General Fault Admittance Method Line-To-Line-To-Ground Faults In Reference And Odd Phases

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Abstract
Line-to-line-to-ground faults are usually analysed using connection of symmetrical component networks at the fault point. As a first step, a reference phase is chosen which results in the simplest connection of the symmetrical component sequence networks for the fault. The simplest connection of symmetrical component sequence networks is a parallel one of the positive, negative and zero sequence networks when phase $a$ of an $abc$ phase sequence is the reference phase and the fault is taken to be between the $b$ and $c$ phases and ground. Putting the fault on an odd phase, say between the $a$ and $c$ phases and ground results in a parallel connection of the positive, negative and zero sequence networks that involve phase shifts, and the solution is more demanding. In practice, the results for the line-to-line-to-ground fault for the reference phase $a$ may be translated to a fault on odd phases by appropriate substitution of phases. In this approach, the solution proceeds by assuming that the fault is in phases $b$ and $c$ and ground and that the symmetrical sequence networks are connected in parallel. The solution of the fault on $b$ and $c$ phases and ground is then translated to apply to the fault on odd phases, say either between phases $c$ and $a$ and ground or between phases $a$ and $b$ and ground. Alternatively, the parallel connection of the sequence networks at the fault point for the odd phases fault is solved for the symmetrical component currents and voltages. These are then used to determine the symmetrical component voltages at the other busbars and hence the symmetrical component currents in the rest of the system. The connection of the sequence networks must be known for the common fault types. In contrast, a solution by the general method of fault admittance matrix does not require prior knowledge of how the sequence networks are connected. A fault may be on any two phases, the double line-to-ground fault on the reference phase or on odd phases, and a solution is obtained for the particular fault. It is therefore more versatile than the classical methods since it does not depend on prior knowledge of how the sequence networks are connected. The paper presents solutions for line-to-line-to-ground faults on the reference and on odd phases of a simple power system containing a delta-earthed-star connected transformer. The results, which include the effects of the delta-earthed-star connected transformer, show that the general fault admittance method solves line-to-line-to-ground faults on odd phases.

Keywords - Line to line to ground fault on odd phases, Unbalanced faults analysis, Fault admittance matrix, Delta-earthed-star transformer.

I. INTRODUCTION
The paper shows that the general fault admittance method of fault analysis may be used to solve line to line to ground faults on odd phases. The method does not require one to have a good understanding of how the sequence networks are connected in the classical approach, so that one may interpret the results obtained for the reference phase fault to the odd phases.

The general fault admittance method differs from the classical approaches based on symmetrical components in that it does not require prior knowledge of how the sequence components of currents and voltages are related [1-3]. In the classical approach, knowledge of how the sequence components are related is required because the sequence networks have to be connected in a prescribed way for a particular fault. Then the sequence currents and voltages at the fault are determined, after which symmetrical component currents and voltages in the rest of the network are calculated. Phase currents and voltages are found by transforming the respective symmetrical component values [3-11].

Another consideration is that in the classical analysis common faults have reference faults that are solved and then the results applied to odd phase faults. For example line-to-line-to-ground faults are always solved with reference to the $a$ phase, in an $abc$ phase system, or its equivalent. The fault is put between phases $b$ and $c$ and ground. It is known that for this type of fault $V_1 = V_2 = V_0$ and that $I_1 + I_2 + I_0 = 0$, where the variables $V$ and $I$ refer to voltage, current respectively and the subscripts 1, 2 and 0 refer to the positive, negative and zero sequence components respectively.
The solution is obtained in relation to the reference phase $a$. However, when the line-to-line-to-ground fault is on the odd phase, either on the $b$ or $c$ phase, i.e. the line to line fault either involves phases $c$ and $a$ or $a$ and $b$ phases, the results for the reference phase line to line to ground fault are transformed to the odd phase. That is the results are interpreted in respect of the odd phases fault reference, which may be $b$ or $c$, and is easily accommodated. Table 1 shows the voltage and current symmetrical component constraints for line-to-line-to-ground faults on the reference phase $a$ and on odd phases $b$ and $c$. In Table 1, the complex operator $\alpha = 1 \angle 120^\circ$.

Table 1: Symmetrical component constraints for Line-to-Line-to-Ground Faults.

<table>
<thead>
<tr>
<th>Reference Phase</th>
<th>Odd Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$b$</td>
</tr>
<tr>
<td>$V_{a}=V_{a}=V_{a}$</td>
<td>$V_{b}=V_{b}=V_{b}$</td>
</tr>
<tr>
<td>$V_{a}=V_{a}=V_{a}$</td>
<td>$V_{b}=V_{b}=V_{b}$</td>
</tr>
<tr>
<td>$I_{a}+I_{a}+I_{a}=0$</td>
<td>$I_{c}+I_{c}+I_{c}=0$</td>
</tr>
</tbody>
</table>

The fault admittance method is general in the sense that any fault impedances may be represented, provided the special case of a zero impedance fault is catered for. Therefore, a line-to-line-to-ground fault with the reference on an odd phase, say on the $b$ or $c$ phases, poses no difficulties and is easily accommodated.

This paper presents the results of line-to-line-to-ground faults on the references of phase $a$ and odd phases $b$ and $c$ of a simple power system obtained using the general fault admittance method.

