Cahier technique no. 194

Current transformers: how to specify them
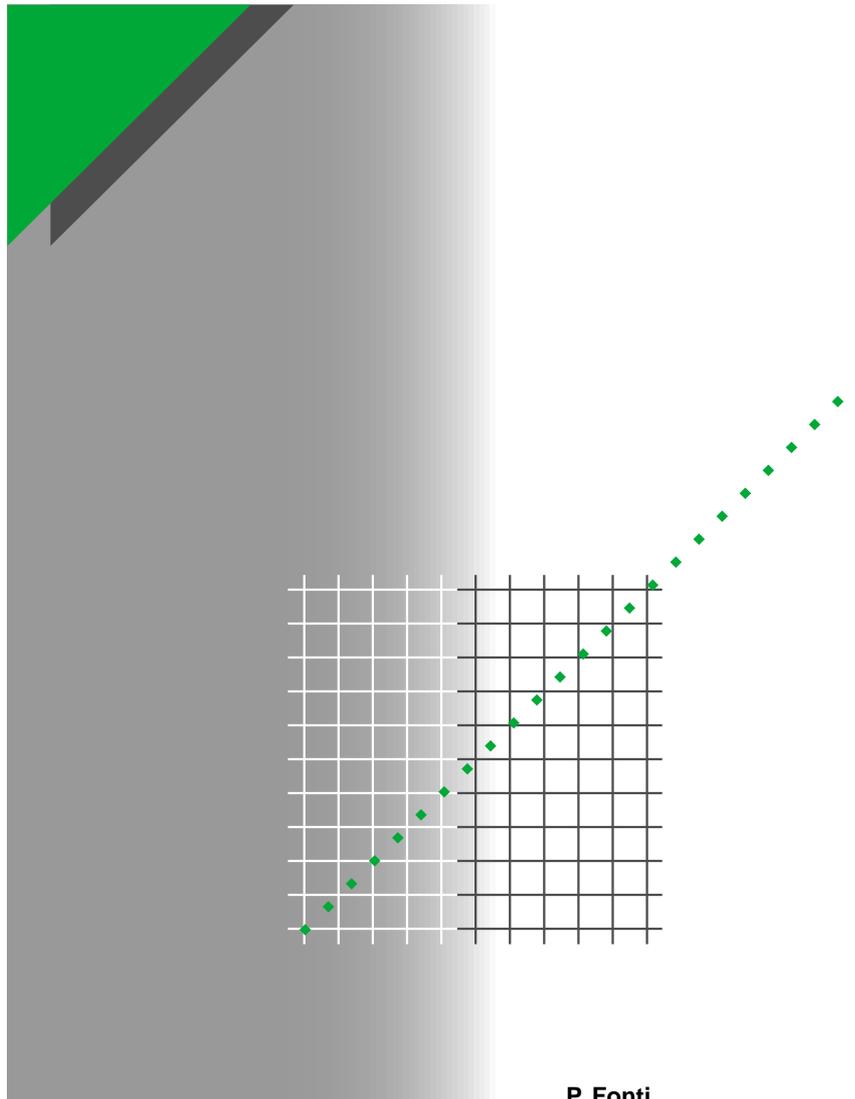
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no. 194

Current transformers:
how to specify them

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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_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:
how to specify them

Electrical power management requires implementation of data processing units able to monitor networks or equipment and, as applicable, to initiate the appropriate actions...

Data sent by current transformers are processed by protection, control and monitoring units that send signals to operate switchgear and/or information to a supervisory unit or to a central control room.

The task, consisting of identifying and rating the current transformers and associating them with the protection and/or metering units, has always given rise to problems, both for electrical engineers (oversizing the characteristics) and for the manufacturer (random feasibility, excessive sizing, high costs).

This document does not cover the technical demonstrations amply referred to in the literature (see Cahiers Techniques no. 164 and 170). Its purpose is to remind users of a few simple rules enabling the best possible definition of the secondary characteristics of a current transformer (CT) according to the protections and applications concerned.

Practically, it offers constructive assistance for technicians who have reached a dead end:

■ either because they do not possess the necessary information,

■ or because the results of their design have led to current transformers that cannot be manufactured by the potential suppliers.

Contents

1 Introduction

The design of MV and HV electrical networks is a complex undertaking that must take into account the needs to be satisfied, i.e.:
■ safety of people and equipment,
■ continuity of supply,
■ installation and operating costs.

The designer uses the load points, their simultaneity coefficient and the above-mentioned criteria to draw up the single-line diagram for the installation (see **fig. 1**).

He must then select the earthing system, define the busways, calculate the fault currents, define the protection system (discrimination, choice of protections, see Cahier Technique no. 174).

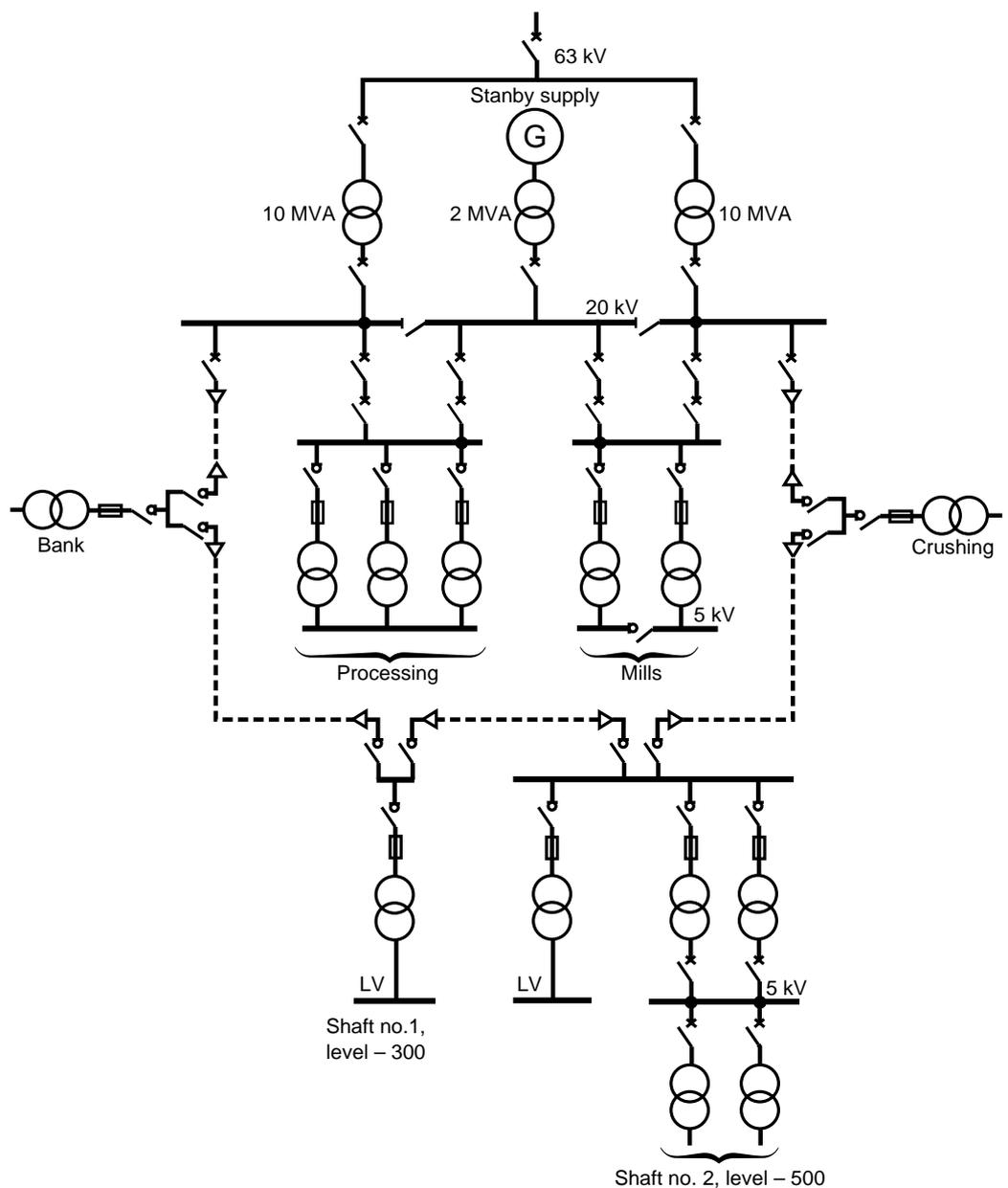**Figure 2** shows an example of protections chosen for the standby supply in figure 1.

Fig. 1 : example of a general single-wire diagram for a mine.

49	Thermal image
46	Negative sequence
51V	Voltage restrained O/C
32P	Reverse active power
32Q	Field loss (max. reactive power)

27	Undervoltage
59	Overvoltage
81	Over and under frequency
59N	Zero sequence voltage

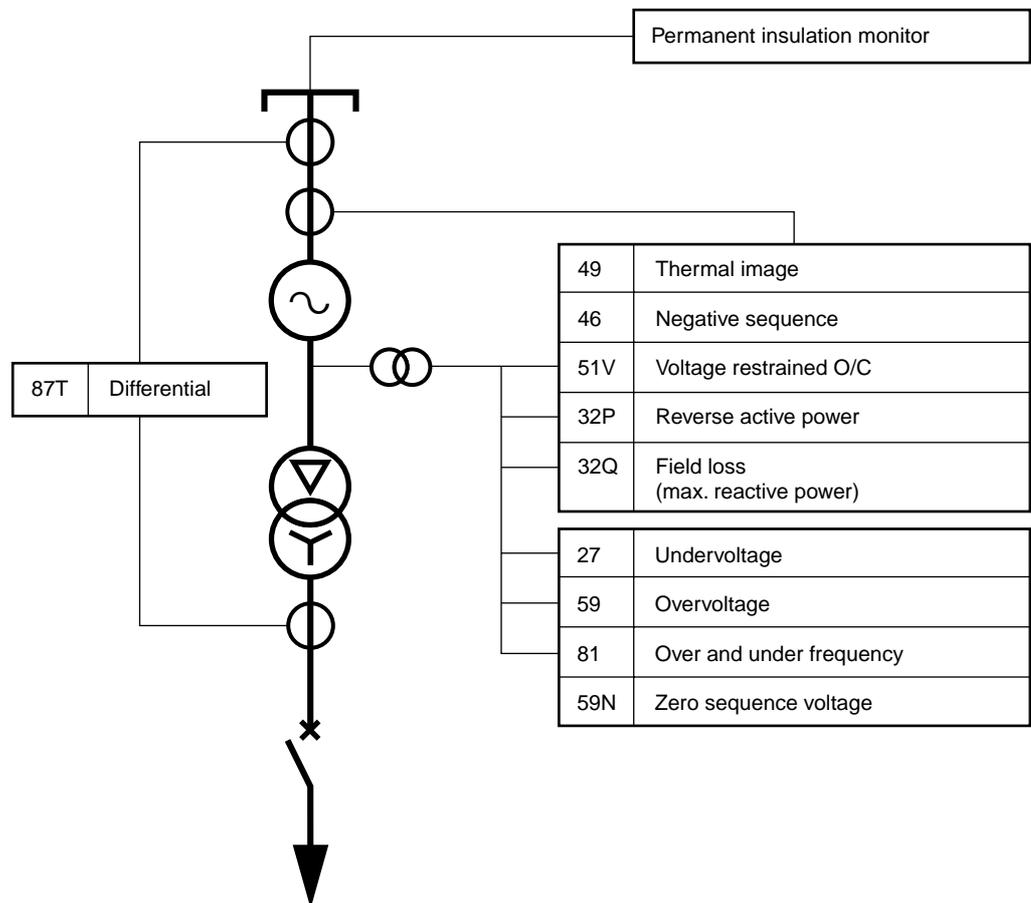| 87T | Differential |

Permanent insulation monitor

Fig. 2 : protections of a MV unit module.

