Fault Locating

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Topics

- Impedance Based
- Reactance Method
- Takagi Method
- Modifications to Takagi Method
- TWS & Double-Ended Negative Sequence
One-Line

- Equivalent Thevenin Sources
- Bus
- Line
- Relay with CT & CCVT
Radial Line

- Apply a fault “m” distance down a radial line

- “m” is a percentage of the line. For example if the fault is 25% from Bus S then (1-m) yields 75%, for a total line impedance, $Z_L$, of 100%
Using ohms law the fault locator at S can calculate the impedance, \( mZ_L \), that the voltage \( V \) is being dropped across for three-phase bolted faults.
The equivalent circuit with respect to Bus S clearly shows that the measured voltage $V$ is being dropped across the portion of the transmission line to the fault point.

\[ (m)Z_L = \frac{V}{I} \quad \text{(Ohms)} \]

\[ m = \frac{(V/I)}{Z_L} \quad \text{(%)} \]

Fault Location = $m$ (Line Length) \quad \text{(miles)}
Assume the fault has some resistance, R and the transmission line is purely inductive.
Let $I_s = 10 \angle 0^\circ \text{A}$, $X_L = 10 \Omega$, & $R_F = 5 \Omega$

- $V_{\text{LINE}} = 10 \angle 0^\circ (10 \angle 90^\circ) = 100 \angle 90^\circ \text{V}$
- $V_F = 10 \angle 0^\circ (5 \angle 0^\circ) = 50 \angle 0^\circ \text{V}$
- $V_s = V_{\text{LINE}} + V_F = 112 \angle 63^\circ \text{V}$
- Distance = $V_s/I_s = 11 \angle 63^\circ \Omega$
- $mZL \neq \text{Distance}$
V/I Limitations

• Using ohms law directly as fault locator is impractical for a variety of reasons. Some of these include:
  ✷ Only works on three-phase faults
  ✷ Only works on radial lines
  ✷ Only works on bolted faults
  ✷ Impacted by Load
Simple Reactance Method

- Transmissions line impedance, Z, is typically dominated by the reactive component, X.

- Fault impedance is typically dominated by the resistive component, R.
Fault Resistance & Reactance Method

- Lets look at the radial example with fault resistance again.

![Diagram showing fault resistance and reactance method]

- The forward voltage drop measured by the fault locator is
  \[ V_s = mZ_L(I_s) + I_s(R_F) \]
Minimize the Effect of $R_F$ using Reactance

\[ V_S = (mZ_L \cdot I_S) + (I_S \cdot R_f) \]

Divide by the measured current $I_S$

\[ \frac{V_S}{I_S} = \frac{(mZ_L \cdot I_S)}{I_S} + \frac{(I_S \cdot R_f)}{I_S} \]

Retain only the imaginary component of each quantity

\[ Im\{Z_S\} = Im\{mZ_L\} + Im\{R_f\} \]

\[ Im\{R_S + jX_S\} = Im\{R_L + jX_L\} \cdot m + Im\{R_f + j0\} \]

\[ X_S = mX_L \]
Reactance Method with Remote Source

- No longer is the system radial

- The current flowing through $R_F$ is now the sum of the local source, $I_s$, and the remote source, $I_R$

$$\vec{I}_f = \vec{I}_s + \vec{I}_R$$
Same Reactance Technique: Now with $I_R$

Write the forward voltage drop equation,

$$V_S = mZ_L \cdot I_S + I_f R_f$$

Divide by $I_s$ to calculate a measured Impedance,

$$\frac{V_S}{I_S} = \frac{mZ_L I_S}{I_S} + \frac{I_f R_f}{I_S}$$

Take the imaginary component of each term to mitigate fault resistance,

$$Im\{Z_S\} = Im\{mZ_L\} + Im\left\{\frac{I_f}{I_S} R_f\right\}$$
Homogenous System & Reactance

- If you have a homogenous system then both $I_S$ and $I_R$ will have the same angle and the imaginary part of $(I_f/I_s)R_f$ is zero.

$$Im \left\{ \frac{I_f \angle \Theta}{I_s \angle \Theta} R_f \right\} = Im \left\{ \frac{|I_f|}{|I_s|} \angle \Theta - \Theta \cdot R_f \right\} = Im \left\{ \frac{|I_f|}{|I_s|} \angle 0^\circ \cdot R_f \right\} = 0$$
Non-Homogenous System & Reactance

- $I_S$ and $I_R$ will not have the same angle and the imaginary part of $(I_f/I_s)R_f$ will show up in the fault location calculation as an error term.

\[
\text{Im}\left\{\frac{I_f\angle\delta}{I_s\angle\alpha} R_f\right\}
\]

\[
\text{Im}\left\{\frac{|I_f|}{|I_s|} \angle(\delta - \alpha) \cdot R_f\right\}
\]

\[
\delta - \alpha \neq 0
\]
The simple reactance method was an improvement over the straight Ohms Law calculation but it still has some drawbacks:

- Impacted by Load
- Non-homogenous systems introduce error in fault resistance term
Takagi Method

- In 1979 Toshio Takagi and Yukinari Yamakoshi filed for a U.S. Patent for a new single-ended fault locating method.

- In 1982 Takagi, et al. deliver their paper.

The key to the Takagi method is the idea of superposition.
Takagi Local & Remote Current

Voltage equation for the left-hand side:

\[ I'_S (Z_S + mZ_L) + I'_R = \frac{Z_S + mZ_L}{Z_R + (1 - m)Z_L} I'_S (1 - m)Z_L + I'_F R_F = V_F \]

Both equations equal \( V_F \). Set the Left side equal to the right side.
No Fault Current in Load Circuit

- $I_f = I'_f$ because there is no fault branch current in the pure load state

Composite Fault Network

Load

Pure Fault Network
From the previous slide, calculated $I'_R$ in terms of $I'_S$.

