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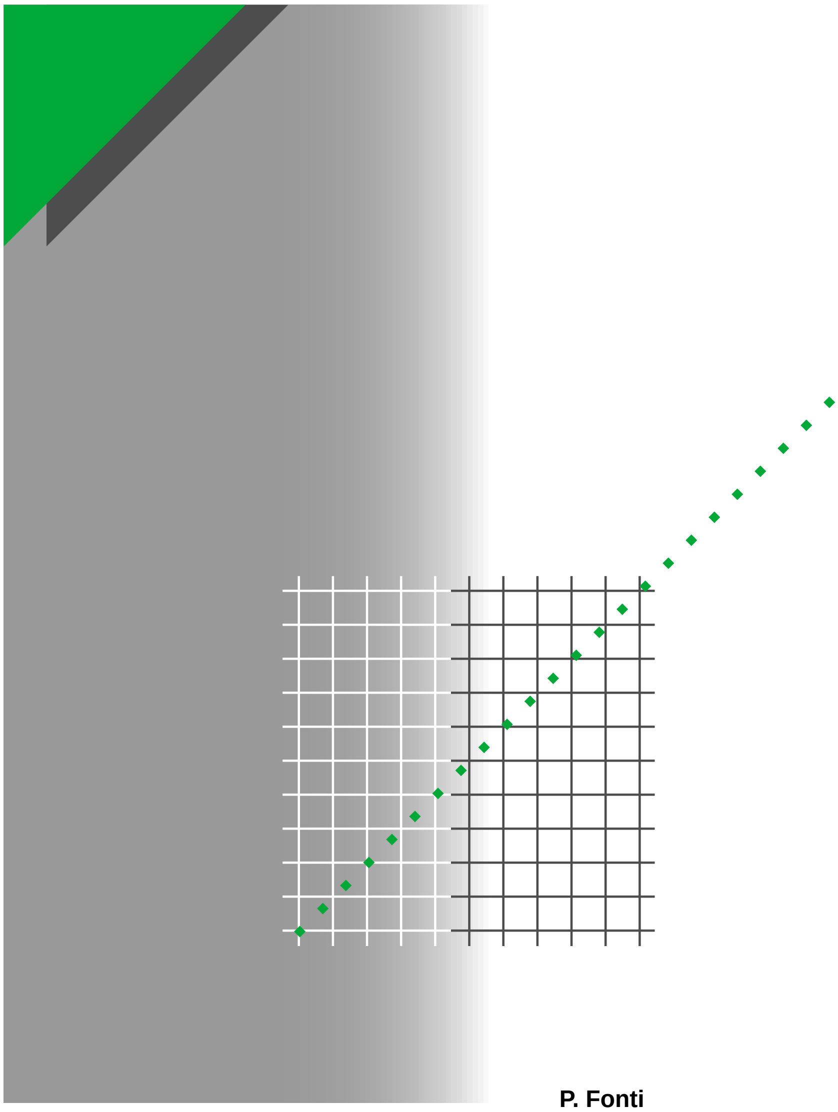
Current transformers: specification errors and solutions



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no. 195

Current transformers: specification errors and solutions

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Lexicon

I_f: maximum through current crossing a protected area.

I_s: current threshold setting.

k_n: nominal accuracy limit factor (ALF) of a CT (associated with its accuracy load).

k_r: real ALF of a CT associated with its real load.

P_i: (= $R_{ct}\ I_n^2$). Internal losses of the CT at I_n.

P_n: (= $R_n\ I_n^2$). Accuracy power of the CT.

P_r: (= $R_r\ I_n^2$). Real load consumption of the CT at I_n.

R_{ct}: CT secondary winding resistance.

R_L: wiring resistance.

R_p: protection relay resistance.

ALF: accuracy limit factor.

CT: current transformer.

Overrating of a CT: selection of a CT whose primary I_n is greater than the I_n immediately greater than the load I_n.

Matching, auxiliary or interposing CT: low voltage CTs installed at the secondary of the main CTs for correcting a ratio and/or the current phase shift.

SF: security factor.

Current transformers: specification errors and solutions

After a reminder of current transformers (CTs), the author highlights the errors most often encountered when defining current transformers, an essential and little known link between the electrical network and the protection relays.

It explains how to find a way out of difficult situations: CTs that cannot be manufactured, delays, additional costs, malfunctions, etc.

This Cahier Technique should be useful for electricians designing installations, for protection specialists, panel builders and all CT manufacturers. It is in the best interest of all to exchange all information required for the safety and optimisation of CTs.

This Cahier Technique is an operational addition to Cahier Technique no. 194 “Current Transformers: how to specify them”.

Contents

1 Specifying current transformers properly

1.1 Introduction

Traditional current transformers (see Cahier Technique no. 164) and hybrid current transformers (see Cahier Technique no. 170) form an essential link within the protection chain of electrical networks.

Their specification, even if it is handled by specialists, often includes errors and is insufficiently optimised.

This often leads to technological impossibilities, operating delays, extra costs, incorrect operation of protections and can even jeopardize the safety of installations and people.

Proper specification of CTs (see Cahier Technique no. 194) requires sound knowledge of:

- the electrical installation diagram,
- the electrical data (voltage, nominal current, short-circuit current, etc.),
- the associated protections,
- the overall network protections (protection plan, the load that they represent for the CTs, as well as wiring and their settings.

Often, due to lack of data or even ignorance of how a CT shall be used, a CT manufacturer says "these features are not feasible", while a standard CT may be suitable.
Although this Cahier Technique emphasises optimisation, it particularly stresses the equivalence between the different definitions of the same current transformer. You should bear in mind that power, class and accuracy limit factor are interdependent values, which have no significance if taken individually. This knowledge is a means of finding a way out of many nearly impossible situations.

Before entering the heart of the matter, a few reminders of CT characteristics are given in the following sections.

