Analysis of Three Phase Faults

Dr. Michael Gibbard
School of Electrical & Electronic Engineering
The University of Adelaide

Presented by:
David Vowles
School of Electrical & Electronic Engineering
The University of Adelaide

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10. ANALYSIS OF THREE_PHASE FAULTS

10.1 Introduction

Of the types of faults, three-phase faults occur most rarely. Typical values for the incidence of the various types are given in Table 10.1.

Fault type	Relative occurrence
Single phase to ground	70%
Two phase to ground	10%
Phase to phase	15%
Three phase	<5%

Table 10.1: Relative occurrence of types of faults

Three-phase or symmetrical faults are studied because they commonly present the most onerous condition that components of the system must be designed to withstand safely and without failure. This is not true, however, for transmission networks in which the star points of most, if not all, transformer high-voltage windings are earthed. In this case the single- and double-phase-to-earth duties may be more severe. Analysis of asymmetrical faults is given in reference texts.

10.1 Sudden three-phase fault at the terminals of a synchronous generator

Let us assume (i) a solid three-phase fault is applied at the terminals of an unloaded generator, (ii) the speed of the unit remains constant, and (iii) there is no action by the excitation system. The form of the transient response for a simple machine model is considered first.

10.1.1 Stator current transient based on a simple model of the synchronous generator

The per-phase equivalent circuit for the simple model is shown in Figure 10.1 (a). It consists of an ideal voltage source,

$$v(t) = E_m \sin(wt + \alpha),$$

$e^{-t/T}$

$T = \frac{L}{r}$

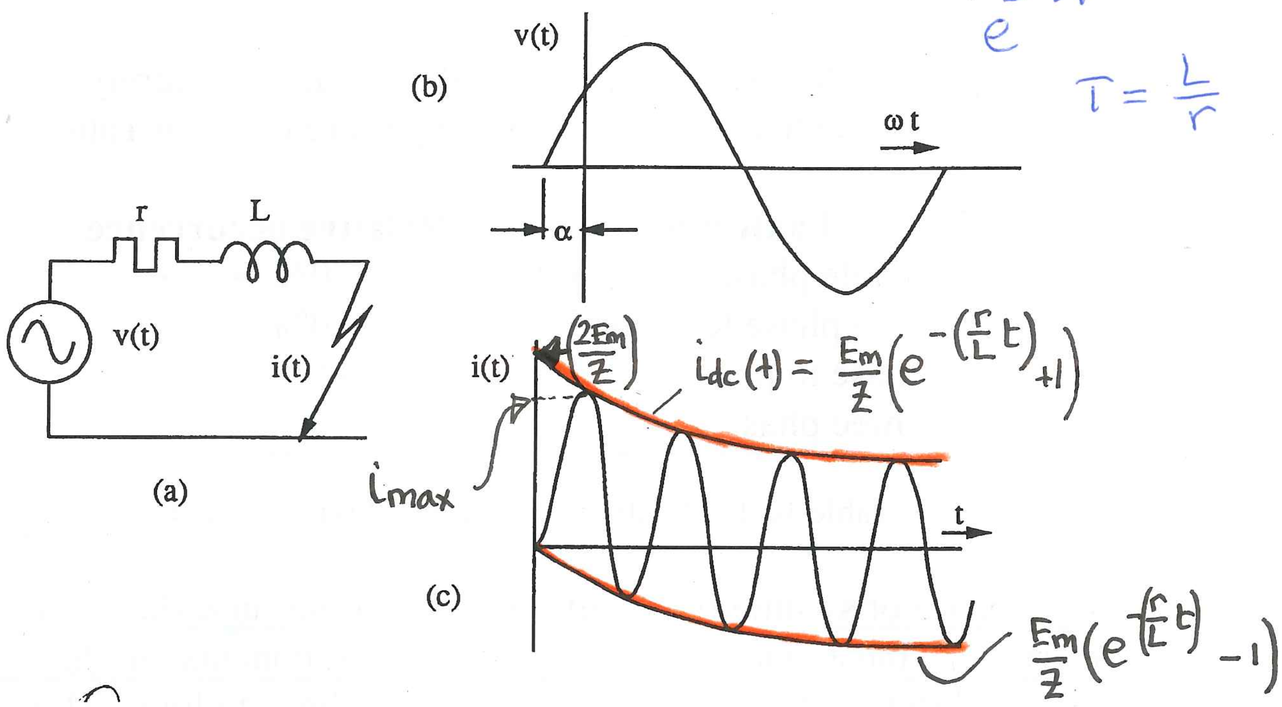


Figure 10.1 (a) Single-phase equivalent circuit of a simple generator, (b) source voltage, (c) current waveform, maximum offset

in series with resistance r ohm and constant inductance L henry. The Differential equation for the instantaneous short-circuit current is

$$r\,i + L\frac{di}{dt} = E_m \sin(wt + \alpha).$$

By use of Laplace transforms it can be shown that the solution for the current is

$$i(t) = \frac{E_m}{Z}[\underbrace{\sin(wt + \alpha - \phi)}_{\text{ac comp.}} - \underbrace{\sin(\alpha - \phi)\exp(-rt/L)}_{\text{dc component}}],$$

where $\quad Z = \sqrt{r^2 + (wL)^2}$ and $\varphi = \tan^{-1}(wL/r)$. $\quad \beta = \alpha - \phi$

The transient waveform of the short-circuit current possesses a dc component which can significantly offset the ac waveform. The condition of maximum current offset, which occurs when the point-of-switching is such that $(\alpha-\phi)=-90$ deg is shown in Figure 10.1 (c). In this case the dc transient has an initial amplitude of E_m/Z and decays with a time constant of L/r s, i.e. the dc component has more-or-less completely disappeared by 4L/r s. The maximum current flow, which occurs at the first peak of the waveform and which can easily be calculated for this simple case, is usually taken as $1.6E_m/Z$.

10.1.2 Stator current transient for the practical generator

For the practical generator, short-circuit tests are carried out at reduced voltage. Assumption (i) to (iii) in section 10.1 are retained.

If the dc component is subtracted from the transient, it is found that the resulting symmetrical short-circuit current decays from some higher initial value to a lower steady-state value as shown in Figure 10.2. The decay of the ac current waveform is related to the decay of flux in the various flux paths in the machine [1].

DC component removed.

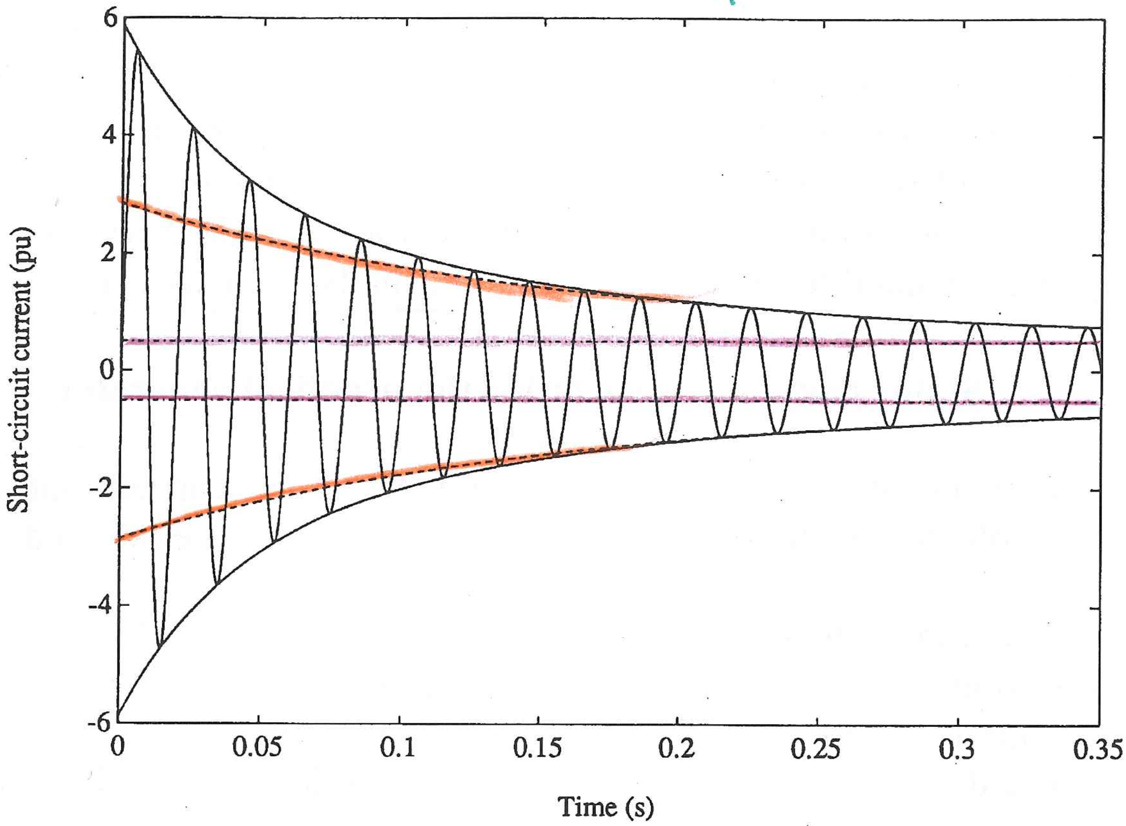


Figure 10.2: Short-circuit current in phase 'a', ac component

———	Current waveform and envelope
- - - - -	Envelope of transient component
-·-·-·-	Envelope of steady-state component

The current transient is conventially considered to consist of three components: the subtransient, the transient and steady-state components. The envelope of the symmetrical ac current waveform, $i_e(t)$, shown in Figure 10.2, is described by the following equation:

$$i_e(t) = E_m\left[\underbrace{\left(\frac{1}{x^{11}_d}-\frac{1}{x^{1}_d}\right)\exp\left(-t/T^{11}{}_d\right)}_{\text{Sub-transient}}+\underbrace{\left(\frac{1}{x^{1}{}_d}-\frac{1}{x_d}\right)\exp\left(-t/T^{1}{}_d\right)}_{\text{Transient}}+\overbrace{\frac{1}{x_d}}^{\text{Steady-State}}\right]$$

where,

$x^{11}{}_d, x^{1}{}_d$ and x_d are the direct-axis subtransient, transient and synchronous reactances, respectively,

Direct-axis reactances and short-circuit time constants

		Typical Values (Round Rotor)
X_d''	direct-axis sub-transient reactance	0·22 pu
X_d'	direct-axis transient reactance	0·30 pu
X_d	direct-axis synchronous reactance	1·80 pu
T_d''	d-axis sub-transient short-circuit time constant	0·03 s
T_d'	d-axis transient short-circuit time constant	1·4 s

$T^{11}{}_d$ and $T^1{}_d$ are the subtransient and transient short-circuit time constants.

With reference both to the above equation and to Figure 10.2, the short-circuit current at time zero is

$$i(0) = I^{11}{}_m = (I^{11}{}_m - I^1{}_m) + (I^1{}_m - I_m) + I_m$$

where the maximum value of each of the three components of the short-circuit current, $I^i{}_m$, can be expressed as follows:

- For the subtransient currrent: $I^{11}{}_m = E_m / x^{11}{}_d$ A (peak), which decays away after a time of 4 x $T^{11}{}_d$ s,

- For the transient current: $I^1{}_m = E_m / x^1{}_d$ A (peak), which decays away after a time of $4xT^1{}_d$ s, and

- For the steady-state current: $I_m = E_m / x_d$ A (peak).

The above currents are divided by $\sqrt{2}$ to calculate their rms values.

10.2 Equivalent circuit of the system for three-phase fault analysis

Balanced conditions are assumed for the analysis, i.e.

- generated voltages are equal in magnitude and displaced by 120 deg from one another (only positive sequence voltages are generated),

- transmission lines, loads, etc. are balanced (the parameters per phase are the same for all phases),

- at the fault point all three phases are shortened solidly together.

Under such conditions the single-phase equivalent circuit of the three-phase system from the generation to the fault location can be employed. This equivalent circuit is shown in Figure 10.3 in which E_G is the per-unit (pu) rms source voltage behind a source impedance Z_G (pu). The impedance Z_s (pu) is the effective system impedance from the generator terminals to the fault point.

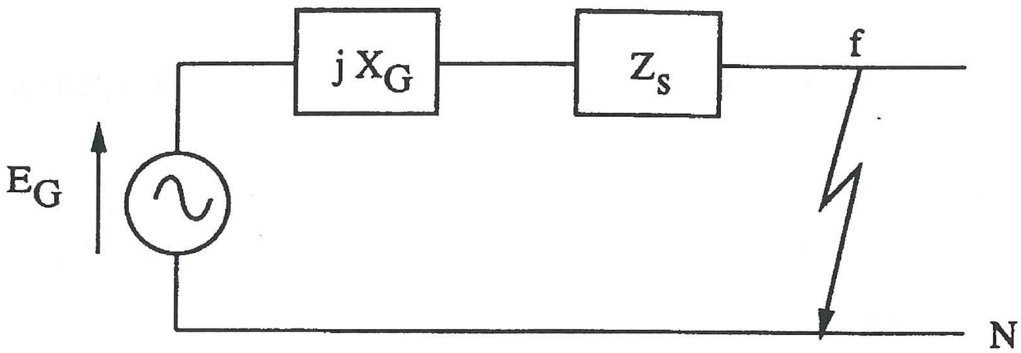


Figure 10.3: Single-phase equivalent circuit for three-phase fault studies

In the equivalent circuit, the choice of the source voltage and impedance is determined by the application or purpose for which the magnitude of the fault current is required. Generally the value of fault current is required in a period in which either the subtransient or the transient effects are pertinent. Typically, from the incidence of the fault to 3 to 5 cycles thereafter, the subtransient effects predominate. The subtransient impedance is chosen as the source impedance, and the voltage-behind-subtransient-reactance is selected as the source voltage, i.e.

$$Z_G = jx^{11}{}_d(pu), \text{and } E_G = E^{11} \text{ rms (pu).}$$

Similarly, if the fault period of interest is from 5 to about 10 cycles following the incidence of the fault, we choose

$$Z_G = jx^{1}{}_d(pu), \text{and } E_G = E^{1} \text{ rms (pu)}$$

because the transient effects are dominant. Note that the fault current is the maximum for the regime selected, i.e. the value prior to any decay in current, and is thus generally the 'worst case' condition for the associated analysis.

