(c) The p.u. Impedance is given by following expressions.

Base $$Z = \frac{\text{Base kV}^2}{\text{Base kVA}} \times 1000$$

$$\text{p.u. } Z = \frac{\text{Ohmic Z}}{\text{Base Z}} = \frac{Z \times \text{Base kVA}}{\text{Base kV}^2 \times 1000}$$

Change of Base

$$\text{p.u. } Z_{new} = \text{p.u. } Z_{old} \times \left(\frac{\text{kVA Base New}}{\text{kVA Base Old}}\right) \times \left(\frac{\text{kV base Old}}{\text{kV base New}}\right)^2$$

(d) For circuits connected by transformer choose same kVA base on both sides and different kV bases on either sides. kV bases should have the ratio same as transformation ratio. The p.u. reactance remains same on either sides.

(e) Thevenin's theorem and network reduction methods are useful in fault calculations.

QUESTIONS

1. Explain the Per Unit System. What are its advantages ?
   Derive expression for p.u. reactance from the chosen base kVA and base kV.
2. The p.u. reactance of a 11 kV, 20,000 kVA, 3 ph. 50 Hz alternator is 0.20 p.u. What will be its p.u. reactance referred to the base kV 110 and base kVA 10,000?
3. A generator is connected to a transmission line through a transformer. The ratings are as follows :
   Generator : 20,000 kVA, 11 kV, positive sequence reactance 15 p.u.
   Transformer 10,000 kVA, 11/110 kV, leakage reactance 6 per cent. Transmission line total reactance 10 ohms. A fault occurs at the other end of the line. Draw reactance diagram taking suitable base kV and 200,000 base kVA.
   Transmission line total reactance 10 ohms. A fault occurs at the other end of the line. Draw reactance diagram taking suitable base kV and 200,000 base kVA.
4. A 20,000 kVA, 11 kA generator 3 ph. has a direct axis synchronous reactance of 20 per cent. A 3-phase short circuit near the terminals. Calculate the steady short circuit current. Generator is at rated voltage and on load. **[Ans.** 5250 A]
5. Two generators are operating in parallel and have sub-transient reactance $X'' = 10\%$. Generator I is rated 2500 kVA, 3.3 kV, generator 2 is rated 500 kVA, 32 kV. Find p.u. reactances of each generator on 15,000 kVA, 3 kV base. What is equivalent p.u. reactance of the two generators on 1500 kVA, 3 kV base ?
6. Three reactance 0.5, 0.2 and 0.3 are connected in delta. Find the equivalent star reactances.
7. Three motors are connected to a common bus. The motors are rated 5000 h.p., 3.3 kV, 0.8 p.f., $X'' = 17\%$. They are supplied by a generator 20,000 kVA, 11 kV and of $X'' = 10\%$ through a transformer 11/3.3 kV, 18,000 kVA and having 5% leakage reactance. Draw the reactance diagram of the system. Take kVA = 1.10 × H.P. Take 20,000 kVA base.
8. Distinguish clearly between per unit method and percentage reactance method. Show that the per unit reactance referred to the circuits connected by transformer is same if same base kVA is taken for both circuits and the base kVs have ratio equal to transformation ratio.
9. State whether correct or wrong. Write corrected statements if necessary.
   (i) Circuit-breakers open during steady state fault condition.
   (ii) The positive sequence reactance of generators is less than their negative sequence reactance.
   (iii) During short-circuits, the current increases with time during first 10 cycles.
   (iv) Percentage reactance of power transformers is always less than one per cent.
   (v) Short-circuit ratio of generators is less than 1.
   (vi) Power system stability depends upon fault clearing time.

20

Symmetrical Faults and Current Limiting Reactors

Fault MVA and Fault Current – Summary. **Solved Examples 20.1 to 20.22** of various types by different methods — Current Limiting Reactors.

In this chapter some examples on symmetrical faults have been solved. Per unit system and procedure mentioned in chapter 19 has been followed.

Significance of Fault MVA.

High fault MVA at a point signifies high strength of power system at that point, low equivalent reactance upto that point. Therefore, large loads can be connected at that point. Low fault level signifies weak system. Fault level indicates the strength of the power system.

20.1. FAULT MVA AND FAULT CURRENT (STEADY STATE)

Calculate total p.u. reactance upto fault point, by network reduction of positive sequence network or reactance diagram. If same kVA base is taken for complete system

P.u. fault current $$= \frac{\text{P.u. voltage at fault point}}{\text{P.u. } X_{equivalent}}$$

P.u. fault level = $\sqrt{3}$ p.u. fault current × p.u. service voltage. Or in other way

Fault MVA $$= \frac{\text{Base MVA}}{\text{P.u. } X_{equivalent}} \text{ (MVA)} \qquad \text{... reactive, lagging.}$$

Fault current $$= \frac{\text{Fault MVA} \times 10^3}{\sqrt{3} \times \text{Base kV}} \text{ (Amp.) } \angle -90°$$

Hence for three phase (symmetrical) fault, we get the expressions, neglecting load current

Fault MVA $$= \frac{\text{Base MVA}}{X_{p.u.\ the\ venine's\ equivalent}} \qquad \text{... reactive, lagging.}$$

Fault current $$= \frac{\text{Fault MVA} \times 1000}{\sqrt{3} \times \text{Base kA}} \text{ (Amp.) } \angle -90°$$

(Base kV at the fault point, assuming the fault occurs at normal voltage. Fault current is of lagging power factor).

20.2. SOLVED EXAMPLES 20.1 TO 20.21

Note. In this chapter some problems on symmetrical faults have been solved. Further, the term sub-transient, transient and steady state are described in Ch. 3 (Notation j is omitted).

Example 20.1. *A 3-phase, 5000 kVA, 6.6 kV generator having 12% sub-transient reactance. A 3-phase short circuit occurs at its terminals, calculate fault MVA and current.*

Solution. (Method I)

Fault MVA $$= \frac{\text{Base MVA}}{\text{\%Reactance}} \times 100$$

Generator % reactance is based on its own voltage and kVA ratings. Hence choose 5000 kVA as base.

Fault MVA $= \dfrac{5}{12} \times 100$ ...(subtransient) $= \mathbf{41.60\ MVA.}$ **Ans.**

Fault current $= \dfrac{VA}{\sqrt{3}V}$ ...(subtransient)

$$= \frac{\text{Fault MVA} \times 1000}{\sqrt{3}\text{kV}} = \frac{41.66 \times 100}{\sqrt{3} \times 6.6} = \mathbf{3644\ A\ \angle -90.} \quad \textbf{Ans.}$$

Method II. From base voltage and p.u. reactance, calculate p.u. fault current. Then calculate fault current in amperes. Then you can calculate fault MVA.

Generator reactance (0.12 p.u.) is base on its kV and kVA ratings.

Base kV (phase) $= \dfrac{6.6}{\sqrt{3}} = 3.8$ kV

Hence 3.8 kV = 1 p.u. (voltage)

Fault current p.u. $= \dfrac{\text{p.u. voltage}}{\text{p.u. reactance}} = \dfrac{1}{j0.12} = 8.32$ p.u. $\angle -90°$ (current)

Base current $= \dfrac{\text{Rating kVA}}{\sqrt{3} \times \text{Rated kVA}} = \dfrac{5000}{\sqrt{3} \times 6.6} = 437$ Amp.

Fault Current = p.u. current × Base current

$= 8.32 \times 437 = \mathbf{3644\ Amp.}$ **Ans.**

Fault power $= \sqrt{3} \times$ Fault current × Service voltage

$= \sqrt{3} \times 3.64 \times 6.6$ MVA

$= \mathbf{41.6\ MVA\ \angle -90°.}$ **Ans.**

Change of Voltage

Suppose in same problem, the generator voltage is 6.4 kV, when fault occurs and not rated voltage, Method II should be adopted. The service voltage is then

$$\frac{6.4}{6.6} = 0.97 \text{ p.u.}$$

p.u. Fault current $= \dfrac{0.97}{0.12} = 8.09$ p.u.

Fault current in ampere = p.u. Current × Base current

$= 8.09 \times 437 = 3538$ Amp.

Check. Current reduces proportionately.

$$\frac{3538}{3640} = 0.97 = \frac{6.4}{6.6} \text{ (checked)}$$

Fault power at service voltage 6.4 kV

$= \sqrt{3} \times$ Fault current × Service voltage

$= \sqrt{3} \times 5.53 \text{ kA} \times 6.4 \text{ kV} = \mathbf{39.2\ MVA}$

Note. For service voltage other than rated voltage adopt method II, to calculate p.u. fault current from p.u. Service voltage/p.u. reactance. If given, load current is added to fault current.

Example 20.2. *A 3-phase, 11 kV 5000 kVA, generator has a steady state reactance X_d of 20%. It is connected to a 3000 kVA transformer having 5.0% leakage reactance and ratio of 11/33 kV. The 33 kV side is connected to a transmission line. A three-phase fault occurs at the other end of the transmission line. The series reactance between the faulted point and the transformer is 30 ohms. Calculate the steady state fault current assuming no load prior to the fault.*

Solution. Let,

Base kVA for complete system = 5000 kVA

Base kV = 11 kV for generator side

Base kV = 33 kV for transmission line side.

P.u. reactance of generator = 0.2 p.u. (given)

New p.u. reactance of transformer

$$= 0.05 \times \frac{5000}{3000} = 0.083 \text{ p.u.}$$

P.u. reactance of transmission line

$$= \frac{\text{Ohms} \times \text{Base kVA}}{\text{Base kV}^2 \times 1000} = 30 \times \frac{5000}{(33)^2 \times 1000} = 0.139 \text{ p.u.}$$

Total p.u. reactance up to fault

$= j0.2 + j\,0.083 + j0.139 = j0.422$ p.u.

Fault MVA $= \dfrac{\text{Base MVA}}{X_{p.u.\,eq.}} = \dfrac{5000 \times 10^{-3}}{0.422} = \mathbf{11.9}$ **Ans.**

Fault current $= \dfrac{\text{Fault MVA} \times 10^2}{\sqrt{3}\text{ Base kV}} = \dfrac{11.9 \times 10^3}{3 \times 33} = \mathbf{208\ Amp.\ \angle -90°}$ **Ans.**

Example 20.3. *Four 11 kV, 25 MVA alternators having a subtransient reactance of 16% are operating in parallel when a 3-phase fault occurs on the generator bus. Find the 3 phase fault MVA fed into the fault.*

Solution. Let,

Base MVA = 25

Base kV = 11

Fault MVA $= \dfrac{\text{Base MVA}}{X_{p.u.\,eq.}}$

The equivalent p.u. reactance of four generators operating in parallel is :

$$\frac{16}{4} = 4\% = j\,0.04 \text{ p.u.}$$

Fault MVA $= \dfrac{25}{0.04} = 625$ MVA

Other Method

Fault current $= \dfrac{\text{p.u. voltage}}{\text{p.u. } X_{eq.}}$

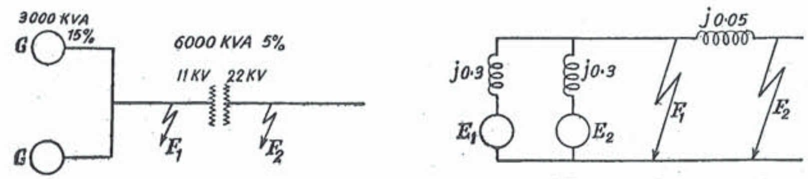
$$\frac{1}{j\,0.04} = 25 \text{ p.u. } \angle -90°$$

Base current $= \dfrac{25 \times 10^3}{\sqrt{3} \times 11} = 1310$ A

Short circuit current $= 25 \times 1310 = 32{,}750$ A

Short circuit MVA $= \dfrac{\sqrt{3} \times V \times I}{10^6} = \dfrac{\sqrt{3} \times 32{,}750 \times 11}{10^3} = \mathbf{625\ MVA}$ **Ans.**

Example 20.4. *Two 11 kV, 3-phase, 3000 kVA generators having sub-transient reactance of 15% operate in parallel. The generators supply power to a transmission line through a 6000 kVA transformer of ratio 11/22 kV and having a leakage reactance of 5%. Calculate fault current and fault MVA for three phase fault on (a) H.T. side (b) L.T. side of a transformer.*



(*a*) One line diagram. (*b*) Reactance diagram.

Fig. 20.1. Diagrams of example 20.4.

Solution.

Draw single line diagram [Fig. 20.1 (*a*)].

Let Base kVA = 6000

Base kV = 11 kV for generator side.

Base kV = 22 kV for transmission side.

Now, p.u. reactance of generator, (subtransient)

$$= j0.15 \times \frac{6000}{3000} = j0.3 \text{ p.u.}$$

Draw reactance diagram [Fig. 20.1 (*b*)].

Calculate Thevenin's equivalent reactance for the faults.

