

THEORY AND TECHNOLOGY OF INSTRUMENT TRANSFORMERS



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1. INTRODUCTION TO INSTRUMENT TRANSFORMERS

1.1. DEFINITIONS

Instrument transformers (ITs) are transformers designed to supply measuring instruments, meters, relays and other similar devices.

There are two types of instrument transformer

- > Current transformers, in which the secondary current is under normal working conditions, practically proportional to the primary current and phase shifted from it by an angle close to zero in the appropriate direction for connections; and
- > Voltage transformers, in which the secondary voltage is under normal working conditions, practically proportional to the primary voltage and phase shifted from it by an angle close to zero in the appropriate direction for connections.

1.2. OBJECTIVE

The purpose of instrument transformers is to reduce the voltage and current of an electrical network to a standardized non hazardous level.

They prevent any direct connection between instruments and high voltage circuits which would be dangerous to operators and would need instrument panels with special insulation. They also do away with the need for expensive special instruments when high currents have to be measured.

Figure 1.1 shows a simple circuit diagram in which one current transformer (CT) and two voltage transformers (VTs) are included. One of the latter is connected between phases and the other between phase and earth.





1. INTRODUCTION TO INSTRUMENT TRANSFORMERS

1.3. GENERAL POINTS IN CURRENT TRANSFORMERS

The primary of a current transformer is made up of one or more coils connected in series with the circuit whose current is to be measured. The secondary supplies the current circuits of one or more measuring apparatus, which are connected in series.

The primary winding may have one, two or four sections, allowing for one, two or three rated primary currents depending on how they are connected.

The secondary windings may also be one or more in number, with each wound on its own magnetic circuit. In this way one secondary does not influence the other. Fig. 1.2 shows a CT with two independent secondaries. The core of a CT is normally ring-type, with the secondary evenly distributed to minimize the secondary flux losses.

The primary consists of one or more coils connected in series with the line. There are also CTs in which the primary is not incorporated; in this case the main insulation may be in the primary (cables, bushings etc.) or in the transformer itself.

Figure 1.3 shows various types of CT.



> Fig. 1.2



> Fig. 1.3



1. INTRODUCTION TO INSTRUMENT TRANSFORMERS

1.4. GENERAL POINTS IN **VOLTAGE TRANSFORMERS**

The primary of a voltage transformer is connected to the terminals between which the voltage is to be measured, and the secondary is connected to the voltage circuits of one or more measuring devices, connected in parallel.

Voltage transformers are more like power transformers than current transformers are.

For reasons of construction and insulation, VTs are normally made with a rectangular core and the secondaries (if there is more than one) are wound on the same core.

Unlike CTs, they are therefore not independent, and the load of one secondary influences the accuracy of the other.

Fig. 1.4 shows a VT with two secondaries and a tap in each.

VTs may be used to measure the voltage between phases or between a phase and earth. In this case one end of its primary winding will be directly earthed, inside or outside the transformer. Fig. 1.5 shows two types of VT. Beyond around 72.5 kV., all VTs are phase/earth type.



> Fig. 1.4



2. THEORY OF INSTRUMENT TRANSFORMERS

2.1. BASICS

A transformer is made up of two windings wound onto a magnetic core. The primary is powered by the voltage u_p and absorbs the current i_p . The secondary supplies the current i_s to the outside load, with voltage u_s . (see fig. 2.1)

If the secondary terminals are open, the primary acts as an auto-induction on the iron core, absorbing the excitation current i_{po} , which comprises a magnetizing component $i_{p\mu}$ and a loss component i_{ow} .

If the whole flux ϕ created by the primary is picked up by the secondary, we can establish:

$$e_p = N_p \frac{d\phi}{dt}$$
 $e_s = N_s \frac{d\phi}{dt}$

Applying Ohm's law and disregarding the resistance of the primary winding, we have:

$$u_{p} - e_{p} = 0; u_{p} = e_{p} = N_{p} \frac{d\phi}{dt}$$
$$u_{s} - e_{s} = 0; u_{s} = e_{s} = N_{s} \frac{d\phi}{dt}$$

where K is the transformer ratio.

When a load is connected to the secondary terminals, secondary current i_s appears. This gives rise to a flux opposed to that created by i_p . To maintain u_p constant the primary current increases so that:

$$\frac{N_{p}i_{p}-N_{s}i_{s}}{R} = \phi$$

Therefore, since F = $\phi \cdot R = N_p \cdot i_{po'}$ what is left is $N_p \cdot i_p = N_s \cdot i_s + N_p \cdot i_{po}$

In a perfect transformer, $N_{_{\rm p}}\cdot i_{_{\rm po}}$ is insignificant, and therefore,

$$N_p i_p = N_s i_s - \frac{i_p}{i_s} = \frac{N_s}{N_p} = \frac{1}{K}$$

If the secondary load is Z_s , we have:

$$i_s = \frac{u_s}{Z_s}$$
, and therefore: $i_p = \frac{i_s}{K} = \frac{u_s}{KZ_s} = \frac{u_p}{K^2Z_s}$

where it can be seen that the effect is similar to placing a load K^2Z_s on the primary. On a real transformer we must bear in mind not only the excitation current i_{po} , but also the resistances Rp and Rs of the windings and the leakage flux ϕ_p and ϕ_s , as shown in fig. 2.2.

Bearing in mind that N $\cdot \phi$ = i \cdot £ the general equations for the transformer are:

$$U_{p} = N_{p} \frac{d\phi}{dt} + R_{p}i_{p} + f_{p} = \frac{di_{p}}{dt}$$
$$U_{s} = N_{s} \frac{d\phi}{dt} + R_{s}i_{s} + f_{s} = \frac{di_{s}}{dt}$$
$$N_{p}i_{p} = N_{s}i_{s} + N_{p}i_{po}$$
[2.1]

And for sine wave sizes:

$$\bar{U}_{p} = N_{p}\bar{E} + R_{p}\bar{I}_{p} + jX_{p}\bar{I}_{p}$$
$$\bar{U}_{s} = N_{s}\bar{E} + R_{s}\bar{I}_{s} + jX_{s}\bar{I}_{s}$$
$$N_{p}\bar{I}_{p} = N_{s}\bar{I}_{s} + N_{p}\bar{I}_{po}$$
$$[2.2]$$

where E is the electromotive force induced in a coil.





2. THEORY OF INSTRUMENT TRANSFORMERS

2.2. EQUIVALENT TRANSFORMER

To study instrument transformers it is of interest to refer to the secondary, whose rated values vary little in general.

Let us look at how primary magnitudes are reflected in the secondary.

From [2.2]:

$$N_{p}\overline{I}_{p} = N_{s}\overline{I}_{s} + N_{p}\overline{I}_{po}$$

Dividing by N_s:

$$\frac{N_{p}}{N_{s}} \bar{I}_{p} = \bar{I}_{s} + \frac{N_{p}}{N_{s}} \bar{I}_{po}; K \bar{I}_{p} = \bar{I}_{s} + K \bar{I}_{po}$$

Where $K\bar{I}_{po}$ is the excitation current absorbed by the transformer if the voltage applied to the secondary is U_p / K .

 $K\bar{I}_{_{DO}}$ will hence be called $\bar{I}_{_{O}}$

Therefore, $K\bar{I}_{p} = \bar{I}_{s} + \bar{I}_{o}$

In the same way, from equations [2.2]:

$$\frac{\bar{U}_{p}}{K} = \frac{N_{p}\bar{E}}{K} + \frac{R_{p}\bar{I}_{p}}{K} + j \frac{X_{p}\bar{I}_{p}}{K}, \text{ from which:}$$
$$\frac{\bar{U}_{p}}{K}N_{s} = \bar{E} + \frac{R_{p}}{K^{2}}(\bar{I}_{s}, \bar{I}_{o}) + j \frac{X_{p}}{K^{2}}(\bar{I}_{s}, \bar{I}_{o})$$

We can see that R_p/K^2 and X_p/K^2 are the resistance and the reactance of the primary, seen from the secondary. corresponds to:

$$\frac{\bar{U}_{p}}{K} = \bar{U}'_{p}; \bar{I}_{p}K = \bar{I}'_{p}; \frac{R_{p}}{K^{2}} = R'_{p}y\frac{X_{p}}{K^{2}} = X'_{p}$$

equations [2.2] are transformed into:

$$\bar{U}'_{p} = N_{s}\bar{E} + (R'_{p} + jX'_{p})\bar{I}'_{p}$$
$$\bar{U}_{s} = N_{s}\bar{E} - (R_{s} + jX_{s})\bar{I}_{s}$$
$$\bar{I}'_{p} = \bar{I}_{s} + \bar{I}_{o}$$
[2.3]

2.3. EQUIVALENT TRANSFORMER CIRCUIT DIAGRAM

From equations [2.3.] we can obtain the equivalent circuit diagram of the transformer. This is shown in fig. 2.3.





3.1. GENERAL EQUATIONS

From fig. 2.3, when the outside load Z is applied, we obtain fig. 3.1. Bearing in mind equations [2.3] we can write:

$$\begin{split} \bar{\mathsf{E}}_{_{\mathrm{S}}} &= \bar{\mathsf{U}}_{_{\mathrm{S}}} + \overline{\mathsf{Z}}_{_{\mathrm{S}}} \, \bar{\mathsf{I}}_{_{\mathrm{S}}} \\ & \bar{\mathsf{I}'}_{_{\mathrm{S}}} = \bar{\mathsf{I}}_{_{\mathrm{S}}} + \bar{\mathsf{I}}_{_{\mathrm{O}}} \end{split}$$
 where $\bar{\mathsf{E}}_{_{\mathrm{C}}} = \mathsf{N}_{_{\mathrm{S}}} \, \bar{\mathsf{E}}$, and as

$$\overline{U}_{c} = \overline{Z} \overline{I}_{c}$$
, it results that: $\overline{E}_{c} = (\overline{Z} + \overline{Z}_{c}) \overline{I}_{c} = \overline{Z}_{c} \overline{I}_{c}$

Recalling Boucherot's formula:

$$\overline{E}_{eff} = 2,22 \frac{f}{50} \text{ N} \overline{B}_{max} \text{S} 10^{-6} \text{ Volts}$$

which is valid for sine wave currents, if we make f= 50Hz, the following results: \bar{E} = 2,22 N $\bar{B}_{max}S$ x 10^{-6}

where: \bar{E} = Voltage in volts S = Net cross section in cm² B_{max} = Induction in Gauss

N = Number of turns

The induction required in the core of the current transformer to power external load Z is therefore:

$$\overline{B} = \frac{(\overline{Z} + \overline{Z}_{s}) \overline{I}_{s}}{2,22 \text{ N}_{s} \text{ S}} \times 10^{6} \text{ Gauss}$$

from which the following conclusions may be drawn:

- > If impedance is fixed, induction is proportional to the secondary current.
- If the secondary current is fixed, induction is proportional to the total secondary load.

