CHAPTER 3
ANALYSIS OF FAULTS THROUGH FAULT IMPEDANCES ON SIX PHASE TRANSMISSION SYSTEM

3.1 INTRODUCTION

Recently, there is growing interest on the concept of six phase transmission as an alternative to the voltage upgrading of a line to increase the power transfer capability within the existing right-of-way. One of the important aspects of a transmission planning is the design of adequate protective schemes which requires a detailed fault analysis. So far, both symmetrical and unsymmetrical fault analysis have been done on six phase transmission systems for short circuit conditions without fault impedances using six - phase symmetrical components [5] D T P T [6,14] and phase co-ordinate method [13] only. In this work the analysis of faults on six phase transmission system with fault impedances using (i) Six phase symmetrical components method (ii). Dual Three Phase Transformation method and interconnection of different sequence networks for various faults that are likely to occur in practice are discussed.

3.2 Analysis of Faults Through Fault Impedances Using Six phase Symmetrical Components Method:

Assume the six phase line is balanced during the pre-fault stage and becomes unbalanced during the post-fault stage. Let \( I_A, I_B, I_C, I_D, I_E \) and \( I_F \) be the currents flowing out of the line at the fault from phases A, B, C, D, E, and F respectively. Six types of ground faults through fault impedances and phase-phase faults through impedance will be considered to outline the analysis. Phase to phase faults through impedances involving more than two phases or highly involved and are rare in occurrence.
Single Phase to Ground Fault:

![Fig 3.1 Schematic of a single phase to ground (A).](image)

The fault depicted in fig 3.1 is the most probable type of fault to occur on a power system. The valid relations at the point of fault from fig 3.1 are

\[ V_A = I_A Z_F \]  
\[ I_B = I_C = I_D = I_E = I_F = 0 \]

For the current values, the corresponding symmetrical components using equation (2.2a)

\[ I_{A0} = I_{A1} = I_{A2} = I_{A3} = I_{A4} = I_{A5} = I_A/6 \]  
\[ V_{A0} + V_{A1} + V_{A2} + V_{A3} + V_{A4} + V_{A5} = V_A = 6 I_{A0} Z_F \]

Using the equations (3.2) and (3.2a) in equation (2.6) gives

\[ I_{A1} = \frac{E_{A1}}{Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + (Z_0 + 6 Z_F)} \]

\[ I_{A0} = \frac{E_{A1}}{Z_1 + Z_2 + Z_3 + Z_4 + Z_5 + (Z_0 + 6 Z_F)} \]

![Fig 3.2 Interconnection of sequence networks for A-g](image)
b) Two phase to ground fault:

![Schematic of a Two phase to ground(AD).](image)

The conditions of the fault location from fig 3.3 are

\[ I_0 = I_C = I_E = I_F = 0 \]  
\[ V_A = V_D = (I_A + I_D) Z_r \]  

Using the inverse transformation on these two equations results in

\[ I_{A0} = I_{A2} = I_{A4} = (I_A + I_D)/6 \]  
\[ V_{A0} = V_{A2} = V_{A4} = 6 I_{A0} Z_r \]  

The substitution of equations (3.4) and (3.4a) in equation (2.6) gives

\[ I_{A1} = \frac{E_{A1}}{Z_1 + Z_3 + Z_5} \]  
\[ I_{A0} = 0 \]

Giving the same results as for A,D fault without ground impedance. Hence it is noted that if \( I_{A0} \) alone is used to relay ground fault, the relay fails to act.
c) Three phase to ground fault:-

Let the three phase to ground fault through impedance $Z_F$ be on phases B,D and F as shown in fig 3.5. The valid relations are

$$I_A = I_C = I_E = 0 \quad \text{(3.7)}$$

$$V_B = V_D = V_F = (I_D + I_F) Z_F \quad \text{(3.7a)}$$

Equations (3.7) and (3.7a) imply

$$I_{A0} + I_{A3} = 0 \quad ; \quad I_{A2} + I_{A4} = 0 \quad ; \quad I_{A3} + I_{A5} = 0 \quad \text{(3.8)}$$

$$V_{A0} - V_{A3} = 6 I_{A0} Z_F; \quad (V_{A1} - V_{A4}) = 0 \quad ; \quad (V_{A2} - V_{A5}) = 0 \quad \text{(3.8a)}$$

Substituting the above result in equation (2.6) gives

$$I_{A1} = \frac{E_{A1}}{Z_i + Z_d} \quad \text{(3.9)}$$

$$I_{A0} = 0 \quad \text{(3.9a)}$$

The above result can also be verified from the fault on phases BDF forming one three phase system and their currents are balanced even under three phase fault conditions.

