Current transformer selection for VAMP series overcurrent and differential relays

This application note applies to Vamp 40, Vamp 50, Vamp 200 and Vamp 300 series

Iron core current transformers (CT) are accurate in amplitude and phase when used near their nominal values. At very low and at very high currents they are far from ideal. For overcurrent and differential protection, the actual performance of CTs at high currents must be checked to ensure correct function of the protection relay.

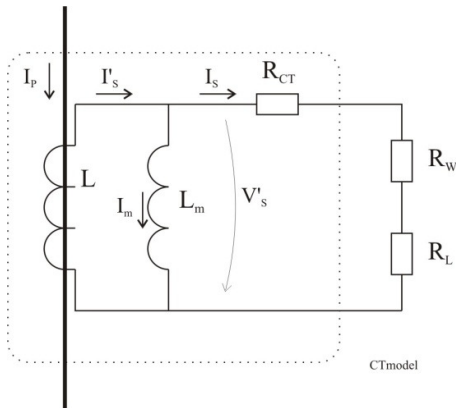### 1. CT classification according IEC 60044-1, 1996

CT model

Figure 1. A CT equivalent circuit. Lm is the saturable magnetisation inductance, L is secondary of an ideal current transformer, RCT is resistance of the CT secondary winding, RW is resistance of wiring and RL is the burden i.e. the protection relay.

Composite error ε_C

Composite error ε_C is the difference between the ideal secondary current and the actual secondary current under steady-state conditions. It includes amplitude and phase errors and also the effects of any possible harmonics in the exciting current.

$$\varepsilon_C = \frac{\sqrt{\dfrac{1}{T}\displaystyle\int_0^T (K_N i_S - i_P)^2\, dt}}{I_P} \cdot 100\% \qquad \text{(eq. 1)}$$

T	=	Cycle time
K_N	=	Rated transformation ratio $I_{NPrimary}/I_{Nsecondary}$
i_S	=	instantaneous secondary current
i_P	=	instantaneous primary current

I_P = Rms value of primary current

NOTICE

All current based protection functions of VAMP relays, except arc protection, thermal protection and 2nd harmonic blocking functions are using the base frequency component of the measured current. The IEC formulae include an RMS value of the current. That is why the composite error defined by IEC 60044-1 is not ideal for VAMP relays. However the difference is not big enough to prevent rough estimation.

Standard accuracy classes

At rated frequency and with rated burden connected, the amplitude error and phase error and composite error of a CT shall not exceed the values given in the following table.

Accuracy class	Amplitude error at rated primary current (%)	Phase displacement at rated primary current (°)	Composite error ε_C at rated accuracy limit primary current (%)
5P	±1	±1	5
10P	±3	-	10

Marking: The accuracy class of a CT is written after the rated power. E.g. 10 VA **5P**10, 15 VA **10P**10, 30 VA **5P**20

Accuracy limit current I_{AL}

Current transformers for protection must retain a reasonable accuracy up to the largest relevant fault current. Rated accuracy limit current is the value of primary current up to which the CT will comply with the requirements for composite error ε_C.

Accuracy limit factor k_{ALF}

The ratio of the accuracy limit current to the rated primary current.

k_{ALF} = I_{AL}/I_N.   (eq. 2)

The standard accuracy limit factors are 5, 10, 15, 20 and 30.

Marking: Accuracy limit factor is written after the accuracy class. E.g. 10 VA 5P**10**, 15 VA 10P**10**, 30 VA 5P**20**.
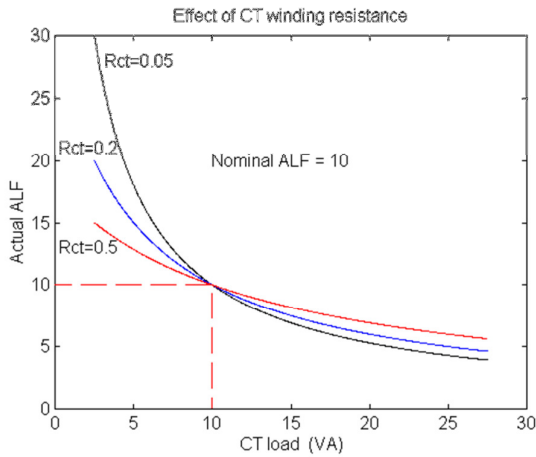
Figure 2. This figure of equation 3 shows that it is essential to know the winding resistance R_{CT} of the CT if the load is much less than the nominal. A 10 VA 5P10 CT with 25% load gives actual ALF values from 15..30 when the winding resistance varies from 0.5 Ω to 0.05 Ω.

The actual accuracy limit factor k_A depends on the actual burden. (Figure 2)

$$k_A = k_{ALF} \frac{|S_i + S_N|}{|S_i + S_A|}$$ (eq. 3)

k_{ALF}	=	Accuracy limit factor at rated current and rated burden
S_i	=	Internal secondary burden. (Winding resistance R_{CT} in Figure 1)
S_N	=	Rated burden of the CT
S_A	=	Actual burden including wiring and the load.

