UNIT I Part-3

FAULT ANALYSIS

Symmetrical & Unsymmetrical Faults

Normally, a power system operates under balanced conditions. When the system becomes unbalanced due to the failures of insulation at any point or due to the contact of live wires, a short–circuit or fault, is said to occur in the line. Faults may occur in the power system due to the number of reasons like natural disturbances (lightning, high-speed winds, earthquakes), insulation breakdown, falling of a tree, bird shorting, etc.

Faults that occurs in transmission lines are broadly classified as

- Symmetrical faults
- Unsymmetrical faults

Symmetrical faults

In such types of faults, all the phases are short-circuited to each other and often to earth. Such fault is balanced in the sense that the systems remain symmetrical, or we can say the lines displaced by an equal angle (i.e. 120° in three phase line). It is the most severe type of fault involving largest current, but it occurs rarely. For this reason balanced short- circuit calculation is performed to determine these large currents.

Need for fault analysis

- To determine the magnitude of fault current throughout the power system after fault occurs.
- To select the ratings for fuses, breakers and switchgear.
- To check the MVA ratings of the existing circuit breakers when new generators are added into a system.

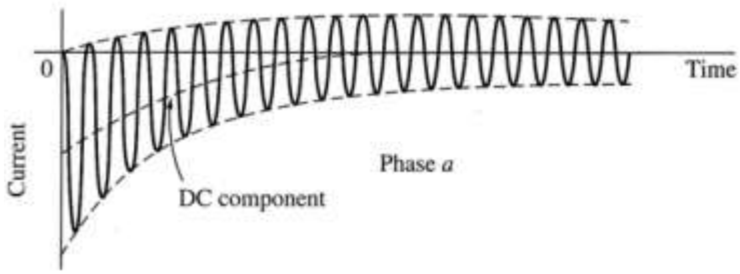
Common Power System Faults

Power system faults may be categorized as one of four types; in order of frequency of occurrence, they are: ·

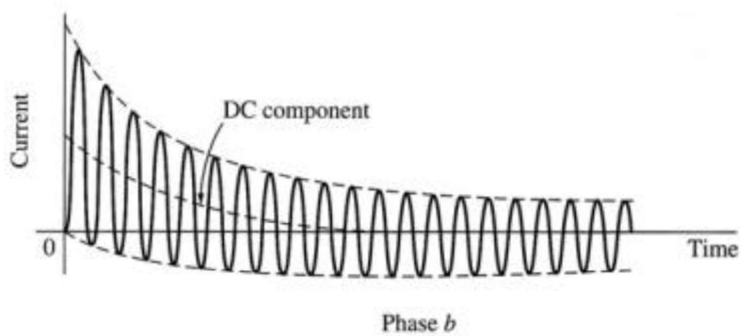
- Single line to ground fault
- Line to line fault
- Double line to ground fault
- Balanced three phase fault

3-Phase fault current transients in Phase fault current transients in synchronous generators synchronous generators

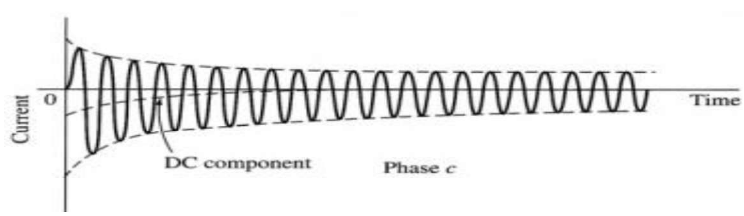
When a symmetrical 3-phase fault occurs at the terminals of a synchronous generator, the resulting current flow in the phases of the generator can appear as shown.



The current can be represented as a transient DC component added on top of a symmetrical AC component.