It should be noted that the subtransient and transient time constants are related to L/r ratios. For faults close to generators, $wL/r = X/r$ ratios are typically greater than the same ratio for remote faults. Because the time constants are longer, the subtransient and transient effects persist longer for close-up faults. Depending on the application of the fault study a simple calculation usually reveals the appropriate choice of generator reactance, $x^{11}{}_d$ or $x^1{}_d$.

10.3 Contributions to fault current from motors

The short-circuit current contribution from synchronous plant, be it a synchronous motor or compensator, behaves in an identical way to that from synchronous generators following a three-phase fault. However, because the X/r ratios are smaller, the current transient tends to decay to the steady state more rapidly.

Under three-phase fault conditions, induction motors also contribute to the fault current while the flux decays to zero or some low value. The flux decay is generally more rapid than for synchronous plant because the X/r ratio is relatively smaller. The subtransient reactance for the induction motor is approximately equal to its locked-rotor value. Because there is no closed field winding there is no 'transient' reactance.

10.4 Simplifying assumptions in fault analysis

A number of assumptions are usually adopted which simplify the fault calculations without prejudicing the results significantly. The assumptions are given below together with an explanation of the validity of the assumption.

- No-load conditions are assumed for the system; line capacitance and shunt reactance (from reactors or capacitor banks) are ignored.

  Under this assumption there is no current flow in the network prior to the incidence of the fault. Thus the magnitude and phase of *all* source voltages are the same at $1.0\underline{/0}$ pu. On the other hand, calculations based on a peak demand condition, say, would yield voltages-behind-reactance of greater than 1.0 pu with differing phase angles. The resulting currents, particularly for faults close to generation, are thus likely to be greater than those under this simplifying assumption. However, for faults close to major loads, the shunting effect of the load reduces the Thevenin equivalent source voltage that in turn reduces the value of the fault current, perhaps only marginally.

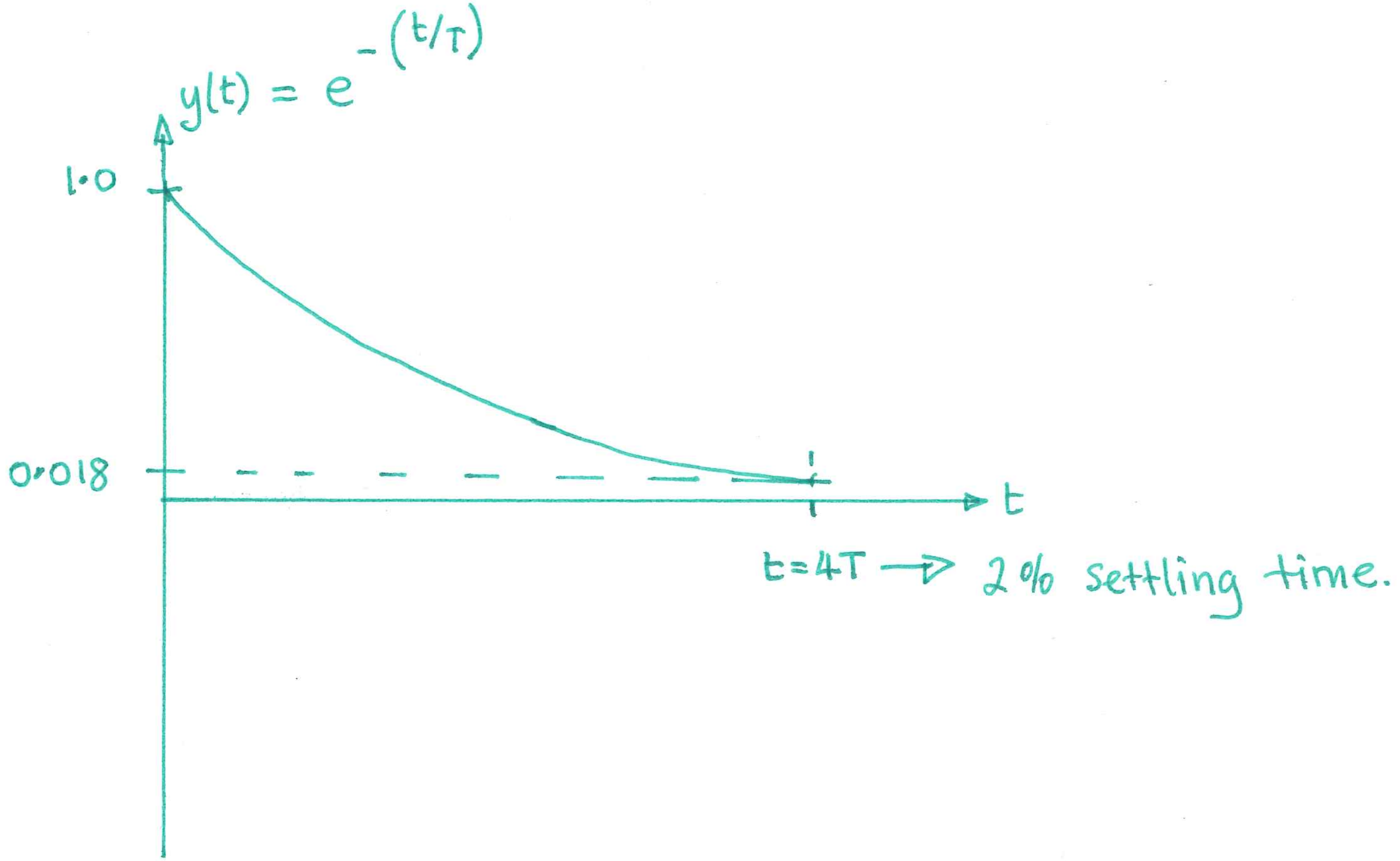
- The resistances of series elements, i.e. transmission lines and transformers, are neglected. This assumption is usually satisfactory at voltages of 66 kV and above for which the series reactance is greater than 5 times the resistance (recall $|Z|$ = $|(0.2+j1.0)|X = 1.02X$). The error in fault current is thus less than 2%; the series reactance typically is not known to this accuracy.

Often the value of the fault current calculated using the above assumptions is increased by a factor of more than 20%. This is to allow for any developments to the power system over the life-time of the component (e.g. a new circuit breaker) for which the fault analysis is being conducted. Under such circumstances, calculations of high accuracy are unnecessary.

10.5 Example

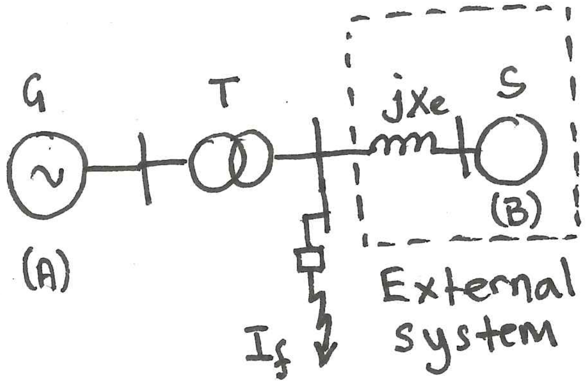
A simple example is used to illustrate the application of the simplifying assumptions and the method of calculation.

Calculate the fault current and the current infeeds for a three-phase fault on the line-side of the circuit breaker shown in Figure 10.4. Line impedances are given in per unit on 330 kV, 1000 MVA.


$y(t) = e^{-(t/T)}$
1·0
0·018
t
t=4T → 2% settling time.

Balanced Three Phase Fault Analysis – Example

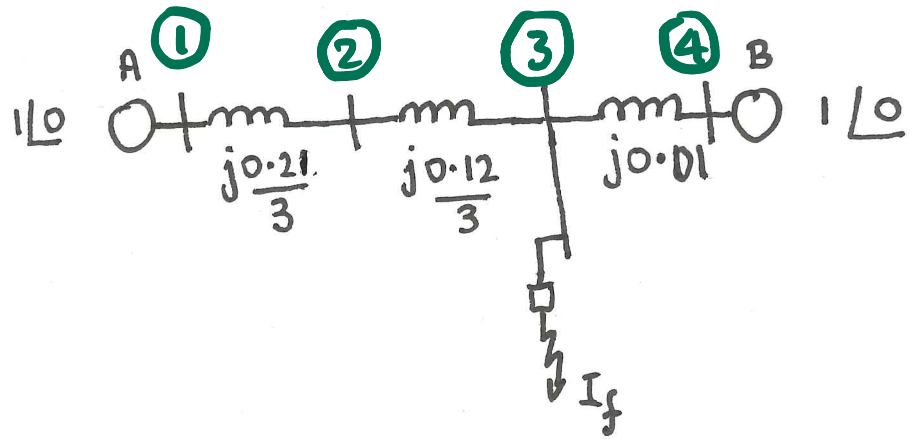
Network



G	$X_d'' = 0{\cdot}21$ pu on 300 MVA, 16 kV
T	$X_t = 0{\cdot}12$ pu on 300 MVA, 16/275 kV
X_e	$0{\cdot}01$ pu on 100 MVA 275 kV
S	ideal voltage source (no internal impedance)

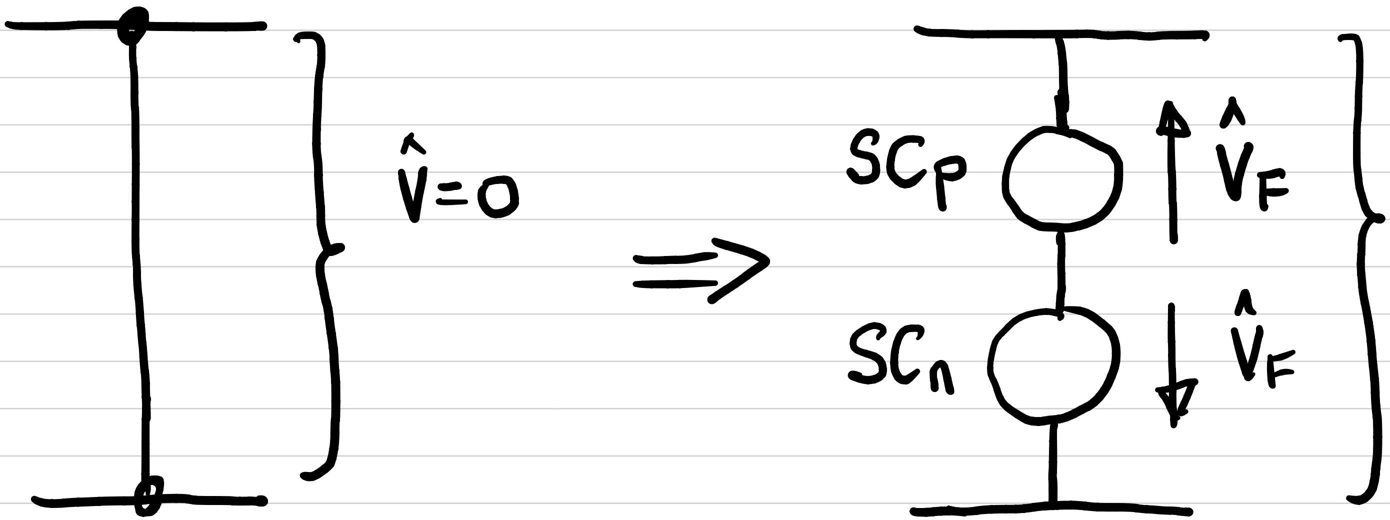
Construct network for fault analysis. Assumptions

- Network unloaded before fault
- All generators represented by voltage $1.0\angle 0$ behind impedance (jX_d'' or jX_d')
- Neglect resistance, shunt reactance, line capacitance