The protection plan must specify the operating or non-operating conditions for all the protections during a fault and during normal operation (transients). It must indicate the protection settings.

However, the plan rarely indicates the characteristics of the protection input circuit and other data necessary to specify the current transformers (CT). This is because it is often very hard for the designer to collect all the necessary data.

The consequences on industrial start-up can be serious: unsuitability, overrating, non-standard specifications and high costs, addition of matching CTs, last minute CT changes, postponement of delivery, commissioning, production times, etc.

More serious still, incorrect definition can lead to malfunctions in the protection channel causing destruction of equipment or, worse still, danger for the operator.

A few examples:

■ Overestimation of the short-circuit current can lead to feasibility problems, overrating and high CT costs.

■ On the other hand, underestimation of the short-circuit current can lead to failure to detect the fault, thus destroying the equipment, placing the operator in danger and generating operating downtime.

■ An output power or accuracy error can result in a malfunction or in failure to trip of the protection devices, thus destroying the equipment, placing the operator in danger and generating operating downtime.

■ An error in defining the accuracy class of a metering winding will lead to incorrect energy billing and thus a loss of income for the electrical utility or the customer.

■ Etc.

The aim of this document is to provide assistance with defining current transformers. Before entering the heart of the subject, a reminder is given of the information necessary to define a CT (see the table in **figure 3**).

Necessary information	Abbreviations	Units
Insulation level	U_n	kV
Nominal short-circuit current	I_{sc}	kA
Duration (1 to 3 seconds)	t	s
Nominal primary current	I_p	A
Number of secondary windings (1 to 3)		
For each secondary winding:		
■ what type		
■ associated protection or metering and setting		
■ output power (relay and wiring consumption)	P_{output}	VA
■ accuracy factor		
□ protection	ALF	
□ metering	SF	
■ Nominal secondary current (1 or 5 A)	I_s	A

Fig. 3 : information necessary to specify a CT with a single primary.

2 Network disturbances and protections

2.1 Disturbances

A MV or HV electrical network is disturbed:

■ exceptionally by lightning overvoltages, by temperature rises further to overloads or following violent short-circuits between phases or phase-to-earth,

■ more frequently, and more naturally, by switching overvoltages (e.g. capacitor energisation) or natural transient conditions (e.g. motor starting or power transformer switching) resulting in high but temporary overcurrents.

The consequences of disturbances

Major disturbances, such as short-circuit currents, can result in serious damage:

■ fatigue or deterioration of network components,

■ danger for people,

■ loss of supply and production, etc.

It is thus necessary to provide the relevant protection devices with the right information to ensure prompt action, as the greater the damage, the longer and more costly the repairs and the heavier the losses.

However, transient and normal disturbances are a necessary evil and installations must be designed to withstand them. Furthermore, the current transformer/protection pair(s) must not cause nuisance tripping.

Elimination of faults

Permanent monitoring of network electrical values by reliable and properly rated current transformers supplying protection relays allows rapid isolation of the faulty area. These relays must ignore transient and normal disturbances but systematically trip when a destructive fault has to be eliminated.

2.2 Protections

Définition of protections

■ Function of protections
The protection functions of a network are intended to monitor one or more parameters of the installation, for example: currents, voltage, temperature, frequency, etc.
These values are permanently measured and compared with setpoints or thresholds beyond which the situation is defined as abnormal and dangerous. When a fault occurs, the protection device issues a tripping signal. Then, in order to durably isolate the faulty part, it prevents reclosing until the device has been repaired.
It can also generate an alarm to inform maintenance personnel and enable them to take the necessary action.

■ The technologies
With the particularly rapid growth of electronics technology, protection relays, originally electromechanical, have become static devices: analogue electronic then digital electronic thanks to microprocessors. These devices perform increasingly sophisticated functions and are more and more often referred to as processing units.

Digital technology is becoming widespread for all applications (network components or protected loads). This technology has an ample data processing capacity, which allows control and monitoring linked to protection functions and communication to a supervisory unit or a centralised control system.

These units are normally supplied with a standard protection, control and indication programme, thus enabling them to be used without extra studies or programming. Only parameters have to be set on commissioning (e.g. the protection settings).

They are designed to fully meet application needs. All you have to do is select the version corresponding to the functions available for each application. Some examples of applications are:

□ transformers,

□ generators,

□ capacitors,

□ motors,

□ substations,

□ etc.

These units incorporate meters such as ammeters, voltmeters, wattmeters, kilowatt hour meters, etc. with fewer wiring and compact space requirements (see **fig. 4**). Furthermore, their reduced power requirements (less demanding than those of electromagnetic relays), requiring less powerful CTs, make them more economic. When combined with protection functions and control logic, they also display alarm and operating messages.

■ The current transformers

The CT characteristics are defined according to the technology selected for the processing unit and the scheduled functions (protection, metering, control and monitoring, indication).

■ Implementation

Choice of protection settings is very tricky. It calls for thorough knowledge of parameter levels according to whether the disturbance is normal or transient or caused by a fault that must be eliminated. Furthermore, it is common knowledge that a short-circuit at one point of the network may be detected right up to the source.

The protection co-ordination study ensures that only the faulty part of the network is de-energised.

The protections relating to short-circuits either phase-to-phase or phase-to-earth use one of the following discrimination types, as applicable:

□ overcurrent,

□ time,

□ logic,

□ differential,

□ directional,

(see Cahiers Techniques no. 174 and 113).

Electromagnetic technique
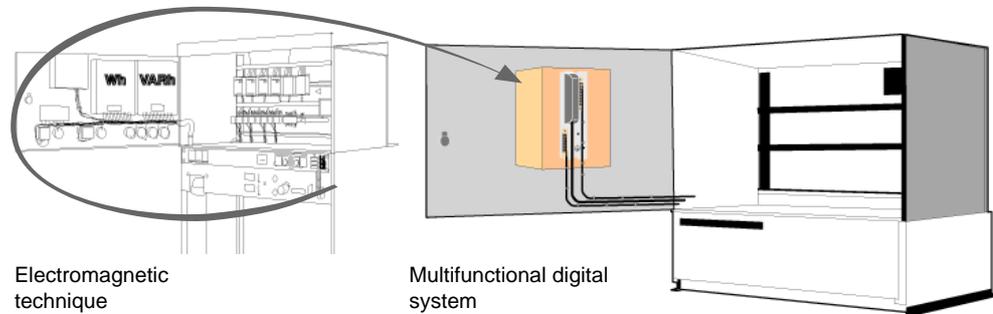
Multifunctional digital system

Fig. 4 : simplification and savings provided by a multifunctional digital system (protection - automation - metering) compared with the former electromagnetic technique.

3 Current transformers

3.1 Reminders of ferromagnetic transformers

Instrument and protection CTs

Current transformers are used to supply information to the protective relays and/or current, power and energy metering "instruments". For this purpose they must supply a secondary current proportional to the primary current flowing through them and must be adapted to network characteristics: voltage, frequency and current.

They are defined by their ratio, power and accuracy class. Their class (accuracy as a function of CT load and of overcurrent) is chosen according to the application.

■ A "protection" CT must saturate sufficiently high to allow a relatively accurate measurement of the fault current by the protection whose operating threshold can be very high. Current transformers are thus expected to have an Accuracy Limit Factor (ALF) that is usually fairly high. Note that the associated "relay" must be able to withstand high overcurrents.

■ An "instrument" CT requires good accuracy around the nominal current value. The metering instruments do not need to withstand currents as high as the protection relays. This is why the "instrument" CTs, unlike the "protection" CTs, have the lowest possible Safety Factor (SF) in order to protect these instruments through earlier saturation.

■ Some CTs have secondary windings dedicated to protection and metering. These "instrument" and "protection" CTs are governed by standard IEC 60044-1 (in France NF C 42-502).

The matching of CTs with protection relays calls for a thorough knowledge of CTs. The following section gives a few reminders of CTs corresponding to this use.

Characterisation of CTs

■ An example of a protection CT:
□ rated primary current: 200 A,
□ rated secondary current: 5 A.

15 VA   5P   10
    → accuracy limit factor = 10
    → accuracy class = 5P
    → accuracy power = 15 VA
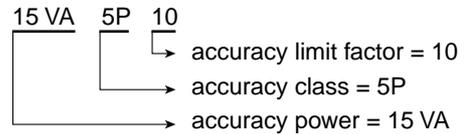
Its accuracy load: P_n = 15 VA

Its accuracy limit factor is ALF = 10

For I = ALF . I_n, its accuracy is 5% (5P), (see **fig. 5**)

To simplify, for the protection CT given in example, the ratio error is less than 5% at 10 I_n, if the real load consumes 15 VA at I_n. However these data are not sufficient. Also, it is useful to know the standard values.
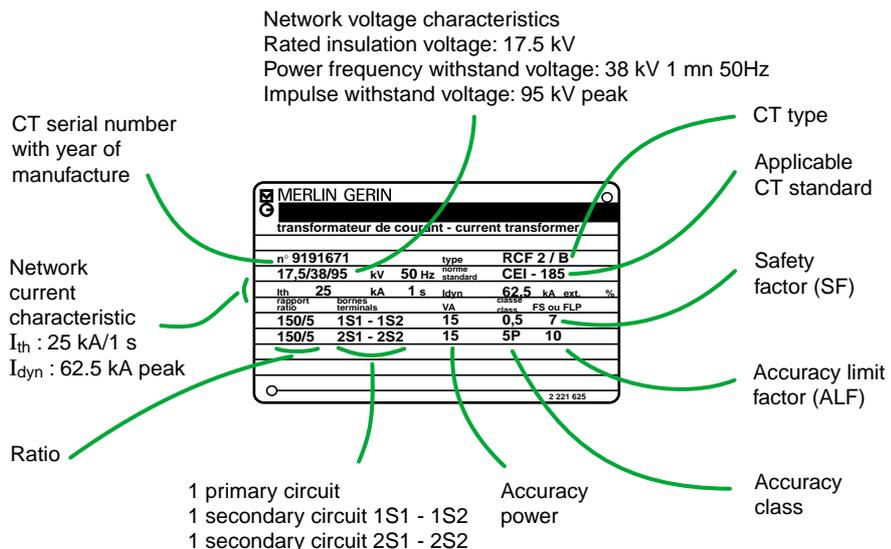

Network voltage characteristics
Rated insulation voltage: 17.5 kV
Power frequency withstand voltage: 38 kV 1 mn 50Hz
Impulse withstand voltage: 95 kV peak

CT serial number with year of manufacture

CT type

Applicable CT standard

Network current characteristic
I_{th} : 25 kA/1 s
I_{dyn} : 62.5 kA peak

Safety factor (SF)

Accuracy limit factor (ALF)

Ratio

Accuracy class

1 primary circuit
1 secondary circuit 1S1 - 1S2
1 secondary circuit 2S1 - 2S2

Accuracy power

Fig. 5 : *example of the nameplate of a current transformer with two secondaries.*

■ A few definitions

□ Rated (nominal) primary current I_1
Defined by standards, it is chosen from the discrete values: 10 - 12.5 - 15 - 20 - 25 - 30 - 40 - 50 - 60 - 75 A and their decimal multiples.