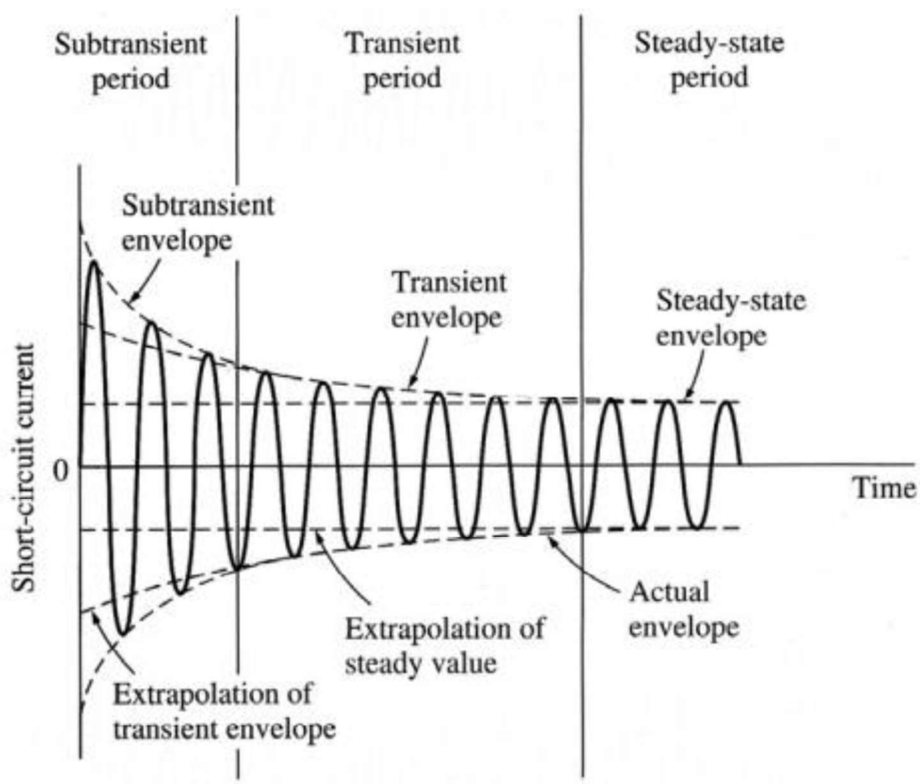
Therefore, while before the fault, only AC voltages and currents were present within the generator, immediately after the fault, both AC and DC currents are present.



Fault current transients in machines Fault current transients in machines

When the fault occurs, the AC component When the fault occurs, the AC component of current jumps to a very large value, but of current jumps to a very large value, but the total current cannot change instantly the total current cannot change instantly since the series inductance of the machine since the series inductance of the machine will prevent this from happening. will prevent this from happening.

The transient DC component of current is The transient DC component of current is just large enough such that the sum of the just large enough such that the sum of the AC and DC components just AC and DC components just after the fault the fault equals the AC current just equals the AC current just before the fault. the fault.Since the instantaneous values of current Since the instantaneous values of current at the moment of the fault are different in at the moment of the fault are different in each phase, the magnitude of DC each phase, the magnitude of DC components will be different in different components will be different in different phases.



There are three periods of time:

- Sub -transient period: first cycle or so after the fault transient period: first cycle or so after the fault – AC current is very AC current is very large and falls rapidly; large and falls rapidly;
- Transient period: current falls at a slower rate; Transient period: current falls at a slower rate;
- Steady -state period: current reaches its steady value. state period: current reaches its steady value.

It is possible to determine t It is possible to determine the time constants f he time constants for the sub or the sub -transient transient and transient periods . and transient periods

SHORT CIRCUIT CAPACITY

- It is the product of magnitudes of the prefault voltage and the post fault current.
- It is used to determine the dimension of a bus bar and the interrupting capacity of a circuit breaker.

Short Circuit Capacity (SCC)

$$|SCC| = |V^0||I_F|$$

$$|I_F| = \frac{|V_T|}{|Z_T|}$$

$$|SCC|_{1\phi} = \frac{|V_T|^2}{|Z_T|} = \frac{S_{b,1\phi}}{|Z_T|_{p.u}} MVA/\phi$$

