Performance Comparison Between Mho Elements and Incremental Quantity-Based Distance Elements

Gabriel Benmouyal, Normann Fischer, and Brian Smyth
Schweitzer Engineering Laboratories, Inc.
Overview

• Present characteristics of incremental distance in impedance plane
• Compare performance of mho elements and incremental distance elements based on their characteristics
• Compare performance with series compensation
• Discover issues with mutually coupled lines and three-terminal lines
Superposition Principle

230 kV System

CT Ratio: 240/1
VT Ratio: 2,000/1
All impedances in primary values

ZL1 = 17.47 (86°) ohms
ZL0 = 62.47 (75.38°) ohms
ZR1 = 20 (78°) ohms
ZR0 = 62.08 (71°) ohms
ZS1 = 10 (73°) ohms
ZS0 = 33 (68.5°) ohms

VM

L

vm

d

Relay

R

VN (θ°)
Single-Phase Faults
Pure-Fault Sequence Network

\[ V = V_{PF} + \Delta V \]
\[ I = I_{PF} + \Delta I \]

\[ Ef_A = VM - (ZS1 + d \cdot ZL1) \cdot I_{LD} \]

\[ Ef_A = VA_{PF} - d \cdot ZL1 \cdot I_{LD} = -\Delta VA + d \cdot ZL1 \cdot (\Delta I_A + K_0 \cdot I_0) + 3R_F \cdot \Delta I_{1F} \]
Incremental Distance Principle

\[ Ef_A = VA_{PF} - d \cdot ZL1 \cdot I_{LD} = \]
\[ -\Delta VA + d \cdot ZL1 \cdot (\Delta IA + K_0 \cdot I_0) + 3R_F \cdot \Delta I_1F \]

\[ Vf_{AG} = VA_{PF} - r \cdot Z1L \cdot IA_{PF} \]
\[ Vd_{AG} = -\Delta VA + r \cdot Z1L \cdot (\Delta IA + K_0 \cdot I_0) \]
Variation of $V_{f_{AG}}$ and $V_{d_{AG}}$ ($r = 80\%$)
Simple Delta Filter
Delta Filters

• Delta filters provide $\Delta V$ and $\Delta I$ during a time interval equal to the delay $\tau$ following a fault

• Delta filters can be used either in frequency domain with phasors or in time domain (high- and ultra-high-speed applications)

• Output is zero in steady state

• Limitations are cascading events, evolving faults, and switch-on-to-fault situations
Incremental Distance Three-Phase Fault Characteristics

\[ Ef_A' = \frac{Ef_A}{\Delta IA} = ZS1 + d \cdot ZL1 + \frac{R_F}{C1} = ZS1 + Z_{\text{APP}_\text{NLD}} \]

\[ Vd_A' = \frac{Vd_A}{\Delta IA} = ZS1 + r \cdot Z1L \]
Incremental Distance Three-Phase Fault Characteristics

\[
\left( Z_{S1} + r \cdot Z_{1L} \right) \geq \left( Z_{S1} + Z_{\text{APP}_\text{NLD}} \right)
\]

\[
x_0 = -\text{real}(Z_{S1})
\]

\[
y_0 = -\text{imag}(Z_{S1})
\]

\[
R = \left| (Z_{S1} + rZ_{L1}) \right|
\]
Three-Phase Fault Characteristics

\[ Z_{\text{APP}}_{\text{NLD}} (d = 0.1, R_F = 1.6465) = \]
\[ \frac{\Delta V A}{\Delta I A} = d \cdot Z_{L1} + \frac{R_F}{C_1} = (2.199 + j0.147) \Omega \]

\[ \sim (-|2Z_{S1} + r Z_{L1}|) \]

Incremental Distance Center

\[ Z_{S1} \]

\[ r \cdot Z_{L1} \]

\[ Z_{\text{APP}} \]

Real \((Z_{\text{APP}})\) (ohms)