Balanced Three Phase Fault Analysis

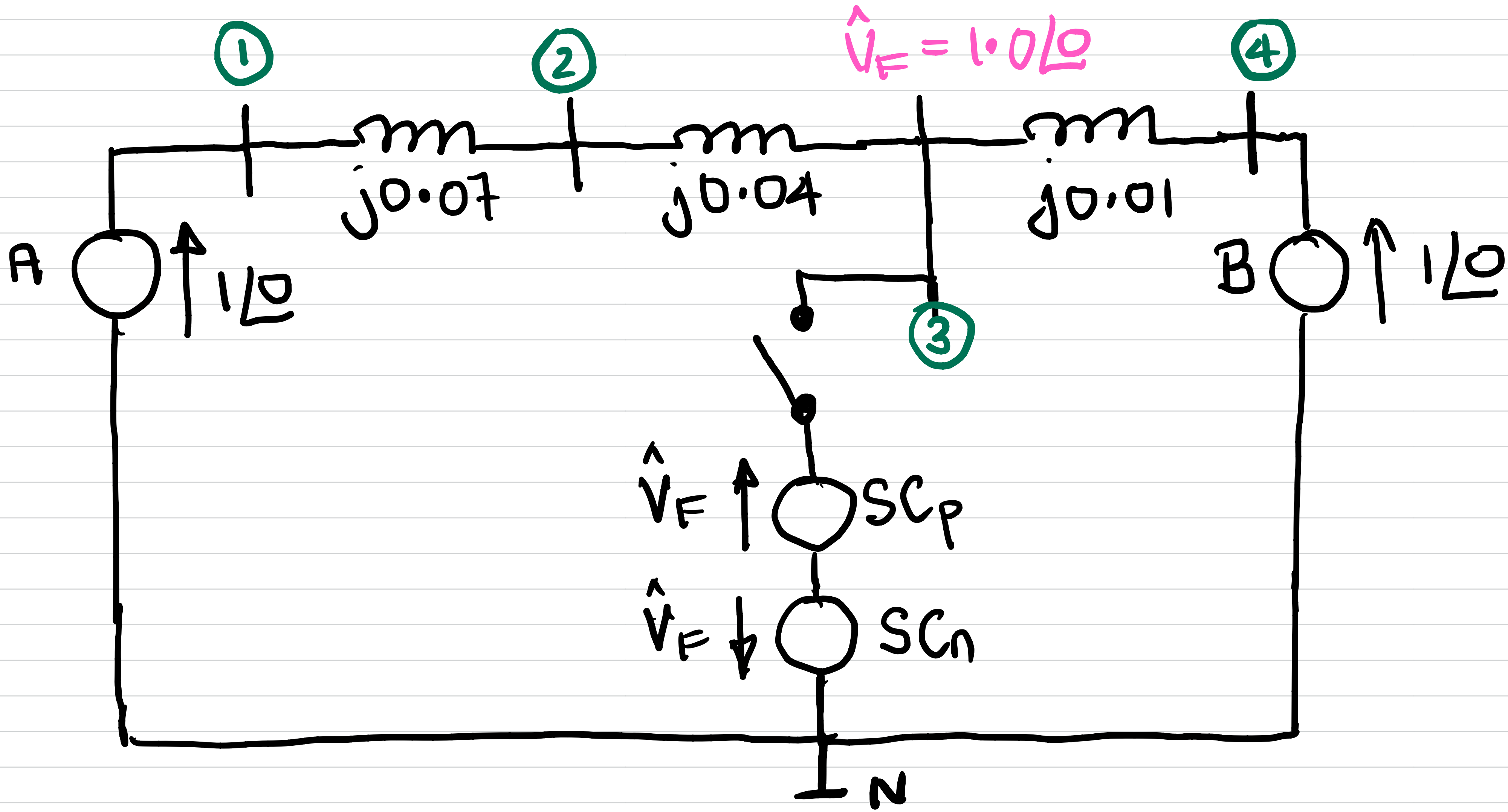
Representation of short circuit



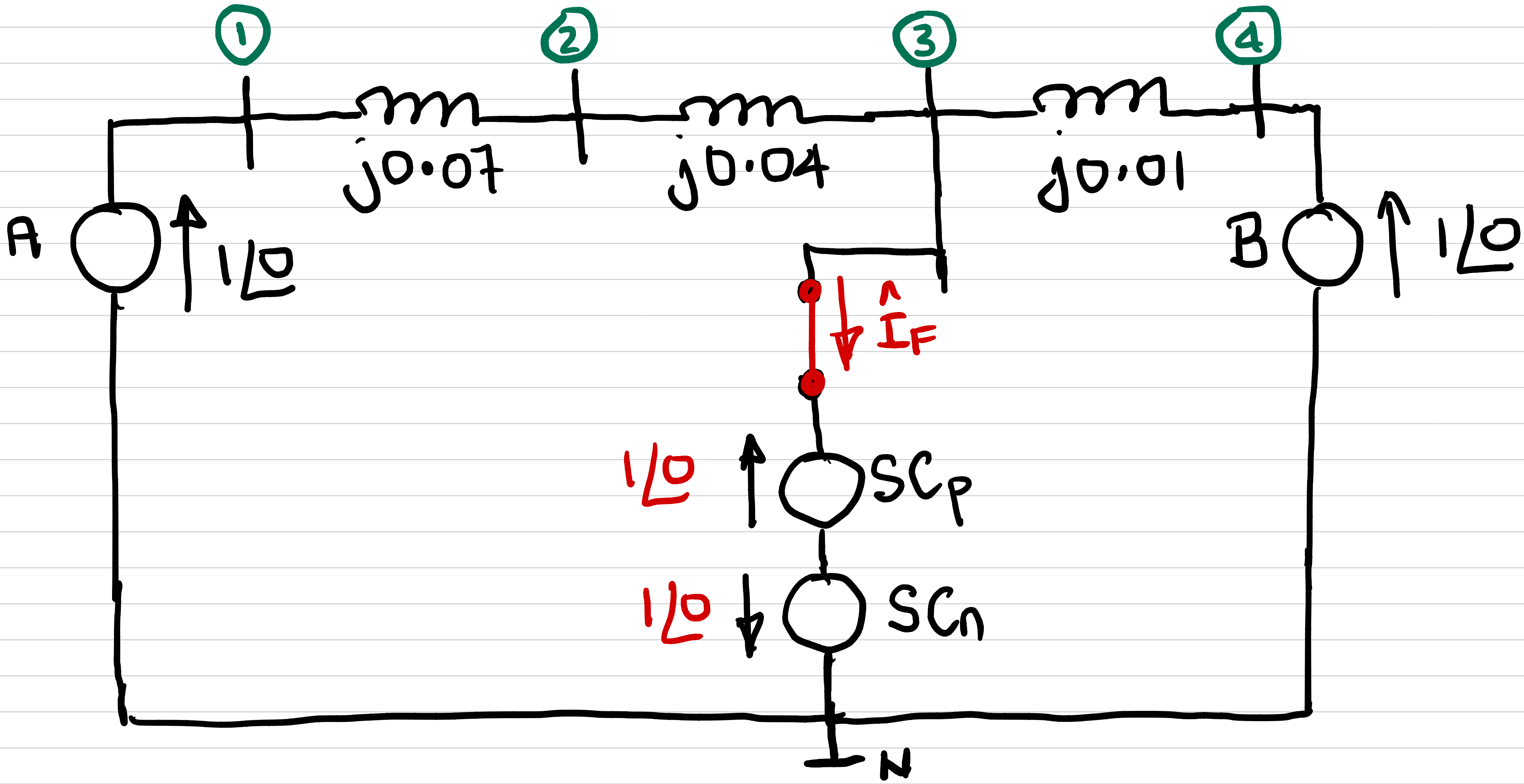
$$\hat{V} = \hat{V}_F - \hat{V}_F$$
$$= 0.$$

Equal and opposite voltage sources

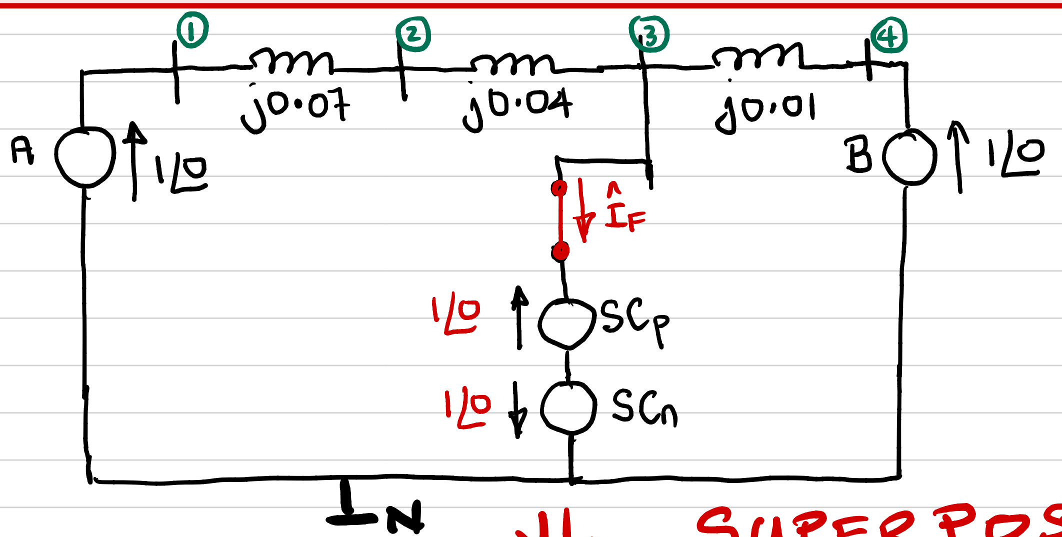
Balanced Three Phase Fault Analysis



Balanced Three Phase Fault Analysis

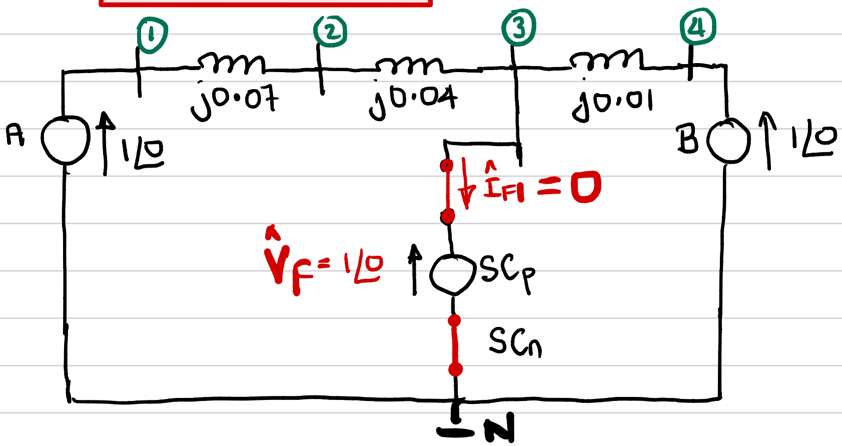


Balanced Three Phase Fault Analysis



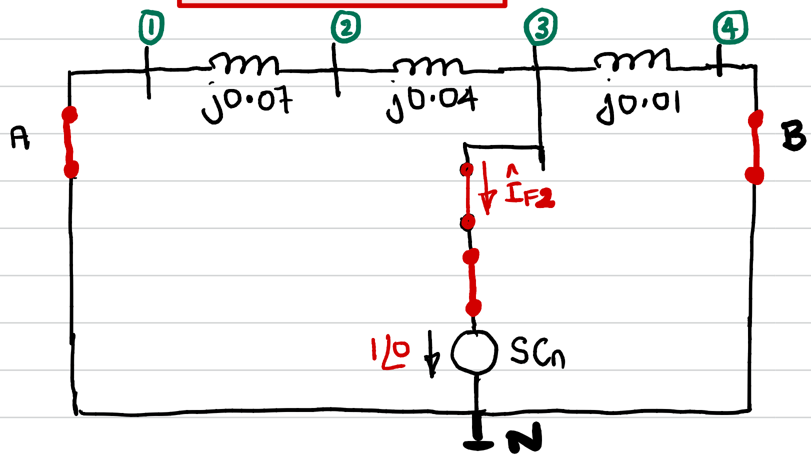
SUPERPOSITION

CIRCUIT 1



short-circuit source SC_n

CIRCUIT 2

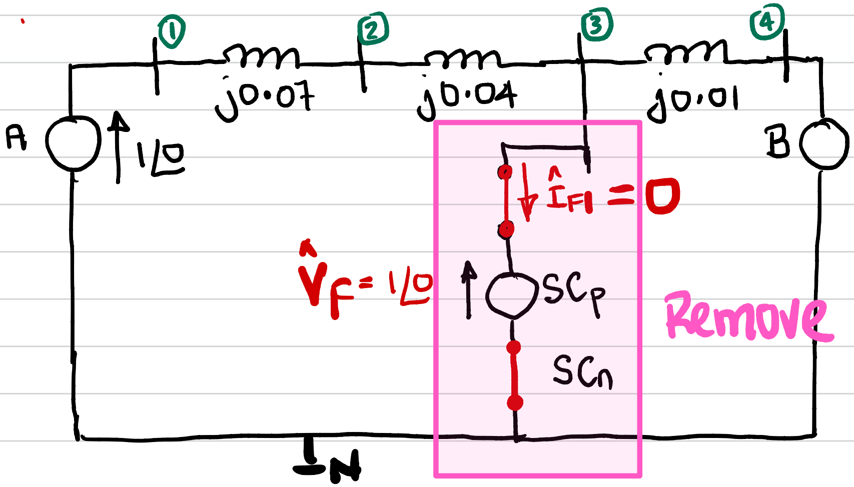


short circuit sources A, B, SC_p

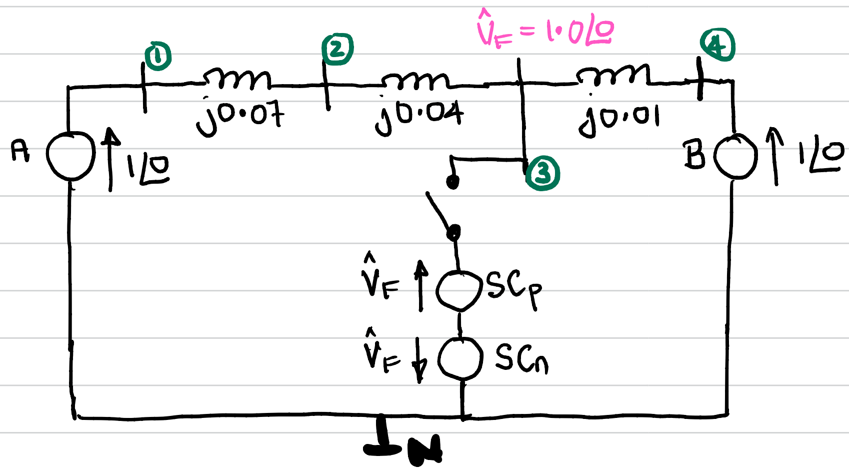
$$\hat{I}_F = \hat{I}_{F1} + \hat{I}_{F2} = \hat{I}_{F2}$$

