Theory Current Transformers

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Topics

- Theory of current transformers (CTs)
- Equivalent Circuit for CTs
- Magnetic saturation
- Time constant
- CT features
- Specifications for a CT
- Types of CT cores
- Calculation example
Transformer Loading (1)

AC voltage source sets up a flux in the coil core.

The exchange flux ($\Phi_0$) induces voltages ($E_1$ and $E_2$) in both coils. $E_1$ and $E_2$ are related as the number of windings $n_1$ and $n_2$. The load current ($I_0$) is very small as long as $E_1$ and $U_1$ almost cancel each other.
Resistance R causes coil current $I_2$ through coil 2 and current $I_1$ flow through coil 1.

Since $I_1 \times n_1 = I_2 \times n_2$, induced flux 1 & 2 cancel each other.

$I_1$ and $I_2$ are inversely proportional to number of turns $n_1$ and $n_2$.
Equivalent circuit of a CT

\[ I'_2 = I_1 \cdot \frac{N_1}{N_2} \]

- \( X_1 \) = Primary leakage reactance
- \( R_1 \) = Primary winding resistance
- \( X_2 \) = Secondary leakage reactance
- \( Z_0 \) = Magnetizing impedance
- \( R_2 \) = Secondary winding resistance
- \( Z_b \) = Secondary load

Note: Normally the leakage fluxes \( X_1 \) and \( X_2 \) can be neglected.
\[ E_s = \text{Secondary induced e.m.f.} \]
\[ V_s = \text{Secondary output voltage} \]
\[ I_p = \text{Primary current} \]
\[ I_s = \text{Secondary current} \]
\[ \theta = \text{Phase angle error} \]
\[ \Phi = \text{Flux} \]
\[ I_s R_s = \text{Secondary resistance voltage drop} \]
\[ I_s X_s = \text{Secondary reactance voltage drop} \]
\[ I_e = \text{Exciting current} \]
\[ I_r = \text{Component of } I_e \text{ in phase with } I_s \]
\[ I_q = \text{Component of } I_e \text{ in quadrature with } I_s \]
Magnetic Field strength and Induction

Magnetic field strength \( H \) (A/m) in the coil is given by:

- \( I \) = Current through the coil in Amperes (A)
- \( n \) = Number of turns in the coil
- \( L \) = Total circumference of the peripheral coil

\[
H = \frac{I \times n}{L}
\]

Induced Magnetic flux density \( B \) (in Wb/m\(^2\) or Tesla) is given by:

- \( \mu \) = Magnetic permeability in (Wb/A.m) in the medium (air or iron core) in the coil
- \( H \) = Magnetic field strength

\[
B = \mu \times H
\]
Saturation

The plot shows the relationship between changing magnetic field strength (H) and associated changing flux density / magnetic induction (B)
Induced Voltages

The effective induced voltage in the coils is given by:

\[ E = 4.44 \times f \times \Phi \times n \]

Magnetic flux \( \Phi \) (in Wb) in the core of the coil is the flux density (B) multiplied by the cross sectional area A (in m²) of the core.

\[ \Phi = B \times A \]

\( B_{\text{max}} \approx 0.6 – 0.8 \) T for Mu metal. \( B_{\text{max}} \approx 2 \) T Cold rolled Steel

Example: Suppose \( B_{\text{max}} = 1.8 \) T and core area of 10 x 10 cm = 0.01 m²

Maximum effective stress induced in one convolution (n = 1) of coil:

\[ 4.44 \times 50 \times 1.8 \times 0.01 = 4 \text{ V} \]
Het beeld hierboven laat een grote primaire stroom zien. Het magnetisch veld in de primaire en secundaire spoel wordt gedurende een deel van de periode constant. Een constant magnetisch veld induceert geen secundaire spanning en dus valt op dat moment de secundaire stroom weg.
When a CT saturation occurs true power factor is dependent on several factors:

1. The overflow factor of the CT
2. The capability of CT (Rated burden)
3. The internal resistance of the CT
4. The connected load, in terms of wiring and power protection relays.
5. The time constant of the network. This gives a DC component which speeds the saturation.