$$|SCC|_{3\phi} = \frac{S_{b,3\phi}}{|Z_T|_{p.u}} MVA$$

$$I_f = \frac{|SCC|_{3\phi} * 10^6}{\sqrt{3} * V_{L,b} * 10^6}$$

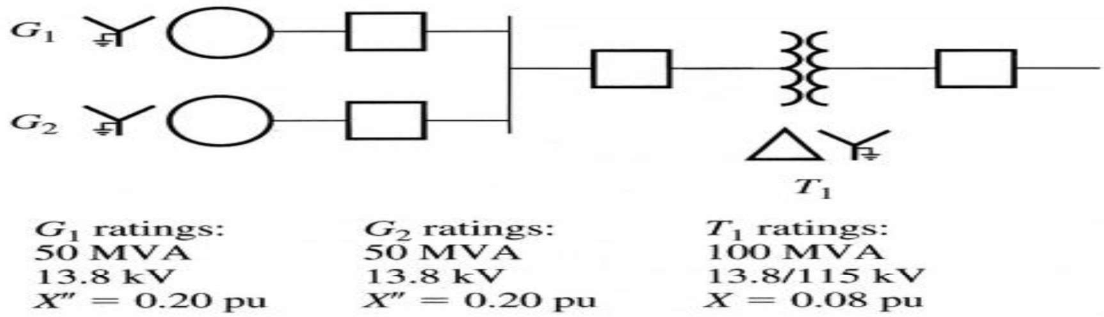
Procedure for calculating short circuit capacity and fault current

- Draw a single line diagram and select common base S_b MVA and kV
- Draw the reactance diagram and calculate the total p.u impedance from the fault point to source (Thevenin impedance Z_T)
- Determine SCC and I_f

EXAMPLE

Two generators are connected in parallel to the low voltage side of a transformer. Generators G1 and G 2 are each rated at 50 MVA, 13.8 kV, with a subtransient resistance of 0.2 pu. Transformer T1 is rated at 100 MVA, 13.8/115 kV with a series reactance of 0.08 pu and negligible resistance.

Assume that initially the voltage on the high side of the transformer is 120 kV, that the transformer is unloaded, and that there are no circulating currents between the generators. Calculate the subtransient fault current that will flow if a 3 phase fault occurs at the high-voltage side of transformer



Let choose the per-unit base values for this power system to be 100 MVA and 115 kV at the high-voltage side and 13.8 kV at the low-voltage side of the transformer. The subtransient reactance of the two generators to the system base is

$$X_{pu,new} = X_{pu,old} \times \left(\frac{kV_{b,old}}{kV_{b,new}}\right)^2 \times \left(\frac{MVA_{b,new}}{MVA_{b,old}}\right)$$

$$X_1" = X_2" = 0.2 \times \left(\frac{13{,}800}{13{,}800}\right)^2 \times \left(\frac{100{,}000}{50{,}000}\right) = j0.4 p.u$$

The reactance of the transformer is already given on the system base, it will not change

$$X_T = 0.08\, p.u$$

The per-unit voltage on the high-voltage side of the transformer is

$$V_{pu} = \frac{Actual\ value}{Base\ value} = \frac{120{,}000}{115{,}000} = j1.044\, p.u$$

Since there is no load on the system, the voltage at the terminals of each generator, and the internal generated voltage of each generator must also be 1.044 pu. The per-phase per-unit equivalent circuit of the system is We observe that the phases of internal generated voltages are arbitrarily chosen as 0 0. The phase angles of both voltages must be the same since the generators were working in parallel

To find the subtransient fault current, we need to solve for the voltage at the bus 1 of the system. To find this voltage, we must convert first the per-unit impedances to admittances, and the voltage sources to equivalent current sources. The Thevenin impedance of each generator is ZTh = j0.4, so the short-circuit current of each generator is

$$I_{su} = \frac{V_{oc}}{Z_{th}} = \frac{1.044\angle 0^0}{j0.4} = 2.61\angle 90^0$$

