

# **Advanced Power System Analysis**

## **Lecture 8**

### **Fault analysis**

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### ***Lecture learning outcomes:***

At the end of this lecture, you will be able to:

- i. Understand the symmetrical three phase fault
- ii. Know the symmetrical fault analysis methods
- iii. Analyze the short-circuit MVA Level calculations
- iv. Know how to select the circuit breaker ratings

# Outlines

- 1. Introduction: Symmetrical Short-circuit**
- 2. Symmetrical Fault Analysis Methods**
- 3. Short-circuit MVA Level Calculations**
- 4. Selection of Circuit Breaker Ratings**
- 5. Solved Problems using Analytical and Software**

**Summary**

**References**

# 1. Introduction: Symmetrical Short-circuit

- Any situation in which all three of the system's phases are either earthed or short-circuited to one another is known as a three-phase fault[1].
- This kind of problem is characterized as a simultaneous short-circuited fault that generates symmetrical current at all three phases.
- It is the most severe kind, but it doesn't happen very often.
- The internal EMF of the machine in the system, internal impedances, and the impedance in the network between the machine and the problem all affect this fault current.
- Figure. 1 shows the circuit schematic for a three-phase fault.

# Introduction

# Cont....

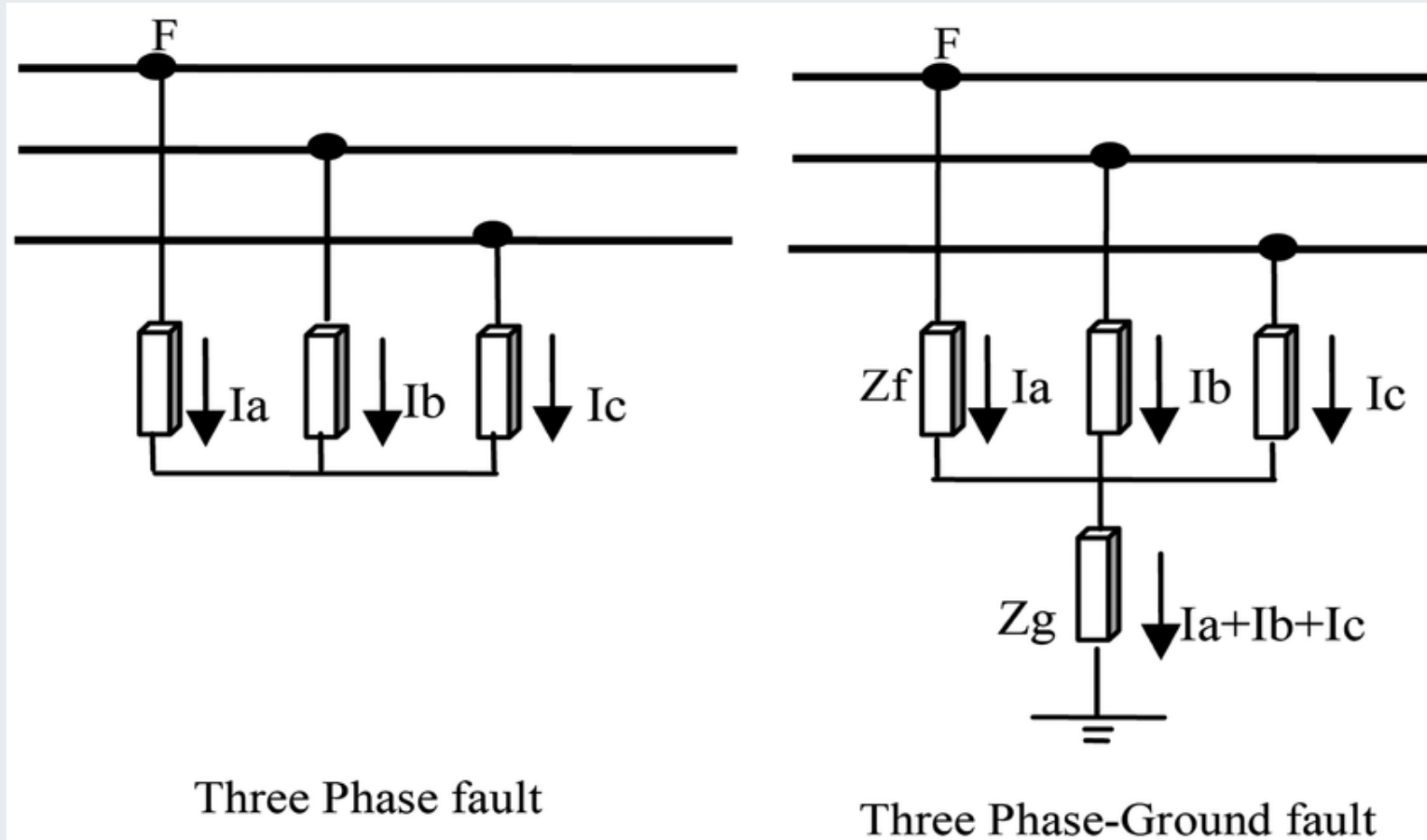


Figure 1. Circuit diagram of three phase fault .