1.2 Reminder of CTs

According to IEC standards (among others), CTs can be defined by:

a - Their ratio, example: 2000/5 A.

b - Their power, example: 15 VA.

c - Their class, example:
- 5P, 10P for a protection winding,
- class 0.5, 1, etc. for a metering winding.

d - The characteristics linked to their saturation:
d-1 Accuracy Limit Factor (ALF) for a protection winding,
d-2 Safety Factor (SF) for a metering winding.

e - Other characteristics:
- thermal withstand, example 50 kA - 1 sec.,
- insulation voltage,
- etc.

In the reminder of this section, we shall be concerned only with characteristics **a, b, c,** and **d** and their consequences (see **fig. 1**).

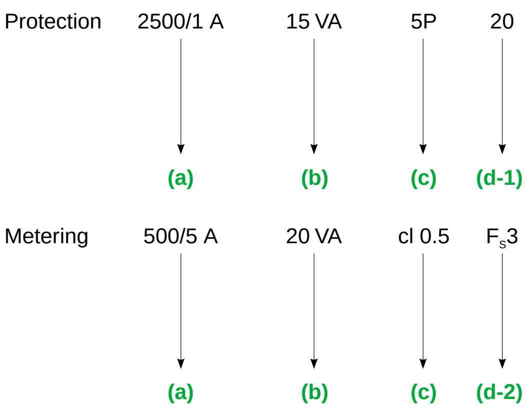


__Fig. 1__ : main characteristic values of the CT.

A 15 VA-5P20 CT has a guaranteed error of less than 5 % when it is subjected to 20 times its nominal current and delivers into its nominal load (15 VA to I_n).
Each of the characteristics **b, c, d** is a function of the two others.

The same CT can be affected a different power, a different accuracy class and a different ALF. However, a given CT only has one magnetising curve and only one secondary winding resistance (at a given temperature).
When these last two elements are known (curve and resistance), we can identify all the necessary correspondences between the various values **a, b,** and **c** to be assigned to the CT or rather between the various triplet combinations:

$(b_1, c_1, d_1) \Leftrightarrow (b_2, c_2, d_2) \Leftrightarrow (b_i, c_i, d_i)$

All the equivalences are deduced from the simple laws of electricity, in particular Ohm's law.

CT equivalent diagram (see **fig. 2**).

- CT ratio: I_{n_1} / I_{n_2} .
- L_m: CT equivalent inductive magnetisation (saturable).
- I_m: magnetising current.
- I_1: primary current.
- I_2: secondary current corresponding to a perfect CT, i.e. $I_2 = I_1 \dfrac{I_{n_2}}{I_{n_1}}$.
- I_s: secondary current effectively crossing the CT secondary: $\vec{I_2} = \vec{I_s} + \vec{I_m}$.

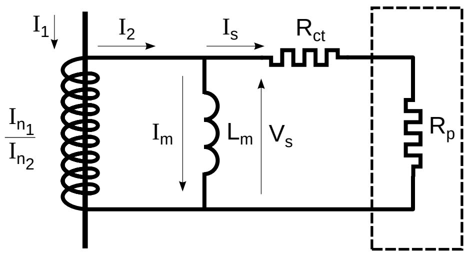


Fig. 2 : a CT equivalent circuit.

It is the magnetising current I_m which generates a metering error. If the CT were perfect, then $I_m = 0$.

The CT magnetisation curve represents the magnetising current as a function of voltage V_s developed at the CT secondary. It can be divided into 3 zones (see **fig. 3**):

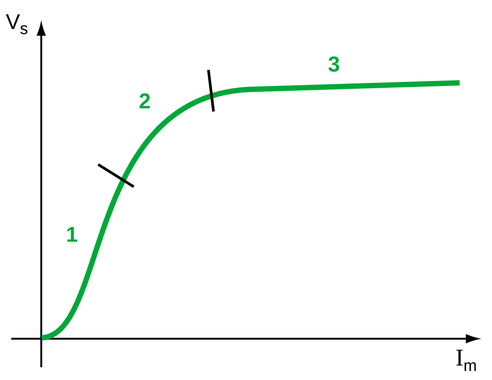
1 - non-saturated zone,
2 - intermediate zone,
3 - saturated zone.

In zone **1**, current I_m is low and voltage V_s increases almost proportionally to the primary current.

Zone **2** is a vague zone between the non-saturated zone and the saturated zone. There is no real break in the magnetisation curve. It is hard to locate a precise point on the curve corresponding to the saturation voltage.

In zone **3**, the curve (V_s I_m) becomes almost horizontal. The error is considerable on the ratio and the secondary current distorted by the saturation.

A certain number of characteristic voltages are highlighted for a CT: they correspond to zone **2** ; knowledge of these voltages is necessary when another definition is given to a particular CT.



1 - Non-satured zone
2 - Intermediate zone
3 - Satured zone

Fig. 3 : magnetisation curve (excitation) $V_s = f(I_m)$ of a CT.

Characteristic voltages linked to a CT

- Knee point voltage defined by the BS 3938 standard: V_k for class X (PX in IEC 60044-1). V_k is determined by the point on the curve V_s (I_m) from which a 10% increase in voltage V_s leads to a 50% increase in the magnetising current.
- Voltage linked to the accuracy limit of the class 5P CTs: $V_{(5P)} = V_{s_1}$.
- Voltage linked to the accuracy limit of the class 10P CTs: $V_{(10P)} = V_{s_2}$.
- Voltage linked to the safety factor F_s $V_{(F_s)} = V_{s_2}$, since the safety factor is linked to an accuracy limit of 10 % just like the class 10P CT.

These various voltages $V_k < V_{(5P)} < V_{(10P)}$ are each linked to an induction level.
With the materials commonly used for CT manufacturing, for example:

- V_k corresponds to 1.4 tesla,
- $V_{(5P)} = V_{s_1}$ corresponds to 1.6 tesla,
- $V_{(10P)} = V_{s_2}$ corresponds to 1.9 tesla,
- $V_{(F_s)} = V_{s_2}$ corresponds to 1.9 tesla.

