394

STATE OF THE ART OF INSTRUMENT TRANSFORMERS

Study Committee
A3

October 2009

cigré

ISBN: 978-2-85873-081-0

Study Committee

A3

State of the Art of Instrument Transformers

ISBN: 978-2-85873-081-0

State of the Art of Instrument Transformers

Introductory remarks from the Chairman of Study Committee A3

It is often suggested that utilities only think about their populations of instrument transformers when they begin to explode. Whilst this is far from the truth, it is true to say that there is limited focus upon the long term asset management aspects of these devices despite the large populations which are in service. It was with this in mind that, in the mid 1990's, CIGRE Study Committee 12 (Transformers) convened Working Group 12.16, Instrument Transformers. Whilst the Working Group was very active over a number of years and assembled a large volume of valuable information, its activities were never formally published by CIGRE and the WG was eventually disbanded without publication of a final report. Nevertheless, unpublished drafts have, for several years, been used as reference by those who are aware of their existence.

The restructuring of CIGRE led to Study Committee A3 inheriting the responsibility for Instrument Transformers and the Study Committee believes strongly that the work done by WG 12.16 has continued value and deserves formal publication. As such this Technical Brochure presents the work of WG 12.16 in the best form possible given the time that has elapsed since the Working Group was disbanded.

The work presented here represents the state of the art of Instrument Transformers at the start of the 21st century. Clearly some aspects, such as non-conventional instrument transformer technology and the development of IEC 61850 have progressed considerably since that time and these are the topics of further work within Study Committees A3. Nevertheless, topics such as design, manufacture, testing, maintenance & diagnostics of conventional instrument transformers remain as relevant today as they were 10 years ago. Furthermore, with the inclusion of instrument transformers in the latest reliability survey being conducted by Study Committee A3, it is timely that the failure survey undertaken by WG 12.16 is finally published formally.

Despite its protracted gestation period this Technical Brochure has significant value for designers & users of instrument transformers alike and, in addition, has a particular value as a tutorial document for this, oft neglected, technology area.

STATE OF THE ART OF INSTRUMENT TRANSFORMERS

1 DESIGN ASPECTS

1.1 Introduction

1.1.1 Framework

This chapter provides a description of the design of Instrument Transformers (ITs) for use in High Voltage (HV) substations. In accordance with the guidelines of CIGRÉ, the description is restricted to Instrument Transformers; free-standing types or those designed for use in gas-insulated substations (GIS), with an HV-insulation system dimensioned for a maximum voltage (U_m, according to IEC 60071) of 72.5 kV and higher and for use at industrial frequencies: 50 and 60 Hz but also 16 2/3 and 25 Hz.

ITs can be provided with a conventional sensing (measuring) system based on the transformer principle but also 'optical' sensing systems, Rogowski coils and conventional systems in combination with amplifiers can be applied.

However, ITs for dc and for higher frequencies, as used in static VAR-compensation installations for example and also resistive dividers, are not considered. The description comprises the following types of instrument transformers:

- Current Transformers (CT)
- Magnetic (Inductive) Voltage Transformers (MVT)
- Capacitor Voltage Transformers (CVT)
- Amplifier Voltage Transformers (AVT)
- Combined measuring transformers ('Combi' = MVT + CT)
- Systems of voltage and current measuring devices (for example in Gas-Insulated Substations)
- Non-Conventional Instrument Transformers

All of these different types of ITs have two main duties in common:

a) Transforming the primary high current or high voltage into a measurement signal (low current, low voltage, optical signal), which can be handled easily and provides a true image of the primary signal

b) Taking this measurement signal from the high voltage of the line or the busbar to virtually earth potential.

These two tasks must be performed often under severe conditions of electrical nature including, lightning and switching surges and short-circuit currents, and under extreme environmental stresses including extremes of ambient temperature, solar radiation, ice, snow, rain and storms, sandstorms, salt fog, industrial pollution and earthquakes. Moreover, the ITs are expected to fulfil all the requirements of the applicable IEC Standards, any special requirements of the customers' specifications and maintain the desired accuracy and transient behaviour during their lifetime of at least 25 years with minimum maintenance. Under these conditions the failure rate should be very low and the risks to personnel and equipment in the event of failure should be reduced to an absolute minimum. Additionally, the ITs should be able to withstand rough handling during transportation and installation.

1.1.2 General requirements

The many designs of ITs have to be made within a set of standardized requirements that have been upgraded over the years. A number of international working groups are now also putting together guidelines and Standards for non-conventional instrument transformers.

The most important IEC Standards, applicable to conventional instrument transformers are:

for Current Transformers:

- IEC 60044-1 - Instrument Transformers, part 1 : Current Transformers
- IEC 60044-6 - Instrument Transformers, part 6 : Requirements for protective Current Transformers for transient performance

for Magnetic (Inductive) Voltage Transformers:

- IEC 60044-2 - Instrument Transformers, part 2 : Inductive Voltage Transformers

for Capacitor Voltage Transformers:

– IEC 60044-5 - Instrument Transformers, part 5 : Capacitor Voltage Transformers

for Combined Measuring Transformers:

– IEC 60044-3 - Instrument Transformers, part 3 : Combined Transformers.