Then the node equation for voltage V1

$$V_1(-j2.5) + V_1(-j2.5) + V_1(-j12.5) = 2.61\angle -90^0 + 2.61\angle -90^0$$

$$V_1 = \frac{5.22\angle 90^0}{-j17.5} = 0.298\angle 0^0$$

Therefore, the subtransient current in the fault is

$$I_F = V_1(-j12.5) = 3.729\angle{-90}^0\ p.u$$

Since the base current at the high-voltage side of the transformer is

$$I_{base} = \frac{S_{3\Phi,base}}{\sqrt{3}V_{LL,base}} = \frac{100{,}000{,}000}{\sqrt{3}115{,}000} = 502\ A$$

the subtransient fault current will be

$I_F = I_{F,p.u}\ I_{base} = 3.729 \times 502 = 1872$ A

ALGORITHM FOR SHORT CIRCUIT ANALYSIS USING BUS IMPEDANCE MATRIX

- Consider a n bus network. Assume that three phase fault is applied at bus k through a fault impedance z_f

Prefault voltages at all the buses are

$$V_{bus}(0)=\begin{bmatrix} V_1(0) \\ V_2(0) \\ . \\ V_k(0) \\ . \\ V_n(0) \end{bmatrix}$$

- Draw the Thevenin equivalent circuit i.e Zeroing all voltage sources and add voltage source at faulted bus k and draw the reactance diagram
- The change in bus voltage due to fault is

$$\Delta V_{bus}=\begin{bmatrix} \Delta V_1 \\ . \\ . \\ \Delta V_k \\ . \\ \Delta V_n \end{bmatrix}$$

- The bus voltages during the fault is

$$V_{bus}(F)=V_{bus}(0)+\Delta V_{bus}$$

- The current entering into all the buses is zero.the current entering into faulted bus k is –ve of the current leaving the bus k

$$\Delta V_{bus}=Z_{bus}I_{bus}$$

$$\Delta V_{bus}=\begin{pmatrix} Z_{11} & . & Z_{1k} & . & Z_{1n} \\ . & . & . & . & . \\ Z_{k1} & . & Z_{kk} & . & Z_{kn} \\ . & . & . & . & . \\ Z_{n1} & . & Z_{nk} & . & Z_{nn} \end{pmatrix}\begin{bmatrix} 0 \\ . \\ -I_k(F) \\ . \\ 0 \end{bmatrix}$$

$$V_k(F)=V_k(0)-Z_{kk}I_k(F)$$

$$V_k(F)=Z_fI_k(F)$$

$$I_k(F)=\frac{V_k(0)}{Z_{kk}+Z_f}$$

$$V_i(F)=V_i(0)-Z_{ik}I_k(F)$$

UNIT IV

FAULT ANALYSIS – UNBALANCED FAULTS

UNSYMMETRICAL FAULTS

- One or two phases are involved
- Voltages and currents become unbalanced and each phase is to be treated individually
- The various types of faults are

Shunt type faults

1.Line to Ground fault (LG)

2. Line to Line fault (LL)

3. Line to Line to Ground fault (LLG)

Series type faults

- Open conductor fault (one or two conductor open fault)

- Symmetrical components can be used to transform three phase unbalanced voltages and currents to balanced voltages and currents
- Three phase unbalanced phasors can be resolved into following three sequences

1.Positive sequence components

2. Negative sequence components

3. Zero sequence components

Single-Line-to-Ground Fault

Let a 1LG fault has occurred at node *k* of a network. The faulted segment is then as shown in Fig. 8where it is assumed that phase-a has touched the ground through an impedance Z_f . Since the system is unloaded before the occurrence of the fault we have

$$I_{fb} = I_{fc} = 0 \qquad (1)$$

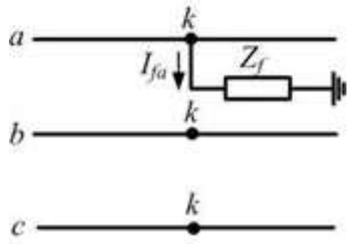


Fig. Representation of 1LG fault.

