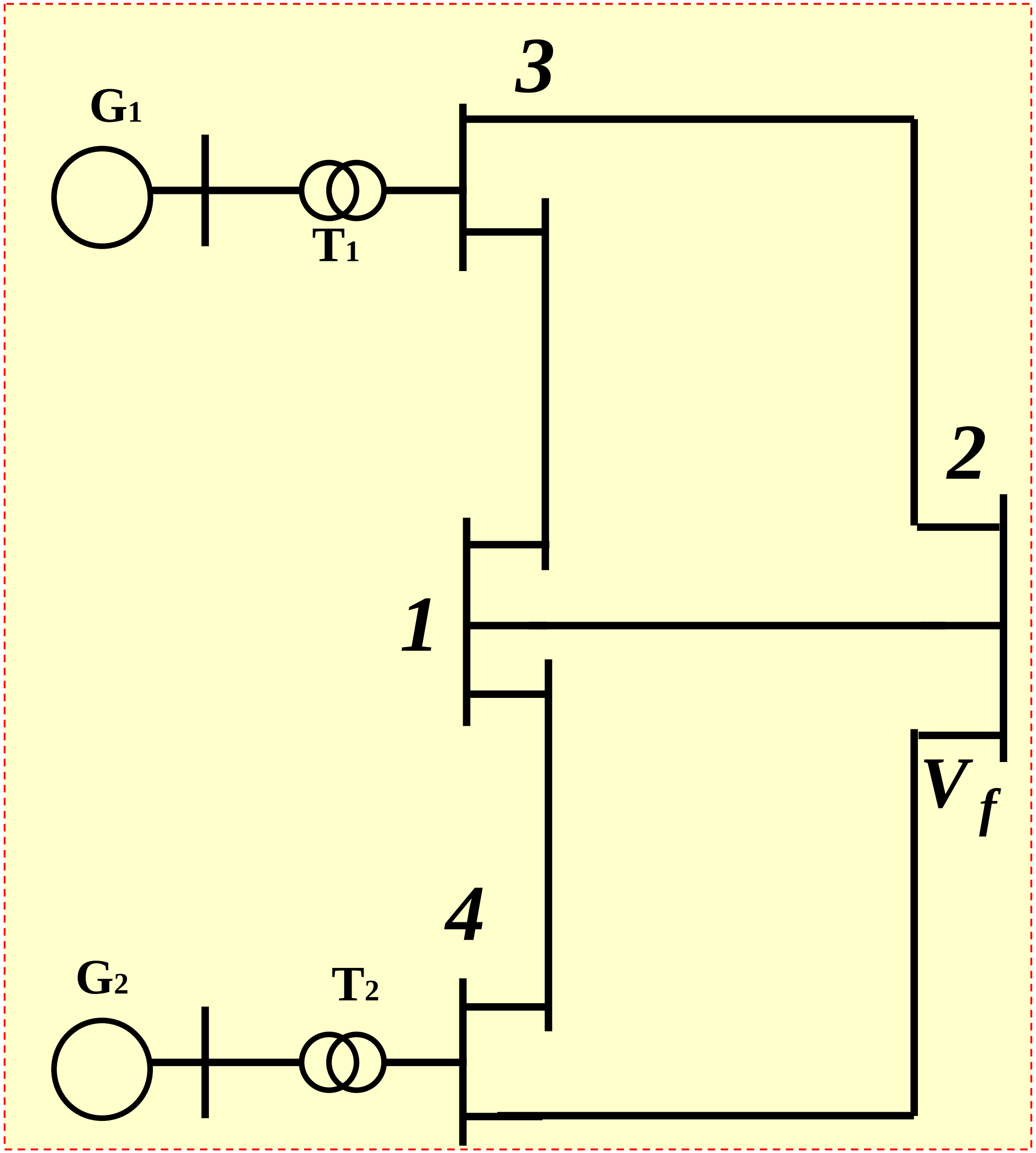
$$(I)_M = 2.505\angle 261.8^o\ pu$$

3 - Symmetrical Fault Calculation Using Bus Impedance Matrix

Consider the system shown in the Figure.