(*a*) *Fault on generator side* : F_1

Equivalent of two reactance (j 0.3 each) in parallel

$$= \frac{j0.3}{2} = j0.15 \text{ p.u.}$$

Fault MVA $= \dfrac{\text{Base MVA}}{X_{equivalent}} = \dfrac{6000 \times 10^{-3}}{0.15} = \mathbf{40\ MVA.}$ **Ans.**

Fault current $= \dfrac{\text{Fault MVA} \times 10^3}{\sqrt{3} \times \text{Base kV}} = \dfrac{40 \times 10^3}{\sqrt{3} \times 11} = \mathbf{2100\ A\underline{/-90^\circ}}.$ **Ans.**

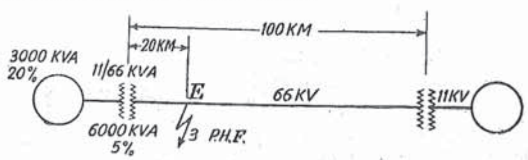
(*b*) *Fault on transmission side* : F_2

Equivalent reactance $= j0.15 + j0.05 = j\ 0.20$ p.u.

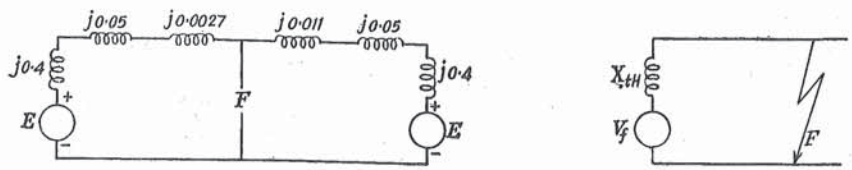
Fault MVA $= \dfrac{6000 \times 10^{-3}}{0.20} = \mathbf{30\ MVA.}$ **Ans.**

Fault current $= \dfrac{30 \times 10^3}{\sqrt{3} \times 22} = \mathbf{786\ A\underline{/-90^\circ}\ (lag).}$ **Ans.**

Example 20.5. (*a*) Two generators rated 11 kV, 3000 kVA, having 20% reactance are interconnected by a 100 km long transmission line. The reactance of line is 0.10 ohms per km. The transformers near the generators are rated 6000 kVA, 11 kV/66 kV and have 5% reactance. A 3 phase fault occurs at a distance of 20 km from one end of the line when the system is on no load but at rated voltage. Calculate fault MVA and fault current.



(*a*) Single line diagram of the system of Ex. 20.5.



(*b*) Reactance diagram or positive sequence network.

(*c*) Thevenin's equivalent circuit.

Fig. 20.2. Figures of Example 20.5.

Solution. Base kVA for the complete system = 6000 kVA

Base kV = 11 for generator sides

Base kV = 66 for transmission circuits.

Per unit reactance to these bases :

(1) Generators : $0.2 \times \dfrac{6000}{3000} = 0.4$ p.u.

(2) Transformers : $= 0.05$ p.u.

Base reactance of transmission line circuit

$$\frac{(66)^2 \times 100}{6000} = \frac{4356}{6} = 726\ \Omega$$

Per unit reactance of 20 km line

$$= \frac{20 \times 0.1}{726} = 0.00276 \text{ p.u.}$$

Per unit reactance of 80 km line = 0.01104 p.u.

From these values, the reactance diagram [Fig. 20.2 (*b*)] is drawn.

Thevenin's equivalent reactance from F.

Note that on short-circuiting the voltage sources, there are two parallel branches, the reactances being.

$$j0.4 + j0.05 + j0.0027 = j0.4527 \text{ p.u.}$$

and $$j0.4 + j0.05 + j0.011 = j0.461 \text{ p.u.}$$

The equivalent is given by

$$\frac{j0.4527 \times j0.461}{j0.4527 + j0.461} = \frac{j0.209}{0.9137} = j0.229 \text{ p.u.}$$

Fault current $= \dfrac{V_f}{X_{p.u.}}$

$$\frac{1 + j0}{j0.229} = -j4.36 \text{ p.u.}$$

V_f is the p.u. voltage at fault point.

Base current in transmission line circuit

$$\frac{\text{Base kVA}}{\sqrt{3}\ \text{Base kV}} = \frac{6000}{\sqrt{3} \times 66} = 52.5 \text{ amperes.}$$

Fault current $= 4.36 \times 52.5 = 229$ amperes.

Fault MVA $= \sqrt{3} \times kV \times I_f \times 10^{-3}$

$= \sqrt{3} \times 66 \times 229 \times 10^{-3} = 26.2$ MVA.

Another method :

Fault MVA $= \dfrac{\text{Base MVA}}{X_{p.u.\ eq.}} = \dfrac{6000 \times 10^{-3}}{0.299} = \mathbf{26.2\ MVA.}$ **Ans.**

Fault current $= \dfrac{26.2 \times 10^3}{\sqrt{3} \times 66} = \mathbf{229\ A, \underline{/-90^\circ}}$ **Ans.***

Example 20.5. (*b*) *Further to example 20.5 (a) calculate the fault current supplied by each transformer and each generator.*

Neglect load current.

* **Note.** As the fault current flows through system reactance, and resistance being negligible, the fault current lags behind corresponding voltage by 90°.

Solution. The total fault current is supplied by two generators. Their contribution depends upon reactances in their branches.

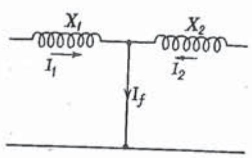


Fig. Ex. 20.5 (a)

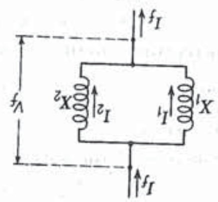


Fig. Ex. 20.5 (b)

Division of current through parallel branches.

$$I_f \times X_{eq} = V_f = I_1 \times X_1 = I_2 \times X_2$$

$$X_{eq} = \frac{X_1 \times X_2}{X_1 + X_2}$$

$$I_f \times \frac{X_1 \times X_2}{X_1 + X_2} = I_1 \times X_1 = I_2 \times X_2$$

Therefore,

$$\boxed{\begin{aligned} I_1 &= I_f \times \frac{X_2}{X_1 + X_2} \quad &\text{...(1)} \\ I_2 &= I_f \times \frac{X_1}{X_1 + X_2} \quad &\text{...(2)} \\ I_f &= I_1 + I_2 \quad &\text{...(3)} \end{aligned}}$$

These are general equations which give the division of total current I_f in two parallel branches having reactance X_1 and X_2.

In this example, $I_f = 229$ A

$$I_1 = 229 \times \frac{0.461}{0.4527 + 0.461}$$

$$= 229 \times \frac{0.461}{0.913} = \mathbf{115.5\ A}$$

$$I_2 = 229 \times \frac{0.4527}{0.913} = \mathbf{113.5\ A} \quad \textbf{Ans.}$$

Check $\quad I_1 + I_2 = 115.5 + 113.5 = \mathbf{229\ A.}$ **Ans.**

Current supplied by generator = Current supplied by transformer × Transformation Ratio

$$I_{G1} = I_1 \times \frac{66}{11}$$

$$= 115.5 \times 6 = \mathbf{693\ A.} \quad \textbf{Ans.}$$

$$I_{G2} = I_2 \times \frac{66}{11}$$

$$= 113 \times 6 = \mathbf{678\ A.} \quad \textbf{Ans.}$$

Note. Load current neglected.

$$I_1 = \frac{I_f \times X_2}{X_1 + X_2} = \frac{I_f \times X_1}{X_1 + X_2}$$

$$I_1 + I_2 = I$$

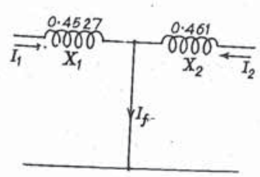


Fig. Ex. 20.5 (c)

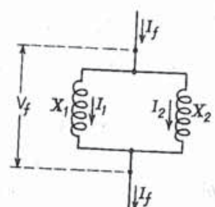


Fig. Ex. 20.5 (d)

Example 20.6. *A 3-phase 6000 kVA, 11 kVA alternator has 10% direct axis sub-transient reactance. It is connected to a 6000 kVA, 11/66 kV transformer having 9% leakage reactance. A symmetrical delta connected fault of impedance 12 + j3 ohms occurs between the lines near the H.T. terminals of the transformer when the system is on no load. Calculate the current supplied by alternator.*

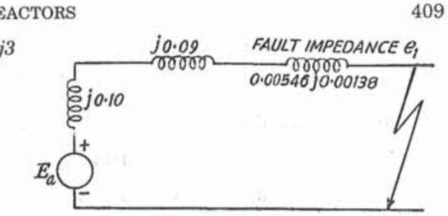


Fig. 20.3. Reactance diagram of Ex. 20.6.

Solution. Base kVA = 6000 for complete system, base kV = 11 and 66 kV for the two circuits connected by transformer.

P.u. reactance of generator $j0.10$ p.u.

P.u. reactance of transformer $j0.09$ p.u.

Converting delta connected impedance to equivalent star connected impedance, we get

$$Z_{eq.} = \frac{12 + j3}{3} = 4 + j1 \text{ ohms/phase}$$

Base Z on H.T. side $= \dfrac{\text{Base kV}^2 \times 1000}{\text{Base kVA}} = \dfrac{(66)^2 \times 1000}{6000} = 66 \times 11 = 726$ ohm

$$\text{P.u. } Z_{eq.} = \frac{4 + j1}{726} = 0.00546 + j0.00138$$

$$E_a = 1 \text{ p.u.} = 1 + j0$$

$$I_f = \frac{1 + j0}{0.00546 + j0.19138}$$

$$= \frac{0.00546 - j0.19138}{0.03663} = 0.149 - j5.225 \text{ p.u.} = 5.23 \text{ p.u.}$$

Base *I*, HT side $= \dfrac{\text{Base of kVA}}{\sqrt{3} \times \text{Base kV}} = \dfrac{6000}{\sqrt{3} \times 66} = 52.5$ Amp.

$$I_f = 5.23 \times 52.5 = \mathbf{274\ Amp.}$$

Current from generator $= 5.23 \times \dfrac{6000}{\sqrt{3} \times 11} = \mathbf{1644\ Amp.}$ **Ans.**

Note. The respective base voltages are taken to calculate base currents on the two sides of transformer. We can also calculate as :

Current from Generator $= I_f \times 66/11$.

Example 20.7. *Two generators are connected to their unit transformer as shown in the figure. Generators and transformers are rated as follows :*

Generator I	:	*20 MVA, 11 kV, 0.2 p.u.*
Transformer 1	:	*20 MVA, 11/110 kV, 0.08 p.u.*
Generator 2	:	*30 MVA, 0.2 p.u., 11 kV*
Transformer 2	:	*30 MVA, 11/110 kV*

0.1 p.u.

Reactance of transmission lines 0.516 p.u. (based on 110 kV, 30 MVA bases).

A 3-phase short-circuit occurs at the receiving end 110 kV bus-bar.

Determine the current supplied by the generators.

Solution.

Base MVA = 30

Base kV = 11, 110 ; respectively on generator, transmission sides

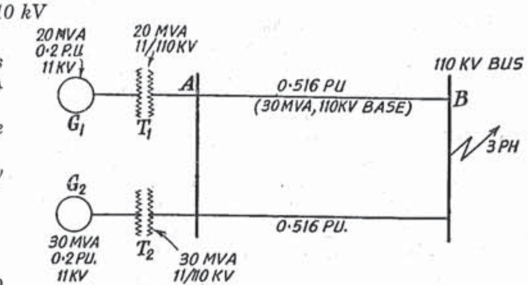


Fig. 20.4. Circuit diagram of Ex. 20.7.

P.u. reactance of Generator 1 to new base

$$= 0.2 \times \frac{30}{20} = 0.3 \text{ p.u.}$$

P.u. reactance of transmission 1 to new base

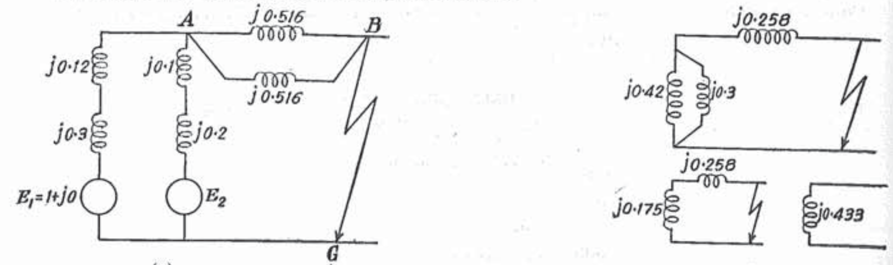
$$= 0.08 \times \frac{30}{20} = 0.12 \text{ p.u.}$$

P.u. reactance of $G_2 = 0.2$ p.u.

P.u. Reactance of $T_2 = 0.1$ p.u.

P.u. Reactance of transmission line = 0.516 p.u.

From these values the reactance diagram is drawn.



(a) (b)

Fig. 20.5. Reactance diagram of Ex. 20.7.

Thevenin's equivalent reactance between B, G is obtained by network reduction and is equal to $j0.433$ p.u.

Short-circuit current $= \dfrac{E_a}{X_{eq.\ p.u.}} = \dfrac{1 + j0}{j0.433} = 2.3$ p.u.

*Current from G_1 $= 2.3 \times \dfrac{0.3}{0.3 + 0.42} = 2.3 \times \dfrac{0.3}{0.72} = 0.96$ p.u.