II. BACKGROUND

Sakala and Daka [1-3] and Elgerd [4] discussed the solution procedure of the general fault admittance method. However, it is presented here in brief, showing the salient features, key equations and the solution procedure.

A line-to-line-to-ground fault presents low value impedances, with zero value for a direct short circuit or metallic fault, between the faulted two phases and ground at the point of fault in the network. In general, a fault may be represented as shown in Figure 1.

In Figure 1, a fault at a busbar is represented by fault admittances in each phase, i.e. the inverse of

![Figure 1: General Fault Representation](image-url)

the fault impedance in the phase, and the admittance in the ground path. Note that the fault admittance for a short-circuited phase is represented by an infinite value, while that for an open-circuited phase is a zero value. Thus, for a line-to-line-to-ground fault the admittances $Y_{y'}$ and $Y_{y''}$ and $Y_{y'''}$ are infinite while on reference phase $a$, the admittance for $Y_{y'}$ is infinite.

The general fault admittance matrix is given by:

$$Y_f = \left[ \begin{array}{c} \frac{1}{Y_{y'}} + \frac{1}{Y_{y''}} + \frac{1}{Y_{y'''}} \\ \frac{1}{Y_{y'}} + \frac{1}{Y_{y''}} + \frac{1}{Y_{y'''}} \\ \frac{1}{Y_{y'}} + \frac{1}{Y_{y''}} + \frac{1}{Y_{y'''}} \end{array} \right]$$

Equation (1) is transformed using the symmetrical component transformation matrix $T$, and its inverse $T^{-1}$, where

$$T = \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix} \quad \text{and} \quad T^{-1} = \frac{1}{3} \begin{bmatrix} 1 & \alpha^2 & \alpha \\ \alpha & 1 & \alpha^2 \\ \alpha^2 & \alpha & 1 \end{bmatrix}$$

in which $\alpha = 1 \angle 120^\circ$ is a complex operator.

The symmetrical component fault admittance matrix is given by the product:

$$Y_f = T^{-1} Y_f T$$

The general expression [1-3] for $Y_f$ is given by:

$$Y_f = \left[ \begin{array}{c} \frac{1}{Y_{y'}} + \frac{1}{Y_{y''}} + \frac{1}{Y_{y'''}} \end{array} \right]$$

where

$$Y_{y'1} = Y_{y'2} = \frac{1}{3} \left( \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] \right) + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right]$$

$$Y_{y'3} = \frac{1}{3} \left( \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] \right) + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right]$$

and

$$Y_{y''1} = Y_{y''2} = \frac{1}{3} \left( \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] \right) + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right]$$

$$Y_{y''3} = \frac{1}{3} \left( \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] \right) + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right]$$

$$Y_{y'''1} = Y_{y'''2} = \frac{1}{3} \left( \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] \right) + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right]$$

$$Y_{y'''3} = \frac{1}{3} \left( \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] \right) + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right] + \frac{1}{Y_{y''}} \left[ Y_{y''} \right]$$

The above expressions simplify considerably depending on the type of fault. For example, for a line to line fault:

\[
Y_{df} = Y_{df} = 0, \quad Y_{gf} = Y_{gf} = 2Y, \quad \text{i.e. } Z_{df} = Z_{df} = \infty
\]

\[
Y = \frac{1}{2Y + 2Y} \begin{bmatrix}
2Y + 2Y & -(2Y + 2Y) & 0 \\
-(2Y + 2Y) & 2Y + 2Y & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

\[
= \begin{bmatrix}
1 & -1 & 0 \\
-1 & 1 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

(3)

For a line-to-line-to-ground fault:

\[
Y_{df} = 0, \quad Y_{gf} = Y_{gf} = 2Y, \quad \text{i.e. } Z_{df} = \text{finite}
\]

\[
Y = \frac{1}{2Y + 2Y} \begin{bmatrix}
2Y + 2Y & 2Y + 2Y & 0 \\
2Y + 2Y & 2Y + 2Y & 2Y + 2Y \\
0 & 2Y + 2Y & 2Y + 2Y
\end{bmatrix}
\]

(4a)

When \( Y_{gf} = Y \) i.e. fault impedance in ground path equal fault impedance in faulted phases equation 4a becomes:

\[
Y = \frac{1}{2Y + 2Y} \begin{bmatrix}
2Y + 2Y & 2Y + 2Y & 0 \\
2Y + 2Y & 2Y + 2Y & 2Y + 2Y \\
0 & 2Y + 2Y & 2Y + 2Y
\end{bmatrix}
\]

(4b)

2.1 Currents in the Fault

At the faulted busbar, say busbar \( j \), the symmetrical component currents in the fault are given by:

\[
I_{pj} = Y_{pj}(U + Z_{pj}Y_{pj})V_{j}^{0}
\]

(5)

where \( U \) is the unit matrix:

\[
U = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

and \( Z_{pj} \) is the \( j^{th} \) component of the symmetrical component bus impedance matrix:

\[
Z_{pj} = \begin{bmatrix}
Z_{pj+} & 0 & 0 \\
0 & Z_{pj+} & 0 \\
0 & 0 & Z_{pj0}
\end{bmatrix}
\]

The element \( Z_{pj+} \) is the Thevenin’s positive sequence impedance at the faulted busbar, \( Z_{pj+} \) is the Thevenin’s negative sequence impedance at the faulted busbar, and \( Z_{pj0} \) is the Thevenin’s zero sequence impedance at the faulted busbar.