IEC 60044-1 Class PX

formerly

British Standard BS3938:
Class X
If a magnetic coil with a resistance is energized and this coil is shorted, the energy stored in the coil discharges in the form of a current through the coil (and subsequent resistance).

The speed and thus the time in which this occurs depends on the ratio of the coil inductance and resistance. This is a time constant.

The time constants in a network may be determined from the short-circuit power factor.
Aangezien $X_L = \omega L$ kan hieruit de tijdconstante $\tau$ als volgt bepaald worden.

$$\tan \phi_k = \frac{\omega L}{R}$$

Daaruit volgt $\tau = \frac{L}{\omega R} = \frac{\tan \phi_k}{\omega} \ [s]$ De hoeksnellheid $\omega = 2\pi f \ [\text{rad/s}]$

Voor het net met $f = 50 \ \text{Hz}$ wordt de tijdconstante $\tau = \frac{\tan \phi_k}{2\pi f} = \frac{\tan \phi_k}{2\pi 50} \ [s]$

Gebruikelijk is het om $\tau$ uit te drukken in milliseconden dan wordt $\tau = \frac{\tan \phi_k}{2\pi 50} \times 10^3 \ [\text{ms}]$

<table>
<thead>
<tr>
<th>Net</th>
<th>$\phi_k$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kV</td>
<td>30°</td>
<td>1,84 ms</td>
</tr>
<tr>
<td>110 kV</td>
<td>75°</td>
<td>11,9 ms</td>
</tr>
<tr>
<td>220 kV</td>
<td>82°</td>
<td>22,6 ms</td>
</tr>
</tbody>
</table>
In de praktijk gaat men er van uit dat na een tijd van $t/\tau = 5$ de stroom nul is.

For a 220 kV line the Iksym is reached after: $22.6 \times 5 = 113$ msec.
Features of current transformers

- A primary winding (usually a cable or other conductors by toroidal).
- Set high primary currents to default value, usually 1 A or 5 A.
- Number of secondary windings in a CT with 1 A sec. current is equal to InP. For CT’s with 5A secondary the number of turns is \( \frac{1}{5} \times \text{InP} \)
- Maximum voltage for each winding is dependent on core material and diameter.
- Secondary is almost shorted and operated far from max tension / saturation.
- For \( \text{Ru}' < \text{Ru} \) the Accuracy limiting factor (\( \text{N}' \)) is higher than the nominal(\( \text{N} \)).
  Internal winding resistance (\( \text{Ri} \)) is then important: \( \text{N}' = \text{N} \times \frac{\text{Ri} + \text{Ru}}{\text{Ri} + \text{Ru}'} \)
- Calculates the continuous 120% Ins. In short circuit conditions InP max lasts for upto 1 or 3 s.
- An open winding leads to a very hot and dangerous voltage (2500 / 1A, 5P650, 5 VA supplies \( \approx 10 \) kV) and causes magnetic saturation. Winding insulation is only rated for a 2 kV peak voltage!
Specifying the nominal CT burden

Typically used classes: 1 – 1,5 – 2 – 2,5 – 5 – 10 – 15 – 30 – 60 VA.

- The reted CT Burden should account for all the power consumption in the circuit (including the losses in the leads and the connected loads).
- For 1 A circuits, 2 VA CT Burden is usually sufficient.

Resistance of the lines calculated with formula: $(0.0175 \times l) / A$

- $0.0175$ is the resistivity of copper $(\Omega \cdot \text{mm}^2 / \text{m})$ at 20° C.
- $l =$ total length of all lines between CT terminals and consumers. (length of cables for return circuit take 2x)
- $A =$ surface cross section of conductor in mm$^2$.

For 1 A circuits, the line losses $(I^2 \times R)$ in VA are equal to the resistance. For 5 A circuits, the line losses $(I^2 \times R)$ in VA is equal to 25 times resistance.
Accuracy Limit Factor N

Typically used classes: P5 - P10 – P15 – P20 - P30

Factor (after the P) gives the current overload as a factor of nominal loading under rated current and 5% (5P) of 10% (10P) gives the accuracy limiting factor applicable at that overload of the CT.

