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current transformers for HV protection

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After one year's specialisation at the university of Stuttgart (Germany), he entered the overseas projects department of Stein Heurtey (iron and steel engineering). In 1980 he joined Merlin Gerin, becoming part of the technical section of the High Voltage Prefabricated Switchgear Department (P.S.H.T.) where he completed a study on current transformers. This Cahier Technique publishes the results of this study.

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content

Current transformers or CTs take up a lot of space in HV cubicles. Thorough knowledge of how they work makes it possible to:

- reduce their dimensions and thus their cost,
- use standard CTs in a larger number of configurations.

The purpose of this study is to learn more about CT operation in association with protection relays and to lay down a few rules for sizing them properly.

After a brief theoretical review of CT operation and current protection devices, the behaviour of the CT-protection relay combination is studied in two particularly important cases in HV:

- overcurrent relay supplied by a heavily saturated CT,
- protection relay connected to two CTs in parallel in duplex cubicles.

This study is completed by experimental results.

1. theoretical review

Current transformers consist of a magnetic circuit in toroid form. The primary is made up of n_1 turns or simply a single conductor crossing the toroid ($n_1 = 1$). The secondary is wound in n_2 regular turns around this toroid (see fig. 1 and 2).

Ampere's theorem states that the sum of the ampere-turns is equal to the circulation of the magnetic field vector.

$$n_1 i_1 + n_2 i_2 = \int_{Toroid} \vec{H}\,\vec{n}\,dl$$

$\vec{H}$ = magnetic field

$\vec{n}$ = tangent unit vector

A transformer is said to be perfect when

$$\int_{Toroid} \vec{H}\,\vec{n}\,dl = 0$$

In the real transformer, this term refers to the error introduced by the magnetic circuit and defines the exciting current i_e formed at the secondary by:

$$n_1 i_1 + n_2 i_2 = n_2 i_e$$

If $n = \frac{n_2}{n_1}$ is the winding ratio, the relationship is written as:

$$\frac{i_1}{n} + i_2 = i_e$$

The transformer can then be represented (see fig. 3) as having two parallel elements:

- a perfect transformer of ratio n delivering a current i_1/n at the secondary,
- an impedance which consumes a current i_e.

Moreover, each winding, both primary and secondary, creates a slight voltage drop due to the resistance of the winding (R_1 and R_2) and to the leakage inductances (ℓ_1 and ℓ_2). Since, in the case of the CT, the secondary winding is tight and regular, ℓ_2 need not be considered.

If φ is the flux common to both windings, the following can be written between the emf e_1, e_2 and the difference in potential v_1, v_2:

$$v_1 = e_1 + R_1 i_1 + \ell_1 \frac{di_1}{dt}$$

$$e_2 = v_2 + R_2 i_2 + \ell_2 \frac{di_2}{dt}$$

$$e_1 = n_1 \frac{d\varphi}{dt} \quad \text{and} \quad e_2 = -n_2 \frac{d\varphi}{dt}$$

If all the functions described are sinusoidal of pulsation ω, the following can be written vectorially:

$$\vec{V_1} = \vec{E_1} + (R_1 + j\ell_1\omega)\vec{I_1}$$

$$\vec{E_2} = \vec{V_2} + R_2\vec{I_2}$$

$$\vec{E_1} = jn_1\omega\vec{\Phi} \quad \vec{E_2} = -jn_2\omega\vec{\Phi}$$

$$\frac{\vec{I_1}}{n} + \vec{I_2} = \vec{I_e}$$

The wiring diagram in figure 3 and equations (1) result in the vectorial representation in figure 4.

The exciting current $\vec{I_e}$ is broken down on the axes $\vec{\Phi}$ and $\vec{E}$ into:

$$\vec{I_e} = \vec{I_a} + \vec{I_m}$$

- where $\vec{I_a}$ represents the part of this current lost in the magnetic circuit (iron losses due to hysteresis and eddy currents).
- and $\vec{I_m}$ is the magnetising current which transfers power from one winding to the other by creation of a magnetomotive force which induces the flux $\vec{\Phi}$.

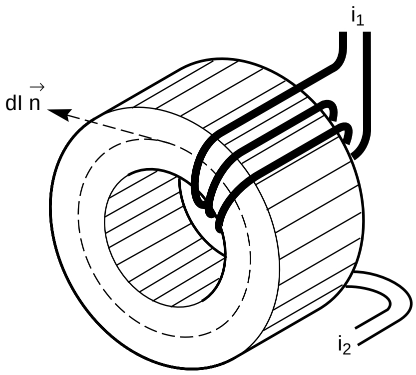


fig. 1.

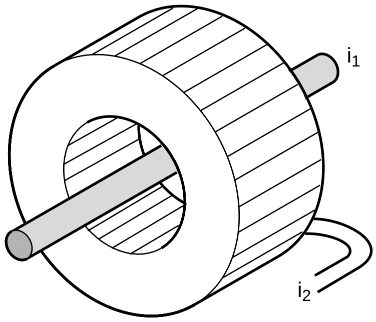


fig. 2.

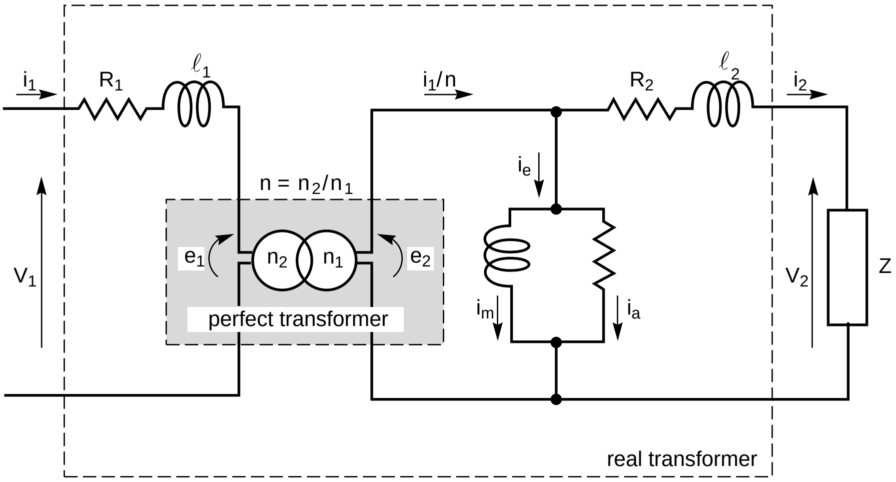


fig. 3: CT schematic diagram.

hysteresis - saturation

Magnetic circuit quality is defined by the relationship it imposes between the induction vector B and the magnetic field vector H.

At a given moment and in a fixed point, these two vectors are linked by the relative permeability of the magnetic material μ_r such that:

$$\vec{B} = \mu_o \, \mu_r \, \vec{H}$$

A magnetic circuit is thus characterised by the curve b = f (h) known as the magnetising curve.

According to the different material types, the curves in figure 5 are obtained, the results of sinusoidal excitation (primary current).

In sinusoidal state, b represents voltage since:

$$\vec{B} = \frac{\Phi}{S} \vec{n}$$

$$\vec{E}_2 = n_2 \, j\omega \, \vec{\Phi}$$

$$\vec{V} \approx \vec{E}_2$$

h represents the exciting current since

$$n_2 \, I_e = \int_{Toroid} \vec{H} \; \vec{n} \, dl$$

assuming that

$$\vec{H} \, \vec{n} = H = constant$$

$$n_2 \, I_e = L \, H$$

Perfect transformer

Permeability of the medium is assumed infinite

$$\vec{H} = 0 \text{ hence } \vec{I}_e = 0 \text{ and } \vec{I}_2 = \frac{\vec{I}_1}{n}$$