Note that as the network is balanced the mutual terms are all zero.

In equation (5) \( V_{j}^{0} \) is the prefault symmetrical component voltage at busbar \( j \) the faulted busbar:

\[
V_{j}^{0} = \begin{bmatrix}
V_{j+} \\
V_{j-} \\
V_{j0}
\end{bmatrix}
\]

where \( V_{j} \) is the positive sequence voltage before the fault. The negative and zero sequence voltages are zero because the system is balanced prior to the fault.

The phase currents in the fault are then obtained by transformation:

\[
I_{pj} = Y_{pj}^{*} = TI_{pj}
\]

(6)

2.2 Voltages at the Busbars

The symmetrical component voltage at the faulted busbar \( j \) is given by:

\[
V_{pj} = \begin{bmatrix}
V_{j+} \\
V_{j-} \\
V_{j0}
\end{bmatrix} = \begin{bmatrix}
Y_{pj+} & Y_{pj-} & Y_{pj0}
\end{bmatrix} \begin{bmatrix}
V_{j+} \\
V_{j-} \\
V_{j0}
\end{bmatrix}
\]

The symmetrical component voltage at a busbar \( i \) for a fault at busbar \( j \) is given by:

\[
V_{pi} = \begin{bmatrix}
V_{i+} \\
V_{i-} \\
V_{i0}
\end{bmatrix} = \begin{bmatrix}
Y_{pi+} & Y_{pi-} & Y_{pi0}
\end{bmatrix} \begin{bmatrix}
V_{j+} \\
V_{j-} \\
V_{j0}
\end{bmatrix}
\]

(8)

where

\[
V_{u}^{0} = \begin{bmatrix}
V_{u+}^{0} \\
V_{u-}^{0} \\
V_{u0}^{0}
\end{bmatrix} = \begin{bmatrix}
Z_{ui+} & Z_{ui-} & Z_{ui0}
\end{bmatrix} \begin{bmatrix}
V_{j+} \\
V_{j-} \\
V_{j0}
\end{bmatrix}
\]

(9)

gives the symmetrical component prefault voltages at busbar \( i \). The negative and zero sequence prefault voltages are zero.

In equation (8), \( Z_{ui} \) is the \( i^{th} \) component of the symmetrical component bus impedance matrix, the mutual terms for row \( i \) and column \( j \) (corresponding to busbars \( i \) and \( j \))

\[
Z_{ui} = \begin{bmatrix}
Z_{ui+} & 0 & 0 \\
0 & Z_{ui+} & 0 \\
0 & 0 & Z_{ui0}
\end{bmatrix}
\]

The phase voltages in the fault, at busbar \( j \), and at busbar \( i \) are then obtained by transformation

\[
V_{pj} = \begin{bmatrix}
V_{p1} \\
V_{p2} \\
V_{p3}
\end{bmatrix} = TV_{pj} \quad \text{and} \quad V_{pi} = \begin{bmatrix}
V_{p1} \\
V_{p2} \\
V_{p3}
\end{bmatrix} = TV_{pi}
\]

2.3 Currents in Lines and Generators

The symmetrical component currents in a line between busbars \( i \) and \( j \) is given by:

\[
I_{pij} = Y_{pij} \left( V_{pji} - V_{pji} \right)
\]

(10)

where

\[
Y_{pij} = \begin{bmatrix}
Y_{pij+} & 0 & 0 \\
0 & Y_{pij-} & 0 \\
0 & 0 & Y_{pij0}
\end{bmatrix}
\]

is the symmetrical component admittance of the branch between busbars \( i \) and \( j \).
The same equation applies to a generator where the source voltage is the prefault induced voltage and the receiving end busbar voltage is the postfault voltage at the busbar.

The phase currents in the branch are found by transformation:

$$
I_{fji} = \begin{bmatrix}
I_{a ji} \\
I_{b ji} \\
I_{g ji}
\end{bmatrix} = T \begin{bmatrix}
I_{fji}
\end{bmatrix}
$$

Equation (4b) gives the symmetrical component fault admittance matrix for a line-to-line-to-ground fault, with equal fault admittances in the phases and ground. It is restated here for easy of reference:

$$
Y'_{ji} = \frac{y}{9} \begin{bmatrix}
5 & -4 & -1 \\
-4 & 5 & -1 \\
-1 & -1 & 2
\end{bmatrix}
$$

The value $Y$ is the fault admittance in the faulted phases and ground.

The symmetrical component fault admittance matrix may be substituted in equation (5) to obtain the simplified expression of $I_{fji}$ given in equation (12), in which $V_{fji}$ is the prefault voltage on bus bar $j$. The simplified formulation in equation (12) is useful for checking the accuracy of the symmetrical component currents in the fault when the general form is used.

$$
I_{fji} = \frac{(Z_{a ji} + Z_{g ji})V_{fji}^j}{Z_{a ji} + Z_{g ji} + Z_{b ji} + Z_{g ji} - Z_{a ji} - Z_{g ji}} \begin{bmatrix}
1 \\
Z_{a ji} + Z_{g ji} \\
Z_{a ji} + Z_{g ji}
\end{bmatrix}
$$

The impedances required to simulate the line-to-line-to-ground fault are the impedances in the faulted phases and ground path. The impedances in the faulted phases and ground path are assumed equal to $5 \times 10^{10}$ Ω. The open circuited phase $a$ is simulated by a very high resistance of the order of $10^{9}$ Ω.

