Modern Solutions to Stabilize Numerical Differential Relays for Current Transformer Saturation during External Faults

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Overview

- Basics on CT saturation
  - DC-offset
  - Remanence
  - saturation free time < 7ms

- Influence of CT saturation on protection

- Stabilization methods for differential protection

- Summary
Current transformer equivalent circuit and magnetising characteristic

\[ \frac{W_p}{W_s} i_p(t) \rightarrow R_{ct} \rightarrow i_s(t) \]

\[ i_\mu(t) \]

\[ u_\mu(t) \]

\[ L_\mu \]

\[ \psi(t) = \int_0^t u_\mu(\tau) d\tau + \psi(0) \]

\[ R_b \]

\[ \Psi \]

Remanence flux

Voltage and flux under unsaturated condition

\[ Flux = \int v_\mu(t) dt = \int i_s(t) \cdot (R_{ct} + R_b) dt \]

for \( i_s(t) = I \sin(\omega t) \)

\[ Flux = \frac{I \cdot (R_{ct} + R_b)}{\omega} (1 - \cos(\omega t)) \]
Saturated condition

Saturated condition

Flux

secondary current

Specification of saturation flux by Vknee

The knee point voltage is the highest exciting voltage generated by a symmetrical secondary short circuit current on which the flux in the CT will not reach the saturation flux.
Dimensioned for the maximum symmetrical short circuit current

Example: $I_{sc}=200000\text{A}$, $\text{CT ratio}=1000/5$, $R_{CT}=0.5 \ \text{Ohm}$, $R_b=0.5 \ \text{Ohm}$

$V_{\text{exciting max}}=I_{sc}(sec) \times (R_{CT}+R_b)=100\text{A} \times 1\Omega \text{hm}=100\text{V}$

Selected CT has $V_{\text{knee}}=100\text{V}$

To avoid saturation $\Rightarrow \quad V_{\text{knee}} = 2 \times I_{sc} (R_{CT} + R_b)$

Prove of overdimension factor of 2

\[
\text{Flux} = \int v_x(t) dt \\
= \int i_x(t) \cdot (R_{CT} + R_b) dt \\
\text{for} \quad i_x(t) = I \sin(\omega t) \\
\text{Flux} = I \cdot (R_{CT} + R_b) \int \sin(\omega t) dt \\
\text{Solution for } \int \sin(\omega t) dt = -\frac{1}{\omega} \cos(\omega t) + C
\]

1. $\text{Flux} = 0$ for $t = 0 \quad \Rightarrow \quad C = 1$
2. $\text{Flux} = -\frac{I \cdot (R_{CT} + R_b)}{\omega}$ for $t = 1 \text{ cycle} \quad \Rightarrow \quad C = 0$

$\text{Flux}_{\text{at 0}} = \frac{I \cdot (R_{CT} + R_b)}{\omega} \cdot (1 - \cos(\omega t))$ \quad $\text{Flux}_{\text{at 1 cycle}} = -\frac{I \cdot (R_{CT} + R_b)}{\omega} \cos(\omega t)$

$\max(\text{Flux}_{\text{at 0}}) = 2 \cdot \frac{I \cdot (R_{CT} + R_b)}{\omega}$ \quad $\max(\text{Flux}_{\text{at 1 cycle}}) = \frac{I \cdot (R_{CT} + R_b)}{\omega}$

\[
\text{overdimension factor} = \frac{\max(\text{Flux}_{\text{at 0}})}{\max(\text{Flux}_{\text{at 1 cycle}})} = 2
\]
DC-Offset

\[ \text{Flux} = \int v_p(t) \, dt \]
\[ = \int i_s(t) \cdot (R_{CT} + R_b) \, dt \]
\[ i_s(t) = I \left( e^{-\frac{t}{\tau_r}} - \cos(\omega t) \right) \]

\[ V_{knee} = I(R_{CT} + R_b) \left\{ \omega T_p \left( e^{\frac{t}{\tau_r}} - 1 \right) - \sin(\omega t) \right\} \]

For no saturation at all: Set \( t = \infty \) and \( -\sin(\omega t) = 1 \)

\[ V_{knee} = I(R_{CT} + R_b) \left\{ 1 + \omega T_p \right\} \text{ or } \]
\[ V_{knee} = I(R_{CT} + R_b) \left\{ 1 + \frac{X}{R} \right\} \]