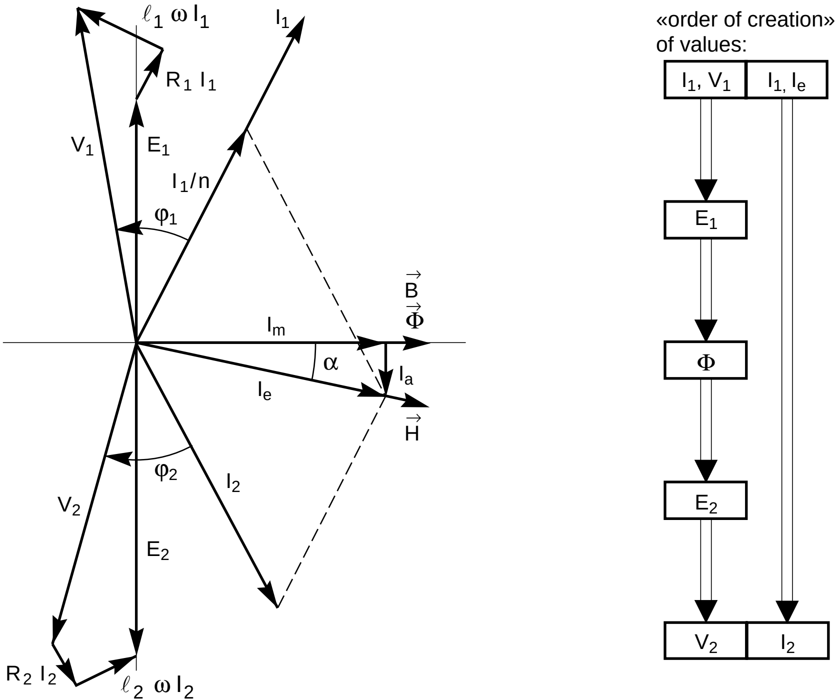
This hypothesis approaches the real situation with CTs since they normally «work» far below saturation. I_2 is then the mirror image of I_1.

Linear transformer

Permeability of the medium is constant B = Cste x H hence i_e and i_2 are sinusoidal functions.

Saturable transformer without hysteresis

Saturation is the sudden variation of μ_r from a high value to a low value at the point known as the «saturation bend». Induction b then increases only slowly and i_e deforms to form a peak.



N.B.: the real proportions, between the representative vectors of primary and secondary values, are not repected.

fig. 4: vectorial representation of a CT.

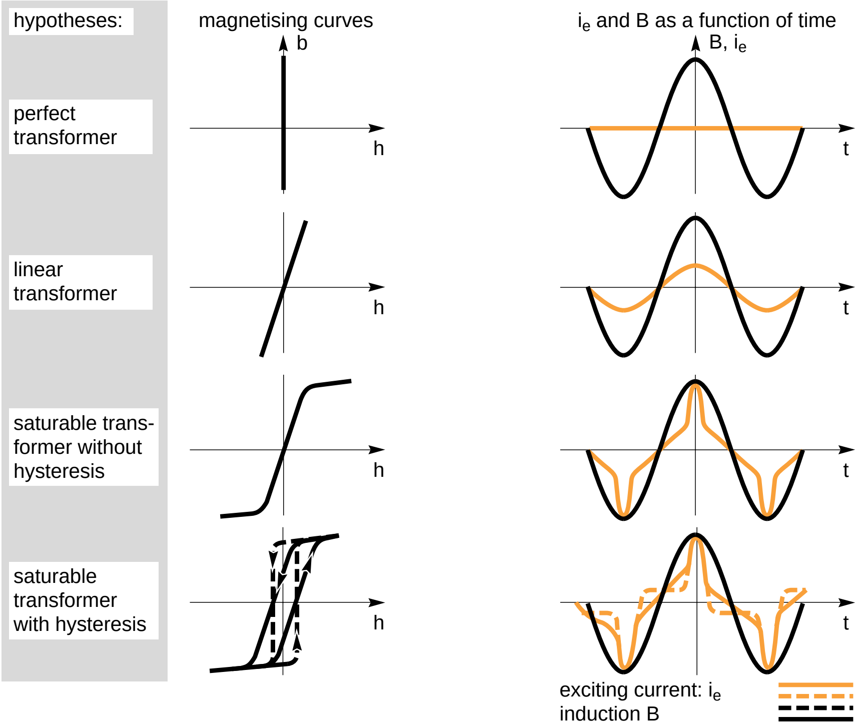


fig. 5: magnetising curves and their incidence on i_e.

Saturable transformer with hysteresis

The magnetising curve is undoubled, thus indicating the resistance of the magnetic circuit to the induction variations. Curve i_e then exhibits a characteristic «swing».

The magnetising curve of a CT can easily be observed using an oscilloscope. A sinusoidal voltage V_2 (t) is applied to the secondary (the primary is not charged). The current i_e (t) absorbed then represents the exciting current and is proportional to the magnetic field vector H.

Integration of voltage V_2 represents the flux φ_2 which is proportional to the magnetic induction vector $\vec{B}$ (see fig. 6a).

Integration of a sinusoidal value causes a rotation of $\pi/2$ (90°). It is thus sufficient on an oscilloscope:

- to sweep with i_e,
- to apply voltage V_2 to the vertical amplifier.

The magnetising curve of the material is thus obtained (see fig. 6b).

characterisation of CTs

CTs are characterised in practice by the following values (according to standards NF C 42-502 and IEC 185).

CT voltage

This is the operating voltage applied to the CT primary. Note that the primary is at the HV potential level and that one of the terminals of the secondary (which must never be opened) is normally earthed.

Just as for all equipment, a maximum 1 min withstand voltage at standard frequency and a maximum impulse withstand voltage are defined (refer to the standards in the appendix).
e.g. for a rated voltage of 24 kV, the CT must withstand 50 kV for 1 mn at 50 Hz and 125 kV impulse voltage.

Rated winding ratio

Normally takes the form: I_1/I_2.

I_2 is very generally 5 A or 1 A (for rated values of I_1, refer to the standards in the appendix).

Rated accuracy class

This depends on whether the CT is used for measurement or protection:

- for measurement CTs

The module error

$$\varepsilon_M = \frac{I_1 / n - I_2}{I_1 / n}$$

The phase error

$$\varepsilon_\varphi = \widehat{(I_1, I_2)}\, 10^{-2} \text{ rd}$$

An accuracy class X is given (generally 0.5 or 1) which expresses limit values of the module error ε_M and of the phase shift error ε_φ as a function of the load ratio N:

$$N = \frac{I_1}{I_{1n}} \quad \text{(N varies from 0.1 to 1 2)}$$

for N = 1 ε_M = X (in class 0.5 for $I_1 = I_{1n}$, ε_M = 0.5 %)

(for value details refer to the standards in the appendix).

- for protection CTs

The composite error ε_c

$$\varepsilon_c = \frac{1}{I_1 / n}\sqrt{\frac{1}{T}\int_o^T \left(i_2 - \frac{i_1}{n}\right)^2 dt}$$

Protection CTs are characterised by 3 symbols: Y, P, F_p:

Y = error rate (5 or 10),
P = protection,
F_p = accuracy limit factor which gives the limit values of errors ε_M, ε_φ and ε_c as a function of the load ratio N.

For N = F_p
ε_c = Y
(in class 10P5 for $I_1 = 5\ I_{1n}$: ε_c = 10 %)
(for value details, refer to the standards in the appendix).

For a CT working at a rated induction B_n, a saturation coefficient K_s such that:

$$K_s = \frac{B_s}{B_n}$$

where B_s is the saturation induction characterising the core material.
In practice $K_s \approx F_p$ and they are often treated as the same in calculations.

Accuracy level power

Expressed in VA, it indicates the power that the secondary can supply while respecting the rated accuracy class Y, P, F_p.
It represents the total consumption of the secondary circuit (except for CT), i.e. the power consumed by all the connected devices as well as the connecting wires.

(for rated values, refer to the standards in the appendix).

Bear in mind that the less the CT is loaded (the more it is below its accuracy level power Y), the greater its accuracy. Its real accuracy level is therefore greater than its rated accuracy level F_p.
This point is developed in chapter 3.

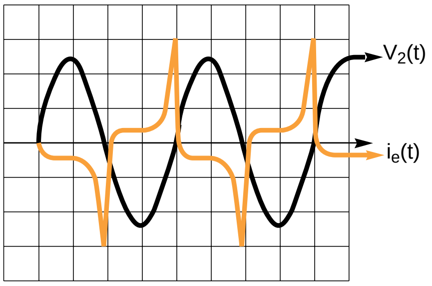
Admissible short term current

Expressed in kA it is the maximum current admissible I_{th} for one second (the secondary being short-circuited). It represents CT thermal overcurrent withstand.
(standard values are given in the standards in the appendix).

