Module 3 : Sequence Components and Fault Analysis
Lecture 13 : Sequence Modeling (Tutorial)

Objectives

In this lecture we will solve tutorial problems on fault analysis in sequence domain.

- Per unit values of all element impedance in the given system.
- Reduction of the circuit for the given fault locations.
- S-L-G fault current for the given system.

1. Fig 13.1 shows the single line diagram of a 13.8kV system connected to a 480V bus through a 13.8kV/480V transformer. Two motor loads of 400hp and 600hp are connected to the bus through three parallel three core copper cables. If a 3 phase bolted fault occurs at $R_1$, compute the fault currents. Repeat the calculations for fault at $R_2$.

Ans: Let us take base power as 1000kVA and base voltage as 480V.

Then base current $= \frac{kVA \times 1000}{\sqrt{3} \times \text{base voltage}}$

$= \frac{1000 \times 1000}{\sqrt{3} \times 480} = 1202.8A$

Base impedance $= \frac{\text{Base voltage (per phase)}}{\text{Base current}} = \frac{480\sqrt{3}}{1202.8} = 0.2304\Omega$

Now, we have to convert all impedances element into per unit values on a common base. Here the impedance base is 0.2304 $\Omega$.

Short circuit contribution from 13.8kV source = 600MVA.

Source Modeling
Short circuit current $= \frac{600 \times 10^6}{\sqrt{3} \times 13.8 \times 10^3} = 25102A$

$X/R$ ratio = 15

Fig 13.1 Three Phase Distribution System:
\[
Z_s = \frac{\text{base kVA}}{\text{short circuit kVA}} = \frac{1000}{600 \times 10^3} = 0.00166 \text{pu}
\]
\[
\frac{X_s}{R_s} = 15 \quad Z_s = \sqrt{R_s^2 + X_s^2} \quad \text{or} \quad Z_s^2 = R_s^2 + X_s^2
\]

1. Ans: \( i.e. (0.00166)^2 = R_s^2 + (15R_s)^2 \)

\[
R_s = 0.00011 \text{pu} \quad X_s = 0.00165 \text{pu}
\]

i.e. \( Z_s \) in pu = 0.00011 + j0.00165

1000kVA Transformer Modeling.

\[
Z_T = 5.75\% \quad R_T = 1.21\%
\]

The per unit value of \( R_T = \frac{\text{base kVA}}{\text{Transformer kVA}} \times \frac{\% R_T}{100} \)

\[
= \frac{1000 \times 1.21}{100} = 0.0121 \text{pu}
\]

Per unit value of \( Z_T = \frac{1000 \times 5.75}{100} = 0.0575 \text{pu} \)

\[
X_T = \sqrt{Z_T^2 - R_T^2} = 0.0562 \text{ pu}
\]

i.e. \( Z_T \) in pu = 0.0121 + j0.0562

Cable \( C_1 \) Modeling

Length of cable \( C_1 = 500 \text{m} \),

Resistance of one conductor per km = 0.178 Ω

Reactance of one conductor per km = 0.108 Ω

Since, three conductors are in parallel, equivalent resistance and reactance for 500m length is given by,

\[
R_{c1} = \frac{0.178}{3} \times \frac{500}{1000} = 0.0297 \Omega
\]

\[
X_{c1} = \frac{0.108}{3} \times \frac{500}{1000} = 0.018 \Omega
\]

Converting \( R_{c1} \) and \( X_{c1} \) into per unit,

\[
R_{c1} \text{ in pu} = \frac{\text{Actual value}}{\text{base value}} = \frac{0.0297}{0.2304} = 0.129
\]

\[
X_{c1} \text{ in pu} = \frac{0.018}{0.2304} = 0.078
\]

i.e. \( Z_{c1} \) in pu = 0.129 + j0.078

1. Ans: Cable \( C_2 \) Modeling

Length of cable \( C_2 = 300 \text{m} \),

Resistance of one conductor per km is given as 0.181 Ω and reactance / km is given as 0.124 Ω. Since, three conductors are in parallel, equivalent resistance and reactance for 300m cable is given by,

\[
R_{c2} = \frac{0.181}{3} \times \frac{300}{1000} = 0.0181 \Omega
\]

\[
X_{c2} = \frac{0.124}{3} \times \frac{300}{1000} = 0.0124 \Omega
\]