3.2. VECTORIAL DIAGRAM

Bearing in mind equations [2.3], from I_s we can obtain the vectorial diagram of a current transformer. To obtain I_o we must use the magnetizing curves of the plate used for the core, finding H_u and H_w from B (Fig. 3.2).

This gives:

$$I_{\mu} = \frac{H_{\mu}L}{N_{s}} \qquad I_{w} = \frac{H_{w}L}{N_{s}}$$

where L is the length of the magnetic circuit. Finally, Fig. 3.3 indicates the vectorial diagram of the CT.



> Fig. 3.1



> Fig. 3.2







3.3. CURRENT AND PHASE ERRORS

The current error ε_i is the error which the transformer introduces into current measurements. It stems from the fact that its transformation ratio is not exactly as rated. Current error ε_i expressed as a percentage, is which corresponds to the following formula:

$$\epsilon_{i}$$
 (%) = $\frac{(K_{n} |_{s} - |_{p})}{|_{p}} \times 100$

where:

 K_n = rated transformation ratio. I_p = actual primary current. I_t = actual secondary current.

The phase shift or phase error of a current transformer, δi , is the phase difference between the vectors of the primary and secondary currents, with vector directions being chosen so that the angle is zero for a perfect transformer.

In practice, for loads with $\cos\beta = 0.8$, phase shift is not a limiting factor, so transformers are calculated for the maximum ratio error, i.e. when I_e and I_a are in phase.

In this case:

$$\epsilon_{i} = \frac{N_{s} I_{o}}{N_{p} I_{p}} \approx \frac{N_{s} I_{o}}{N_{s} I_{s}}$$

Be mindful of the following equations:

> Boucherot's formula:

$$E_s = 2,22 N_s B_{max} S 10^{-6}$$

> The Maxwell-Ampere law:

$$H = N_s I_o / L$$

> Ohm's Law:

$$I_s = E_s/Z_t$$

we obtain the following:

$$\epsilon_{i}$$
 (%) = 450000 $\frac{L Z_{t}}{N_{s}^{2} S_{\mu}}$ [3.1]

where:

- L = Average length of the magnetic circuit [cm].
- Zt = Total impedance of the secondary (internal plus load) [in ohms].
- $Ns = N^{\circ}$ of turns on the secondary winding.

- S = Cross section of the magnetic core $[cm^2]$.
- μ = B/H = Permeability of the magnetic core [Gauss / AV / cm].

Once formula [3.1] is obtained, it shows the various factors involved in current transformer errors, and allows the following conclusions to be drawn:

1. With regard to core material:

Figure 3.4 shows the magnetizing curves of various materials.

Curve I is for an old material with a high silicon content, and is shown for the sake of comparison. Curve II represents a material with a high saturation rate, and curve III one with a low saturation rate but high permeability at low induction.

Figures 3.5 and 3.6 show the values μ and $1/\mu$, for these materials. We can see that for a minimum error we must use the minimum value of $1/\mu$, so plate I is of no interest.



> Fig. 3.4



Curve II, for oriented grain material, is significant when the number of ampere-turns is high enough to reach the accuracy with a small cross section of iron or when a high saturation factor is sought.

Curve III is for Mumetal type material, which allows high induction at a low number of ampere-turns, and a low safety factor. The choice of material will depend on various technical and economic requirements.

Fig. 3.7 shows how the error varies when Is varies but Z_t remains constant. This curve shows the variation in μ in the face of a variation in B, which remains proportional to I_c .

2. As regards to apparent power:

The apparent power is practically proportional to the total impedance, as $Z_s << Z_t$ and therefore the error is directly proportional to the apparent power. The core cross section must be made proportional to the apparent power to keep the error within permitted limits, taking into account that if the average line is increased, cross section must be increased to cancel out the effect.

It is interesting to note that if a current transformer is designed to work with maximum μ at rated current and load, when it works with a load Z_t/4 the error is reduced to one quarter if μ remains constant, i.e. for 4 I_{sn}. This is shown in fig. 3.8.

Since the error is always negative, in practice this curve is centred on the x-axis, giving a positive advance equal to or less than the error. This is achieved by modifying the turns ratio. Fig. 3.9 shows an actual case.

3. As regards to the number of ampere-turns:

If we maintain $I_s = 5A$ the number of ampereturns is directly proportional to $N_{s'}$, and therefore the error is inversely proportional to the square of the number of ampereturns of the secondary.

It is therefore significant to raise the number of ampereturns, though there are limits imposed by thermal and dynamic conditions which force the average line of the iron circuit to be increased, which causes a loss of precision. Furthermore, the increase in the number of turns of the secondary raises the overall impedance and therefore also increases the error.





3

ls

Isn

> Fig. 3.8



2



3.4. CURRENT TRANSFORMERS FOR MEASURING

These are current transformers designed to power measuring devices, counters and similar equipment.

3.4.1. ACCURACY CLASS

The accuracy class of a current transformer for measuring is given by a number (class rate) representing the ratio error limit expressed as a percentage of the rated primary current when the transformer is running at its "accuracy load".

Accuracy classes for current transformers for measuring are 0.1, 0.2, 0.5, 1 and 3.

Practical guide:

Class 0.1 - Laboratory.

- Class 0.2 Laboratory, portable reference patterns, high accuracy counters.
- Class 0.5 Normal counters and meters.
- Class 1 Panel apparatuses.
- Class 3 Uses where great accuracy is not required.

3.4.2. EXTENDED CURRENT RATINGS

These are current transformers for measuring whose accuracy and heating characteristics extend to more than 120% of the rated primary current.

150-200% of the rated primary current is usually considered as the limit of the range.

For special applications in CT with class 0.2 and 0.5 with I_{sn} = 5A, accuracy may be extended to 1% of I_{pn}, In this case the classes are denominated 0.2S and 0.5S.

3.4.3. INSTRUMENT SECURITY FACTOR (FS)

To protect equipment powered by the transformer against short-circuits in the network into which the primary is inserted, the "rated safety factor" is taken into account. This is calculated as follows:

$$F_s = I_{ps} / I_{pn}$$

where,

 $I_{_{\rm ps}}$ is the "rated safety current" $I_{_{\rm on}}$ is the "rated primary current"

The rated safety current is the primary current at which the transformer begins to saturate. At that point the secondary current multiplied by the rated transformation ratio should be 0.9 or less times the primary current.

This means that we can equate it as:

Fig. 3.10 shows the ratio between the primary and secondary currents for $F_{c} \leq 5$.

In order for a current transformer to be able to reach a high accuracy rate with a low rated safety factor, highly permeable, fast saturating magnetic plate must be used to construct the core. This is normally achieved, though it is not always possible, using expensive high nickel content plate (e.g. Mumetal). Therefore before selecting Fs we must check if it really needs to be applied. If so, the manufacturer must be consulted considering possible increases in transformer prices.





3.4.4. TESTING

Checking the class of a measuring current transformer includes the measure of its transformation ratio with a precision of 0.01%.

This test can be performed only in specialized laboratories. However, comparison with properly calibrated reference transformers via checking bridges will show the errors in transformers to a high enough standard of accuracy.

To check the rated safety factor two methods can be used:

- > Powering the primary winding at the rated safety current and checking that the error in the secondary at its precision load is 10% or more.
- > Exciting the transformer via the secondary winding until $U_o = F_s I_{sn} Z_t$ is obtained at the secondary terminals and checking that $I_o \ge 0,1 F_s I_{sn}$.

It is important to recall that the safety factor depends on the secondary load, and increases proportionally to the reduction in total load.

Note: Some standards permit both these test methods, but it must be taken into account that the direct method measures the ratio error and the indirect the compound error. However the figures for F_s obtained by the two methods differ very little, and the convenience of the application of the indirect method is reason enough for using it.

> 420 kV Current Transformers model CA. CFE, Chicoasen (Mexico)





3.5. CURRENT TRANSFORMERS FOR PROTECTION

These are current transformers intended for power protective relays. They must therefore guarantee sufficient accuracy at current levels several times higher than the rated current.

With these currents, the error to be considered is the "composite error", which is defined as the effective figure for the integrated difference over a period between the instantaneous primary current and the product of the rated transformation ratio by the actual instantaneous secondary currents. In percentage terms this is given by the following formula:

$$\Sigma_{\rm c} (\%) = \frac{100}{I_{\rm p}} \sqrt{\frac{1}{T} \int_{0}^{T} (K_{\rm n} \cdot i_{\rm s} - i_{\rm p})^2 \, dt}$$

If ${\rm i_p}$ and ${\rm i_s}$ are sine wave in shape, the composite error is the vectorial sum of the ratio error and the phase error.

In this case the above formula changes to:

$$\Sigma_{\rm c} = \sqrt{\epsilon_{\rm i}^2 + \delta_{\rm i}^2}$$

3.5.1. ACCURACY CLASS

The accuracy class of a current transformer for protection is given by a number (class rate) and the letter "P" (standing for "protection"). The class rate indicates the upper limit of the composite error for the rated accuracy limit current and the accuracy load. After the letter "P" the rated accuracy limit factor is shown. The normal accuracy classes are 5P and 10P.

For protection systems in which the characteristics of the transformer are an integral part of the system (such as fast acting differential protection devices) there are protection classes PR and PX.

Class PR refers to transformers which must guarantee protection as a limited remanence factor (remanent flux to saturation flux ratio) for which, in some cases, a value for the time constant of the secondary loop and/or a maximum value for the secondary winding resistance can be specified. Class PX is applied to low leakage inductance transformers (without air gap) for which knowing the secondary excitation curve, the secondary winding resistance, the secondary load resistance and the turns ratio is enough to determine their performance in the protection system to which they are connected.





3.5.2. ACCURACY LIMIT FACTOR (ALF)

The "rated accuracy limit current" is the highest primary current for which the transformer, with the accuracy load, meets the required limits for the composite error.