Url: <https://www.researchgate.net/publication/3275710/figure/fig4/AS:394697127284739@1471114536548/Two-most-common-symmetrical-fault-types.png>

# Introduction

# Cont....

- The balanced three-phase faults may be analyzed using **per phase basis** analysis or equivalent single-phase circuit.
- The short circuit analysis of symmetrical fault is usually carried out in per-unit quantities
- This in general is a balanced condition, and we just need to know the positive-sequence network to analyse faults.
- Further, the single line diagram can be used, as all the three-phases carry equal currents displaced by  $120^\circ$ .

# Introduction

# Cont....

- Three-phase faults, with or without earth, usually makes only 5% of the first faults in a power system[2].
- Line-earth faults make up 80% of unbalanced faults, followed by double line faults with or without earth (15%), which frequently develop into three-phase faults, and open circuit faults.
- A fault describes a change in the structural network that is comparable to that brought on by the addition of impedance at the fault location.
- The defect is known as a fastened fault or solid fault if the fault impedance is zero.

## 2. Symmetrical Fault Analysis Methods

- **Analytical techniques and computer-aided** modeling/ simulation are used to do the fault analysis[3].
- The development of **mathematical formulas for power system** modeling, which aids in identifying fault currents, is the mainstay of analytical techniques.
- In contrast, the computer-aided approaches simulate fault scenarios and analyses the system's response using various **power system software**.
- The most widely used analytical techniques are the bus-impedance matrix, superposition, and Thevenin equivalent approaches.

# Symmetrical Fault Analysis Methods

Cont....

- **Common software's are:**
- Power World simulator
- PSAT
- ETAP
- Digsilent
- PSS
- Others

# Symmetrical Fault Analysis Methods

## Cont....

**The Thevenin's** theorem : is used for three phase balanced fault analysis using the following steps:

- Assume all pre-fault voltage magnitudes are 1.0 per unit and all pre-fault currents are zero.
- Draw the single line diagram.
- Draw the per unit reactance diagram, which is determined from the per unit analysis
- Determine the Pre-fault bus voltage and currents, which are obtained from the load flow analysis result.
- Replace the reactance's of synchronous machines by their sub-transient or transient values.
- Short-circuited all the emf sources, to determine the passive Thevenin's network

# Symmetrical Fault Analysis Methods

# Cont....

- Draw the Thvenin's equivalent circuit viewed from the faulted bus.
- Determine the fault current using the theorem

$$I_f = \frac{E_{th}}{j(X_{th} + X_f)} \quad \text{eqn.(1)}$$

where,  $E_{th}$  or  $V^\circ$  is the pre-fault voltage

- Determine the current contributed by the generator and motor , etc

$$I_G = \frac{X_m}{j(X_g + X + X_m)} I_f \quad \text{eqn.(2)}$$

$$I_m = \frac{j(X_g + X)}{j(X_g + X + X_m)} I_f \quad \text{eqn.(3)}$$

- Determine the post-fault voltage

$$V_{i(f)} = V_{i(0)} + \Delta V = V_{i(0)} + (-jX_{th} I_f)$$

eqn.(4)

- Determine the post-fault line flows

$$I_{ij(f)} = \frac{(V_{i(f)} - V_{j(f)})}{Z_{ij}}$$

eqn.(5)

# 3. Short-circuit MVA Level Calculations

- In a power system, the maximum fault current that can flow into a zero impedance fault is necessary to be known for switch gear solution[4].
- It can be either symmetrical three-phase value or value of any asymmetrical condition.
- Thus, the fault-level describes the value for the symmetrical condition.
- The fault level is usually expressed in MVA or the corresponding per unit value, with the maximum fault current value being converted using the nominal voltage rating.

# Short-circuit MVA Level Calculations

# Cont....

- The short-circuit capacity , SCC is defined by the product of magnitude of pre-fault bus voltage and post-fault current as given by:

$$\begin{aligned} \text{Short - circuit - capacity} &= |E_{th}| * |I_f| \\ &= |E_{th}| * \left| \frac{E_{th}}{Z_{th}} \right| = \left| \frac{E_{th}^2}{Z_{th}} \right| \end{aligned} \quad \text{eqn.(6)}$$

- The per unit voltage for nominal value is unity, so that:

$$\text{Faultlevel}(P.u) = \frac{1}{Z_{th}} \quad \text{eqn.(7)}$$

$$\begin{aligned} \text{FaultMVA} &= \text{Faultlevel}(P.u) * MVA_{base} \\ &= \frac{MVA_{base}}{Z_{th}} \end{aligned}$$

# Short-circuit MVA Level Calculations

## Cont....

- Then, the base current is determined as:

$$I_{base}^{current} = \frac{MVA_{base}}{\sqrt{3}V_{base} (kV)} * 10^3 \quad \text{eqn.(8)}$$

- Then, fault current in Amp is:

$$I_f (A) = I_f p.u) * I_{base}^{current} \quad \text{eqn.(9)}$$

- The SCC of a bus is known as the fault level of the bus.
- Thus, the ability power network bus to maintain its voltage is directly proportional to its SCC.
- Generally, an infinitely strong bus /grid has an infinite SCC, with zero equivalent impedance and will maintain its voltage under all conditions.

# Short-circuit MVA Level Calculations

# Cont....

- Synchronous generators cause the short-circuit current's magnitude to vary with time.
- It starts off at its highest value and then steadily declines.
- Circuit breakers are severely affected by these higher fault levels, allowing the usage of current-limiting reactors.
- Since CBs must tolerate recovery voltage across the breaker after an arc interruption, the short-circuit MVA is a more accurate measure of the stress on CBs than the short-circuit current.
- The internal Emf of the network's machines, their impedances, and the impedances between the machines and the fault all affect the current that flows during a problem.