Balanced Three Phase Fault Analysis

CIRCUIT 1



PREFAULT NETWORK

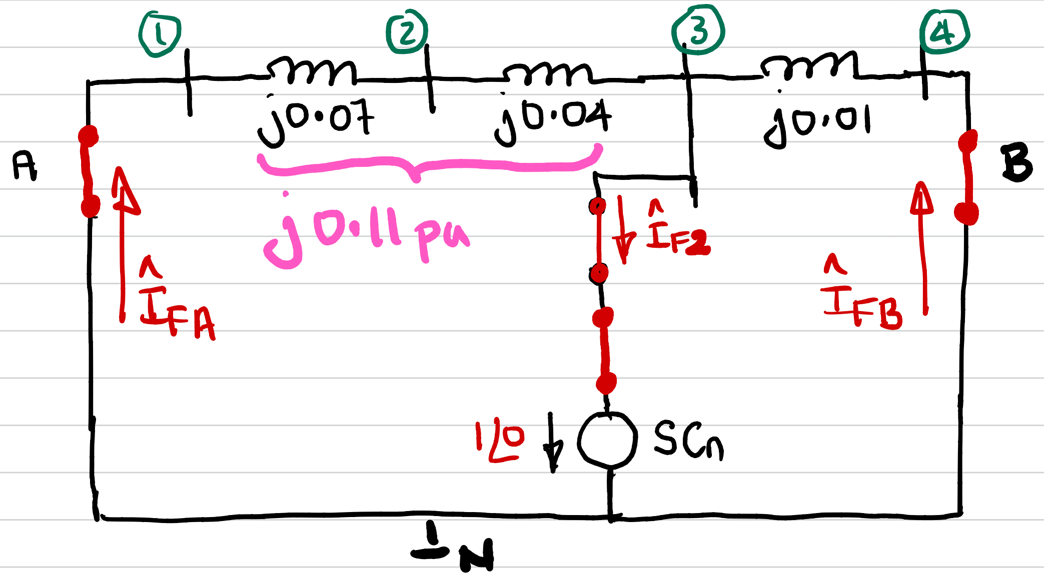


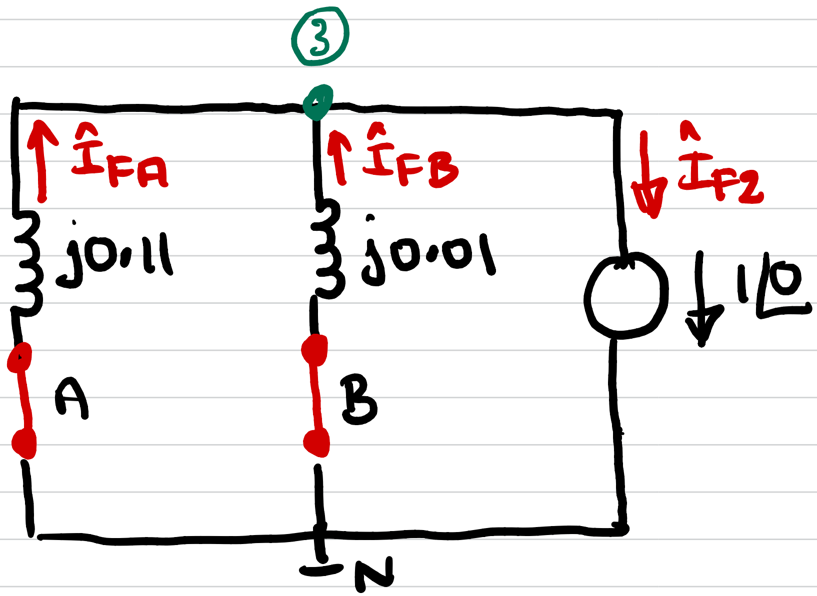
Since voltage of SCp $= \hat{V}_F = 1\angle 0$ which was the pre-fault voltage of the faulted node we can remove SCp without any change

Since $\hat{I}_{F1} = 0$ we only need to analyse circuit #2

Balanced Three Phase Fault Analysis

CIRCUIT 2





$$\hat{I}_F = \hat{I}_{F2} = \hat{I}_{FA} + \hat{I}_{FB}$$

$$\hat{I}_{FA} = \frac{1.0\angle 0}{j0.11} \qquad \hat{I}_{FB} = \frac{1.0\angle 0^\circ}{j0.01}$$

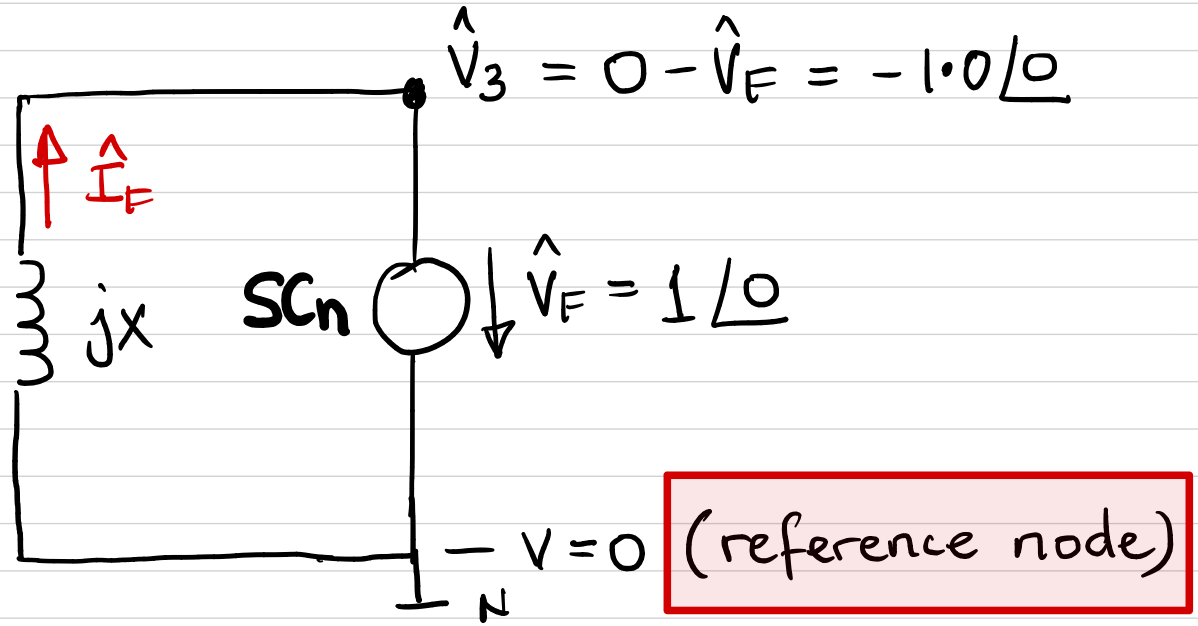
$$\hat{I}_{FA} = -j9.0909 \text{ pu} \qquad \hat{I}_{FB} = -j100 \text{ pu}$$

From Generator   From External System

$$\boxed{\hat{I}_F = -j109.1 \text{ pu}}$$

TEASING OUT THE FAULT CURRENT CALCULATION DUE TO THE NEGATED VOLTAGE SOURCE

REDUCED CIRCUIT #2



$$\hat{I}_F = \frac{-(\hat{V}_3 - 0)}{jX} = \frac{-\hat{V}_3}{jX} = \frac{-(-\hat{V}_F)}{jX} = \frac{\hat{V}_F}{jX}$$

Balanced Three Phase Fault Analysis - Example

Fault current components

$I_g = I_{fA} = \underline{-j9{\cdot}0909 \text{ pu}}$ ⟶ @ 16 kV node $-j9{\cdot}0909 \times 3{\cdot}6084 = \underline{-j32{\cdot}8 \text{ kA}}$

$I_s = I_{fB} = \underline{-j100}$ pu ⟶ @ 275 kV node $-j100 \times 209{\cdot}95 = \underline{-j21{\cdot}0 \text{ kA}}$

$I_f = I_{fA} + I_{fB} = \underline{-j109{\cdot}1 \text{ pu}}$ ⟶ @ 275 kV node $-j109{\cdot}1 \times 209{\cdot}95 = \underline{-j22{\cdot}91 \text{ kA}}$

I_{base} at 275 kV (rms, l-l)

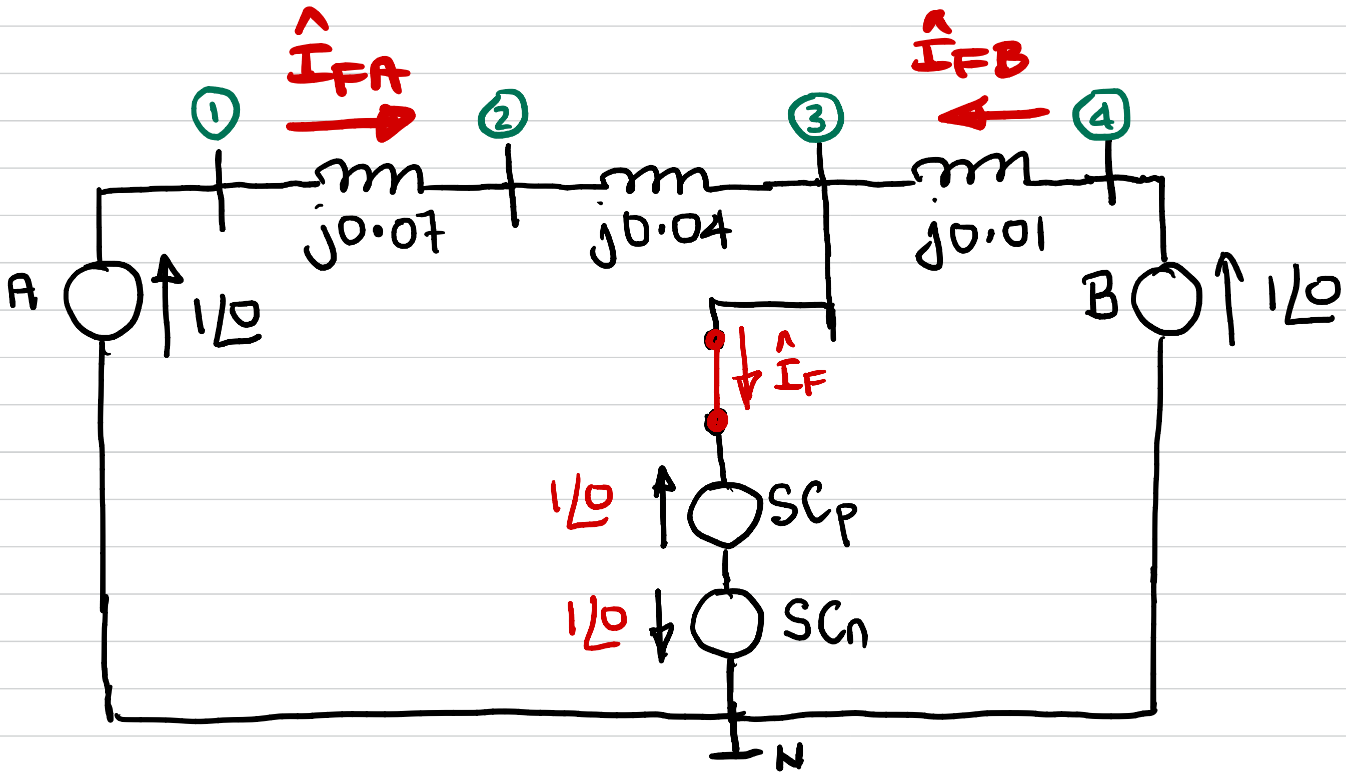
$$= \frac{100}{\sqrt{3} \times 275} \times 1000 = 209{\cdot}95 \text{ A}$$

I_{base} at 16 kV (rms, l-l)

$$= \frac{100}{\sqrt{3} \times 16} \times 1000 = 3608{\cdot}4 \text{ A}$$

Balanced Three Phase Fault Analysis

CALCULATE VOLTAGE AT NODE 2 DURING FAULT.



Return to the complete network

$$\hat{I}_{FA} = -j\,9{\cdot}0909 \text{ pu}$$

$$\hat{V}_2 = \hat{V}_A - j0{\cdot}07\,\hat{I}_{FA}$$

$$= 1{\cdot}0 - 0{\cdot}07 \times 9{\cdot}0909$$

$$\hat{V}_2 = 0{\cdot}3636 \text{ pu}$$

The base voltage of node 2 is 16 kV so $\hat{V}_2 = 16 \times 0{\cdot}3636$

$= 5{\cdot}818$ kV

(rms ph-ph)

Also, we confirm that the voltage of node 3 (the faulted bus) during the fault is zero.

$$\hat{V}_3 = 1.0 - j(0.07 + 0.04) \times \hat{I}_{FA}$$

$$= 1.0 - 0.11 \times 9.0909$$

$$= 0 \quad \text{as required.}$$

Furthermore

$$\hat{V}_3 = 1.0 - j0.01 \times \hat{I}_{FB} = 1.0 - 0.01 \times 100$$

$$= 0 \quad \text{as required.}$$

Balanced Three Phase Fault Analysis - Example

Fault level (S)

$$S = \sqrt{3} \times \underbrace{|V_{nom}|}_{\substack{l\text{-}l \text{ rms} \\ kV}} \times \underbrace{|I_f|}_{\substack{\text{rms} \\ kA}} \quad MVA$$

$$= \sqrt{3} \times 275 \times 22{\cdot}91$$

$$\underline{S = 10{,}910 \text{ MVA}}$$

$$S = \underbrace{|I_f|}_{pu} \times \text{MVA base}$$

$$= 109{\cdot}1 \times 100$$

$$\underline{S = 10{,}910 \text{ MVA}}$$

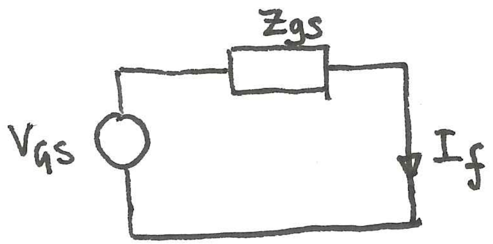
$$S = |I_f| \quad pu$$

$$\underline{S = 109{\cdot}1 \quad pu}$$

Balanced Three Phase Fault Analysis - Example

Fault level in pu at a busbar yields effective source impedance

$V_{gs} = 1.0$ pu, $I = I_f$

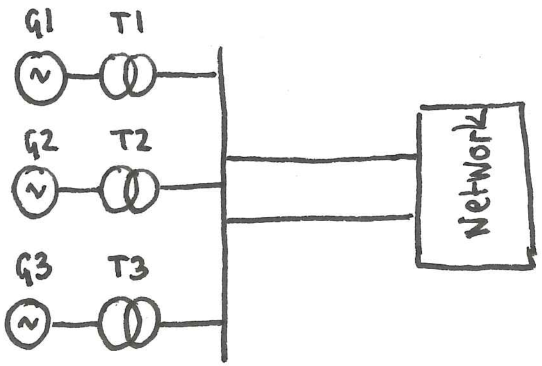


$$|Z_{gs}| = \frac{|V_{gs}|}{|I_f|} = \frac{|V_{gs}|^2}{|V_{gs} \times I_f|} = \frac{1}{S\ (pu)}$$