Remanence

The flux inside the CT will not go to zero after the fault current is interrupted!
Considering remanence flux

\[ K_{\text{Remanence}} = \frac{100}{100 - \text{Prozent of Remanence}} \]

Example: Worst case of remanence (iron closed CT’s) = 80%

\[ K_{\text{Remanence}} = \frac{100}{100 - 80} = 5 \]

CT dimensioning for no saturation under all worst case condition

Example: Isc=20000A, CT ratio =1000/5, RCT=0.5 Ohm, Rb=0.5 Ohm
Tp=60ms, iron closed CT

1. considering DC offset

\[ V_{\text{knee}} = I(R_{\text{CT}} + R_b)\left[1 + \omega T_p \right] \]
\[ V_{\text{knee}} = 100A \cdot 1Ohm(1+22.6) = 2260V \]

2. considering 80% remanence

\[ K_{\text{Remanence}} = \frac{100}{100 - 80} = 5 \quad \Rightarrow \quad V_{\text{knee}} = 5 \cdot 2260V = 11300V \]

The dimension of a CT that will not saturate for the maximum short circuit current that has a full DC offset with a long time constant and is at 80% in remanence, will lead to uneconomical and oversized CT’s.
With consideration of saturation free time \( t_{sat} \)

The requirement that no saturation is allowed will lead to uneconomical and oversized CT’s

\[
V_{knee} = I(R_{CT} + R_b) \left[ 1 + \frac{X}{R} \right]
\]

Modern numerical relays only require a certain saturation free time \( t_{sat} \). The following formula takes this into consideration:

\[
V_{knee} = I(R_{CT} + R_b) \left[ -\omega T_p \left( e^{\frac{t_{sat}}{T_p}} - 1 \right) - \sin(\omega t_{sat}) \right]
\]

Many times a simplified version where \(-\sin(\omega t)\) is replaced by 1 is used

\[
V_{knee} = I(R_{CT} + R_b) \left[ -\omega T_p \left( e^{\frac{t_{sat}}{T_p}} - 1 \right) + 1 \right]
\]

What does the different formulas describe?

Special consideration needed

\[
V_{knee} = I(R_{CT} + R_b) \left[ -\omega T_p \left( e^{\frac{t_{sat}}{T_p}} - 1 \right) + 1 \right]
\]
Saturation free times < 7ms

Flux for saturation free time < 7 ms
Which formula should be applied

No saturation
\[
V_{knee} = I(R_{CT} + R_b) \left[ 1 + \frac{X}{R} \right]
\]

Saturation free time > 12 ms
\[
V_{knee} = I(R_{CT} + R_b) \left[ -\omega T_p \left( e^{\frac{T_{sat}}{T_p}} - 1 \right) + 1 \right]
\]

Saturation free time between 7-12 ms
\[
V_{knee} = I(R_{CT} + R_b) \left[ -\omega T_p \left( e^{\frac{T_{sat}}{T_p}} - 1 \right) - \sin(\omega T_{sat}) \right]
\]

Saturation free time < 7ms
\[
V_{knee} = I(R_{CT} + R_b) [1 - \cos(\omega T_{sat})]
\]

Influence of CT saturation on protection

- **Distance protection**
  - Close in faults
    - Direction has to be correct
    - High speed tripping decision before saturation
  - Zone end fault
    - Accuracy and timing will be effected

- **Overcurrent protection**
  - based on RMS or fundamental
  - 50 element not influenced if remaining current is above pickup
  - 51 element experienced an additional time delay

- **Differential protection**
  - Critical for the security of the protection!
Differential protection

Kirchhoff’s Law

\[ I_1 + I_2 + I_3 = 0 \]

\[ I_{\text{DIFF}} = \frac{|I_1 - I_2|}{I_{\text{REST}}} \]

Differential protection with CT saturation
Small currents with long DC time constant

Summary

- $I_{res}$
- $I_{diff}$
- $I_1$
- $I_2$
- AND
- $I_{diff} < value$
- DC-offset

Increase $I_{diff}$ pick up
Summary

- By specifying a CT the following must be considered:
  - Max fault current
  - CT burden
  - DC time constant
  - Remanence
  - Required saturation free time

- Saturation free time must be specified by each relay manufacturer

- Small current with long DC time constant can also cause saturation

- Modern numerical relays using intelligent algorithms can deal with CT saturation much better than their electromechanical and analog static predecessors

Questions

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