□ Rated (nominal) secondary current I_2
Equals 1 or 5 A.

□ Ratio (I_1 / I_2)
The primary and secondary currents are standard, thus these values are discrete.

□ Accuracy load
Load value on which the accuracy conditions are based.

□ Rated (nominal) accuracy power P_n
Expressed in VA, it is the apparent power supplied to the secondary circuit for the nominal (rated) secondary current and the accuracy load. The standard values are:
1 - 2.5 - 5 - 10 - 15 - 30 VA.

□ Real power P_r
In this Cahier Technique, it is the power corresponding to the real load consumption of the CT at I_n.

□ Accuracy class
This class defines the error limits guaranteed on the ratio and on the phase shift in specified power and current conditions.
For the nominal 5P and 10P classes, the table in **figure 6** defines these limits.

□ Special accuracy class
Class X is a class defined by British standard BS 3938. It must also be defined in the future standard IEC 60044-1 under the name of class PX. This class specifies the minimum value of the knee point voltage V_k of the CT.
It also imposes a maximum value of R_{ct} (CT secondary winding resistance). Sometimes, it specifies the maximum value of the magnetising current I_o at knee point voltage.
If we consider the magnetising curve $V(I_o)$ of the CT, the knee point voltage V_k is defined as the point on this curve from which a 10% increase in

voltage causes a 50% increase in the magnetising current I_o.
Class X corresponds to a better metering accuracy than classes 5P and even more so 10P (see **fig. 7**).
It is always possible to find an equivalence between a CT defined in class X and a 5P CT or in some cases even a 10P CT (refer to Cahier Technique no. 195 which deals with equivalences).

□ Real accuracy factor (F_p or K_r)
This is the ratio between the overcurrent corresponding to the nominal error and the rated current of the CT when the real load is different from the nominal load.

□ Accuracy limit factor (ALF or K_n)
This is the ratio between the nominal overcurrent (e.g. 10 I_n) and the rated current (I_n).

□ Short time withstand current
Expressed in kA, this is the maximum current I_{th} that can be withstood for one second (when the secondary is short-circuited). It represents the
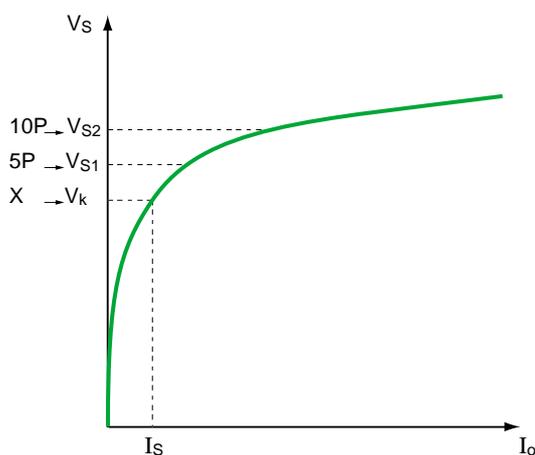

Fig. 7 : voltages corresponding to different CT classes.

| Accuracy class | Current error for the nominal current as a % | Phase shift for the nominal current | | Composite error for the accuracy limit current as a % |
		Minutes	Centiradians	
5P	± 1	± 60	± 1.8	5
10P	± 3	–	–	10

Fig. 6 : errors on the module and the phase at nominal current according to standard IEC 60044-1.

thermal withstand of the CT to overcurrents (the standard values are given by the standards mentioned in the appendix).

□ CT rated voltage

This is the rated voltage to which the CT primary is subjected. It is important to remember that the primary is at HV potential and that one of the terminals of the secondary (which must never be opened) is normally earthed.

Just as for any devices, a maximum withstand voltage for one minute at power frequency and a maximum impulse voltage withstand are also defined. Their values are defined by the standards.

For example: for a rated voltage of 24 kV, the CT must withstand 50 kV for 1 minute at 50 Hz and 125 kV at the impulse voltage.

■ CT with several secondaries

Some CTs may have several secondaries dedicated to protection or to metering.

The most typical cases are CTs with 2 secondaries, more rarely with 3 secondaries. Physically, these CTs group in the same mould the equivalent of 2 or 3 separate CTs that can have different classes and ratios (see **fig. 8**).

Influence of the load on the accuracy limit factor

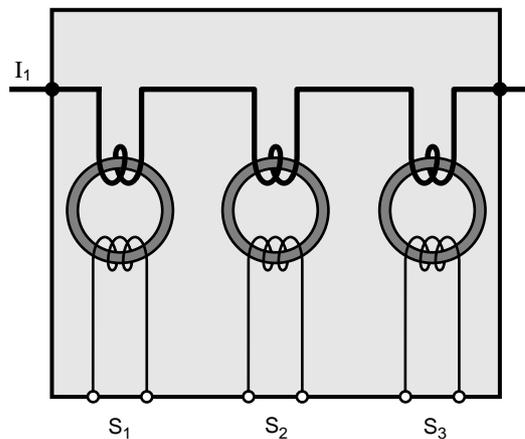Remember that the equivalent simplified diagram of the magnetic current transformer is shown in **figure 9** .
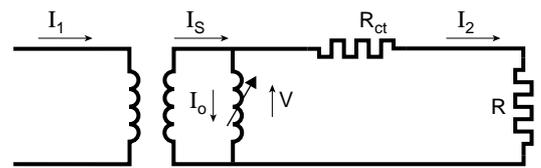
Fig. 9 : CT equivalent diagram.

Applied to this diagram, Ohm's law lets us write: $V = I_2 (R_{ct} + R)$, where:

R_{ct} : CT secondary winding resistance
R: load resistance including wiring,

□ if $I_2 = k_n I_n$ and $R = R_n = P_n / I_n^2$,

$V_n = k_n I_n (R_{ct} + R_n)$ (1)   (k_n = nominal ALF)

□ if $I_2 = k_n I_n$ and $R = R_p = P_r / I_n^2$,

$V_r = k_n I_n (R_{ct} + R_p)$

On **figure 10** we can see that although R_p is far smaller than R_n, the CT saturation knee point is far from being reached at the declared accuracy limit factor k_n.

The real accuracy limit factor corresponding to the real load (protection + wiring) can be calculated. This is $ALF_r = k_r$ for which the saturation knee point voltage V_n is reached:

$V_n = k_r I_n (R_{ct} + R_p)$ (2)

If R_p is less than R_n, k_r is greater than k_n ($ALF_r > ALF$)

Fig. 8 : manufacturing principle of a CT with 3 secondaries (with 3 windings in the same mould).
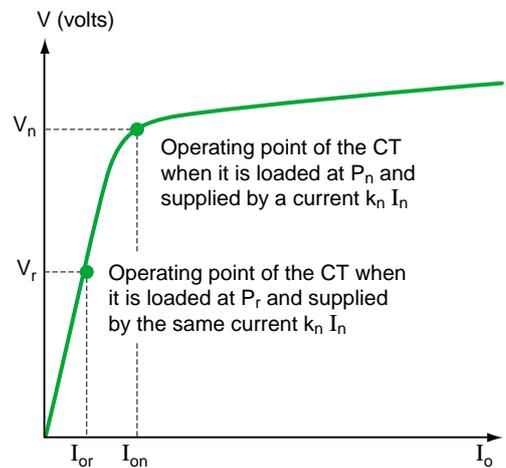
Fig. 10 : operating points of the CT according to its load.

By combining the equations (1) and (2), we find the following formula:

$$k_r = k_n \frac{R_{ct} + R_n}{R_{ct} + R_p} \text{ , or } k_r = k_n \frac{P_i + P_n}{P_i + P_r}$$

where:

$P_i = R_{ct} I_n^2$ = internal losses of the CT at I_n

$P_n = R_n I_n^2$ = CT accuracy power

$P_r = R_p I_n^2$ = real load consumption of the CT at I_n.

It is obvious that proper operation of a protection relay is linked to the behaviour of the associated CT and to its real load and not to the behaviour of the CT associated with a theoretical nominal load.

Real needs enable us to determine the minimum accuracy power to be chosen. Using a CT with a load $P_r < P_n$ increases the ALF. Likewise, the ALF increases more if the R_{ct} (internal losses P_i) is low (see **fig. 11**).

Calculation of the real ALF (k_r) of a CT, associated with its real load, ensures that the right CT is chosen in all traditional cases.

Note: for very demanding protections (e.g. differential protections), current transformers are most often defined in class X. This class is always defined according to the real load of the CT and to its own internal losses.
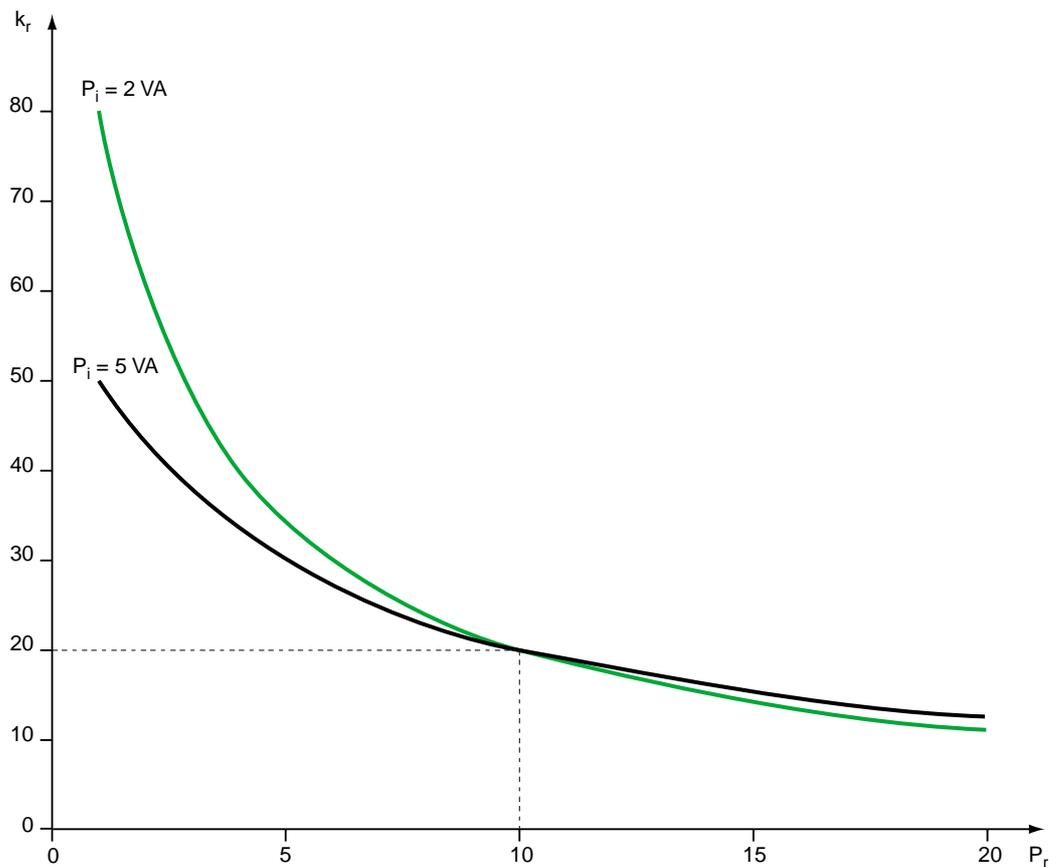

Fig. 11 : behaviour of the accuracy limit factor $k_r = f(P_r)$ of two CTs of 10 VA-5P20 with different internal losses (R_{ct}) according to the real load connected to the secondary.