The following ratios can be deduced:

$$\frac{V_k}{V_{s_1}} = \frac{1.4}{1.6} \; ; \; \frac{V_k}{V_{s_2}} = \frac{1.4}{1.9} \; ; \; \frac{V_{s_1}}{V_{s_2}} = \frac{1.6}{1.9} \; ; \; \text{etc.}$$

If one of these voltages is known, it is simple to deduce the others.

How to calculate the characteristic values from a CT defined in the 5P or 10P class.

- Let us take an example:

Let us assume a 10 VA-5P15 CT with a ratio of 2000/5. "10 VA-5P15" means that when there is a load equal to its nominal load $R_p = \frac{P_n}{I_n^2}$,

CT accuracy is guaranteed better than 5% up to $I_s = 15\, I_n$. From this point on, it is sufficient to refer to the CT equivalent circuit and to Ohm's law to obtain the value of $V_{(5P)}$ or V_{s_1} (see **fig. 4**).

The result is simply: $V_{s_1} = (R_{ct} + R_p)\, I_s$,

i.e. $V_{s_1} = (R_{ct} + R_p)\, 15\, I_n$.

This relation shows that knowledge of the internal resistance of the CT secondary winding is absolutely necessary to correlate the various possible definitions of the CT.

We shall say that a good CT definition must include, whatever the case, the value of R_{ct}.

In our case, let us assume that $R_{ct} = 0.6\ \Omega$,

where $R_n = \frac{10}{5^2} = 0.4\ \Omega$, the calculation yields:

$V_{s_1} = 15 \times 5\ (0.6 + 0.4) = 75$ volts.

With the induction values mentioned above for the 10P classes and class X, V_{s_2} and V_k can be calculated.

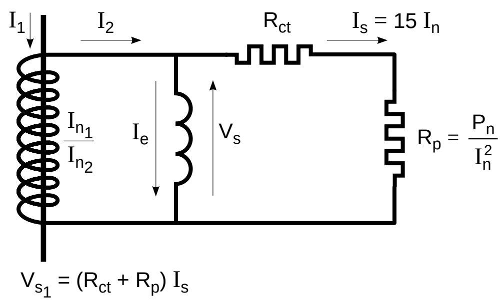


***Fig. 4** : calculating the characteristic voltage of a CT.*

2 Examples of specification errors

2.1 Optimisation and safety

Examination of a protection plan shows that it is designed, for the transformer feeders at switchboard level, to fit CTs of different ratios 50/5 and 1000/5 with the same definition 15 VA-5P20.

These CTs are associated to the same overcurrent protection relays with settings of 15 I_n (of CTs) for 50 A feeders, and 12 I_n (of CTs) for 1000 A feeders. Same load (0.05 VA), same wiring (1.25 VA) and relay settings not too much different: it seems logical that the two sets of CTs have the same definition. However a quick calculation of the necessary power shows that this is not the case…

■ For the 1000/5

The necessary ALF (see Cahier Technique no. 194) is $\frac{2\ I_r}{I_n}$, i.e. $k_r = 24$.

Knowing that $k_r = \frac{k_n\ (P_i + P_n)}{P_i + P_p}$, where:

□ an internal resistance $R_{ct} = 0.6\ \Omega$,

□ $k_n = 20$,

□ CT internal losses at $I_n = P_i$

$P_i = R_{ct} \times I_n^2 = 0.6 \times 5^2 = 15$ VA,

□ a real CT load at $I_n = P_n = 1.3$ VA,

we obtain: $k_r = 36.8 > 24$.

The CT is thus more than suitable.

■ For the 50/5

The necessary ALF is $15\ I_n \times 2$, i.e. $k_r = 30$.

□ First of all, such a CT is theoretically not feasible. Its internal resistance would be around 0.02 Ω. But we can show that it is oversized in power.

□ Furthermore, with $R_{ct} = 0.02\ \Omega$, $P_i = 0.5$ VA; and with $k_n = 20$ and $P_p = 1.3$ VA we obtain $k_r = 172 \geqslant 30$.

More serious still, in event of a trip failure of the transformer feeder, the short-circuit current (I_{th} of the 40 kA /1 s switchboard) will cause an rms current greater than: 172 x 5 A = 860 A to flow at the CT secondary.
(Without saturation 40000 A /50 A x 5 A = 4 kA). The relay and the wiring will be destroyed as well as the CT.
A 5 VA CT is thus more than enough ($k_r = 67 > 30$). A 2.5 VA CT is also suitable: it is less expensive, takes up less space and, most important, it can be manufactured.

■ Conclusion

The power of low ratio CTs must be calculated as their naturally low R_{ct} induces a risk of dangerous oversizing.

Figure 5 sheds some light on the interactions between k_r, P_p, P_i.

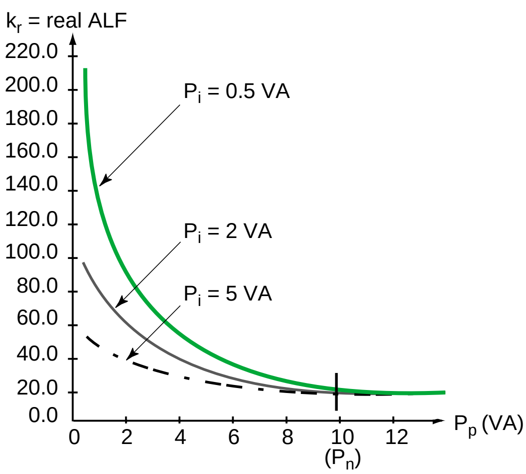


***Fig. 5**: accuracy limit factor behaviour of three CTs (with different R_{ct}), of 10 VA-5P20 as a function of the real load connected to the secondary P_p.*

2.2 When CTs do not seem to be suitable…

This paragraph traces the difficulties encountered further to the manufacturing of CTs for a 33 kV public distribution switchboard consisting of 8 line feeders, without taking into account final needs. The entire problem came up on site a short while before energisation, when the CTs were already installed in the MV panels (see **fig. 6**).

■ The needs formulated when the contract was awarded.

The aim was to have a double primary 300-600 and three 1 A secondary windings:

□ a 5 VA-5P20, to supply a Sepam 2000 protection unit,

□ a 15 VA classe 0.5, for remote metering,

□ a class X, for distance protection.