The two generators are supplying the buses 1, 2, 3 and 4.

Let the pre-fault voltage between bus 2 and ref. Bus be (V_f).

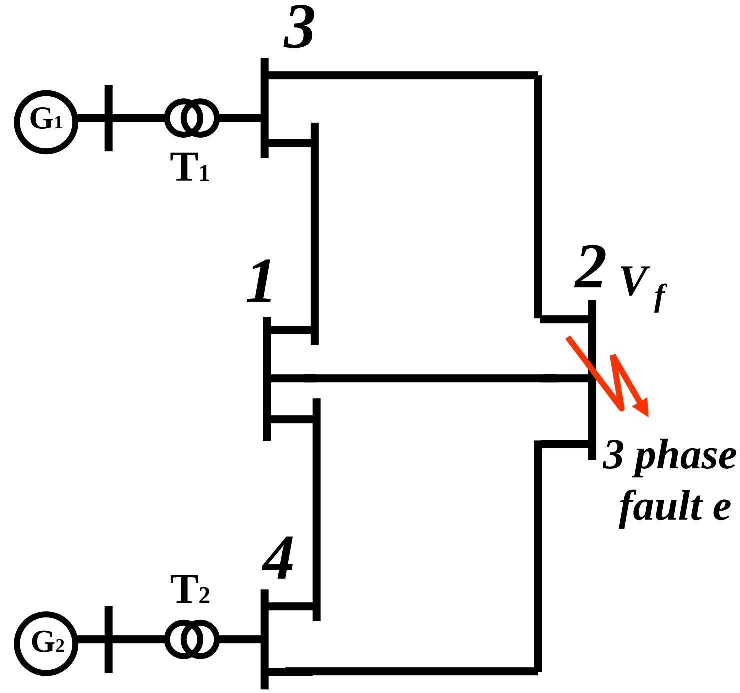


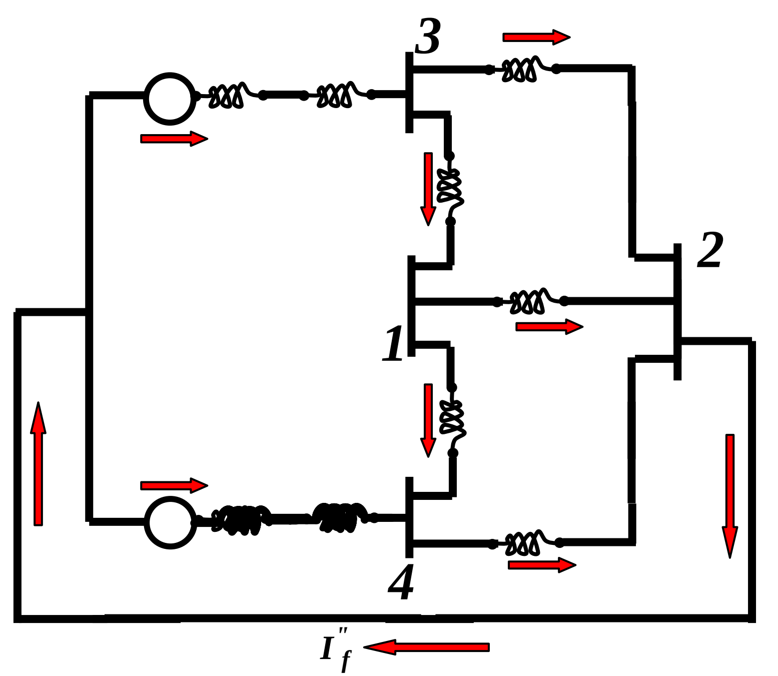
If a 3 phase short circuit occurs a bus 2.

Then, the system can be analyzed using the reactance circuit.