Also the phase-a voltage at the fault point is given by

From (1) we can write

$$V_{ka} = Z_f I_{fa} \tag{2}$$

$$I_{fa012} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_{fa} \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

Solving (.3) we get

$$I_{fa0} = I_{fa1} = I_{fa2} = \frac{I_{fa}}{3} \tag{4}$$

his implies that the three sequence currents are in series for the 1LG fault. Let us denote the zero, positive and negative sequence Thevenin impedance at the faulted point as Z_{kk0} , Z_{kk1} and Z_{kk2} respectively.

$$\begin{aligned} V_{ka0} &= -Z_{kk0} I_{fa0} \\ V_{ka1} &= V_f - Z_{kk1} I_{fa1} \\ V_{ka2} &= -Z_{kk2} I_{fa2} \end{aligned} \tag{5}$$

Then from (4) and (5) we can write

$$\begin{aligned} V_{ka} &= V_{ka0} + V_{ka1} + V_{ka2} \\ &= V_f - \left(Z_{kk0} + Z_{kk1} + Z_{kk2}\right) I_{fa0} \end{aligned} \tag{6}$$

Again since

$$V_{ka} = Z_f I_{fa} = Z_f \left(I_{fa0} + I_{fa1} + I_{fa2}\right) = 3 Z_f I_{fa0} \tag{7}$$

The Thevenin equivalent of the sequence network is shown in Fig. 8.3.

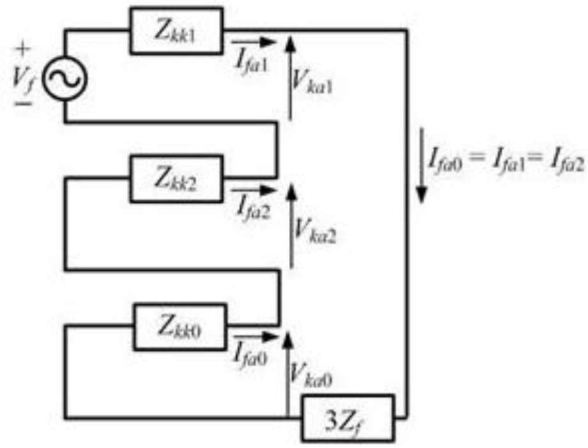
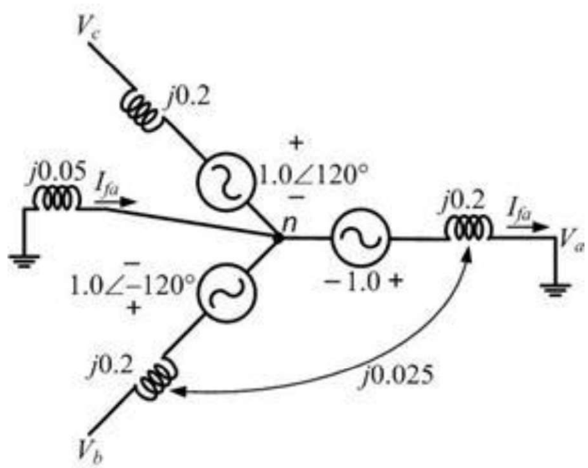


Fig. Thevenin equivalent of a 1LG fault.

Example 1

A three-phase Y-connected synchronous generator is running unloaded with rated voltage when a 1LG fault occurs at its terminals. The generator is rated 20 kV, 220 MVA, with subsynchronous reactance of 0.2 per unit. Assume that the subtransient mutual reactance between the windings is 0.025 per unit. The neutral of the generator is grounded through a 0.05 per unit reactance. The equivalent circuit of the generator is shown in Fig. We have to find out the negative and zero sequence reactances.



Since the generator is unloaded the internal emfs are

$$E_{an} = 1.0 \quad E_{bn} = 1.0\angle{-120^0} \quad E_{cn} = 1.0\angle 120^0$$

Since no current flows in phases b and c, once the fault occurs, we have from Fig.

$$I_{fa} = \frac{1}{j(0.2 + 0.05)} = 2 - j4.0$$

Then we also have

$$V_n = -X_n I_{fa} = -0.2$$

From Fig. we get

$$V_a = 0$$
$$V_b = E_{bn} + V_n + j0.025 I_{fa} = -0.6 - j0.866 = 1.0536\angle -124.72^0$$
$$V_c = E_{cn} + V_n + j0.025 I_{fa} = -0.6 + j0.866 = 1.0536\angle 124.72^0$$