3.2 Non-magnetic transformers

The output signal, delivered by the non-magnetic transformers (also known as ROGOWSKI coils) is a voltage proportional to the derivative of the primary current.

(Lenz law: $e = -n\dfrac{d\phi}{dt}$)

They do not saturate and their response is linear. Consequently, they can be used over wide current ranges: the only limitation is the dynamics and the linearity of the input circuit of the associated protection.

The technology of the protection, control and monitoring units connected to these non-magnetic transformers is of the digital microprocessor type. This technology is able to process signals of very low amplitude.

For a given non-magnetic transformer, in view of the linearity of the output signal, the nominal primary current is replaced by a wide range, for example 30 to 300 A.

In addition to the advantage of linearity, the use of non-magnetic CTs reduces:

■ risks of error when choosing primary current at the design stage of the installation,

■ the number of models to be managed. It also minimises the delivery times.
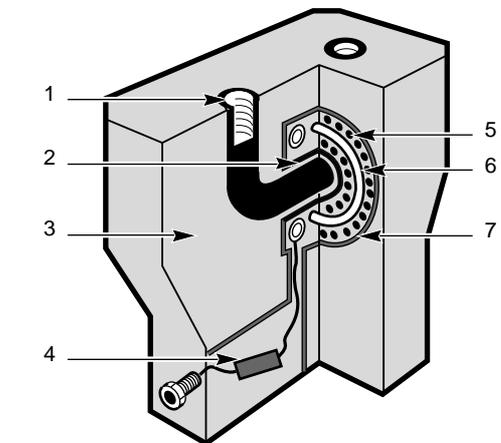
Today these transformers are seldom used. A standard (IEC 60044-8) should define them. Schneider Electric has been using these transformers (see **fig. 12**) in association with the Sepam protection, control, monitoring and metering units since 1986.

To specify them, all you have to do is indicate:

1 - Primary winding
2 - Dielectric screen
3 - Dielectric insulation
4 - Setting resistance
5 - Secondary winding
6 - Secondary winding support
7 - Magnetic shielding

Fig. 12 : cross-section of a non-magnetic transformer used in MV.

■ the CT insulation level, defined just as for a traditional CT,

■ the rated thermal short-circuit current (I_{th}) and the dynamic current (I_{dyn}) set according to the same rules as for the CTs,

■ the utilisation range (rated primary current and the thermal current).

3.3 CT manufacturing and implementation

CTs are industrial products designed according to standards. They are mass produced, thereby reducing costs and guaranteeing their characteristics.

Their live part is duplicate moulded in order to comply with insulation, temperature rise and electrodynamic withstand requirements. The number of moulds corresponding to a standard range is necessarily limited.

Furthermore, the switchgear and CTs are most often installed in panels that have been optimised, standardised and subjected to qualification tests. In this case, use of standard moulds is compulsory as CTs perform other functions such as the "bushings" between the cable and the circuit-breaker compartments (see **fig. 13** overleaf). Consequently, any modification in volume or shape of a CT results in major study, production and test investments.

To solve special cases, without overcosts or additional technical risks, it is therefore always advisable to look for solutions in order to "fit the mould" of standard CTs. Panel structure is thus maintained intact. These solutions are:

■ good rating of electrical characteristics: for example avoid overrating in power and ALF,
■ use of CTs with two or three windings,
■ use of "relays" performing several protection functions with the same current information.
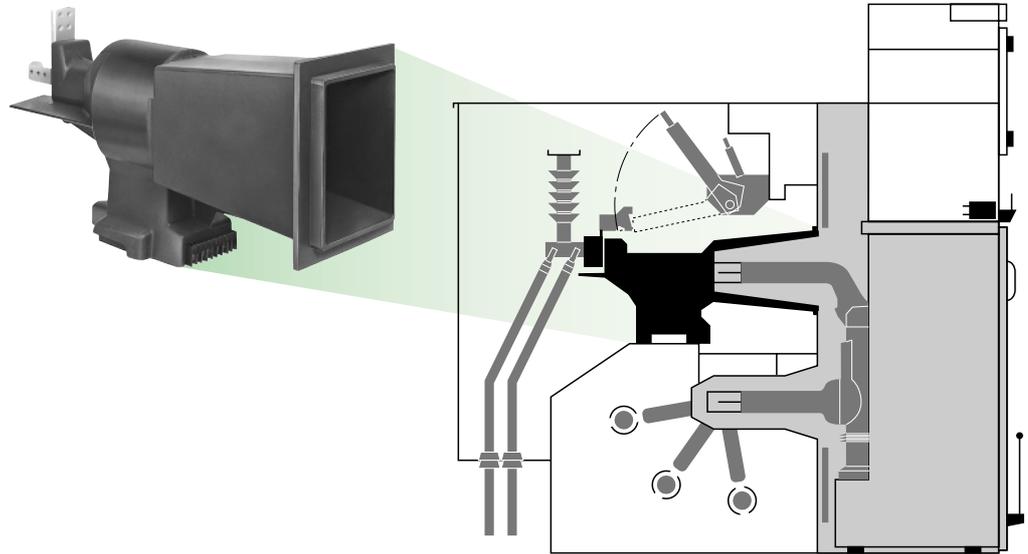

Fig. 13 : cross-sectional view of the panel and multifunctional CT.

4 Choosing CTs according to protections and applications

Thorough knowledge of CTs, their possibilities and their limits is useful only when they are associated with a specific protection relay whose characteristics and scope of action regarding the monitored current range are known.

The protection relays installed on an electrical network are defined in the protection plan.

This plan specifies the position and setting of the selected protections. It also defines the position of the CTs, their ratio and, more rarely, their power, accuracy and ALF. In point of fact, complete specification of CTs also requires knowledge of:

■ the protection input impedance,

■ the wiring impedance,

■ the protection operating thresholds (normally taken into account in the protection co-ordination study).

Today, most protections are of the digital technology kind and are highly accurate.
CT accuracy is thus a decisive factor.
The type of protection also affects the required CT accuracy:

■ an overcurrent protection only takes the current value into account,

■ a differential protection compares two currents,

■ an earth fault protection treats the sum of the three phase currents.

4.1 Choosing CT ALF according to protections

When choosing a CT out of the standard CTs, a reminder is necessary of the relationship linking the nominal ALF (linked to R_n) and the real ALF linked to the real load R_p:

$$k_n = k_r \frac{R_{ct} + R_p}{R_{ct} + R_n} \quad \text{or} \quad k_r = k_n \frac{R_{ct} + R_n}{R_{ct} + R_p}$$

A CT can supply several different protections either separate or grouped in a multi-protection system (e.g. the Sepam). This leads us to examine the protections determining CT sizing.

Definite time overcurrent protection

The threshold I_s (protection setting) can be set, for example, from 2 to 10 I_n of the CT if the CT I_n is the application I_n.

To ensure that the CT will not affect the operating accuracy of the protection, it is necessary to have no saturation up to the setting point. But it is usual to take a "safety coefficient" of 2 (see **fig. 14**).

Thus the ALF_r (k_r) at real load will be:

$$\mathbf{k_r \geqslant 2} \ \frac{\mathbf{I_s}}{\mathbf{I_n}} \quad \text{if } I_s = 10 \ I_n \Rightarrow k_r \geqslant 20$$

Example:

200/5 CT - 10 VA-5P10,
Load I_n: 160 A
$I_s = 8 \ I_n$ of load
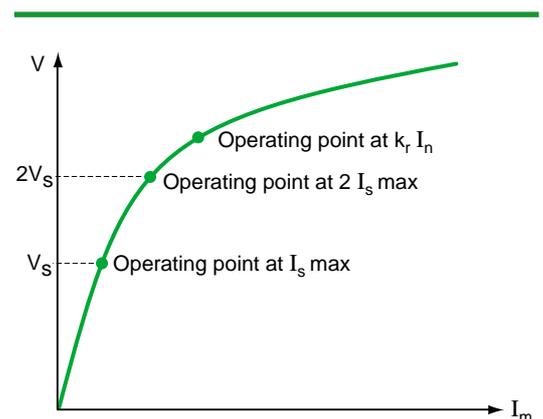Let us verify if the proposed CT is suitable:

Fig. 14 : operating points of the CT at maximum threshold.

$$\frac{I_s \ \text{of O/C}}{I_n \ \text{of CT}} = 8 \ \frac{160}{200} = 6.4$$

the minimum recommended ALF_r (k_r) is thus:

$k_r \geqslant 2 \times 6.4 = 12.8$.

If the CT load and its internal resistance are known with, for example:

$$R_{ct} + R_p = \frac{1}{2} \ (R_{ct} + R_n)$$

we obtain:

$k_r = k_n \times 2 = 20$ higher than the minimum value required. Thus the CT is suitable.

Inverse time overcurrent protection

If the aim is correct accuracy over the entire relay inverse curve, it is necessary to know at what point it becomes a definite time curve. For most relays it occurs at the minimum value between $20\,I_s$ and $24\,I_n$ (CT). So, assuming $I_{sc}\text{max}$ is the maximum short-circuit current, the same reasoning as above, using a safety coefficient of 1.5, gives:

$k_r\text{min} =$ minimum value between:

$$30\,\frac{I_s}{I_n(CT)},\ 36,\ \text{and}\ 1.5\,\frac{I_{sc}\,\text{max}}{I_n(CT)}$$

Directional current protection

The rules, unless otherwise specified (refer to Cahier Technique no. 181) are the same as for the overcurrent protections.
Note that for the three current protections described above:

■ If several current protections are supplied by the same CT, it is the one with the lowest curve (the shortest time delay) for high currents that determines the sizing.

■ In difficult cases, the safety coefficient of 2 can be lowered to 1.5.

Earth fault protection

As the protection is supplied by the vector sum of the secondary currents of 3 CTs connected as per the Nicholson arrangement (see **fig. 15**), it is preferable to use identical CTs produced by the same manufacturer. However, if there is a DC component (energisation of a transformer) or when a high current occurs, this arrangement (parallel-connection of the secondary of the 3 CTs) will deliver a false earth fault current which may cause nuisance tripping of the protection.

To give an example, with the 5P10 CTs, a protection threshold of 10 % of CT I_n is a limit below which there is a risk of nuisance tripping for definite time protections.

The CT accuracy limit factor is given by the

expression: $k_{rh} > X\,\dfrac{I_{hs}}{I_n}$.

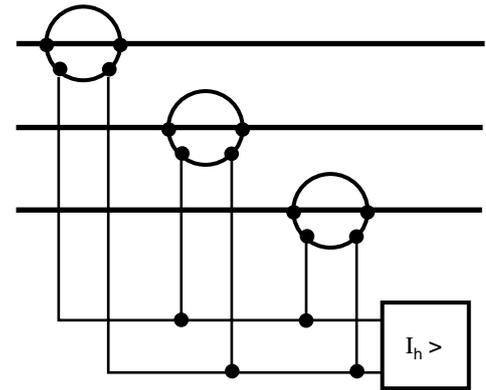The safety coefficient (X) is normally equal to 6 (given by the relay manufacturers).

Fig. 15 : the vector sum of the phase currents gives the earth fault current.

This corresponds to the fact that the CT (associated with the phase with the earth fault) must be able to develop a voltage
$V_h = X\,I_{hs}\,(R_{ct} + 2\,R_L + R_h)$.
Note:

■ If a CT also supplies an overcurrent relay, R_h must be replaced by $R_h + R_p$.