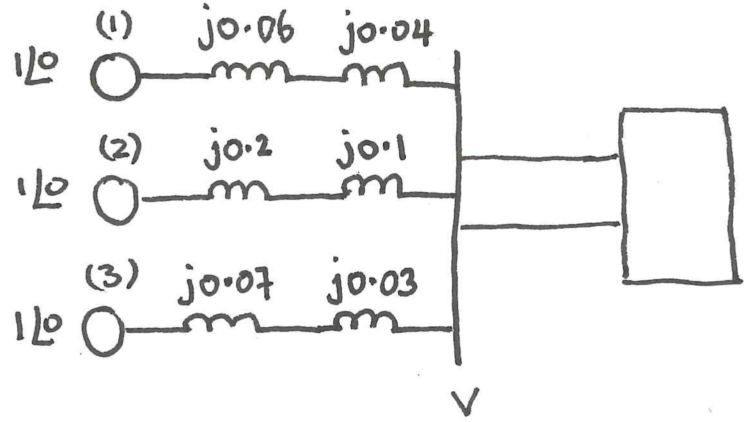
$$|Z_{gs}| = \frac{1}{109.1} = 0.00917 \text{ pu.}$$

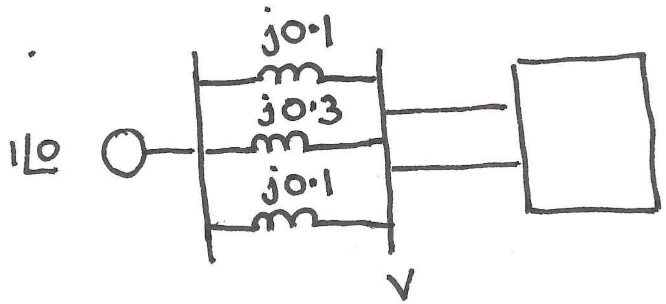
Balanced Three Phase Fault Analysis - Example

Parallel Generators



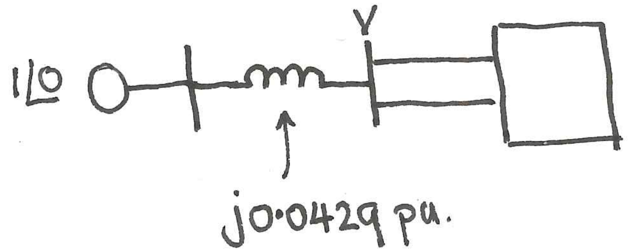
	G1/T1	G2/T2	G3/T3
X_d''	0·24	0·2	0·21
X_t	0·16	0·1	0·15
MVA base	400	100	300





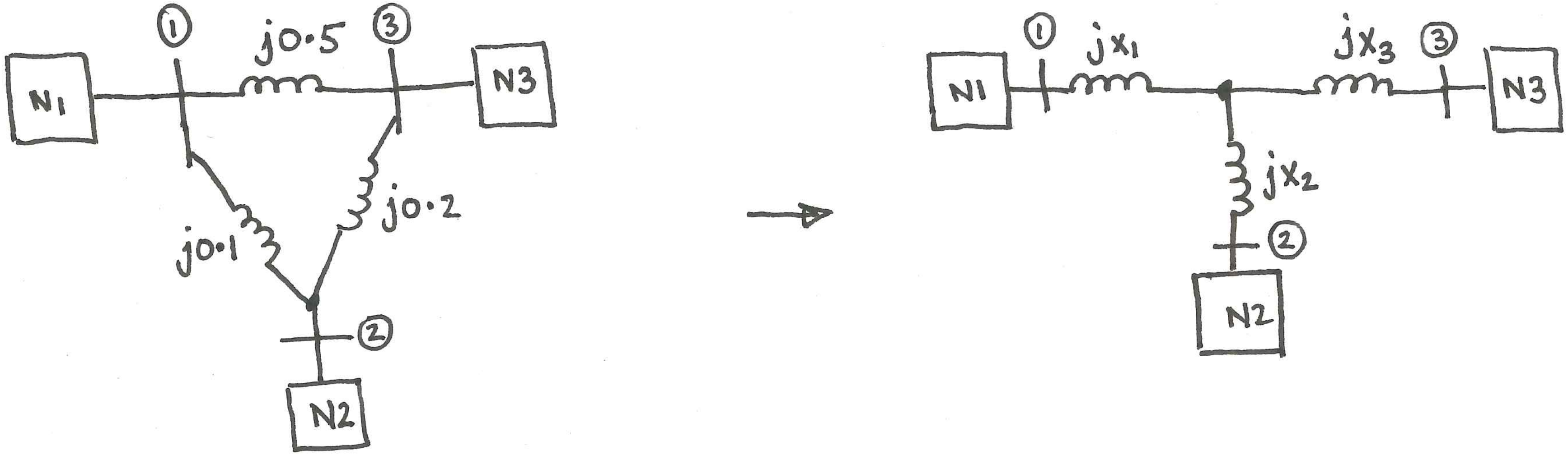
$$X_{eq} = \frac{1}{\frac{1}{j0 \cdot 1} + \frac{1}{j0 \cdot 3} + \frac{1}{j0 \cdot 1}}$$

$$= j0 \cdot 0429 \text{ pu}$$



Balanced Three Phase Fault Analysis - Example

Delta → Star transformation



$jX_{12} = j0{\cdot}1$

$jX_{23} = j0{\cdot}2$

$jX_{31} = j0{\cdot}5$

$X = X_{12} + X_{23} + X_{31}$

$= j0{\cdot}8$

$$jX_1 = \frac{(jX_{12})(jX_{31})}{jX} = j\,\frac{0{\cdot}1 * 0{\cdot}5}{0{\cdot}8} = j0{\cdot}0625\,pu$$

$$jX_2 = \frac{(jX_{23})(jX_{12})}{jX} = j0{\cdot}025\ pu$$

$$jX_3 = \frac{(jX_{31})(jX_{23})}{jX} = j0{\cdot}125\ pu$$

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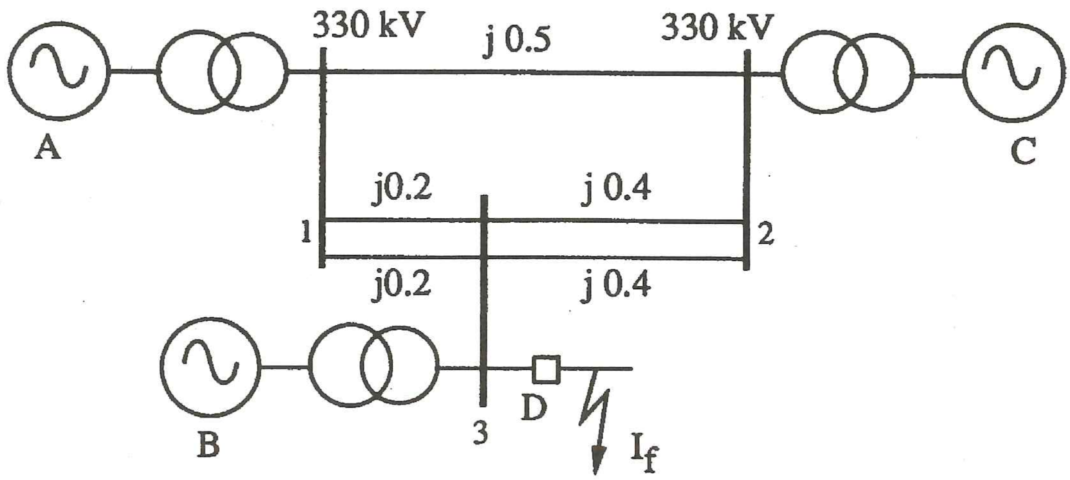


Figure 10.4: Power system

Station	No & Rating of generating units	$x^1{}_d$	x_t
A	2 x 250 MVA	28	12
B	4 x 100 MVA	32	12
C	2 x 4 MVA	35	8

Table 10.2 Parameters of generators. (Reactances in % on rating)

Let us select 1000 MVA as the system base MVA and convert the reactances, given on unit ratings, to values on the system base MVA.

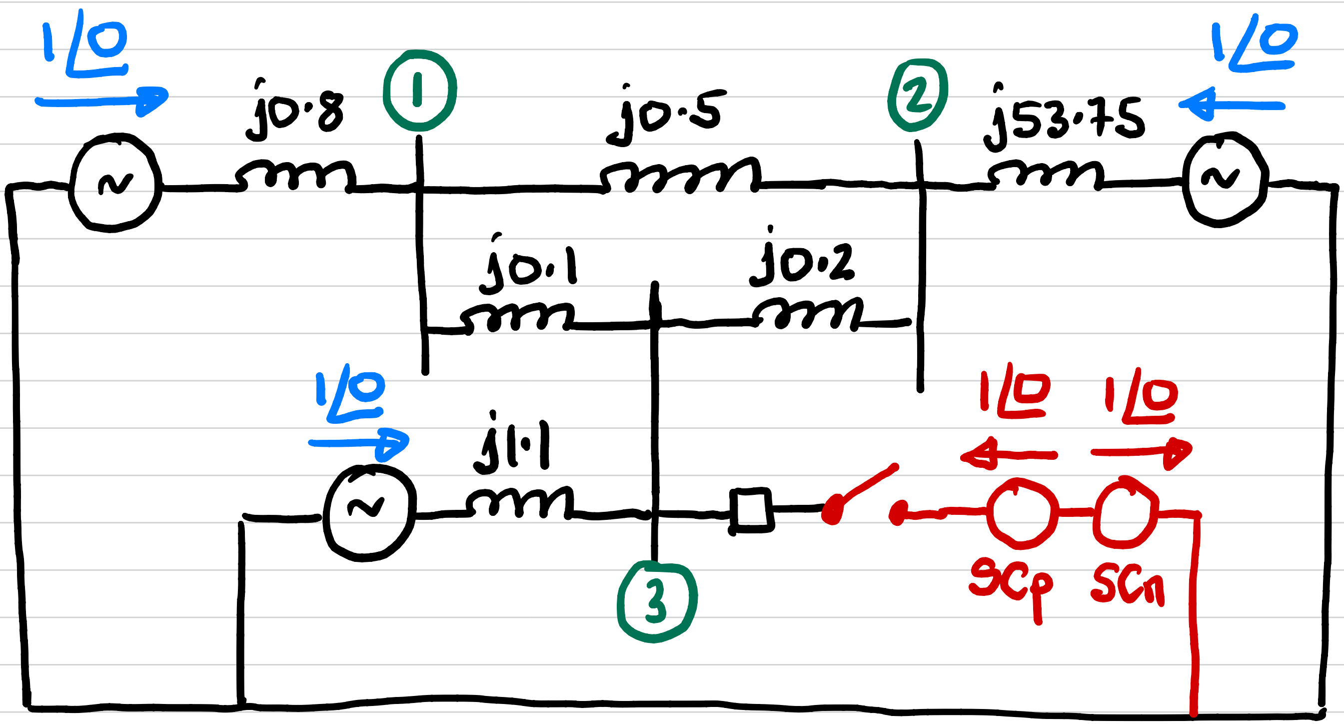
The sum of the generator transient reactance and transformer leakage reactance is:

Station A: (0.28 + 0.12) = 0.40 pu on 250 MVA for 1 unit
1.60 pu on 1000 MVA for 1 unit
0.80 pu on 1000 MVA for 2 units

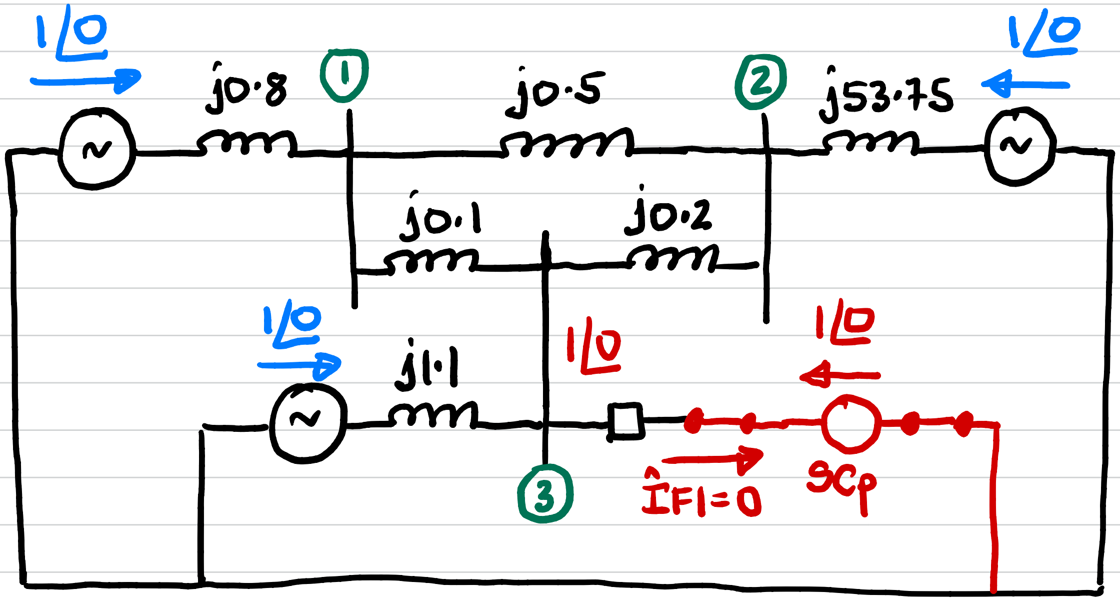
Station B: (0.32 + 0.12) = 0.44 pu on 100 MVA for 1 unit
1.10 pu on 1000 MVA for 4 units

Station C. (0.35 + 0.08) = 0.43 pu on 4 MVA for 1 unit
53.75 pu on 1000 MVA for 2 units