The "rated accuracy limit factor" is the ratio of the rated accuracy limit current (I_{lpn}) to the rated primary current (I_{pn}) .

$$ALF = I_{lpn} / I_{pn}$$

Remember that the accuracy limit factor depends on the load, and if this is higher than the accuracy load the accuracy limit factor is lower than rated. The "safety factor" and the "accuracy limit factor" are similar in concept, as they indicate the multiple of $I_{\rm pn}$ at which the CT begins to saturate at its rated load.

The following formula can be used to calculate both these new factors:

$$F = \frac{A}{\overline{Z}_{c} + \overline{Z}}$$

where A is a constant which can be obtained from the rated figures for F and Z. (see fig. 3.10)

3.5.3. TESTS

In current transformers for protection the accuracy must be checked for the rated current, using the same system as in measuring transformers. The composite error can be checked for the accuracy limit current in two ways:

- By running a practically sine-wave type current through the primary winding at an effective level equal to the accuracy limit current.
- b. By determining the excitation current for the rated frequency and a practically sinewave type voltage with an effective level equal to the secondary limit electromotive force.

The first of these methods is hard to apply, except in transformers with low primary currents and a low rated accuracy limit factor. It can be used in type testing.

For individual tests the excitation method is the only one applicable.

Note: We have differentiated clearly between current transformers for measuring and those for protection, but the two tasks can often be performed by the same unit via two or more independent cores.





3.6. CURRENT TRANSFORMERS FOR PROTECTION WHICH REQUIRE TRANSIENT REGIME RESPONSE

3.6.1. GENERAL POINTS

If a CT for protection is required to respond correctly during the early cycles of a shortcircuit, the core must be oversized so that it does not saturate with the non-cyclic component.

The initial level of the non-cyclic component varies (depending on the voltage when the short circuit occurs and on the characteristics of the line) between 0 and $\sqrt{2} I_{cc}$, where I_{cc} is the effective symmetrical short-circuit current. If we consider this maximum level, the transient short circuit current is:

 $i_{cc} = \sqrt{2} I_{cc} (e^{-t/T1} - \cos wt)$

where $T_1 = L/R$ is the time constant of the line.

If we consider that the secondary load is resistive, the flow required to prevent the CT from saturating is:

$$\phi_{T} = \phi_{A} \left[\frac{w T_{1} T_{2}}{T_{1} - T_{2}} \left(e^{\frac{t}{T_{1}}} - e^{\frac{t}{T_{2}}} \right) - \text{sen wt} \right]$$
[3.2]

where:

 T_2 = is the transformer time constant.

 ϕ_A^2 = is the peak level of the sine-wave

component of the flux.

To simplify this formula, sine wt can be taken as -1. If $T_2 >> T_1$ (as is normally the case in CTs), it results that:

$$\phi_{T} = \phi_{A} (w T_{1} + 1)$$

In high voltage lines it must normally be taken into account that after the first short circuit there is a rapid reconnection which increases the residual flow in the CT.

Fig. 3.11 shows icc (a) and CT flow (b). The oversizing coefficient of the core of the CT (K_{TD}) is the ratio between ϕT and ϕA .

From formula [3.2], bearing the reconnection in mind, it results that:



[3.3]

where:

T1 = is the time constant of the line.

- T2 = is the time constant of the CT.
- t' = is the duration of the first short circuit.
- FRT = is the fault repetition time (dead time).
- TD = is the time from which CT saturation is admitted.





To learn how to oversize a normal protection CT so that its behaviour during the transient period can be studied, the following formula can be used:

$$K'_{TD} = \frac{F_n (R_s + Z_n)}{K_{ssc} (R_s + R)}$$

where:

- F_n = is the rated precision limit factor.
- R_s = is the secondary winding resistance.
- Z_n° = is the rated load impedance.
- R_{ssc}^{n} = is the ratio between the symmetrical short-circuit current (I_{cc}) and the rated primary current.
- R = is the actual secondary resistance.

If the actual load is not resistive, addend n°1 in formula [3.3] can be replaced by 1/cos β where R_s also intervenes in the calculation of β .

3.6.2. CLASSIFICATION OF CTS

CTs are classed in three types:

TPX: CTs with no gap in the core, but with sufficient cross section to respond correctly during the transient period. They reflect the non-cyclic component well. T_2 is large in comparison to T_1 .

TPY: CTs with small gaps in the core to reduce residual induction. They reflect the non-cyclic component fairly well. T_2 depends on the degree of precision required (as a guideline, it can vary between 0.3 and 1 second).

TPZ: CTs with larger gaps than in TPY. They reflect the alternating component well, but not the non-cyclic component. T₂ is around 0.07 second. Due to the gaps, a high degree of precision cannot be obtained at I_n .

Example: consider the oversizing factors of each type of CT, for $T_1 = 0.1s$, t' = 0.08s, $T_p = 0.035s$, FRT = 0.5s and f = 50 Hz.

a. TPX. Consider	T ₂ = 10s K _{TD} = 26.4.
b. TPY.	T ₂ = 0,5s K _{TD} = 14.7.
c. TPZ.	T ₂ = 0,07s K _{TD} = 7.6.

Fig. 3.12 shows how a TPZ secondary (1S1-1S2) and a secondary with normal protection (2S1-2S2) respond to a totally shifted primary current.



> Fig. 3.12



3.7. BURDEN

This is the impedance in the outside circuit connected to the secondary winding, expressed in Ohms, with an indication of its power factor. It may also be indicated by its power factor and the apparent burden in volt-amperes absorbed for the rated secondary current.

For instance: 30VA precision burden for $I_{sn} = 5 \text{ A}$

$$Z = \frac{30}{5^2} = 1,2 \text{ Ohms}$$

When secondary loads are calculated the load of the connecting cables must be added to that of the measuring apparatuses. Fig. 3.13 is a graph of consumption in VA for the cables normally used.

Table 3.1 below indicated consumption in VA of normal amperometric coils.





Table 3.1. Consumption of some Apparatuses Powered by CTs						
Apparatus	VA at In.					
Ammeters						
Indicators	0.25 to 2					
Recorders	1,5 to 9					
Counters	0.5 to 3					
Wattmeters						
Indicators	1 to 3					
Recorders	1.5 to 8					
Phase meters						
Indicators	2 to 6					
Recorders	6 to 12					
Maximeters	3					
Power converters	3 to 6					
Relays						
Overcurrent, inv. time	5 to 8					
Overcurrent, timed	1 to 5					
Overcurrent, instantaneous	1 to 10					
Directional	1.5 to 10					
Power, timed	1.5 to 3					
Trip switch	3 to 12					
Distance	6 to 20					
Regulators	10 to 150					

In TP type CTs only just the power needed must be called for, and consumption in cables must be kept low. This will make up in part for the oversizing of the core in comparison with CTs with normal protection.



3.8. RESISTANCE TO SHORT CIRCUITS

Being connected in series to power lines, current transformers are subject to the same current and voltage overloads as the lines themselves.

In general these overcurrents are far higher than the rated currents of the CTs, and have thermal and dynamic effects which may damage transformers.

Thermal effects make it necessary to size the CT's primary correctly. All the heat produced is considered as being stored in the primary conductor, the maximum heating of which is laid down in each standard.

To prevent transformers from breaking under the dynamic stresses caused in the primary, a suitable mechanical attachment must be ensured in the primary. These mechanical stresses are a function of the peak shortcircuit current.

The resistance to short circuits in current transformers is determined by the thermal and dynamic limit currents.

3.8.1. RATED SHORT-TIME THERMAL CURRENT (Ith)

This is a highly effective primary current at which the transformer can withstand the Joule effect for one second without damage, with the secondary circuit shorted.

Once the maximum short-circuit power in the line where the CT is fitted is known, the thermal current can be calculated using the following formula:

$$I_{th} = \frac{P}{\sqrt{3} \times V}$$

where:

- I_{th} = the thermal short-circuit current (kA rms)
- P = the short circuit power (MVA), and

If the short-circuit duration is other than 1 second (between 0.5 and 5) the duration should be indicated after $I_{\rm th}$.

The ratio of times to currents is as follows:

 $I_{th1} \times \sqrt{t1} = I_{th2} \times \sqrt{t2}$

For thermal class A transformers a current density of 180 A/mm² is admissible in copper wires, corresponding to a temperature increase of 235 $^{\circ}$ C (the IEEE/ANSI standard is somewhat more severe in this respect).

Unless otherwise indicated, CT's are constructed with I_{th} = 80 In though they may be built up to I_{th} = 1000 In. However, bear in mind that in this case the power and precision class which can be supplied by a particular type of apparatus will be reduced, as the rated ampere-turns will be lower (see 3.3).

3.8.2. RATED DYNAMIC CURRENT (Idyn)

This is the peak of the first amplitude of the current which a transformer can withstand without damage when the secondary circuit is shorted.

The dynamic short-circuit current is obtained from the thermal current, taking into account that the latter is given in terms of effective level and the former in terms of peak level. The coefficient due to the non-cyclic component is normally taken as 1.8 (IEC and other standards).

Therefore:

$$I_{dvn} = 1,8 \sqrt{2}$$
 Ith. = 2,5 Ith

where:

I_{dyn} = Dynamic short circuit current (kA pk).

In the IEEE/ANSI standard the two currents are defined separately and the dynamic limit current is expressed in effective kA with a fully shifted current, i.e.:

$$lpk = 2 \times \sqrt{2} \times I_{dyn} = 2,83 I_{dyn}$$

where

I_{dyn} = Dynamic short circuit current (kA pk)



3.9. OPERATION OF AN OPEN CIRCUIT CURRENT TRANSFORMER

Let us assume that a current transformer has been built with a ratio of 1000:1 and a torus type core with an average line length of 35 cm whose magnetic plate may be considered as saturated with 1 AV/cm. Operating with the secondary circuit open, as from $I_p = 35A = 0.035 I_m$ the core is saturated.

As from 0.1 I_{pn} the flow slope increases rapidly, as does the voltage in the secondary terminals, whose peak level is proportional to $\sqrt{I_p}$. Losses in the core also increase, and raise the temperature to unacceptable levels.