■ If the CTs are initially designed for overcurrent protection, we recommend you check that they are suitable for supplying earth fault protection too. Thus, the k_{rh} of a 100/1 CT - 10 VA-5P10 is given by the expression:

$$k_{rh} = \frac{R_{ct} + P_n/I_n^2}{R_{ct} + 2\,R_L + R_p + R_h}\,k_n.$$

Bearing in mind that the impedance of the relay used depends on the setting of I_h (in this case 0.1 A), the digital application gives:

$$R_h = \frac{1VA}{(0.1A)^2} = 100,$$

$$k_{rh} = 10\left(\frac{3+10}{3+1+4+100}\right) = 1.2$$

a value to be compared with the expression of the needed k_{rh}:

$$k_{rh} = 6\,\frac{0.1}{1} = 0.6,\ \text{the CT is suitable.}$$

If the short-circuit current is very high and if the protection time delay is short, to avoid nuisance tripping it may be necessary to add a "stabilising" resistance in series with the earth fault relay. Its purpose will be examined in paragraph 4.3.

In order to avoid difficulties that may arise with the 3 CT arrangement, it is preferable, whenever possible, to use a toroidal CT around the 3 phases (see **fig. 16**). Note that the 3 phases must be placed in the centre of the toroid to avoid local saturation of the magnetic material.

Use of a toroidal CT allows very low operating thresholds (a few amps) to be chosen.

Differential protections

Increasingly used for the protection of transformers, rotating machines and busbars, they have the advantage of being fast and independent from the other protections in terms of discrimination. These "relays" often operate during the transient fault current period. Just as for the earth fault protections, an aperiodic DC component may result in transient saturation of the CTs and thus generate a false differential current. Since differential protections are tricky to implement, manufacturers normally supply the necessary information to design and install the CTs.
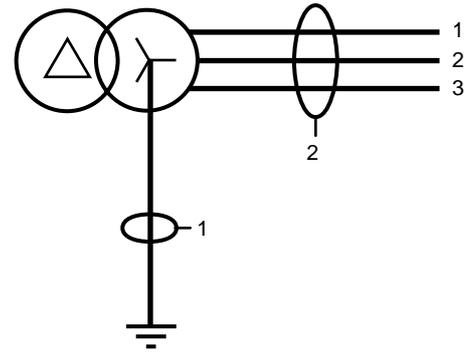

Fig. 16 : the toroid placed in (1) or (2) gives the same information… but the toroid placed in (1) also monitors the faults located upstream of the toroid (2).

Conclusions

■ It is the high setting of the overcurrent protections that determines the minimum k_r (real ALF) to be complied with.

■ It is the stability of the relay up against transient phenomena that determines the ALF or class X for earth fault and differential protections.

4.2 Characterising CTs according to applications

In this context the term "applications" means the components of the electrical network to be protected: line incomers and feeders, transformers, busbars, generators, motors, capacitor banks, etc.

Each component requires the use of several protections. An example is given by the diagram in **figure 17** (overleaf) in which the protections are identified by their ANSI code (American National Standard Institute).

However, to optimise choice of a CT, you need to know which protections it supplies, as well as their settings, real impedance, short-circuit current, etc.

The difficulty lies in the fact that these values are rarely known by the CT specifier when his choice has to be finalised.

For this reason this section proposes to study the various applications where **values can be defined by excess.** They can therefore be chosen without risk as they will necessarily cover needs. However, they will lead to a less restrictive definition which is more realistic than the one proposed by relay suppliers in their catalogues.

In point of fact, each supplier gives some guidelines for choice covering all the setting ranges of his relay associated with CTs assumed to have high internal losses and also maximum wiring impedances.
For the various applications, we shall list the protection functions commonly used. The most unfavourable protection will be chosen to size the current transformers.

Note: Initially, the earth fault and differential protections will not be taken into account.

Fig. 17 : *example of a protection plan.*

Applications with typical protections

Examination of the protections normally implemented for the various applications (see **fig. 18**), shows that it is always the high threshold overcurrent protection which is the CT sizing factor. The exception to this rule is, however, the motors protected by fuses for which the locked rotor protection is the most restrictive.

To optimise the CTs, the settings of these protections need to be taken into account.

■ Line incomers and feeders

The high threshold overcurrent protection is normally set between $3 \leqslant I_s \leqslant 10 \, I_n$, hence a

$k_{rm} \geqslant 2 \, \dfrac{I_s}{I_n}$ with at maximum a $k_{rm} = 20$.

If an inverse time protection is used:
$k_r min$ = minimum value between:

$30 \, \dfrac{I_s}{I_n(CT)}$, 36, and $1.5 \, \dfrac{I_{sc} \, max}{I_n(CT)}$

■ Generator incomer

There is no reason to select a setting > 7 I_n, given the relatively low short-circuit current of a generator,
hence a $k_{rm} \geqslant 14$.

■ Transformer incomer

If we take the example of the protections downstream of a HV/MV transformer, the setting threshold must be lower, for example, than 70 % of the I_{sc} at the secondary side, i.e. as an initial approximation:

$$I_{sc} = 0.7 \, I_{n2} \, \frac{100}{Z_{sc}} \, .$$

If we apply the rule: $k_{rm} \geqslant 2 \, \dfrac{I_s}{I_n}$,

it becomes: $k_{rm} \geqslant 1.4 \, \dfrac{100}{Z_{sc}} \, .$

This k_{rm} is "maximised"; in reality it is the discrimination study of the downstream network that sets the I_s and thus determines the k_{rm}.

ANSI code	Typical protections	Applications						
		Line incomer and feeder	Generator incomer	Trans-former incomer	Trans-former feeder	Capacitor feeder	Motor feeder with circuit-breaker	contactor + fuses
37	Undercurrent						■	■
46	Unbalance		■				■	■
49	Thermal image		■	■	(■)	■	■	■
50	Instantaneous high threshold overcurrent				■		■	
50N	Instantaneous earth fault				■			
51N	Time delayed earth fault	■	■	■	■	■	■	■
51N1	Star-star capacitor unbalance					■		
51LR	Locked rotor / too long start						■	■
51V	Voltage restrained overcurrent		■					
51-1	Time delayed low threshold overcurrent	■	■	■	■	■		
51-2	Time delayed high threshold overcurrent	■	■	■		■		
66	Number of starts						■	■
67	Directional overcurrent	■	■	■				
67N	Directional earth fault	■	■	■				

Fig. 18 : protections implemented by application, in the most common cases.

■ Transformer feeder

The operating current of the high threshold overcurrent protection (I_s), placed upstream of the transformer, must be higher than the current observed at the primary (I_{sct}) on a short-circuit at the transformer secondary terminals.

As a first approximation we can state that:

$$I_{sct} \leqslant I_{n1} \frac{100}{Z_{sc}}$$

where

$$I_{n1} = \frac{P_n}{\sqrt{3}\ U_{n1}} = \text{nominal primary current,}$$

P_n = nominal power of the power transformer,
U_{n1} = primary voltage.

In fact, the upstream source impedance also helps to limit I_{sct}. We can thus be certain that:

$$I_s \leqslant I_{n1} \frac{100}{Z_{sc}}$$

If the general rule $k_{rm} \geqslant 2\ \dfrac{I_s}{I_n}$ applies,

we obtain: $k_{rm} \geqslant 2\ \dfrac{I_{n1}}{I_n}\ \dfrac{100}{Z_{sc}}$.

The typical values for short-circuit impedances of power transformers can range from 4 % for small transformers to 20 % for the largest ones (see **fig. 19**).
This would result in requiring minimum k_{rm}

ranging from $10\ \dfrac{I_{n1}}{I_n}$ for large transformers to

$50\ \dfrac{I_{n1}}{I_n}$ for the smallest ones.

These values may be too difficult to obtain for low rated CTs particularly when their thermal withstand is high (e.g. 40 kA, 1 s).
Therefore, in difficult cases, the problem of feasibility could be solved by overrating the CT primary or by using a reduced coefficient (1.5 instead of 2) as described in paragraph 4.1, which gives:

$$k_{rm} \geqslant 1.5\ \frac{I_{n1}}{I_n}\ \frac{100}{Z_{sc}}.$$

If you choose to overrate a CT, you must ensure that the setting of the transformer thermal

Transformer rating (MVA)	Z_{sc} (%)
0.5	4
0.63	4
0.8	4
1	5
2.5	5
5	6
10	8
20	10
30	12
40	13
80	18
160	20

Fig. 19 : *typical short-circuit impedances for power transformers.*

protection is still possible. Otherwise you must plan this protection downstream of the transformer.

■ Capacitor feeder

The time delayed high threshold recommended by capacitor suppliers is 3 I_n (0.3 s).
If we take $I_s$max = 5 I_n ; **$k_{rm} \geqslant 10$**.

■ Motor feeder

The high threshold must be set above the starting current, which is always $\leqslant 7\ I_n$.
If we take $I_s$max = 8 I_n ; **$k_{rm} \geqslant 16$**.

If the short-circuit protection is provided by fuses, then the "locked rotor / too long start" protection is the most restrictive. Its setting is between 2.5 and 4 I_n ; **$k_{rm} \geqslant 8$**.

Note: From the above, we have assumed that CT I_n = application I_n. If this is not the case, the resulting k_{rm} must be multiplied by the ratio:

$$\frac{I_n\ \text{(application)}}{I_n\ \text{(CT)}}.$$

The table in **figure 20** summarises the minimum ALF to be complied with according to the applications.

	k_r mini for definite time overcurrent	k_r mini for inverse time overcurrent
■ I_s is known, all applications		
	$k_r = 2 \dfrac{I_s}{I_n}$	between: $30 \dfrac{I_s}{I_{n(CT)}}$, 36, and $1.5 \dfrac{I_{sc}\,max}{I_{n(CT)}}$
■ I_s is unknown		
Transformer feeders	$k_r = 2 \dfrac{I_{n1}}{I_n} \dfrac{100}{Z_{sc}}$	Not concerned
Transformer incomers,	$k_r = 20$ (by excess)	between: $30 \dfrac{I_s}{I_{n(CT)}}$, 36, and $1.5 \dfrac{I_{sc}\,max}{I_{n(CT)}}$,
Line incomers and feeders		if no definite time on a second threshold
Capacitor feeders	$k_r = 10$ (by excess)	Not concerned
Circuit-breaker motor feeders	$k_r = 16$	Not concerned
Contactor with fuse motor feeders	$k_r = 8$	
Generator incomers	$k_r = 14$*	$k_r = 14$*

In this table: I_s is the setting current of the overcurrent threshold for which the response time is shortest for the high currents,
I_n is the CT nominal primary current,
I_{n1} is the power transformer nominal current,
(*) = general cases.

Fig. 20 : real ALF (k_r) required for overcurrent according to the applications.

4.3 Special case of differential protection

Although the manufacturers of relays dedicated to differential protection impose the necessary CT secondary characteristics required for proper operation, it is useful, for understanding and avoiding errors, to possess minimum knowledge of this type of protection.

A differential protection monitors an area limited by CTs which measure incoming and outgoing currents. If the outgoing currents are not consistent with the incoming currents, this is normally because a fault has occurred in the protected area.

We shall examine in turn high impedance, pilot wire, percentage differential and low impedance differential protections with their respective CT requirements.

According to the type of protection and its use, relay manufacturers have had to apply a variety of principles varying in complexity in order to guarantee the stability of their relays against transient phenomena likely to cause nuisance tripping of this protection.