# 4. Selection of Circuit Breaker Ratings

- It is protective devices that can be used in power system to correct the system in the event of a fault.
- In normal working condition they can be **used as a switch**.

**Hence the two functions of CBs are as follows:**

- To act as switch for normal load conditions
- To automatically isolate the faulty part in the event of a fault

# Selection of Circuit Breaker Ratings

Cont....

- Two of the CB ratings which require the computation of SC current are:
  1. Rated momentary current and
  2. Rated symmetrical interrupting current.
- Symmetrical short-circuit current is obtained by using sub-transient reactance for synchronous machines.
- Momentary current (rms) is then calculated by multiplying the symmetrical momentary current by a factor of 1.6 to account for the presence of dc offset current.

# Selection of Circuit Breaker Ratings

## Cont....

The CB for a particular application is selected on the basis of the following ratings.

- Normal working power level specified as rated interrupting current or rated interrupting kVA.
- The fault level specified as either the rated short-circuit interrupting current or rated short-circuit current interrupting MVA.
- Momentary current rating
- Normal working voltage
- Speed of CB

# Selection of Circuit Breaker Ratings Cont....

- Sub-transient reactance's for synchronous generators and transient reactance's for synchronous motors are used to calculate the symmetrical current that has to be interrupted.
- The symmetrical SC current is multiplied by a factor as shown in the table below to account for the DC offset value that must be added in order to obtain the current to be interrupted.

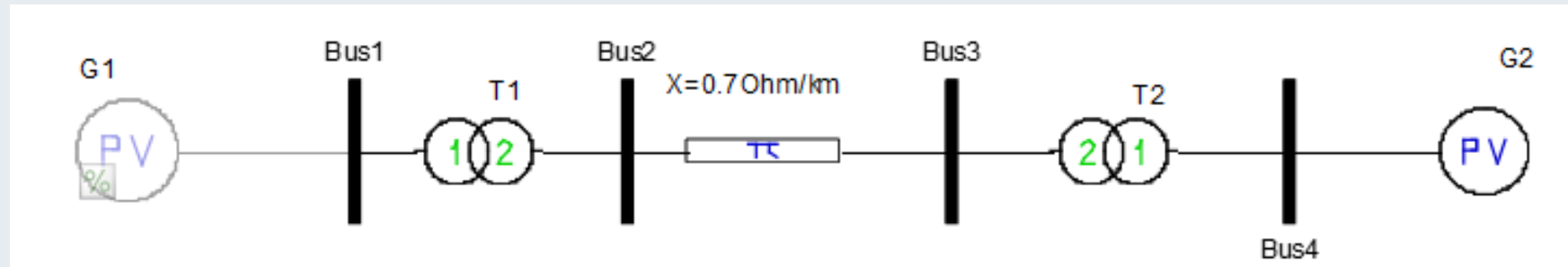
<i>Speed of CB</i>	<i>Multiplying factor</i>
8 cycles or more	1.0
5 cycles	1.1
3 cycles	1.2
2 cycles	1.4
1½ cycles	1.5

$$\text{Short circuit current Interrupting, MVA} = \sqrt{3} * |V_{pfl}| * |I_{fl}| \quad \text{eqn.(10)}$$

$$\text{Short circuit current Interrupting, P.u} = \sqrt{3} * |V_{pfl,p.u}| * |I_{fl,p.u}| * MVA_b$$

# 5. Solved Problems using Analytical and Software

Example 1. The two identical generators G1 and G2 rated 15 kV, 25MVA and have a transient reactance of 0.2 p.u. at their own bases. Two transformers, T1 and T2 are also identical rated 15/45 kV, 8 MVA and reactance of 0.06 p.u. based on their own MVA base. It's observed that 60 km long 0.7 ohm/km/phase transmission line is connected between the two generators. Determine, the three phase fault current, when fault occurs at one-third of the line.



# Solved Problems

Cont....

Solution :

- Select:  $MVA_b=25$  MVA and  $Kv_b=15$ kv
- Reactance of two generators are same with the given value since the selected base values are similar:

$$X_{G1} = X_{G2} = 0.2 p.u$$

- The reactance of two transformers T1 and T2 in new base , 25 MVA while referring primary side voltage is given by:

$$X_{T1}^{new} = \left(\frac{15kv}{15kv}\right)^2 * \frac{25MVA}{8MVA} * 0.06 = 0.18755 = X_{T2}^{new}$$

# Solved Problems

# Cont....

- The reactance of transmission line in per unit if fault is takes place at its one-third and the remaining two-third are given by:

$$X_{Tx}^{ohm} = \frac{1}{3} * 60km * 0.7ohm / km = 14 ohm$$

$$X_{Tx}^{ohm} = \frac{2}{3} * 60km * 0.7ohm / km = 28 ohm$$

$$V_b = \frac{V_b(\text{Low voltage side})}{KV \text{ rating at low voltage side}} * KV \text{ rating at HV side}$$