Therefore

$$V_{a012} = C\begin{bmatrix} 0 \\ 1.0536\angle -124.72^0 \\ 1.0536\angle 124.72^0 \end{bmatrix} = \begin{bmatrix} -0.4 \\ 0.7 \\ -0.3 \end{bmatrix}$$
$$I_{fa1} = \frac{E_{an} - V_{a1}}{Z_1} = \frac{1 - 0.7}{j0.225} = -j1.333$$

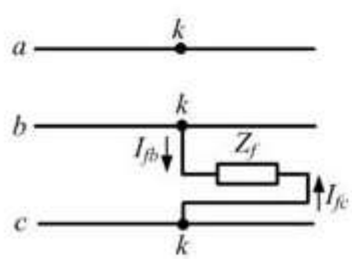
$$I_{fa0} = I_{fa1} = I_{fa2}$$
$$Z_{go} = \frac{-V_{a0}}{I_{a0}} - 3Z_n = j(0.3 - 0.15) = j0.15$$

$$Z_2 = \frac{-V_{a2}}{I_{a2}} = j0.225$$
$$I_{fa0} = \frac{1}{j(0.225 + 0.225 + 0.15 + 3 \times 0.05)} = -j1.333$$

Line-to-Line Fault

The faulted segment for an L-L fault is shown in Fig. where it is assumed that the fault has occurred at node *k* of the network. In this the phases b and c got shorted through the impedance Z_f. Since the system is unloaded before the occurrence of the fault we have

$$I_{fa} = 0 \qquad (1)$$



Also since phases b and c are shorted we have

$$I_{fb} = -I_{fc} \tag{2}$$

Therefore from (1) and (2) we have

$$I_{fa012} = C\begin{bmatrix} 0 \\ I_{fb} \\ -I_{fb} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 0 \\ (a-a^2)I_{fb} \\ (a^2-a)I_{fb} \end{bmatrix} \tag{3}$$

We can then summarize from (3)

$$I_{fa0} = 0$$
$$I_{fa1} = -I_{fa2} \tag{4}$$

herefore no zero sequence current is injected into the network at bus k and hence the zero sequence remains a dead network for an L-L fault. The positive and negative sequence currents are negative of each other.

Now from Fig. we get the following expression for the voltage at the faulted point

$$V_{kb} - V_{kc} = Z_f I_{fb} \tag{5}$$

Again

$$\begin{aligned} V_{kb} - V_{kc} &= V_{kb0} + V_{kb1} + V_{kb2} - V_{kc0} - V_{kc1} - V_{kc2} \\ &= (V_{kb1} - V_{kc1}) + (V_{kb2} - V_{kc2}) \\ &= (a^2 - a)V_{ka1} + (a - a^2)V_{ka2} \\ &= (a^2 - a)(V_{ka1} - V_{ka2}) \end{aligned} \tag{6}$$

Moreover since $I_{fa0} = I_{fb0} = 0$ and $I_{fa1} = -I_{fb2}$, we can write

$$I_{fb} = I_{fb1} + I_{fb2} = a^2 I_{fa1} + aI_{fb2} = (a^2 - a)I_{fa1} \tag{7}$$

Therefore combining (5) - (7) we get

$$V_{ka1} - V_{ka2} = Z_f I_{fa1} \tag{8}$$

Equations (5) and (8) indicate that the positive and negative sequence networks are in parallel. The sequence network is then as shown in Fig. From this network we get

$$I_{fa1} = -I_{fa2} = \frac{V_f}{Z_{kk1} + Z_{kk2} + Z_f}$$

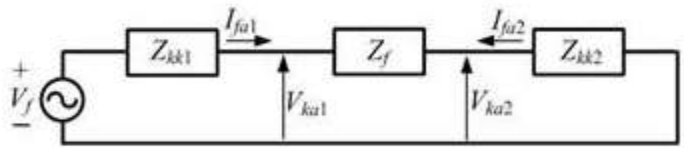


Fig. Thevenin equivalent of an LL fault.