High impedance differential protection

This type of protection is normally used for protection of motors, generators, busbars as well as for "restricted earth fault" protection of transformers.

■ General

This type of protection is used to protect an area with the same voltage level.

In healthy conditions, the input current i'_e is identical to the output current i'_s and thus the differential current $i'_d = 0$ (see **fig. 21**)

A high fault current can flow through the monitored area and cause CT saturation, hence the risk of nuisance tripping of the protection (non stability). The "stability" of the relay is obtained by connecting it in series with a "stabilising" resistance R_{st}.

This resistance is calculated in such a way that the derived current in the differential circuit $(R_{st} + R_p)$ cannot reach the relay setting threshold when the maximum through current saturates a CT with its DC component. This results in:

(1) $(R_{st} + R_p) \geqslant (R_{ct} + 2\,R_L)\,\dfrac{I_{ssc}}{I_r}$

where

I_{ssc} = maximum through current observed at the CT secondary,

I_r = relay secondary setting current.

R_{st} may vary between a few ohms and a few hundred ohms (exceptionally it may be greater than 1000 ohms).

For the relay to operate properly at I_r if a fault occurs in the area, the knee point voltage V_k must be greater than:

$2\,(R_{st} + R_p + R_{ct} + 2\,R_L)\,I_r$.

As a rule $R_{ct} + 2\,R_L$ are negligible compared with $R_{st} + R_p$ thus:

(2) $V_k \geqslant 2\,I_r\,(R_{st} + R_p)$.

By combining the equations **(1)** and **(2)** we find:

(3) $V_k \geqslant 2\,I_{ssc}\,(R_{ct} + 2\,R_L)$.

These equations show that R_{st} (expression 1) and V_k have greater values when R_{ct} is high.

A high value stabilising resistance generates high overvoltages at the CT secondary. Therefore when overvoltages in excess of 3000 V are anticipated, a protection by a non-linear resistance (ZnO) is added.

The result of these observations is that the CTs are optimised if R_{ct} and V_k are as low as possible and if the through current (seen from the CT secondary, i.e. I_{scc}) is defined without excess.

Whatever the application where the high impedance differential is used, all the CTs must have:

□ the same ratio,

□ the same magnetising curve (same minimum V_k),

□ the same maximum R_{ct},

and comply with expression **(3)** ; for V_k, since the relevant CTs are not at the same distance from the relay, take the maximum R_L.

For this protection, a maximum value of the magnetising current I_o must also be defined at V_k /2 according to the required sensitivity.
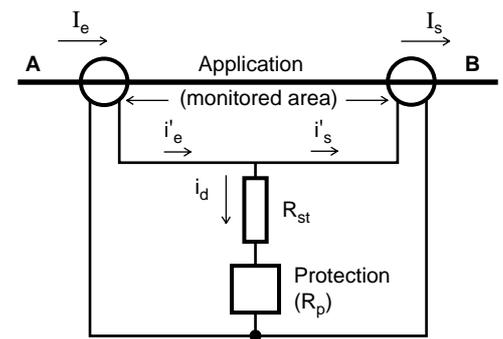

Fig. 21 : *high impedance differential principle.*

For the relay to detect a current I_r, a voltage $V_s = V_k$ /2 must be developed at the terminals of the parallel-connected CTs; for this purpose, the minimum primary current I_{rms} really detected by the relay will be $I_{rms} = n(I_r + \rho\,I_o)$, where

n = CT ratio and

ρ = number of parallel-connected CTs (there may be many of them on a busbar protection!).

■ Application to the "motor" differential protection

The maximum through current for which the motor must remain insensitive is in this case the motor starting current:

$I_{ssc} = I_{st}$ (seen at the secondary).

If you do not know this current I_{st}, you know that:

$I_{st} < 7\,I_{n\ motor}$

■ Application to the "generator" differential protection

The maximum through current is in this case the short-circuit current supplied by this generator only.

If you know the generator subtransient reactance X'' %, the following will be taken:

$I_{ssc} = I_n\,\dfrac{100}{X''}$;

If this value is not known, X'' % = 15 will be taken

Note: the peak voltage at the CT secondary must be calculated using:

I_{ssc} maxi = $I''_{generator} + I_{sc}$ network.

■ Application to the "busbar" differential protection (see **fig. 22**).

In this case, the through current is equal to switchboard I_{sc} :

I_{ssc} = switchboard I_{sc} seen from the CT secondary.

■ Application to the "restricted earth fault" differential protection of transformers (REF)

□ In the case of **figure 23a** , this protection detects the insulation faults at the transformer secondary windings and up to the CTs located downstream.
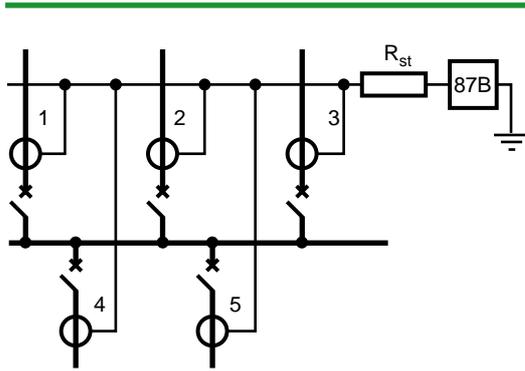
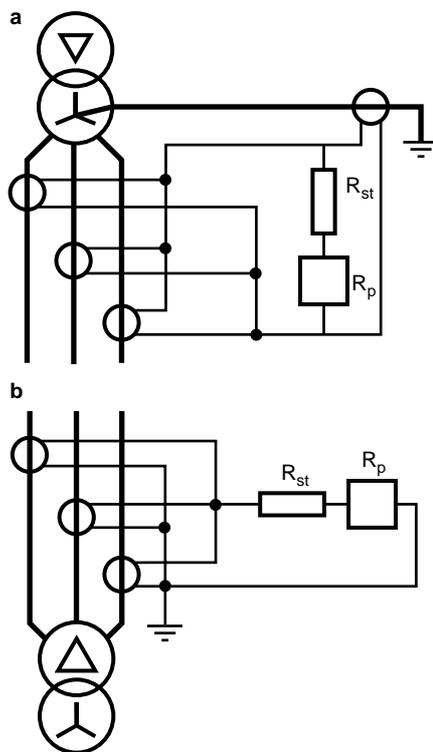*Fig. 22 : high impedance "busbar" differential protection.*

*Fig. 23 : "restricted earth fault" protection of the secondary [**a**] or primary [**b**] windings of a transformer.*

□ In the case of **figure 23b** , this protection detects the insulation faults at the transformer primary and advantageously improves the typical earth fault protection which is sensitive to transformer violent inrush currents and to the through currents resulting from a downstream asymmetrical short-circuit.

In this case also, we shall calculate R_{st} and V_k based on the maximum through current in the CTs for a fault outside the protected area. As a first approximation, we can say that this current is less than the current limited by the transformer impedance, i.e. $I_{through} = \dfrac{P_{sct}}{U_n\sqrt{3}}$,

where $P_{sct} = P_n \dfrac{100}{Z_{sc}}$, (transformer short-circuit power); if we know the upstream short-circuit power (P_u), a more accurate value can be calculated replacing

P_{sct} with $\dfrac{(P_{sct}\,P_u)}{(P_{sct} + P_u)}$.

The through fault current must then be converted into I_{ssc} seen at the CT secondary.

Line or cable differential protection with pilot wires (see **fig. 24**).

A relay of this type is installed at each end of the cable or the line.

On the pilot wires, each relay reproduces a voltage which is the image of the sum:

$a\,I_1 + b\,I_2 + c\,I_3 + d\,I_h$.

If the two voltages are different, both relays trip.

NB:

Note that the coefficients a, b, c and d are different to ensure that all fault types correspond to a sum other than zero. Consequently, the operating threshold of a two-phase fault or of a phase-to-earth fault is slightly different according to the faulty phase.

In this case also, class X CTs are required, and each manufacturer gives an empirical formula for the minimum knee point voltage V_k.
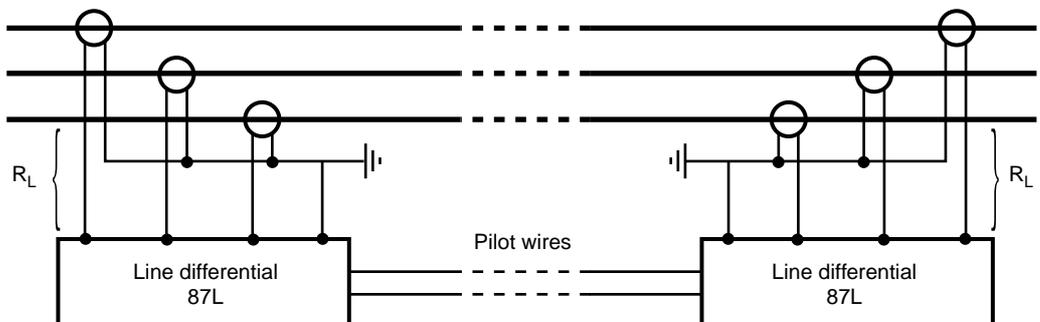

Fig. 24 : line or cable differential protection with pilot wires.

An example of the minimum knee point voltage required:

$$V_k \text{ mini} = 0{,}5 \, N \, k_t \, I_n \, (R_{ct} + X \, R_L)$$

where N, k_t and X are constants associated with the relay response time, its sensitivity and its type of connection.

Another example:

$$V_k \text{ mini} = \frac{50}{I_n} + I_f \, (R_{ct} + 2 \, R_L)$$

where:

I_n is the CT nominal secondary current (1 or 5 A),
I_f is the through short-circuit current, seen at the CT secondary.

The stability of this relay is achieved both by complying with the required knee point voltage and by a percentage differential operating threshold which will increase with the through current by use of retaining windings.
The CTs at the ends of the line must have the same ratio and must comply with the minimum V_k and maximum I_o specified by the manufacturer. However, their magnetising curves and R_{ct} do not need to be identical.

Percentage biased differential protection for transformers

The term "percentage differential" stems from the fact that the operating threshold increases with the through current.
Simple comparison of the currents in each upstream phase with the currents in the same downstream phases is not suitable for transformer differential protection.

This is because:
□ the upstream and downstream currents of a power transformer do not have the same amplitude or the same phase angle,

□ when the transformer is energised, its magnetising current is only seen upstream,

□ the presence of an earthing generator in the protected area (e.g. earthing the transformer neutral) can trip the protection, while the fault is, for example, located on a downstream feeder.

■ Precautions to be taken to solve these problems:

The aim is to ensure that the relay sees upstream and downstream currents of the same amplitude and in phase during normal operating conditions. This can be achieved by intelligent choice of CT ratio and connections.

Matching CTs are used for this purpose and often help to eliminate the zero-sequence current that could trip the protection when an earth fault occurs outside the protected area.

However, most of the new digital relays are able to perform internally, by parameter setting, the adjustments necessary to "reset" the currents, thus considerably simplifying their implementation.

Furthermore, it must be noted that all the "transformer differential" relays are immunised to the 2nd order harmonic blocking their operation when the transformer is energised.