- Thus,  $V_b = \frac{15kv}{15kv} * 45kv = 45kV$

- Then, base impedance, per unit impedances at one-third and two-third are given by :

$$Z_b = \frac{V_b^2}{S_b} = \frac{45^2 kv}{25MVA} = 81Ohm$$

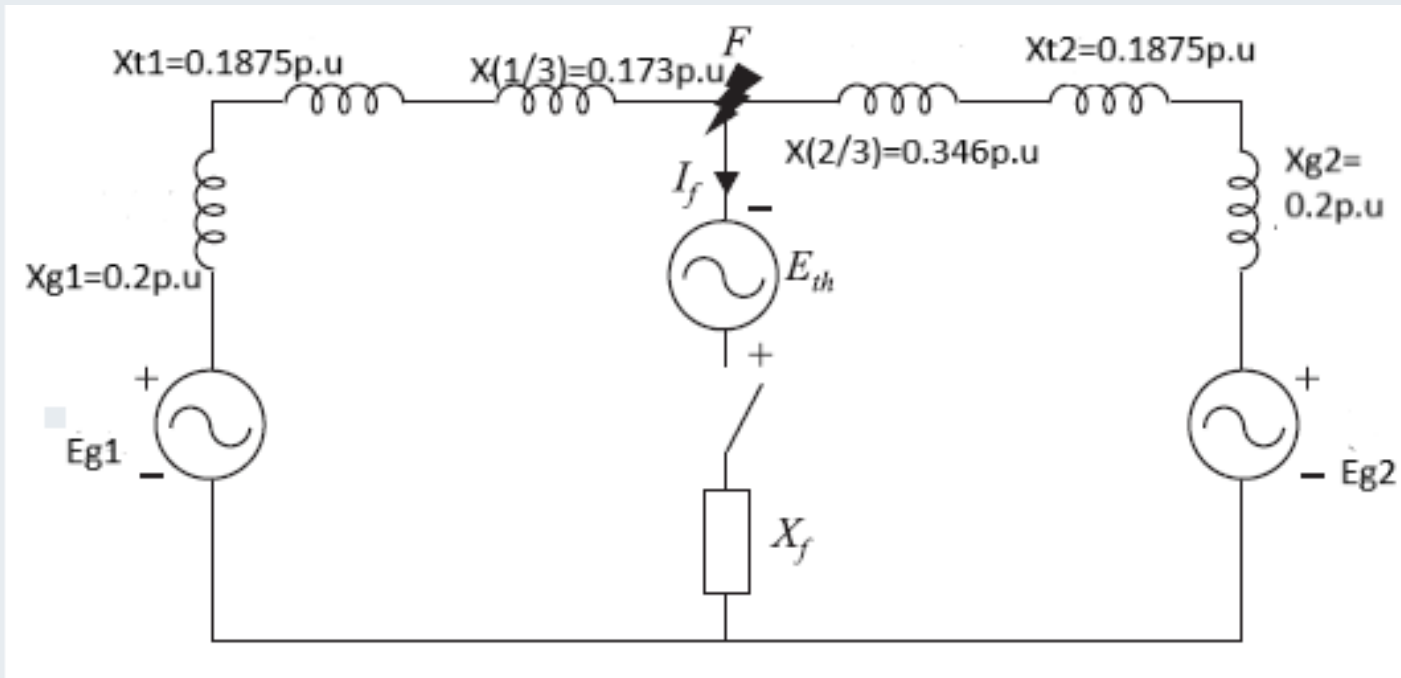
$$X_{Tx(1/3)}^{P.u} = \frac{14}{81} = 0.173p.u$$

$$X_{Tx(2/3)}^{P.u} = \frac{28}{81} = 0.346p.u$$

# Solved Problems

# Cont....

- The pre-fault reactance diagram is given as:



$$X_{Th} = \frac{0.5605 * 0.7335}{0.5605 + 0.7335} = 0.3177 \text{ p.u}$$

- Then, the Thevenin equivalent impedance is calculated as:

- Then, the fault current while considering pre-fault voltage unity and the fault impedance =0 is given by:

$$I_f = \frac{E_{Th}}{(X_{Th} + X_f)} = \frac{1\text{p.u.}}{0.3177\text{p.u.} + 0} = -j3.148 \text{ p.u.}$$

$$I_b = \frac{MVA_b}{\sqrt{3} * K V_b} * 10^3$$
$$= \frac{25}{\sqrt{3} * 15} * 10^3 = 962.28 \text{ A}$$

- Fault current in amp is equal to fault current in p.u. \* base current:

$$I_f (\text{A}) = I_f * I_b = 3.148 * 962.28 \text{ A}$$
$$= 3,029.26 \text{ A}$$