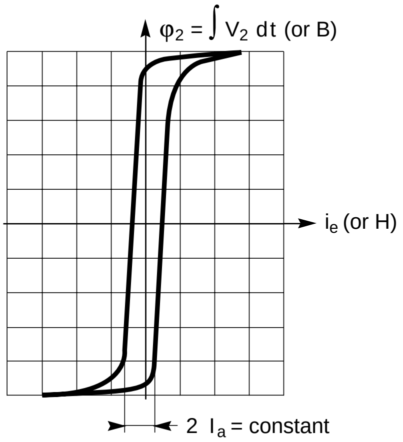
For times other than 1 second, the heat conservation law I^2 t = cste can be applied:

for t < 1 sec. the calculation gives $I > I_{th}$, thus increasing electrodynamic forces.

However, the limit guaranteed value is $I_{dyn} = 2.5\ I_{th}$.



a - scales: i_e = 0.25 A per square
V_2 = 50 V per square.



b - scales: i_e = 0.25 A per square
φ_2 = 0.077 V.s per square.

fig. 6 : oscillographic reading of curves i(t) V_2(t) and h(b) of a CT, 50/5, 15 VA, 10P20 where: V_2 = 83 V and I_e = 0.26 A.

2. general current protection information

Protection devices have many functions since they have to:
- protect equipment from destruction or damage as a result of faults (short-circuit, overload...),
- ensure normal operation of the installation and its equipment (control, load shedding...),
- guarantee safety of personnel.


CT with cross primary winding (cable) 1 secondary - 600/1

Wound type CT with wound primary winding 1 secondary - 200/5

Wound type CT with wound primary winding 2 secondaries - 200/5 and 100/5

fig.7: different types of CTs.

current transformers

Since relays cannot be connected directly onto the MV network, the information they receive comes from current transformers or CTs (see fig. 7) and from voltage transformers or VTs. When primary current is high, the CTs are of the cross bar type, and when it is low they are of the wound primary type.

CTs have a number of roles to play in electrical networks:
- supplying at their secondary a current exactly mirroring the one flowing in the HV conductor concerned,
- providing galvanic insulation between the HV and the measuring and protection circuits,
- protecting the measuring and protection circuits from damage when a fault occurs on the HV network.

Using this current image in the HV conductor, the relay generates in turn a tripping order according to the type of protection it provides and the values at which it has been preset [threshold(s), time delay(s)....].

This order is transmitted to one or more breaking devices (circuit-breaker, contactor, switch).

CT configurations vary according to the type of protection to be provided.

Overcurrent protection (see fig. 8)
This directly uses the «current» information supplied at the CT secondary to detect short-circuit or overload currents or calculate the thermal status of a machine. Note that this configuration type must also contain the protection devices using in addition to VTs:
- directional overcurrent protection,
- power protection (active or reactive).

Earth leakage protection (see fig. 9)
This measures the current difference between two CTs, one connected downstream and the other upstream from part of the network to be monitored (a motor, a transformer, a busbar...) to quickly detect and isolate any faults inside that part.

Zero sequence protection
This monitors the zero sequence component I_o of the three-phase current which appears during phase-earth faults. There are two possible configurations:
- a toroid transformer encircling the three phase conductors (if possible). This configuration (see fig. 10a) enables detection of small zero sequence currents (1 to 100 A).
- three CTs achieving in the neutral connection of their secondary the sum of the three phase currents. This configuration (see fig. 10b) is the only one possible for large and numerous cables or busbar ducts. It is not recommended when the zero sequence current to be detected is 5% less than In (or even 12% for consumer substations according to standard NF C 13-100 (French Standard)).

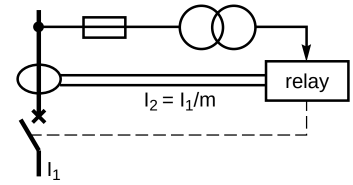


fig. 8.

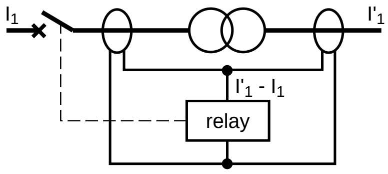


fig. 9.

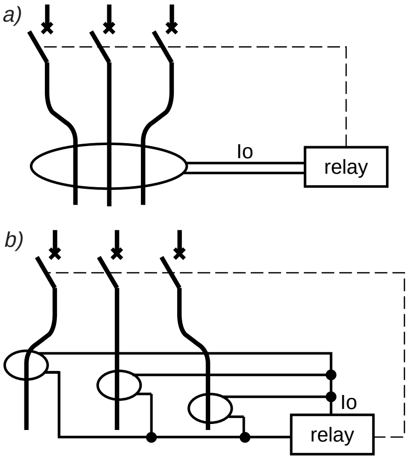


fig. 10.

functional CTs

In HV cubicles, the «current transformer» function takes on a new dimension as a result of its content and shape.

Thus:
- a number of CTs can be moulded in the same enclosure: one core for the measurement function, one core for the protection function and sometimes even a third core for earth leakage protection,

- the enclosure is used to ensure insulation between two compartments and plugging-in of the breaking device: the CT is then said to be «functional». An application example is given in the metalclad cubicles for withdrawable switchgear (see fig. 11 and 12).

Overall dimensions are thus reduced by using one insulating enclosure (the most appropriate), thus also reducing costs.

the protection relays

The equipment currently available is based on the three technologies: electromechanical, analog and digital.

The oldest of these is electromechanical technology: relays are simple and specialised (current, voltage, frequency, ... monitoring) but their accuracy is poor as their settings may be altered over time.

The last two technologies benefit from the advantages provided by electronics (see fig. 13):

- compact dimensions of the device,
- low power required for acquisition of «current» information (a few fractions of VA),
- response time not dependent on the current received by the relay,
- reliability increased by lack of mechanical parts (no dirt accumulation or corrosion, not affected by impacts),
- low cost since they use mass produced non-specific electronic components.

Finally, in the nineteen eighties, digital technology made it possible, thanks to microprocessor processing power, to produce information processing units able to:

- globally provide the various protections,
- replace relays (automation) in the cubicle,
- provide operators with measurement of electrical parameters.

These units, with their increased vocation, are:

- flexible (protections are chosen simply by programming),
- parameterisable (large choice of settings),
- reliable (they are fitted with self-monitoring or with watchdog and self-test),
- economic (reduced wiring and implementation time).

Their digital communication and powerful algorithms also enable additional functions such as logic discrimination to be performed.

This communication capacity means that genuine network operation (similar to technical management of industrial installations) is now possible.

Finally, their ability to acquire and process the information provided by sensors allows them to make full use of the performances of the new non-magnetic sensors.

technological evolution

In this current sensor field, sensors with wide measuring bands are being increasingly used instead of current transformers (1 or 5 A). These sensors based on Rogowski's principle (non-magnetic sensors) are currently on the market and provide distributors with optimised solutions (fewer alternative versions and simplified choice) which are far more efficient (improved response curve linearity) than traditional transformers.

fig. 11: functional CT for HV metalclad cubicles (Merlin Gerin).

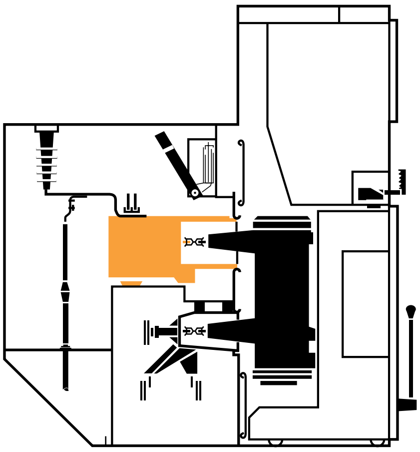


fig. 12: installation example of functional CTs in a Fluair 200 12 kV HV metalclad cubicle (Merlin Gerin).

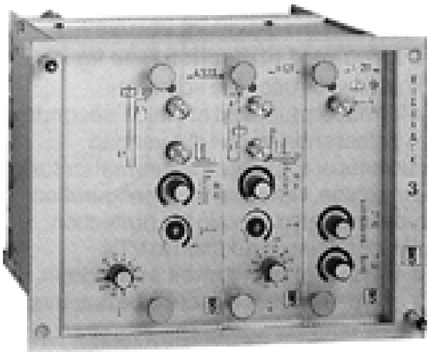


fig. 13: Vigirack static relays (Merlin Gerin).