■ CT voltage V_k

In 99 % of cases, a class X is requested.
The minimum knee point voltage is imposed and depends on the resistance of the secondary winding "R_{ct}" of the CT and of its real load R_r. More complex specifications are sometimes mentioned, which include the X/R ratio of the network or the magnetising current of the power transformer. However, faced with the problems that users have in obtaining all these parameters, relay suppliers sometimes provide simplified empirical formulas which lead to a slight oversizing.
Examples of minimum knee point voltage imposed for the Sepam 2000 D02 (Schneider Electric):

$$V_k \text{ mini} = A \, I_b \, (R_{ct} + 2 \, R_L)$$

where:

$2 \, R_L$ = total resistance of the secondary wiring,
R_{ct} = CT secondary winding resistance,
I_b = power transformer nominal current seen at the CT secondary,
A = constant depending on transformer power:
Some suppliers take into account the through current, for example:

$$V_k \geqslant \frac{4 \, I_f}{\sqrt{3}} \left(R_{ct} + 3 \left(R_L + R_p \right) \right)$$

on the star side of the power transformer,

and $V_k \geqslant 4 \, I_f \, (R_{ct} + 2 \, R_L + R_p)$

on the delta side of the power transformer.

The through current will be defined in the same way as for the restricted earth fault protection.

Note:
Use of matching CTs leads to different expressions of the knee point voltage for the main CTs which must take into account the extra load that they represent.

To conclude, the stability of this protection is ensured by:

■ the threshold which increases with the through current (restraint system),

■ the right choice of CT knee point voltage V_k,

■ a system ensuring immunity to 2nd order harmonics generated by inrush currents,

■ the most sophisticated relays are also immune to 5th order harmonics which occur during power transformer overexcitation (saturation).
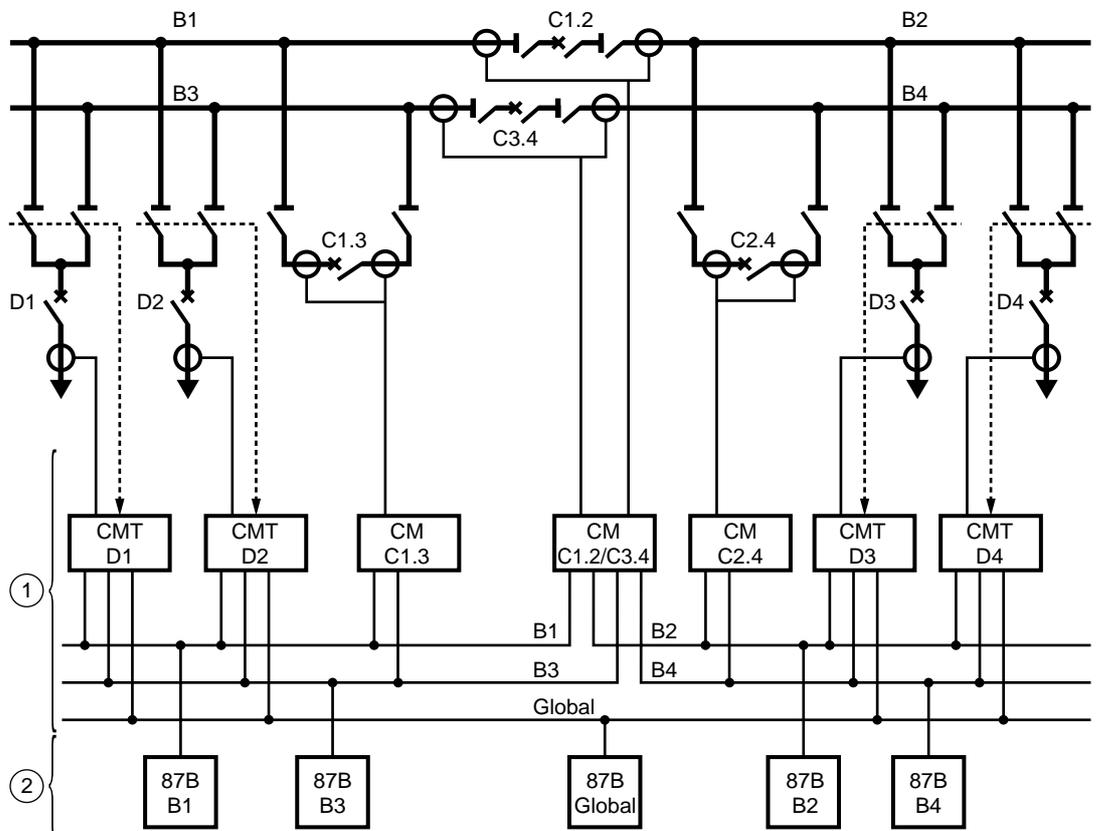
Low impedance differential protection

This protection is used for busbar differential protection. It is very costly and space-consuming, as it requires a large number of modules and matching CTs which need one or more cubicles according to switchboard size (see **fig. 25**).

In the case of a double busbar switchboard, the protection must be continually "informed" on the position of the transfer switches in order to direct the currents of each feeder and incomer to the relay associated with monitoring of the busbar on which this feeder or incomer is connected.

The CTs associated with this sophisticated protection may have different ratios. Their secondaries are also defined as class X in most cases. However, as saturation can be tolerated, knee point voltage requirements are less severe than for high impedance differential protection.

CMT = current metering and transfer (for feeders D1, D2, D3 and D4)
CM = current metering (for crossing and in-line couplers C1.2, C1.3, C2.4 and C3.4)
1 = transfer and metering
2 = protection

Fig. 25 : *example of a low impedance differential protection for a double busbar.*

4.4 Distance protections

These protections, extremely common in high voltage, are increasingly used for very long medium voltage lines, as pilot wires do not need to be installed (see **fig. 26**).

The formula generally used for CTs defined as class X is as follows:

$$V_k \geqslant I_f \left(1 + \frac{X}{R}\right)\left(R_p + R_{ct} + 2\,R_L\right)$$

Besides the usual terms already defined, the following parameters can also be found:

$\frac{X}{R}$: reactance/resistance ratio between the

source and a three-phase short-circuit occurring at the end of the protected area.

I_f is in this case equal to the three-phase short-circuit current at the end of the monitored area, seen at the secondary side of the upstream CT.

R_p : relay resistance.

In many cases, information regarding the line to be protected (cross-section, length) is non-existent or impossible to obtain before the switchboard is delivered. However, the calculation example in **figure 27** shows the considerable difference between CT characteristics according to line length. Between 1 and 12 km, there is a ratio of 10 between the characteristics.

This type of relay is always used for very long lines. It would not be reasonable, without information, to resign ourselves to using for I_f the value I_{sc} at the head of the line. The example in figure 27 shows that the short-circuit current drops from 26.2 kA to 13.4 kA for a 2 km line only, then to 3.8 kA for a 12 km line.

Knowledge, even approximate, of line length is an important factor in optimising CTs.
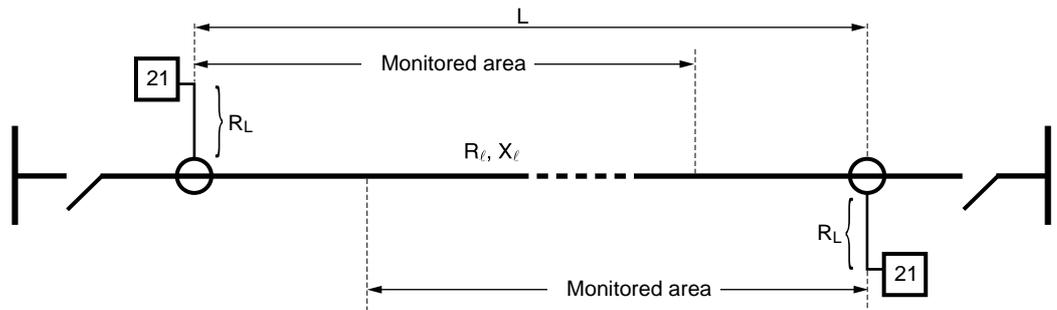

Fig. 26 : *distance protections: at each end of the line a relay monitors 80 % of the line with instantaneous operation.*

Source			Line			Calculations				
I_{sc}	R_s	X_s	L (km)	R_ℓ	X_ℓ	X_t / R_t	Z_t	I_{sc} (kA)	I_f (A)	V_k (V)
26.2	0.015	0.727	1	0.12	0.338	7.925	1.073	17.75	29.59	$(264.1 \times R_{ct}) + 108.28$
26.2	0.015	0.727	2	0.2396	0.675	5.518	1.425	13.37	22.28	$(145.23 \times R_{ct}) + 59.54$
26.2	0.015	0.727	5	0.599	1.688	3.936	2.492	7.646	12.74	$(62.90 \times R_{ct}) + 25.79$
26.2	0.015	0.727	12	1.4376	4.051	3.29	4.994	3.815	6.358	$(27.28 \times R_{ct}) + 11.18$
26.2	0.015	0.727	24	2.8752	8.102	3.055	9.29	2.051	3.418	$(13.86 \times R_{ct}) + 5.68$
26.2	0.015	0.727	40	4.792	13.5	2.961	15.02	1.268	2.114	$(8.37 \times R_{ct}) + 3.43$

U = 33 kV
CT primary side: 600
CT secondary side: 1
R_p = 0.36 Ω
$2\,R_L$ = 0.05 Ω

Line cross-section = 150 mm²
R_ℓ = 0.12 Ω/km
X_ℓ = 0.388 Ω/km
R_s , X_s = source resistance and reactance

$X_t = X_s + X_\ell$
$R_t = R_s + R_\ell$

$$V_k \geqslant I_f \left(1 + \frac{X_t}{R_t}\right)\left(R_p + R_{ct} + 2\,R_L\right)$$

Fig. 27 : *calculation of CT knee point voltage V_k for distance protection relays, for various line lengths, showing the advantage of using the I_{sc} as a reference at the end of the line to define these CTs.*

5 CT specification examples

We shall deal in an incomplete but educational manner with two examples of specifications concerning conventional protections and two examples concerning differential protections.

5.1 Motor feeder protections

For this application the functions are, for example:
□ overcurrent,
□ thermal image,
□ unbalance.

With electromagnetic relays, serial-connected in the CT secondary, the minimum specification often encountered is 20 VA-5P30.

With multifunction digital "relays", the specification is often 5 VA-5P20… it is superabundant.

The minimum ALF is $2 \dfrac{8 \; I_n \; (\text{motor})}{I_n \; (\text{CT})}$,

i.e. $k_r \geqslant 16$ if I_n (motor) = I_n (CT).

But taking account of a motor I_n (200 A) for a 300/1A CT: 16 x(300/200) = 12.

The relay consumption is for example 0.025 VA (Sepam 2000) and 0.05 VA for wiring (6 m in 2.5^2); the 5 VA-5P20 CT has internal losses of 2 VA.

Let us calculate k_r :

$$k_r = 20 \; \frac{2 + 5}{2 + 0.075} = 67.5$$

a value far greater than 12!

A 2.5 VA-5P10 CT (where P_i = 1.5 VA) is more than sufficient. Its k_r is:

$$k_r = 10 \; \frac{1.5 + 2.5}{1.5 + 0.075} = 25$$

5.2 Transformer feeder protections

This is the high threshold overcurrent protection which sizes the CT (refer to paragraph 4.2):

$$k_r \geqslant 1.5 \; \frac{I_{n1}}{I_n} \; \frac{100}{Z_{sc}}$$

where I_{n1} = $I_{nominal}$ of the transformer primary and I_n = $I_{nominal}$ of the CT primary.

Let us take the example of a 1 MVA transformer; Z_{sc} = 5 %; $U_{primary}$ = 22 kV, hence I_{n1} = 26.2 A. This gives, when I_n = 30 A, a minimum k_r of 26.

Taking into account that the thermal withstand of the requested CT is 50 kA-1s… the CT cannot be manufactured. In actual fact the problems start as soon as I_{th} / I_n > 500, and in this case 50000/30 = 1666!