This problem is certainly significant in transformers for protection because of the size of the core, so the peak voltage in the secondary terminals is sometimes limited to 4 or 8 kV and the maximum operating time of the transformer in these conditions is determined by mutual agreement between customer and manufacturer, as in principle current transformers are not guaranteed to operate with the secondary open if the peak voltage is more than 3.5 kV peak.

3.10. SPECIAL VERSIONS OF CURRENT TRANSFORMERS

3.10.1. TRANSFORMERS WITH SEVERAL CORES

This could almost be called a normal variant, as most transformers are built with one core for measuring and at least one other for protection.

As many cores as desired may be built, provided the overall dimensions allows to be economically manufactured.

3.10.2. CASCADE TRANSFORMERS

These are built for high voltages, and divide the overall voltage into several steps.

Dielectrically, this is an interesting method, but from the point of view of precision it must be taken into account that the top core must supply the power for all the secondaries.

It is therefore difficult to make up a highly precise measuring secondary of a protection secondary with a high rated precision limit factor.

3.10.3. TRANSFORMERS WITH HIGH PRIMARY CURRENTS

There is local saturation in these transformers due to the off-centre position and shape of the primary bar and principally to the proximity of other bars which prevent high precision from being obtained.

To cancel out these defects, compensation windings must be introduced which ensure constant flow over the whole length of the core.



> 800 kV Current

3. CURRENT TRANSFORMERS

3.11. CHOOSING A CURRENT TRANSFORMER

To ensure that a facility runs properly the current transformer must be chosen carefully, bearing the following points in mind:

- 1. Type of facility: indoor or outdoor. If it is greater than 1000 m above sea-level, altitude is also a factor to be taken into account.
- 2. Insulation level: we recommend choosing as per the various standards.
- **3**. Rated transformation ratio: remember that double or triple ratios can be used and the range can be extended if necessary.
- 4. Precision class as per the various standards.
- 5. Rated power as per the various standards. We recommend not choosing too high a power level. If there is a big difference between the rated power and the power of the apparatus to be installed, a resistor in series can be fitted.
- 6. Rated safety factor (if necessary).
- 7. Rated precision limit factor (protection transformers).

- 8. Thermal and dynamic limit currents. These should not be set too high, as this could make the transformer much more expensive.
- 9. Rated frequency.
- 10. Number of secondaries (cores).
- 11. Construction details.

If there are TP type protection secondaries, the following should also be taken into consideration:

- 12. Line time constant (T_1) .
- 13. Short circuit characteristics (t', FRT, T_p).
- 14. Precision needed at I_n.
- 15. Precision needed during the transient period. This may refer only to the symmetrical component (TPZ) or also to the non-cyclic component (TPX, TPY).





4.1. GENERAL EQUATIONS

See fig. 2.3 and 3.1.

$$\begin{split} \bar{U}_{s} &= \bar{E}_{s} - R_{s}\bar{I}_{s} - jX_{s}\bar{I}_{s} \\ \bar{U'}_{p} &= \bar{E}_{s} + R'_{p}\bar{I'}_{p} + jX'_{p}\bar{I'}_{p} \end{split}$$

and given that:

$$\overline{I'}_{p=}\overline{I}_{s}+\overline{I}_{o}$$

it results as:

Therefore shows that that transformer errors in load are due to:

- > unloaded errors,
- > errors due to the secondary current through the short circuit impedance.

From Boucherot's formula we know that:

and since the error is small:

so if U'_p remains constant a voltage transformer will work at constant induction, even if the secondary load varies within admissible limits.

4.2. VECTORIAL DIAGRAM

From equation [4.1] the vectorial diagram of a voltage transformer can be obtained, as shown in fig. 4.1.

Starting from U_{s} , and as it is shown in the vectorial diagram of current transformers, we attain the lo of the magnetizing curves of the plate.



> Fig. 4.1



4.3. VOLTAGE AND PHASE ERRORS

A voltage error is an error introduced by the transformer in a voltage measurement, resulting from its transformation ratio not being exactly as the rated one.

The voltage error ε_{u} is expressed as a percentage, and is given by the formula:

$$\varepsilon_{u} \% = \frac{(K_{n} U_{s} - U_{p}) 100}{U_{p}}$$

where,

- K_n = is the rated transformation ratio.
- U_p = is the actual primary voltage.
- U_s['] = is the secondary voltage corresponding to U_s under measuring conditions.

The phase error of a voltage transformer $\epsilon_{\rm u}$ is the phase difference between the vectors of the primary and secondary voltage.

Both, the ratio error and the phase error are made up of the unloaded error plus the load error, as shown in fig. 4.1.

Fig. 4.2. shows the no-load triangles, which vary according to ${\rm U}_{\rm p}.$

The operating margin of the transformer in UNE, IEC and other standards is between 0.8 and 1.21 $\rm U_{pn}.$

Fig. 4.3 shows the errors given by the Kapp diagram according to $\cos \beta$, starting from the unloaded triangle at 0.8 U_{pn}.

To obtain the Kapp diagram at 1.2 U_{pn}, we have to start from point B on fig. 4.2, etc. If the variation in load is considered, we get figure 4.4, where it can be seen how errors vary according to voltage, to load and to $\cos \beta$ of the load.

Load errors are parallel lines whose angle depends on $\cos \beta$ of the load, as shown in fig. 4.4. Since ratio error is negative, for a number of turns equal to the rated transformation ratio, the error is usually centred by means of a correction in the ratio of the number of turns in order to make the best use of the core.

Fig. 4.5. shows how VT errors appear when the transformation ratio is correctly modified.





4.4. VOLTAGE TRANSFORMERS FOR MEASURING

4.4.1. DEFINITIONS

These are voltage transformers designed to power measuring devices, counters and similar equipment.

4.4.2. PRECISION CLASS

The precision class of a measuring voltage transformer is given by a number (class rate), representing the ratio error limit expressed as a percentage of the rated primary current, when the transformer is running at its "precision load".

This precision must be maintained for voltages between 80 and 120% of the rated level, with loads between 25 and 100% of the precision load.

Precision classes for voltage transformers are 0.1, 0.2, 0.5, 1 and 3.

Guide to applications: Class 0.1 - Laboratory.

- Class 0.2 Laboratory, portable reference patterns, high precision counters.
- Class 0.5 Normal counters and meters.
- Class 1 Panel apparatuses.
- Class 3 Uses where great precision is not required.

4.5. VOLTAGE TRANSFORMERS FOR PROTECTION

4.5.1 DEFINITIONS

These are voltage transformers for power protective relays.

If a VT is going to be used for both measuring and protection, two separate windings are not normally necessary as in the case of CTs, unless galvanic separation is required. Therefore in IEC standards VTs for protection are required to have a precision class, the same way as VTs for measuring.

On the same type of VT, precision power is greater when there is a single secondary than the sum of the precision power of each secondary if there are two, as the space given over to insulation of the two secondaries from each other must be considered.

The "residual voltage winding" is a winding intended to form an open triangle (together with the relevant windings of two other single-phase transformers) to supply residual voltage if there is a fault to earth.

Since the secondaries of a VT are interdependent, it must be specified whether the precision powers are simultaneous or not. as if one of the secondaries is under load only for short periods of time, then loads can be taken as nonsimultaneous.

4.5.2. ACCURACY CLASS

Except for residual voltage windings, VTs for protection must also be specified as VTs for measuring.

Accuracy class for protection VTs is given by a number that indicates the maximum error expressed in percentage. 5% of the rated voltage. This number is followed by the letter "P".

The usual accuracy classes are 3P and 6P.



4.6. BURDEN

It is defined at the same way as for current transformers (see section 3.7).

Table 4.1 indicates the normal consumption of the voltmeter coils, of devices powered by voltage transformers:

Table 4.1. Consumption of some devices connected to VTs					
Apparatuses	Approx. Consumption in VA				
Voltmeters					
Indicators	2 - 6				
Recorders	10 - 25				
Zero meters	5 - 20				
Wattmeters					
Indicators	1 - 4				
Recorders	3 - 15				
Phase meters					
Indicators	4 - 5				
Recorders	15 - 20				
Meters	3 - 5				
Frequency meters					
Indicators	1 - 5				
Recorders	10 - 15				
Relays					
Maximum voltage	10 - 15				
Timed maximum voltage or current	25 - 35				
Selective	2 - 10				
Directional	25 - 40				
Minimum voltage	5 - 15				
Earth contact	10 - 30				
Distance	10 - 30				
Synchronoscopes	6 - 15				
Voltage regulators	30 - 50				





4.7. SPECIAL VERSIONS OF VOLTAGE TRANSFORMERS

4.7.1. TRANSFORMERS WITH SEVERAL RATED PRIMARY VOLTAGES

These transformers can be made in four ways:

- > series-parallel coupling in the primary;
- > primary coil with taps;
- > series-parallel coupling in the secondary;
- > secondary coil with taps.

In the first two ways there are problems with insulation and with the use of the core, which limit their use basically to low voltage work, mainly reference patterns.

The secondary series-parallel system is used only if the two sections of the secondary winding have the same number of turns, otherwise there is an internal circulation current which absorbs power. The two sections must be insulated between them to at least 2 kV.

The secondary with taps system is very interesting specially when series-parallel systems are not possible or when the power requirements are the same for both versions.

Before choosing a transformer with these characteristics, it is better to consult the manufacturer in order to determine the most economical system.

4.7.2. TRANSFORMERS WITH SEVERAL RATED SECONDARY VOLTAGES

These can be made in two ways:

- > series-parallel coupling in the secondary;
- > secondary winding with taps

The series-parallel coupling in the secondary can only be used when the ratio is 2:1. It retains all the characteristics of a normal transformer regarding its possibilities.

When the voltage ratio is not 2:1, normally, the more used system is the secondary with taps.

4.7.3. CASCADE TRANSFORMERS

When the rated insulation voltage of a voltage transformer is high, it is difficult to achieve it with a single coil.

Cascade construction involves the distribution of the primary winding in several coils, with the secondary or secondaries on the last coil. This cascade construction means that each coil only has to withstand a fraction of the total voltage.

A cascade transformer is made up of one or more cores with 2 coils each. The core is rectangular shaped, and set to the potential average of the two coils.

The advantages of cascade voltage transformers include very small errors under no load, credit to the reduction of the impedance in the primary winding. Fig. 4.6 shows the circuit diagram of a cascade transformer with two cores and four coils.