Plugging into $I_F$ equation:

$$I'_F = I'_S + I'_R$$

$$I'_F = I_F$$

$$I_F = I'_S + \frac{Z_S + mZ_L}{Z_R + (1 - m)Z_L} I'_S$$
From the previous fault location algorithms we developed the forward voltage drop equation with respect to fault locator:

\[ V_S = mZ_L \cdot I_S + I_f R_f \]

Plug-in our new equation for the fault branch current, \( I_f \):

\[ V_S = mZ_L I_S + R_F I'_S \cdot \frac{Z_R + Z_S + Z_L}{Z_R + (1 - m)Z_L} \]
Pause for Error

\[ V_s = mz_L I_s + R_F I'_s \]

\[ |n| \angle \gamma = \frac{I_s}{I'_s} \]

\[ \frac{Z_R + Z_S + Z_L}{Z_R + (1 - m)Z_L} = |d| \angle \beta \]

If there is load flow on the system \( \gamma \) will be non-zero but if the magnitude of fault duty is much greater than load, the angle \( \gamma \) will approach zero.

\( \beta \) will be zero if the numerator and denominator have the same phase angle, (homogeneous system)
Takagi Distance

\[ V_s = mZ_L I_s + R_F I_s' \cdot \frac{Z_R + Z_S + Z_L}{Z_R + (1 - m)Z_L} \]

If we:
- Multiply by the complex conjugate of I’s,
- Take the imaginary part of the equation to eliminate fault resistance,
- Assume the system is totally homogeneous, and finally
- Solve for m

We will get the following equation:

\[ m = \frac{Im\{V_s I_s'^*\}}{Im\{Z_L I_s I_s'^*\}} \]
The Takagi can use the zero sequence term for ground faults, eliminating the need for pre-fault data

\[ m = \frac{Im\{V_s 3I_{0S}^*\}}{Im\{Z_L I_s 3I_{0S}^*\}} \]

The negative sequence can also be used

\[ m = \frac{Im\{V_s I_{2S}^*\}}{Im\{Z_L I_s I_{2S}^*\}} \]
• There is magnetic coupling between phases on a current carrying transmission line, $Z_m$. 
Mutual Coupling

- Apply a bolted fault some length $m$ down the line.

A voltage is induced in each phase through the mutual coupling. Here $Z_m$ is written explicitly as $Z_{ab}$ and $Z_{ac}$.
The forward voltage drop equation for the faulted phase is

\[ V_a = m(Z_s I_a + Z_m I_b + Z_m I_c) + R_f I_f \]

Adding & Subtracting the same quantity

\[ V_a = m(Z_s I_a - Z_m I_a + Z_m I_a + Z_m I_b + Z_m I_c) + R_f I_f \]

Gathering terms

\[ V_a = m[(Z_s - Z_m)I_a + Z_m(I_a + I_b + I_c)] + R_f I_f \]
Voltage Equation Cont’d

Recognize that \( I_a + I_b + I_c \) is the residual or zero sequence current

\[
V_a = m[(Z_s - Z_m)I_a + Z_m(I_{res})] + R_f I_f
\]

\( Z_m \) is a difficult quantity to handle directly. Through the use of Symmetrical Component theory it can be shown that:

\[
Z_{L1} = Z_s - Z_m \quad \text{and} \quad Z_{L0} = Z_s + 2Z_m
\]

Solving for \( Z_s \) in the \( Z_{L0} \) equation and plugging this into the \( Z_{L1} \) equation yields a \( Z_m \) that is equal to:

\[
Z_m = \frac{Z_{L0} - Z_{L1}}{3}
\]
$V_a$ and the mysterious $k$

$V_a$ is now expressed in terms of positive and zero sequence line parameters which can be loaded into a relay as settings

$$V_a = m[(Z_{L1})I_a + \frac{Z_{L0} - Z_{L1}}{3} (I_{res})] + R_f I_f$$

Factor out $mZ_{L1}$, (the distance to the fault)

$$V_a = mZ_{L1} \left[ I_a + \frac{Z_{L0} - Z_{L1}}{3Z_{L1}} (I_{res}) \right] + R_f I_f$$

Define $k$ to make the equation prettier

$$k = \frac{Z_{L0} - Z_{L1}}{3Z_{L1}}$$
Modified Takagi

\[ V_a = mZ_{L1}[I_a + k(I_{res})] + R_f I_f \]

Once again take the imaginary component of both sides and solve for \( mZ_{L1} \)

\[ Im\{V_a\} = mZ_{L1} Im\{I_a + k(I_{res})\} + Im\{R_f I_f\} \]

\[ mZ_{L1} = \frac{Im\{V_a\}}{Im\{I_a + k(I_{res})\}} \]
Two Terminal Methods

• More accurate than single-ended methods

• Minimizes/Eliminates effects of
  - Fault Resistance
  - Loading
  - Line Charging Current

• More overhead. Data must be gathered or shared from multiple locations
Traveling Wave

- A fault will cause a transient to propagate along the line as a wave
- The wave is a composite of frequencies with a fast rising front and slower decaying tail
- The waves travel at near the speed of light and eventually decay
- By time tagging the wave fronts as they cross both terminals a very precise fault location can be calculated
The waves leave the disturbed area traveling at the velocity of propagation which is a little less than the speed of light.
In 1999 Demetrios A. Tziouvaras, Jeff Roberts, and Gabriel Benmouyal of SEL introduced a new double-ended technique that uses the negative sequence quantities from both terminals to fault locate.

By using the negative sequence methodology proposed by SEL the following sources of error are mitigated:

- Prefault load
- Zero sequence mutual coupling
- Zero sequence infeed from line taps
- Fault Resistance