Example 2

Let us consider the same generator as given in Example 1. Assume that the generator is unloaded when a bolted (Z_f = 0) short circuit occurs between phases b and c. Then we get from (2) $I_{fb} = -I_{fc}$. Also since the generator is unloaded, we have $I_{fa} = 0$.

$$V_{an} = E_{an} = 1.0$$
$$V_{bn} = E_{bn} - j0.225 I_{fb} = 1.\angle - 120^0 - j0.225 I_{fb}$$

$$V_{cn} = E_{cn} - j0.225 I_{fc} = 1.\angle 120^0 + j0.225 I_{fb}$$

Also since $V_{bn} = V_{cn}$, we can combine the above two equations to get

$$I_{fb} = -I_{fc} = \frac{1\angle - 120^0 - 1\angle 120^0}{j0.45} = -3.849$$

Then

$$I_{fa012} = C \begin{bmatrix} 0 \\ -3.849 \\ 3.849 \end{bmatrix} = \begin{bmatrix} 0 \\ -j2.2222 \\ j2.2222 \end{bmatrix}$$

We can also obtain the above equation from (9) as

$$I_{fa1} = -I_{fb2} = \frac{1}{j0.225 + j0.225} = -j2.222$$

Also since the neutral current I n is zero, we can write V a = 1.0 and

$$V_b = V_c = V_{bn} = V_{bn} = -0.5$$

Hence the sequence components of the line voltages are

$$V_{a012} = C \begin{bmatrix} 1.0 \\ -0.5 \\ -0.5 \end{bmatrix} = \begin{bmatrix} 0 \\ 0.5 \\ 0.5 \end{bmatrix}$$

Also note that

$$V_{a1} = 1.0 - j0.2251 I_{fa1}$$
$$V_{a2} = -j0.2251 I_{fa2} = 0.5$$

which are the same as obtained before.

Double- Line -to Ground Fault

The faulted segment for a 2LG fault is shown in Fig. where it is assumed that the fault has occurred at node *k* of the network. In this the phases b and c got shorted through the impedance Z_f to the ground.

$$I_{fa0} = \frac{1}{3}\left(I_{fa} + I_{fb} + I_{fc}\right) = \frac{1}{3}\left(I_{fb} + I_{fc}\right)$$
$$\Rightarrow 3I_{fa0} = I_{fb} + I_{fc} \quad (1)$$

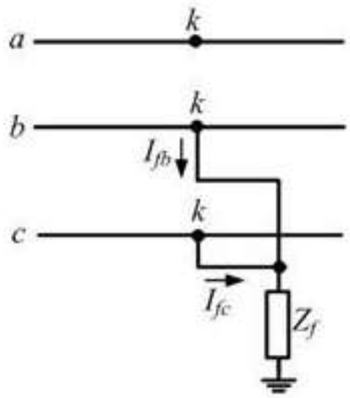


Fig. Representation of 2LG fault.

Also voltages of phases b and c are given by

$$V_{kb} = V_{kc} = Z_f\left(I_b + I_c\right) = 3Z_f I_{fa0} \quad (2)$$

Therefore

$$V_{ka012} = C\begin{bmatrix} V_{ka} \\ V_{kb} \\ V_{kb} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} V_{ka} + 2V_{kb} \\ V_{ka} + \left(a + a^2\right)V_{kb} \\ V_{ka} + \left(a + a^2\right)V_{kb} \end{bmatrix} \quad (3)$$

We thus get the following two equations from (3)

$$V_{ka1} = V_{ka2} = V_{ka0} - 3Z_f I_{fa0} \quad (4)$$

$$V_{ka1} = V_{ka2}$$

$$3V_{ka0} = V_{ka} + 2V_{kb} = V_{ka0} + V_{ka1} + V_{ka2} + 2V_{kb} \quad (5)$$

Substituting (8.18) and (8.20) in (8.21) and rearranging we get

$$V_{ka1} = V_{ka2} = V_{ka0} - 3Z_f I_{fa0} \quad (6)$$

Also since $I_{fa} = 0$ we have

$$I_{fa0} + I_{fa1} + I_{fa2} = 0 \quad (7)$$

The Thevenin equivalent circuit for 2LG fault is shown in Fig. 8.8. From this figure we ge

$$I_{fa1} = \frac{V_f}{Z_{kk1} + Z_{kk2} \| (Z_{kk0} + 3Z_f)} = \frac{V_f}{Z_{kk1} + \frac{Z_{kk2}(Z_{kk0} + 3Z_f)}{Z_{kk2} + Z_{kk0} + 3Z_f}} \quad (8)$$

$$I_{fa0} = -I_{fa1}\left(\frac{Z_{kk2}}{Z_{kk2} + Z_{kk0} + 3Z_f}\right) \quad (9)$$

$$I_{fa2} = -I_{fa1}\left(\frac{Z_{kk0} + 3Z_f}{Z_{kk2} + Z_{kk0} + 3Z_f}\right) \quad (10)$$