4.7.4. TRANSFORMERS WITH SEVERAL SECONDARY WINDINGS

Voltage transformers can be built with several secondary windings on the same core. Although the load on each one will affect the others, the limitations found in current transformers do not apply here because of the safety and saturation factors.

In voltage transformers, with P2 to earth, which are to be installed in networks with no neutral to earth, it is advisable to fit a tertiary (i.e. a second secondary) to protect the transformer against ferro-resonance (see point 4.9).

The increase in the cost of the transformer due to this secondary is generally small.





4.8. LINE DISCHARGE VOLTAGE TRANSFORMERS

When a high voltage line is isolated by opening the circuit breakers, the capacitative energy stored in it may cause voltage overloads on reconnection.

There are several procedures for discharging lines, but experience has shown that VTs do this job well if they are sized properly. If not, discharging may not be fast enough or the VTs may be damaged by heat or dynamic effects.

In a simplified study of this problem, considering that when the VT is not saturated, the discharge current is insignificant and the line voltage is constant. When saturation takes place, the reactance decreases to the value of the primary winding in air, L. In this case the circuit to be considered is shown in figure 4.7.a, where C is the line capacity and R the resistance of the primary winding of the VT.

If $R^2 C > 4L$, discharge is non-cyclic and slow. If R² C < 4L, discharge oscillates, as indicated in fig. 4.7b.

As regards to heating, it is considered that all the energy stored in the line goes to heating the copper of the VT primary. This energy is:

$$W = \frac{1}{2} CV^2$$

where V is the line voltage on opening.

As regards to mechanical stress, the maximum discharge current must be taken into consideration.

In the oscillation case this is:

$$i_{max} = \frac{V}{Lw_1} e^{-\frac{R\pi}{4L_{w_1}}}$$

where

$$W_1 = \frac{\sqrt{4L - R^2 C}}{2 L C}$$

is the natural pulse of the circuit.

To calculate the times t_1 (saturation of the VT) and t, the following formulae may be used:

$$t_1 = \frac{B \text{ sat } x \text{ N}_1 x \text{ S}}{V} \text{ x 10}^{-8}$$
 [Sec.]

where:

V

- B sat = is the saturation induction (Gauss).
- = is the number of turns in the primary N_1 winding. S
 - = is the core cross section (cm²).
 - = is the initial discharge voltage (V).







4.9. OVERVOLTAGES

Like other devices installed on the high voltage side, voltage transformers are subjected to a series of overvoltages. It must withstand these without damaging its insulation. Remember that all transformers (both voltage and current) are tested for one minute at the test voltage and at industrial frequency, and are able to withstand the test voltage with shock wave, that corresponds to their level of insulation.

As an example, a measuring transformer with a rated insulation voltage of 72.5 kV rms and with a working voltage of U_s = 72.5 / $/\sqrt{3}$ = 42 kV rms, is tested at 140 kV rms (3,3 U_s) for one minute, and has to withstand 325 kV peak (5.5 U_s) of lighting impulse.

However, in voltage transformers, series or parallel ferroresonance (depending on the network-transformer characteristics) is not an uncommon phenomenon.

This is a complex phenomenon, as it may be single or three-phase, and may occur at the fundamental, harmonic or sub-harmonic frequencies. Let us see what series and parallel ferro-resonances are.

4.9.1. SERIES FERRO-RESONANCE

Assuming that in the circuit in fig. 4.8a, where the capacity C and the saturatable inductance of the VT are in series, C is such that the straight line I/wC cuts UL at point M. (fig. 4.8b).

If the rated voltage is U₁, the point of operation is A with a current of I₁. When there is an overvoltage, greater than U₂, we go from point A through B and C to D. When the voltage drops again to U₁, the new point of equilibrium is E, where I'₁ >> I₁. If this new situation lasts for a long time the VT overheats, and it may even burn.

To return to point of equilibrium A the voltage in the network must be reduced or the VT must be loaded so that the ferro-resonance is damped.

This phenomenon arises in capacitative voltage transformers. It may also arise in a 3-phase network with neutral to earth with one phase open if the capacity is high (e.g. a circuit breaker with a distribution capacitor).







4.9.2. PARALLEL FERRO-RESONANCE

Fig. 4.9a shows a parallel circuit. Fig. 4.9b is similar to fig. 4.8b, with I and U swapped.

Now, when ferro-resonance is analyzed, we assume that equilibrium is established for I = I₁. Due to overvoltage or overcurrent we go, as in the series case, to point D and then E, where U'₁ >> U₁ and there is a permanent overvoltage.

If we want this to happen in a 3-phase network, the neutral must be insulated. The shift of the neutral, respect to earth, causes an overvoltage in one or two VTs which may be greater than the compound voltage.

To avoid or dampen this phenomenon, it is necessary to place a suitable resistor in the open triangle of the tertiaries of the VTs, as shown in fig. 4.10. Between 25 Ω and 50 Ω is an usual value.



> Fig. 4.9



> Fig. 4.10



 > 123 kV Inductive Voltage Transformers. Transpower zzvvv(New Zealand)



4.10. OPERATION OF VOLTAGE TRANSFORMERS WITH SHORT-CIRCUITED SECONDARIES

The "rated thermal burden" of a VT is the maximum power which can be supplied on a permanent basis without the heating limits being exceeded, when the secondary voltage is the rated one.

If the secondary load is higher than the rated thermal burden, the VT may be damaged, unless operating time is limited.

When the secondary circuit is shorted, the secondary current is only limited by the internal impedance of the VT. The VT can only operate for very short periods in these conditions. Some standards require this time to be at least 1 second.

The VT can be protected by placing fuses or circuit breakers in the secondary circuit, but it beware that if these devices fail, the substation protection system may operate incorrectly.

Since most VT failures, involving secondary short circuits, are caused by incorrect connection of this circuit, it is very practical to fit provisional fuses until it can be checked that installation is correct.

4.11. CHOOSING A VOLTAGE TRANSFORMER

By choosing a voltage transformer, consider the following points:

- 1. Type of service: indoor or outdoor. Altitude is also a factor to be considered, when it is higher than 1.000 m above sea level.
- 2. Insulation level.
- 3. Rated transformation ratio.
- 4. Precision class.
- 5. Precision power.
- 6. Voltage factor.
- 7. Rated frequency.
- 8. Number of secondaries.
- 9. Construction details.



5. OTHER INSTRUMENT TRANSFORMERS

5.1. COMBINED INSTRUMENT TRANSFORMERS

These are units which contain a voltage transformer and a current transformer in the same casing. This system has cost-effective advantages, especially for high voltage units where porcelain accounts for much of the cost of instrument transformers.

It is also important for cases where as little space as possible needs to be occupied at the sub-station. When designing combined units, the influence of CTs on the errors in VTs and vice versa must be considered. The standard gives the maximum admissible levels of influence.

> 72.5 kV Combined Transfores at subestation line imput. L'ONEE (Morocco)





5. OTHER INSTRUMENT TRANSFORMERS

5.2. CAPACITIVE VOLTAGE TRANSFORMERS (CVTS)

5.2.1. DEFINITIONS

These are voltage transformers made up of a capacitance divider and a electro-magnetic element.

Additionally,

$$U_{P} = U_{1} \frac{C_{1}}{C_{1} + C_{2}}$$

The capacitance divider (CD) is made up of two capacitors, C_1 and C_2 , connected in series as shown in fig. 5.1 to obtain an intermediate voltage terminal. An inductance L_1 is connected to this terminal, along with an inductive intermediate voltage transformer (IVT).

5.2.2. CVT OPERATION

Fig. 5.2 shows the equivalent circuit diagram of a CVT. The diagram is similar to fig. 2.3, given that R'_p now represents the resistance of the windings of the IVT and the inductance L_1 , the iron losses of L_1 and the dielectric losses of C_1 and C_2 and X'_p represents the reactance due to the capacitance C_1+C_2 , to the inductance L_1 and to the IVT primary.

The response of a CVT in transient state is not as fast as that of an inductive VT, and in some cases fast protection requirements mean that CVTs cannot be used.

However, apart from their measuring and protection uses, CVTs also enable high voltage lines to be used for communication via high frequency carrier currents.



> Fig. 5.1



> Fig. 5.2

 550 kV Capacitive Voltage Transformer. UTE (Uruguay)





6. DIELECTRIC INSULATION

6.1. INSULATION OF INSTRUMENT TRANSFORMERS

From a dielectric point of view, the instrument transformer, like all electric machines, develop as new materials and new requirements appear. In our brief analysis in the development of instrument transformers (ITs) we shall consider three cases: a) low voltage; b) medium voltage; and c) high and very high voltage.

In low voltage the dielectric problem is minimal. The insulations used depend on other requirements, such'as: thermal class, mechanical resistance, etc. Modern materials can be used, include insulating band (e.g. Mylar), epoxy and polyurethane resins for moulded ITs, thermoplastics (ABS, etc) and thermosetting plastics (phenolic resins, etc.) for housing.

In medium voltage (e.g. up to 72.5 kV) for indoor use synthetic resins have enabled the size of ITs to be reduced considerably as they both insulate the primary from the core and the secondary and provide and insulating surface between HV and LV in air.

For outdoor use, cyclo-aliphatic resins have come to replace porcelain in some cases due to their high resistance to surface currents and the possibility of obtaining large leakage paths. Experience has shown that these resins are suitable for outdoor service, except in heavy conductive atmospheric pollution. In VTs mineral oil is still used to some extent as an inside insulator due to the excellent impregnation of coils obtained. If resin is used as an outside insulator, insulating gas (e.g. SF6) is used to impregnate the coils. To prevent partial discharges the main insulator must be without pores. This is hard to achieve in VT coils if impregnation is not suitable.

In high and very high voltage, either porcelain or an insulator consisting of fibre glass and silicon sheds are used for external insulation and paper-oil or SF6 gas for internal insulation.

An important point in oil paper insulation is the drying of the paper and its impregnation with oil.

During drying vacuum is maintained, which brings the moisture content of the paper to below 0.2%.

Without losing the vacuum, the paper is then impregnated with mineral oil which has also been dried in a vacuum. This makes for partial discharge levels well below the limits set by standards. Tg δ is less than 0.3%.

To improve the use of this dielectric, the electrical field must be studied carefully, avoiding areas with high gradients.





6.2. INSULATION TESTING

To ensure correct operation, all transformers are subjected to various tests before leaving the factory. Those related with the dielectric problem may be individual tests, type tests or special tests.