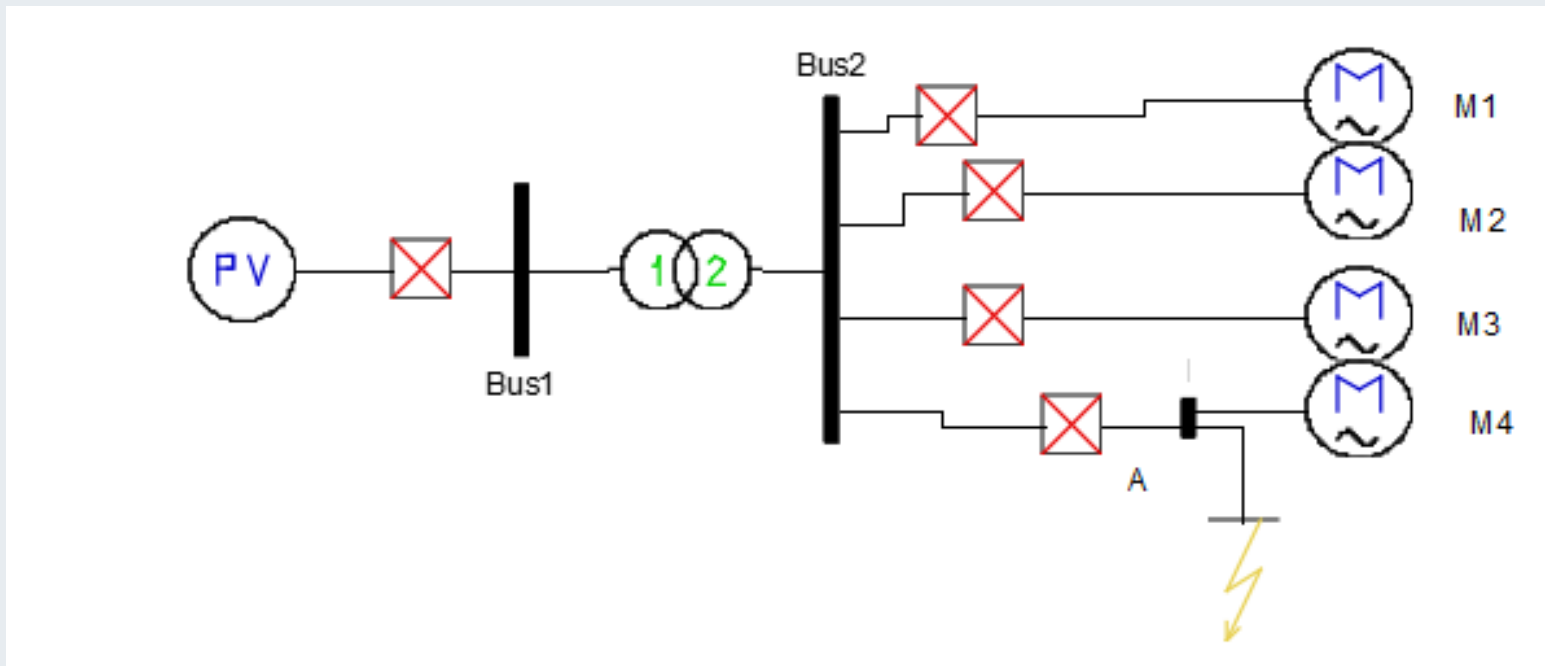
$$I_N^{W/o.f} = \frac{E_g}{X_T} = \frac{1 pu}{0.5605 + 0.7335}$$
$$= 0.7728 \text{ p.u}$$
$$I_N^{W/o.f} (A) = 0.7728 \times 962.28 \text{ A}$$
$$= 743.65 \text{ A}$$

- It is observed that the short circuit current is very high compared to the normal current.

# Solved Problems

# Cont....

- Example 2: A 30 MVA, 15 kV generator with 10% sub-transient reactance is connected through a transformer to a bus which supplies four identical motors, as shown in Fig. below . The sub-transient reactance  $X_d''$  of each motor is 10% on a base of 10 MVA, 3.3 kV. The three-phase rating of the transformer is 30 MVA, 15/3.3 kV, with a leakage reactance of 10%. The bus voltage at the motors is 3.3 kV when a three-phase fault occurs at the point F. For the fault specified, calculate (i) the sub-transient current in the fault , (ii) the sub-transient current in breaker A and (iii) the momentary current in breaker A.



# Solved Problems

# Cont....

- Solution : First we need to develop the circuit diagram as:

$$S_{\text{base}}=30 \text{ MVA}, V_b=15\text{kv}$$

Then,  $X_g''@30\text{MVA}=0.1\text{p.u.}$ ,

$$X_{T1}^{\text{new}} = \left(\frac{15\text{kv}}{15\text{kv}}\right)^2 * \frac{30\text{MVA}}{30\text{MVA}} * 0.1 = 0.10$$

$$KV_{b(\text{lowv})} = \frac{V_b(\text{Low voltage side})}{KV \text{ rating at low voltage side}} * KV \text{ rating at HV side}$$
$$= \frac{15}{15} * 3.3 = 3.3KV$$