A huge current I''_f will run in the system during the fault condition.

If the pre-fault voltage between bus 2 and ref. bus is V_f, then the voltage during fault is zero.

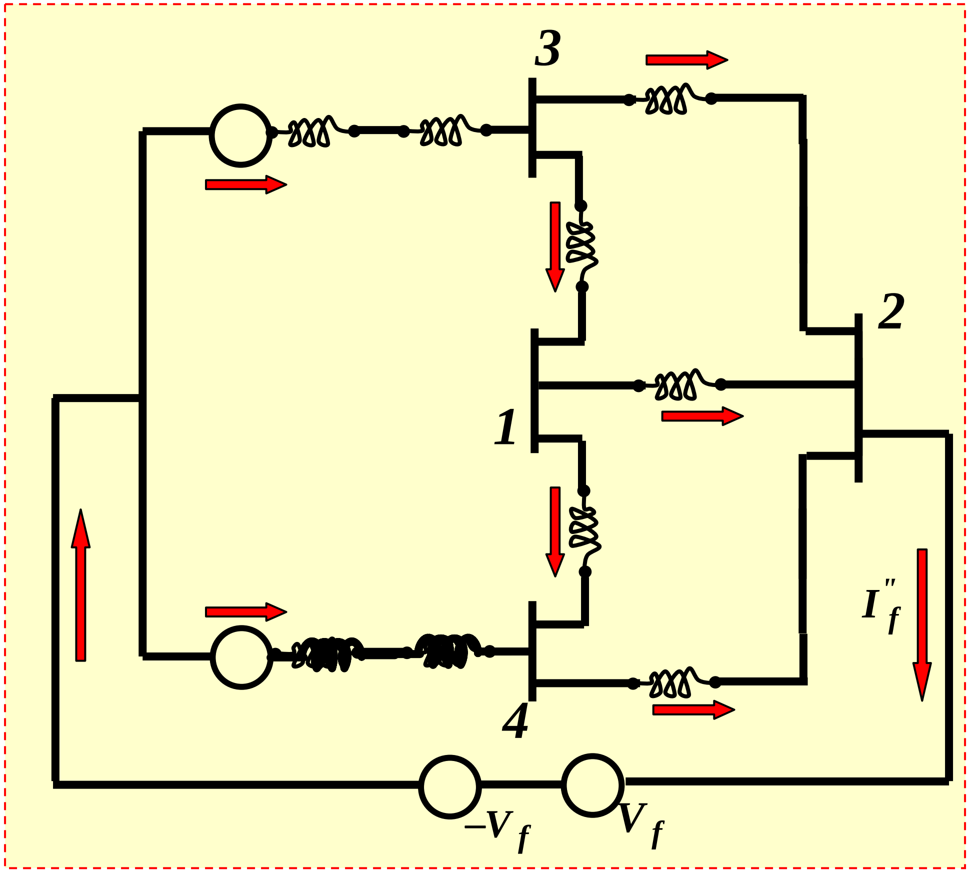




During the three-phase fault, the voltage between bus 2 and the reference becomes zero. Therefore, the 3 phase fault at bus 2 can be simulated by making the voltage between bus 2 and Ref. is equal to zero during the fault condition.

