Chapter-6
FAULT ANALYSIS

Prof. Dr. Ömer Usta
ITU
Electrical Engineering

FAULTED POWER SYSTEM ANALYSIS

- Unlike the power flow analysis the fault analysis is carried out to estimate the behavior of the power system under faulted transient conditions

Fault types:

- **Symmetric faults**: The system remains balanced, such as three-phase faults.

These faults are relatively rare, but are the easiest to analyze. Balanced fault analysis can be carried out by using single phase equivalent circuit of the related network.

Unbalanced faults: System is no longer balanced,

- They are very common, but more difficult to analyze, Examples: single-line to ground, double-line to ground, line-to-line faults and open-phase faults (series faults).

Fault Analysis

Magnitude of fault currents is determined by:

- the impedance of the network
- the internal impedances of the generators
- the resistance of the fault (arc resistance)

Network impedances are governed by

- transmission line impedances
- transformer connections and impedances
- grounding connections and resistances

Generator behavior immediately after a fault is divided into three periods

- sub-transient period, lasting for the first few cycle
- transient period, covering a relatively longer time
- steady state period

Fault currents cause equipment damage due to both thermal and mechanical processes

Goal of fault analysis is to:

- determine the magnitudes of the currents present during the fault
- determine the maximum current to insure devices can survive the fault
- determine the maximum current the circuit breakers (CBs) need to interrupt to correctly size the CBs
- specify ratings for circuit breakers and fuses
- determine protective relay settings
- specify the impedance of transformers and generators

Fault Studies

Sub-transient period, $X_g = X_d''$, *X_d'' is the sub-transient reactance*

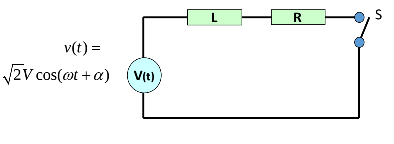
- determine the interrupting capacity of HV circuit breakers
- determine the operation timing of the protective relay system for high-voltage networks

Transient period, $X_g = X_d'$, *is the transient reactance*

- determine the interrupting capacity of MV circuit breakers
- determine the operation timing of the protective relay system for medium-voltage networks
- transient stability studies

Steady State Period, $X_g = X_d$ determine the steady-state fault current.

To understand fault analysis we need to review the behavior of an RL circuit



- Before the switch is closed obviously i(t) = 0.
- When the switch is closed at t=0, the current will have two components:

1- a steady-state value
2- a transient value

1. Steady-state current component (from standard phasor analysis)

$$\mathrm{i}_{\mathrm{ac}}(t) = \frac{\sqrt{2}V\cos(\omega t+\alpha)}{Z}$$

where $Z = \sqrt{R^2+(\omega L)^2} = \sqrt{R^2+X^2}$

$$I_{ac} = \frac{V}{Z}$$

2. Exponentially decaying dc current component

$$\mathrm{i}_{\mathrm{dc}}(t) = C_1 e^{-t/T}$$

where T is the time constant, $T = L/R$

The value of C_1 is determined from the initial conditions:

$$i(0) = 0 = \mathrm{i}_{\mathrm{ac}}(t)+\mathrm{i}_{\mathrm{dc}}(t) = \frac{\sqrt{2}V}{Z}\cos(\omega t+\alpha-\theta_Z)+C_1 e^{-t/T}$$

$$C_1 = -\frac{\sqrt{2}V}{Z}\cos(\alpha-\theta_Z) \quad \text{which depends on } \alpha$$

Hence i(t) is a sinusoidal superimposed on a decaying dc current. The magnitude of $\mathrm{i}_{\mathrm{dc}}(0)$ depends on when the switch is closed. For fault analysis we're just concerned with the worst case: $C_1 = \frac{\sqrt{2}V}{Z}$

$$i(t) = \mathrm{i}_{\mathrm{ac}}(t)+\mathrm{i}_{\mathrm{dc}}(t)$$

$$i(t) = \frac{\sqrt{2}V}{Z}\cos(\omega t)+\frac{\sqrt{2}V}{Z}e^{-t/T}$$

$$= \underbrace{\frac{\sqrt{2}V}{Z}(\cos(\omega t)}_{\text{Steady-state component}}+\underbrace{e^{-t/T}}_{\text{Transient Component}})$$

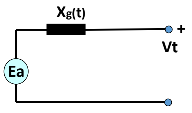
The function i(t) $= \frac{\sqrt{2}V}{Z}(\cos(\omega t)+e^{-t/T})$ is not periodic, so we can't formally define an RMS value. However, as an approximation define

$$\mathrm{I}_{\mathrm{RMS}}(t) = \sqrt{i_{ac}^2(t)+i_{dc}^2(t)}$$

$$= \sqrt{I_{ac}^2+2I_{ac}^2 e^{-2t/T}}$$

This function has a maximum value of $\sqrt{3}I_{ac}$

Therefore the dc component is included simply by multiplying the ac fault currents by $\sqrt{3}$



- During a fault the only devices that can contribute fault current are those with energy storage
- Thus the models of generators (and other rotating machines) are very important since they contribute the bulk of the fault current.
- Generators can be approximated as a constant voltage behind a time-varying reactance.