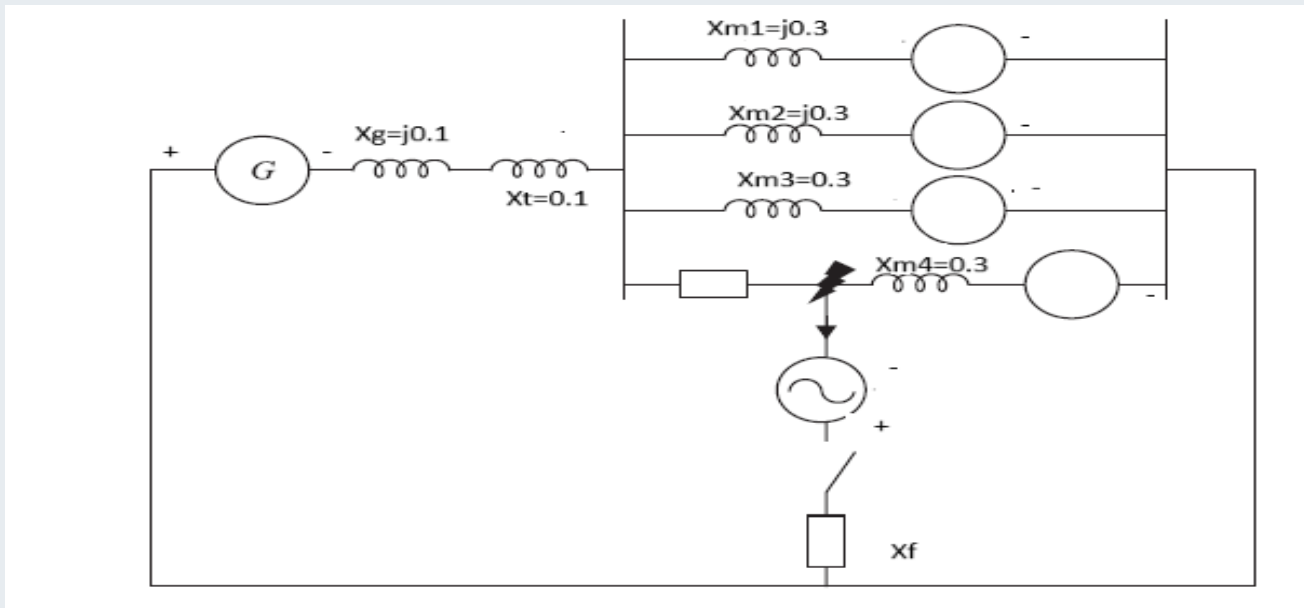
# Solved Problems

# Cont....

- The per unit reactance of each motor in new base is:

$$X_{m(1)}^{new.base} = \left(\frac{3.3}{3.3}\right)^2 * \frac{30MVA}{10MVA} * 0.1$$
$$= 0.3 p.u = X_{m(2)}^{new.base} = X_{m(2)}^{new.base} = X_{m(2)}^{new.base}$$

- The pre-fault circuit diagram is given as:



- The **sub-transient reactance's** are then determined while considering the initial no load conditions
- Which means all reactance's are connected in parallel if the fault is at point A is given by:

$$\frac{1}{X_{th}} = \frac{1}{j0.2} + \frac{1}{j0.3} + \frac{1}{j0.3} + \frac{1}{j0.3} + \frac{1}{j0.3}$$

$$\frac{1}{X_{th}} = -j5 - 4(j3.33) = -j18.32\text{p.u}$$

$$X_{th} = \frac{1}{-j18.32\text{p.u}} = j0.0546\text{p.u}$$

- Then, the fault current for unity pre-fault voltage is calculated as :

$$I_f = \frac{E_{th}}{X_{th} + X_f} = \frac{1\text{p.u}}{j0.0546 + 0.0} = -j18.315\text{p.u}$$

# Solved Problems

Cont....

- The fault current in ampere is determined as:

$$I_b = \frac{MVA_b}{\sqrt{3} * KV_B} * 10^3 = \frac{30}{\sqrt{3} * 3.3} * 10^3 = 5,249.34A$$

$$I_f (A) = 5,249.34A * 18.315$$

$$= 96,141.73A$$

- It is observed that the fault current exponentially increased to higher Value.
- Thus, the sub transient current in breaker A is supplied by the generator and three motors, and the sub transients in breaker A maybe written as.

# Solved Problems

Cont....

- Which is:

$$\frac{1}{X_{th}} = \frac{1}{j0.2} + \frac{1}{j0.3} + \frac{1}{j0.3} + \frac{1}{j0.3}$$

$$\frac{1}{X_{th}} = -j5 - 3(j3.33) = -j14.99\text{p.u}$$

$$X_{th} = \frac{1}{-j14.99\text{p.u}} = j0.067\text{p.u}$$

- Then, the fault current for unity pre-fault voltage is calculated as :

$$I_f = \frac{1\text{p.u}}{0.067} = 14.92\text{p.u}$$

$$I_f (A) = 5,249.34\text{A} * 14.92$$

$$= 78,320.15\text{A}$$

- Finally, to determine the momentary current through breaker, we need to add the DC offset , and need s to multiply the current by a factor of 1.6 as a momentary current is given by:

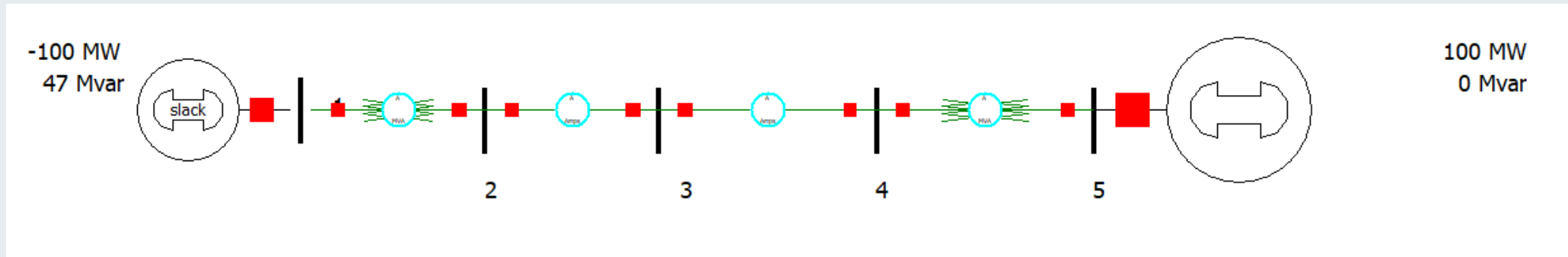
$$I_{Breaker} (A) = 1.6 * 78,320.15\text{A}$$

$$= 125,312.24$$

- Example 1. The two identical generators G1 and G2 rated 15 kV, 25MVA and have a transient reactance of 0.2 p.u. at their own bases. Two transformers, T1 and T2 are also identical rated 15/45 kV, 8 MVA and reactance of 0.06 p.u. based on their own MVA base. It's observed that 60 km long 0.7 ohm/km/phase transmission line is connected between the two generators. Determine, the three phase fault current, when fault occurs at one-third of the line using **PowerWorld** simulator software's

