Basics of Current and Voltage Transformers
Equivalent current transformer circuit

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

- \( X_1 \) = 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
Current transformer, simplified equivalent circuit

\[ i'_1 = \frac{N_2}{1} \cdot i_1 \]

\[ L_2 \ll L_W \]

\[ R_2 \]

\[ i_2 \]

\[ i_m \]

\[ R_B \]
Current transformer:
Phase displacement ($\delta$) and current ratio error ($\varepsilon$)
CT classes to IEC 60044-1: 5P or 10P

<table>
<thead>
<tr>
<th>Specification:</th>
<th>300/1 A</th>
<th>5P 10, 30 VA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio $I_n$-Prim / $I_n$-Sek.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% accuracy at $I = n \times I_n$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accuracy limit factor ALF</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rated burden (nominal power) $P_{NB}$

$R_{CT} \leq 5 \text{ Ohm}$

$P_i = I_{sec.}^2 \times R_{CT}$

Actual accuracy limit factor in operation is higher as the CT is normally underburdened: Operating ALF: $ALF'$

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

Dimension criterium:

$$ALF' \geq \frac{I_{SC}\text{-max}}{I_n} \times K_{TF}$$

$K_{TF}$ (over-dimensioning factor) considers the single sided CT over-magnetising due to the d.c. component in short circuit current $I_{SC}$.

$K_{TF}$ values required in practice depend on relay type and design. Recommendations are provided by manufacturers (see Application Guides)
Definition of the CT knee-point voltage

IEC 60044-1 Class PX
formerly
British Standard BS3938:
Class X
IEC 60044-1 specifies the following classes:

<table>
<thead>
<tr>
<th>Accuracy class</th>
<th>Current error at nominal current (I_n)</th>
<th>Angle error $\delta$ at rated current $I_n$</th>
<th>Total error at $n \times I_n$ (rated accuracy limit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5P</td>
<td>± 1 %</td>
<td>± 60 minutes</td>
<td>5 %</td>
</tr>
<tr>
<td>10P</td>
<td>± 5%</td>
<td></td>
<td>10 %</td>
</tr>
</tbody>
</table>

IEC 60044-1, Current transformer, Standard for steady-state performance.
Current transformers, Standard for transient performance

**IEC 60044-6** specifies four classes:

<table>
<thead>
<tr>
<th>Class</th>
<th>Error at rated current</th>
<th>Maximum error at rated accuracy limit</th>
<th>Remanence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ratio error</td>
<td>Angle error</td>
<td></td>
</tr>
<tr>
<td><strong>TPX</strong> (closed iron core)</td>
<td>± 0,5 %</td>
<td>± 30 min</td>
<td>℥ ≤ 10%</td>
</tr>
<tr>
<td><strong>TPY</strong> with anti-remanence air gap</td>
<td>± 1,0 %</td>
<td>± 30 min</td>
<td>&lt; 10 %</td>
</tr>
<tr>
<td><strong>TPZ</strong> linear core</td>
<td>± 1,0 %</td>
<td>± 180 ± 18 min</td>
<td>℥ ≤ 10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(a.c. current only)</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>TPS</strong> closed iron core</td>
<td>Special version for high impedance protection</td>
<td></td>
<td>No limit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Knee point voltage, internal secondary resistance)</td>
<td></td>
</tr>
</tbody>
</table>
Current transformer saturation

Steady-state saturation with AC current

Transient saturation with offset current
Transient CT saturation due to DC component

- Short circuit current (I_{SC})
- DC flux non-saturated
- AC flux
- Magnetising current (I_m)
Course of CT-flux during off-set short-circuit current

\[
\frac{B}{B_{\sim}} = 1 + \omega \cdot \frac{T_N \cdot T_S}{T_N - T_S} \left( e^{\frac{t}{T_N}} - e^{\frac{t}{T_S}} \right)
\]

\[
\frac{B_{\text{Max}}}{B_{\sim}} = 1 + \omega \cdot T_S \cdot \left( \frac{T_N}{T_S} \right)^{\frac{TS}{T_N - T_S}}
\]

\[
t_{B\text{Max}} = \frac{T_N \cdot T_S}{T_S - T_N} \cdot \ln \frac{T_S}{T_N}
\]

\[
T_S = \frac{L_w}{R_i + R_B} = \frac{1}{\omega \cdot \tan \delta}
\]

For 50 Hz: \( T_S = \frac{10900}{\delta_{\text{[min]}}} \)[ms]
CT transient over-dimensioning factor $K_{TF}$

$$K_{TF} = 1 + \omega T_S \left( \frac{T_N}{T_S} \right)^{\frac{T_S}{T_S-T_N}}$$

$T_N$ = network time constant (short-circuit time constant)

$T_S$ = CT secondary time constant
CT with closed iron core,
Over-dimensioning factor $K'_{TF}$ for specified time to saturation ($t_M$)

\[
K'_{TF} = 1 + \omega T_N \cdot \left(1 - e^{-\frac{t_M}{T_N}}\right)
\]