Current from G_2 $= 2.3 \times \dfrac{0.42}{0.72} = 1.34$ p.u.

$$I_{G1} + I_{G2} = 0.96 + 1.34 = 2.30 \text{ p.u. (check)}$$

Current taken from G_1 in Amp.

$$= 0.96 \times \frac{30{,}000}{\sqrt{3} \times 11} = 1510 \text{ A (lagging)}$$

Current from G_2 in Amp. $= 1.34 \times \dfrac{30{,}000}{\sqrt{3} \times 11} = 2105$ A (lagging)

(Since Base kVA = 30,000 and Base kV is 11.)

Example 20.8. *A 25000 kV, 11 kV generator with 15% subtransient reactance is connected through a transformer to a bus that supplies 4 identical motors as shown in Fig. 20.6. Each motor has $X_d'' = 30\%$, $X_d' = 30\%$ based on 5000 kVA, 6.6. kV. Three-phase rating of the transformer is 25000 kVA, 11/6.6 kV and leakage reactance is 10%. Bus voltage is 6.6. kV when a three-phase fault occurs the terminals of one motor. Calculate the following :*

(1) Sub-transient fault current.

(2) Sub-transient current in breaker A.

*(3) Momentary current rating** of circuit breaker.*

* Current gets distributed amongst parallel generators according to proportion of reactances. See Ex. 20.5 (*b*).

** Momentary current rating is defined as r.m.s. value of the short-circuit current at the instant of first current peak. The American Standards on circuit breakers specify the momentary current rating of breaker.

(4) Current to be interrupted by breaker A; breaker time is 5 cycles. Use multiplying factor 1.1 for d.c. component (Asymmetry).

Solution.*

Base kVA = 25,000 for complete-system, p.u. reactance of motor

$$X_d' = j0.2 \times \frac{25{,}000}{5{,}000} = j1.0 \text{ p.u. ... subtransient}$$

$$X_d' = j0.3 \times \frac{25{,}000}{5000} = j1.5 \text{ p.u. ...transient}$$

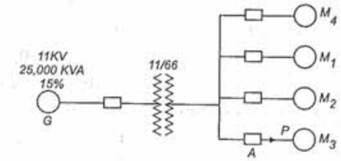
Correspondingly the reactance diagram, one for sub-transient and other for transient state.

Sub-transient state

$$Z_{th} = j0.125$$

$$V_f = 1.0 \text{ p.u.}$$

$$I_f'' = \frac{V_f}{Z_{th}} = \frac{1.0 + j0}{j0.125} = -j8.0 \text{ p.u.}$$

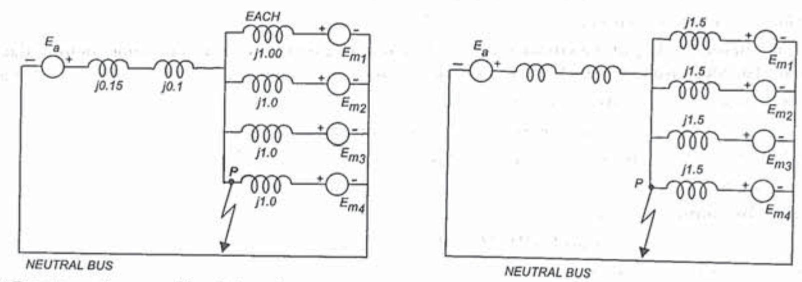


(*a*) Circuit diagram.

Base current is 6.6. kV circuit is

$$\frac{25{,}000}{\sqrt{3} \times 6.6} = 2182 \text{ Amp.}$$

I_f'' in Amp $= 2182 \times 8 = 17{,}456$ Amp. $\underline{/ -90°}$



(*b*) Reactance diagram with sub-transient reactances. (c) Reactance diagram with transient reactances

Fig. 20.6. Diagrams of Ex. 20.8.

Generator Contribution

$$-j8.0 \times \frac{0.25}{0.5} = -j4.0 \text{ p.u.}$$

Each motor contributes 25% of the remaining fault current.

Total motor contribution

$$= -j8 - (-4j) = -j4 \text{ p.u.}$$

∴ Contribution of each motor $- j1.0$ p.u.

Short-circuit current passing through circuit-breaker A

= Contribution of 3 motors + Contribution of generator

$$= -j4.0 + 3(-j1.0) = -7.0$$

$$I_A'' = -j7.0 \times 2182 = 15{,}274 \text{ Amp. (r.m.s.)}$$

* For solution of Subtransient current, take Subtransient reactances X'' For solution of Transient Current, take Transient Reactances X' Refer Ch. 3.

Momentary current

$$= 1.6 \times I_A'' = 1.6 \times 15274 = 24{,}440 \text{ A} \quad \text{[Factor 1.6 for Doubling Effect*]}$$

Now come to the Transient State

Assume transient reactance of generator $X' = 0.15$ p.u.

$$Z_{th}' = j\frac{0.375 \times 0.25}{0.375 + 0.25} = j0.15 \text{ p.u.}$$

S.C. Current (Transient)

$$I' = \frac{E_a}{Z_{th}'} = \frac{1}{j0.15} = -j6.66 \text{ p.u.}$$

Generator Contribution

$$\frac{1}{j0.15} \times \frac{0.375}{j0.625} = k4.0 \text{ p.u.}$$

Motor Contribution (each)

$$\frac{1}{4} \times \frac{1}{j0.15} \times \frac{0.25}{0.625} = -j0.67 \text{ p.u.}$$

Current to be interrupted

Generator contribution + Contribution of 3 motors

i.e. $[4.0 + 3 \times 0.67] = 6.01$ p.u.

Current to be interrupted

The current 6.01 p.u. calculated above is symmetrical current and does not include d.c. component. To take into account d.c. component multiply by 1.1 because breaker time is 5 cycles.

Breaking current (Asymmetrical)

$$= 1.1 \times 6.01 = 6.611 \text{ p.u. (r.m.s.)}$$

and *Breaking current (Symmetrical) = 6.01 p.u. (r.m.s.)*

In amperes :

Asy. Breaking current

$$= 6.611 \times 21.82 = 14{,}500 \text{ A (r.m.s.)}$$

Symm. Breaking current

$$= 6.01 \times 21.82 = 13{,}000$$

Breaking capacity in kVA of breaker A (Required Minimum)

$$= \sqrt{3} \times \text{kV} \times I_{sh}$$

$$= \sqrt{3} \times 6.6 \times 14{,}500 = 166{,}000 \text{ kVA.}$$

Example 20.9. *A 3 ph, 50 Hz, 1 MVA, 66/3.3 kV power transformer having percentage reactance of 6 per cent is connected singly to a 66 kV bus having fault level of 100 MVA. Calculate fault level (short circuit level) on 3.3. kV side of the transformer.*

Solution. Fault level on 66 kV side = 100 MVA (given)

This means, for a 3 phase fault on h.v. side, the fault MVA would be 100. Applying the rule

$$\text{Fault MVA} = \frac{\text{Base MVA}}{\text{p.u. } X_{eq.}} \qquad ...(1)$$

We can determine the p.u. $X_{eq.}$ of the source up to H.V. side. Any base MVA may be selected.

Let Base MVA = 1 MVA for both sides of transformer

Fault MVA on H.V. Side = 100 MVA (given)

* Ref. Sec. 3.4.

p.u. $X_{eq.}$ of source up to H.V. side, from Eq. (1),

$$= \frac{\text{Base MVA}}{\text{Fault MVA}} = \frac{1}{100} = 0.01 \text{ p.u. (on selected base)}$$

P.u. Reactance of Transformer for same base as its rating

$$= \frac{\text{Per cent reactance}}{100} = \frac{6}{100} = 0.06 \text{ p.u.}$$

Total equivalent reactance

$$= \text{Eqt. reactance of source} + \text{Eqt. reactance of transformer}$$
$$= 0.01 + 0.6 = 0.61 \text{ p.u.}$$

Fault level on 3.3. kV side

$$= \frac{\text{Base MVA}}{\text{Eqt. p.u. reactance}} = \frac{1}{0.61}$$

$$= \mathbf{1.64\ MVA.} \quad \textbf{Ans.} \qquad ...(a)$$

$$\text{Fault current} = \frac{1.64 \times 10^3}{\sqrt{3} \times 3.3} = \mathbf{288\ A.} \quad \textbf{Ans.}$$

Note. If we assume source of zero reactance, fault MVA on L.V. side would be, from Eqn. (1)

$$= \frac{1}{0.6} = 1.67 \text{ MVA} \qquad ...(b)$$

which is on higher and safer side, as regards selection of circuit breaker, compared with value (*a*) above.

Hence fault level on L.T. side of a transformer can be approximately calculated by

$$\text{Fault level on L.V. Side} = \frac{\text{Transformer kVA}}{\text{p.u. reactance of transformer}}$$

The value thus obtained is on higher and safer side.

Example 20.10. *Calculate maximum possible fault level on Low-tension side of the transformer 500 kVA, 4.75 p.c. Reactance. State the assumption made.*

Solution. Assuming the source of zero equivalent reactance.

Maximum fault level on L.T. side of Transformer

$$= \frac{\text{Transformer kVA}}{\text{p.u. Reactance of transformer}}$$

$$\therefore \text{ Fault level on L.T. side} = \frac{500}{4.75} \times 100 = 10{,}500 \text{ kVA.}$$

Example 20.11. *Two incoming lines with fault levels at their terminals equal to 75 MVA and 150 MVA, terminate on a common bus in a sub-station. A 1 MVA step-down transformer having 5 per cent reactance is connected to this bus. No other lines need be considered. Calculate fault level on L.T. side of the transformer.*

Solution. Total fault level on the bus on H.T. side of transformer,

$$= 75 + 150 = 225 \text{ MVA}$$

Let Base MVA = 225.

$\therefore$ p.u. reactance of transformer w.r.t. new base

$$= 0.05 \times \frac{225}{1} = 11.25 \text{ p.u.}$$

Equivalent reactance of source

$$= \frac{\textbf{Base MVA}}{\textbf{Fault MVA}} = \frac{225}{225} = 1 \text{ p.u.}$$

Total p.u. reactance upto L.T. Side

= Eqt. p.u. reactance of source + p.u. reactance of transformer

= 1 + 11.25 = 12.25 p.u.

Fault level $= \frac{\text{Base MVA}}{\text{P.u. reactance (total)}} = \frac{225}{11.25} = \mathbf{18.38\ MVA.}$ **Ans.**

Note. Had we neglected source reactance the answer would have been

$$= \frac{225}{11.25} = 20 \text{ MVA}$$

or simply, $\frac{\text{Transformer MVA}}{\text{p.u. reactance}} = \frac{1}{0.05} = 20$ MVA.

Part-B. A 1 MVA capacitor bank was installed on the L.t. side of power transformer. Calculate effective fault MVA on LT side.

Answer : 18.38 – 1 = 17.38 MVA

Example 20.12. *Two buses having fault level of 50 MVA and 100 MVA respectively are interconnected by a line of negligible impedance. Calculate fault level at any point on the line.*

Solution. Let base MVA = 100

Equivalent reactance of source behind the bus I

$$= \frac{\text{Base MVA}}{\text{Fault level of bus I}} = \frac{100}{50} = 2 \text{ p.u.}$$

Similarly, the equivalent reactance of source behind bus II

$$= \frac{100}{100} = 1 \text{ p.u.}$$

These two sources are in parallel as regards Thevenin's equivalent reactance.

Hence total equivalent reactance

$$\frac{1}{1.5} = 0.667 \text{ p.u.}$$

Hence fault level on the line $= \frac{\text{Base MVA}}{\text{Equivalent reactance}} = \frac{100}{0.667} = 150$ MVA.

Note. Total fault level here is the sum of two fault levels as the reactance of line is neglected (*i.e.* 100 + 50 = 150 MVA.)

20.3. PROCEDURE RECOMMENDED BY STANDARDS FOR SHORT-CIRCUIT CALCULATIONS IN DISTRIBUTION SYSTEMS.

Single source, symmetrical short-circuit

(1) Initial symmetrical short-circuit current, I_k''

$$I_k'' = \frac{1.1\,V}{\sqrt{3}\,\sqrt{R^2 + X^2}} \quad \text{...(20.1)}$$

where I_k'' = initial symmetrical short circuit current

i.e. the r.m.s. value of symmetrical short-circuit current.

V = rated voltage line to line

R = resistance per phase, ohms

X = reactance per phase, ohms (subtransient for this case)

1.1 = factor to take into account the rise in generator voltage. [Refer example 20.14]

(2) peak short circuit current, I_s

$$I_s = x\sqrt{2}I_k'' \quad \text{...(20.2)}$$

where I_s = Peak short-circuit current, *i.e.* highest instantaneous value of current after the short-circuit.

x = factor to take into account the asymmetry, depends on R/X ratio of generator

$\sqrt{s}$ = To convert r.m.s. to peak value. [Refer Example 20.13]

Example 20.13.

Generator : *3750 kVA*

6600 V

23% X''

0.866 Ω per phase R.

Calculate, (a) Initial symmetrical short-circuit current.

(*b*) Peak short-circuit current for a 3 phase terminal fault.