3. response of a CT in saturated state

The emergence of static relays leads to revision of protection behaviour as a whole in the case of strong currents: as the CT saturates beyond a certain threshold, the first reaction is often to avoid this by raising the threshold. However, this results in both additional costs (more efficient, larger, more space consuming CT) and in the risk of excessive temperature rise of the relays.

On the contrary, saturation plays a useful role for the «measurement» function since primary current image accuracy is only useful up to the value of the rated current I_{1n}. Beyond this point, the measurement ceases to be of any use and saturation must occur for a low current (2 to 3 I_{1n}) in order to limit the secondary current and protect the measuring instruments.

It is thus necessary to know the response of the CT in saturated state to ensure the protection device works properly when the primary current exceeds rated current strength, particularly for the high values which appear if a short-circuit occurs.

In theory, induction in the core reaches a plateau at the saturation bend, thus limiting current strength at the secondary. In actual fact the experiment performed will show that current strength at the secondary slightly increases and that protection relay operation is quite satisfactory.

experiments - wiring

A current i_1 is injected in the CT primary, and the current supplied by the secondary in a load Z containing a relay R and a resistance is analysed (see fig. 14).

The currents at the secondary I_2 are given, according to the current supplied at the primary (represented by the parameter $N = \frac{I_1}{I_{1n}}$) for various loads Z and various CTs (see fig. 15).

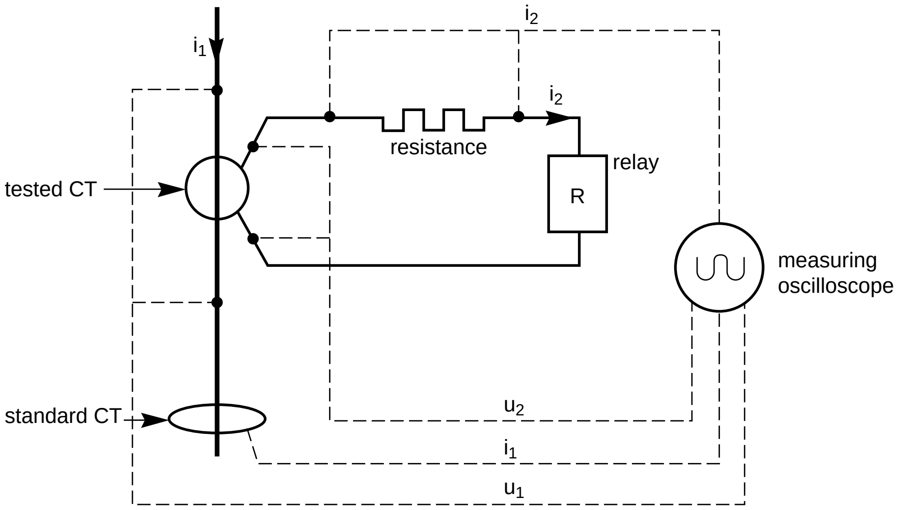


fig. 14: diagram for checking proper relay operation.

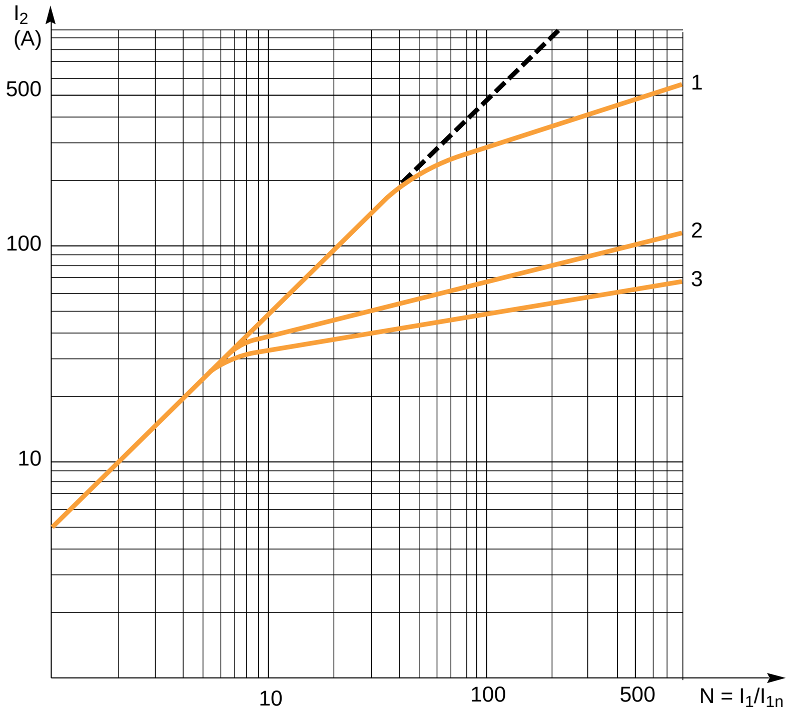


Fig. 15: I_2 = f(N) for 1 CT only (15 VA 10P5 100/5).
Load Z at the secondary:
1. relay only,
2. Z = rated Z of CT, i.e. 0.6 Ω and cos φ = 1,
3. Z = rated Z of CT, i.e. 0.6 Ω and cos φ = 0.8.

testing with symmetrical constant currents

Testing at resistive rated load

The test was carried out using a CT with low performance: 10P5, 50/5 with a rated load Z of 15 VA (at 5 A) made up of an overcurrent relay and a resistance.

Two relays were used:
□ a Vigirack static relay,
□ an electromechanical relay.

As both these relays have a low internal resistance, a resistance was added to reach roughly 0.6 Ω, i.e. 15 VA at 5 A (connecting wiring included). Because the inductance of the electromechanical relay was low (15 µH, i.e. cos φ = 0.95 for the relay only), the load can be considered to be purely resistive in both cases.

The test consisted in making current I1 vary in the range I_{1n} = 50 A at I_{1max} = 54 kA

$$\text{I.e. } N_{max} = \frac{54,000}{50} = 1,080 \text{ and}$$

$$\eta = \frac{N_{max}}{F_p} = \frac{1,080}{5} = 216$$

(the latter value indicates the level of saturation to which the CT was subjected).

■ results

The current i_2 (t) collected at the secondary takes the form of a peak above: N = 10 (see fig. 16a).

Nevertheless, the rms current I_2 continues to increase as is shown in line 2 in figure 15.

As I_2 increases, the power supplied at the secondary $P_2 = Z\ I_2^2$ and the power delivered at each relay $P_r = R\ I_2^2$ also increase. This accounts for **the tripping of both relay types** as from threshold ß to which they were set right up to N_{max}.

Testing at rated partly inductive load

This test resembles the previous one. However, a choke is placed in the secondary circuit to represent the case of an electromechanical relay connected by itself to the secondary which would consume the rated power of the CT. In practice, these relays never fall below cos = 0.8.

In this test, the current I_1 explored the range I_{1n} = 50 A to $I_{1\,max}$ = 16,400 A,

$$\text{i.e. } N_{max} = 328 \text{ and } \eta = \frac{N_{max}}{F_p} = 65.6$$

■ results

Current i_2 (t) assumes the curve given in figure 16b. The presence of a choke spreads out the peak, hence the lower value I_2 (see line 3 in figure 15).

With respect to testing at pure resistive load:
□ I_2 is multiplied by a factor of 0.65,
□ the total power supplied at the secondary is multipled by a factor of 0.4,
□ both relays trip from their threshold ß right up to N_{max}.

Testing at reduced load

The secondary load only comprises the relay and the connecting wires.

Compared with the rated load of 15 VA, this represents a load of roughly 9%.

■ results

Curves i_2 (t) (see fig. 16c) and i_2 (N) (see line 1 in figure 15) show that the saturation bend is far higher than at rated load.
This bend follows the law:

$$K_s \left(P_2 + R_2 I_2\right)^2 = \text{constant}$$

with $P_2 = Z\ I_2^2$ is the total power supplied at the secondary (consumed by the relay and the connecting wires).
R_2 = internal resistance of the CT secondary winding,
K_s = saturation coefficient (real or rated).

Thus, in practice, when a CT delivers into a load less than its rated accuracy level power (in VA), saturation occurs at a far higher overcurrent level than the rated saturation coefficient K_s.

This phenomenon must be taken into consideration and calculated for each application since it may generate overcurrents in the secondary which are incompatible with the thermal and dynamic withstands of the relays connected to the CT secondary (for calculation, refer to the conclusions given below).