$t_M \to \infty$:

\[
K_{TF} = 1 + \omega T_N = 1 + \frac{X_N}{R_N}
\]
CT over-dimensioning factor $K_{TF}(t_M,T_N)$ in the case of short time to saturation ($t_M$)
Current transformer magnetising and de-magnetising

\[ B = B_R + (B_{\text{Max.}} - B_R) \cdot e^{-\frac{t}{T_S}} \]

\[ I_p \]

\[ B \]

\[ I_m \]

\[ B_{\text{Max}} \]

\[ B_R \]
Current transformer
Course of flux in the case of non-successful auto-reclosure

\[ B_{\text{max}} = \frac{B_{\text{max}}}{B_{\sim}} = \left[ 1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S} \left( e^{-\frac{t_{F_1}}{T_N}} - e^{-\frac{t_{F_1}}{T_S}} \right) \cdot e^{-\frac{t_{D_T} + t_{F_2}}{T_S}} \right] + \left[ 1 + \frac{\omega \cdot T_N \cdot T_S}{T_N - T_S} \left( e^{-\frac{t_{F_2}}{T_N}} - e^{-\frac{t_{F_2}}{T_S}} \right) \right] \]

- \( t_{F_1} \) = duration of 1st fault
- \( t_{D_T} \) = dead time
- \( t_{F_2} \) = duration of 2nd fault
Current transformer magnetising curve and point of remanence

\[ H = i_m \cdot w \]

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

- up to 80%
- < 10%
- negligible
Current transformers TPX und TPY
Course of the flux with non-successful auto-reclosure

- closed iron core (TPX)
- core with anti-remanence air-gaps (TPY)
## Standards of voltage transformers

### VT classes to IEC 60044-2

<table>
<thead>
<tr>
<th>Class designation</th>
<th>Permissible error at 0.05 · $U_N$ and 1.0 · $U_N$</th>
<th>Permissible angle error in minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Voltage error $F_U$</td>
<td>Angle error $\delta$</td>
</tr>
<tr>
<td>3P</td>
<td>$\pm 3.0 %$</td>
<td>120 minutes</td>
</tr>
<tr>
<td>5P</td>
<td>$\pm 6.0 %$</td>
<td>240 minutes</td>
</tr>
</tbody>
</table>

All 3P and 5P protection CTs must additionally comply with one of the below VT metering classes!

### VT classes for measurement IEC 60044-2

<table>
<thead>
<tr>
<th>Class designation</th>
<th>Permissible voltage error in % at 1.0 · $U_N$</th>
<th>Permissible angle error in minutes at 1.0·$U_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Not determined</td>
</tr>
</tbody>
</table>
Capacitive voltage transformer, Equivalent circuit

\[ C_1 = 5 \text{ nF} \]
\[ C_2 = 95 \text{ nF} \]
\[ C_E = C_1 + C_2 \]

\[ U^*_1 = U_P \cdot \frac{C_1}{C_1 + C_2} \]

\[ U^*_2 = \frac{100 \text{ V}}{\sqrt{3}} \]

\[ 400 \text{ kV} \]
\[ 20 \text{ kV} \]
\[ 100 \text{ V} \]
Measured voltage transients after fault at voltage maximum and zero-crossing (Example)

Legend:
- $U_p(t)$: Primary voltage
- $U_s(t)$: Secondary voltage
- (1): Fault inception
- (2): Aperiodic damping of $U_s(t)$
- (3): Periodic damping of $U_s(t)$

### Transient performance of CVTs, Recommendations acc. to IEC 60044-5

<table>
<thead>
<tr>
<th>Time Ts in ms</th>
<th>Ratio $\frac{U_s(t)}{\sqrt{2} \cdot U_s} \cdot 100%$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Classes</strong></td>
</tr>
<tr>
<td></td>
<td>3PT1</td>
</tr>
<tr>
<td>10</td>
<td>---</td>
</tr>
<tr>
<td>20</td>
<td>$\leq 10$</td>
</tr>
<tr>
<td>40</td>
<td>$\leq 10$</td>
</tr>
<tr>
<td>60</td>
<td>$\leq 10$</td>
</tr>
<tr>
<td>90</td>
<td>$\leq 10$</td>
</tr>
</tbody>
</table>