This is simulated by inserting a source with a magnitude equal to $(-V_f)$

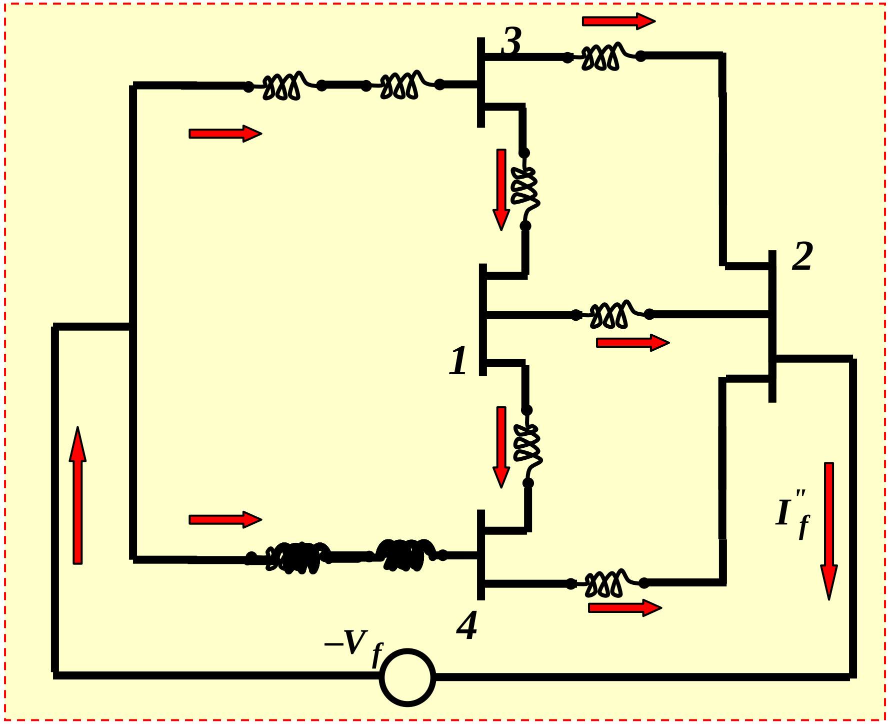
Therefore, the voltage between bus 2 and reference is zero and fault current runs in the system.



This means that, the Fault current I''_f ***during the three-phase short circuit results from the voltage source*** $(-V_f)$

Therefore, to compute the short circuit current, we have to find the current <u>entering</u> bus 2 due to only $(-V_f)$

Ignoring all other currents entering other buses (ignore sources).



The Nodal Impedance Equation during the fault is:

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \\ \Delta V_4 \end{bmatrix} = \begin{bmatrix} \Delta V_1 \\ -Vf \\ \Delta V_3 \\ \Delta V_4 \end{bmatrix} = \underbrace{\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix}}_{Z_{BUS}} \begin{bmatrix} 0 \\ -I''_f \\ 0 \\ 0 \end{bmatrix}$$

Note:

ΔV_i ***is the voltage difference between node i and the reference node due to the current*** I''_f .

Or

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \\ \Delta V_4 \end{bmatrix} = \begin{bmatrix} \Delta V_1 \\ -Vf \\ \Delta V_3 \\ \Delta V_4 \end{bmatrix} = \begin{bmatrix} -Z_{12}I_f^{''} \\ -Z_{22}I_f^{''} \\ -Z_{32}I_f^{''} \\ -Z_{42}I_f^{''} \end{bmatrix}$$

And from the second row, the fault current is:

$$I_f^{''} = \frac{V_f}{Z_{22}}$$

Substituting in the previous equation:

$$\begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \\ \Delta V_4 \end{bmatrix} = \begin{bmatrix} \Delta V_1 \\ -Vf \\ \Delta V_3 \\ \Delta V_4 \end{bmatrix} = \begin{bmatrix} -\frac{Z_{12}}{Z_{22}}V_f \\ -V_f \\ -\frac{Z_{32}}{Z_{22}}V_f \\ -\frac{Z_{42}}{Z_{22}}V_f \end{bmatrix}$$

Assuming no load is connected in the system, no current will flow before fault and all bus voltages are the same and equal to the pre-fault voltage (V_f)

Using Superposition, then during the fault:

$$V_{i(\text{Bus } i \text{ voltage})} = V_{f(\text{Pre-fault voltage})} + \Delta V_i$$

ΔV_i *is the voltage change in bus i due to fault current in bus 2.*

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} V_f \\ V_f \\ V_f \\ V_f \end{bmatrix} + \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \\ \Delta V_4 \end{bmatrix} = V_f \begin{bmatrix} 1-\dfrac{Z_{12}}{Z_{22}} \\ 0 \\ 1-\dfrac{Z_{32}}{Z_{22}} \\ 1-\dfrac{Z_{42}}{Z_{22}} \end{bmatrix}$$

Example:

A three-phase fault occurs at bus 2 of the network shown in the Figure.