Solution:

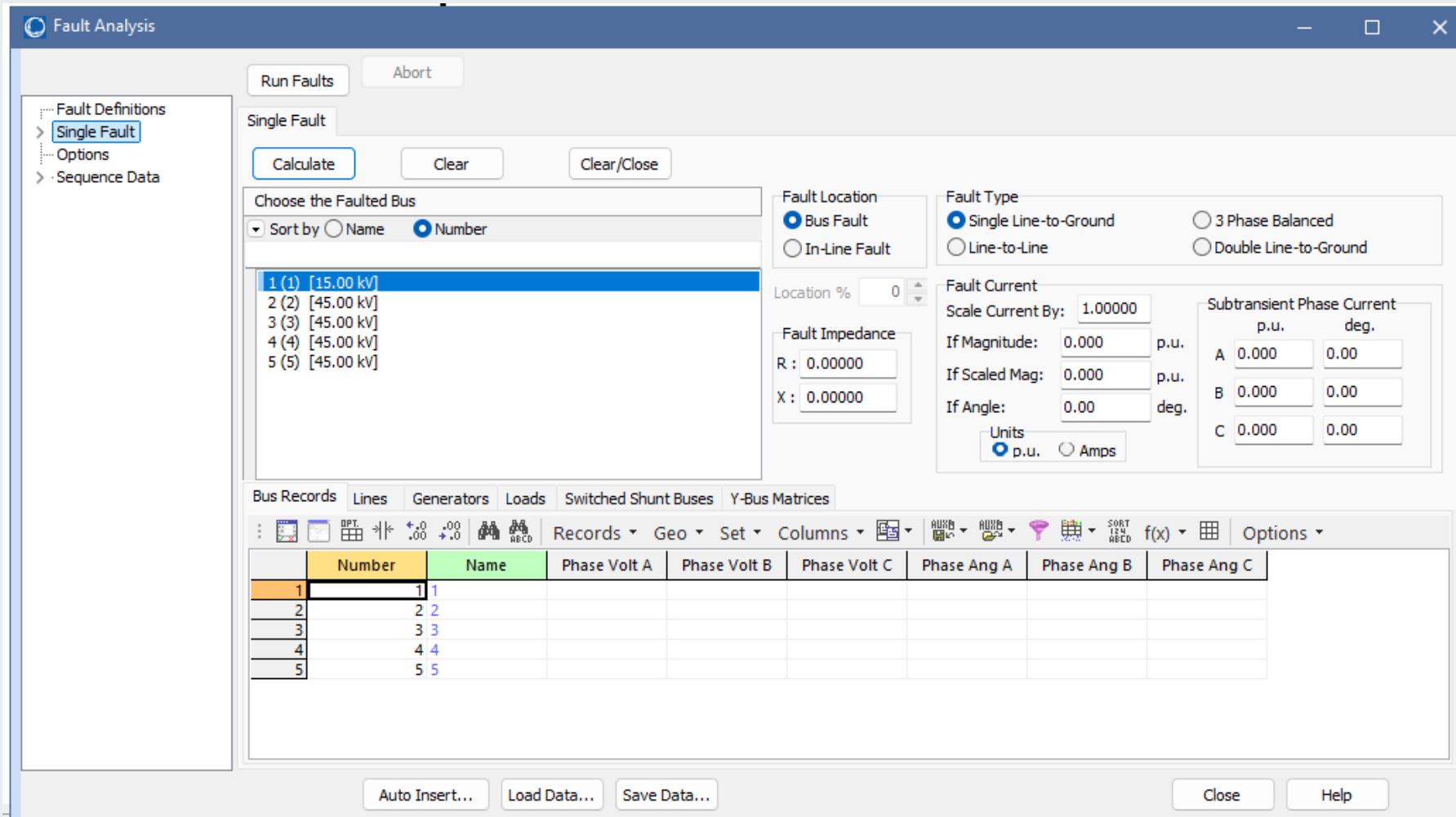
1. The first step is converting all the network parameters into the same per unit value, which is already determined.
2. Model the network using PowerWorld simulator as presented in Fig.below



- Then, for the three phase fault at bus 3, one-third of 60km transmission line is calculated as:
- Thus, select the fault analysis techniques from the power world simulator toolbar and the following data will be displayed.

# Solved Problems

# Cont....



Then, apply the fault at bus 3 and the following fault results will be generated

# Solved Problems

# Cont....

The screenshot displays the 'Fault Analysis' software interface. The 'Single Fault' tab is active, showing configuration options for a fault on bus 3. The fault type is '3 Phase Balanced'. The fault current is set to 1.381 p.u. with a phase angle of -65.12 degrees. The subtransient phase currents are also displayed.