PRE-FAULT NETWORK DIAGRAM FOR FAULT ANALYSIS



Network diagram $\triangleq$ Impedance diagram

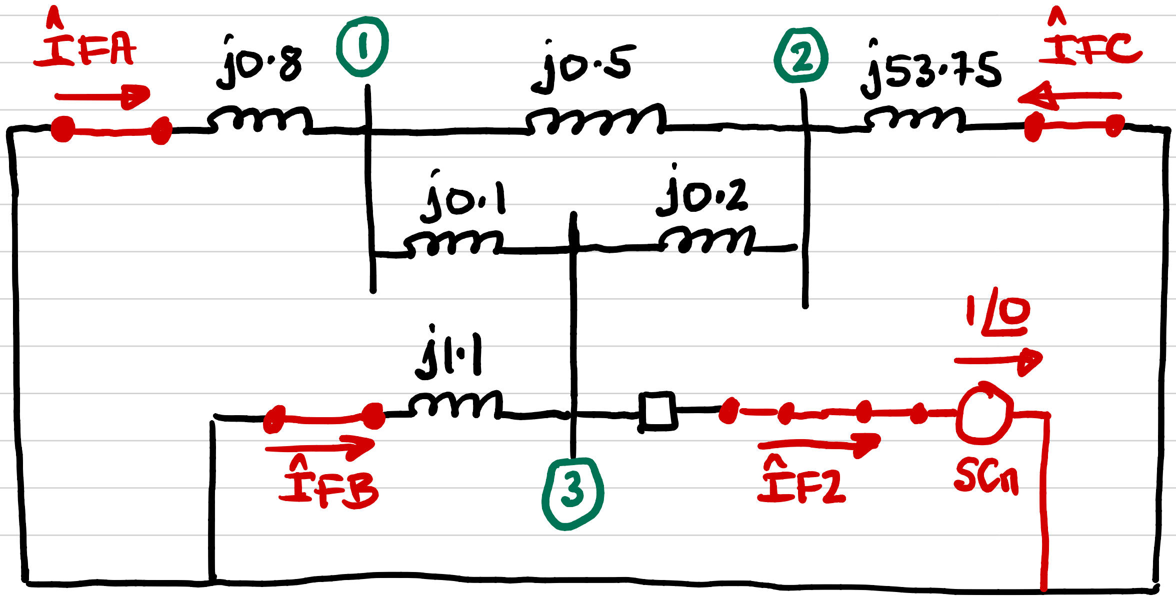


← **CIRCUIT 1**

(Equivalent to pre-fault network)

We can neglect Circuit 1 for fault current calculation purposes

CIRCUIT 2 →

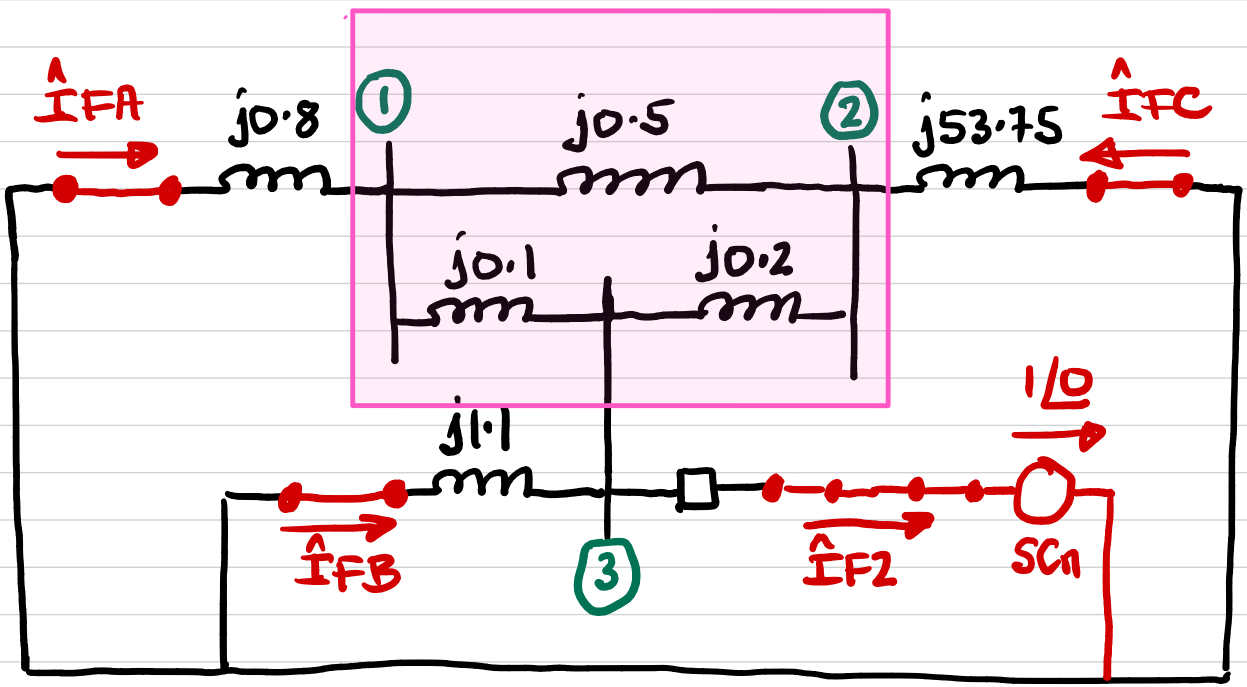


Total fault current

$$\hat{I}_F = \underset{\substack{\parallel \\ 0}}{\hat{I}_{F1}} + \hat{I}_{F2} = \hat{I}_{F2}$$

ANALYSE CIRCUIT 2 TO CALCULATE FAULT CURRENT

DELTA CONNECTION



$jx_{12} = j0.5$ pu

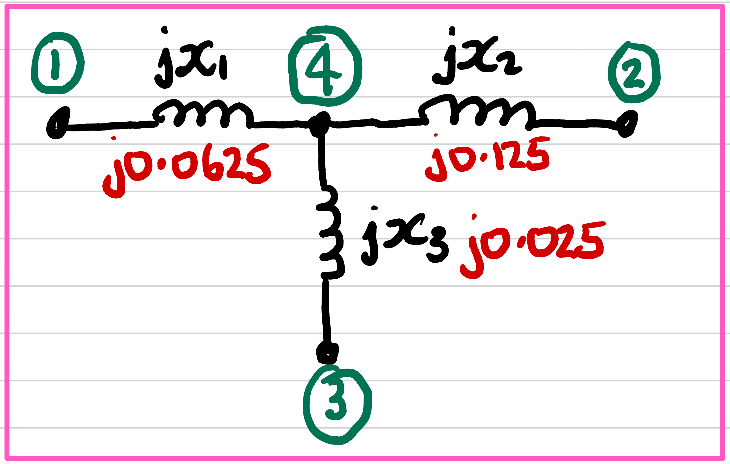
$jx_{23} = j0.2$ pu

$jx_{31} = j0.1$ pu

$jx = jx_{12} + jx_{23} + jx_{31}$

$= j0.8$

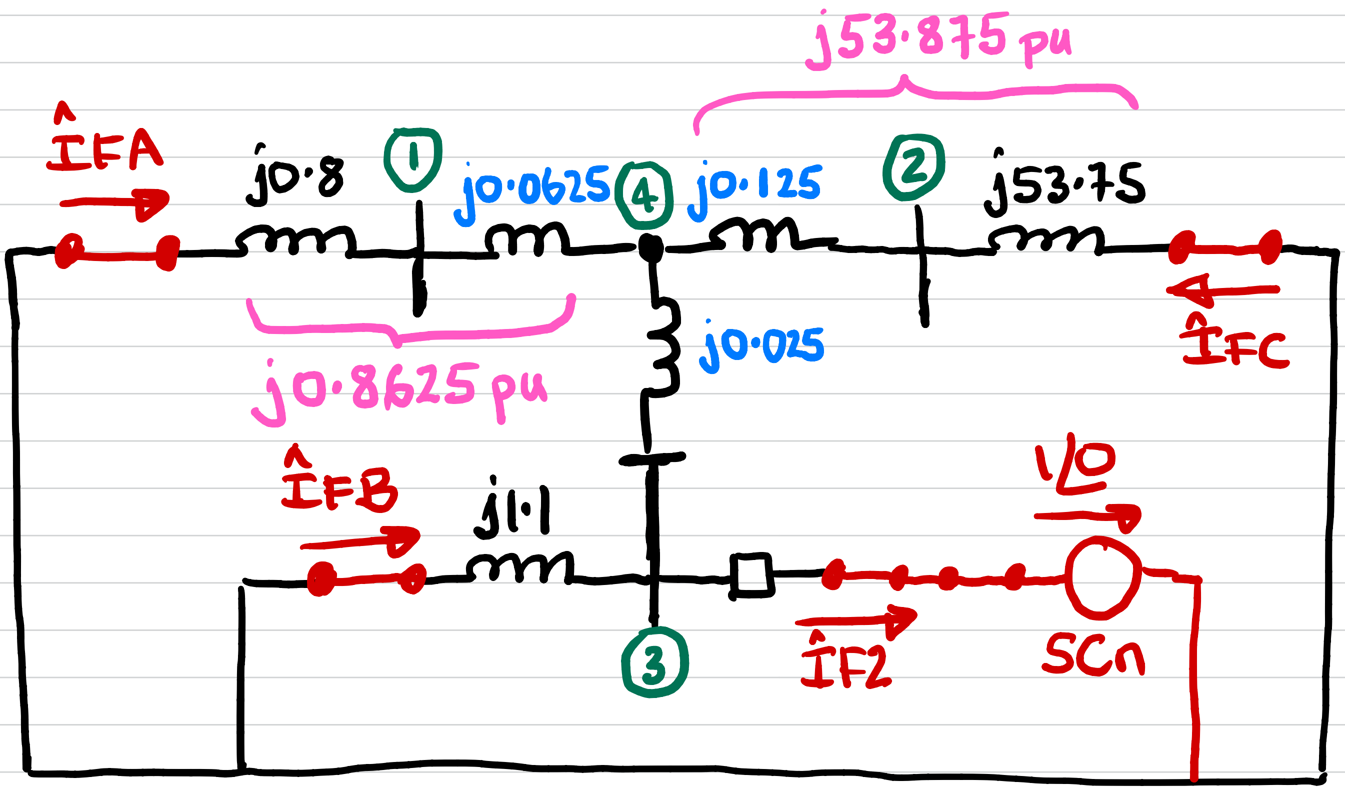
STAR EQUIVALENT

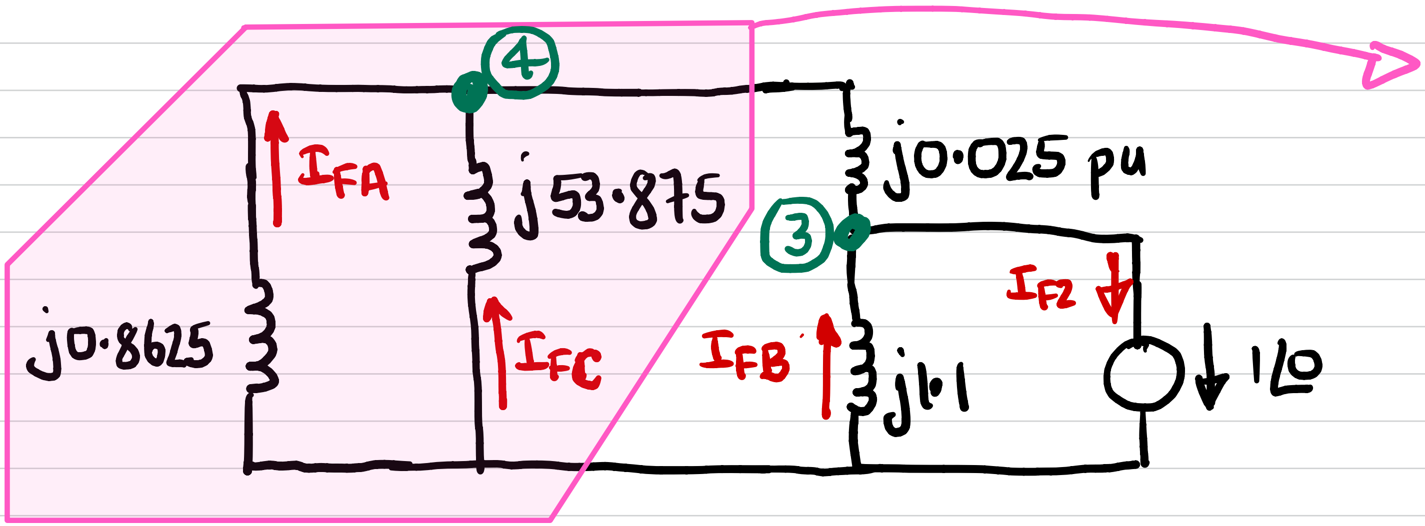


$jx_1 = (jx_{12}\, jx_{31})/jx = j0.0625$ pu

$jx_2 = (jx_{12}\, jx_{23})/jx = j0.125$ pu

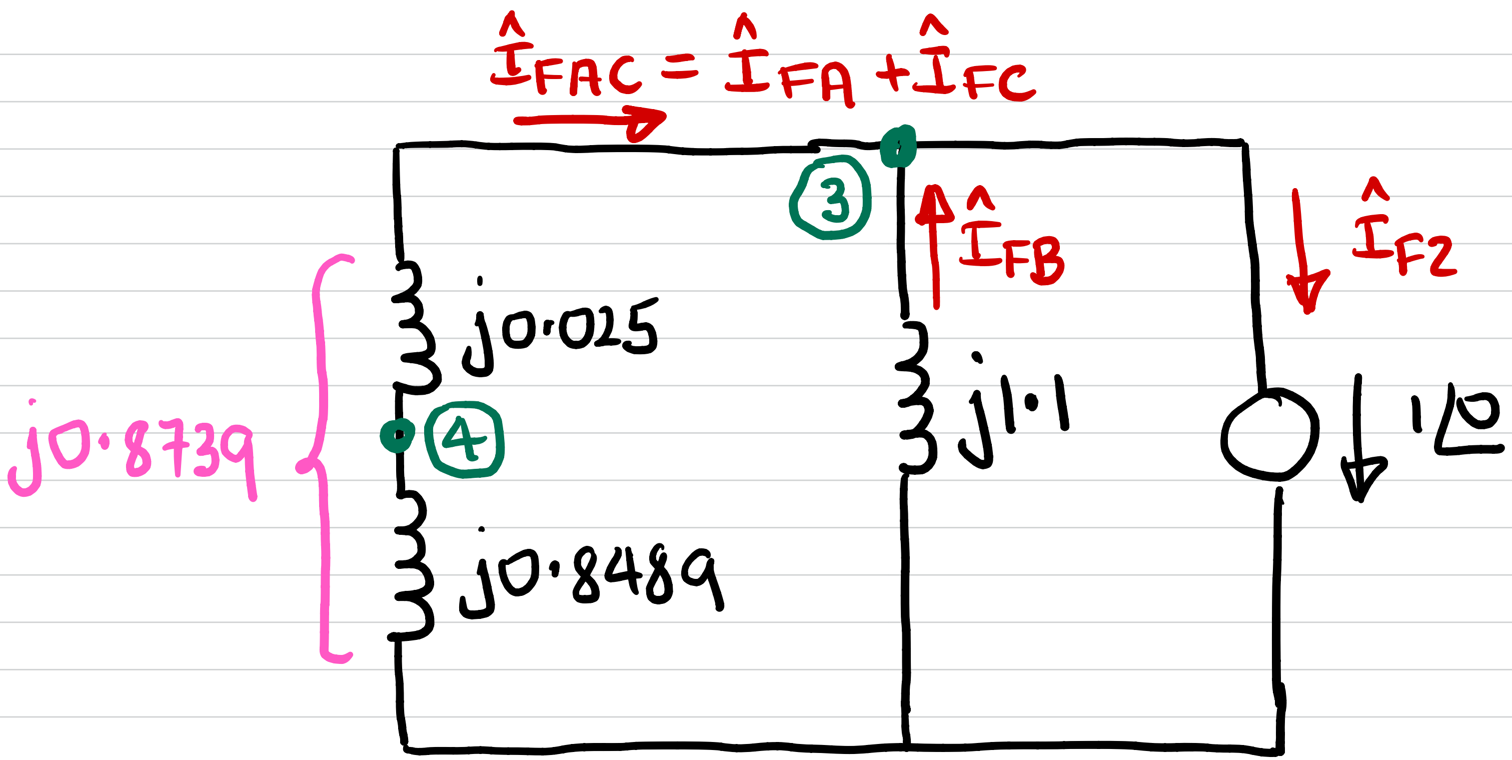
$jx_3 = (jx_{23}\, jx_{31})/jx = j0.025$ pu