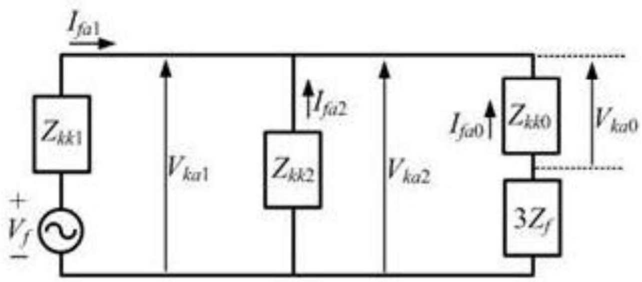


Fig. Thevenin equivalent of a 2LG fault.

Example 3

Let us consider the same generator as given in Examples 1 and 2. Let us assume that the generator is operating without any load when a bolted 2LG fault occurs in phases b and c. The equivalent circuit for this fault is shown in Fig. 8.9. From this figure we can write

$$E_{bn} + V_n = 1\angle -120° + V_n = j0.2I_{fb} - j0.025I_{fc}$$

$$E_{cn} + V_n = 1\angle 120° + V_n = j0.2I_{fc} - j0.025I_{fb}$$

$$V_n = -j0.05(I_{fb} + I_{fc})$$

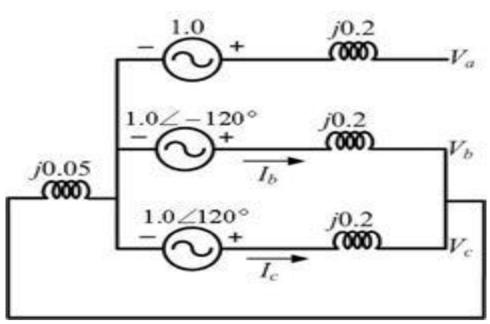


Fig. Equivalent circuit of the generator for a 2LG fault in phases b and c.

Combining the above three equations we can write the following vector-matrix form

$$j\begin{bmatrix} 0.25 & 0.025 \\ 0.025 & 0.25 \end{bmatrix}\begin{bmatrix} I_{fb} \\ I_{fc} \end{bmatrix} = \begin{bmatrix} 1\angle -120^\circ \\ 1\angle 120^\circ \end{bmatrix}$$

Solving the above equation we get

$I_{fb} = -3.849 + j1.8182$

$I_{fc} = 3.849 + j1.8182$

Hence

We can also obtain the above values using (8)-(10). Note from Example 1 that

$$Z_1 = Z_2 = j0.225, Z_0 = j(0.15 + 3 \times 0.05) = j0.3 \ \ and\ Z_f = 0$$

Then

$$I_{fa1} = \frac{1}{j0.225 + \left(\frac{j0.225 \times j0.3}{j0.525}\right)} = -j2.8283$$

$$I_{fa0} = -I_{fa1}\frac{j0.225}{j0.525} = j1.2121$$

Now the sequence components of the voltages are

$$V_{a1} = 1.0 - j0.225 I_{fa1} = 0.3636$$

$$V_{a2} = j0.225 I_{fa2} = 0.3636$$

$$V_{a0} = -j0.3 I_{fa0} = 0.3636$$

Also note from above Fig. that

$$V_a = E_{an} + V_n + j0.0225\left(I_{fb} + I_{fc}\right) = 1.0909$$

and Vb = Vc = 0. Therefore

$$V_{a012} = C\begin{bmatrix} 1.0909 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0.3636 \\ 0.3636 \\ 0.3636 \end{bmatrix}$$

which are the same as obtained before.