If the current is an asymmetric short circuit current like in Figure 3 the needed accuracy limit factor should be multiplied by coefficient k_{DC}. This guarantees accurate protection i.e. total avoidance of saturation, but may yield to a big CT.

$$k_{DC} = 1 + \omega\tau$$ (eq. 4)

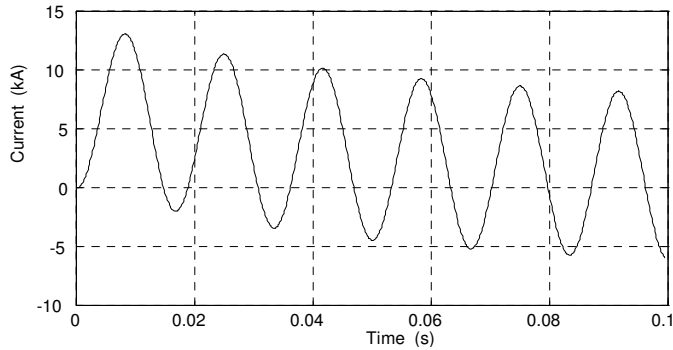|		
ω	=	Angle frequency $2\pi f$
τ	=	Time constant of the short circuit current

Figure 3. Asymmetric short circuit current with time constant τ = 50ms

2. CT requirements for differential protection

When the through current equals and exceeds $k_A \times I_N$ there may be enough secondary differential current to trip a relay although there is no in zone fault. This is because the CTs are unique and they do not behave equally when saturating.

To avoid false tripping caused by heavy through faults the actual accuracy limit factor k_A of the CTs should obey equation:

$$k_A > c \cdot I_k \cdot \frac{I_{NTra}}{I_{NCT}} \qquad \text{(eq. 5)}$$

c = Safety factor from Table 1 or k_{DC} from equation 4 for accurate protection and complete saturation avoidance.

I_k = Maximum through fault short circuit current

I_{NTra} = Rated current of the transformer

I_{NCT} = Rated primary current of the CT

Table 1. Safety factor c for accuracy limit factor.

Protection application	Safety factor c
Overcurrent	1.4
Transformer differential, Δ-winding or unearthed Y-winding	3
Transformer differential, earthed Y-winding	4
Generator differential	3

Formula to solve needed CT power rating S_N

By replacing the complex power terms with corresponding resistances in equation 3 we get

$$k_A = k_{ALF} \frac{R_{CT} + R_N}{R_{CT} + R_W + R_L} \qquad \text{(eq. 6)}$$

where the nominal burden resistance is

$$R_N = \frac{S_N}{I_{NCT\,sec}^2} \qquad\qquad \text{(eq. 7)}$$

R_{CT}	=	Winding resistance (See Figure 1)
R_W	=	Wiring resistance (from CT to the relay and back)
R_L	=	Resistance of the protection relay input
S_N	=	Nominal burden of the CT
I_{NCTsec}	=	Nominal secondary current of the CT

By solving S_N and substituting k_A according equation 5, we get

$$S_N > \left[\frac{c I_k I_{NTra}}{k_{ALF} I_{NCT}} (R_{CT} + R_W + R_L) - R_{CT} \right] I_{NCT\,sec}^2 \qquad \text{(eq. 8)}$$

Example 1

Transformer:	16 MVA YNd11 Z_k = 10% 110 kV / 21 kV (84 A / 440 A)
CTs on HV side:	100/1 5P20 10 VA Winding resistance R_{CT} = 0.2 Ω (R_{CT} depends on the CT type, I_{NCT} and power rating. Let's say that the selected CT type, 100 A and an initial guess of 10 VA, yields to 0.2 Ω.)
CTs on LV side:	500/1 5P20 10 VA Winding resistance R_{CT} = 1.0 Ω (R_{CT} depends on the CT type, I_{NCT} and power rating. Let's say that the selected CT type, 500 A and an initial guess of 10 VA, yields to 1.0 Ω.)

Maximum through fault short circuit current I_k =10 x I_N

R_L	=	0.05 Ω	Typical burden of a VAMP relay 1 A current input.
R_{WHV}	=	0.688 Ω	Wiring impedance of high voltage side. (2x80 m Cu, 4 mm^2)
R_{WLV}	=	0.275 Ω	Wiring impedance of low voltage side. (2x20 m Cu, 2.5 mm^2)
f	=	50 Hz	Frequency
τ	=	50 ms	DC time constant

For ideal unsaturated behaviour Equation 4 gives:

k_{DC} $=$ $1 + 2\pi50 \times 0.05 = 16.7$

The needed CT power on HV side will be (eq. 8)

$$S_N > \left[\frac{16.7 \cdot 10 \cdot 84}{20 \cdot 100} \cdot (0.2 + 0.688 + 0.05) - 0.2\right] \cdot 1^2 = 6.38 \text{ VA}$$

$\Rightarrow$ 10 VA is a good choice for HV side!

And on the LV side

$$S_N > \left[\frac{16.7 \cdot 10 \cdot 440}{20 \cdot 500} \cdot (1.0 + 0.275 + 0.05) - 1.0\right] \cdot 1^2 = 8.74 \text{ VA}$$

$\Rightarrow$ 10 VA is a good choice for LV side!