PARALLEL

$$j\frac{53.875 * 0.8625}{53.875 + 0.8625} = j0.8489 \text{ pu}$$



$$\hat{I}_{FB} = \frac{1\angle 0}{j1{\cdot}1} = -j0{\cdot}9091 \text{ pu}$$

$$\hat{I}_{FAC} = \frac{1\angle 0}{j(0{\cdot}025 + 0{\cdot}8489)} = -j1{\cdot}1443 \text{ pu}$$

$$\hat{I}_{F2} = I_{FAC} + I_{FB} = -j2{\cdot}0534 \text{ pu} = \hat{I}_F$$

We can calculate $\hat{I}_{FA}$ and $\hat{I}_{FC}$

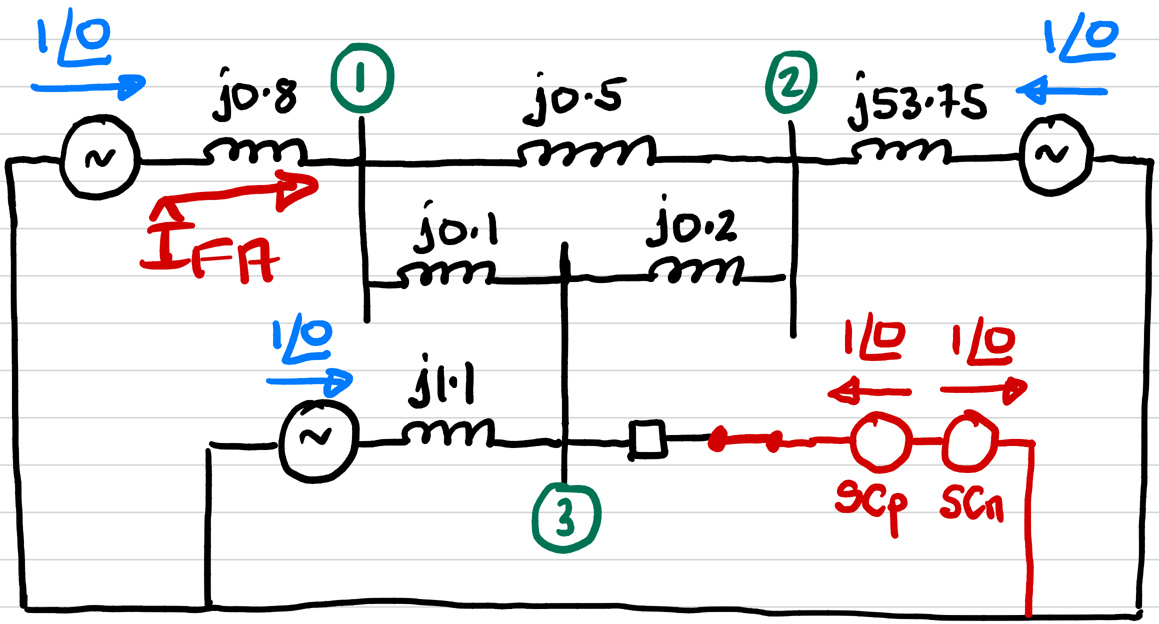
$$\hat{I}_{FA} = \frac{-\hat{V}_4}{j0{\cdot}8625} \qquad \hat{I}_{FC} = \frac{-\hat{V}_4}{j53{\cdot}875} \qquad \hat{V}_4 = -j0{\cdot}8489\,\hat{I}_{FAC}$$

$$\therefore \hat{I}_{FA} = \frac{0{\cdot}8489}{0{\cdot}8625} \times \hat{I}_{FAC} = 0{\cdot}9842 \times \hat{I}_{FAC}$$

$$= -j1{\cdot}1263 \text{ pu}$$

$$\hat{I}_{FC} = \hat{I}_{FAC} - \hat{I}_{FA} = -j0{\cdot}0180 \text{ pu}$$

CALCULATE THE VOLTAGE AT NODE 1 DURING THE FAULT.



Return to complete circuit diagram.

$$\hat{V}_1 = 1 - j0{\cdot}8 \times \hat{I}_{FA}$$

$$= 1 - j0{\cdot}8 \times (-j1{\cdot}1263)$$

$$= 1 - 0{\cdot}9010$$

$$\underline{\hat{V}_1 = 0{\cdot}0990 \text{ pu}}$$

ALTERNATIVE METHOD

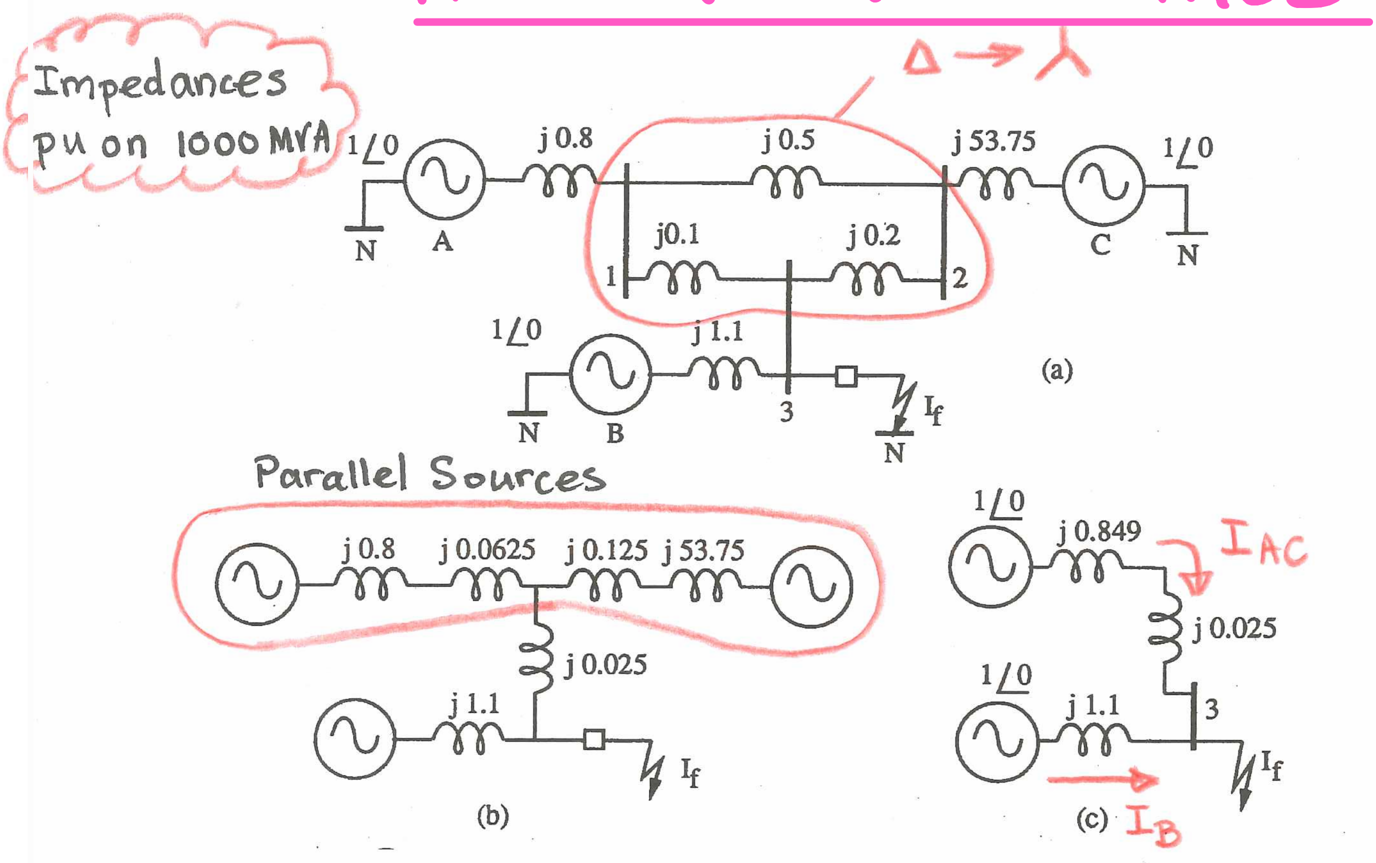


Figure 10.5: (a) System impedance diagram, (b) after delta-star transformation, (c) reduced network

The impedance diagram for the system is shown in Figure 10.5 (a). The delta arrangement of impedances between buses 1, 2 and 3 is replaced by the equivalent star connection (see the Appendix for the delta-to-star- transformation). The impedance diagram is modified as shown in Figure 10.5 (b). Because all generated voltages are $1.0\underline{/0}$ pu, the two sources of stations A and C are replaced by a common source of the same voltage, and the resulting parallel impedance replaced by an equivalent impedance; this is shown in Figure 10.5 (c). The current infeed, $\underline{I}_{AC}$, to the fault from stations A and C, and that from station B, I_B are respectively:

$$\underline{I}_{AC} = 1\underline{/0}/\,j0.874 = 1.144\underline{/-90} \text{ pu,} \quad \text{and}$$

$$\underline{I}_B = 1\underline{/0}\; j1.1 = 0.909\,\underline{/-90} \text{ pu,}$$

The fault current is $\underline{I}_f = \underline{I}_{AC} + \underline{I}_B = 2.053\underline{/-90}$ pu. The base current is

$$I_{base} = 1000\times10^6/(\sqrt{3}\times330\times10^3) = 1750A. \quad \text{(@ 330 kV bus)}$$

Hence the magnitude of the fault current is 2.053 x 1750 = 3572 A. = I_f

10.6 Three-phase fault level

The fault level, in VA, at any point in a power system is defined as

$$\sqrt{3}\times|\text{nominal system voltage (V l-l) at fault location}|\times$$
$$\times|\text{fault current (A)}|$$

In per-unit the fault level is

$$|\text{nominal voltage (pu)}| \text{ x } |\text{fault current (pu)}|$$

In Example 10.5 the fault is for all intents and purposes on bus 3. The fault level at bus 3 is therefore

$$S = \sqrt{3}\times330\times10^3\times3592 = 2053\text{ MVA, or in pu,}$$
$$1.0 \quad \text{pu voltage x 2.053 pu current} = 2.053 \text{ pu MVA.}$$

A useful feature of the concept of fault level is that its pu value at a busbar yields the value of the effective source impedance, Z_{Gs}. If a voltage source V_{Gs} of 1 pu were connected through this impedance to the faulted busbar the calculated value of fault current $\underline{I}_f$ would result. The value of the source impedance in pu is

$$|Z_{Gs}| = |V_{Gs}|/|\underline{I}_f| = V_{Gs}^2/(|V_{Gs}\underline{I}_f|) = 1/(\text{fault level in pu})$$

when $V_{Gs} = 1$ pu. In the case of Example 10.5 the source reactance is Z_{Gs} = 1 / 2.053 = 0.487 pu. Knowledge of fault levels at busbars is required for example, in the calculation of the voltage dip on the starting of an induction motor.

10.8 Applications of fault analysis

Fault analysis is commonly used in the following studies or applications:

- The calculation of forces on windings, busbars and conductors which carry fault current.
- The determination of the interrupting or breaking capacity of circuit breakers.
- The calculation of current and voltage levels under fault conditions to establish the settings for protection equipment.
- The calculation of earth currents and earth potential rise.
- Interference with communication systems.

With the exception of protection and interference we shall discuss these topics briefly.

10.9 Calculation of short-circuit forces

The force acting of a current-carrying conductor is the result of the interaction of the current and the magnetic field in which it lies. The magnitude of the forces between conductors carrying fault current can be very large. Recall that the force f between two long, parallel conductors, distance d m apart in air, carrying current is i_1 and i_2, is

$$f = \mu_0 \, i_1 \, i_2 \, / (2\pi d) \quad \text{Newton/metre}$$

If the currents flow in the opposite directions in the conductors, the force acts to move them apart – and vice-versa when current flow in the same direction. An alternative view-point is that the short-circuit forces act to reduce the reluctance of the magnetic circuit. For example, if free to do so (the bracing and clamping having failed), transformer coils are compressed together and are expanded in diameter (… they unwind!).

In order to design the mechanical structures containing or supporting the conductors, the maximum short-circuit forces are required. These occur when the instantaneous current is a maximum i.e. during the first half-cycle. Thus in the calculation of the fault current the subtransient reactance is used; the dc offset may be included as well.