Solution. (*a*) **Initial sym. short-circuit current**

$$I_k'' = \frac{1.1\,V}{\sqrt{3}\,\sqrt{R^2 + X^2}}$$

$$X'' = 23\%$$

$$= \frac{23}{100} \times \frac{\text{kV}^2}{\text{kVA}} \times 1000 \text{ ohms}$$

$$= \frac{23 \times (6.6)^2 \times 10}{3750} = 2.67 \text{ ohms}$$

$$R = 0.866\ \Omega \text{ per phase}$$

$$\sqrt{R^2 + X^2} = Z = \sqrt{(2.67)^2 + (0.866)^2} = 2.8\ \Omega$$

$$I_k'' = \frac{1.1 \times 6.6 \times 1000}{\sqrt{3} \times 2.8}$$

Initial sym. short-circuit current

I_k'' = **1500 Amp. Ans.**

(*b*) **Peak short-circuit current I_x**

$$I_s = \sqrt{2}xI_k''$$

$$R/X = \frac{0.866}{2.67} = 0.32$$

*Ratio	R/X	0	0.1	0.2	0.3	0.4	0.5
*Factor	x	2	1.75	1.55	1.4	1.3	1.22

x = 1.38 (from table by interpolation)

$I_s = \sqrt{2} \times 1.38 \times 1500 =$ **2930 Amp.**

Example 20.14. *Two alternators A and B are connected in parallel. The details of the alternators are as follows :*

Alternator A : 50,000 kVA, sub-transient reactance 25%

Alternator B : 25,000 kVA, sub-transient reactance 25%.

These alternators are connected to delta star transformer T of rating 75,000 kVA, 11 kV Delta ; 66 kV Star of 10% reactance.

A three-phase fault occurs on HT side of the transformer. Find the sub-transient currents in each generator and in the HT side of the transformer. The system is on no load before fault, with voltage on HT side equal to 66 kV.

Solution. Let us adopt per unit system.

Select Base kVA 75,000

Base kV = 11 kV on L.T. side

Base kV = 66 kV on H.T. side.

Machine reactances will be converted to per unit reactances with new bases.

Percentage reactance with new base

$$= \left[\begin{matrix}\text{\%Reactance with} \\ \text{old base}\end{matrix}\right] \times \frac{\text{Base kVA new}}{\text{Base kVA old}} \times \left(\frac{\text{Base kV old}}{\text{Base kV new}}\right)^2$$

Alternator A :

Per unit reactance

$$= 0.25 \times \frac{75{,}000}{50{,}000} \times \left(\frac{11}{11}\right)^2 = 0.375 \text{ per unit.}$$

Alternator B :

Per unit reactance

$$= 0.25 \times \frac{75{,}000}{25{,}000} = 0.75 \text{ per unit.}$$

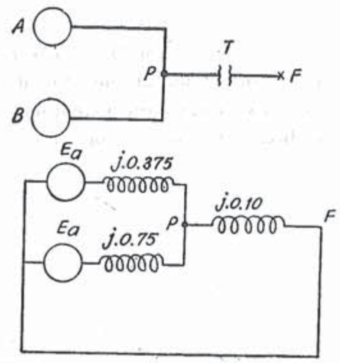


Fig. 20.7. Diagram of Ex. 20.14.

Transformer : per unit reactance = 0.10 p.u. (unchanged).

The currents can be easily calculated from the solution of network of Fig. 20.7.

$E_a = 1 + j0$ p.u. (voltage per phase)

Total reactance consists of a parallel branch in series with a reactance, *i.e.*,

$$\frac{j0.375 \times j0.75}{j0.375 + j0.75} + j0.10 = j\,0.25 + j0.10 = j0.35$$

Note. To calculate sub-transient currents, take sub-transient reactance. To calculate transient currents, take transient reactance.

The total sub-transient current

$$= \frac{E_a}{j0.35} = \frac{1}{j0.35} = -j2.860 \text{ p.u.}$$

This current gets divided into two parallel branches in inverse proportion of their reactance. Thus

$$I_A'' = -j2.86 \times \frac{j0.75}{j0.75 + j0.375}$$

$$= -j2.86 \times \frac{0.75}{1.125} = -j1.91 \text{ p.u.}$$

$$I_B'' = -j2.86 \times \frac{0.375}{1.125} = -j0.955 \text{ p.u.}$$

The total sub-transient current on H.T. side

$$= -j\,2.86 \text{ p.u.}$$

$$= -j2.86 \times \frac{\text{Base kVA}}{\sqrt{3}\text{ Base kVA}} \text{ amp.}$$

$$= -j2.86 \times \frac{75{,}000}{\sqrt{3} \times 66} = 1876 \text{ amp.}$$

Base kV is 66 on H.T. side.

Current in Alternator A $= -j1.91 \times \frac{75{,}000}{\sqrt{3} \times 11} = 7519$ amp.

Base kV is 11 on H.T. side.

Current in Alternator B $= -j\,0.955 \times \frac{75{,}000}{\sqrt{3} \times 11} = 3{,}760$ Amp.

[**Ans.** *Sub-transient current :* Generator A 7519 A
Generator B 3,760 A
H.T. Side 1,875 A]

Example 20.15. *A 7,500 kVA, 6.6 kV generator connected through a 5 cycle breaker has reactances*

$$X_d'' = 9\%, X_d' = 15\%, X_d = 100\%.$$

It is operating no-load at rated terminal voltage when a three phase short-circuit occurs beyond the breaker. Find :

(1) Sustained short-circuit current.

(2) Initial symmetrical r.m.s. current.

(3) Maximum possible d.c. component of short-circuit current.

(4) Making capacity required for circuit-breaker.

(5) Breaking capacity required for circuit-breaker.

(6) Interrupting MVA of circuit-breaker.

Solution. (1) Sustained short-circuit current is the steady state current.

Adopting per unit method :

Sustained short-circuited current $= I$

$$I = \frac{E_a}{X_d} = \frac{1.0}{1.0} = 1 \text{ p.u.}$$

where E_a = voltage per phase

I = sustained short circuit current, Amp.

X_d = Synchronous reactance.

Rated current $= \frac{\text{Generator rated kVA}}{\sqrt{3} \times \text{Rated kV}} = \frac{7500}{\sqrt{3} \times 6.6} = 656$ A.

(1) Since the per unit reactances of generator are based on its ratings as bases, the rated current refers to its per unit current.

∴ Per unit current 1.p.u. = 656 A

(1) $X_d = 100\%$, I_s = Sustained short-circuit current = 1 p.u. = 656 A.

(2) Initial symmetrical r.m.s. current $= I''$

$$= \frac{E_a}{X_d''} = \frac{1.00}{0.09} \text{ p.u.} = \frac{1}{0.09} \text{ p.u.}$$

$$= 656 \times \frac{1}{0.09} = 7289 \text{ A} = 7.28 \text{ kA r.m.s.}$$

(3) Maximum D.C. component

$$= \frac{E_m}{X_d''} = \frac{\sqrt{2}E_a}{X_d''} = \sqrt{2} \times 7.28 = 10.3 \text{ kA.}$$

(4) Making capacity required

$$= 2 \times \sqrt{2} \times \text{Initial Symmetrical Current}$$

Where, factor 2 is for doubling factor and $\sqrt{2}$ is for converting r.m.s. to peak

$$= 2\sqrt{2} \times 7.28 = 20.6 \text{ kA peak.}$$

(5) Consider transient reactance for calculating the breaking current. Since breaker operates in transient state,

$$I' = \frac{E_a}{X_d'} = \frac{1}{0.15} \text{ p.u.}$$

$$= 656 \times \frac{1}{0.15} = 4373 \text{ Amp.}$$

Transient Current $= 4.37$ kA.

Breaking Current $= 1.4 \times I'$

Where 1.4 is a factor for Asymmetry of the wave for a 5 cycle breaker (Assumed)

$= 1.4 \times 4.37 = 6.12$ kA

(6) MVA capacity $= \sqrt{3} \times \text{kV} \times \text{kA} = \sqrt{3} \times 6.6 \times 6.12 =$ **69.96 kA.** Asy.

[**Answers** :

(1) Sustained short circuit current $= I = 656$ A.

(2) Initial Sym. S.C. Current $I'' = 7.28$ kA.

(3) Maximum d.c. comp. = 10.3. kA.

(4) Making capacity required = 20.6 kA peak.

(5) Transient short-circuit current $= I' = 4.37$ kA.

(6) Interrupting capacity required = 69.96 kA, Asy.

Note. (Refer Ch. 3).

$$I'' > I > I$$

SUMMARY

(1) For three-phase symmetrical fault

$$\text{Fault MVA} = \frac{\text{Base MVA}}{\text{Equivalent } X_{p.u.}}$$

$$\text{Fault current} = \frac{\text{Fault MVA} \times 10^3}{\sqrt{3} \times \text{kV at fault point}} = \frac{V_{p.u.}}{X_{eq.\ p.u.}}$$

(2) For symmetrical fault calculations, the Thevenin's equivalent reactance upto fault is calculated and then fault MVA is calculated by applying the expressions given above.

(3) The problems are either for steady state, transient or sub-transient state. Correspondingly the steady state or transient or sub-transient reactances are used for calculations.

(4) Fault current is of lagging power factor.

(5) Capacitor banks provide leading fault MVAr.

SERIES REACTORS

20.4. REACTORS IN POWER SYSTEMS

There are several types of reactors used in Power Systems.

These include :

— Current limiting reactors : Saturated. (Series reactors).

— Reactors in neutral to earth connection called arc suppression coils/Peterson coil/ground fault neutralizers.

— Shunt reactors (Compensation Reactors). (Ref. Sec. 18.25)

— Reactors in harmonic filters.

— Smoothing reactors in HVDC systems.

Current limiting reactors are inserted in series with the line, to limit the current flow in the event of a short-circuit and thereby bring down the fault level. The current limiting reactors are also called Series Reactors.

The reactors between neutral and ground help in eliminating or suppressing arcing grounds. They are covered in the chapter 'Neutral Earthing'. (Ch. 18)

Shunt reactors are connected with transmission lines, for absorbing reactive power.

20.5. PRINCIPLE OF CURRENT LIMITING REACTORS

A current limiting reactor is an inductive coil having a large inductive reactance (ωL) and is used for limiting short-circuit currents to be interrupted by circuit-breakers. If X is the reactance

of a circuit, E is the voltage, neglecting the resistance, the short circuit current I_{sc} is given by E/X. Therefore by increasing series reactance, X of the system, the short circuit currents can be decreased. The short circuit currents depend upon the generating capacity, voltage at the fault point and the total reactance between the generators and the fault point. The circuit breakers should have enough breaking current capacity such that the fault currents are less than the breaking current capacity. If fault currents are beyond the capacity of the circuit breaker, the circuit breaker, may not interrupt the fault current. In a system where several generating stations are interconnected by short feeders, the fault currents can be high, the circuit breakers of suitable breaking capacity may not be available. The fault current, then, should be limited by some means so that available or existing circuit-breakers can be used safely. Further, when the system is extended by adding more generating stations or more generator units, the fault current to be interrupted by the same circuit breaker will be greater than before. In such a case the circuit breaker should be replaced by another of higher breaking current capacity or the fault current can be limited by means of reactors. By including a reactor or a few reactors at strategic locations, the short circuit current at several points can be reduced. Hence current limiting reactors are useful in limiting short-circuit current so that the circuit breakers can interrupt them. However the voltage drops and losses caused by reactors should be small.

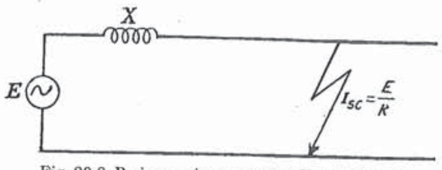


Fig. 20.8. By increasing reactance X, short circuit current I_{sc} can be reduced.

Summarising (1) Reactors limit the short-circuit currents.

(2) They are used in systems when extensions are made and the circuit-breaker breaking current capacities become inadequate.

(3) They are employed in large systems, so as to limit the short circuit MVA, to match with the breaking current capacity of circuit breaker.

Reactors are also used in short-circuit test plants. Are furnace installations. In furnace-plant, reactors are used to limit the arc current. These reactors are connected in the primary circuit of furnace transformer.

It is reported that in France, the power system is designed such that the fault levels at various points of the system are below certain limit. This is achieved by inserting series reactors at strategic locations in the system. Since 1980's suitable SF_6 and vacuum circuit breakers of high ratings are available for each voltage level and the need of series reactors is practically eliminated.

20.6. DESIGN FEATURES OF CURRENT LIMITING REACTORS

The essential requirement of current limiting reactor is that the reactance should not reduce due to saturation under short-circuit conditions. If fault current is more than about three times rated full load current, an iron core reactor having essentially constant permeability would necessitate a very large cross-section of core. Hence air core coils are sometimes used for current limiting reactors. Air core reactors are of two type (1) Dry-type Air Core Reactors and (2) Oil immersed Air Core Reactor, magnetically shielded or without shielding.