■ The equipment delivered.

As it was impossible to manufacture three windings in the same functional CT with these characteristics, additional CTs were required. They were dedicated to “class X” and installed downstream of the double secondary CT.

■ The error observed on site.

CTs operating with distance protection must be installed as close as possible to the circuit-breaker to ensure the greatest possible protected zone. However the class X CTs were not close enough.

■ What should we do?

The proposal was thus made to replace all the CTs, i.e. 2 CTs by phase, 6 CTs by feeder, i.e. a total of 48 CTs for 8 feeders! Disassembly, manufacture of new CTs and reassembly led to additional delays and costs…

■ Was there another solution?

□ An initial possibility was to consider use of additional CTs (class X) to supply the Sepam 2000. The supplier confirmed this possibility: the CT dedicated to distance protection (class X) corresponds to 10 VA-5P20 on ratio 300 and to 20 VA-5P20 on ratio 600/1.

It was thus possible to associate the additional CTs with the Sepam 2000.
What a relief! already 24 CTs less to replace.

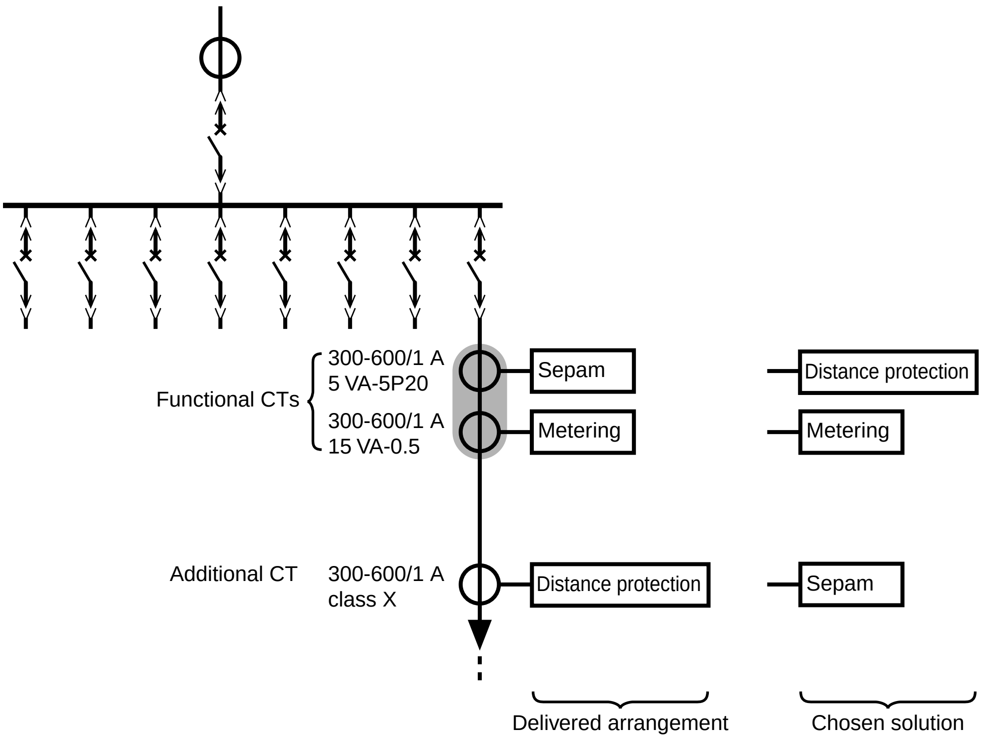


Fig. 6 *: a 33 kV switchboard CT arrangement: the unsatisfactory diagram and the new solution proposed.*

□ The second possibility concerned the CTs with two windings: could the 5VA-5P20 windings be suitable for the distance protections?

The fact is that, voluntarily, all the CTs were identical and corresponded to the worst possible case, while the lines were of different lengths (from 2 km to 38 km). The short lines had a cross-section of 50 mm^2, the others 150 mm^2.

To come back to the real needs of distance protections, it was observed that for 6 feeders, class 5 VA-5P20 corresponded to a suitable class X whatever CT primary was chosen (300 or 600). For the two other feeders, the resulting class X was satisfactory only on the 600/1 ratio!

A solution that the customer accepted for the two 150 mm^2 feeders.

■ We can draw the following conclusion from this contract, which reveals all the consequences of unsatisfactory CT manufacture: the idea of replacing all components is often the first considered, but with the help of specialists it is possible to avoid pointlessly wasting time and money.

2.3 The most frequent errors

These errors normally lead to oversizing of the CTs which increases costs and can be dangerous. Many CT definition errors stem from ignorance of their operation and from the unknown or incomplete characteristics of the network component to be protected and of the associated protections.

The better informed the CT manufacturer, the fewer errors and the more the CT will be optimised.

Protections and conventional CTs

For these protections which do not require class X defined CTs, **the most frequent "errors" are:**

■ Using two CTs or one CT with two secondaries for two protective relays the manufacturers of which recommend different ALF or different accuracy classes. As the CT manufacturers can translate 10P to 5P (according to the corresponding induction levels), and can move from one ALF to another by adjusting power, they can find a CT matching the needs of both relays.

■ Taking into account the wiring resistance although the protection manufacturer has already integrated it into the needs formulated for the CT.

Let us take an example of two relays whose technical data indicate for 1 A CTs:

CT_1 for relay 1: 5 VA-10P15
(assuming $2\ R_L < 1.5\ \Omega$),

CT_2 for relay 2: 10 VA-5P15
(assuming $2\ R_L < 2\ \Omega$).

A single CT may be suitable for both relays: in theory a 10 VA-5P15. You need to:

□ Avoid adding up the powers (5 + 10 VA) required for each relay. In point of fact, for the CT_2, relay 1 only represents a load (just like wiring) and vice versa.

□ Check, in this case for the CT_2, that:
$2\ R_L + R_{p1} \leqslant 2\ \Omega$; and if CT_1 was selected, that:
$2\ R_L + R_{p2} \leqslant 1.5\ \Omega$. If this was not verified, the relay supplier can suggest that "x" VA be added per additional ohm.