Fig 3.6 Inter connection of sequence networks for BDF-g.
d) Four-phase to ground fault:

\[
\begin{align*}
&\text{Fig 3.7 Schematic of a four Phase to ground (BCEF).} \\
&\text{The conditions at the fault location are} \\
&IA = ID = 0 \quad \text{(3.10)} \\
&V_B = V_C = V_E = V_F = (I_B + I_C + I_E + I_F)Z_F \quad \text{(3.10a)}
\end{align*}
\]

The equations (3.10) and (3.10a) gives

\[
\begin{align*}
&I_{A0} + I_{A2} + I_{A4} = 0 \quad ; \quad I_{A1} + I_{A3} + I_{A5} = 0 \quad \text{(3.11)} \\
&(V_{A0} - 6 I_{A0} Z_F) = V_{A2} = V_{A4}; \quad V_{A1} = V_{A3} = V_{A5} \quad \text{(3.11a)}
\end{align*}
\]

The equations (3.11) and (3.11a) clearly suggest that all the sequence networks connected in parallel for simulating fault. Using these equations in (2.6) gives

\[
\begin{align*}
&I_{A1} = \frac{E_{A1}}{(Z_3 + Z_5)} \quad \text{(3.12)} \\
&I_{A0} = 0 \quad \text{(3.12a)}
\end{align*}
\]

This result can be verified from the fact that the phases B and E are in phase opposition and also phases C & F are in phase opposition.

\[
\text{Fig 3.8 Interconnection of sequence networks for BCEF-g.}
\]
e) Five - phase to ground fault:

![Fig 3.9 Schematic of a five phase to ground (BCDEF).](image)

Assume that the fault occur on phases B,C,D,E and F. It is doubtful that this type of fault will even occur on a six-phase system. Though the probability of it's occurrence is rare, it is worthwhile to analyze this fault.

The conditions at the fault location are

\[
I_A = 0
\]

\[
V_B = V_C = V_D = V_E = V_F = (I_D + I_C + I_D + I_E + I_F) Z_F
\]

\[
I_{A0} + I_{A1} + I_{A2} + I_{A3} + I_{A4} + I_{A5} = 0
\]

\[
(V_{A0} - 6 I_{A0} Z_F) = V_{A1} = V_{A2} = V_{A3} = V_{A4} = V_{A5}
\]

The above equations imply

The equations (3.14) and (3.14a) clearly suggest that all the sequence networks should be connected in parallel for simulating fault. Using these equations in (2.6) gives

\[
I_{A1} = \frac{E_{A1}}{Z_{1'} + \left[ Z_2 || \frac{1}{s} Z_3 || \frac{1}{s} Z_4 || \frac{1}{s} Z_5 || \frac{1}{s} (Z_0 + 6 Z_F) \right]}
\]
This is a dual of single phase to ground fault.

![Diagram showing interconnection of sequence networks for BCDEF-g.](image)

Fig. 3.10 Interconnection of sequence networks for BCDEF-g.

f) Six-phase to ground fault:

![Schematic of six-phase to ground fault (ABCDEF).](image)

Fig. 3.11 Schematic of six-phase to ground (ABCDEF).

Through this type of fault is the least probable one to occur, the analysis is simple, since it is a symmetrical fault. The terminal conditions are

\[ V_A = V_B = V_C = V_D = V_E = V_F = (I_A + I_B + I_C + I_D + I_E + I_F) Z_F \]  
\[ \text{VAO} = 6 IA0 ZF; \quad VA1 = 0; \quad VA2 = 0; \quad VA3 = 0; \quad VA4 = 0; \quad VA5 = 0 \]  
\[ I_{AO} = I_{A1} = I_{A2} = I_{A3} = I_{A4} = I_{A5} = 0 \]  
\[ (3.16) \]

The equation (3.16) imply

\[ V_{AO} = 6 I_{AO} Z_F; \quad V_{A1} = 0; \quad V_{A2} = 0; \quad V_{A3} = 0; \quad V_{A4} = 0; \quad V_{A5} = 0 \]  
\[ \text{VAO} = 6 IA0 ZF; \quad VA1 = 0; \quad VA2 = 0; \quad VA3 = 0; \quad VA4 = 0; \quad VA5 = 0 \]  
\[ (3.17) \]

Using (3.17) and (3.17a) in (2.6) imply

\[ I_{A1} = \frac{E_{A1}}{Z_1} \]  
\[ I_{AO} = 0 \]  
\[ (3.18) \]

\[ (3.18a) \]
Fig 3.12 Interconnection of sequence networks for ABCDEF-g.