Dry type reactors are generally cooled by natural or forced air cooling. These are used only upto 33 kV. For higher voltage oil immersed designs prevail. The air insulated (dry type) reactors occupy relatively larger space. They need a large clearance from adjacent constructional work. Because of the absence of iron, the reactance of air-corded reactors is almost constant. With oil filled design, laminations of iron shields are provided around the outside conductors so as to avoid the entering of magnetic flux in the surrounding iron parts. Due to iron shield a drop of about 10% occurs in the reactance, during short-circuits. Oil- immersed reactors can be used upto any voltage level, for outdoor or indoor constructions. The advantages of oil-immersed reactors are :

1. High factor of safety against flashover.
2. Smaller size.
3. High thermal capacity.

The oil-immersed type of reactor employs insulation and cooling arrangements similar to those used in power transformers. If air core is used, laminated iron-shield is provided outside the coils. If iron core is used, air gaps are introduced in the core to prevent saturation and to get desired value magnetising current.

Special care should be taken about the foundation, that it should withstand the electrodynamic forces during the short-circuit. In case of dry-reactors, there should be clearance between the reactor and surrounding metal structures, reinforcement, fabrication work etc.

20.7. DRY, AIR CORED SERIES REACTOR

In this type of reactor, the core is of air and the entire construction of the reactor, the core is free from ferromagnetic materials (iron, steel). There is absence of dielectric oil and cooling is provided by air. The reactor consists of concrete supports of glass-reinforced synthetic resins on which the winding is rigidly placed. The whole construction is rugged. Due to absence of iron, the reactance remains fairly constant during high short-circuit currents. Such reactors are not shielded, hence require special room free from reinforcement, closed metal circuits. The magnetic fluxes surrounding the reactor cause heating of structural works, metal bodies etc. the vicinity of the reactors.

20.8. OIL IMMERSED NON-MAGNETICALLY SHIELDED REACTOR

Principle. Imagine a current carrying inductance coil without iron core. The magnetic flux of such a coil will surround the coil. Now, suppose the coil is placed axially in a cylindrical aluminium tube, and paths are provided for the current induced in the aluminium enclosures. The induced currents in the enclosures will flow longitudinally in the enclosures and will provide magnetic flux. By proper design of the enclosures, the fluxes due to enclosure currents can be made almost equal to the fluxes due to the magnetic flux due to coil current. The magnetic flux due to the enclosure current opposes the magnetic flux due to coil current : outside the enclosure thereby provides magnetic shield.

The non-magnetically shielded oil immersed reactor looks like a power transformer. It has a coil without iron core. The coil assembly is placed in tank filled with transformer oil. Features are similar to power transformer. The aluminium enclosure of tube shape are placed in between the tank and the inductance coil. Paths are provided for circulating the induced currents. This method of shielding is simpler in construction.

20.9. OIL IMMERSED SHIELDED REACTORS

Such a reactor is similar to power transformers in several aspects, but has no continuous iron core. There is either no core or gapped core. Single disc-winding is placed on the central core of the magnetic circuit. The core is with air-gaps. Strong ceramic discs are placed between adjucent disc coils of the reactor. The entire winding is held under pressure to prevent vibrations and noise. The coil assembly is oil immersed and is enclosed in a tank. Cooling is similar to that in power transformers.

Sub-assemblies of laminated silicon-steel sheets are fixed rigidly at strategic locations between the inductive coil and the tank. The magnetic fields surrounding the coil are thereby get a path and the fluxes outside the shields are minimised.

20.10. TERMS AND DEFINITIONS

1. **Series Reactor**. It is an inductance coil connected in series with the system for one of the following purposes :

— Limiting current during fault condition.

— Limiting current during synchronising, load sharing, fluctuating loads, etc.

2. **Continuous Rated Current.** The r.m.s. value of current which the reactor can carry continuously, with temperature rise of current carrying parts and other parts, within specified limits. [*e.g.* 800 A].

3. **Rated Short-time Current.** The symmetrical r.m.s. value of fault current which the reactor can carry for specified short time [*e.g.* 40 kA for 1 sec.]

4. **Rated Impedance.** Impedance expressed in ohms per phase or in per unit specified for the reactor.

5. **Rated Over Current Factor.** The ratio of rated short time current to continuous current, e.g. 25.

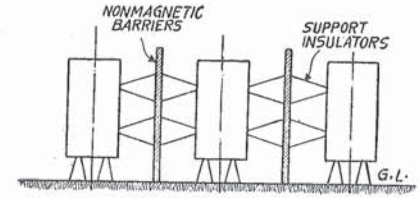
6. **Rated Through-put kVA.** $\sqrt{3}$ × Rated Voltage × Rated Current (for 3 phase reactors).

7. **Rated Voltage**. The line to line service voltage for which the reactor is designed.

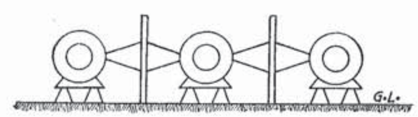
8. **Short Circuit Rating**. The reactors should be capable of withstanding the mechanical and thermal stresses during short circuit at its terminals for a specified period of time.

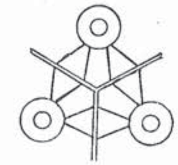
20.11. PHYSICAL ARRANGEMENT OF SERIES REACTORS

Fig. 20.9 illustrates various alternative methods of the physical arrangement of series reactors for 3-phase circuits.



ELEVATION
(*a*) With axis vertical and in a single row.





ELEVATION
(*b*) With axis horizontal, side by side.

PLAN
(c) With axis vertical, Triangular Formation.

Fig. 20.9. Physical Arrangement of Reactor for 3-phase system.

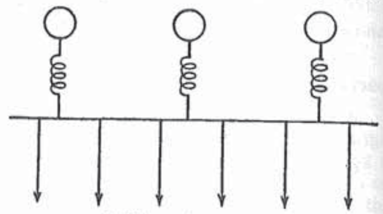
20.12. SELECTION OF REACTORS

While selecting a current limiting reactor, following aspects should be noted :

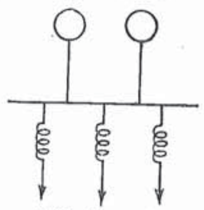
(1) **Type.** Dry or oil-immersed, iron-cored or Air-cooled, etc.
(2) **Phases.** Single-phase or three-phase.
(3) Indoor or outdoor.
(4) Reactance in ohms.
(5) Normal current rating, short-time current rating.
(6) Reactor through-put kVA.
(7) Rated voltage.
(8) Circuit characteristics-Frequency, voltage etc.

20.13. LOCATION OF SERIES REACTORS

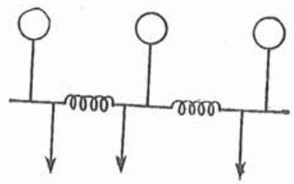
(*a*) *Generator Reactors.* In this scheme reactors are inserted between the generator and the generator bus [Fig. 20.10 (*a*)]. Modern turbo-generators have large reactance obtained by means of deep slots and other design features. The high reactance is provided to safeguard the generators in case of dead three-phase short-circuit as its terminals. Therefore, generator reactors are normally unnecessary in the modern installations. When new generators are installed in an old power station, generator reactors may be added for the older generators. The magnitude or such reactors is very approximately about 0.05 per unit. In this method when fault occurs on one feeder or busbar, the voltage of the common busbar drops down to a low value and stability is likely to be lost.



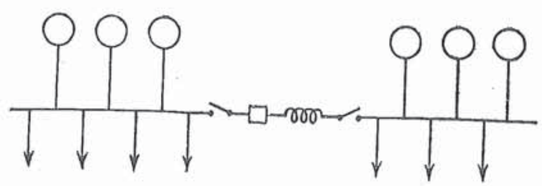
(*a*) Generator reactor.



(*b*) Feeder reactor.



(*c*) Busbar reactor.



(*d*) Busbar reactors between sections of bus.
Fig. 20.10. Locations of Series Reactors.

(*b*) *Feeder Reactors.* The reactors in this case are connected in series with the feeders. The advantage is that the voltage of the bus does not drop substantially in the event of a fault on the feeder. Hence the other feeder are affected less. The disadvantage is that, there are so many feeders and, therefore, many reactors are necessary. Further there is a constant loss in the reactor as full feeder current flows through it.

(*c*) *The Busbar Reactor.* The constant loss in reactor is avoided by inserting the reactors is busbars [Fig. 20.10 (*c*)]. In this system only a small powers-flows through the reactors during normal condition. During short-circuit on the feeder, only one generator feeds the fault directly, by-passing the reactors. While the other generators, feed the fault through the reactor.

Sometimes busbars are sectionalized and the reactors are included only between sections of the bus [Fig. 20.10 (*d*)].

With increasing size of today's power system, there is a constant need of checking the fault levels at all the important power stations and sub-stations almost every year. The capacities of circuit breakers and other switchgear should be verified. If necessary, new circuit breakers of higher rating should be installed or current limiting reactors should be introduced to limit the fault level

within the capacity of existing switchgear. Otherwise, due to inadequate capacity, the circuit-breakers may not be able to clear short-circuits, resulting in disasters. Such incidents occurred during 1950s in our system. Now (1980's) circuit-breakers of adequate ratings are available for every voltage level and series reactors are rarely used.

(*d*) **Smoothing reactors.** These are installed in series with rectifier sets on DC side to reduce ripple in DC current and minimise requirement of harmonic filters.

Example 20.16. (*a*) *Find short-circuit current in a single-phase system shown below. The reactance between the transformer and the fault point F is 2 ohms. The voltage at F is 6.6 kV.*

Solution.

Note. It is a single phase system.

(*i*) Take 2000 kVA as base kVA.

(*ii*) % Reactance of transformer to the new base kVA

$$= 7 \times \frac{2000}{1200} = 11.7$$

(*iii*) Base $I = \dfrac{\text{Base kVA}}{\text{Base kV}}$ for single phase circuit

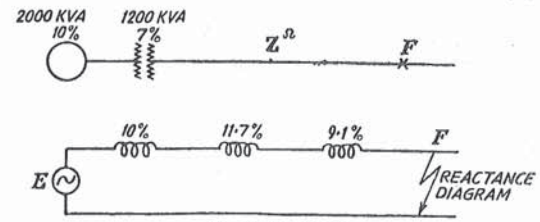


Fig. Ex. 20.16 (*a*)

$$= \frac{2000}{6.6} = 303 \text{ A}$$

(*iv*) Base impedance $= \dfrac{\text{Base Voltage}}{\text{Base Current}} = \dfrac{6.6 \times 10^3}{303} = 21.8\ \Omega$

Example 20.16. (*b*) *Solved by direct ohmic method.*

Solution. Ohmic reactance of generator, from Eqn. (20.1)

$$= \frac{F \times \%X}{I \times 100} = \frac{6600 \times 10}{303 \times 100} = 2.18\ \Omega.$$

Similarly ohmic reactance of transformer

$$\frac{6600 \times 7 \times \dfrac{2000}{1200}}{303 \times 100} = 2.56\ \Omega$$

Total reactance $= 2.18 + 2.57 + 2 = 6.75$ ohms

$$I_{sh} = \frac{6600}{6.75} = 980 \text{ A.}$$

OR by % reactance method.

% Reactance of generator 10%

% Reactance of transformer 11.7%, from (*ii*) above

% Reactance of line upto *F*

$$= \frac{\text{Ohmic Reactance}}{\text{Base Reactance}} \times 100 = \frac{2}{21.8} \times 100 = 9.2\%$$

Total percentage reactance

$$= 10 + 11.7 + 9.2 = 30.9\%$$

Short-circuit current

$$I_{sh} = I \times \frac{100}{\%X} = \frac{303 \times 100}{30.9} = \mathbf{980\ Amp.} \quad \textbf{Ans.}$$

Example 20.16. (*c*) *Further to problem 20.1, reactance of 5% is connected to the generator, in between the generator and transformer. Calculate the new short-circuit current. The 5% reactance is based on generator ratings.*

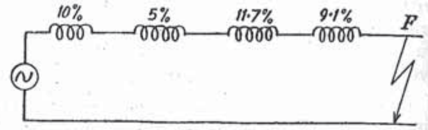


Fig. Ex. 20.16 (*c*)

Solution. Add 5% reactance in series with the generator.

Total % reactance $= 10 + 5 + 11.7 + 9.1 = 35.8\%$

$$I_{sh} = \frac{I \times 100}{\%X} = 303 \times \frac{100}{35.8} = \mathbf{845\ Amp.} \quad \textbf{Ans.}$$

We note that by including a reactor, I_{sh} has reduced.