In type tests the design of the transformer in general is checked out. These tests can be avoided (with the agreement of the customer) if the manufacturer presents a test certificate for transformers of the same or similar model.

In individual tests the insulation of each transformer is tested. These tests may feature the following:

- 1. Dielectric test at industrial frequency between high voltage and low voltage.
- 2. Partial discharge test and tangent of loss angle.
- 3. Various dielectric tests at industrial frequency between nearby insulated elements.

The first test consists of subjecting the insulation between HV and LV to voltage gradients far higher than those it will encounter in service for a short period (generally one minute). This is a classic test which enables a certain safety coefficient to be guaranteed in the insulation.

However transformers which have been subjected to this test often have shorter lifetimes than expected. This may be due to small faults in the insulation which could not be detected, and which cause premature aging. Success in dealing with this major problem has been achieved by performing partial discharge tests.

The main test in the second group is the partial discharge test, consisting of detecting the small discharges which occur between the walls of the cavities in the insulation when it is faulty.

Fig. 6.2a shows a faulty dielectric subjected to A/C voltage. The voltage between the opposing walls of the cavity is greater than that of the contiguous insulator, due to the lower dielectric constant of the gas. Furthermore its rigidity is lower than that of the rest of the insulator, especially if there is some degree of vacuum (Paschen's law).

This results in discharges between the ends of the cavity at a working voltage well below that of the rigidity of the insulator, which discharges gradually damaging the insulator. These are high frequency discharges, and can be detected as indicated in fig. 6.2b, where C_1 is the capacitance of the dielectric in parallel with the cavity, C_2 is the capacitatance of the cavity and C_3 is that of the dielectric in series with it. Capacitance C_k (coupling) serves to detect the apparent partial discharge in impedance Z more easily.

There are various procedures set down in IEC 60270 standard, but the most suitable for ITs is the measuring of the apparent discharge in pC. At ARTECHE, we have been measuring partial discharges in transformers for 50 years.

This is a non-destructive test, so improvements in insulation as treatments are given can be checked out. This test also enables us to check whether the dielectric test at industrial frequency has damaged the insulation, by comparing the level of partial discharges before and after that test.

The tangent of angle of loss test $(Tg\delta)$ is an excellent indicator of treatment quality in oil paper transformers, and reveals any changes in insulation during service.

The third group of tests includes tests to check insulation between insulated coils on the same winding, between secondaries, etc.

Finally, chromatic analysis of the gases dissolved in oils can be carried out on high voltage transformers which have been in service for some time. This test can pick up any thermal, partial discharge or other anomaly before the insulation fails completely. However it can only be performed in specialist laboratories and is costly.





7. STANDARDS

7.1. STANDARDS CONSULTED

Consulted standards are: IEC 61869 y IEEE C57.13

7.2. INSULATION LEVELS

Table 7.1 shows the insulation levels according to the different standards.

Some standards also include chopped lighting impulse waves and tests in wet conditions.

Lightning impulse voltage pertains to a wave of 1.2/50 µs and switching impulse is for 250/2500 µs. These are type tests.

Table 7.1

	IE	c				IEEE		
	Rate	ed Insulation L	.evel			Rate	d Insulation L	evel
Highest voltage kVrms	Power- frequency (kV)	Lightning impulse (kVp)	Switching impulse (kVp)	Highest Voltage (kV)	Rated Voltage (kV)	Power- frequency (kV)	Lightning impulse (kVp)	Switching impulse (kVp)
0.72	3	-	-	0.66	0.6	4	10	-
1.2	6	-	-	1.2	1.2	10	30	-
3.6	10	20 / 40	_	2.75	2.4	15	45	-
7.2	20	40 / 60	-	5.60	5.0	19	60	-
12	28	60 / 75	-	9.52	8.7	26	75	-
17.5	38	75 / 95	-	15.5	15	34	95/110	-
24	50	95 / 125	-	25.5	25	40/50	125/150	-
36	70	145 / 170	-	36.5	34.5	70	200	-
52	95	250	-	48.3	46	95	250	-
72.5	140	325	-	72.5	69	140	350	-
100	185	450	-					
123	185 / 230	450 / 550	-	123	115	185/230	450/550	-
145	230 / 275	550 / 650	-	145	138	275	650	-
170	275 / 325	650 / 750	-	170	161	325	750	-
245	395/460	950/1050	-	245	230	395/460	900/1050	-
300	395 / 460	950 / 1050	750 / 850					
362	460 / 510	1050 / 1175	850 / 950	362	345	575	1300	825
420	570 / 630	1300 / 1425	950/1050					
550	630 / 680	1425 / 1550	1050 / 1175	550	500	750/800	1675/1800	1175
800	880/975	1950/2100	1425/1550	800	765	920	2050	1425

7.3. ENVIRONMENTAL CONDITIONS

In IEC standard normal temperature limits for outdoor service go from -40° C to $+40^{\circ}$ C (-40/40; -25/40; -5/40 categories) although it is also possible, as special condition, reaching from -50° C to $+50^{\circ}$ C (-50/40; -5/50 categories).

In the IEEE the normal limits for the temperature are -30 and $+50^{\circ}$ C although it is also possible different values as special conditions.

In both cases the normal altitude is below 1000 m. For higher altitudes external insulation must be increased.

Table 7.2 gives the minimum levels for the creepage distance.

Table 7.2

Pollution level	Minimum nominal specific creepage distance (mm/kV between phases)
l Light	16
II Medium	20
III Heavy	25
IV Very heavy	31



7.4.1. RATED PRIMARY CURRENTS

As per IEC

a. Single ratio transformers:

<u>10</u> - 12.5 - <u>15</u> - <u>20</u> - 25 - <u>30</u> - 40 - <u>50</u> - 60 - <u>75</u>

and their multiples or decimal submultiples. The preferential figures are underlined.

b. Multiratio transformers:

The standard values given in a) refer to the lowest values of rated primary current.

7.4.2. RATED SECONDARY CURRENTS

In general 1 and 5 A are considered, with the last one being the preferential level.

Also other levels are admited, especially 2A. and, in CTs which are to be connected in a triangle, the above levels may be divided by $\sqrt{3}$.

7.4.3. CONTINUOUS THERMAL CURRENTS

The current transformer must withstand its rated continuous thermal current without exceeding in the winding the admissible temperature for the relevant thermal class of the insulation.

The IEC standard admits as many heating limits as classes of insulation. IEEE/ANSI admits three types of transformers from the temperature rise point of view: the 55 and 65°C temperature rise type in both 30 and 55°C ambient temperature and the 80°C increase for dry insulation.

Table 7.3 shows continuous thermal rated heating current rating factors according to different standards expressed as number of times the rated current.

IEEE/ANSI also specifies the variation in thermal limit current (RF) according to ambient temperature.

7.4.4. STANDARD BURDENS

The IEC standards admit the following rated burdens expressed in volt-amperes:

2.5 - 5 - 10 - 15 - 30 and greater. Power factor $\cos \beta = 0.8$

The IEEE/ANSI standard expresses the burdens in a different way. They are:

B-0.1, B-0.2, B-0.5, B-0.9, B-1.8, B-1, B-2, B-4 y B-8

where the number appearing after the letter B (burden) indicates the impedance in Ohms at 60 Hz. Burdens B-0.1, B-0.2, B-0.5, B- 0.9 and B-1.8 are used for measuring with cos β = 0.9, and B-1, B-2, B-4 and B-8 are used for protection with cos β = 0.5.

Table 7.4 shows the approximate equivalence between IEC and IEEE/ANSI burdens.

Table 7.3

Extended current ratings							
IEC	IEEE/ANSI						
1	1						
1.2 - 1.5 - 2	1.33 - 1.5 - 2 - 3 - 4						
	3 - 4						

Table 7.4

Equivalence of IEC and IEEE/ANSI burdens							
IEC	IEEE/ANSI						
2.5 VA	B-0.1						
5 VA	B-0.2						
15 VA	B-0.5 (≈ 12.5 VA)						
20 VA	B-0.9 (≈ 22.5 VA)						
30 VA	B-1 (≈ 25 VA)						
40 VA	B-1.8 (≈ 45 VA)						
50 VA	B-2						
100 VA	B-4						
200 VA	B-8						



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7.4.5. ACCURACY CLASSES FOR MEASURING CURRENT TRANSFORMERS

Tables 7.5, 7.6, 7.7 and figures 7.1 y 7.2 show the maximum errors admitted by IEC and IEEE standards.

Table 7.5

IEC standard												
	± Percentage current (ratio) error at percentage of					± Phase displacement at percentage of rated current shown below						
Accuracy class	rated current shown below			Minutes					Centiradians			
	5	20	100	120	5	20	100	120	5	20	100	120
0.1	0.4	0.2	0.1	0.1	15	8	5	5	0.45	0.24	0.15	0.15
0.2	0.75	0.35	0.2	0.2	30	15	10	10	0.9	0.45	0.3	0.3
0.5	1.5	0.75	0.5	0.5	90	45	30	30	2.7	1.35	0.9	0.9
1.0	3.0	1.5	1.0	1.0	180	90	60	60	5.4	2.7	1.8	1.8

Table 7.6

IEC standard (Extended range)															
	± Percentage current (ratio) error at			± Phase displacement at percentage of rated current shown below											
Accuracy class	percentage of rated current shown below			Minutes				Centiradians							
	1	5	20	100	120	1	5	20	100	120	1	5	20	100	120
0.2 S	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
0.5 S	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

Table 7.7

IEEE/ANSI standards								
Accuracy class	± Percentage current (rat rated current	io) error at percentage of shown below	± Phase displacement at p shown	ercentage of rated current below				
	100 (**) 10		100 (**)	10				
0.3	0.3	0.6	15	30				
0.6	0.6	1.2	30	60				
1.2	1.2	2.4	60	120				

(*) The permitted ratio and phase errors are inter-dependent. With the data in the table a graph must be made up along the lines of fig. 7.2a, and only those errors within the parallelogram must be admitted.

(**) These figures must be complied with also for RF (see 7.4.3).

The power factor may vary between 0.6 and 1.

IEEE Standard for High-Accuracy Instrument Transformers IEEE C57.13.6 defines higher accuracy classes that extend the accuracy range beyond the traditional IEEE C57.13 requirements stated above.