### III. LINE-TO-LINE-TO-GROUND FAULT SIMULATION

The transformer windings are delta connected on the low voltage side and earthed-star connected on the high voltage side, with the neutral solidly grounded. The phase shift of the transformer is $30^\circ$, i.e. from the generator side to the line side. Figure 3 shows the relationship of transformer voltages for a delta-star transformer connection Yd11 that has a $30^\circ$ phase shift.

<table>
<thead>
<tr>
<th>Item</th>
<th>$S_{base}$ (MVA)</th>
<th>$V_{base}$ (kV)</th>
<th>$X_1$ (pu)</th>
<th>$X_2$ (pu)</th>
<th>$X_0$ (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_1$</td>
<td>100</td>
<td>20</td>
<td>0.15</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>$T_1$</td>
<td>100</td>
<td>20/220</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$L_1$</td>
<td>100</td>
<td>220</td>
<td>0.25</td>
<td>0.25</td>
<td>0.7125</td>
</tr>
</tbody>
</table>

The computer program incorporates an input program that calculates the sequence admittance and impedance matrices and then assembles the symmetrical component bus impedance matrix for the power system. The symmetrical component bus impedance matrix incorporates all the sequences values and has $3n$ rows and $3n$ columns where $n$ is the number of bus bars. In general, the mutual terms between sequence values are zero as a three-phase power system is, by design, balanced.

The power system is assumed to be at no load before the occurrence of a fault. In practice the pre-fault conditions, established by a load flow study may be used. In developing the computer program the assumption of no load, and therefore voltages of...
1.0 per unit at the bus bars and in the generator, is adequate.

The line-to-line-to-ground faults are assumed to be at busbar \( I \), the load busbar. They are described by the impedances in the respective phases and ground path.

The presence of the delta-earthed-star transformer poses a challenge in terms of its modelling. In the computer program the transformer is modelled in one of two ways; as a normal star-star connection, for the positive and negative sequence networks or as a delta star transformer with a phase shift. In the former model, the phase shifts are incorporated when assembling the sequence currents to obtain the phase values.

In particular on the delta connected side of the transformer the positive sequence currents’ angles are increased by the phase shift while the angle of the negative sequence currents are reduced by the same value. The zero sequence currents, if any, are not affected by the phase shifts. Both models for the delta star transformer give same results. The \( \sqrt{3} \) line current factor is used to find the line currents on the delta side of the delta star transformer.

V. RESULTS AND DISCUSSIONS

5.1 Fault Simulation Impedances

The Thevenin’s self sequence impedances of the network seen from the faulted bus bar are:

\[
\begin{bmatrix}
0.5 & 0 & 0 \\
0 & 0.5 & 0 \\
0 & 0 & 0.8125
\end{bmatrix}
\]

In the classical solution, the positive, negative and zero sequence currents due to a line-to-line-to-ground fault on phases \( b \) and \( c \) and ground summate to zero and are found by solving the parallel combination of the three sequence networks. Thus the sequence (positive, negative and zero) currents due to fault in the reference phase at the faulted bus bar are:

\[
\begin{bmatrix}
1.2353 \\
-0.7647 \\
-0.4706
\end{bmatrix}
\]

These sequence currents are compared with computed ones for the different line-to-line-to-ground faults, with the references on phase \( a \) and the odd phases \( b \) and \( c \).

5.2 Simulation Results

The results obtained from the computer program are listed in Table 3. A summary of the transformer phase currents is given in Figures 4a, 4b and 4c for line-to-line-to-ground faults with references on phases \( a, b \) and \( c \) respectively.

5.3 Fault Admittance Matrix and Sequence Impedances at the Faulted Busbar.

The symmetrical component fault admittance matrix obtained from the program for the line-to-line-to-ground faults are in agreement with the theoretical values, obtained using equation (4b). The self sequence impedances at the faulted bus bar obtained from the program are equal to the theoretical values.

5.4 Fault Currents

The symmetrical component fault currents obtained from the program using equations (5) and (12) are in agreement. In particular, the positive, negative and zero sequence currents for the line-to-line-to-ground fault with reference to phase \( a \) summate to zero. The sum of the negative and zero sequence currents is equal and opposite that of the positive sequence current. This is consistent with the classical approach that connects the positive, negative and zero sequence networks in parallel.

When the line-to-line-to-ground fault is between phases \( c \) and \( a \), with an odd phase reference of \( b \) the positive sequence current has a phase angle of -30° while the angles for the negative and zero currents are 270° and -30° respectively. The negative sequence component for the fault with reference \( b \) leads the respective component with the fault with reference phase \( a \) by 120° while the zero sequence current lags by 120°.

The results are consistent with theory, since the current symmetrical component constraints requirements for a line-to-line-to-ground fault with phase \( b \) reference are met, that is \( a' I_1 + a I_2 + I_0 = 0 \).

Similarly when the line-to-line-to-ground fault is between phases \( a \) and \( b \) with an odd phase reference \( c \) the negative sequence component current leads the positive sequence current by 60° while the zero sequence current lags the positive sequence current.
by 60°. The symmetrical component sequence currents constraint is met; i.e. \[ aI_1 + a^2I_2 + I_0 = 0. \]

The phase currents in the fault obtained from the program are in agreement with the theoretical values. In particular, the currents in the healthy phases are zero and the currents in the ground path are of equal magnitude but displaced by 120° for the three cases. The sum of the phase currents in the transmission line are equal to the current in the faults. Note that the current at the receiving end of the line is by convention considered as flowing into the line, rather than out of it.