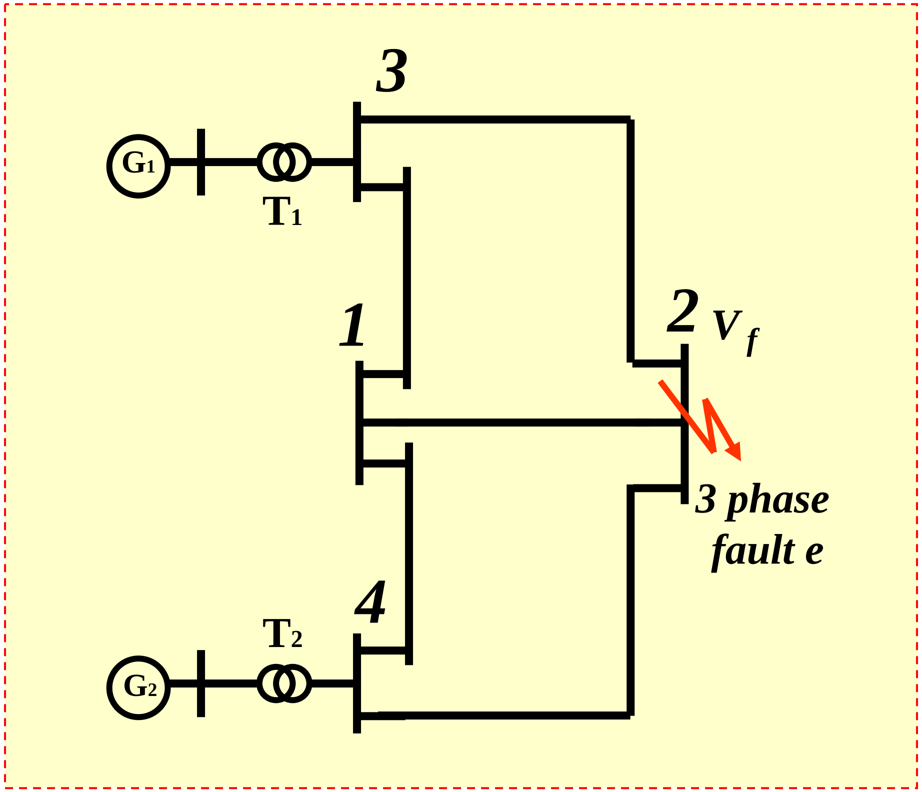
Determine:

1. the sub-transient current during the fault,

2.the voltages at all the buses

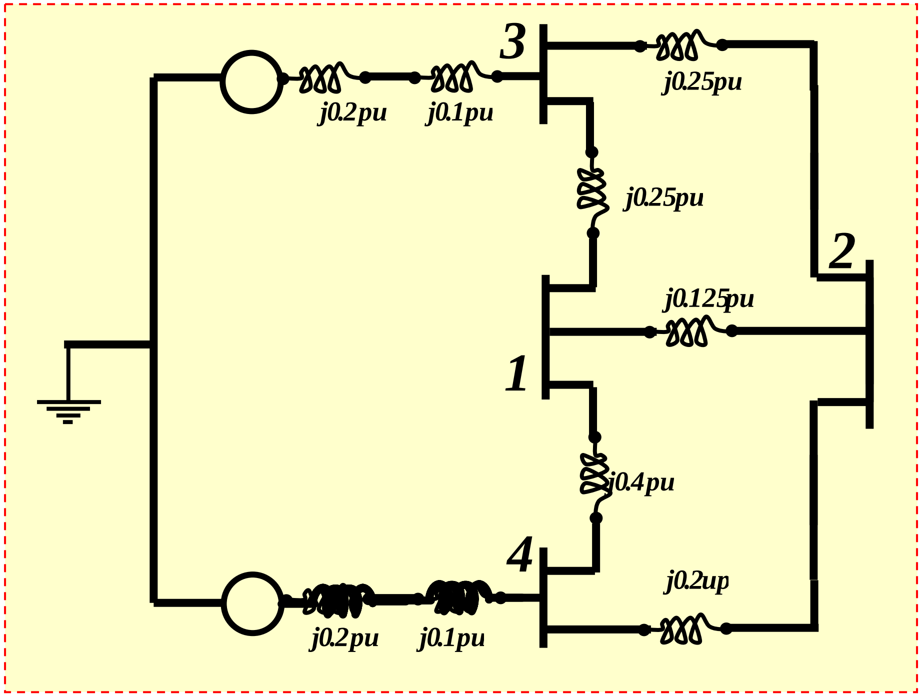
3.The current flow during the fault from buses 3-2, 1-2 and 4-2.

Consider the pre-fault voltage at bus 2 equal to 1 pu. and neglect the pre-fault currents.



Solution:

Construct the reactance circuit under normal operation condition.



Construct the bus impedance Matrix (Z_{BUS})

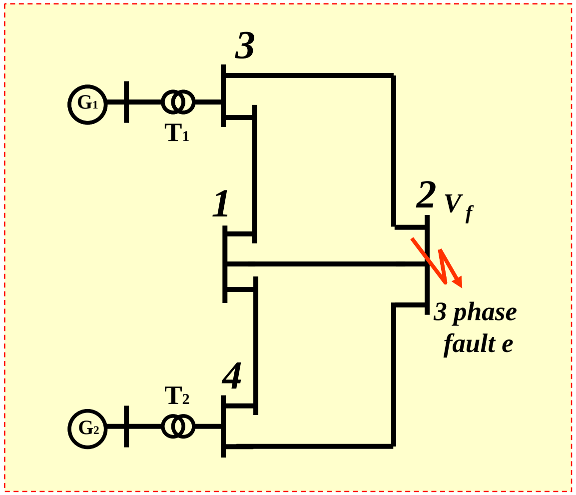
$$Z_{BUS} = \begin{bmatrix} j0.2436 & j0.1938 & j0.1544 & j0.1456 \\ j0.1938 & j0.2295 & j0.1494 & j0.1506 \\ j0.1544 & j0.1494 & j0.1954 & j0.1046 \\ j0.1456 & j0.1506 & j0.1046 & j0.1954 \end{bmatrix}$$

NOTE:

Constructing Z_{Bus} will be discussed later.

Since there are no-load currents, the pre-fault voltage at all the buses is equal to 1.0 pu. When the fault occurs at bus 2,

$$I_f'' = \frac{V_f}{Z_{22}} = \frac{1.0}{j0.2295} = -j4.357 \ \ pu$$



$$Z_{BUS} = \begin{bmatrix} j0.2436 & j0.1938 & j0.1544 & j0.1456 \\ j0.1938 & j0.2295 & j0.1494 & j0.1506 \\ j0.1544 & j0.1494 & j0.1954 & j0.1046 \\ j0.1456 & j0.1506 & j0.1046 & j0.1954 \end{bmatrix}$$

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = V_f \begin{bmatrix} 1 - \dfrac{Z_{12}}{Z_{22}} \\ 0 \\ 1 - \dfrac{Z_{32}}{Z_{22}} \\ 1 - \dfrac{Z_{42}}{Z_{22}} \end{bmatrix}$$