The time varying reactance is typically approximated using three different values, each valid for a different time period:

X_d'' = direct-axis subtransient reactance

X_d' = direct-axis transient reactance

X_d = direct-axis synchronous reactance

For a balanced three-phase fault on the generator terminal the ac fault current is (see page 245)

$$i_{ac}(t) = \sqrt{2}E_a' \left[\begin{array}{l} \dfrac{1}{X_d} + \left(\dfrac{1}{X_d'} - \dfrac{1}{X_d}\right) e^{-t/T_d'} + \\ \left(\dfrac{1}{X_d''} - \dfrac{1}{X_d'}\right) e^{-t/T_d''} \end{array} \right] \sin(\omega t + \alpha)$$

where

T_d'' = direct-axis subtransient time constant (≈ 0.035sec)

T_d' = direct-axis transient time constant (≈ 1sec)

The phasor current is then

$$I_{ac} = E_a' \left[\begin{array}{l} \dfrac{1}{X_d} + \left(\dfrac{1}{X_d'} - \dfrac{1}{X_d}\right) e^{-t/T_d'} + \\ \left(\dfrac{1}{X_d''} - \dfrac{1}{X_d'}\right) e^{-t/T_d''} \end{array} \right]$$

The maximum DC offset is

$$I_{DC}(t) = \frac{\sqrt{2}\, E_a'}{X_d''} e^{-t/T_A}$$

where T_A is the armature time constant (≈ 0.2 seconds)

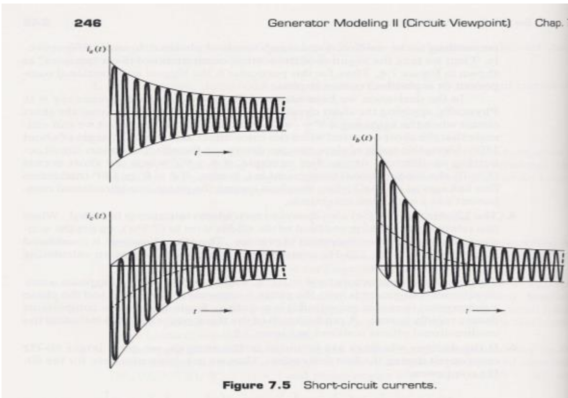
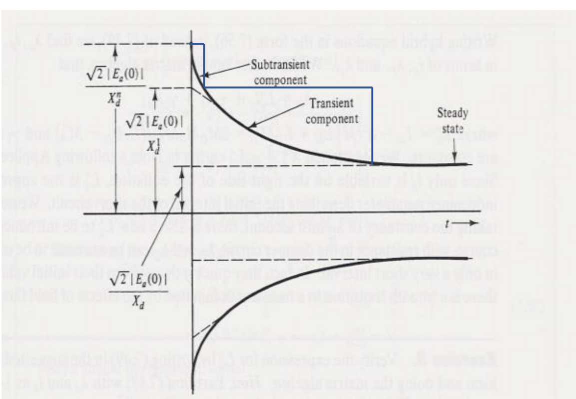
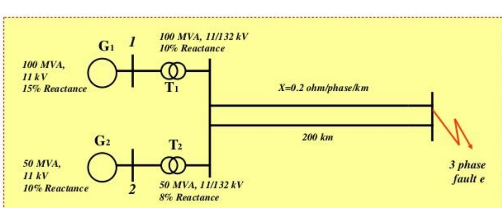


Figure 7.5 Short-circuit currents.



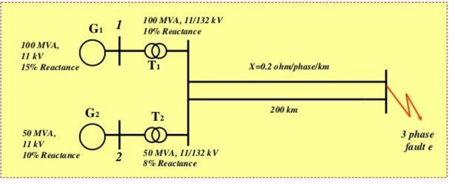
Example:

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.