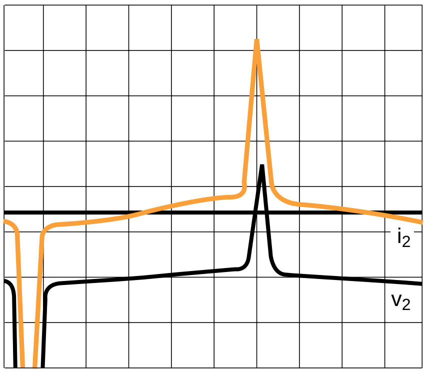


fig. 16 a - CT 15 VA 10P5 50/5
testing at purely resistive rated load
I_1 = 16,400 A
scale: i_2 = 100 A/square; v_2 = 100 V/square.

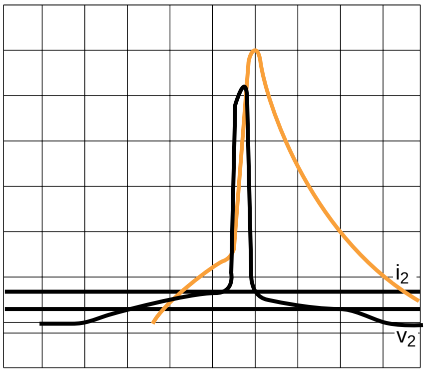


fig. 16 b - CT 15 VA 10P5 50/5
testing at rated load with cos φ = 0.8
I_1 = 16,400 A
scale: i_2 = 25 A/square; v_2 = 50 V/square.

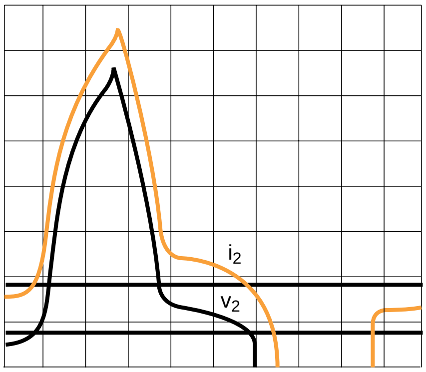


fig. 16 c - CT 15 VA 10P5 50/5
testing at reduced rated load
relays + connecting wires - I_1 = 14,200 A
scale: i_2 = 100 A/square; v_2 = 5 V/square.

testing with asymmetrical currents

The test was performed using an asymmetrical current, i.e. the sum of a symmetrical sinusoidal current and a DC component with the following characteristics:

$$\frac{\hat{I}}{I_{rms}} \approx 2.3$$

These values are slightly less than those in standard NF C 64-100 for which

$$\frac{\hat{I}}{I_{rms}} = 205 = 18\sqrt{2}$$

i.e. 20% of asymmetry at 70 ms.

The secondary load is identical to that of the main test at resistive rated load comprising an electromechanical or static relay.

■ results

Both relays correctly respond in a few ms and in the same manner as in symmetrical testing throughout the range explored (up to $\hat{I}_1$ = 140 kA peak with I_{rms} = 54 kA).

Remarks:

■ the first peak seen at the secondary by the relays is enough to make them trip, if its energy is sufficient: this is the case for I_{rms} greater than 2 kA but below this value (see fig. 17a) the third peak is required;

■ the CT does not saturate during the first negative peak of the primary current for $\hat{I}_1$ = 4 kÂ ;

■ the response delivered by the CT on the first negative peak of the primary (or even secondary) is normally shorter than the responses in steady state (which is reached as from the sixth peak);

■ the above points show that for higher peak factors (case of off-load energising of transformers with an

$$\frac{\hat{I}}{I_{rms}} = 3.7$$

), there is a risk of the response at the secondary disappearing during the first peaks. If, in addition, the time constant of the primary current DC component is high (t = 80 ms in the case quoted), this disappearance continues until the primary current crosses the 0 axis. This phenomenon is shown on the curves in figure 17 (tripping time moves to 68 ms).

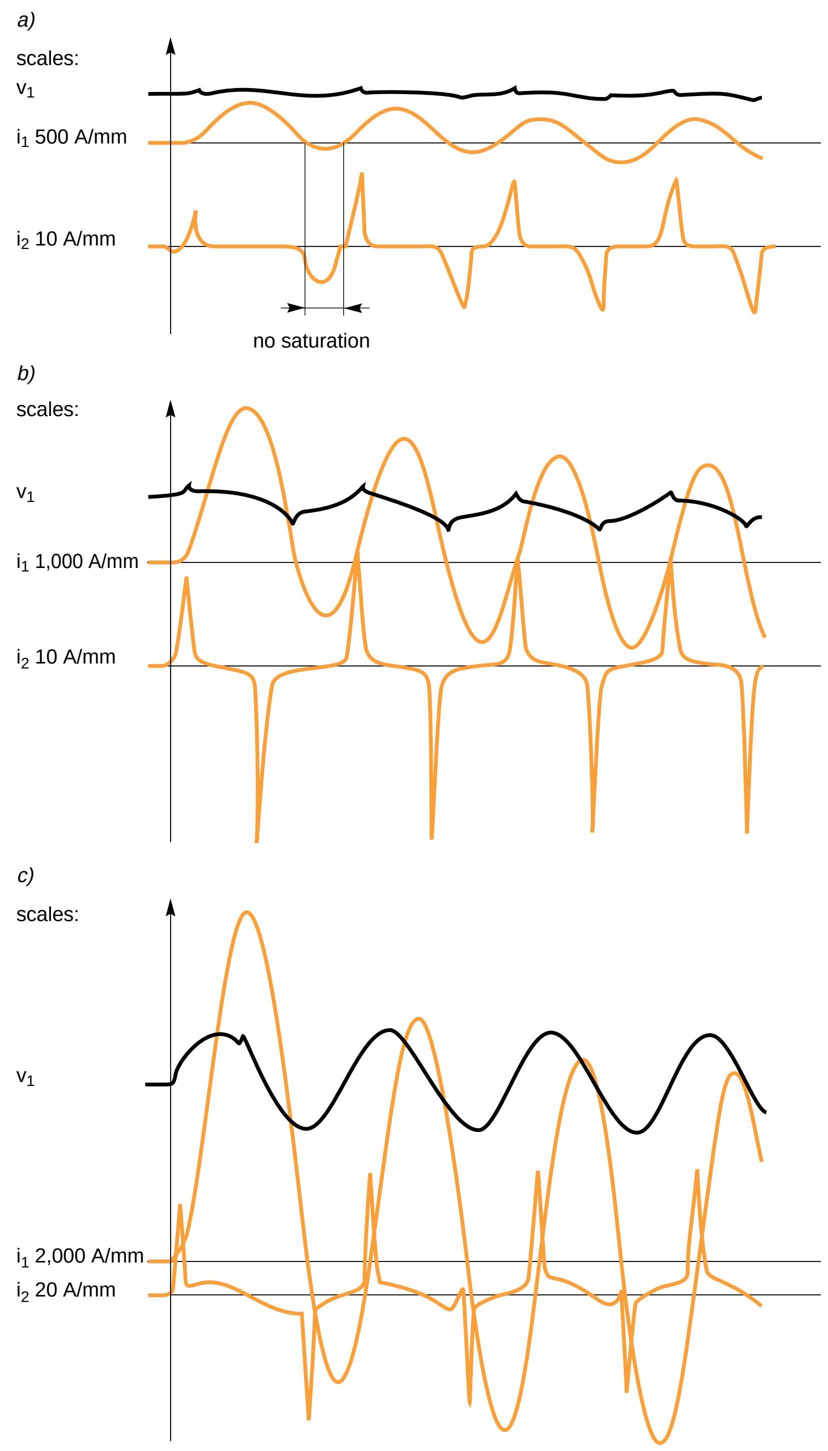


fig. 17: CT secondary responses on an asymmetrical primary current for:

a) I_{rms}. ≈ 1.4 kA,

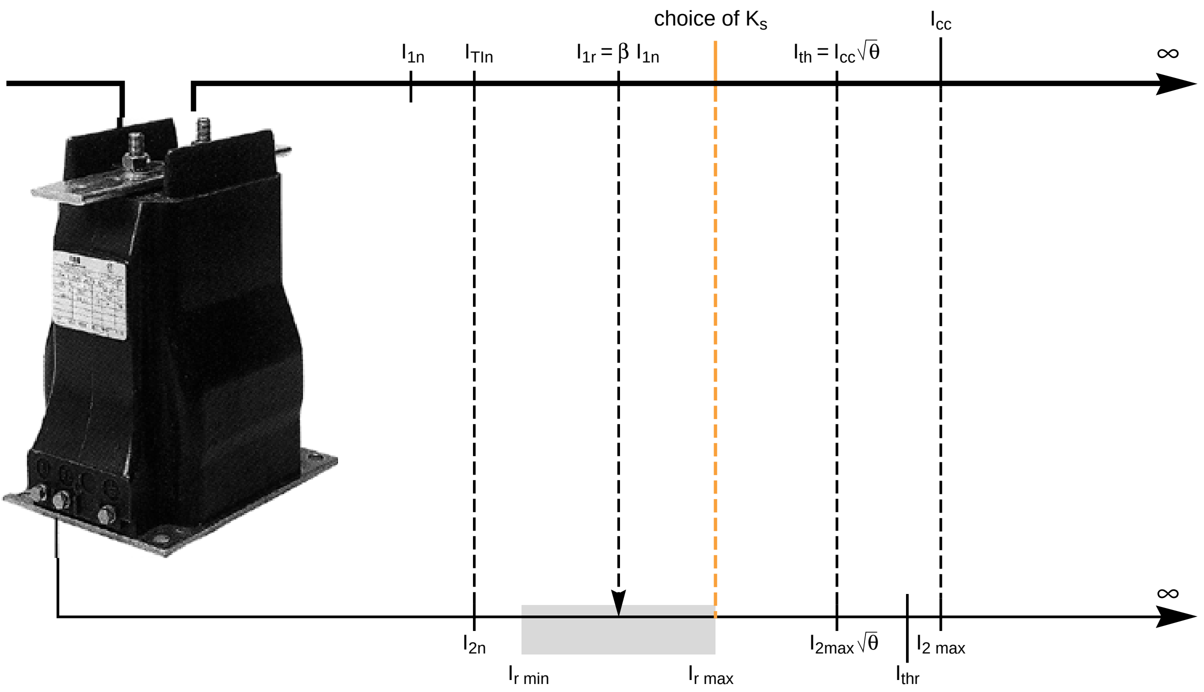
b) I_{rms}. ≈ for 14 kA and $\hat{I}_1$ ≈ 32 kA,

c) I_{rms}. ≈ 54 kA and $\hat{I}_1$ ≈ 140 kA.

conclusions on CTs delivering on an overcurrent relay

The above tests show that for both electromagnetic and static relays, tripping is obtained whatever the current value, even if the CT is strongly saturated.

Thus, the CT saturation coefficient Ks must be calculated not according to the short-circuit current Icc but according to the maximum setting threshold of the associated relay (see fig. 18 and 19).



of the network

I_{1n} = rated current
I_{1r} = $\beta\ I_{1n}$ setting current
I_{cc} = short-circuit current
θ = maximum short-circuit time

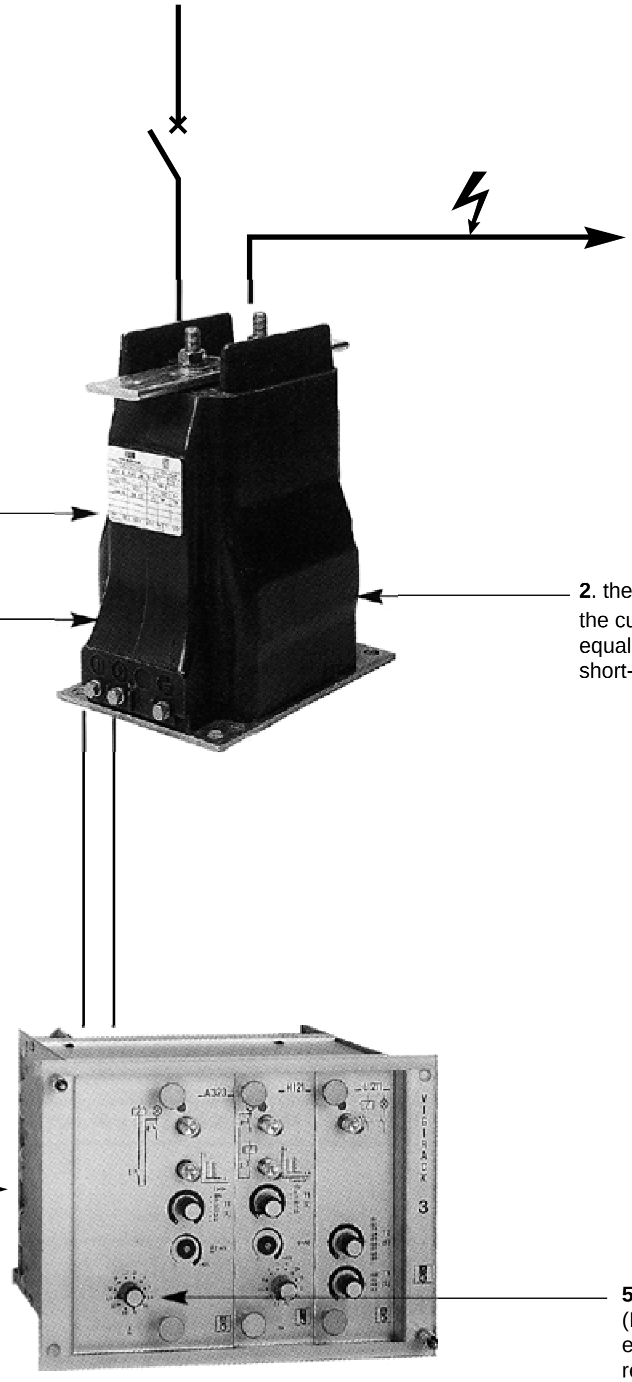
of the relay

$I_{r\ min}$ to $I_{r\ max}$ = setting range
I_{thr} = admissible short term current (1s)

of the CT

I_{TIn} = rated primary rating
I_{2n} = rated secondary current
$I_{2\ max}$ = CT response to I_{cc}

fig. 18: characteristics to be considered for defining a CT.



1. the saturation threshold K_S must correspond to the maximum setting value of the relay.

3. this CT must electrodynamically withstand the peak value 2.5 I_{cc}.

2. the CT must thermally withstand the current I_{cc} for a time θ at least equal to the breaking time of the short-circuit by the circuit-breaker.

4. the secondary circuit must thermally withstand the maximum secondary rms current $I_{2\ max}$ created by I_{cc} at a primary for the time θ.

5. the relay setting range ($I_{r\ mini}$, $I_{r\ maxi}$) must be large enough to cover the CT response at the setting current of network B I_{1n}.

fig. 19: general rules for sizing a CT.

4. parallel cubicle operation

Power supplies with double busbars are frequently used in HV network configurations.

There are currently two solutions for most cubicles:

- the double busbar cubicle: the circuit-breaker may be connected to either busbar without discontinuity of service. One of the drawbacks often encountered in this system is highly complex lockings:
- cubicles connected in duplex (see fig. 20). Using standard elements, this solution can advantageously replace the double busbar, as it is more reliable.

As on the new cubicle generations, the CTs are standard elements used to provide insulation between compartments and to plug in the breaking device. This arrangement makes it necessary to connect the relays (which are not backed up) on each CT secondary. This has resulted in the study below concerning operation of two identical CTs connected in parallel on the same load.