Recommendations to IEC 60044-5
**CT dimensioning**

\[ K_{OD} = K_{TF} \]

\[ \text{rated CT burden: } P_{BN} \]
\[ \text{internal burden of the CT: } P_i = R_i \cdot I_{2N}^2 \]

\[ \text{Actual connected burden: } P_B = R_B \cdot I_{2N}^2 \]

\[ R_B = R_i + R_R \]
\[ R_i = \text{resistance of connecting cables} \]
\[ R_R = \text{burden resistance of the relay} \]

\[ \text{No saturation for the total short-circuit duration: } K'_{TF} = \frac{B_{\text{Max}}}{\hat{B}_\sim} = 1 + \omega T_N = 1 + \frac{X_N}{R_N} \]

\[ \text{No saturation for the specified time } t_M: \quad K''_{TF} = \left[ 1 + \frac{\omega \cdot T_N \cdot T_s}{T_N - T_s} \left( e^{-\frac{t_M}{T_N}} - e^{-\frac{t_M}{T_s}} \right) \right] \]

\[ \text{with } ALF' \geq K_{OD} \cdot \frac{I_K}{I_N} \]

\[ K_{OD} \geq K_{TF} \cdot K_{Rem} \]

\[ K_{Rem} = \frac{1}{1 - \frac{\% \text{Remanence}}{100}} \]

\[ \text{Remanence only considered in extra high voltage systems (EHV)} \]
\[ K_{TF}-\text{values acc. to relay manufacturers' guides} \]
## Practical CT requirements

### Transient over-dimensioning factors $K_{TF}$ (AR not considered)

<table>
<thead>
<tr>
<th>Distance</th>
<th>Close-in fault:</th>
<th>Fault at balance point:</th>
</tr>
</thead>
<tbody>
<tr>
<td>7SA6 and 7SA522</td>
<td>$K_{TF} \geq 5$</td>
<td>$K_{TF} \geq 2$ ($\geq 1$ if $T_N &lt; 30\text{ms}$)</td>
</tr>
</tbody>
</table>

### Overcurrent

| 7SJ56 | $\text{ALF} \geq I \gg \text{setting}/I_N$, at least 20 |

<table>
<thead>
<tr>
<th>Transformer Differential</th>
<th>Internal fault</th>
<th>External fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>7UT6</td>
<td>$K_{TF} \geq 0.75$</td>
<td>$K_{TF} \geq 1.2$</td>
</tr>
<tr>
<td>(Saturation free time $\geq 4\text{ ms}$)</td>
<td>(Saturation free time $\geq 5\text{ ms}$)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Line differential</th>
<th>Internal fault</th>
<th>External fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>7SD61</td>
<td>$K_{TF} \geq 0.5$</td>
<td>$K_{TF} \geq 1.2$</td>
</tr>
<tr>
<td>(Saturation free time $\geq 3\text{ ms}$)</td>
<td>(Saturation free time $\geq 5\text{ ms}$)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bus differential</th>
<th>Internal fault</th>
<th>External fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>7SS52</td>
<td>$K_{TF} \geq 0.5$</td>
<td>$K_{TF} \geq 0.5$</td>
</tr>
<tr>
<td>(Saturation free time $\geq 3\text{ ms}$)</td>
<td>(Saturation free time $\geq 3\text{ ms}$)</td>
<td></td>
</tr>
</tbody>
</table>
CT dimensioning for
Example differential protection (1)

1. Calculation of fault currents

110 kV, 3 GVA
110/20 kV
40 MVA
$u_T=12\%$

Impedances related to 110 kV:

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

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

Line: $Z_L = \frac{l [km]}{z_L [\Omega/km]} = 8 \cdot 0.4 = 3.2 \, \Omega$

Impedances related to 20 kV:

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

Transf.: $Z_T = \frac{U_N^2 [kV^2]}{P_{N-T} [MVA]} \cdot \frac{u_T [%]}{100} = \frac{20^2}{40} \cdot \frac{12\%}{100} = 1.2 \, \Omega$
Dimensioning of the 110 kV CTs for the transformer differential protection:

Manufacturer recommends for relay 7UT61:

1) Saturation free time $\geq 4\text{ms}$ for internal faults
2) Over-dimensioning factor $K_{TF} \geq 1.2$

The saturation free time of 3 ms corresponds to $K_{TF} \geq 0.75$

See diagram, page 59

Criterion 1) therefore reads:

$$ALF' \geq K_{TF} \cdot \frac{I_{F1}}{I_N} = 0.75 \cdot \frac{17300}{300} = 43$$

For criterion 2) we get:

$$ALF' \geq K_{TF} \cdot \frac{I_{F2}}{I_N} = 1.2 \cdot \frac{1730}{300} = 7$$

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, \( R_2 \leq 2 \, \text{Ohm} \) (\( P_i \leq 2 \, \text{VA} \))

**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, \( R_2 \leq 2 \, \text{Ohm} \) (\( P_i \leq 2 \, \text{VA} \))

**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 \( K_{TF} \geq 0.5 \)

See diagram, page 59

**Criterion 1') therefore reads:**

\[ ALF' \geq K_{TF} \cdot \frac{I_{F3}}{I_N} = 0.5 \cdot \frac{9550}{200} = 24 \]

**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

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

(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_2 \leq 0.04 \text{ Ohm} (P_i \leq 1 \text{ VA})