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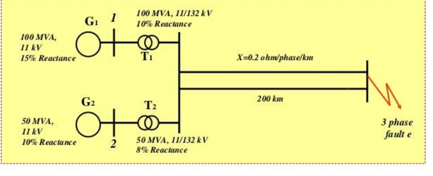
Solution:

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



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

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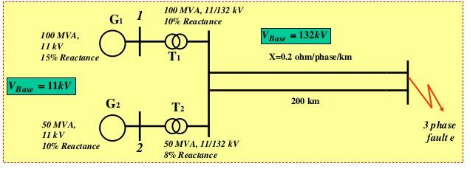
G_1 The per unit reactance $XG_1 = j0.15$

G_2 The per unit reactance $XG_2 = j0.1 * \frac{100}{50} = j0.2$

T_1 The per unit reactance $XT_1 = j0.1$

T_2 The per unit reactance $XT_2 = j0.08 * \frac{100}{50} = j0.16$

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



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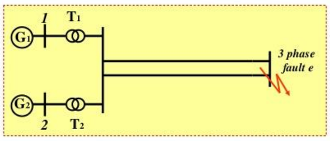
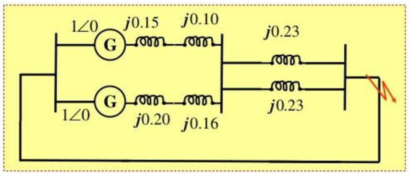
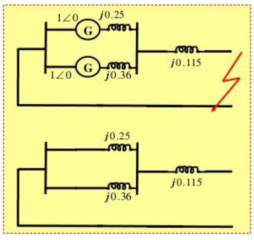
From the single line diagram of the system *draw a single line reactance diagram* showing one phase and neutral. Indicate all the reactances, etc. on the single line reactance diagram.



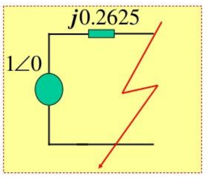


Find the *total impedance* (reactance) of the system as seen from the fault side.



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

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



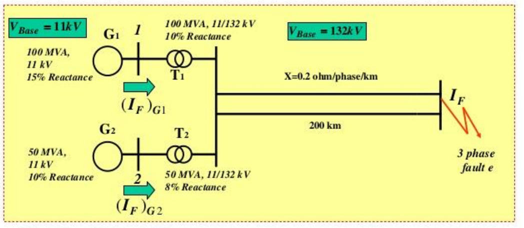
$$I_F = \frac{1\angle 0}{j0.2625} = -j3.8095\,pu$$

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

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

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

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

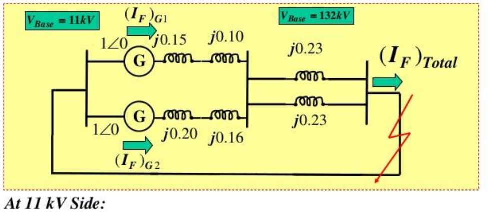


The Fault Level is:

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

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

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

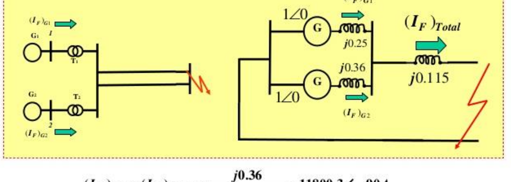


At 11 kV Side:

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

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

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



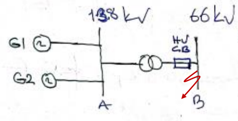
$$(I_F)_{G1} = (I_F)_{T,11kV} \frac{j0.36}{j0.36 + j0.25} = 11800.3\angle -90A$$

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

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

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

Example: (254) 4.16



$x_d'' = 0.25 = x_d'$

Generator 1: 50 MVA and 13.8 kV

Generator 2: 25 MVA and 13.8 kV

Transformer: 75 MVA, 13.8/69 kV Δ Y

$x_t = 0.10$ pu

If a three-phase fault occurs at the busbar connected high voltage terminal of the transformer when the voltage at that bus is 66 kV. (Assume that no pre-fault current)

ⓐ Find the sub-transient fault current and sub-transient fault current of the generators.

$(V_{Bold}) = (V_{Bnew})$

Selected Base values are; 69/13.8 kV, 75 MVA

$(x_d'')_1 = (x_d'')_1 = 0.25 \frac{75}{50} = 0.375$ pu | $(x_d'')_2 = (x_d')_1 = 0.25 \frac{75}{25} = 0.75$ pu

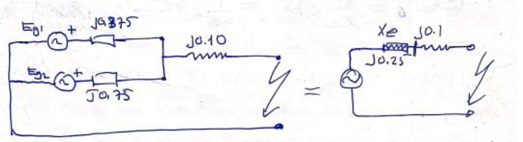
$E_{g1} = E_{g2} = 66/69 = 0.957$ pu.