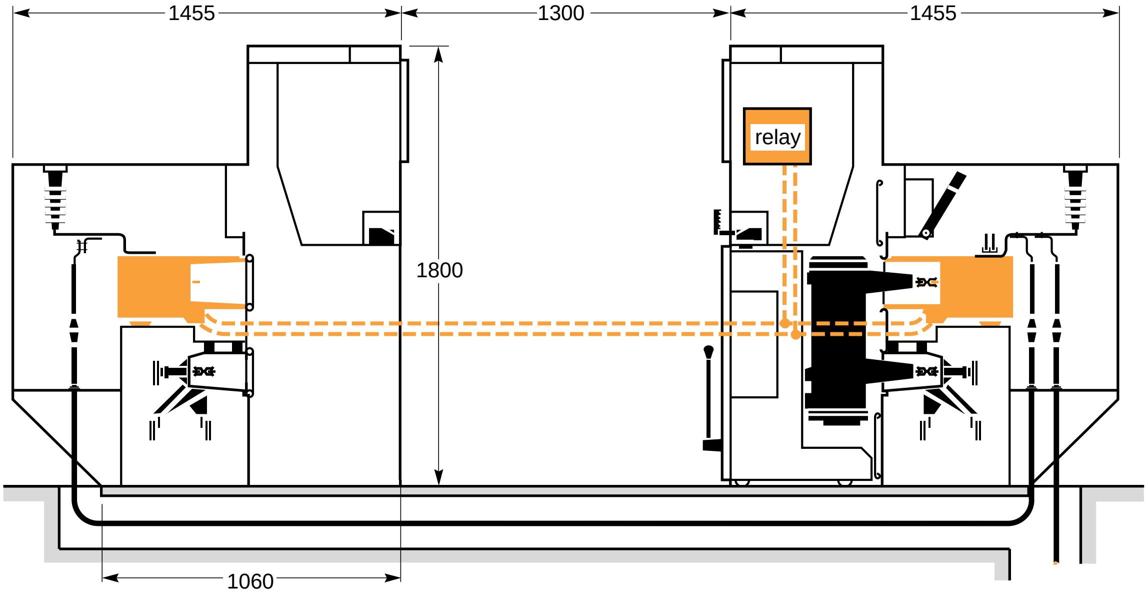


fig. 20: connection of 2 cubicles in duplex relay

Wiring diagram

Connection of two cubicles in duplex, as shown in figure 18, results in the diagram in figure 21 for protection.

One of the CTs (said to be «live») is supplied at the primary by the HV network; its secondary supplies a current i_2 broken down into a current i_m on the secondary of the other CT (said to be «dead») and a current i_r on the rated load of 15 VA made up of an electromagnetic or static relay and a pure resistance.

The tests were performed on two identical CTs of the same series (15 VA 50/5 10P5 as in the above paragraphs).

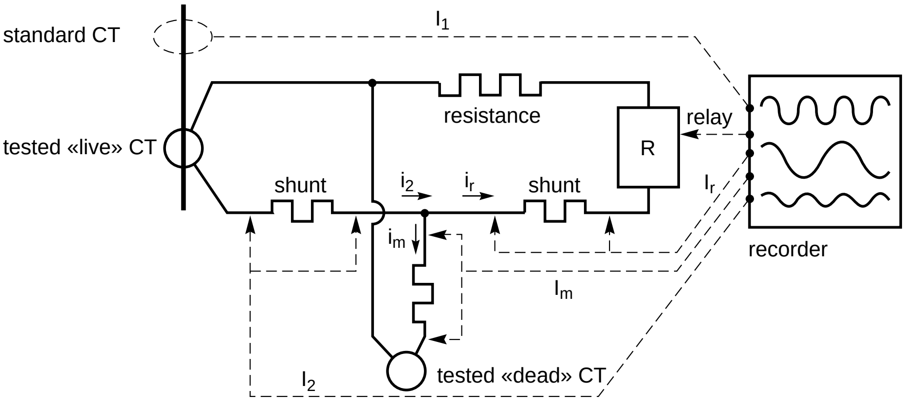


fig. 21: wiring diagram for study of a parallel-connected CT.

Results

These are given in the curves of figures 22 (currents as a function of time) and figure 23 (root mean square currents and tripping times). The following observations are made:

■ both relays quickly respond from their tripping threshold ß to $\eta = 72$,

■ the static relay trips in a constant time $T \approx 20$ ms, whereas the electromagnetic relay reacts as a function of I_2 ($T \approx 80$ ms at the tripping threshold to $T \approx$ a few ms at $\eta = 72$);

■ the secondary current I_2 continues to increase but two separate zones appear:

☐ before $\eta = 10$, $I_r \approx I_2$ and $I_m << I_r$ the secondary current flows entirely into the relays since the «dead» CT acts as an infinite impedance,

☐ after $\eta = 10$ $I_m \rightarrow I_2$, which means that the secondary current mostly flows into the «dead» CT but, however, I_r continues to grow, thus causing the relays to trip (do not forget that i_r is dephased by $\frac{\pi}{2}$ with respect to i_m);

■ the current Ir flowing in the relays during testing with two CTs is lower than for testing with one CT (at N = 300, roughly - 40%).

Conclusion

The connection of two CTs in parallel presents no problem:

■ for low currents: hardly any current flows into the «dead» CT,

■ for high currents: sufficient current flows into the relay to trip it.

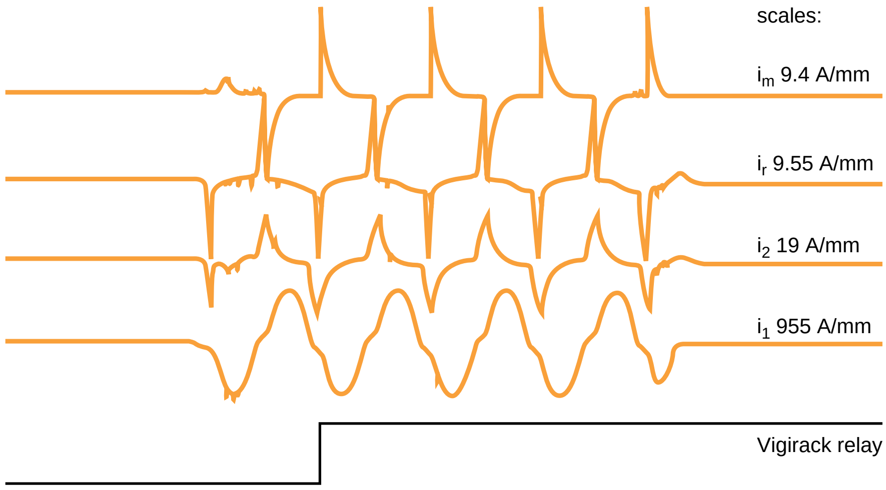


fig. 22: currents at the secondary of 2 parallel-connected CTs. I_1 *= 12,500 A.*

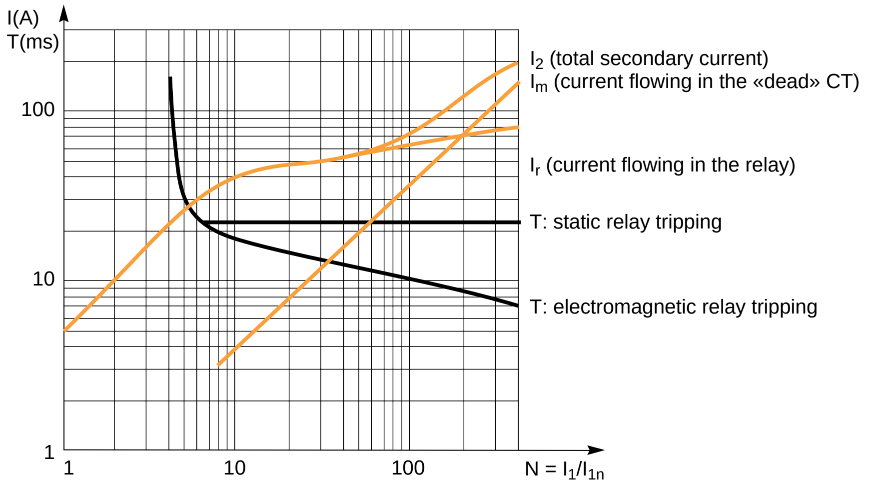


fig. 23: rms currents and tripping times of the relays connected to 2 CTs in parallel (10P5 50/5 15 VA).

5. general conclusions

The conclusions in chapters 4 and 5 show that:

- the relays operate correctly in both cases studied:
  - high CT saturation,
  - parallel-connection of two CTs;
- static relays give the most reliable response (constant operating time for all currents greater than the setting threshold).

Moreover, static relays generally have a very small acquisition time, thus meaning operation is more reliable when the CT is strongly saturated and supplies a very short current impulse.