Imaginary \((Z_{\text{APP}})\) (ohms)
Three-Phase Faults
Resistance Coverage

Distance to Fault (pu)
Resistance Coverage (secondary ohms)

Incremental Distance
Mho PSVM
Mho PSV

R_F
R_F
R_F
R_F
V = 0

a
b
c
Three-Phase Fault With ZS1 Divided by 20

![Diagram showing a plot with axes labeled Real \((Z_{APP})\) (ohms) and Imaginary \((Z_{APP})\) (ohms). The plot includes circles representing incremental distance center, ZS1, and r \(\times ZL1\). The diagram also shows Mho PSVM and Mho PSV markers.]
Three-Phase Fault Resistance Coverage
With ZS1 Divided by 20
Single-Phase Fault Characteristics

- $Z_{APP}$
- $Z_{L1}$
- $K_{SLO} \cdot Z_{S1}$

Incremental Distance Center

$Z_{APP}$
- $d = 0.5$ pu
- $R_F = 1.43$ ohms

Graph showing the relationship between real and imaginary impedance components for a single-phase fault.
Distance Element Characteristics

- Mho element characteristics in impedance plane always exist.
- Incremental distance element characteristics in impedance plane are defined only if $\Delta V$ and $\Delta I$ are non-zero (they do not exist in steady state).
- In steady state, mho element asserts for overload condition (incremental distance element does not).
Series Compensation
MOV / Capacitor Equivalent

![Diagram of MOV and Capacitor Equivalent](image)

- Reactance (ohms) vs. Current (secondary A)
- Resistance (ohms) vs. Current (secondary A)
Voltage Inversion
No MOV, \( d = 0, R_F = 0 \)

\[
\begin{align*}
\left| ZC_{EQ} \right| & > \left| d \cdot ZL1 \right| \\
\left| ZS1 + d \cdot ZL1 \right| & > \left| ZC_{EQ} \right| \\
-19.6 \text{ ohms} & > 0 \\
25.4 \text{ ohms} & > -j19.6 \text{ ohms}
\end{align*}
\]
Current Inversion

No MOV, \( d = 0, R_F = 0, ZS1 \) Divided by 2

\[
|Z_{C_{EQ}}| > |ZS1 + d \cdot ZL1|
\]

\[-j19.6 \text{ ohms} > 12.7 \text{ ohms}\]
Linearized Sequence Network for Three-Phase Fault
Apparent Impedances for Three-Phase Fault

\( d = 0, \ r = 50\% \)
Three-Phase Fault Resistance Coverage

Distance to Fault (pu) vs. Resistance (ohms)

- Incremental Distance
- Mho PSVM
- Mho PSV
Impact of Element Reach
Example of Remote Infeed

\[
Z_{U1} = 6 \ (78^\circ) \text{ ohms} \\
Z_{U0} = 18.7 \ (71^\circ) \text{ ohms}
\]

\[
V_P (\alpha^\circ)
\]

\[
Z_{L1}, Z_{L0}
\]

\[
R
\]

\[
Z_{R1}, Z_{R0}
\]

\[
V_M (\theta^\circ)
\]

\[
Z_{S1}, Z_{S0}
\]

\[
\text{Relay}
\]

\[
d
\]
Mho AB Loop Scalar Product for Three-Phase Fault Applied From $d = 0$ to $1\, \text{pu}$
$V_{f_{AB}}$ and $V_{d_{AB}}$ for Three-Phase Fault Applied From $d = 0$ to $1 \text{ pu}$
Conclusion

- Incremental distance characteristics do not exist in steady state
- Incremental distance elements have increased sensitivity, increased resistance coverage, and immunity to voltage or current inversion
- Incremental distance element reach is affected in same way as mho elements (series compensation, remote infeed or outfeed, and parallel lines)
Conclusion

• Limits of incremental distance elements are limits imposed by delta filters (window typically of 1 cycle)

• Optimal configuration consists of mho element that is parallel with incremental distance element (high- or ultra-high-speed element with slower conventional mho element backup)

• Single comparator was considered in the study
Questions?