$X_t = 0.10$ pu

25

$E_{g1} = E_{g2} = 66/69 = 0.957$ pu. | $= 0.75$ pu

$X_t = 0.10$ pu



$X_e = \frac{0.375 \cdot 0.75}{0.75 + 0.375} = 0.25$ pu

Sub-transient current in the circuit

$I_{sc}'' = \frac{0.957}{j0.35} = -j2.75$ pu

Voltage at the LV terminal of the transformer $V_a = 0.957 - (-j2.74)(j0.1) = 0.274$ ~~0.274~~

$I_1'' = \frac{0.957 - 0.274}{j0.375} = -1.823$ pu for G1

$I_2'' = \frac{0.957 - 0.274}{j0.75} = -j0.912$ pu for G2

Since $I_B = \frac{S_B}{\sqrt{3} V_B} = \frac{75 \times 10^6}{\sqrt{3}\, 13.8} =$

$I_1'' = -1.823$ pu $\times I_B = 5720$ A

$I_2'' = 0.912$ pu $\times I_B = 2860$ A

3138 A = 3.14 kA

short circuit capacity of (interrupting capacity of) high voltage circuit breaker

~~$(S_{sc})_2 = \sqrt{3}\, U I_{sc}'' = \sqrt{3} \times 66 \times 2.75 \times 3138 = 986.5$ MVA~~

OR $= \sqrt{3}\, U I_{sc} =$

$(S_{sc}) = \frac{1}{X_e} \times 75 = \frac{1}{0.35} \times 75 = 214.285$ MVA

PROBLEM: A 625-kV generator with X''d = 0.20 per u nit is connected to a bus through a circuit breaker, as shown following Figure. Connected through circuit breakers to the same bus are three synchronous motors rated 250 hp, 2.4 kV, 1 .0 power factor, 90% e fficiency, with X''d = 0.20 per unit. The motors are operating at full bad, unity power factor, and rated voltage , with the load equally divided among the machines.

(a) Draw the impedance diagram with the impedances marked i n per unit on a base of 625 kVA, 2.4 kV.

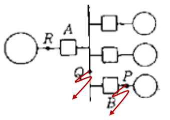
(b) Find the symmetrical short-circuit current in amperes, which must being terrupted by breakers A and B for a three-phase fault at point P. Simplify the calcu lations by neglecting the prefault current.

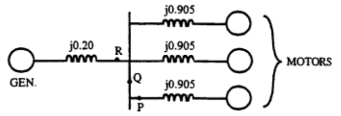
(c) Repeat part (b) for a three -phase fault at point Q.

(d) Repeat part (b) for a three-phase fault at point R

Solution:

(a)





$$\text{Motor input} = \frac{250 \times 0.746}{0.9} = 207.2 \text{ kVA}$$

$$X_m'' = 0.2 \times \frac{625}{207.2} = 0.603 \text{ per unit}$$

For interrupting current use ***Xm=1.5 xX''m , is given***

$$1.5X_m = 1.5 \times 0.603 = 0.905 \text{ per unit}$$

$$\text{Base I} = \frac{625}{\sqrt{3} \times 2.4} = 150.4 \text{ per unit}$$

$$Z_{th} = \frac{(j0.905/3)j0.2}{j0.905/3 + j0.2} = j0.1203 \text{ per unit}$$

$$I_f'' = \frac{1}{j0.1203} = -j8.315 \text{ per unit}$$

From the generator:

$$I = -j8.315\left(\frac{j0.905/3}{j0.905/3 + j0.2}\right) = -j5.000 \text{ per unit, or } 752 \text{ A}$$

From each motor:

$$I = \frac{[-j8.315 - (-j5.0)]}{3} = -j1.105 \text{ per unit, or } 166.2 \text{ A}$$

(b) Fault at P

Thru A: $I = 752$ A (gen. only)
Thru B: $I = -j5.0 + 2(-j1.105) = -j7.210$ per unit or 1084 A

(c) Fault at Q

Thru A: $I = 752$ A (gen. only)
Thru B: $I = 166.2$ A (one motor)

(d) Fault at R

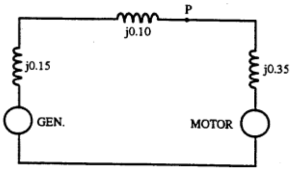
Thru A: $I = 3(166.2) = 493.6$ A
Thru B: $I = 166.2$ A

Maximum currents to be interrupted by A and B are 752 A and 1084 A, respectively.

Problem:

A generator is connected through a transformer to a synchronous motor. Reduced to the same base, the per-unit subtransient reactances of the generator and motor are 0.15 and 0.35, respectively, and the leakage reactance of the transformer is 0.10 per unit. A three-phase fault occurs at the terminals of the motor when the terminal voltage of the generator is 0.9 per unit and the output current of the generator is 1.0 per unit at 0.8 power factor leading. Find the subtransient current in per unit in the fault, in the generator and in the motor. Use the terminal voltage of the generator as the reference phasor and obtain the solution (*a*) by computing the voltages behind subtransient reactance in the generator and motor and (*b*) by using Thévenin's theorem.

Solution:



P: fault point