Adding the specified power for several protections linked to an application results in CTs that are often impossible to manufacture or that jeopardise safety during short-circuits.

Use of multifunction numerical relays avoids such errors. You only need to size the CT for the most restrictive protection (see Cahier Technique no. 194).

■ Changing the required characteristics without verifying the consequences.

□ A CT manufacturer cannot make a low ratio CT and suggests increasing this ratio; let us take an example:

- Requested: 30/1 CT - 2.5 VA-5P20,
- CT manufacturer's proposal: 60/1,
- With motor I_n = 16 A and minimum thermal protection setting: 40 % of CT I_n, i.e.
60 x 0.4 = 24 A.

The protection setting at 16 A (normal thermal protection setting at motor I_n), is then impossible.

The solution is to increase the rating and lower the ALF requirement:

40/1 - 2.5 VA-5P10. This CT, feasible, allows the required setting (40 x 0.4 = 16 A).

□ A buyer accepts a thermal withstand of 0.1 s proposed by the CT manufacturer instead of 1 s. What is likely to happen is that, on a short-circuit, if the real fault duration exceeds 0.1 s, thermal and probably electrodynamic withstand will be insufficient and may result in CT destruction.

■ Due to lack of information on real requirements.

Let us take the following case, relatively educational: a CT with two primaries and three secondaries (200-1000/1-1-1) is requested with:

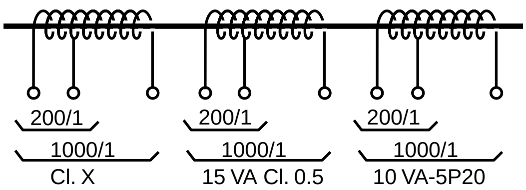
- the first secondary: 1 A, class X (given V_k),
- the second secondary: 1 A-15 VA class 0.5 for metering,
- the third secondary: 1 A-10 VA-5P20.

The supplier can propose a CT with three magnetic cores and secondary tappings to meet the 200 A or 1000 A need at the primary. However, such a CT is hard to manufacture because to obtain 15 VA-class 0.5 and 10 VA-5P20 on 200/1 ratios, you need 5 x 15 VA-class 0.5 and 5 x 10 VA-5P20 on 1000/1 ratios! Moreover, the supplier must comply with class X for both ratios!

In point of fact, class X concerns only the 1000/1 ratio (for busbar differential protection). The 200/1 ratios concern metering and the traditional protections (see **fig. 7**). The CT to be manufactured is then easier, less bulky, cheaper and definitely feasible. This example shows that the lack of information shared between those involved is a source of errors and of non-optimisation. A consultation that does not begin properly may result in a CT that cannot be manufactured.

■ Taking into account the relay impedance R_h for calculation of real load (see **fig. 8**) in the CT calculation for overcurrent or in the calculation for CTs in class X.
A word of warning: R_h is only considered when calculating CTs for zero sequence current I_h (see Cahier Technique no. 194).
For high impedance differential protections, in the calculation of V_k given by:
$2 I_f (R_{ct} + 2 R_L + R_a)$,
where R_a = other loads, R_h must not intervene.
This is the load of one phase (we assume that no current flows through the neutral).

a - The CT manufacturer's understanding



b - The real need

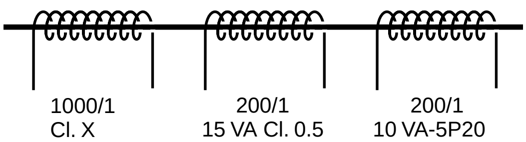


Fig. 7 : example of poor understanding between the customer and the CT manufacturer.

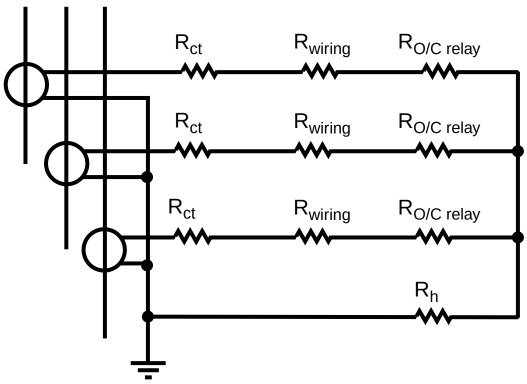


Fig. 8 : internal and load impedances of a CT.

V_k is indeed calculated for relay stability conditions, i.e. no phase or earth fault, in the protected zone, no incorrect unbalance, therefore, in the differential connection $I = 0$ and the voltage of that connection = 0.

Differential protections and class X

For these applications, **the most usual errors are:**

■ Asking the CT manufacturer to supply CTs with the greatest V_k that he can build using a standard mould.
This occurs when the differential protection relay (make, type) is not defined.
There are three consequences:
□ overcost,
□ possibility of high overvoltages and overcurrents at the CT secondary which can lead to destruction of the circuit and the relay,
□ with no requirements for the CT R_{ct}, it is not certain that the V_k expression corresponding to the relay used, will be complied with.
To illustrate this case, let us take the example of a high impedance busbar differential protection. The CT supplied is a 2000/5 where V_k = 400 V and $R_{ct} = 2.5\ \Omega$.
For the relay used, the expression to be satisfied is: $V_k \geqslant 200\ R_{ct} + 20$, i.e. 520 V.
The V_k = 400 V is not sufficient!
More serious still, the requirement of too high a V_k may lead to the manufacturing of a non-standard CT (see the first two consequences above) requiring a specially designed stabilising resistance and an overvoltage limitor as well as the use of a deeper panel!

■ Error on the through current
This error is very common. Let us take the example of a high impedance differential protection where the switchboard I_{sc} is taken into

account instead of the maximum through current. The aim is to protect a motor, the CTs have a ratio of 100/1.

□ Result obtained with the through current ($7\ I_n$ of CT):

$V_k \geqslant 14\ (R_{ct} + 2\ R_L)$.

