Traveling Wave Relays

- Transients are the basis of detection
- Work on the time domain reflectometer principle
- Some systems are being tried (BPA)
- Requires
  - Better instrumentation
  - Precision time synchronism
  - High speed data communications between terminals.

Traveling Wave Relays

- Detection uses the phase voltage
  - Faults generate a step change in voltage or current magnitude
- Need to know \( Z_c \) and \( \tau_c \) for transmission line

![Diagram of Traveling Wave Relays](image-url)
Traveling Wave Relays

- Transmission line models must now include capacitance
- Uses the Distributed parameter Line model
- Voltage and current waves travel at the same speed
- Characterized by:

\[ Z_c = \sqrt{\frac{L_s}{C_s}} \quad \text{or} \quad Z'_c = \sqrt{\frac{Z_c + R_s}{C_s}} \quad \text{and} \quad \tau = \sqrt{L_s \frac{C_s}{Ls}} \]

\[
\begin{align*}
R_s &= 5.38205E-01 \quad L_s = 1.14045E-02 \quad C_s = 4.51987E-08 \\
R_s &= 5.38205E-01 \quad XL_s = 4.29940E+00 \quad XC_s = 5.86872E+04 \\
R_m &= 2.95306E-01 \quad L_m = 5.35933E-03 \quad C_m = -6.48638E-09 \\
R_m &= 2.95306E-01 \quad XL_m = 2.02042E+00 \quad XC_m = -4.08946E+05 \\
\end{align*}
\]

Sequence Impedance - Distributed Line Parameter Model

\[
\begin{align*}
R_0 &= 1.12882E+00 \quad L_0 = 2.21232E-02 \quad C_0 = 3.22259E-08 \\
R_0 &= 1.12882E+00 \quad XL_0 = 8.34024E+00 \quad XC_0 = 8.23122E+04 \\
R_1 &= 2.42899E-01 \quad L_1 = 6.04519E-03 \quad C_1 = 5.16850E-08 \\
R_1 &= 2.42899E-01 \quad XL_1 = 2.27898E+00 \quad XC_1 = 5.13221E+04 \\
R_2 &= R_1, \quad L_1 = L_1, \quad \text{and} \quad C_2 = C_1
\end{align*}
\]
Traveling Wave Relays

Model Surge Impedance - Distributed Line Parameter Model

\[ Z_0 = 8.32324 \times 10^2 \text{ at } -3.85395 \times 10^0 \text{ deg.} \]

Travel speed = 1.19846 \times 10^5 \text{ miles/sec (64\% speed of light)}

\[ \tau_{c_0} = \frac{\text{distance}}{\text{Travel speed}} = \text{distance} \times 8.3440 \mu s \]

\[ Z_1 = 3.42964 \times 10^2 \text{ at } -3.04187 \times 10^0 \text{ deg.} \]

Travel speed = 1.81035 \times 10^5 \text{ miles/sec (97\% speed of light)}

\[ \tau_{c_1} = \frac{\text{distance}}{\text{Travel speed}} = \text{distance} \times 5.5238 \mu s \]

Traveling Wave Relays

- Determining direction requires knowing when the remote terminal detects wave front.

- Let:
  - \( t_r \) = remote time of detection
  - \( t_s \) = local time of detection
  - \( t_l \) = travel time for line

- Algorithm
  if \( |t_s - t_r| < t_l \) then fault in zone else not
Traveling Wave Relays

Voltage transients

Optimistic: Fault occurs at a voltage peak

Current transients
Traveling Wave Relays

- **Problems**
  - Ground mode and line mode travel at different rates
  - Detection requires strong transient signals
  - Conventional instrumentation inadequate

- **Advantages**
  - fast
  - fast
  - fast

Fault Location

- **Standard equipment on microprocessor based relays**
- **Single ended is desirable**
  - cheap (packaged with relay)
  - fairly reliable
  - does not require communications
  - inherent with traveling wave and distance relays
Fault Location

- **Significant Problems**: Line configurations
  - Strong zero-sequence mutual coupling
  - Multiple remote terminals (most commonly three-terminal applications)
  - Large angle differences between power system sources and the protected line
  - Non-transposed transmission lines

- **Can be overcome using communications and time**
  - Heisenberg uncertainty principle applies

- **Fundamental**: Single phase – single end:

  \[
  Z = \frac{V}{I}
  \]

  \[
  V_a = I_a (mZ_1 + R_F) = m (I_a Z_1) + I_a R_F
  \]

  \[
  m = \frac{V_a - I_a R_F}{I_a Z_1} \quad \text{Okay if } R_F = 0
  \]

  \[
  m = \frac{\text{Im}[V_a - I_a]}{\text{Im}[(I_a Z_1) I_a]} \quad \text{Accuracy of } Z_1 \text{ affects accuracy of calculation of } m
  \]
Fault Location

- Single line to ground faults for multi-phase lines
  - Need to know $Z_{1L}$ and $Z_{0L}$
  - Works best for radial lines

$$m = \frac{\text{Im}(Va Ia)}{\text{Im}(Z_{1L} (Ia - k_0 Ia_0) Ia)}$$  \text{Ground faults}

$$m = \frac{\text{Im}(Vbc \overline{Ibc})}{\text{Im}((Ibc Z_L) Ibc)}$$  \text{Phase faults}

Fault Location

- Fault locating for multi-terminal lines
- Two approaches:
  - With communications
  - Without communications
- Start by writing loop equations (Ohm’s law)

Ground fault

$$Va = m (Ia Z_{1L}) + I_F R_F$$

Phase fault

$$Vbc = m (Iab Z_{1L}) + I_F R_F$$

Fault Location

- Single ended fault calculations for multi-terminal lines
- Two simple methods
  - simple reactance (been there – done that)
  - algorithm based on work by Takagi
- Reactance method
  - Measures apparent impedance
  \[ V_{aS} = m Z_L \left( I_{aS} + I_{a0} K_0 \right) + (I_{aS} + I_{aR}) R_F \]
  \[ X_{L \text{ apt}} = \text{Im} \left( \frac{V_{aS}}{I_{aS}} \right) \quad m = \frac{X_{L \text{ apt}}}{\text{Im}(Z_L)} \]

Fault Location

- Works well
  - Homogeneous systems
  - Low fault resistance
  - Low power flow
- Errors caused by \( R_F \): Ignore or eliminate
  - Ignoring – assumes best case scenario
  - Elimination – Use negative sequence current
  \[ m = \frac{\text{Im}\left[ V_{as} \overline{I_{as2}} \right]}{\text{Im}\left[ Z_L (I_{as} + k_0 3 \cdot I_{a0}) \overline{I_{as2}} \right]} \]
Fault Location

• Takagi method
  – does not use $I_{A2}^*$ or $I_{R}^*$
  – Uses complex conjugate of a superposition term
  – Requires good pre-fault data

• Superposition term:
  – $I\phi$ pre-fault - $I\phi$ post-fault

$$\alpha = \left( I_{\phi \text{PRE \_FAULT}} - I_{\phi \text{POST \_FAULT}} \right)$$

Fault Location

• Read for next time
  – Selected papers link
    • 6001.pdf (SEL)
    • 6089.pdf (SEL)
    • review of methods.pdf (ABB)