Example 20.17. (*a*) *Two-three-phase generators of ratings 1000 kVA and 1500 kVA and voltage 3.3 kV have percentage reactances of 10 and 20 respectively per cent with respect to their ratings. These are connected to bus-bar. A three-phase short-circuit occurs on the bus. Find the short circuit current.*

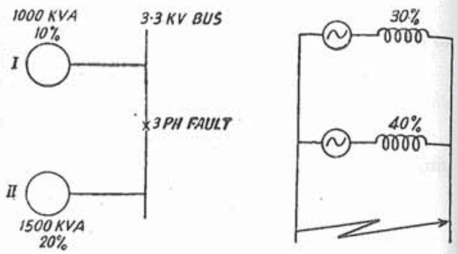


Fig. Ex. 20.17 (*a*)

Solution. Assume base kVA 3000

%Reactance of generator I to this base

$$= 10 \times \frac{3000}{1000} = 30\%$$

%Reactance of generator II to new base

$$= 20 \times \frac{3000}{1500} = 40\%$$

These two reactance are in parallel, total $\%X$

$$= \frac{1}{\frac{1}{30} + \frac{1}{40}} = 17.14$$

Short circuit kVA $= \dfrac{\text{Base kVA} \times 100}{\%X}$

$$= \frac{3000}{17.14} \times 100 = 17.500 \text{ kVA}$$

Short-circuit current $= \dfrac{\text{Short circuit kVA}}{\sqrt{3} \times \text{kV}}$

$$I_{sh} = \frac{17{,}500}{\sqrt{3} \times 3.3} = \mathbf{3050\ A.} \quad \textbf{Ans.}$$

Example 20.17. (*b*) *In the above problem find the reactance of a reactor to be connected in series with generator of 1000 kVA to limit the short circuit kVA of bus-bar to 10,000.*

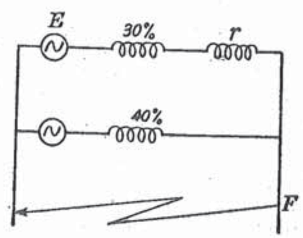


Fig. Ex. 20.17 (*b*)

Solution. [Continued from problem 20.17 (*a*)]

Short circuit kVA = 10,000

$$= \frac{\text{Base kVA}}{\%\text{X}} \times 100$$

$$\therefore \quad \%X = \frac{3000 \times 100}{10{,}000} = 30\%$$

This resultant percentage reactance is obtained by adding the reactor in series with the 1000 kVA generators. Suppose the newly added reactor is of % reactance r, then

$$\frac{1}{30} = \frac{1}{30 + r} + \frac{1}{40}$$

$$\frac{1}{120} = \frac{1}{30 + r}$$

$$30 + r = 120$$

$$r = 90\%$$

The reactance of 90%, based on the base 3000 kVA, should be connected in series with the generator to limit the short-circuit kVA to 10,000.

Example 20.18. (*a*) *Two generators of 3000 kVA and 10% reactance and one grid supply are connected to a generator bus as shown in the figure. The rating of the circuit-breakers on the feeder is 150 MVA. The capacities and reactances of the generators and the transformer are as shown in the figure. Calculate the reactance of the reactor X to limit the short circuit MVA on feeders to 150.*

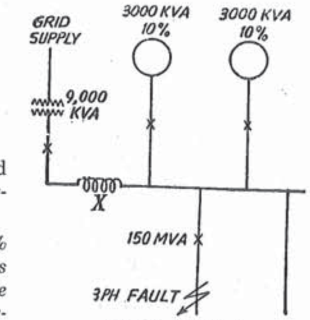


Fig. Ex. 20.18 (*a*)
(Note. Transformer reactance is 5%)

Neglect the equivalent reactance of the grid and assume the grid supply to be of infinite fault level.

Solution. Step 1. Convert the % reactance to the common new base.

Step 2. Calculate total reactance upto fault by series parallel combination.

Step 3. Short Circuit MVA is limited to 150 MVA

$$= \frac{\text{Base MVA}}{\%X_T} \times 100$$

From which the unknown X can be determined. Let the base kVA = 9000.

% Reactance of generators to the new base kVA

$$= \frac{9000}{3000} \times 10 = 30\%$$

The two generators are in parallel the combined reactance is given by

$$\frac{1}{30} + \frac{1}{30} = \frac{1}{X_c} = \frac{1}{15}$$

$$X_c = 15\%.$$

This is parallel with the grid-transformer and the reactors X. The combined reactance of the set up is given by :

$$\frac{1}{X_T} = \frac{1}{5 + X} + \frac{1}{15}$$

$$= \frac{15 + (5 + X)}{15\,(5 + X)} = \frac{20 + X}{75 + 15X}$$

$$X_T = \frac{75 + 15X}{20 + X} \text{ \% reactance.}$$

Short-circuit MVA $= \dfrac{\text{Base MVA}}{X_T} \times 100$

Short-circuit MVA is limited to 150

$$150 = \frac{9}{\frac{75 + 15X}{20 + X}} \times 100$$

$$\therefore \quad 3 = \frac{9 \times 2}{\frac{75 + 15X}{20 + X}}$$

$$\therefore \quad 3\,(75 + 15X) = 18\,(20 + X)$$
$$225 + 45X = 360 + 18X$$
$$135 = 27X$$
$$X = \frac{135}{27} = 5.$$

Reactance of 5% (based on base kVA 9000) should be added between the transformer and generator bus.

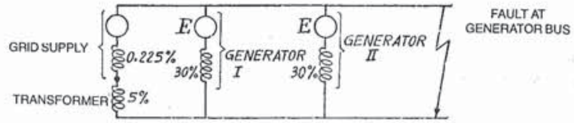


Fig. Ex. 20.18 (*a*) Equivalent Diagram.

Example 20.18. (*b*) *The incoming grid supply in example 20.17 has a fault level of 4000 MVA instead of infinity. Calculate fault level at generator bus neglecting reactor X.*

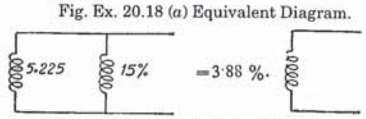


Fig. Ex. 20.18 (*b*) Equivalent Reactance.

Solution. (Consider from Ex 20.18 (*a*), with above changes)

Fault MVA

$$= \frac{\text{Base MVA}}{\%\text{Reactance}} \times 100 \qquad ...(1)$$

The fault level of the incoming supply is given. Hence, the supply can be considered as a generator having equivalent reactance. The equivalent reactance can be calculated from the expression (1) above.

Equivalent % reactance of the grid supply

$$= \frac{\text{Base MVA}}{\text{Fault MVA}} \times 100$$

Choosing same bases as in Ex. 20.17 (*a*) (*i.e.* 9 MVA).

Equivalent % reactance of the grid supply

$$= \frac{9}{4000} \times 100 = \frac{900}{4000} = 0.225\%.$$

Equivalent diagrams :

Equivalent reactance upto generator bus = 3.88%.

Fault level $= \dfrac{\text{Base kVA}}{\%\text{Reactance}} \times 100$

$$= \frac{9000}{3.88} \times 100 = 231{,}000 \text{ kVA} = 231 \text{ MVA}$$

New fault level at generator bus = **231 MVA.** **Ans.**

Example 20.19. *Explain briefly the advantages gained by insertion of reactors in the busbars of a large generating station. A generating station has four identical three phase alternators A, B, C, D, each of 20,000 kVA, 11 kV having 20% reactance. They are connected to a bus-bar which has a bus-bar reactor of 25% reactance on the basis of 20,000 kVA base, inserted between B and C. A 66 kV feeder is taken off from the bus-bars through a 10,000 kVA transformer having 5% reactance. A short circuit occurs across all phases at the high voltage terminals of the transformer, calculate the current fed into the fault.*

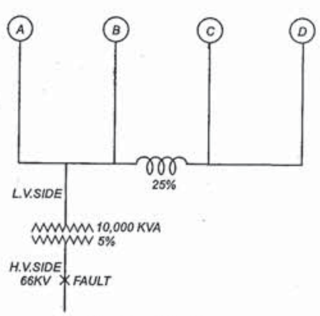


Fig. Ex. 20.19 (*a*)

Solution. Select base kVA and base kV.

Note. Choose base kVA, base kV : choose same base kVA on both sides of transformer. Choose different kV bases on either sides of transformer. The kV bases on both sides should

have the ratio same as the ratio of transformer. With this choice of bases the percent reactances referred to either sides remains same.

Base kVA = 20,000 on either sides of transformer

Base kV = 11 kV on generator side, 66 kV on feeder side.

Per cent reactance of transformer referred to new base kVA.

$$= \% \text{ reactance on old base} \times \frac{\text{New base kVA}}{\text{Old base kVA}}$$

$$= 5 \times \frac{20{,}000}{10{,}000} = 10\%$$

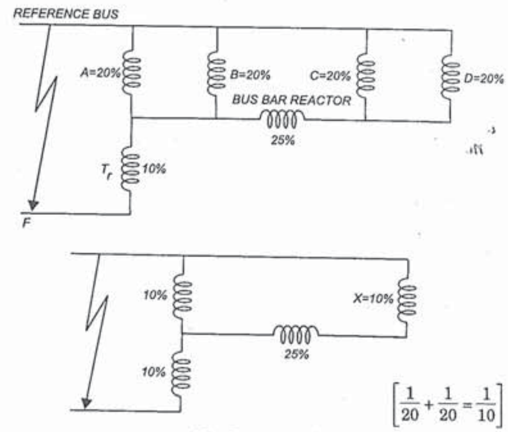
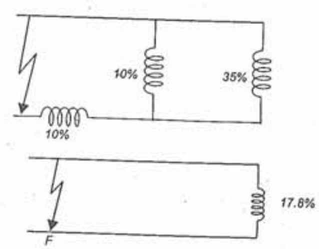


Fig. Ex. 20.19 (*b*).

Other % reactances remain unchanged. Thevenin's equivalent of the circuit contains reactances of generators *A*, *B* in parallel, generators *C*, *D* in parallel as shown in Fig. 20.19 (*b*).

Thevenin's equivalent reactance between *F* and reference bus. It is obtained by reduction of the network by series-parallel simplification as follows :

Thevenin's equivalent reactance is 17.8%.



Short circuit MVA $= \dfrac{\text{Base MVA}}{\text{Thev. \% reactance}} \times 100$

$$= \frac{20}{17.8} \times 100 = 112.5 \text{ MVA}$$

Short-circuit current $= \dfrac{\text{S.C. MVA} \times 1000}{\sqrt{3} \times \text{kV at fault point}}$

$$= \frac{112.5 \times 100}{\sqrt{3} \times 66} = 977 \text{ A}$$

Ans. Short circuit MVA 112.5.

Short circuit current = 977 A.

Example 20.20. (*a*) *Determine the ratio of the percentage reactance of the reactors to that of generators in a tie bar system if short circuit current is not to exceed two times the short circuit current of single section.*

Solution. Let the percentage reactance of a generator be g and that of the reactor be R. When there is a short-circuit on a feeder, except one R, remaining reactors and generators are in parallel. Suppose there are n number of sections. The percentage reactance of reactors in parallel is

$$\frac{g+R}{n-1}$$

This is in series with the reactor R connected to feeder on which fault occurs,

$$\frac{g+R}{n-1}+R=\frac{g+nR}{n-1}$$

This is in parallel with generator on whose feeder the fault occurs. The resulting reactance X is given by

$$\frac{1}{X}=\frac{1}{g}+\frac{1}{\dfrac{g+nR}{n-1}}$$

Giving $\quad X=g\,\dfrac{g+nR}{ng+nR}$

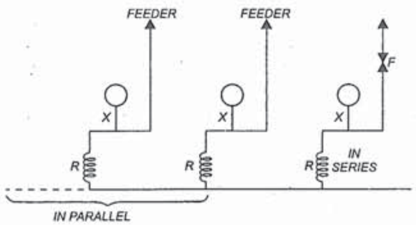


Fig. 20.20. Tie bar system.

Short circuit current

$$=\frac{\text{Full load current}}{\%\text{ reactance}}\times 100$$

Let $\quad I_{sh}$ = Short circuit current

I = Normal full load current

$$I_{sh}=I\times 100\,\frac{(ng+nR)}{g\,(g+nR)} \qquad \text{...(1)}$$

Short circuit current of one section, $n=1$

$$I_1=\frac{I}{g}\times 100 \qquad \text{...(2)}$$

According to the example the short circuit current in (1) should be twice that given by (2),

Assuming n is α,

$$I_{sh}=I\times 100\,\frac{\frac{1}{n}\,(ng+nR)}{g\left(\dfrac{g}{n}+\dfrac{nR}{n}\right)}$$

Taking limit as $n\to\alpha$ in this example

$$I_{sh}=I\times 100\,\frac{g+R}{gR}$$

$$I_{sh}=I_1\left(\frac{g+R}{R}\right)$$

$$\frac{I_{sh}}{I_1}+\frac{g+R}{R}$$

which is equal to 2.

$\therefore \quad \dfrac{g+R}{R}=2$

$\therefore \quad$ **g = R. Ans.**

Example 20.20 (*b*). Tie Bar Reactors.

A generating station has four generators, each rated 11 kV, 20 MVA, 50 Hz with transient reactance of 20%. The main busbars are divided into four sections, each section is connected to a tie-bar via a reactor R (Ref. Fig. 20.20).

If a three phase short-circuit takes place on of the sectional busbars, the voltage of remaining three busbar sections falls to 60% of normal value.

Calculate the % reactance of reactors R. Also calculate ohmic value of reactor R.

Solution. Draw single line diagram.

Ref. Fig. 20.20. Draw similar diagram with one more generator and reactor.

Consider fault F as indicated in the Figure.

Let Base kV = 11

Base kVA = 20,000

Let reactance per R per cent

Let percentage reactance of generator $=g$

For fault F,

The total equivalent reactance upto fault includes the following combination :

One of the generators feed the fault directly. Other three generators feed the fault *via* their respective reactors R's and then together through one reactor R.

Ref. Example 20.20 (*a*),

Thus in this case $n=4$

Percentage Reactance of three parallel branches :

$$\frac{g+R}{n-1}=\frac{20+R}{3}\%=(6.67+0.33\,R)\%$$

This is in series with one R.