□ Result obtained with switchboard I_{sc} (I_{sc} = 40 kA):

$V_k \geqslant 800\ (R_{ct} + 2\ R_L)$

It is not necessary to go into too much detail to understand the importance of choosing the right parameter!

The table in **figure 9** gives the through current values to be taken into account when the through current is the CT calculation base (see Cahier Technique no. 194).

■ With line differential protections, taking into account the pilot wires in the calculation of R_{wiring}.

In point of fact, R_L is given by the wiring linking the CTs to the relay located on the same side (end) of the line (see **fig. 10**).

You must not take into account the length of the pilot wires which run from one end to the other of the protected line.

Reminders

With respect to high impedance differential protections:

■ For the calculation of min. V_k, take account of the through current (see fig. 9).

■ Calculation of the stabilising resistance R_{st} is a function of min. V_k and of the relay setting current.

■ Calculation of peak voltage (V_p) is based on the internal I_{sc} of the protected zone and on the real V_k of the CT.

Applications	Through Imax	Excess through Imax	Comments
BB differential protection	Switchboard real I_{sc}	Switchboard I_{th}	Take real I_{sc} if no increase possible. Else take I_{th}
Motor differential protection	Motor starting I	$7\ I_n$ (motor) otherwise $7 \times I_n$ (CT)	If you know neither the starting I nor the motor I_n, take $7 \times I_n$ (CT)
Generator differential protection	Generator I_{sc} contribution only, i.e. I_n (100 / X'')	$7\ I_n$ (generator) otherwise $7 \times I_n$ (CT)	X'' = generator subtransient reactance as a %. If unknown, we assume X'' % ⩾ 15 i.e. 100/15 = 6.67 (7 is taken by excess)
Restricted earth fault differential protection	I_{sc} seen at the CT primary for a fault at the transformer secondary, i.e. $I_{sc} = P_{sc} / U\sqrt{3}$ $P_{sc} = (P_t \cdot P_a) / (P_t + P_a)$	If P_a unknown, we take $P_{sc} = P_t$ $P_t = P_n\ (100 / Z_{sc})$	P_a = upstream short-circuit power and P_t = power limited by transformer Z_{sc} % = transformer short-circuit impedance
Line differential protection	I_{sc} at 80 % of line	Switchboard I_{th} by default	Switchboard I_{th} by default

Fig. 9 : determining the through current properly.

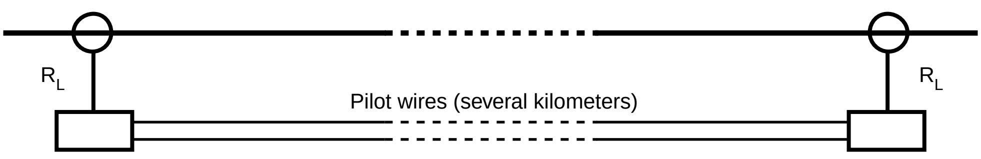


Fig. 10 : R_L is given by the wiring between the CT and the relays located on the same side of the line.

2.4 And if the CT cannot be manufactured?

When a CT manufacturer says that he is unable to manufacture the requested CT, nine times out of ten this is because the CT has been incorrectly specified. To eliminate all the cumulated safety margins taken by all the people involved, the CT must be redefined on the basis of real needs:

- real currents in the installation,
- types of protection, required power,
- discrimination study and protection plan (settings).

This approach must be adopted whenever the specification leads to a non standard CT. Costs, lead times and safety are the factors at stake.

Let us take an example:

We have calculated the class X of a 1000/5 CT for a generator differential protection, assuming that X'' = 15 %.
Not knowing the exact characteristics of the generator, we have assumed that the generator I_n equals the CT I_n.

This results in: $I_f = \frac{100}{15} I_n$ of the CT

i.e. $V_k \geqslant 2 \times 6.7 \times 5\ (R_{ct} + 2\ R_L)$

We have rounded off 6.7 as 7.

We assumed:
$2\ R_L$ = 300 m of 2.5 mm^2, i.e. 2.4 Ω
hence: $V_k \geqslant 70\ R_{ct} + 168$.

Since this CT requires two other windings, this value could not be achieved using the standard mould.
The solution was found by using 4 mm^2 connections and by requesting the generator characteristics. Then:
$2\ R_L = 1.5\ \Omega$
Generator I_n = 830 A.
X'' = 25 %, hence:

$$V_k \geqslant 2 \times \frac{830 \times 100}{25} \times \frac{5}{1000} (R_{ct} + 1.5)$$

$V_k = 33.2\ R_{ct} + 50$

The difference is marked and shows the importance of obtaining the right information and of knowing the safety margins.

If the CT is declared impossible to manufacture, a solution, i.e. a compromise, must be found between all those involved. There is always a way out, which can be found with the help of specialists.
As an example, here are a few leads:

- play on the equivalences between CTs (see next section),
- reduce the safety coefficient (for instance 2 to 1.5 for an overcurrent protection),
- change the secondary from 5 to 1 A (see **fig. 11**),
- increase wiring cross-section,
- overrate the CTs (primary I_n),
- move the relay with respect to the CT,
- use matching CTs with low consumption,
- and so on.

The overrating of a CT can solve a manufacturing problem

Let us take two examples:

- A 100/1 CT with a load of 2.5 VA requires an ALF of 25 for an overcurrent protection.

The standard CTs proposed are 2.5 VA-5P20. If a CT with a ratio of 150/1 - 2.5 VA-5P20 is proposed, the ALF need will be reduced in the CT primary ratio, i.e. necessary
ALF = 25 x (100/150) = 16.7. An ALF of 20 is thus sufficient!

- If the class X requested for a CT is proportional to a through current or a primary I_{sc}, these values are multiplied by the CT ratio; thus, the required knee point voltage will be less for an overrated CT, unless its increasing resistance R_{ct} starts to neutralise the ratio benefit.

In all cases, it will be possible to create a higher knee point voltage than with a CT of lower ratio, as it is proportional to the number of secondary turns.
Globally, the chance of obtaining workable characteristics will be greater.
The same reasoning can be made for a 1 A secondary CT compared with a 5 A CT.
However, the factor gain of 5 obtained on the formula by the CT ratio is often completely erased, if not reversed, by a far greater increase of secondary winding resistance.