Limit Factor (N) calculated by multiplying the following factors:

- The Symmetric factor Kscc = \( \frac{I_{k_{max}}}{I_{pn}} \).
  Thus a higher primary nominal current (Ipn) limits the Kscc.

- Asymmetry factor Ktd depends on the net timeconstant. However, rapid protection, core type and smart digital relays limit KTD.
CT vermogen
Overstroom factor “$K_{ssc}$”
Kerntype P = beveiliging
Nauwkeurigheid in % bij $K_{ssc} \times I_n$

$$K'_{ssc} = K_{ssc} \frac{R_{ct} + R_b}{R_{ct} + R'_b}$$

$$K'_{ssc} > K_{td} \frac{I_{ssc \ max \ ext \ fault}}{I_{pn}}$$

$$n' = n \frac{Z_i + Z_{u_{nom}}}{Z_i + Z_{u_{werk}}}$$

$$ALF' = ALF \times \frac{P_i + P_{NB}}{P_i + P_{BB}}$$

$$ALF'' \geq \frac{I_{SC - max}}{I_n} \times K_{TF}$$
CT Classes used in protection applications

- **Type P, PX, TPX, TPS**: Closed core types, also known as high remenence.
- **Type TPY, PR**: Anti remenenance core, also known as low remenence.
- **Type TPZ**: Linear cores, also known as non remenence types.

The diagram illustrates the magnetic flux density (B) as a function of the product of current and weight (i \* w). The regions are labeled:

- **I**: closed iron core (TPX)
- **II**: core with anti-remanence air-gaps (TPY)
- **III**: Linearised core (TPZ)

The graph shows the magnetic flux density up to 80% and less than 10%, indicating the remanence characteristics of each type.
CT Behaviour during reclosing

- $t_{F1}$
- $l_{DT}$
- $l_{F2}$
- $l$

- Closed iron core (TPX)
- Core with anti-remanence air-gaps (TPY)
CT dimensioning for Example differential protection (1)

1. Calculation of fault currents

110 kV, 3 GVA

110/20 kV
40 MVA
\(u_f=12\%\)

F1: 300/1A
F2: 1200/1A
F3: \(7\)UT61
F4: \(7\)SD61
F5: \(200/1A\)

Impedances related to 110 kV:

Net: \[Z_N = \frac{U_N^2}{S_{SC}} \left[\frac{kV^2}{MVA}\right] = \frac{110^2}{3000} = 4.03 \ \Omega\]

Transf.: \[Z_T = \frac{U_N^2}{P_{N-T}} \left[\frac{kV^2}{MVA}\right] \cdot \frac{u_T}{100} = \frac{110^2}{40} \cdot \frac{12\%}{100} = 36.3 \ \Omega\]

Impedances related to 20 kV:

Net: \[Z_N = \frac{U_N^2}{S_{SC}} \left[\frac{kV^2}{MVA}\right] = \frac{20^2}{3000} = 0.13 \ \Omega\]

Transf.: \[Z_T = \frac{U_N^2}{P_{N-T}} \left[\frac{kV^2}{MVA}\right] \cdot \frac{u_T}{100} = \frac{20^2}{40} \cdot \frac{12\%}{100} = 1.2 \ \Omega\]

Line: \[Z_L = \left[\frac{\Omega}{\text{km}}\right] \cdot z_L ' \left[\Omega/\text{km}\right] = 8 \cdot 0.4 = 3.2 \ \Omega\]
CT dimensioning for Example differential protection (2)

\[
F1 \quad I_{F1} = \frac{1.1 \cdot U_N/\sqrt{3}}{Z_N} = \frac{1.1 \cdot 110kV/\sqrt{3}}{4.03\Omega} = 17.3 \text{ kA}
\]