Faced with this kind of problem, the CT primary can be overrated.

In view of their characteristics, **figure 28** shows the overratings of CTs able to match the required ALF and satisfy CT feasibility.

Transformer U = 22 kV				CT characteristics	
Power (MVA)	Z_{sc} (%)	I_{sc} max (kA)	I_n TFO (A)	I_n (A)	ALF required (I_{sc}/ I_n x 1.5)
0.5	4	0.3	13	40	12.3
0.63	4	0.4	17	40	15.5
0.8	4	0.5	21	40	19.7
1	5	0.5	26	50	15.7
2.5	5	1.3	66	100	19.7
5	6	2.2	131	200	16.4
10	8	3.3	262	300	16.4
20	10	5.2	525	600	13.1
30	12	6.6	787	1000	9.8
40	13	8.1	1050	1500	8.1
80	16	13.1	2099	2500	7.9

Fig. 28 : standard CT for a 22 kV transformer feeder.

In the example: choose $I_{n1} = 50$ instead of 30 A. The minimum k_r moves from 26 to 15.7. The ratio I_{th} / I_n becomes $50000/50 = 1000$. It is still higher than 500, but such a CT is now feasible.

Schneider Electric, manufacturer of protection CTs and MV panels, offers standard 2.5 VA-5P20 CTs suitable for electronic and digital protection and which consume less than 0.5 VA with a wiring resistance of $2 R_L < 0.1 \ \Omega$.

5.3 Transformer differential protection

In this example, the relay used is a Sepam 2000 D02 (Schneider Electric). This relay does not need an interposing CT (see **fig. 29**).

The minimum knee point voltage V_k required is given by the formula:

$V_k = A I_b (R_{ct} + 2 R_L)$

where:

I_b = power transformer nominal current at the CT secondary,

R_{ct} = CT secondary winding resistance,

R_L = resistance of a conductor linking the CT and the relay,

A = constant depending on transformer power:

■ 30 for 2 MVA < Pn < 14 MVA,

■ 24 for 15 MVA < Pn < 39 MVA,

■ 16 for 40 MVA < Pn < 70 MVA.

Let us take an example

Pn = 50 MVA hence: A = 16,

$I_1 = 600$ A $\qquad U_1 = 63$ kV $\qquad I_{n1} = 1$ A,
$I_2 = 3000$ A $\qquad U_2 = 11$ kV $\qquad I_{n2} = 1$ A,

$$I_{b1} = \left[\frac{P_n}{\left(\sqrt{3} \ U_2 \right)} \right] \left(\frac{I_{n1}}{I_1} \right) = 0.764 \ A,$$

$$I_{b2} = \left[\frac{P_n}{\left(\sqrt{3} \ U_2 \right)} \right] \left(\frac{I_{n2}}{I_2} \right) = 0.875 \ A,$$

where:

I_1 = nominal current of the CT at the primary side of the power transformer,

I_2 = nominal current of the CT at the secondary side of the power transformer,

I_{n1} = nominal current of the secondary windings of the CT located at the primary side of the power transformer,
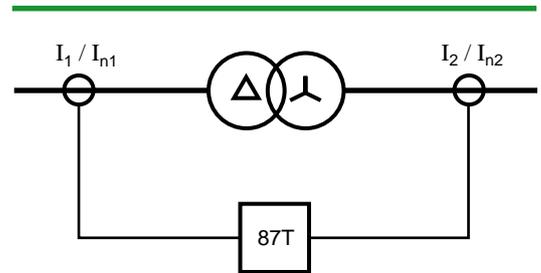

Fig. 29 : transformer differential protection principle.

I_{n2} = nominal current of the secondary windings of the CT located at the secondary side of the power transformer.

Calculating CTs

We assume that the relay is located in the downstream switchboard, resulting in a wiring $2 R_L$ of 1000 m for upstream CTs and 10 m for downstream CTs.

■ CTs at the primary side of the power transformer

If the wiring is 2.5 mm^2 (i.e. 8 Ω per km):

$2 R_L = 8 \times 1000/1000 = 8 \ \Omega$.

This gives:

$V_k > 16 \times 0.764 (R_{ct} + 8)$

$V_k > 12.2 R_{ct} + 98$

■ CTs at the secondary side of the power transformer

If the wiring is 2.5 mm^2 (i.e. 8 Ω per km):

$2 R_L = 8 \times 10/1000 = 0.08 \ \Omega$.

This gives:

$V_k > 16 \times 0.875 (R_{ct} + 0.08)$

$V_k > 14 R_{ct} + 1.12$

5.4 Differential protection for busbars (87B)

For 87B busbar differential protection (see **fig. 30**), the relay used is a Sepam 100 LD (Schneider Electric). The minimum knee point voltage V_k required for this relay is given by:

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

where:

I_f = maximum through current at the CT secondary,

R_{ct} = CT secondary winding resistance,

$2 R_L$ = resistance of the wiring loop between the CT and the relay.

Calculating 2 R_L

$2 R_L = \rho \, (2 L/S)$

Loop length: $2 L = 45$ m,

Wiring cross-section: $S = 2{,}5$ mm^2,

where $\rho = 1.8 \times 10^{-8}$,

$2 R_L = 0.324 \, \Omega$

Calculating I_f

$$I_f = I_{sc} \; \frac{I_{2n}}{I_{1n}}$$

I_{1n} = CT nominal primary current,

I_{2n} = CT nominal secondary current,

I_{sc} = short-circuit current at switchboard level,

$I_{1n} = 1250$ A

$I_{2n} = 1$ A

$I_{sc} = 25$ kA

$I_f = 20$ A

Now V_k can be determined:

$V_k > 2 \times 20 \times (R_t + 0.32)$,

i.e.

$V_k > 40 \, R_{ct} + 13$

After consultation, the proposed CT has an R_{ct} of 6 Ω and a V_{kr} equal to 270 V.

It is suitable as:

$40 \times 6 + 13 = 252.96$ V < 270 V.

Calculating R_{st}

$$R_{st} = \frac{V_k}{2 \, I_r} - R_p$$

I_r = setting current,

R_p = relay resistance,

V_k = minimum knee point voltage required.

We choose:

$I_r = 5 \% \, I_{2n} = 0.05$ A

In this case we can consider that $R_p = 0$

$R_{st} = 2530 \, \Omega$

Calculating V_{peak}

$$V_p = 2\sqrt{2 \, V_{kr} \left(V_s - V_{kr} \right)}$$

$V_s = (R_s + R_p) \, I_{ssc}$

where:

I_{ssc} = maximum fault current seen at the CT secondary: in this case $I_{ssc} = I_r$

V_{kr} = real value of the knee point voltage of the CT (270 V),

$V_s = 50600$ V,

we find: $V_p = 10426$ V.

$V_p > 3000$ V, a surge limiter is necessary.

Calculating the fault current I_d really detected

$I_d = I_r + I_o \, m$,

where:

I_o = magnetising current at $V_k / 2$ (data given by the CT manufacturer),

m = number of CTs per phase used for busbar protection, in this case = 5,

$I_o = 0.006$ A,

We find: **$I_d = 0.08$ A**, i.e. 100 A on the primary side.

We thus observe that earth faults will also be detected in a satisfactory manner since in this network the earth fault current is limited to 300 A.
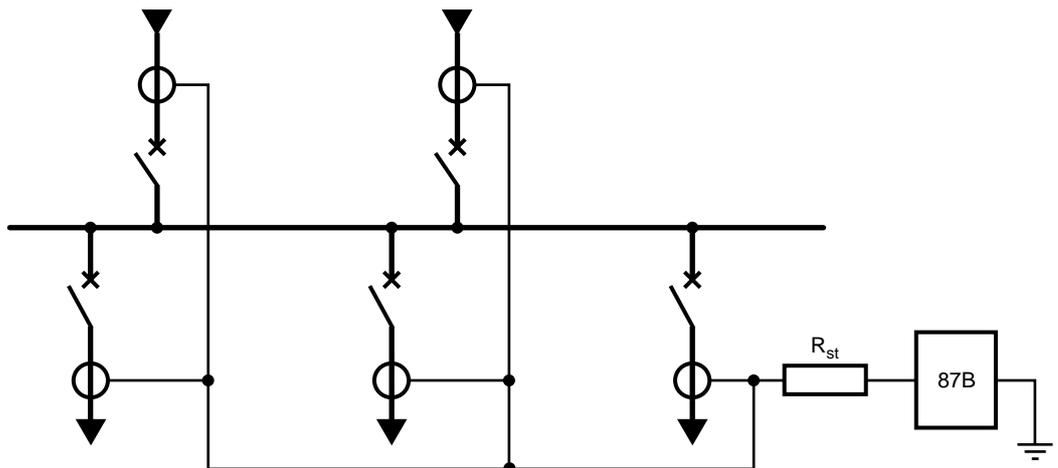

Fig. 30 : busbar differential diagram.

This section has given only a few examples of CT specification (ALF or V_k) according to the applications.
Their complete and optimised specification requires active and co-ordinated participation of many contributors. The main information required for each protection is given in the table in **figure 31** .

Information to be provided	Typical protections	Differential protections						Contributors
		High impedance differential protection (see note)				% differential	Pilot wire	
	Overcurrent 51 + 51 N	BB 87B	Motor 87M	Gen. 87G	Earth 87N	Transfo. 87T	Line 87L	
Switchboard real I_{sc}		■	■	■	■	■	■	Network designer
Maximum through current		■	■	■	■	■	■	
Maximum earth fault current I_{hl} if earth fault detection	■	■	■	■	■	■	■	
Transformer rating					■	■		
Transformer Z_{sc}					■	■		
Vector group of the power transformer						■		
CT ratio	■	■	■	■	■	■	■	Protection plan designer
Relay manufacturer and type	■	■	■	■	■	■	■	
Relay setting current I_r	■	■	■	■	■			
Motor starting current			■					Motor manufacturer
Generator subtransient short- circuit reactance				■				Generator manufacturer
Distance between CT and relay	■	■	■	■	■	■	■	Switchboard designer
Cross-section of wiring used (or value of R_L)	■	■	■	■	■	■	■	

Note:
When consulting the class X CT suppliers, you MUST ask for all the values of minimum V_k, maximum R_{ct} and maximum I_o as these are essential for completing the study.
Besides the minimum V_k, the value of real V_k is also necessary to calculate peak voltage, when high impedance differential relays are used.

Fig. 31 : information to be provided by each contributor for defining CTs.

6 Conclusion

Current transformers are essential links between electrical busways and the devices protecting the MV and HV network components.

Their precise definition and optimisation are not simple and require thorough understanding of their operation and close co-operation of many contributors. As a rule the choice of a CT is easier when it is associated with conventional protections. However, when differential protections (class X) are chosen, they must be examined with care and require good communication with the CT manufacturer.

However, as we have shown in this document, it is possible to specify CTs by excess according to protections and applications. This solution is a means of avoiding many problems relating to safety, costs and lead times.

CT technology must also be taken into account as it can offer advantages, for example:
■ standard CTs are optimised and available,
■ CTs with several secondaries offer space and cost savings,
■ multifunctional CTs, used in standard panels, allow cost savings.

If, despite all the precautions taken, problems arise, there is always a solution. This is the purpose of Cahier Technique no. 195 which highlights the traps (most common errors) and the possible solutions.

Finally, this Cahier Technique demonstrates the extreme care that installation designers must take when defining CTs, in particular when drawing up the protection plan and the discrimination study.

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