Figures 4a, 4b and 4c summarise the transformer phase currents for the line-to-line-to-ground faults with references on phases a, b and c respectively. The currents in the transformer, on the line side, are equal to the currents in the line, after allowing for the sign changes due to convention. Note that the fault currents only flow in the windings of the faulted phases on the earthed-star connected side, and on the delta connected side as well. All the results satisfy the ampere-turn balance requirements of the transformer.

The currents at the sending end of the transformer, the delta connected side, flow into the leading faulted phase, i.e. phase b of the bc fault, phase c of the ca fault and phase a of the ab fault, and return in the remaining phases. In all the cases, the leading faulted phase carries twice the current in the other phases.

The phase fault currents flowing from the generator are equal to the phase currents into the transformer for all the three line-to-line-to-ground faults. For each fault the current in the leading faulted phase is twice the current in the other phases, which are equal in magnitude. All the generator phases have fault currents. It is a feature of the delta earthed-star connection that a line-to-line load on the star connected side is supplied from three phases on the delta side, both the transformer and generator.

5.5 Fault Voltages

The symmetrical component voltages at the fault point obtained from the program using equation (7) are in agreement with the theoretical values. In particular, the sequence voltages constraints in Table 1 are satisfied: The sequence positive, negative and zero component voltages for the phase a reference fault are equal, consistent with the concept of the three sequence networks being connected in parallel. When the line-to-line-to-ground fault is on the odd phases the respective symmetrical component voltage constraints are also satisfied; i.e. \[ V_{s1} = V_{s2} = V_{s0} \] that is \[ a^2V_1 = aV_2 = V_0 \] for the line-to-line-to-ground (cag) fault with reference on odd
phase \( b \); and \( V_{ca} = V_{cb} = V_{c0} \) that is \( aV_0 = a^2V_2 = V_0 \) for the line-to-line-to-ground (\( abg \)) fault with reference on odd phase \( c \).

Also note that at the faulted bus bar the magnitudes of the phase voltages of the healthy phases are at 1.1471 greater than unity, their prefault values, while the voltages in the faulted phases are zero.

The phase voltages at bus bar 2 show that the voltages in the faulted phases are 59% of the prefault values while the voltages in the healthy phases are 93% of the prefault values. At bus bar 3, the voltages in general lead the voltages at bus bar 2. In particular the voltages in the leading faulted phases lead the corresponding phase voltages at bus bar 2 by 42.3°. The increase in the phase shift between phase voltages of the faulted phases is due to the voltage drops in the transformer and generator. The voltages of the faulted phases that carry the return fault currents on the delta connected side of the transformer, i.e. phase \( c \) for the \( bca \) fault and \( a \) for the \( ca \) fault and \( b \) for the \( abg \) fault, lead the voltages at bus bar 2 by 24.2°. The voltages in the healthy phases at bus bar 3 lead those of bus bar 2 by 23.5°.

### VI. CONCLUSION

The general fault admittance method may be used to study line-to-line-to-ground faults on the reference phase \( a \) as well as with references on the odd phases \( b \) and \( c \). The ability to handle line-to-line-to-ground faults with references on the odd phases makes it easier to study these faults as the method does not require the knowledge needed to translate the fault from the reference phase to the odd phase references of phases \( b \) and \( c \).

The line-to-line-to-ground fault is interesting for studying the delta earthed star transformer arrangement. It is seen that although only two phase carry the fault current on the earthed star side the currents on the delta connected side are in all three phases, although the winding on the delta side of the healthy phase does not carry any current. The current in the leading faulted phase on the delta side of the transformer is twice that in the other phases, with each phase carrying half of the return current.

Phase shifts in a delta earthed star connected transformer can be deduced from the results. The results give an insight in the effect that a delta earthed star transformer has on a power system during line-to-line faults.

The main advantage of the general fault admittance method is that the user is not required to know beforehand how the sequence networks should be connected at the fault point in order to obtain the sequence fault currents and voltages. The user can deduce the various relationships from the results. The method is therefore easier to use and teach than the classical approach in which each network is solved in isolation and then the results combined to obtain initially the sequence currents and voltages and then the phase quantities.

### REFERENCES


Table 3: Simulation Results - Unbalanced Fault

General Fault Admittance Method – Delta-star Transformer Model
Number of busbars = 3
Number of transmission lines = 1
Number of transformers = 1
Number of generators = 1
Faulted busbar = 1
Fault type = 4