Do not forget, however, that the transient phenomena considered were limited to the asymmetrical current less than:

$$\frac{\hat{I}}{I_{rms}} = 2.5$$

Nevertheless, CT saturation, as shown in this experiment, should not be considered a handicap:

- when a CT «supplies» one or more measuring instruments, saturation, by limiting rms current at the secondary, protects the devices which, moreover, do not generally need to be very accurate above I_{1n}.
- when a CT «supplies» a protection device, operation is ensured even if saturation occurs. The idea of sizing a CT according to the highest current it may have to withstand at the primary must therefore be rejected. Moreover, this oversizing is risky for the relay and cabling which could be seriously damaged.

appendix: CT standards

NF C 42-502 (French Standard)

Rated insulation levels

The insulation levels recommended by the standard are given in table II A presented in figure 24.

highest voltage for equipment (kV)	withstand voltage 1 minute at standard frequency (rms value) (kV)	withstand voltage to impulse voltage (peak value) (kV)
0.6	3	
1.2	6	
2.4	11	
3.6	16	45
7.2	22	60
12	28	75
17.5	38	95
23	45	95
24	50	125
36	70	170
52	95	250
72.5	140	325

fig. 24: insulation levels (table II A).

accuracy class	**current error** (ratio error) as a percentage, ±, for current values given as a percentage of rated current				**phase shift, ±** for current values given as a percentage of rated current							
					minutes				centiradians			
% I_{1n}	10	20	100	120	10	20	100	120	10	20	100	120
0.1	0.25	0.20	0.1	0.1	10	8	5	5	0.30	0.24	0.15	0.15
0.2	0.5	0.35	0.2	0.2	20	15	10	10	0.60	0.45	0.3	0.3
0.5	1.0	0.75	0.5	0.5	60	45	30	30	1.8	1.35	0.9	0.9
1	2.0	1.5	1.0	1.0	120	90	60	60	3.6	2.7	1.8	1.8

Note: after agreement between manufacturer and user, guarantees can be provided for accuracy and phase shift, between 120% and 200% of I_n n.

fig. 25: error limits (table III).

accuracy class	**current error** (ratio error) as a percentage, ±, for current values given as a percentage of rated current	
% I_{1n}	50	120
3	3	3
5	5	5

There is no phase shift limit for classes 3 and 5.

fig. 26: error limits (table IV).

Normal rated current values

- at the primary (in A): **10** - 12.5 - **15** - **20** - 25 - **30** - 40 - **50** - 60 - **75** and their decimal multiples or submultiples.

Preferential values are given in bold.

- at the secondary (in A): 1 - 5

Accuracy class

- measurement CTs

The normal accuracy classes are:

0.1 - 0.2 - 0.5 - 1 - 3 - 5.

The rated frequency operating range is 96% to 102% of rated frequency.

For transformers of accuracy classes 0.1 - 0.2 - 0.5 and 1, the current error and phase shift in the rated frequency range must not exceed the values in table III (see fig. 25) when the secondary load is between 25% and 100% of accuracy load.

For transformers of accuracy classes 3 and 5, the current error in the rated frequency range must not exceed the values in table IV (see fig. 26) when the secondary load is between 50% and 100% of accuracy load.

In all cases, the load used must be inductive with a power factor of 0.8, unless the corrresponding power is less than 5 VA, in which case its power factor is the unit. On no account must the load be less than 1 VA.

- Protection CTs

The normal accuracy limit factor values are: 5 - 10 - 15 - 20 - 30 - 40.

The rated frequency operating range is 90% to 110% of rated frequency.

The normal accuracy classes are 5P and 10P.

For accuracy level power and in the rated frequency range, the current error, phase shift and composite error must not exceed the values in table V (see fig. 27).

To determine the current error and phase shift, the load must be inductive and equal to the accuracy load with a power factor of 0.8, unless the corresponding power is less than 10 VA; in this case the load could be resistive (unit power factor). To determine the composite error, the load power factor may be between 0.8 (inductive circuit) and the unit, the value being set by mutual agreement between manufacturer and user.

Accuracy level power

The normal accuracy level power values are: 2.5 - 5.0 - 10 - 15 - 30 - 75 - 100 VA.

Admissible peak current and short term current

Admissible peak current and short term current (I_{th}). The short term current (I_{th}) must be specified for each transformer.

Their preferential values are given in paragraph 10.1 (see fig. 28).

Notes

- for the highest network voltage less than or equal to 36 kV, the admissible short term current value is constructively linked to rated current value. It is thus frequently expressed as a multiple of rated current, for which the preferential values are: 40 - 80 - 100 - 200 and 300.
- if no admissible values as a function of time are given, it is accepted that the transformer can withstand for a time t, expressed in seconds, a current with a root mean square value given by the formula:

$$I'_{th} = \frac{I_{th}}{\sqrt{t_2}}$$

where $t_2 > t_1$ bearing in mind that I_{th} is given for t_1 (= 1s).

accuracy class	**ratio error** for currents between I_n and 2 I_n (as a %)	**phase shift** for rated current		**composite error** for accuracy limit current (as a %)
		minutes	centiradians	
5P	± 1	± 60	± 1.8	5
10P	± 3			10

fig. 27: error limits (table V) .

- the admissible times for the admissible short term current are set from the cold state. However, at the user's request, the manufacturer is obliged to indicate, for a given type of device, the admissible short term current based on a state corresponding to operation, the heating current and maximum ambient temperature. However, in the latter case, verification of admissible short term current cannot be made mandatory as an acceptance test.

Admissible current peak value (I_{dyn}).

The admissible current peak value is 2.5 I_{th}. However, another value can be accepted provided it is stated on the identification plate.

highest network voltage (kV)	I_{th} (kA)				
3.6	10	16	25	40	
7.2	8	12.5	16	25	40
12	8	12.5	16	25	40
17.5	8	12.5	16	25	40
23	8	12.5	16	25	40
24	8	12.5	16	25	40
36	8	12.5	16	25	40
72.5	20	25			
100	20				
245	20	31.5			
420	40				

fig. 28: preferential values of I_{th} (paragraph 10.1).

IEC 185

This is the reference standard. The NF C 42-502 (Norme Française) differs only slightly from it. The differences are as follows:

Rated insulation levels

The IEC standard gives two tables:

- the same table as the NF C standard for European countries,
- another table as per USA practice with slightly more stringent values: refer to table II B (see fig. 29).

Normal rated current values

Same preferential values at the primary. At the secondary possibility of a I_{2n} = 2 A.

Accuracy class

- measurement CT

Current errors in module and phase are the same in class 3 and 5. For classes 0.1 - 0.2 - 0.5 and 1, the errors are the same, except for the 10% of I_{1n} column which is replaced by 5% of I_{1n} with the errors listed in table IV A in figure 30. Moreover, the IEC standard defines two additional classes, 0.2 S and 0.5 S for CTs with special applications (connection with special electrical energy meters). In this table, the module and phase errors are given for I_{2n} = 5 A only.

- protection CT

The IEC gives the same limit errors. The only difference is that the accuracy limit factor, F_p = 40, does not exist.

Accuracy level power

The IEC only gives the same normal values up to 30 VA. Beyond this point, power can be chosen to meet needs.

Peak current and short term current

Unlike the NF C standard, the IEC standard does not define preferential values of I_{th} for each network voltage. However, application of the law $i^2 t$ = Cste to define the I_{th} is limited to: 0.5 < t < 5 s.

highest voltage for equipment Um (rms value) kV	**rated lightning impulse withstand voltage** (peak value) network power ≤ 500 kVA kV	> 500 kVA kV	**rated short term withstand voltage** at standard frequency (rms value) kV
4.40	60	75	19
13.20 13.97 14.52	95	110	34
26.4	150		50
36.5	200		70

fig. 29: rated insulation voltages set for the U.S.A (table II B).

accuracy class	**error ε_M** for I_1 = 5 % of I_{1n}	**error ε_φ** for I_1 = 5 % of I_{1n} minutes	centiradians
0.1	0.4	15	0.45
0.2	0.75	30	0.9
0.5	1.5	90	2.7
1	3	180	5.4

accuracy class		**error ε_M** for values as a % of rated current I_{1n}					**error ε_φ** for values as a % of rated current I_{1n} minutes					centiradians				
	% I_{1n}	1	5	20	100	120	1	5	20	100	120	1	5	20	100	120
0.2S		0.75	0.35	0.2	0.2	0.2	30	15	10	10	10	0.9	0.45	0.3	0.3	0.3
0.5S		1.5	0.75	0.5	0.5	0.5	90	45	30	30	30	2.7	1.35	0.9	0.9	0.9

fig. 30: accuracy class (table IV A).

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