10.10 The interrupting capacity of circuit breakers

Following the incidence of the fault, the protection typically takes 1 to 2 cycles to initiate the signal to trip the circuit breaker. As the poles of the circuit breaker part an arc is established which is interrupted only at a current zero. The arc will be re-established if the ionised products from the earlier arcing have not been purged. Arcing may thus continue over several half-cycles of the current waveform until it is finally interrupted. The events that occur during the clearing of three-phase fault current are illustrated in Figure 10.6.

Typically, for high-voltage circuit breakers, the clearing of faults occurs in 3 to 5 cycles from the incidence of the fault. For the purpose of specifying the interrupting capacity of the breaker, the relevant a.c. and d.c. components of current are those at the instant that the breaker contacts separate. The d.c. component is specified as the ratio of the d.c. current to the r.m.s. value of the a.c. component, expressed in percent.

The interrupting capacity of a circuit breaker, also known as the rated short-circuit breaking current, is defined in the Australian Standard [2] as the highest a.c. component of the three-phase short-circuit current which it shall be capable of breaking. The Standard also states that the breaker should be capable of interrupting "… any short-circuit breaking up to its rated short-circuit breaking current containing any a.c. component up to the rated value and associated with it any percentage d.c. component up to that specified….".

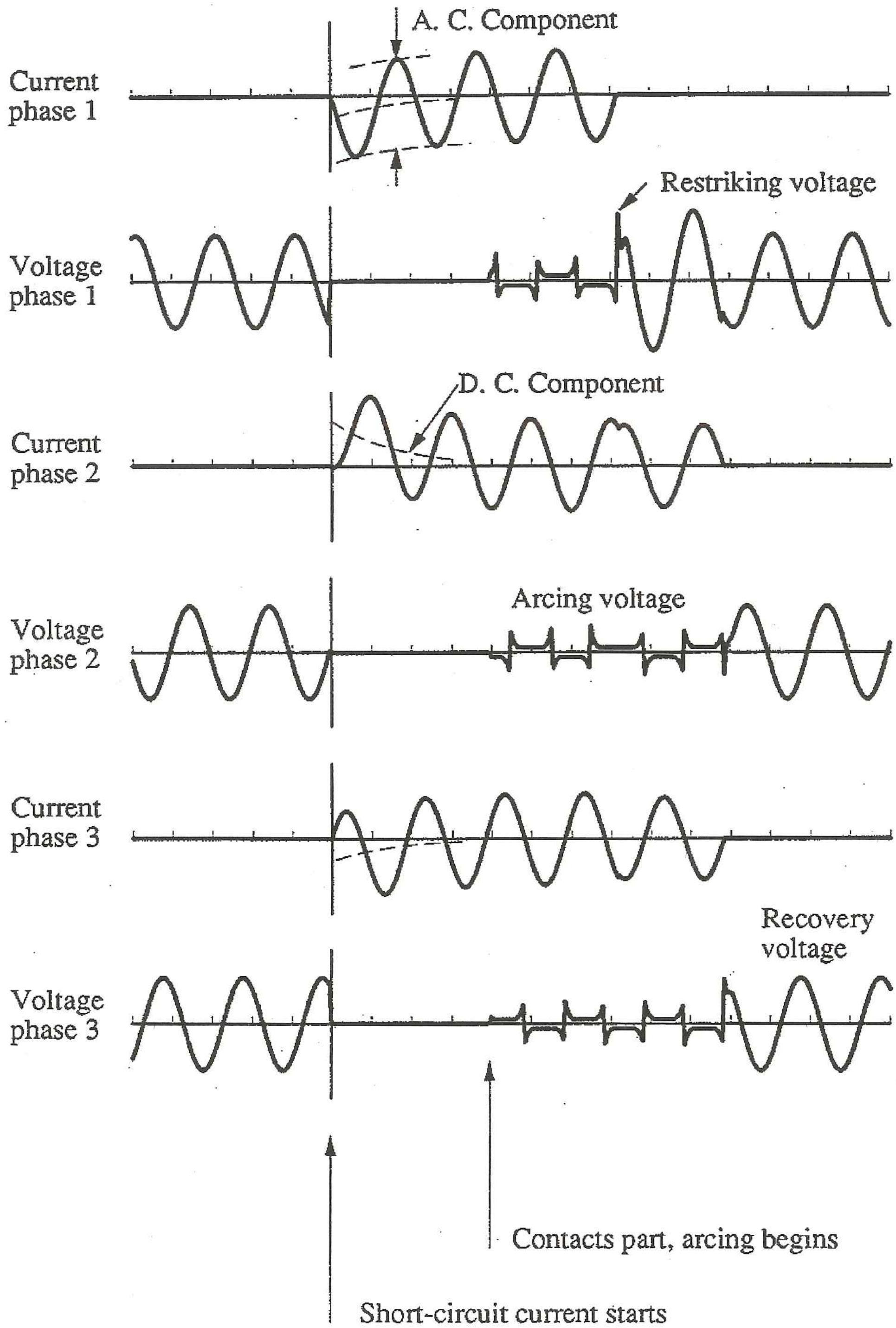


Figure 10.6: Typical three-phase fault current and voltage waveforms during the operation of a circuit breaker.
Note: Time markers are shown at 10 ms intervals. The arc voltages have been exaggerated for illustrative purposes; arcing times are normally less than 20 ms.
(With acknowledgement to A/Prof. A.D. Stokes, Uni of Sydney)

10.10.1 Example

For the system described in Example 10.5 the subtransient reactance of each machine is 16% on rating. Determine the interrupting capacity of the breaker D given that the X/r ratio is 40 and the protection operating time is 2 cycles of the 50 Hz supply.

The time constant for the decay of the subtransient component of fault current is $L/r = (X/r)/(2\pi f) = 0.127$ s or about 6 cycles. The breaker is likely to have cleared the fault within 5 cycles of its incidence and thus the use of the subtransient reactance for the calculations is appropriate.

Carrying out a calculation similar to that in example 10.5, using subtransient rather than transient reactances for the generators, we find the three-phase short-circuit current that the circuit breaker is required to interrupt is 5260 A rms. According to [2] we can select the rated breaking current to be either 6.3 or 8 kA.

The value of the dc component 2 cycles after the incidence of the fault is

$$I_{dc} = I_{ac(peak)} \exp(-rt/L) = \sqrt{2} \text{ x } 5260 \exp(-\frac{2\pi 50}{40} t)$$
$$= 7430 \text{ x } 0.730 = 5430 \text{ A},$$

where $t = 2/50 = \overset{0.04}{\cancel{0.40}}$ s. The percentage dc component for the circuit breaker is thus specified to be

$$(I_{dc} / I_{ac(peak)}) \times 100 = 73\%.$$

10.11 Earth currents and earth potential rise

Because earth currents do not exist for solid three-phase faults between conductors this topic, strictly speaking, is out of context.

However, it is an important application of asymmetrical fault analysis that is covered in reference texts.

When single – or two-phase to ground faults occur, fault current flows through an earth-return path which has finite resistance or impedance. Earth is typically a poor conductor; rock clearly has a very high resistivity while marshy soil possesses a low value.

When fault current enters the earth at the surface, say through a conducting rod (of negligible impedance) driven a short distance into the ground, it is constrained to flow through a channel of a small diameter. Let us assume that the earth resistivity is uniform to a depth that the earth current flows. As the current penetrates the earth from the rod it flows a right angles to an equi-potential surface as shown in Figure 10.7. This surface is a hemisphere of radius R. As R increases the current density decreases and the volt-drop per metre (the voltage gradient) along the radius line falls. Because the hemi-spherical equi-potential surfaces reach the earth's surface, there is a voltage drop from the conducting rod radially outwards along the earth's surface, as shown in Figure 10.7. The volt-drop is with respect to 'remote' earth, a zero potential surface.

The voltage at the rod is called the earth-potential rise and the voltage drop per unit length along the earth's surface is called the earth-potential gradient. The 'earth resistance' of the rod, with respect to remote earth, is the ratio of the earth potential rise to the value of fault current.

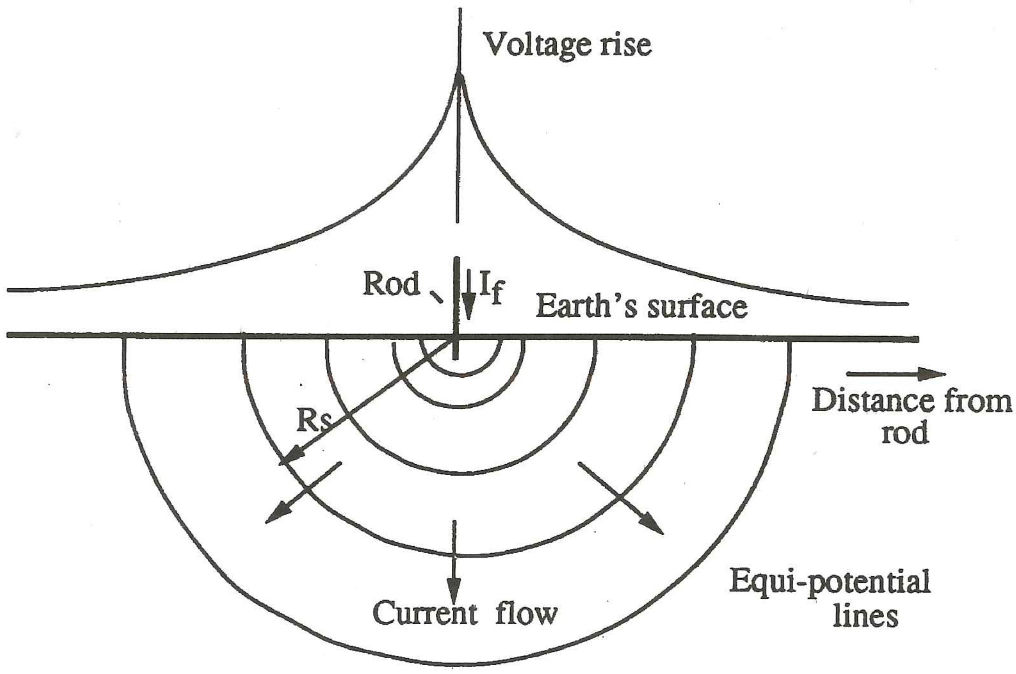
Because the voltage gradient along the earth's surface close to the rod is high, there is a danger of electrocution to man or animals in the vicinity of the rod. Where such danger exists, measures must be taken to reduce the 'touch' and 'step' potentials to safe values.

Earth-potential rise is of concern in installations such as substations. Firstly, for an earth fault in the substation it is desirable that negligible potential gradient exist across the area of the substation (otherwise any potentials developed could pose a hazard to man or equipment).

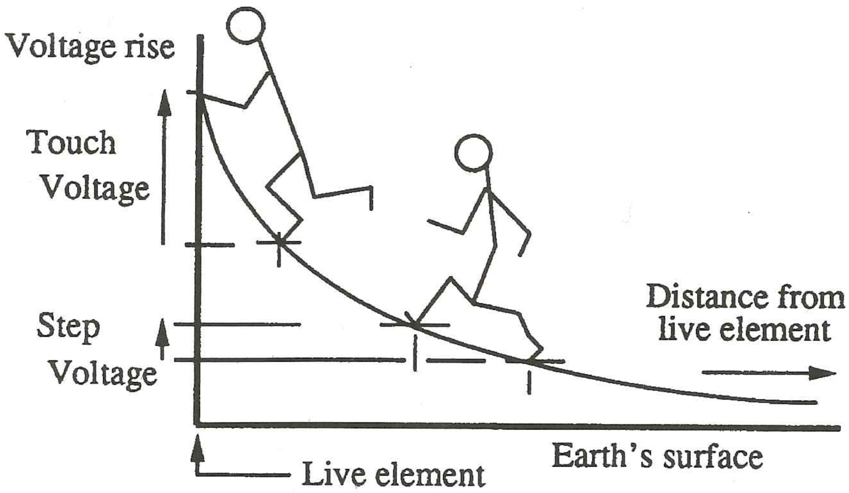
This is achieved by laying a grid of earth conductors, an earth mat, under the station and bonding equipment, structures, fencing, etc to it. Secondly, because of electrical links between the substation and the 'remote' world by telephone lines or protection cabling, the earth-potential rise of the substation could result in electrical breakdown of these links or associated equipment. A seemingly low value of 1 ohm for the earth resistance results in an earth potential rise of 10 kV for a maximum fault current of 10 kA. Thus, through the design of the earth mat, it is necessary to limit the earth resistance of the substation to restrict the potential rise to an acceptable value.

References

1. Adkins, B. and Harley, R.G.: The general theory of alternating current machines: Applications to practical problems. Chapman and Hall, London, 1975.
2. Australian Standard AS 2006-1986, "High voltage A.C. switchgear and control gear – circuit breakers for rated voltages above 1000 V".



(a) Earth potential rise



(a) Step and touch voltages

Figure 10.7: Earth fault and earth potential rise

Appendix

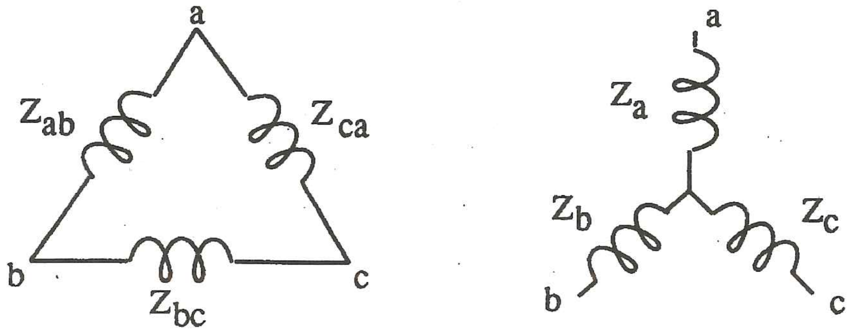


Figure 10.8: The delta-and star-connected networks

A delta-connected network in Figure 10.8 can be transformed to a star arrangement by means of the following relationships:

$$Z_a = Z_{ab}Z_{ca} / Z, \qquad Z_b = Z_{bc}Z_{ab} / Z, \qquad Z_c = Z_{ca}Z_{bc} / Z$$

where $$Z = Z_{ab} + Z_{bc} + Z_{ca}.$$

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