General Line to line to line to ground fault - Fault impedances

<table>
<thead>
<tr>
<th>Phases</th>
<th>Real and Imaginary Parts of Fault Admittance Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phases BCg fault</td>
<td></td>
</tr>
<tr>
<td>Phase a</td>
<td>(R + j X) 1.0000e+050 +j 0.0000e+000</td>
</tr>
<tr>
<td>Phase b</td>
<td>(R + j X) 5.0000e-010 +j 0.0000e+000</td>
</tr>
<tr>
<td>Phase c</td>
<td>(R + j X) 5.0000e-010 +j 0.0000e+000</td>
</tr>
<tr>
<td>Ground</td>
<td>(R + j X) 5.0000e-010 +j 0.0000e+000</td>
</tr>
<tr>
<td>Phases CAg fault</td>
<td></td>
</tr>
<tr>
<td>Phase a</td>
<td>(R + j X) 5.0000e-010 +j 0.0000e+000</td>
</tr>
<tr>
<td>Phase b</td>
<td>(R + j X) 1.0000e+050 +j 0.0000e+000</td>
</tr>
<tr>
<td>Phase c</td>
<td>(R + j X) 5.0000e-010 +j 0.0000e+000</td>
</tr>
<tr>
<td>Ground</td>
<td>(R + j X) 5.0000e-010 +j 0.0000e+000</td>
</tr>
<tr>
<td>Phases ABg fault</td>
<td></td>
</tr>
<tr>
<td>Phase a</td>
<td>(R + j X) 5.0000e-010 +j 0.0000e+000</td>
</tr>
<tr>
<td>Phase b</td>
<td>(R + j X) 5.0000e-010 +j 0.0000e+000</td>
</tr>
<tr>
<td>Phase c</td>
<td>(R + j X) 1.0000e+050 +j 0.0000e+000</td>
</tr>
<tr>
<td>Ground</td>
<td>(R + j X) 5.0000e-010 +j 0.0000e+000</td>
</tr>
</tbody>
</table>

Fault Admittance Matrix - Real and Imaginary Parts of Fault Admittance Matrix

<table>
<thead>
<tr>
<th>Phases</th>
<th>Real and Imaginary Parts of Fault Admittance Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phases BCg fault</td>
<td></td>
</tr>
<tr>
<td>1.1111e+009 +j 0.0000e+000</td>
<td>-8.8889e+008 +j 0.0000e+000</td>
</tr>
<tr>
<td>-8.8889e+008 +j 0.0000e+000</td>
<td>1.1111e+009 +j 0.0000e+000</td>
</tr>
<tr>
<td>-2.2222e+008 +j 0.0000e+000</td>
<td>-2.2222e+008 +j 0.0000e+000</td>
</tr>
<tr>
<td>Phases CAg fault</td>
<td></td>
</tr>
<tr>
<td>1.1111e+009 +j 0.0000e+000</td>
<td>4.4444e+008 +j 7.6980e+000</td>
</tr>
<tr>
<td>4.4444e+008 +j -7.6980e+000</td>
<td>1.1111e+009 +j 0.0000e+000</td>
</tr>
<tr>
<td>1.1111e+009 +j 1.9245e+008</td>
<td>1.1111e+008 +j -1.9245e+008</td>
</tr>
<tr>
<td>Phases ABg fault</td>
<td></td>
</tr>
<tr>
<td>1.1111e+009 +j 0.0000e+000</td>
<td>4.4444e+008 +j -7.6980e+000</td>
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<tr>
<td>4.4444e+008 +j 7.6980e+000</td>
<td>1.1111e+009 +j 0.0000e+000</td>
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<tr>
<td>1.1111e+008 +j -1.9245e+008</td>
<td>1.1111e+008 +j 1.9245e+008</td>
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</tbody>
</table>

Thevenin's Symmetrical Component Impedance Matrix of Faulted Busbar - Real and imaginary parts

<table>
<thead>
<tr>
<th>Phases</th>
<th>Real and Imaginary Parts of Fault Admittance Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phases BCg fault</td>
<td></td>
</tr>
<tr>
<td>0.0000 +j 0.5000</td>
<td>0.0000 +j 0.5000</td>
</tr>
<tr>
<td>0.0000 +j 0.5000</td>
<td>0.0000 +j 0.5000</td>
</tr>
<tr>
<td>0.0000 +j 0.5000</td>
<td>0.0000 +j 0.5000</td>
</tr>
<tr>
<td>0.0000 +j 0.5000</td>
<td>0.0000 +j 0.5000</td>
</tr>
</tbody>
</table>

Fault Current in Symmetrical Components - Real, Imaginary, Magnitude and Angle

<table>
<thead>
<tr>
<th>Phases</th>
<th>Real and Imaginary Parts of Fault Admittance Matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase BCg fault</td>
<td></td>
</tr>
<tr>
<td>+ve</td>
<td>0.0000 -1.2353</td>
</tr>
<tr>
<td>-ve</td>
<td>0.0000 0.7647</td>
</tr>
<tr>
<td>zero</td>
<td>0.0000 0.4706</td>
</tr>
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</table>
Fault current in phase components - Rectangular and Polar Coordinates

<table>
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<tr>
<th>Phases</th>
<th>+ve</th>
<th>-ve</th>
<th>zero</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAg</td>
<td>0.0000 +j 0.0000</td>
<td>0.0000 +j -1.2353</td>
<td>0.0000 +j 1.4118</td>
</tr>
<tr>
<td>ABg</td>
<td>0.0000 +j -1.2353</td>
<td>0.0000 +j 0.7647</td>
<td>0.0000 +j -0.4075</td>
</tr>
<tr>
<td>zero</td>
<td>0.0000 +j 0.7647</td>
<td>0.0000 +j -0.2353</td>
<td>0.0000 +j 0.4706</td>
</tr>
</tbody>
</table>

Symmetrical Component Voltages at Faulted Busbar - Rectangular and Polar Coordinates