Converting into pu
\[ R_{c2} \text{ in pu} = \frac{0.0181}{0.2304} = 0.0786 \text{ pu} \]
\[ X_{c2} \text{ in pu} = \frac{0.0124}{0.2304} = 0.0538 \text{ pu} \]

i.e. \[ Z_{c2} \text{ in pu} = 0.0786 + j0.0538 \]

Motors

Note that 1hp = 746 watts; if we assume a motor power factor of 0.746, then equivalent motor kVA will be unity. Hence, we will assume that 1hp is equivalent to 1kVA.

Subtransient reactance = 25% 
\[ \frac{X}{R} \text{ Ratio} = 6 \]

Per unit reactance of motor 1
\[ \frac{X_{m1}}{R_{m1}} = \frac{\text{base kVA} \times \%X_{m1}}{\text{motor kVA}} = \frac{1000 \times 25}{400 \times 100} = 0.625 \text{ pu} \]
\[ R_{m1} = 0.625 \text{ pu} \]

For motor 2
\[ \frac{X_{m2}}{R_{m2}} = \frac{1000 \times 25}{600 \times 100} = 0.416 \text{ pu} \]
\[ R_{m2} = 0.416 \text{ pu} \]

\[ Z_{m2} \text{ in pu} = 0.069 + j0.416 \]

The equivalent circuit of the system used to calculate the Thevenin’s equivalent at node A is shown in fig 13.2. The dotted lines indicate the ground potential.

1. Ans: Fault at \( R_1 \)

We now desire to compute Thevenin’s impedance at node A.

For fault at \( R_1 \), the network as shown in fig 13.2 can be reduced to network as shown in fig 13.3. Hence, Thevenin’s impedance, \( Z_{th} \) is given by,

\[ \frac{1}{Z_{th}} = \frac{1}{Z_s + Z_T} + \frac{1}{Z_{c1} + Z_{m1}} + \frac{1}{Z_{c2} + Z_{m2}} \]

\[ = \frac{1}{0.01221 + j0.05785} + \frac{1}{0.233 + j0.703} + \frac{1}{0.1476 + j0.4698} \]
\[ = \frac{1}{0.059[78.1°]} + \frac{1}{0.74[71.6°]} + \frac{1}{0.49[72.6°]} \]
\[ = 16.95[-78.1°] + 1.35[-71.6°] + 2.04[-72.6°] \]
\[ = 3.5 - j16.6 + 0.426 - j1.28 + 0.61 - j1.9 \]
\[ = 4.536 - j19.78 = 20.3[-77.1°] \]
Therefore, three phase fault current at fault $F_1 = \frac{\text{base current}}{Z_{th}}$

$$= \frac{1202.8}{0.049} = 24547 \text{A}$$

1. Ans: Fault at $F_2$

For fault at $F_2$, the network shown in fig 13.2. can be reduced as shown in fig 13.4.

Calculation of $Z$

$$Z = Z_{z1} + \frac{1}{Z_{z1} + Z_T + Z_{z2} + Z_{m2}}$$

$$= 0.129 + j0.078 + \frac{1}{\frac{1}{0.01221+ j0.05785} + \frac{1}{0.1476+ j0.4698}}$$

$$= 0.129 + j0.078 + \frac{1}{\frac{1}{3.5 - j16.6 + 0.61 - j1.9}}$$

$$= 0.129 + j0.078 + \frac{1}{4.11 - j18.5} = 0.129 + j0.078 + 0.054 \angle 77.5$$

$$= 0.129 + j0.078 + 0.012 + j0.053 = 0.141 + j0.131 \text{pu}$$

$$\frac{1}{Z_{th}} = \frac{1}{Z} + \frac{1}{Z_{m1}} = \frac{1}{0.141 + j0.131} + \frac{1}{0.104 + j0.625}$$