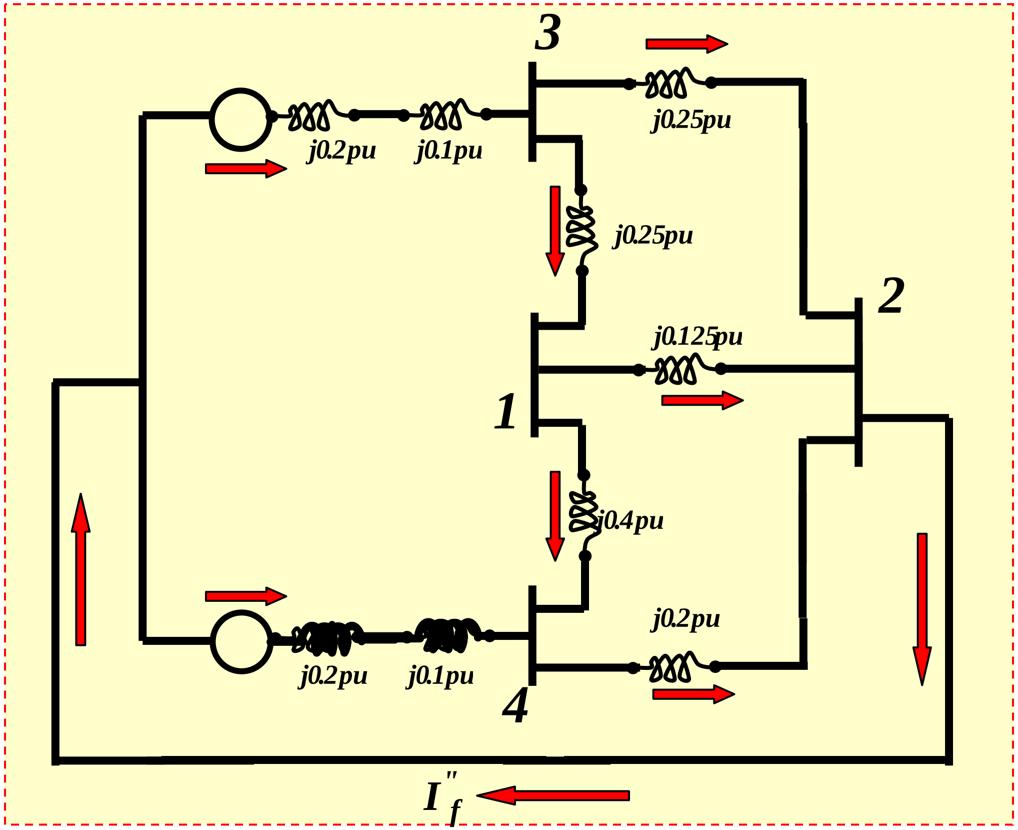
$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = V_f \begin{bmatrix} 1 - \dfrac{Z_{12}}{Z_{22}} \\ 0 \\ 1 - \dfrac{Z_{32}}{Z_{22}} \\ 1 - \dfrac{Z_{42}}{Z_{22}} \end{bmatrix} = \begin{bmatrix} 1 - \dfrac{j0.1938}{j0.2295} \\ 0 \\ 1 - \dfrac{j0.1494}{j0.2295} \\ 1 - \dfrac{j0.1506}{j0.2295} \end{bmatrix} = \begin{bmatrix} 0.155 \\ 0 \\ 0.349 \\ 0.343 \end{bmatrix}$$

The current flows from bus 1 to bus 2 is:

$$I_{12} = \frac{V_1 - V_2}{j0.125}$$

$$I_{12} = \frac{0.1556}{j0.125}$$

$$I_{12} = -j1.2448 \ \ pu$$



The current flows from bus 3 to bus 2 is:

$$I_{32} = \frac{V3 - V_2}{j0.25}$$

$$I_{32} = -j1.396 \ \ pu$$

The current flows from bus 4 to bus 2 is:

$$I_{42} = -j1.719 \ \ pu$$

The current flows from bus 3 to bus 1 is:

$$I_{31} = \frac{V_3 - V_1}{j0.25} = -j0.7736 \ \ pu$$