\[
F2 \quad I_{F2} = \frac{1.1 \cdot U_N/\sqrt{3}}{Z_N + Z_T} = \frac{1.1 \cdot 110kV/\sqrt{3}}{4.03\Omega + 36.3\Omega} = 1.73 \text{ kA}
\]

\[
F3 \quad I_{F3} = \frac{1.1 \cdot U_N/\sqrt{3}}{Z_N + Z_T} = \frac{1.1 \cdot 20kV/\sqrt{3}}{0.13\Omega + 1.2\Omega} = 9.55 \text{ kA}
\]

\[
F4 \quad I_{F4} = \frac{1.1 \cdot U_N/\sqrt{3}}{Z_N + Z_T + Z_L} = \frac{1.1 \cdot 20kV/\sqrt{3}}{0.13\Omega + 1.2\Omega + 3.2\Omega} = 2.8 \text{ kA}
\]

Dimensioning of the 110 kV CTs for the transformer differential protection:

Manufacturer recommends for relay 7UT61:

1) Saturation free time ≥ 4ms for internal faults
2) Over-dimensioning factor \( K_{TF} \geq 1.2 \)
   for through flowing currents (external faults)

The saturation free time of 3 ms
 corresponds to \( K_{TF} ≥ 0.75 \)

Criterion 1) therefore reads:

\[
ALF' ≥ K_{TF} \cdot \frac{I_{F1}}{I_N} = 0.75 \cdot \frac{17300}{300} = 43
\]

For criterion 2) we get:

\[
ALF' > K_{TF} \cdot \frac{I_{F2}}{I_N} = 1.2 \cdot \frac{1730}{300} = 7
\]

The 110 kV CTs must be dimensioned according to criterion 1).
CT dimensioning for Example differential protection (3)

We try to use a CT type: 300/1, 10 VA, 5P?, internal burden 2 VA.

\[ ALF' \geq \frac{P_i + P_{\text{operation}}}{P_i + P_{\text{rated}}} \cdot ALF' = \frac{2 + 2.5}{2 + 10} \cdot 43 = 16.1 \quad \text{(Connected burden estimated to about 2.5 VA)} \]

Chosen, with a security margin. 300/1 A, 5P20, 10 VA, \( R_e \leq 2 \text{ Ohm} \) \( (P_i \leq 2 \text{ VA}) \)

Specification of the CTs at the 20 kV side of the transformer:

It is good relaying practice to choose the same dimensioning as for the CTs on the 110 kV side:

1200/1, 10 VA, 5P20, \( R_e \leq 2 \text{ Ohm} \) \( (P_i \leq 2 \text{ VA}) \)

Dimensioning of the 20 kV CTs for line protection:

For relay 7SD61, it is required:

1') Saturation free time \( \geq 3 \text{ ms} \) for internal faults

2') Over-dimensioning factor \( K_{TF} \geq 1.2 \) for through flowing currents (external faults)

The saturation free time of 3 ms corresponds to \( K_{TF} \geq 0.5 \)

Criterion 1') therefore reads:

\[ ALF' \geq K_{TF} \cdot \frac{I_{F3}}{I_N} - 0.5 \cdot \frac{9.550}{200} - 24 \]

For criterion 2') we get:

\[ ALF' \geq K_{TF} \cdot \frac{I_{F4}}{I_N} - 1.2 \cdot \frac{2800}{200} - 16.8 \]

The 20 kV line CTs must be dimensioned according to criterion 1').
CT dimensioning for Example differential protection (4)

For the 20 kV line we have considered the CT type: 200/5 A, 5 VA, 5P?, Internal burden ca. 1 VA

\[ ALF \geq \frac{P_i + P_{operation}}{P_i + P_{rated}} \cdot ALF' = \frac{1+1}{1+5} \cdot 24 = 8 \]  

(Connected burden about 1 VA)

Specification of line CTs:

We choose the next higher standard accuracy limit factor \( ALF = 10 \):

Herewith, we can specify: CT Type TPX, 200/5 A, 5 VA, 5P10, \( R_s \leq 0.04 \) Ohm (\( P_i \leq 1 \) VA)
Questions