(g) Phase – phase Fault:-

Let the fault be on phases A and D as shown in fig3.13. The conditions at the location of the fault are

\[ I_3 = I_c = I_e = I_f = 0 \quad ; \quad I_A + I_D = 0 \]

\[ V_A = (V_D + I_A Z_F) \]

The above two equations imply.

\[ I_{A0} = I_{A2} = I_{A4} = 0 \quad ; \quad I_{A1} = I_{A3} = I_{A5} \]

\[ V_{A0} + V_{A2} + V_{A4} = (V_A + V_D)/2 \]

Substituting the equations (3.20) and (3.20a) in (2.6) gives

\[ I_{A1} = \frac{E_{A1}}{Z_1 + Z_3 + Z_5 + 1.5 Z_F} \]

\[ I_{A0} = 0 \]
3.3 Analysis of faults through fault impedances using Dual Three Phase Transformation Method:

In the derivation of equations for the symmetrical components of current and voltages in a general six phase system during fault at any point, we shall designate $I_a$, $I_c$, $I_b$, $I_a'$, $I_c'$, $I_b'$, as the currents flowing out of the original system at the fault from phases $a$, $c$, $b$, $a'$, $c'$ and $b'$.

Similarly the phase to ground voltages are designated as $V_a$, $V_c$, $V_b$, $V_a'$, $V_c'$ and $V_b'$.

a) Single phase to ground fault:

![Fig 3.15 Schematic of single phase to ground fault](a-g)

The valid conditions at the fault location from fig 3.15 are
The equations (3.22) and (3.22a) imply
\[ I_c' = I_a = I_a^1 = I_c^1 = 0 \]  \hfill (3.22)
\[ V_a = I_a Z_F \]  \hfill (3.22a)

The equations (3.22) and (3.22a) imply
\[ I_{a0} = I_{a1} = I_{a2} ; \quad I_{a1} = I_{a2} = 0 \]  \hfill (3.23)
\[ V_{a0} + V_{a1} + V_{a2} = 3 I_{a0} Z_F ; \quad V_{a0} + V_{a1} + V_{a2} = 0 \]  \hfill (3.23a)

The equations (3.23) and (3.23a) suggest that the sequence networks must be connected in series using these equations in (2.17) gives

\[ I_{a1} = \frac{E_{at}}{\left[ Z_1 + Z_2 + (Z_0 - Z_{\infty}) + 3 Z_F \right]} ; \quad I_{a1}^1 = 0 \]  \hfill (3.24)
\[ I_{a0} = \frac{E_{at}}{\left[ Z_1 + Z_2 + (Z_0 - Z_{\infty}) + 3 Z_F \right]} ; \quad I_{a0}^1 = 0 \]  \hfill (3.24a)

Fig 3.16 Interconnection of sequence networks for a-g using D T P T method.
(b) Double line to ground fault:

Fig 3.17 Schematic of a two phase to ground fault (a a' - g).

The terminal conditions for double line to ground fault on a a' from fig 3.17 are

\[ I_c^1 = I_b^1 = I_c^1 = I_b^1 = 0 \quad \text{-------------------(3.25)} \]
\[ V_a = V_a^1 = (I_a + I_b^1)Z_f \quad \text{-------------------(3.25a)} \]

Using the inverse transformation on these equations results

\[ I_{a0} = I_{a1} = I_{a2} \quad ; \quad I_{a0} = I_{a1}^1 = I_{a2}^1 \quad \text{-------------------(3.26)} \]
\[ V_{a0} + V_{a1} + V_{a2} = 0 \quad ; \quad V_{a0}^1 + V_{a1}^1 + V_{a2}^1 = 0 \quad \text{-------------------(3.26a)} \]

Using equations (3.26) and (3.26a) in (2.17a) gives

\[ I_{a1} = \frac{E_{a1}}{[Z_1 + Z_2 + (Z_0 - Z_{00})]} \quad \text{-------------------(3.27)} \]
\[ I_{a1}^1 = \frac{E_{a1}^1}{[Z_1 + Z_2 + (Z_0 - Z_{00})]} \quad \text{-------------------(3.27a)} \]

