Differential Protection Principle

Differential Overcurrent Protection

Protected Equipment (Normal Load)

87 $I_{op} = 0$
**Differential Overcurrent Protection**

No Relay Operation If CTs Are Considered Ideal

\[ I_{OP} = 0 \]

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**Differential Overcurrent Protection**

\[ I_{OP} > I_{PU} \]

Relay Operates

Internal Fault
Unequal CT Saturation

Problem of Unequal CT Performance

- CT saturation causes error differential current for external faults
- Resulting high element pickup limits sensitivity
Percentage Differential Protection

Compares $I_{OP}$ with $I_{RT}$:

$$I_{OP} = |I_1 + I_2| \quad I_{RT} = k \left| I_1 - I_2 \right|$$

$$I_{RT} = k \left( |I_1| + |I_2| \right) \quad I_{RT} = \text{Max} \left( |I_1|, |I_2| \right)$$

Percentage Differential Single-Slope Characteristic

Operation: $I_{OP} > I_{PU}$ and $I_{OP} > SLP \cdot I_{RT}$

- Operating Region
- Restraining Region
- CT Errors
Percentage Differential Dual-Slope Characteristic

Adaptive Percentage Differential Characteristic
Challenges of Transformer Differential Protection

- CT saturation
- Current magnitude mismatch
- Current phase shift across the transformer
- Zero-sequence current sources
- Magnetizing inrush currents
- High excitation current on overexcitation

Transformer Connections
Common Two-Winding Transformer Connections

DABY or Dy1 Transformer Connection

\[
(\bar{I}_a - \bar{I}_b)(N_2/N_1) = \sqrt{3}\bar{I}_a(N_2/N_1) \angle 30^\circ
\]
YDAC or Yd1 Transformer Connection

\[ I_A \left( \frac{N_1}{N_2} \right) = \left( \frac{I_A - I_C}{\sqrt{3}} \right) \left( \frac{N_1}{N_2} \right) \angle 30^\circ \]

Current Scaling and Phase-Shift Compensation
Traditional Compensation Is Not Perfect

Desired CT ratio relationship:

\[
\frac{N_2}{N_1} \left(\frac{1}{CTR_1}\right) = \frac{1}{CTR_2}
\]

\[
CTR_2 = \left(\frac{N_1}{N_2}\right)CTR_1 = \sqrt{3}\left(\frac{V_1}{V_2}\right)CTR_1
\]

- Not always possible with standard CT ratios
- Electromechanical relays have taps
- Compensation is not perfect
Mismatch Calculation for Electromechanical Relays

\[
\text{Mismatch} = \frac{\left| \frac{\bar{I}_1}{\bar{I}_2} \right| - \frac{TAP_1}{TAP_2}}{MR} \cdot 100
\]

\[
MR = \min \left( \frac{|\bar{I}_1|}{|\bar{I}_2|}, \frac{TAP_1}{TAP_2} \right)
\]

Compensation With Digital Relays

Digital relays carry out current scaling and phase-shift compensation internally

- Exact current scaling
- Phase-shift compensation for all transformer connections
- Wye CT connection is allowed
Current Scaling With Digital Relays

Digital relays can fully compensate for the current amplitude differences

\[ TAP_n = \frac{1,000 \cdot S_{MAX} \cdot C_n}{\sqrt{3} \cdot V_n \cdot CTR_n} \]

Digital Relays Allow Connection of CTs in Wye
Current Scaling and Phase-Shift Compensation

DAB Connection Compensation

\[
\begin{bmatrix}
I_{W2C} \\
I_{W2T} \\
I_{B2C} \\
I_{W2T} \\
I_{C2C} \\
I_{C2T}
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1 \\
-1 & 0 & 1
\end{bmatrix} \begin{bmatrix}
I_{AW2T} \\
I_{BW2T} \\
I_{CW2T}
\end{bmatrix}
\]
Wye Connection Compensation

\[
\begin{align*}
I_{AW1} & \frac{1}{TAP1} I_{AW1} \\
IBW1 & \frac{1}{TAP1} IBW1 \\
ICW1 & \frac{1}{TAP1} ICW1
\end{align*}
\]

\[
\begin{align*}
I1W1C & = \frac{IAW1}{TAP1} \\
I2W1C & = \frac{IBW1}{TAP1} \\
I3W1C & = \frac{ICW1}{TAP1}
\end{align*}
\]

\[
\begin{bmatrix}
I1W1C \\
I2W1C \\
I3W1C
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
IAW1T \\
IBW1T \\
ICW1T
\end{bmatrix}
\]

Zero-Sequence Current Removal
Zero-Sequence Current for an External Fault

Delta compensation removes zero-sequence current

Restricted Earth Fault (REF) Protection
Transformer Currents for Internal Ground Faults

![Chart showing phase current and neutral current for winding percentage.]

REF Protection for a Two-Winding Transformer

\[ T = \text{Re} \left[ I_X \cdot I_Y^* \right] \]

![Diagram of transformer protection system with equations and symbols.]

CT Ratio Compensation

Residual Current Calculation

\[ I_{RW1} \]

\[ I_X \]

\[ I_Y \]
Overexcitation Protection

\[ \phi \propto \frac{V}{f} \cdot \frac{f_{\text{NOM}}}{V_{\text{NOM}}} \]

- Overexcitation occurs when \( V/f \) exceeds 1.05 (full load) or 1.1 (no load)
- Causes heating, high exciting current, vibration, and noise
- Volts/hertz (24) protection should trip the transformer