<table>
<thead>
<tr>
<th>Phases</th>
<th>+ve</th>
<th>-ve</th>
<th>zero</th>
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</thead>
<tbody>
<tr>
<td>BCg</td>
<td>0.3824 +j 0.0000</td>
<td>0.3824 +j -0.3311</td>
<td>0.3824 +j -0.0000</td>
</tr>
<tr>
<td>CAg</td>
<td>0.3824 +j 0.0000</td>
<td>0.3824 +j -0.3311</td>
<td>0.3824 +j -0.0000</td>
</tr>
<tr>
<td>ABg</td>
<td>0.0000 +j 0.0000</td>
<td>0.0000 +j -0.0000</td>
<td>0.0000 +j -0.0000</td>
</tr>
</tbody>
</table>

Phase Voltages at Faulted Busbar

<table>
<thead>
<tr>
<th>Phases</th>
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<th>-ve</th>
<th>zero</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCg</td>
<td>1.1471 +j 0.0000</td>
<td>1.1471 +j -0.0000</td>
<td>1.1471 +j -0.0000</td>
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<tr>
<td>CAg</td>
<td>1.1471 +j 0.0000</td>
<td>1.1471 +j -0.0000</td>
<td>1.1471 +j -0.0000</td>
</tr>
<tr>
<td>ABg</td>
<td>0.0000 +j 0.0000</td>
<td>0.0000 +j -0.0000</td>
<td>0.0000 +j -0.0000</td>
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Postfault Voltages at Busbar number = 1

<table>
<thead>
<tr>
<th>Phases</th>
<th>+ve</th>
<th>-ve</th>
<th>zero</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCg</td>
<td>1.1471 +j 0.0000</td>
<td>1.1471 +j -0.0000</td>
<td>1.1471 +j -0.0000</td>
</tr>
<tr>
<td>CAg</td>
<td>1.1471 +j 0.0000</td>
<td>1.1471 +j -0.0000</td>
<td>1.1471 +j -0.0000</td>
</tr>
<tr>
<td>ABg</td>
<td>0.0000 +j 0.0000</td>
<td>0.0000 +j -0.0000</td>
<td>0.0000 +j -0.0000</td>
</tr>
</tbody>
</table>
Phases CAg fault
Phase a  0.0000 -0.0000  0.0000  -36.1654
Phase b  -0.5735 -0.9934  1.1471  240.0000
Phase c  -0.0000  0.0000  0.0000  154.9240

Phases ABg fault
Phase a  -0.0000  0.0000  0.0000  176.2053
Phase b  0.0000 -0.0000  0.0000  -22.9986
Phase c  -0.5735  0.9934  1.1471  120.0000

Postfault Voltages at Busbar number = 2
Phases BCg fault
<table>
<thead>
<tr>
<th>Real</th>
<th>Imag</th>
<th>Magn</th>
<th>Angle [Deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase a</td>
<td>0.9294</td>
<td>0.0000</td>
<td>0.9294</td>
</tr>
<tr>
<td>Phase b</td>
<td>-0.3941</td>
<td>-0.4330</td>
<td>0.5855</td>
</tr>
<tr>
<td>Phase c</td>
<td>-0.3941</td>
<td>0.4330</td>
<td>0.5855</td>
</tr>
</tbody>
</table>

Phases CAg fault
Phase a  0.5721  0.1248  0.5855  12.3077
Phase b  -0.4647  -0.8049  0.9294  240.0000
Phase c  -0.1779  0.5578  0.5855  107.6923

Phases ABg fault
Phase a  0.5721  -0.1248  0.5855  -12.3077
Phase b  -0.1779  -0.5578  0.5855  252.3077
Phase c  -0.4647  0.8049  0.9294  120.0000

Phases BCg fault
Phase a  0.8049  0.3500  0.8777  23.5013
Phase b  0.0000  -0.7000  0.7000  -90.0000
Phase c  -0.7056  0.5221  0.8777  143.5013

Phases CAg fault
Phase a  1.8704  -22.1729  1.8704  202.1729
Phase b  1.8704  22.1729  1.8704  37.8271
Phase c  1.8704  180.0000  1.8704  91.0179

Phases ABg fault
Phase a  1.8704  142.1729  1.8704  217.8271
Phase b  1.8704  -37.8271  1.8704  88.9821
Phase c  1.8704  3.4641  1.8704  22.1729

Postfault Voltages at Busbar number = 3
Phases BCg fault
<table>
<thead>
<tr>
<th>Real</th>
<th>Imag</th>
<th>Magn</th>
<th>Angle [Deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase a</td>
<td>0.8049</td>
<td>0.3500</td>
<td>0.8777</td>
</tr>
<tr>
<td>Phase b</td>
<td>0.0000</td>
<td>-0.7000</td>
<td>0.7000</td>
</tr>
<tr>
<td>Phase c</td>
<td>-0.7056</td>
<td>0.5221</td>
<td>0.8777</td>
</tr>
</tbody>
</table>

Phases CAg fault
Phase a  1.8704  -22.1729  1.8704  202.1729
Phase b  1.8704  22.1729  1.8704  37.8271
Phase c  1.8704  180.0000  1.8704  91.0179

Phases ABg fault
Phase a  1.8704  142.1729  1.8704  217.8271
Phase b  1.8704  -37.8271  1.8704  88.9821
Phase c  1.8704  3.4641  1.8704  22.1729