Length (m)	**5**	**10**	**20**	**50**	**100**	**200**	**400**
Wiring losses (VA) for:							
I_n = 1 A	0.04	0.08	0.16	0.4	0.8	1.6	3.2
I_n = 5 A	1	2	4	10	20	40	80

Fig. 11 *: losses in wiring for a 2.5 mm^2 cross-section (8 Ω/km at 20° C). With 1 A, losses are 25 times less.*

Indeed, the space required for the number of turns x 5 results in reduction in wiring cross-section, thus naturally increasing its linear resistance. The new resistance can thus be amply multiplied by 10 with respect to the 5 A CT.

■ If you are tempted to impose a CT overrating, you must check the repercussions of the change in ratio.

For example:

□ If the CT supplies a pilot wire differential protection, you must ensure that the corresponding CT at the other end of the line has also the same ratio change.

□ In the case of a restricted earth protection, you must ensure that:

- the CT installed on the neutral point is also modified,

- the earth fault detection is not compromised by the overrating.

□ For all protection types, you must check that setting of the protection is still possible.

Optimisation of the differential protection CTs

Let us take the example of a transformer differential protection (see **fig. 12**).

■ Calculating the through current.

The transformer impedance limits the through current to: ($P_{sct} = \frac{5 \times 100}{8} = 62.5$ MVA).

□ Short-circuit power becomes:

$$P_{sc} = \frac{600 \times 62.5}{600 + 62.5} = 56.6 \text{ MVA}.$$

□ The through current at the secondary is:

- 11 kV side:

$$I_{f1} = \frac{56.6 \times 10^6}{11\sqrt{3} \times 10^3} \times \frac{5}{300} = 49.5 \text{ A},$$

- 3.3 kV side:

$$I_{f2} = \frac{56.6 \times 10^6}{3.3\sqrt{3} \times 10^3} \times \frac{5}{1000} = 49.5 \text{ A},$$

■ Formulas to be applied for V_k (standard protection):

□ Calculating the matching CTs

with a ratio of: $\frac{5}{5/\sqrt{3}}$

$$V_{ka\ mini} = \frac{4 I_{f1}}{\sqrt{3}} \left[R_{sr} + 3\left(R_{L3} + R_p\right)\right]$$

□ Calculating main CTs

- 11 kV side: 300/5

$$V_{k\ p1\ min} = 4 I_{f1} (R_{ct} + R_{L1} + R_{sp}) + V_{ka\ mini} \frac{5}{5\sqrt{3}}$$

- 3.3 kV side: 1000/5

$$V_{k\ p2\ min} = 4 I_{f2} (R_{ct} + R_{L2} + R_r)$$

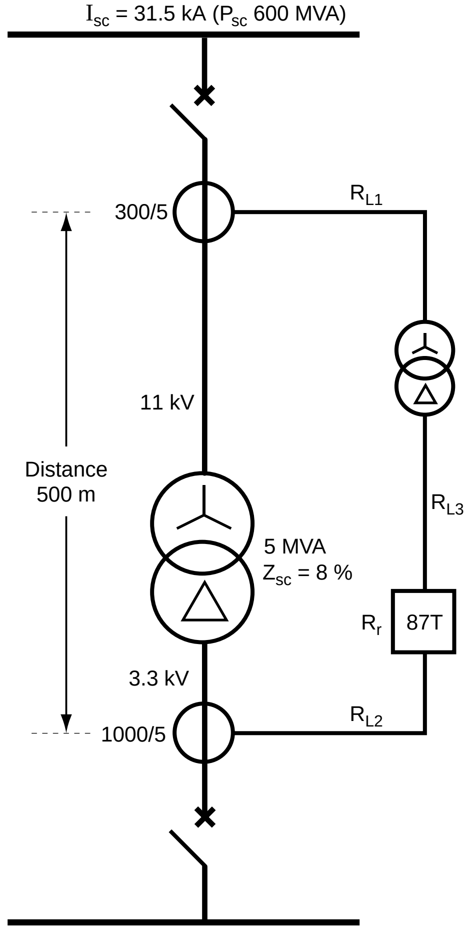


***Fig. 12 :** transformer differential protection.*

■ Optimisation approach.

Let us examine the case of the 300/5 CT placed in the 11 kV switchboard.

□ First hypothesis

The matching CT $\frac{5}{5/\sqrt{3}}$ is the one proposed as standard by the relay manufacturer. It is located with the relay on the 3.3 kV side. Wiring is 2.5 mm² throughout.

$R_{L1} = 4\ \Omega$

$R_{L2} = 0.08\ \Omega$

$R_{L3} = 0.024\ \Omega$

$R_{sr} = 0.25\ \Omega$, secondary winding resistance of the matching CT,

$R_{sp} = 0.15\ \Omega$, primary winding resistance of the matching CT,

$R_p = 0.02\ \Omega$, relay resistance.

We find:

- $V_{ka\ mini}$ = 43.7 V (standard V_{ka}= 58 V),

- $V_{kp1\ mini} = 198\ R_{ct}$ + **847**

□ Second hypothesis

The same as the first, except that R_{L1} wiring is in 10 mm², hence $R_{L1} = 1\ \Omega$

The result is:

- $V_{kp1\ mini} = 198\ R_{ct} + \mathbf{243}$

□ Third hypothesis

The matching CT is on the 11 kV side as well as the relay: $R_{L1} = 0.08\ \Omega$

- $V_{kp1\ mini} = 198\ R_{ct} + \mathbf{61}$

□ Fourth hypothesis

Same as the third hypothesis, except for the matching CT which is not standard, but which is imposed on the CT manufacturer where:

$R_s \leqslant 0.1\ \Omega$,

$R_p \leqslant 0.1\ \Omega$,

which results in:

- $V_{ka\ mini} = 26.5$ V

- $V_{kp1\ mini} = 198\ R_{ct} + \mathbf{41}$

We observe that by modifying the wiring cross-section, the position and the characteristics of the matching CT, the gain on the minimum needed V_k of the 300/5 CT is around 800 V.

