Power System Protection
Ground faults in isolated neutral systems
Briefly about the speaker

• Professor at Norwegian Univ. Science and Technology – Dept. Electrical Engineering
  – Power system transients and protection
  – High voltage engineering, stress calculations
  – Recent focus on Power Transformers

• Developer of ATPDraw

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Solid vs. isolated neutral

+ No over-voltages in fault situations
- High fault current
+ Easy fault detection
+ Ground faults persist
  • Fast trip and reclosing
- Poor power quality
- Extra stress

- Undefined voltages to ground. \( \sqrt{3} \) rise during ground faults. MOV dimensioning.
+ Low fault current
- Difficult fault detection/location
+ Can continue to operate during ground fault. Increased power quality
  • Safety issues: down/broken conductors
Why is the fault current low in isolated neutral systems?

- Fault current must return through line capacitances. High return impedance.

Ground faults:
- The most common fault
- Often temporary
  - Trees/branches, snow/ice/wind,
  - Birds
  - Lightning
- Simultaneous faults....

\[ I_f = \frac{3 \cdot V_f}{Z_1 + Z_2 + Z_0 + 3R_f} \]
Usage of isolated neutral

• In Norway
  – LV system 230 V IT
  – MV system 12-24 kV
  – Distribution level 66-132 kV
• The 230 V IT system is gradually replaced by 400 V TN (solidly grounded) due to risk of undetected ground faults, double ground faults, and lower loss in a 400 V TN system.
• In MV; requirements to detect a 3kΩ ground fault
• Power quality is very important to the industry
  – Fast trip & reclosing not acceptable
Zero sequence measurements

- Current $I_0$: Sum $I_a$, $I_b$, $I_c$
  - Summing the current numerically
  - Residual connection
  - Summation transformer (Toroidal/Rogowski coil)

- Voltage $U_0$: Sum $U_a$, $U_b$, $U_c$
  - Open delta
  - Neutral point (isolated or resonance earth)
Isolated neutral network

- Normal to only consider ground capacitance
  - symmetrical system,
  - ignore conductive line charging
  - no voltage drop along line
  - imbalance in loads canceled by D-coupled transformers
- Fault current mainly returns in the two healthy phases
- Fault resistance important

\[ h = e^{j120^\circ} \]
Consequences

- Fault current is independent on where the fault occurs
- For calculation of feeder current and voltages capacitances can be concentrated
- The voltage to ground will rise for the healthy phases
- Easy to detect that there is a ground fault (by looking at $V_0$), difficult to detect where (by looking at $I_0$ in various feeders)
Phasors and equivalent

• Equivalent circuit during fault (phase A):

\[ I_f = \frac{V_{pa} \cdot 3 j \omega C_g}{1 + 3 j \omega C_g R_f} \]

\[ V_N = V_0 = \frac{-V_{pa}}{1 + 3 j \omega C_g R_f} = \frac{-I_f}{3 j \omega C_g} \]

Before Line-voltages unchanged

After

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Zero sequence in single radial

- Same zero-sequence voltage in the entire system; selectivity is challenging
- The fault is traditionally located by sectionalizing (often manual)
- Zero sequence current varies along the line:

\[ 3I_0 \approx \text{constant} \]

\[ U_0 \approx \text{constant} \]

\[ R_f \]

\[ I_0 \]

pos.
From fault to zero sequence current

\[ V_p \]
\[ h^2 \cdot V_p \]
\[ h \cdot V_p \]
\[ C' \cdot x \]
\[ C' \cdot (l-x) \]

**Currents:**

\[ I_a(x) = (V_N + V_{pa}) \cdot j\omega C'_g \cdot (l-x) \]
\[ I_b(x) = (V_N + h^2 \cdot V_{pa}) \cdot j\omega C'_g \cdot (l-x) \]
\[ I_c(x) = (V_N + h \cdot V_{pa}) \cdot j\omega C'_g \cdot (l-x) + I_f \cdot H(d-x) \]

\[ 3I_0(x) = (I_a + I_b + I_c) \approx V_N \cdot j\omega 3C'_g \cdot (l-x) + I_f \cdot H(d-x) = \begin{cases} -V_N \cdot j\omega 3C'_g \cdot x, & x < d \\ V_N \cdot j\omega 3C'_g \cdot (l-x), & x > d \end{cases} \]

ignore voltage drop, no load-effect
Multiple radials

• Three radials fed by the same transformer
  – Fault current in the faulty feeder is the negative sum of the current in the two healthy feeders

\[ I_{01} = V_N \cdot j\omega C_{g1} \]
\[ I_{02} = V_N \cdot j\omega C_{g2} \]
\[ I_{03} = -(I_{01} + I_{02}) \]

• With two radials the currents are equal in size so directional protection is required
• With an increasing number of feeders simple over-current protection becomes possible
Directional over-current relay

- Often the preferred solution
- Measure zero sequence voltage and zero sequence current in each radial
- Then for each radial:

\[
\begin{align*}
V_0 & \quad I_{01} \\
\quad & \quad I_{02} \\
\quad & \quad I_{03}
\end{align*}
\]

Forward direction

\[
\begin{align*}
\alpha & \quad I_{0n} \\
& \quad V_0 \\
& \quad \text{Healthy feeder}
\end{align*}
\]

Tripping zone
Faulty feeder
Relaying logic

• Is zero sequence voltage above threshold?
  – $V_0 > V_{lim}$ (type 59G over-voltage relay)

• Is zero sequence current above threshold and in correct quadrant (3rd)?
  – $I_0 > I_{lim}$ (type 67N directional over-current relay)
Example- earth fault protection

- Fault current (independent on location)
  - Depends on fault resistance

\[ I_f \approx \frac{U_{pa}}{R_f + 1/(j\omega \cdot 50 \text{mi} \cdot C'_g)} = \frac{22 \text{ kV} / \sqrt{3}}{R_f - j4244\Omega} \Rightarrow \begin{cases} I_{f,\text{min}} &= 2.44 \angle 54.7^\circ \text{ A} @ 3 \text{ k}\Omega \\ I_{f,\text{max}} &= 3.0 \angle 90^\circ \text{ A} @ 0 \Omega \end{cases} \]

50 miles line in total
Total capacitance is 50 mi \cdot C'_g [F/mi]
5 nF/mi assumed in this case.
NB! Much higher in cable systems.
Earth fault line 1 (28 mi)

- Partition of the earth fault current measured for each radial
- Healthy lines 2&3 feed 14 + 8 parts into line 1
Earth fault line 2 (14 mi)

- Partition of the earth fault current measured for each radial
- Healthy lines 1&3 feed 28 + 8 parts into line 2
Earth fault line 3 (8 mi)

- Partition of the earth fault current measured for each radial
- Healthy lines 1 & 2 feed 28 + 14 parts into line 3