Fig 3.18 Interconnection of sequence networks for a a' - g using D T P T method
(c) Three Phase to ground Fault:-

The terminal conditions for the three phase to ground fault through fault impedance on \( a' \ b' \ c' \) are

\[
\begin{align*}
I_a &= I_b = I_c = 0 \\
V_a' &= V_b' = V_c' = (I_a' + I_b' + I_c') Z_F
\end{align*}
\]

Equations (3.28) and (3.28a) imply

\[
\begin{align*}
I_{a0} &= I_{b1} = I_{c2} = 0 \\
V_{a10} &= V_{a1} = V_{a2} = 0
\end{align*}
\]

Substituting these equations in (2.17a) gives

\[
\begin{align*}
I_{a1} &= 0 \quad ; \quad I_{a1} = \frac{E_{a1}}{Z_1} \\
I_{a0} &= 0 \quad ; \quad I_{a1} = 0
\end{align*}
\]

Fig 3.20 Interconnection of sequence networks for \( a' b' c' - g \) using D T P T method.
d) Four Phase to ground fault:

![Diagram of a four phase to ground fault]

The valid relations are

\[ I_a = I_a^1 = 0 \]  \hspace{1cm} (3.31)

\[ V_b = V_c = V_b^1 = V_c^1 = (I_b + I_c + I_b^1 + I_c^1) Z_f \]  \hspace{1cm} (3.31a)

Using the inverse transformation on these two equations results

\[ I_{a0} + I_{a1} + I_{a2} = 0 \ ; \ I_{a1} + I_{a2}^1 + I_{a0}^1 = 0 \]  \hspace{1cm} (3.32)

\[ V_{a0} = V_{a1} = V_{a2} \ ; \ V_{a1}^1 = V_{a2}^1 \]  \hspace{1cm} (3.32a)

Substituting equations in (2.17a) gives

\[ I_{a1} = \frac{E_{a1}}{Z_1 + Z_2 \|_{e1} (Z_0 - Z_{00})} \]  \hspace{1cm} (3.33)

\[ I_{a2}^1 = \frac{E_{a1}^1}{Z_1 + Z_2 \|_{e1} (Z_0 - Z_{00})} \]  \hspace{1cm} (3.33a)

![Diagram of sequence networks for bc b' c' - g using D T P T method]
e) Five Phase to ground fault:

The terminal conditions from fig 3.23 are:

\[ I_a = 0 \]  \hspace{2cm} (3.34) \\
\[ V_b = V_c = V_a' = V_b' = V_c' = (I_b + I_c + I_a' + I_b' + I_c') Z_F \]  \hspace{2cm} (3.34a)

Using the inverse transformation on these two equations results in:

\[ I_{s0} + I_{s1} + I_{s2} = 0 ; \quad I_{s0}' = I_{s2}' = 0 \] \hspace{2cm} (3.35) \\
\[ (V_{s0} - 3 I_{s0} Z_F) = V_{s1} = V_{s2} ; \quad V_{s1}' = V_{s2}' = 0 \] \hspace{2cm} (3.35a)

Imposing these equations in (2.17a) gives:

\[ I_{s1} = \frac{E_{s1}}{Z_1 + (Z_0 - Z_{00} + 3 Z_F) || Z_2} \] \hspace{2cm} (3.36) \\
\[ I_{s1}' = \frac{E_{s1}'}{Z_1} \] \hspace{2cm} (3.36a)

Fig 3.24 Interconnection of sequence networks for bc a' b' c' -g using D T P T method.
f) Six Phase to ground fault:-

![Schematic of a six phase to ground fault](image)

Fig 3.25 Schematic of a six phase to ground fault (abc a' b' c' -g).