Total Equivalent Reactance

$$=6.67+0.33+R+R=(6.67+1.33\,R)\%$$

Voltage of three sections dropped to 60% of nominal value. Hence 100 – 60 = 40%. Voltage drop takes place in the reactances X of generators, (Ref. Fig. 20.20) and remaining 60% voltage drop takes place in reactors R.

$\dfrac{g+R}{n-1}$ is total reactance in parallel branches

$$=\frac{g}{n-1}+\frac{R}{n-1}.$$

The first term on right hand side gives equivalent reactance of three generators in parallel. The second term gives equivalent reactance of three reactors in parallel

Thus for circuit containing three parallel branches and one series R,

$$\left(\frac{g+R}{n-1}+R\right)\text{ becomes}$$

$$\frac{g+nR}{n-1}\text{ as seen in Ex. 20.20 }(a)$$

This has two terms *i.e.*

$$\frac{g}{n-1}\text{ for generator reactance}$$

$$\frac{nR}{n-1}\text{ for series reactors}$$

Coming back to the example,

Voltage drop in generator reactance g is 40% of total voltage drop upto fault.

Hence 40% voltage drops in reactance

$$\frac{g}{n-1}\ i.e.\ \frac{20}{4-1}=\frac{20}{3}=6.67\% \qquad \text{...(I)}$$

100% voltage drop is in total reactance, *i.e.* in

$$= \frac{g + nR}{n - R}$$

$$= (6.67 + 1.33\ R)\% \qquad \text{...(II)}$$

But (I) is 40% of (II)

Hence, $6.67 = \frac{40}{100}(6.67 + 1.33\ R)$

$6.67 = 2.668 + 0.532\ R$

Solving this for R, we get

$$R = \frac{6.67 - 2.67}{0.532} = \frac{4.00}{0.532} = 7.5\%$$

Hence Reactance of Reactors is 7.5% based on 11 kV and 20,000 kVA Base **(Ans.)**

Ref. Eqn. 6 in sec. 19.6 for conversion.

$$\text{Actual Reactance Ohms} = \text{p.u. Reactance} \times \frac{\text{Base kv}^2}{\text{Base kVA}} \times 1000$$

$$= \frac{7.5}{100} \times \frac{11^2}{20{,}000} \times 1000$$

$$= \frac{7.5 \times 121}{2000} = \mathbf{0.455\ ohms.} \quad \textbf{(Ans.)}$$

Example 20.21. *Fig. 20.21 illustrates a typical unit in thermal power station. The reactances of Generators and Transformal are as follows.*

Generator : Subtransient reactance $X'' = 20\%$

Transient reactance $X' = 28\%$

Synchronous Direct Axis reactance $X_s = 250\%$

Transformer leakage reactance = 15%

The generator is rated 25 kV, 500 MW, 0.8 pf

The transformer is rated 220/25 kV, 600 MVA.

Assume infinite fault level at 200 kV Bus and neglect fault level of Auxiliary Bus.

For a three phase symmetrical fault on the T-off, calculate the following of sub-transient, transient and steady state condition.

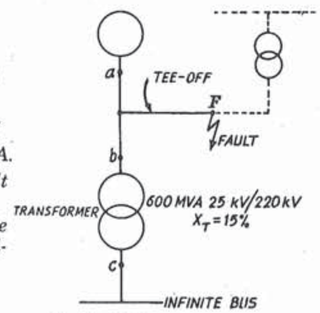


Fig. Ex. 20.21 (*a*) Line Diagram.

(1) Fault MVA

(2) Fault current in T-off

(3) Fault current contributed by generator side.

(4) Fault current contributed from transformer side.

Solution. Select base kVA and base kV.

Let base kVA $= 600 \times 10^3$

base kV $= 25$ kV

(The rating of Transformer).

Calculate new p.u. reactances.

The p.u. Reactance of transformer given in the example refers to its own bases.

Hence p.u. Reactance of transformer referred to selected Bases in the same *i.e.*

$$X_t = 0.15$$

X_t remains unchanged for sub-transient, transient and steady state.

The generator rating is 500 MVA, 0.8 p.f.

$$\text{MVA} = \frac{\text{MW}}{\text{p.f.}} = \frac{500}{0.8} = 625$$

Generator reactances referred to new base MVA are calculated as follows :

$$\text{p.u. } X_q \text{ New} = \text{p.u. } X_g \text{ Old} \times \frac{\text{kVA Base New}}{\text{kVA Base Old}}$$

$$= \text{p.u. } X_g \text{ Old} \times \frac{600}{625}$$

$$= \text{p.u. } X_g \text{ Old} \times 0.96$$

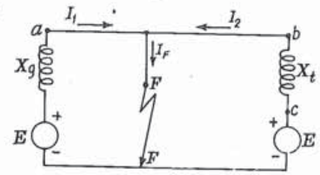


Fig. Ex. 20.21 (*b*) Reactance Diagram.

New p.u. Reactances of Generator

$$X_g'' = 0.2 \times 0.96 = 0.192 \text{ p.u.}$$

$$X_g' = 0.28 \times 0.96 = 0.269 \text{ p.u.}$$

$$X_s = 2.5 \times 0.96 = 2.4 \text{ p.u.}$$

For calculating sub-transient current, use sub-transient reactance X_g''.

For calculating transient current, use transient reactance X_g'.

For calculating steady state current, use steady state direct axis-synchronous reactance X_s.

$$X_t = 0.15 \text{ p.u. in all cases.}$$

Draw Reactance Diagram (Fig. Ex. 20.21 *b*).

Derive Equivalent Reactance as seen from fault point by removing fault branch and short-circuiting the e.m.f. sources.

Representation of Infinite Source

In this example the 220 kV bus has infinite fault level. It means, if a fault occurs on this bus, there is no internal reactance to limit the fault power. Hence infinite bus can be represented by an e.m.f. source with zero internal reactance as shown in Fig. Ex. 20.21 (*b*).

Equivalent Reactances

Refer Fig. Ex. 20.21 (*c*).

$$X_{eq} = \frac{1}{\frac{1}{X_g} + \frac{1}{X_t}} = \frac{X_g \times X_t}{X_g + X_t}$$

Sub-transient Reactance

$$X_{eq}'' = \frac{X_g X_t}{X_g'' + X_t} = \frac{0.192 \times 0.15}{0.192 + 0.15} = \frac{0.0298}{0.342} = \mathbf{0.083\ p.u.}$$

Transient Reactance

$$X_{eq}' = \frac{X_g' X_t}{X_g' + X_t} = \frac{0.269 \times 0.15}{0.269 + 0.15} = \mathbf{0.0965\ p.u.}$$

Steady State Reactance

$$X_{eg} = \frac{2.5 \times 0.15}{2.5 + 0.15} = \frac{0.375}{2.65} = \mathbf{0.143\ p.u.}$$

Total fault current I_F flows through T-off branch,

$$I_F'' = \frac{E}{X_{eq}''} = \frac{1}{0.083} = 12.05 \text{ p.u.}$$

$$I_F' = \frac{E}{X_{eq}'} = \frac{1}{0.0065} = 10.35 \text{ p.u.}$$

$$I_F = \frac{E}{X_{eq}} = \frac{1}{j\,0.14} = 7 \text{ p.u.}$$

The fault current I_F is composed of two components I_1 and I_2 [Refer Fig. Ex. 20.21 (*e*)].

$$I_1 = I_F \times \frac{X_t}{X_g + X_t}$$

$$I_2 = I_F \times \frac{X_g}{X_g + X_t}$$

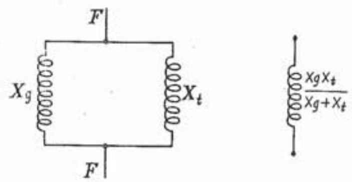


Fig. Ex. 20.21 (c) Thevenin's Equivalent reactance seen from Fault-branch.

[Refer Example 20.5 (*b*)]

$$I_1'' = I_F'' \times \frac{X_t}{X_g'' + X_t} = 12.05 \times \frac{0.15}{0.342} = 5.3$$

$$I_2' = I_F'' \times \frac{X_g}{X_g'' + X_t} = 12.05 \times \frac{0.192}{0.342} = 6.75.$$

Check $I_1'' + I_2'' = I_F''$

$$\text{Base current} = \frac{\text{Base MVA} \times 10^3}{\sqrt{3} \times \text{Base kV}} = \frac{600 \times 10^3}{\sqrt{3} \times 22.2} = 15.6 \text{ kA}$$

Sub-transient currents are as follows :

Total sub-transient fault current in T-off.

$$= 12.05 \times 15.6 \times 10^3 = \mathbf{188 \text{ k Amp.}} \quad \textbf{Ans.}$$

Sub-transient current from Generator side

$$= I_1'' = 5.3 \times 15.6 \times 10^3 \text{ A} = \mathbf{82.9 \text{ k Amp.}} \quad \textbf{Ans.}$$

Sub-transient current from Transformer side

$$= I_2'' = 6.75 \times 15.6 \times 10^3 = \mathbf{105.2 \text{ k Amp.}} \quad \textbf{Ans.}$$

Check $I_1'' + I_2'' = 82.9 + 105.2 = 188.1$ kA.

Calculate transient current and steady state current by following similar procedure.

20.14. EFFECTIVE SHORT CIRCUIT LEVEL (ESCL) BY CONSIDERING kVAr CONTRIBUTION OF SHUNT CAPACITOR BANKS

In earlier Sections of Ch. 20, the Normal Short Circuit Level (Normal Fault Levels) have been calculated by *neglecting* the contribution of large capacitor banks. The Normal Fault Levels so calculated are of lagging power factor currents with phase angle of 90° lag behind the voltage phasors. It is a universal practice to install *High voltage shunt capacitor banks* in receiving substations for power factor improvement and voltage regulation. Very large AC Shunt Capacitor Banks are installed in HVDC Substations for harmonic filters and shunt compensation of convertor. Shunt Capacitors *reduce* fault level by supplying current at leading power factor.

During a three phase symmetrical busbar fault at a particular voltage level, the capacitor banks connected to that busbar contribute fault MVA at leading power factor at phase angle 90° lead *i.e.* opposite to the normal fault level supplied by the generators.

The *Effective Short Circuit Level MVAe* (Effective Fault Level) is calculated by taking into account the contribution of shunt capacitor banks. Refer Fig. 20.21.

The Effective Fault Level MVAe at point P in a 3 Phase AC System is :

$$\begin{bmatrix}\text{Effective Fault}\\ \text{Level MVAe}\end{bmatrix} = \begin{bmatrix}\text{Normal Fault}\\ \text{Level MVAn}\end{bmatrix} - \begin{bmatrix}\text{Fault Level Contributed}\\ \text{by Capacitor Bank MVAc}\end{bmatrix}$$

$$\text{MVAe} = \text{MVAn} - \text{MVAc}$$

Note : *While calculating Effective Fault Level. Calculate the normal fault level as per procedure of symmetrical fault calculations. Then deduct MVAr contribution of the capacitor bank to obtain the Effective Fault Level.*

20.15. EFFECTIVE SHORT CIRCUIT RATIO (ESCR)

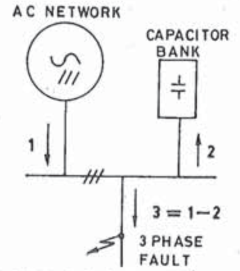


Fig. Ex. 20.21. Calculation of Effective Fault Level
MVAe (3) = MVAn (1) – MVAc (2)
S = Effective fault MVA 1 = Normal fault MVA, 2 = MVAr of Capacitor Bank

The concept of Effective Fault level (Effective Short Circuit Level) and Effective Short Circuit Ratio (ESCR) is useful in evaluating the strengthy of AC Power System to incorporate HVDC System.

The AC MVAr supplied by capacitor banks in HVDC Substations is of the order of 60% of Convertor MVA load. These capacitor banks contribute very significantly to the fault level on AC busses behind the convertor transformers. In this regard SCR ESCR are considered at the p lanning state of HVDC Project for detemining suitability of SC System to accomodate the HVDC System.

Normal Short Circuit Ratio

$$= \frac{\text{Normal Fault Level of AC Bus MVAn}}{\text{Rated Power of HVDC System MW}}$$

Effective Short Circuit Ratio

$$= \frac{\text{Effective Fault Level of AC Bus}}{\text{Rated Power of HVDC System}}$$

The effective Short Circuit Ratio of AC System at the AC substation busses should be more than 5 for planning the HVDC system connection, (Ref. Ch. 11).

Example 20.22. *Normal Short Circuit Level (Normal Fault level) at the 132 kV bus in a receiving station (before connecting the 132 kV, 200 MVAr shunt capacitor bank), was 6800 MVA. During 1995 a new 132 kV, 200 MVAr Shunt Capacitor Bank was connected to the 132 kV bus without any transformer between the bus and the capacitor bank. (a) Calculate the new Effective Short Circuit Level at the 132 kV Bus.*

(*b*) Calculate Normal Fort Current and Effective Fault Current.

Solution.