The same approach adopted for the 1000/5 CT, placed on the 3.3 kV side, yields results that are fairly similar concerning V_k. However, in view of the fact that a 1000/5 CT is easier to manufacture than a 300/5 CT, it is more advantageous to place the relay and the matching CT on the 11 kV side.

If a 1 A CT is used, the same hypotheses as above enable a move from:

- $V_{kp1} = 39.6\ R_{ct} + \mathbf{249}$ to $V_{kp1} = 39.6\ R_{ct} + \mathbf{17}$

The 1 A CTs may be easier to manufacture than the 5 A CTs, but all depends on the relative weight of the R_{ct} and the wiring in the V_k expression.

3 Equivalence of the various possible definitions of the same CT

In many cases, you need to know how to "juggle" with the various CT characteristics; ratio, power, class, ALF. The reason for this is not only in order to get out of a tricky position, but also to be able to use standard CTs that are available, less costly and tested.

This section thus aims to show how CT characteristics can be manipulated. First, however, it should be pointed out that the only CT constants are its magnetising curve and resistance and, naturally, its ratio.

3.1 How to move from P_{n_1}-5Pk_1 to P_{n_2}-5Pk_2

V_{s_1} and R_{ct} are fixed.

$$V_{s_1} = \left(R_{ct} + \frac{P_{n_1}}{I_n^2}\right) k_1 I_n = \left(R_{ct} + \frac{P_{n_2}}{I_n^2}\right) k_2 I_n$$

$$= \left(R_{ct} + \frac{P_{n_i}}{I_n^2}\right) k_i I_n$$

Knowing that $P_i = R_{ct}\ I_n^2$ (internal ohmic losses of the CT), we obtain:

$(P_i + P_{n_1})\ k_1 = (P_i + P_{n_2})\ k_2 = (P_i + P_{n_3})\ k_3$.

Sometimes, some people ignore P_i: this is a serious error as P_i can be roughly of the same value, if not higher, than P_n.

- if P_{n_2} is imposed, we shall obtain:

$$k_2 = \frac{(P_i + P_{n_1})}{(P_i + P_{n_2})} k_1 \text{ or } k_2 = \frac{(R_{ct}\ I_n^2 + P_{n_1})}{(R_{ct}\ I_n^2 + P_{n_2})} k_1$$

- if k_2 is imposed, we shall obtain:

$$P_{n_2} = \frac{k_1}{k_2} P_{n_1} + \left(\frac{k_1}{k_2} - 1\right) P_i$$

or else:

$$P_{n_2} = \frac{k_1}{k_2} P_{n_1} + \left(\frac{k_1}{k_2} - 1\right) R_{ct}\ I_n^2$$

3.2 How to move from P_{n_1}-5Pk_1 to P_{n_2}-10Pk_2

We have:

$$V_{s_1} = \left(R_{ct} + \frac{P_{n_1}}{I_n^2}\right) k_1\ I_n$$

$$V_{s_2} = \left(R_{ct} + \frac{P_{n_2}}{I_n^2}\right) k_2\ I_n$$

But:

$$V_{s_1} = \frac{1.6}{1.9} V_{s_2}$$

- if P_{n_2} is imposed:

$$k_2 = \frac{1.9}{1.6} \frac{(R_{ct}\ I_n^2 + P_{n_1})}{(R_{ct}\ I_n^2 + P_{n_2})} k_1 \text{ or}$$

$$k_2 = \frac{1.9}{1.6} \frac{(P_i + P_{n_1})}{(P_i + P_{n_2})} k_1$$

- if k_2 is imposed, we shall have:

$$P_{n_2} = \frac{1.9}{1.6} \frac{k_1}{k_2} P_{n_1} + \left(\frac{1.9}{1.6} \frac{k_1}{k_2} - 1\right) R_{ct}\ I_n^2$$

If you wish to move from a 10P to a 5P definition, the above expressions apply: just reverse the induction ratio.

3.3 What is the V_k of a CT: P_n-XPk

How to move from P_n-5Pk to V_k

We have seen that:

$$V_{s_1} = \left(R_{ct} + \frac{P_{n_1}}{I_n^2}\right) k\ I_n$$

and $V_k = \frac{1.4}{1.6} V_{s_1}$

hence $V_k = \frac{1.4}{1.6}\left(R_{ct} + \frac{P_n}{I_n^2}\right) k\ I_n$

How to move from P_n-10Pk to V_k

We also have:

$$V_k = \frac{1.4}{1.9} V_{s_2}$$

hence

$$V_k = \frac{1.4}{1.9}\left(R_{ct} + \frac{P_n}{I_n^2}\right) k\ I_n$$

3.4 How to move from a class X (V_k, R_{ct}) to a class 5P: P_n-5Pk

- Assuming that k is imposed, we shall obtain:

$$P_n = \frac{1.6}{1.4}\left(\frac{V_k\ I_n}{k}\right) - R_{ct}\ I_n^2$$

If the result is negative, this means that the necessary ALF cannot be obtained with this CT as its internal losses are too great.

- Assuming that P_n is imposed, in this case:

$$k = \frac{1.6}{1.4}\left(\frac{V_k\ I_n}{P_n + R_{ct}\ I_n^2}\right)$$

Note:
In this section, the induction levels: 1.4 - 1.6 - 1.9 are given as examples since they vary from one manufacturer to another.

4 Conclusion

This Cahier Technique completes Cahier Technique no. 194 in its aim to increase awareness of all those involved in the process from design of an electrical network to implementation of protections, of the time wasted and the financial losses resulting from incorrect specification of CTs. In particular, it gives some examples of errors not to make and leads for solutions when the original specification is not satisfactory or when you apparently come up against a dead end.

It stresses that although communication with the CT manufacturer and particularly knowledge of induction levels enables a solution to be found by playing with equivalences, it is by identifying the exact needs at all stages in the process, that the optimised solution can be found.

We hope that you will find this document useful.

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