Postfault Currents in Lines
Phases BCg fault
<table>
<thead>
<tr>
<th>Line No.</th>
<th>SE Bus</th>
<th>RE Bus</th>
<th>Phase a Current</th>
<th>Phase a Magn</th>
<th>Phase a Angle</th>
<th>Phase b Current</th>
<th>Phase b Magn</th>
<th>Phase b Angle</th>
<th>Phase c Current</th>
<th>Phase c Magn</th>
<th>Phase c Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.0000</td>
<td>90.0000</td>
<td>1.8704</td>
<td>157.8271</td>
<td>1.8704</td>
<td>22.1729</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0.0000</td>
<td>-90.0000</td>
<td>1.8704</td>
<td>-22.1729</td>
<td>1.8704</td>
<td>202.1729</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Phases CAg fault
<table>
<thead>
<tr>
<th>Line No.</th>
<th>SE Bus</th>
<th>RE Bus</th>
<th>Phase a Current</th>
<th>Phase a Magn</th>
<th>Phase a Angle</th>
<th>Phase b Current</th>
<th>Phase b Magn</th>
<th>Phase b Angle</th>
<th>Phase c Current</th>
<th>Phase c Magn</th>
<th>Phase c Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>1.8704</td>
<td>37.8271</td>
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<td></td>
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</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1.8704</td>
<td>82.1729</td>
<td>0.0000</td>
<td>114.2383</td>
<td>1.8704</td>
<td>217.8271</td>
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</table>

Phases ABg fault
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<thead>
<tr>
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<th>RE Bus</th>
<th>Phase a Current</th>
<th>Phase a Magn</th>
<th>Phase a Angle</th>
<th>Phase b Current</th>
<th>Phase b Magn</th>
<th>Phase b Angle</th>
<th>Phase c Current</th>
<th>Phase c Magn</th>
<th>Phase c Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1.8704</td>
<td>-82.1729</td>
<td>1.8704</td>
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<td>0.0000</td>
<td>-88.9821</td>
<td></td>
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<tr>
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<td>1</td>
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<td>1.8704</td>
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<td>91.0179</td>
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</tr>
</tbody>
</table>

Postfault Currents in Transformers
Phases BCg fault
<table>
<thead>
<tr>
<th>Transf No.</th>
<th>SE Bus</th>
<th>RE Bus</th>
<th>Phase a Current</th>
<th>Phase a Magn</th>
<th>Phase a Angle</th>
<th>Phase b Current</th>
<th>Phase b Magn</th>
<th>Phase b Angle</th>
<th>Phase c Current</th>
<th>Phase c Magn</th>
<th>Phase c Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1.8704</td>
<td>-22.1729</td>
<td>3.4641</td>
<td>180.0000</td>
<td>1.8704</td>
<td>22.1729</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
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<td>202.1729</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Neutral Current at Receiving end  
<table>
<thead>
<tr>
<th>Real</th>
<th>Imag</th>
<th>Magn</th>
<th>Deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0000</td>
<td>-1.4118</td>
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<td>-90.0000</td>
</tr>
</tbody>
</table>

Link Currents in Delta Connection at Sending End  

<table>
<thead>
<tr>
<th>No.</th>
<th>Bus</th>
<th>Bus</th>
<th>Phase a Magn</th>
<th>Phase a Angle Deg.</th>
<th>Phase b Magn</th>
<th>Phase b Angle Deg.</th>
<th>Phase c Magn</th>
<th>Phase c Angle Deg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1.8704</td>
<td>-22.1729</td>
<td>1.8704</td>
<td>202.1729</td>
<td>0.0000</td>
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Phases CAg fault  

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<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1.8704</td>
<td>109.7578</td>
<td>1.8704</td>
<td>217.8271</td>
<td>3.4641</td>
<td>60.0000</td>
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</tbody>
</table>

Neutral Current at Receiving End  

<table>
<thead>
<tr>
<th>Real</th>
<th>Imag</th>
<th>Magn</th>
<th>Deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.2226</td>
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</table>

Link Currents in Delta Connection at Sending End  

<table>
<thead>
<tr>
<th>No.</th>
<th>Bus</th>
<th>Bus</th>
<th>Phase a Magn</th>
<th>Phase a Angle Deg.</th>
<th>Phase b Magn</th>
<th>Phase b Angle Deg.</th>
<th>Phase c Magn</th>
<th>Phase c Angle Deg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2</td>
<td>0.0000</td>
<td>109.7578</td>
<td>1.8704</td>
<td>217.8271</td>
<td>1.8704</td>
<td>82.1729</td>
</tr>
</tbody>
</table>

Phases ABg fault  

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>2</td>
<td>3.4641</td>
<td>-60.0000</td>
<td>1.8704</td>
<td>142.1729</td>
<td>1.8704</td>
<td>97.8271</td>
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</tbody>
</table>

Neutral Current at Receiving End  

<table>
<thead>
<tr>
<th>Real</th>
<th>Imag</th>
<th>Magn</th>
<th>Deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2226</td>
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Link Currents in Delta Connection at Sending End  

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Postfault Currents in Generators  

Phases BCg fault  

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Generator Neutral current  

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<th>Magn</th>
<th>Deg</th>
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<tbody>
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<td>0.0000</td>
<td>0.0000</td>
<td>109.9831</td>
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### Phases CAg fault

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Generator Neutral current

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### Phases ABg fault

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<tbody>
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Generator Neutral current

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