1. Ans:

$$= \frac{1}{0.192\angle 42.7^\circ} + \frac{1}{0.633\angle 80.5^\circ} = 3.83 - j3.53 + 0.26 - j1.56$$

$$= 4.09 - j5.09 = 6.53\angle 51.2^\circ$$

i.e., $Z_{th} = \frac{1}{6.53\angle 51.2^\circ} = 0.153\angle 51.2^\circ$

Therefore, the total three phase fault current at $F_2 = \frac{\text{base ampere}}{\text{per unit} Z_{th}}$

$$= \frac{1202.8}{0.126} = 7851.44 \text{A}$$

Fig 13.5 shows the single line diagram of a 3 bus system. The sequence data for transmission lines and
2. generators are given in table 1. If a bolted single line to ground fault occurs at F, calculate the fault current. If the fault impedance is j0.1 pu; what will be the fault current?

Ans: Let us take E as 1 pu. For a SLG fault, Fault current

\[
F = \frac{3E}{Z_0 + Z_1 + Z_2 + 3Z_f}
\]

where \(Z_0\) = Zero sequence impedance
\(Z_1\) = Positive sequence impedance
\(Z_2\) = Negative sequence impedance
We have to find out the Thevenin's equivalent zero, positive and negative sequence impedances with respect to fault F.

<table>
<thead>
<tr>
<th>Description</th>
<th>Sequence Data in pu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zero</td>
</tr>
<tr>
<td>Generator - A</td>
<td>j0.03</td>
</tr>
<tr>
<td>Generator - B</td>
<td>j0.02</td>
</tr>
<tr>
<td>Transmission Line 1</td>
<td>j0.14</td>
</tr>
<tr>
<td>Transmission Line 2</td>
<td>j0.17</td>
</tr>
<tr>
<td>Transmission Line 3</td>
<td>j0.10</td>
</tr>
<tr>
<td>Transmission Line 4</td>
<td>j0.12</td>
</tr>
</tbody>
</table>

2. Ans: Zero Sequence Impedance

For calculating \(Z_0\), the circuit shown in fig 13.5 is reduced as shown in fig 13.6.

\[
Z_0 = j0.021 + j0.031 = j0.052 pu
\]
2. Ans: Positive Sequence Impedance

Similarly, positive sequence impedance $Z_1$ can be found out by reducing the circuit as shown in fig 13.7.

i.e. $Z_1$, positive sequence impedance = $j0.01 + j0.124$

= $j0.134$ pu

2. Ans: Negative Sequence Impedance
Negative sequence impedance $Z_2$

For negative sequence impedance the circuit can be as shown in fig 13.8.

i.e. negative sequence impedance $Z_2 = j0.01 + j0.08 = j0.09 \text{ pu}$

Now, fault current $I_f = \frac{3E}{Z_1 + Z_2 + Z_0} = \frac{3 \times 10 \text{ pu}}{j0.134 + j0.09 + j0.052}$

$= \frac{3 \times 10}{j0.276} = \frac{3 \times 10}{j0.276} \text{ or } 10.869^\circ -90^\circ$

If fault impedance $Z_f = j0.1$, then $I_f = \frac{3E}{Z_1 + Z_2 + Z_0 + 3Z_f} = \frac{3 \times 10 \text{ pu}}{j0.276 + j0.1 \times 3} = 5.208^\circ -90^\circ$

Review Questions

1. Calculate the symmetrical fault currents at locations $F_1$ and $F_2$ of fig 13.9.
2. For the system shown in example no. 2, find out the fault current for
   a) SLG fault with j0.1 fault impedance.
   b) L-L fault and L-L-G fault between b-c phases.
   c) L-L fault and L-L-G fault with j0.1 fault impedance. Single line diagram of this question is shown in fig 13.5.

3. Single line diagram of a system is shown in fig 13.10. The base value is taken as 30MVA, 34.5kV. The positive and negative sequence impedances of load are 1.0 \(25.84^\circ \text{pu}\), 0.60 \(29^\circ \text{pu}\) respectively. Load voltage is kept at 1.0 pu. Calculate the fault current for fault at F. Assume that zero sequence reactance of generator is zero.

Recap

In this lecture we have learnt the following:

- To calculate per unit values of different elements in a system.
- Reduction of the given complex circuit for different fault locations.
- Three phase symmetrical fault current calculation.
Fault current calculation of the given system.