NOTICE

CTs with one ampere secondaries are recommended for differential protection. They are - from saturation point of view - much more than five times better than CTs with five ampere secondaries. Please note that a 500/5 5P10 CT can be used as a 100/1 5P50.

3. CT requirements for overcurrent protection

Undirectional overcurrent protection does not set as high requirements for a CT as the differential protection.

The nominal primary current should be enough for the maximum short circuit current according equation:

$$I_{CTpri} \geq \frac{I_k}{100} \qquad\qquad \text{(eq. 9)}$$

I_{CTpri} $=$ Nominal primary current of the CT
I_k $=$ Maximum short circuit current

The needed minimum value for the actual accuracy limit factor k_A (equation 3.) depends on the highest setting value, the applied delay type definite/inverse and the needed fault current grading for selectivity. A reasonable actual accuracy limit factor for most cases should be according equation 9.

$$k_A > c \cdot I_{SET} \qquad\qquad \text{(eq. 10)}$$

c   =   Safety factor from Table 1 or k_{DC} from equation 4 if accurate
                   trip limit is needed i.e. total saturation avoidance.
I_{SET} =   Relative setting of the most coarse overcurrent stage
k_{DC} =   Extra coefficient for decaying dc component according
                   equation 4.

The needed power rating for the CT is

$$S_N > \left[\frac{cI_{SET}}{k_{ALF}}\left(R_{CT} + R_W + R_L\right) - R_{CT} \right] I_{NCT\,sec}^2 \quad \text{(eq. 11)}$$

Example 2

Network:
I_k =   30 kA   Maximum short circuit current
R_L =   0.008 Ω   Typical burden of a VAMP relay 5 A current input.
R_W =   0.09 Ω   Secondary wiring impedance

CT:
1000/5   10P10   15 VA (10P10 $\Rightarrow$ 10% error @ 10x1000 A)
R_{CT} =   0.3 Ω   Secondary winding resistance

Settings of the most coarse overcurrent stage:
I_{set} =   10 x I_N = 10000 A
Delay type   =   definite time
f   =   50 Hz   Frequency
τ   =   50 ms   DC time constant

According equation 9 the CT primary value is ok (30k/1000 = 30 and 30 is well under 100.).

Let's use the safety factor 1.4 from table 1 instead of the k_{DC} coefficient and allow some inaccuracy for high set overcurrent protection.
Next we check if the power rating is adequate (equation 11).

$$S_N > \left[\frac{1.4 \cdot 10}{10} \cdot \left(0.3 + 0.09 + 0.008\right) - 0.3 \right] \cdot 5^2 = 6.43 \ \text{VA}$$

$\Rightarrow$ 10 VA is enough, but any decaying DC component might saturate the CT causing some inaccuracy for the high set overcurrent stage.

4. Maximum allowed wiring distance between CT and a relay
From equation 11 we can solve the maximum possible wiring resistance:

$$R_{W\,max} = \left(\frac{S_N}{I_{NCT\,sec}^2} + R_{CT} \right) \cdot \frac{k_{ALF}}{cI_{SET}} - R_{CT} - R_L \quad \text{(eq. 12)}$$

This resistance corresponds to a wire length of

$$L_{max} = \frac{RA}{\delta} \qquad \text{(eq. 13)}$$

Where

L_{max}	=	Maximum wire length
R	=	Wiring resistance
A	=	Cross-sectional area of the wire
δ	=	unit resistance of the wire

The corresponding distance will be half of the wire length, because there are two wires from the CT to the relay.

Max. distance = L_{max}/2 $\qquad$ (eq. 14)

Example 3

Let us calculate the maximum possible distance between CT and protection relay with in the following case.

CT	=	500/5 10P<u>10</u>	
k_{AFL}	=	<u>10</u>	Accuracy limit factor at rated current and rated burden according CT specification.
I_{NCTsec}	=	5 A	Nominal secondary current of the CT
S_N	=	15 VA	Rated burden of the CT
R_L	=	0.008 Ω	Burden of a VAMP relay 5 A current input.
R_{CT}	=	0.15 Ω	Secondary winding resistance
c	=	1.4	Safety factor. See Table 1.
I_{SET}	=	8xI_N	Overcurrent setting
Wire	=	2.5 mm^2 Cu	Cross-sectional area and material
δ_{Cu}	=	17.2 nΩm	Unit resistance of copper
k_{DC}	=	1	This ignores any decaying DC component

From equation 11 we get the maximum allowed wiring resistance

$$R_{W\,max} = \left(\frac{15}{5^2} + 0.15\right) \cdot \frac{10}{1.4 \cdot 8} - 0.15 - 0.008 = 0.512\Omega$$

and from equation 13 we get the corresponding wire length

$$L_{max} = \frac{0.512 \cdot 2.5 \cdot 10^{-6}}{17.2 \cdot 10^{-9}} = 74.4m$$

Thus the maximum possible distance will be according equation 14

Distance$_{max}$ = 74.4/2 = **37 m**.

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