- > "High Accuracy Class 0.15" means that from 100% of nominal current through the rating factor, accuracy is guaranteed to be $\pm 0.15\%$, and from 5% of nominal current through 100% of nominal current accuracy is guaranteed to be $\pm 0.3\%$.
- > "Accuracy Class 0.15S" means that from 5% of nominal current through the rating factor, accuracy is guaranteed to be 0.15%.
- > "High Accuracy, Extended Range Class 0.15" means that from 1% of nominal current through the rating factor, accuracy is guaranteed to be $\pm 0.15\%$





7.4.6. PRECISION CLASSES IN CURRENT TRANSFORMERS FOR PROTECTION

The IEC standard admits the classes and errors indicated in Table 7.8. Secondaries must be loaded to their rated precision power

The IEEE/ANSI standard admits classes C, K and T for current transformers for protection. Class C and K transformers are those whose coils are evenly distributed, and therefore have unimportant flow losses. The errors of these transformers can be determined by calculation. K classification shall have a condition in its Knee-point voltage.

All (classes C, K and T) transformers must have ratio errors of less than 10% at 20 In. They are designated by a C, K or T followed by a figure representing the secondary voltage in overcurrent operation. For instance C100 indicates that at 20 Isn = 20x5 = 100A, the voltage in the secondary terminals is 100V (so, the burden is therefore 1 Ohm).



7.4.7. SHORT CIRCUIT CURRENTS

Network short circuit currents cause thermal and dynamic problems in transformers.

If I_{cc} is the short circuit current of the network and t its maximum duration in seconds (between 0.5 and 5 sec.), the thermal limit current of the transformer expressed for 1 sec. must meet the following condition:

$$I_{th} \ge I_{cc} \sqrt{t}$$

 $\mathrm{I_{th}}$ and $\mathrm{I_{cc}}$ are rms values.

The dynamic effect is due to the maximum amplitude of the short circuit current wave. Some standards therefore link the thermal and dynamic currents in the worst case.

IEC requires:

$$I_{dvn} \ge 2.5 I_{th}$$

In IEEE/ANSI standard current is expressed as the peak level of the symmetrical component of a fully shifted wave.

Therefore:

$$I_{dvn} = 2 \times \sqrt{2} \times I_{th} = 2,83 I_{th}$$

Та	b	e	7.	8

IEC standard								
Current error at rated		Phase displacement at	rated primary current	Composite error at rated accuracy				
Accuracy class	primary current %	Minutes	Centiradians	limit primary current %				
5P	± 1	± 60	± 1.8	5				
10P	± 3	-	-	10				





7.4.8. TERMINAL MARKINGS AND DESIGNATION

Terminals must be marked clearly and indelibly on the surface or in their immediate proximity. Terminal designation varies from one standard to another. Table 7.9 shows some examples.

The IEEE/ANSI standard requires the letter H to be used for the primary and X for the secondary. If there are several secondaries Y,Z,V, etc. may be used. Polarity is indicated by a number after each letter, e.g. H1, H2, X1, X2, etc. with the odd numbers representing terminals of the same polarity.

7.4.9. DATA TO BE SHOWN ON THE RATING PLATE

IEC standards require all current transformers to show at least the following data:

- a. Manufacturer's name or an indication enabling the manufacturer to be easily identified
- Serial number or type of apparatus and b. manufacture date/year.
- Rated transformation ratio in the following С. form:

 $K_n = I_{pn} / I_{sn}$ (e.g.: $K_n = 100/5$) d. Rated frequency. (Hz)

- e. Rated output, accuracy class and corresponding terminal designation for each winding.
- f. Highest voltage for equipment and its rated insulation level.
- g. Rated short-circuit thermal and dynamic currents in kA.
- h. Weight in kg.
- Service temperature. i.,
- Mechanical class. i.

In low voltage transformers f) and g) are not compulsory.

Current transformers for measuring must also indicate, if relevant, the instrument security factor (in the form $Fs \le x$) for the indicated burden.

Extended range transformers must show the continuous thermal current rating factor after the accuracy class (e.g. 15VA class 0.5 extension 150%).

Current transformers for protection must also show the accuracy limit factor (e.g. 30VA class 5P10).

7.4.10. INDIVIDUAL OR **ROUTINE TEST**

These are tests to which all transformers are subjected to. The IEC standard considers the following as routime tests:

- a. Checking of terminal markings. This consists of checking that the terminals are correctly marked.
- b. Power frequency withstand test on the primary winding. The insulation must withstand the power frequency voltage corresponding to its insulation level for one minute. This voltage is applied between the primary and the secondary winding(s) connected to earth (see Table 7.1). If the primary winding is subdivided into two or more sections, each section must withstand a rms voltage of 3kV between itself and all the other sections for one minute
- c. Power frequency withstand test on secondary windings. Each secondary winding must withstand a rms voltage of 3kV between itself and the other secondary windings connected to earth. for one minute.
- d. Inter-turn Overvoltage test. This involves checking the secondary winding(s) for one minute at the induced voltage (if its peak value is less than 4.5 kV), supplying the primary winding at its rated current and with the secondary open, or vice versa. If the voltage appearing in the secondary terminals is greater than 4.5 kV peak this voltage is used for the test.





7. STANDARDS

e. Accuracy tests. In current transformers for metering and relaying the tests are run to check compliance with the relevant standards.

In current transformers for protection, compound error tests must be run using the excitation method, which consists of determining the excitation current (for the rated frequency), applying a practically sinusoidal voltage to the secondary at a level equal to the product of the accuracy limit factor by the rated secondary current and by the vectorial sum of the burden impedance and the transformer secondary winding impedance.

f. Partial discharges. This requirement is applicable to current transformers having Um not less than 7.2 kV.

Table 7.10 shows the IEC limits of partial discharge level (in pC) that must not be exceeded at the voltage indicated after a prestressing of 100 or 80% of the power-frequency withstand voltage.

7.4.11. TYPE TESTS

These are tests to which only one transformer, of each model are subjected. These tests need not be performed if the manufacturer submits test certificates for similar transformers which are acceptable to the purchaser.

According to the IEC standard these tests are the following:

 Short-time current test. This consists of checking the resistance of transformers to the rated thermal and dynamic currents.

These tests are always expensive to perform. So, they are generally taken as passed in thermal aspect if the density adopted by the manufacturer is no higher than 180 A/mm², if cooper and 120 A/mm² if aluminium, and in dynamic aspect if the manufacturer has tests for other models of similar size and mechanical attachment to those in question.

- b. Temperature rise test. The transformer must withstand a primary current equivalent to its continuous thermal current as per 7.4.3 permanently, without exceeding its temperature rise limits, under normal operating conditions.
- c. Lightning and switching impulse test.

Normally, for lightning impulse test, 15 consecutive pulses of positive and negative polarity with full waves of 1.2/50 μ s are applied and, for switching impulse test, 15 full positive pulses of 250/2500 μ s. Although, when the highest voltage of the material is \geq 300 Kv only 3 pulses of both polarities are necessary in the lightning impulse test.

d. Wet tests for outdoor type transformers. These tests are aimed at checking the validity of the external insulation.

According to the highest voltage of the material, power frequency or switching impulse test are applied.

- e. Radio interference voltage measurement. Test for the appearance of the corona effect (external discharges) and its limitation so as not to disrupt radioelectric transmissions.
- f. Accuracy tests. In current transformers for measuring the checking of the accuracy class at all the levels indicated in the relevant table may be taken as a type test.

			Permissible	Permissible PD level/pC	
Type of transformer and connection	Type of earthing of the system	PD test voltage (kV rms)	Type of insulation		
			Liquid	Solid	
Phase-to-earth voltage and current transformers	Earthed neutral	Um	10	50	
	system	ystem 1.2 Um / √3	5	20	
	Isolated or non-effectively earthed	1.2 Um	10	50	
		1.2 Um / √3	5	20	
Phase-to-phase voltage transformers	Earthed neutral system	1.2 Um	5	20	
	Isolated or non-effectively earthed	1.2 Um	5	20	

Table 7.10



Also it must be checked that the transformer met the instrument security factor using the overcurrent or excitation methods in a similar way as the accuracy limit factor of protective transformers.

In current transformers for protection the checking of compound error by the primary overcurrent method or by the excitation method is treated as a type test.

7.4.12. SPECIAL TESTS

Tests which must be arranged by the manufacturer and the buyer and are usually quite expensive. They are designer tests which justify the behaviour of a certain transformer family. According to the IEC standard, they are the following:

- a. Chopped lightning impulse. Two chopped waves are inserted in combination with the negative polarity lightning impulse test.
- Mechanical tests. The transformers must withstand static mechanical stresses (table 7.11) which comprise service demands including those due to wind and ice.
- c. Multiple chopped impulses. A test which verifies the appropriate behaviour of electric field distribution screens before high-frecuency waves derived from disconnector operations. 600 reduced value (70%) negative polarity chopped impulses are applied with gas dissolved in oil testing before and after their application. The criterion to assess if the design is valid or not is the in gas concentrations.
- d. Overvoltage transferred to secondaries. This test indicates the electromagnetic compatibility of a tranformer. By applying a step impulse in the high voltage part it is possible to verify which percentage passes to the low voltage part.

- e. Internal arc test. This test is performed on a real transformer, equipped with all accessories and in service conditions. An internal fault in the transformer is made and a current that will cause the explosion of the transformer is applied. Both the value and duration of this current, the type of fault caused and criteria to pass this test are set out in IEC 61869-1, but some other criteria agreed between customer and manufacturer can be used.
- Measurement of capacitance and tg δ . f. These two measurements are made together, before and after dielectric test at 50 Hz and 10 kV and Um/ $\sqrt{3}$. Capacitance measurement test checks consistency of production. There are no limits as each design has its own value, acceptance criteria for this test is that there should be no significant variation in the different measures. The δ test checks quality of the drying process, which influence in new transformers, the dielectric dissipation factor of the insulation. The recommended limit in the standard is 0.5%. In Arteche this test is a routine test for 100% of the production.