Normal Short Circuit Level at 132 kV Bus :

$$\text{MVAn} = 6800 \text{ MVA } (\angle -90° \text{ Lag})$$

Contribution of New Capacitor Bank :

$$\text{MVAc} = 200 \text{ MVA } (\angle +90° \text{ Lead})$$

Effective Short Circuit level at 132 kV Bus :

$$\text{MVAe} = \text{MVAn} - \text{MVAc}$$

$$\text{MVAe} = \text{MVAn} - \text{MVAc}$$

$$= 6800 - 200 = 6600 \angle -90°$$

Normal Fault Current

$$If \cdot n = \frac{\text{MVAn}}{\sqrt{3}\text{KV}} = \frac{6800 \text{ MVA}}{\sqrt{3} \times 132 \text{ kV}} = 29.74 \text{ kA} \angle -90°$$

Effective Fault Current

$$If \cdot e = \frac{\text{MVAe}}{\sqrt{3} \text{ KV}} = \frac{6600 \text{ MVA}}{\sqrt{3} \times 132 \text{ kV}} = 29.74 \text{ kA} \angle -90°.$$

Example 20.23. *The Normal Short Circuit Level at the 400 kV bus of Rihand Power Station of Rihand Delhi HVDC System was 30,000 MVA. A 600 MVAr Shunt Capacitor Bank has been connected to the 400 kV Bus for AC harmonic filter and shunt compensation for HVDC power level of 1500 MW. Calculate the Effective (Equivalent) Short Circuit level by considering the contribution of the capacitor bank. Calculate the (a) Short Circuit Ratio (b) Effective short Circuit Ratio of the HVDC DC System. Give your comment regarding acceptability of the ESCR.*

Solution. Normal Fault Level at 400 kV Bus MVAn = 30000 MVA (given)

Normal Short Circuit Level of HVDC System

$$= \frac{\text{MVAn}}{\text{MW rating of HVDC System}} = \frac{30000}{1500} = 20 \quad \textbf{(Ans.)}$$

Effective fault level at 400 kV Bus

$$\text{MVAe} = \text{MVAn} - \text{MVAc}$$
$$= 30000 - 600 = 24000 \text{ MVA.} \quad \textbf{Ans.}$$

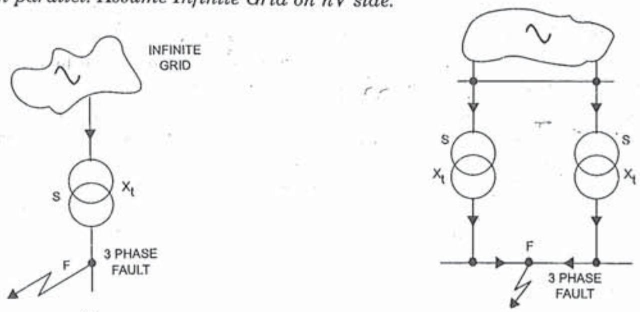
Effective Circuit Level of HVDC System

$$= \frac{\text{Effective Fault level MVAe}}{\text{MW rating of HVDC System}} = \frac{24000}{1500} = 16 \quad \textbf{Ans.}$$

Comment : ESCR is 16 and is acceptable. (Minimum ESCR = 5 required for locating HVDC Substation) **Ans.**

Example : 20.24. *Fault levels on secondary sides of power transformers.*

Ref. Fig. 20.22 (a) and (b). Rating of Transformer is S = 1 MVA ; Reactance X_t = 5 per cent. Calculate Fault Levels for a 3-phase fault F on secondary side for (a) Single transformer, (b) Two transformers in parallel. Assume Infinite Grid on hV side.



(*a*) (*b*)

Fig. Ex. 20.22

Solution. (*a*) Fault Level on LT side

$$= \frac{S}{X_t} \times 100 = \frac{1}{5} \times 100 = \mathbf{20\ MVA} \quad \textbf{Ans.}$$

(*b*) Fault Level on LT side $\quad = \dfrac{S}{X_{t/2}} \times 100 = \mathbf{40\ MVA} \quad$ **Ans.**

[Reactance of X_t of two transformers in parallel is $X_{t/2}$. Ref. Ex. 20.10 also.]

QUESTIONS

1. Describe the use of Series Reactors in power system.

   Fault level at the incoming bus in a sub-station fed from a single incoming line is 400 MVA. Calculate the % reactance to be inserted in the incoming line to limit the fault level at the bus to 350 MVA. Select Base MVA equal to 500 MVA. [**Ans.** 18% p.u.]

2. Describe the following :
   1. Magnetically shielded oil immersed reactors,
   2. Air-cooled dry type reactors.
   3. Non-magnetically shielded reactors.

3. Discuss the need of current limiting reactors in power systems.

4. Describe the principle of current limiting reactors.

5. Write short notes on the following :
   1. Ratings of series reactors.
   2. Physical arrangement of three phase series reactors.
   3. Difference between applications of series reactor and shunt reactor.

6. Two sections A and B linked with a bus-bar reactor of 10% reactance at 5000 kVA base. The bus-bar A is connected to two generators, 11kV, 1000 kVA and 10% reactance each. Bus-bar B is connected to two 8000 kVA generators of 12% reactance each. A 3-phase dead short circuit occurs on bus bars of section B. Calculate fault MVA and steady state fault current. [**Ans.** 174 MVA, 9.1 kV]

7. Two generators are connected in parallel to low voltage delta side of three-phase transformer, generator I is rated 50,000 kVA, 13.8 kV. Generator II is rated 25,000 kVA, 13.8 kV. Each generator has subtransient reactance of 25%. Transformer is rated 75,000 kVA, 13.8 kV delta (generator side), 69 kV star and has a reactance of 10%. Before fault occurred, the voltage on H.T. side is 66 kV. Transformer is without load and there are no circulating, currents. A 3-phase short circuit occurs on H.T. side of the transformer. Calculate the sub-transient current in each generator.

   [**Ans.** 5720 A, 2860 A]

8. Explain briefly the advantages of inserting series reactances in bus-bars. There are four identical 3-phase generators, A, B, C, D in a generating station each rated 20,000 kV and having 20% reactance. There is a reactor of 25% reactance based on 11 kV, 20,000 kVA between B and C bus sections. A 66 kV feeder is taken from bus A and is connected via transformer rated 10,000 kVA, 5% reactance. A three-phase short circuit occurs on 66 kV side of transformer. Calculate fault current.

   [**Ans.** 975 amperes]

9. A 3-phase 6000 kVA, 6.6 kV alternator has a reactance of 10% and is connected through a 6000 kVA, 6.6 kV/33 kV transformer of 9% leakage reactance to a transmission line having resistance 0.09 ohm and reactance of 0.36 ohm per km respectively. A 3-phase symmetrical delta connected fault occurs between the three phases at a distance of 10 km from transformer. Alternator voltage is 7.2 kV. Find alternator current. Neglect the load current.

10. Show that a generating plant having N section bus bars each rated Q kVA and have x% reactance, connected on the tie bar system through bus bar reactances of p% has a total short circuit kVA on one section given by

$$\frac{Q}{x} + Q\,\frac{(N-1)}{(pN+x)} \times 100.$$

   If the section rating is 50,000 kVA, x=20% and p=10%, find the short circuit kVA with (*a*) 3 sections (*b*) 9 section (*c*) show that with infinite sections the maximum fault kVA=750,000.

[**Hint.** Solved problem 20.20]

11. The estimated short circuit MVA at the bus bars of a generating station is 10,000 MVA, and at another station of 570 MVA. Generator voltage at each station is 11 kV. These stations are now linked by an inter-connector having reactance of 0.4 (ohm) per phase. Estimate the fault MVA at each station.

12. A generator connected through a 5 cycle circuit breaker (multiplying factor to obtain breaking capacity=1.1) is connected to a transformer with a breaker in-between.

   The generator has reactances

$$X_d'' = 9\%,\ X_d' = 15\%,\ X_d = 100\%,$$

   and rating 7500 kVA, 6.9 kV. A 3-phase, short circuit occurs between the breaker and the transformer.

   Find (*a*) Sustained short circuit current in the breaker

   (*b*) Initial symmetrical r.m.s. current.

   (*c*) Maximum possible d.c. component at the short-circuit current.

   (*d*) Making current of the circuit-breaker.

   (*e*) Current to be interrupted by the circuit-breaker (r.m.s.).

   (*f*) Breaker interrupting MVA.

   [Hint. Refer Chapter 3]

13. A 150 MVA, 6.6 kV, 3-phase generator has 15% reactance and current limiting reactor of 8%. Find the ratio of electrodynamic forces of short circuit current to forces on full load currents (*a*) without reactor (*b*) with reactor.

[**Hint**. Electrodynamic force is proportional to I^2]. [**Ans.** 44:1, 19:1]

14. Two generators operate in parallel and are connected to a 33 kV transmission line through a transformer. Calculate fault MVA if a 3-phase fault occurs.

(*a*) at the beginning of transmission line.

(*b*) far end of the transmission line.

The data given are as follows:

Generator I, 10,000 kVA, 11 kV, 10% reactance

Generator II, 50,000 kVA, 11 kV, 7.5% reactance

Transformer 15,000 kVA, 11 kV/33, 6% reactance

Impedance of transmission line : $(5 + j20)$ ohm.

15. A delta connected fault, each branch of the delta having reactance of 1.2 ohm is applied to an alternator on no load, and operating at rated terminal voltage. The generator has p.u. reactance of 0.2, and is rated 10 kV, 10,000 kVA. Calculate the line currents during the fault and fault MVA.

16. Three 6.6 kV alternators of rating 2000, 5000 and 8000 kVA and per unit reactances (positive sequence) of 0.08, 0.12 and 0.16 respectively are reactance of 0.125 ohms, 3 phase fault occurs at the other end of the feeder. Calculate fault power. [**Ans.** 87.2 MVA]

17. Three star connected 11 kV alternators are operating in parallel. Each of them is connected the common bus through a reactor. The alternators are rated 11 kV, 10 MVA and have subtransient reactance of 0.06 p.u.

Two 10 MVA, 0.02 p.u. 11 kV/33 kV transformers are connected in parallel to this bus bar and supply a transmission line of impedance $0.2 + j\,0.7$ ohm per km.

At another substation 10 km away from the generating station is 25 MVA 33 kV/11 kV transformer of 0.06 p.u. reactance. Calculate the reactance of current limiting reactors if each alternator is not to carry $2\frac{1}{2}$ times full load current, when a symmetrical **3 phase short** circuit occurs on 11 kV Bus bar in the sub-station.

18. Three 11 kV alternators rated 10,000 kVA with resistance of 0.02 p.u. and reactance of 0.15 p.u. have their bus-bars connected in 3-phase delta connected (mesh connection) reactors of each $(0.015 + j0.39)$ p.u. impedance per phase on 10,000 kVA rating. A 20,000 kVA transformer having $(0.01 + j0.10)$ p.u. impedance is connected to the bus bar of one machine and feeds 132 kv transmission line having resistance of 9 ohms and reactance of 50 ohms per phase. A 3-phase short-circuit occurs at the load end of the line. What must be the minimum rating of the circuit- breaker located at the point of fault ? Find currents which flow from each of the machines. [**Ans.** 73.7 MVA, 1725/1075 A]

19. A sub-station bus receives power from two incoming lines. The fault levels of the lines at the sub-station end are 50 MVA and 150 MVA respectively when they are not connected to the sub-station. Calculate the fault level at the sub-station bus when lines are connected to it. [**Ans.** 200 MVA]

20. Fault level at incoming-bus of a sub-station is 150 MVA. A single 50 MVA transformer of p.u. reactance 8% is connected between the incoming bus and outgoing bus.

Calculate the fault level at out-going bus by

(*a*) Neglecting the equivalent reactance from source size.

(*b*) Without neglecting the above. [**Ans.** 625; 122 MVA]

21. Calculate the maximum possible fault level (short circuit level) at the secondary side of a single connected power transformer ; 500 kVA, 5% reactance. [**Ans.** 10 MVA]

22. A generator is rated 500 kVA, has a reactance of 132%. Calculate 3-ph. fault current when generator was on no load with terminal voltage of 6.5kV. (Note change in voltage).

A generator is rated : 500 kVA, 6.6 kV

$X_d = 132\%$ (steady state direct axis reactance)

A sustained 3-phase fault occurred when the generator was on no-load and at 6.5 kV voltage. Calculate fault current. (Note change in voltage)

23. A generator is rated 6.6 kV, 3600 kVA and has $X_d = 132\%$, $X_d'' = 23\%$, $X_d' = 31\%$.

Calculate (1) Sustained S.C. current *I* ; (2) Transient S.C. current *I* and (3) Sub-transient S.C. current. When generator was at rated voltage and on :

(A) Full load, (B) No load. [**Ans.** B: 240; 1020 A; 1370 A]

[**Hint.** Add Full load current and fault current to get total current].

A generator has following ratings :

3600 kVA, 6.6 kV, X_d =132%, X_d''= 23%, X_d' = 31%

Calculate (1) Sustained short-circuit current.
(2) Transient short-circuit current.
(3) Initial symmetrical short-circuit current.

When generator is at rated voltage and (A) Full Load, (B) No Load.

$$\textbf{Ans.} \begin{bmatrix} [B] & (1) = 240\,A \\ & (2) = 1020\,A \\ & (3) = 1370\,A \end{bmatrix}$$

[**Hint.** (A) Add full load current and fault current to get total current.