Below the configuration, a table shows the results for various components in the system. The table has columns for Number, Name, Phase Volt A, Phase Volt B, Phase Volt C, Phase Ang A, Phase Ang B, and Phase Ang C. Row 3 is highlighted, showing a phase voltage of 0.25262 p.u. and a phase angle of 91.83 degrees for phase C.

	Number	Name	Phase Volt A	Phase Volt B	Phase Volt C	Phase Ang A	Phase Ang B	Phase Ang C
1	1	1	0.52642	0.52642	0.52642	-28.17	-148.17	91.83
2	4	4	0.43970	0.43970	0.43970	91.55	-28.45	-148.45
3	2	2	0.25262	0.25262	0.25262	-28.17	-148.17	91.83
4	5	5	0.01834	0.59610	0.57776	180.00	0.00	180.00
5	3	3	0.00000	0.00000	0.00000	-157.34	82.66	-37.34
6	6	FaultPt	0.00000	0.00000	0.00000	90.00	90.00	90.00

# Solved Problems

# Cont....

The screenshot displays the 'Fault Analysis' software interface. The 'Single Fault' tab is active, showing the following configuration:

- Choose the Faulted Bus:** Bus 3 (45.00 kV) is selected.
- Fault Location:** Bus Fault (selected).
- Fault Type:** 3 Phase Balanced (selected).
- Scale Current By:** 1.00000
- Location %:** 0
- Fault Impedance:** R = 0.00000, X = 0.00000
- Subtransient Phase Current (Amps, deg.):**

	Amps	deg.
A	1771.910	-65.12
B	1771.870	174.88
C	1771.870	54.88

The 'Bus Records' tab is also visible, showing a table of bus data:

Number	Name	Phase Volt A	Phase Volt B	Phase Volt C	Phase Ang A	Phase Ang B	Phase Ang C
1	1 1	0.52642	0.52642	0.52642	-28.17	-148.17	91.83
2	4 4	0.43970	0.43970	0.43970	91.55	-28.45	-148.45
3	2 2	0.25262	0.25262	0.25262	-28.17	-148.17	91.83
4	5 5	0.01834	0.59610	0.57776	180.00	0.00	180.00
5	3 3	0.00000	0.00000	0.00000	-157.34	82.66	-37.34
6	6 FaultPt	0.00000	0.00000	0.00000	90.00	90.00	90.00

# Solved Problems

# Cont....

The screenshot displays the 'Fault Analysis' software interface. The 'Single Fault' tab is active, showing the following configuration:

- Run Faults** and **Abort** buttons are at the top.
- Calculate**, **Clear**, and **Clear/Close** buttons are below the 'Single Fault' header.
- Choose the Faulted Bus**: A list of buses is shown, with bus 3 (45.00 kV) selected. The list includes:
  - 1 (1) [15.00 kV]
  - 2 (2) [45.00 kV]
  - 3 (3) [45.00 kV]
  - 4 (4) [45.00 kV]
  - 5 (5) [15.00 kV]
  - FaultPt (6) [45.00 kV]
- Fault Location**:  Bus Fault,  In-Line Fault.
- Fault Type**:  Single Line-to-Ground,  3 Phase Balanced,  Line-to-Line,  Double Line-to-Ground.
- Location %**: 0
- Fault Impedance**: R: 0.00000, X: 0.00000.
- Fault Current**: Scale Current By: 1.00000.
  - If Magnitude: 1771.910 Amps
  - If Scaled Mag: 1771.910 Amps
  - If Angle: -65.12 deg.
- Subtransient Phase Current**:
 

	Amps	deg.
A	1771.910	-65.12
B	1771.870	174.88
C	1771.870	54.88
- Units**:  p.u.,  Amps.

Below the configuration, there are tabs for **Bus Records**, **Lines**, **Generators**, **Loads**, **Switched Shunt Buses**, and **Y-Bus Matrices**. The **Bus Records** tab is active, showing a table with the following data:

	From Number	From Name	To Number	To Name	Circuit	Xfrmr	Phase Cur A From	Phase Cur B From	Phase Cur C From	Phase Cur A To	Phase Cur B To
1	1	1	2	2	1	YES	5620.50	5620.50	5620.50	1873.50	1873.50
2	2	2	3	3	1	NO	1873.50	1873.50	1873.50	1873.50	1873.50
3	3	3	4	4	1	NO	1630.44	1630.44	1630.44	1630.44	1630.44
4	5	5	4	4	1	YES	4891.33	4891.33	4891.33	1630.44	1630.44

At the bottom of the interface, there are buttons for **Auto Insert...**, **Load Data...**, **Save Data...**, **Close**, and **Help**.

# Summary

- In this lecture, the symmetrical or balanced three phase fault analysis is presented .
- The three phase symmetrical fault is when three power lines are shorted together with or without ground impedences.
- This types of fault is the most severe types of faults in power system network though its frequency of occurrence is rare
- Besides this, the short circuit MVA , the circuit breakers fault level and its momentary current selection is also discussed in this lecture.
- the two technics known as analytical method and software simulation of fault analysis is also discussed in this presentation. Lastly, the analytical method example of determining the magnitude of fault current for sub transient condition and the circuit breaker momentary current is determined.

# References

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**Thank you !**