Table 7.11

Static withstand test loads				
Highest voltage for the equipment U	Static withstand test load $F_{R}^{}(N)$			
kV	Load Class	Load Class II		
72.5 a 100	1,250	2,500		
123 a 170	2,000	3,000		
245 a 362	2,500	4,000		
> 420	4.000	6.000		



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7.5. VOLTAGE TRANSFORMERS

7.5.1. RATED PRIMARY **VOLTAGES**

Table 7.12

12 175

24

36

52

72.5

123

145

245

420

550

IEC standard Insulation rated voltage Rated primary voltage

11,000

13,200 - 16,500

22,000

27,500 - 33,000

44,000

55,000 - 66,000

110,000

132,000

220,000

380,000 - 400,000

500,000

The values for rated primary voltage are	ir
IEC 60038. Some of these values can be see	er
in Table 7.12	

In single phase voltage transformers which can only be connected between phase and earth, the standardized allocated primary voltages are taken to be the figures indicated divided by $\sqrt{3}$.

In IEEE/ANSI standard other figures are given, and 5 groups of voltage transformers are available:

Group 1: Transformers which can be connected line-to-line in a system with voltage U_n, or lineto-ground in a system with voltage $\sqrt{3}U_{n}$.

Group 2: Transformers which can be connected line-to-line or line-to-ground, both in a system with voltage U_.

Group 3-4-5: Transformers which can be only for line-to-ground connection.

7.5.2. ALLOCATED SECONDARY **VOLTAGES**

Many standards allow the same figures. IEC groups them as follows:

For single phase transformers used in single phase networks or between phases of 3-phases networks:

- a. Based on usual practice in a group of European countries: 100V and 110V 200V for extended secondary circuits.
- b. Based on usual practice in the USA and Canada: 120V for distribution systems. 115V for transmission systems. 230V for extended secondary circuits.

For single phase transformers to be used phase-to-earth in 3-phase systems where the rated primary voltage is a number divided by $\sqrt{3}$, the rated secondary voltage should be one of the figures indicated divided by $\sqrt{3}$, thus retaining the rated transformation ratio.

> Dielectric test in H.V. laboratory





7.5.3. TRANSFORMATION RATIOS

All the standards aim to give a simple value for transformation ratio. The IEC standard therefore recommends that the rated transformation ratio be one of the following:

> 10-12-15-20-25-30-40-50-60-80 and their decimal multiples.

7.5.4. RATED VOLTAGE FACTOR

This is the factor by which the rated primary voltage must be multiplied to determine the maximum voltage for which the transformer must comply with heating specifications, during the indicated time, and the accuracy specifications.

Table 7.13 shows the standardized figures for the voltage factor admitted by the IEC standard.

IEEE/ANSI gives a voltage factor fo 1.1 for all voltage transformers in general, as far as precision and heating problems are concerned.

For group 1 and 3 transformers voltage factors of 1.25 are reached in continuous service and 1.73 for 1 minute, under certain temperature and load conditions.

7.5.5. TEMPERATURE-RISE LIMIT

According to the IEC standard the temperaturerise of a transformer in continuous service should not exceed the levels indicated for the relevant insulation class for a voltage factor of 1.2. If the voltage factor is 1.5 or 1.9 they must be tested at the resulting voltage for the time indicated in Table 7.14, starting from stable thermal conditions attained at 1.2 times the allocated primary voltage and without exceeding the admissible temperature increase by more than 10°C.

7.5.6. RATED OUTPUT

The IEC standard gives the following rated output for a power factor of 0.8 lagging, expressed in volt-amperes:

<u>10</u>-15-<u>25</u>-30-<u>50</u>-75-<u>100</u>-150-<u>200</u>-300-400-<u>500</u> The preferential figures are underlined.

IEEE/ANSI admits the standard levels indicated in Table 7.14.

Table 7.13 Standard values of rated voltage factors

Rated voltage factor	Rated time	Method of connecting the primary winding and system earthing conditions
1.2	Continuous	Between phases in any network Between transformer star-point and earth in any network
1.2	Continuous	Retween phase and earth in an effectively earthed neutral system (Sub-clause 4.23 a)
1.5	30 s	Between phase and earth in an enectively earthed neutral system (Sub-clause 4.25 a)
1.2	Continuous	Between phase and earth in a non-effectively earthed neutral system
1.9	30 s	(Sub-clause 4.23 b) with automatic earth fault tripping
1.2	Continuous	Between phase and earth in an isolated neutral system without automatic earth fault
1.9	8 h	automatic earth fault tripping

Table 7.14

Designation	Voltamp.	Power factor
W	12.5	0.10
X	25	0.70
Y	75	0.85
Z	200	0.85
ZZ	400	0.85
M	35	0.20



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7.5.7. ACCURACY CLASSES FOR MEASURING VOLTAGE TRANSFORMERS

Under the IEC standard voltage transformers must meet their accuracy class requirements for any voltage between 80 and 120% of rated voltage and with burdens between 25 and 100% of the rated burden at a power factor of 0.8 lagging.

Table 7.15 shows the limits of voltage error and phase displacement according to accuracy class.

The maximum admissible errors under the IEEE/ANSI standard are for points within the parallelograms of fig. 7.3. This requirement must be met for burdens from zero to rated burden and for voltages from 0.9 to 1.1 Un, with a power factor between 0.6 lagging and 1.

Fig. 7.4 shows the limits of error under the IEC standard for precision classes 0.5 and 1.

7.5.8. PRECISION CLASSES IN VOLTAGE TRANSFORMERS FOR PROTECTION

The IEC standard admits the classes and limits shown in Table 7.16. Errors must not exceed the levels in the table at 5% of the rated voltage and at the product of the rated voltage by the voltage factor (1.2, 1.5 or 1.9) for any load between 25 and 100% of the rated load with a factor of 0.8 inductive.

At 2% of rated voltage, the error limits will be twice as high as those indicated in table 7.16, with the same burden conditions.

7.5.9. RESISTANCE OF VOLTAGE TRANSFORMERS TO SHORT CIRCUITS

When there is a short circuit in the secondary terminals transformers suffer mechanical and thermal stress.

Standards specify that all voltage transformers must be able to withstand a secondary short circuit for one second without exceeding termperature limits when energized at rated voltage.

Table 7.15. Limits of voltage error and phasedisplacement

Class	Percentage voltage (ratio) error ±	Phase displacement ±	
0.1	0.1	5	
0.2	0.2	10	
0.5	0.5	20	
1	1.0	40	
3	3.0	Not specified	



> Fig. 7.3



> Fig. 7.4

Table 7.16.Limits of voltage error and phase displacement

Class	Percentage voltage (ratio) error ±	Phase displacement ± min.
3 P	3.0	120
6 P	6.0	240



7.5.10. TERMINAL MARKINGS

Table 7.17 shows some examples of terminal markings as per IEC.

The designation indicated in 7.4.8. for current transformers under IEEE/ANSI also applies to voltage transformers.

7.5.11. DATA TO BE SHOWN ON THE ID PLATE

The IEC standard requires to show the following data:

- a. Manufacturer's name or an indication enabling the manufacturer to be easily identified.
- b. Serial number and manufacture date/year.
- c. Type of apparatus.
- d. Rated primary and secondary voltages.
- e. Rated frequency.
- f. Rated output, the corresponding accuracy class and terminal marking for each winding.
- g. Highest system voltage for the material and its rated insulation level, separated by diagonal strokes.
- h. Rated voltage factor, and corresponding rated time if necessary.
- i. Insulation class if different from class A.
- j. Weight in kg.
- k. Service temperature.
- I. Mechanical class.
- m. Capacitance of the transformer and each individual capacitor (only for CVT).

7.5.12. INDIVIDUAL OR ROUTINE TESTS

Standards regard the following:

- a. Verification of terminal markings.
- b. Power frequency withstand test on the primary windings. As in the case of current transformers, the insulation of the primary windings must withstand the power frequency voltage corresponding to its insulation level for one minute.

Table 7.17

For this test, a distinction must be made between transformers for phase-phase connection and those for phase earth connection.

Transformers between phases must withstand a test involving voltage applied between the two primary terminals, joined together, and the secondary windings connected to earth, and two further tests with induced voltage.

The two latter tests may be performed by applying voltage through the secondary or through the primary. In both cases the voltage measured on the high voltage side must be the same as the specified test voltage. During this test one terminal of the secondary winding should be joined to one terminal of the primary winding, and both should be earthed.

Transformers connected between phase and earth are tested only via this second method, taking care that the primary terminal which is to be connected to earth during service (N) is the one which is connected to earth during the test. Also, N terminal must be tested as if another secondary was.

- c. Power frequency withstand test on secondary windings and sections. Each secondary winding or section must withstand an effective voltage of 3 kV with all the other windings and sections connected to each other and to earth.
- d. Partial discharges.

In general the comments above 7.4.10 f) concerning current transformers apply here also.

When the operating voltage is well below the specified insulation level there may be difficulties in performing this test due to saturation of the core. An agreement between manufacturer and user is required.

e. Accuracy tests. Check that the maximum admissible errors are not exceeded. This can be done with a low number of voltages and burdens.





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7.5.13. TYPE TESTS

Standards regard the following:

- a. Temperature-rise test. Consists of checking that the transformer meets the requirements of 7.5.4.
- b. Lightning and switching impulse test.

3 or 15 consecutive pulses are applied with positive and negative polarity, with full waves of 1.2/50 μ s for lightning impulse and 15 positive pulses of 250/2500 μ s for switching impulse test, depending on the highest voltage of the material.

c. Wet tests for outdoor transformers. These tests are aimed for checking the validity of the external insulation.

Both power frequency and impulse waves are applied, according to the highest voltage of the material

- d. Short circuit test. Consists of checking that the transformer meets the requirements of 7.5.9.
- e. Radio interference voltage measurement. Tests for the appearance of the corona effect (external discharges) and its limitation so as not to disrupt radioelectric transmissions.
- f. Accuracy tests to check that the maximum admissible errors given in table 7.15 are not exceeded.

7.5.14. SPECIAL TESTS

Same tests as CT are applied with some particular considerations.

Capacitance and tg $\boldsymbol{\delta}$ test is considered a routine test for CVT.

The mechanical stress which a TI must withstand is shown in Table 7.18.

Table 7.18

Static withstand test loads					
	Static withstand test load $F_{_{\!R}}$				
Highest voltage for equipment U	Voltage transformers with:				
kV	Voltage terminals	Through current terminals			
		Load Class I	Load Class II		
72,5 a 100	500	1.250	2.500		
123 a 170	1.000	2.000	3.000		
245 a 362	1.250	2.500	4.000		
≥ 420	1.500	4.000	6.000		



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