Though this type of fault is the least probable fault the analysis is simple and it is a symmetrical fault. The valid conditions from fig 3.25 are

\[ V_a = V_b = V_c = V_a' = V_b' = V_c' = (I_a + I_b + I_c + I_{a'} + I_{b'} + I_{c'}) Z_F \quad (3.37) \]

Using the inverse transformation results in

\[ V_{s1} = E_{s1} - I_{s1} Z_l = 0 \quad ; \quad V_{a1} = E_{a1} - I_{a1} Z_l = 0 \quad \text{(3.38)} \]

Imposing these equations in (2.17a) gives

\[ I_{s1} = \frac{E_{s1}}{Z_l} \quad ; \quad I_{a1} = \frac{E_{a1}}{Z_l} \quad \text{---------- (3.39)} \]

\[ I_{s0} = 0 \quad ; \quad I_{a0} = 0 \quad \text{---------- (3.39a)} \]

![Interconnection of sequence networks for abc a' b' c' -g using D T P T method](image)
g) Phase – Phase fault:

The boundary Conditions are
\[ I_b = I_c = I_b^1 = I_c^1 = 0 \quad ; \quad I_a + I_a^1 = 0 \] \hspace{1cm} (3.40)
\[ V_a = V_a^1 + I_a Z_F \] \hspace{1cm} (3.40a)

The above equations gives
\[ I_{a0} = I_{a1} = I_{a2} = (I_a / 3) \quad ; \quad I_{a0}^1 = I_{a1}^1 = I_{a2}^1 = (I_a^1 / 3) \] \hspace{1cm} (3.41)
\[ V_{a0} + V_{a1} + V_{a2} = V_a \quad ; \quad V_{a0}^1 + V_{a1}^1 + V_{a2}^1 = V_a^1 \] \hspace{1cm} (3.41a)

Using these equations in (2.17a) gives
\[ I_{a1} = \frac{E_{a1} \cdot E_{a1}^1}{2Z_1 + 2Z_2 + [2(Z_0 - Z_{00}) + 3Z_F]} \] \hspace{1cm} (3.42)

Fig 3.27 Schematic of a phase – phase fault (a a').

Fig 3.28 Interconnection of sequence networks for a a' using DTPT method.
3.4 **Illustrative Example on a Sample System:**

Length of six phase transposed transmission line = 50 miles

Rating of Generator = 100 MVA and 138 KV

Self impedance $Z_s = 8.574 + j 37.87 \, \Omega$

Mutual impedance $Z_m = 5.571 + j 14.655 \, \Omega$

Zero Sequence impedance $Z_0 = 36.429 + j 111.165 \, \Omega$

Positive Sequence impedance $Z_1 = 3.003 + j 23.235 \, \Omega$

Fault Impedance $Z_F = 4 + j 0 \, \Omega$

The results of various faults are tabulated in tables 3.1 and 3.2 by making use of symmetrical components and DTPT methods. The results of DTPT method are fully agreeing with symmetrical components method and phase-co-ordinate method, which are reported by others.
<table>
<thead>
<tr>
<th>Type of Fault</th>
<th>IA</th>
<th>IB</th>
<th>IC</th>
<th>ID</th>
<th>IE</th>
<th>IF</th>
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<td>-73°</td>
<td>5689</td>
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<td>5689</td>
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<td>167°</td>
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<td>Type of Fault</td>
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<td>$I_a$ Ang. (Deg)</td>
<td>$I_{c_1}$ Mag. (Amp)</td>
<td>$I_{c_1}$ Ang. (Deg)</td>
<td>$I_b$ Mag. (Amp)</td>
<td>$I_b$ Ang. (Deg)</td>
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<td>5688</td>
<td>169°</td>
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<td>-134°</td>
</tr>
<tr>
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<td>0.03</td>
<td>88°</td>
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<td>-134°</td>
</tr>
<tr>
<td>1φ-g; a g</td>
<td>3459</td>
<td>-74°</td>
<td>0</td>
<td>0°</td>
<td>0</td>
<td>0°</td>
</tr>
</tbody>
</table>
Different types of faults through impedances of a six phase system both involving ground and not involving ground has been analysed using (i) Six phase symmetrical components method and (ii) Dual Three Phase Transformation. The results obtained for both the methods agree fully.

Also it has been observed during the analysis of the faults through impedances, that in certain cases of faults, i.e. the ground fault through fault impedance, the zero-sequence component of the fault current is absent inspite of it being a ground fault. Hence it may be noted that if only zero sequence currents are used to relay ground faults, the protection scheme fails to act in such cases. This point is to be borne in mind while designing a protection scheme for six phase system.

A sample system data is taken from [44] and the faults through impedences are analyzed using (i) Six phase symmetrical components, (ii) Dual Three Phase Transformation method. The results of D T P T method are fully agreeing with symmetrical component method and phase-co-ordinate method, which are reported by others.