Other Standards applicable to conventional instrument transformers are:

– IEC 60044-4 - Instrument Transformers, part 4 : Measurement of Partial Discharges
– IEC 60358 - Coupling Capacitors and Capacitor Dividers
–

for Electronic Voltage Transformers :

– IEC 60044-7 - Instrument transformers, part 7 : Electronic Voltage Transformers

for Electronic Current transformers :

– IEC 60044-8 - Instrument transformers, part 8 : Electronic Current Transformers (2002-07).

In the United States, the ANSI-IEEE Standard in use are:

– IEEE C57.13 - IEEE Standard Requirements for Instrument Transformers.
– ANSI C93.2 - Coupling Capacitor Voltage Transformers

In Canada, the CSA Standards in use are:

– CAN3-C13-M83 - Instrument Transformers
– CAN3-C13.1-M79 - Capacitive Voltage Transformers.

Where appropriate, other National Standards are applied in addition to the above mentioned Standards. In these National Standards small deviations from, and additions to, the IEC publications will be incorporated. However, the application of additional Standards should be restricted as far as possible [1, 2].

1.1.3 Nomenclature

In the course of the years, a large number of designs have been invented and developed in order to meet all of the above requirements. At first sight it seems very difficult to give a consistent and, above all, short description of all these different designs.

However, many similarities between free-standing ITs can be recognized, starting with their two main functions:

a) Duty I : the measuring or sensing function
b) Duty II : the insulating function.

Next, common components and also various auxiliary parts can be referenced. Finally there are many design features which have to perform different tasks and which are either specified in Standards requirements or are dependent on common constraints. Other tasks are related to specific requirements or special constraints.

These considerations have led us to use the approach adopted for this "design" chapter. The basic instrument transformer duties can be found in Figure 1.1

The "range extension" duties of free standing units have led, for instance, to designs of current and voltage transformers for many power system functions. The widespread use of ITs has great advantages as it allows:

a) standardization of instruments, protection relays and meters around fixed ratings (*i.e.* 1 A or 5 A and 100-120 V), in order to greatly reduce the overall costs both of transformers and instruments and permit many designs,
b) insulation of sensitive equipment from high voltages and harsh substation environments so that they may be earthed and operated at low potential,
c) operation of several functions with the use of one single field device,
d) low power ratings of instruments in the control room,
e) safe operation of substation functions.

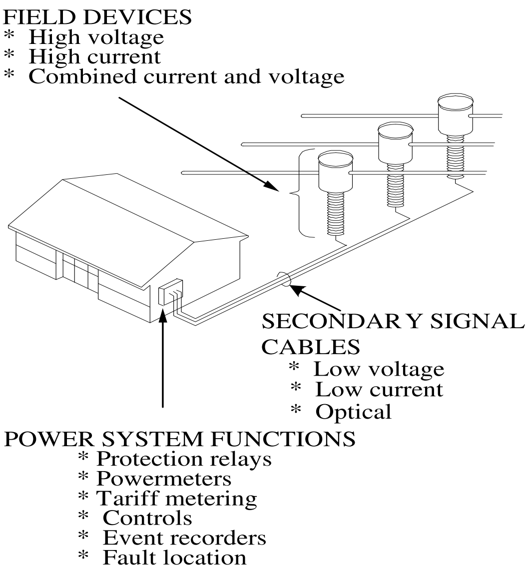


Figure 1.1: Description of free standing instrument transformer duties

The framework of this chapter thus addresses the main design features of ITs, which are indicated schematically in Figure 1.2 and which apply to the most widespread family - free-standing devices. The great diversity of sensing designs and insulating combinations (including paper-oil, insulating film - SF_6, porcelain insulating columns, solid insulation, etc.) are presented briefly in the following chapters.

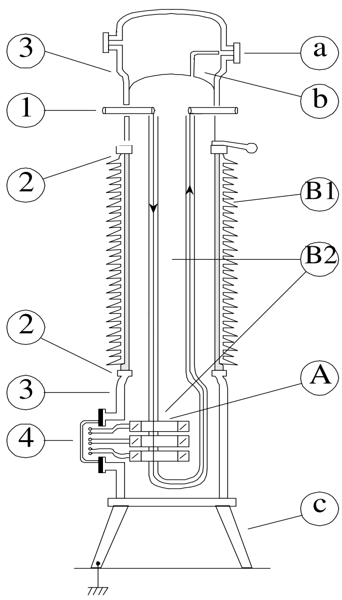


Figure 1.2: Nomenclature of instrument transformer design features

1.2 Conventional Instrument Transformers

Originally all conventional ITs were freestanding types. With the introduction of GIS however, new types of conventional ITs, connected directly to the GIS, became necessary.

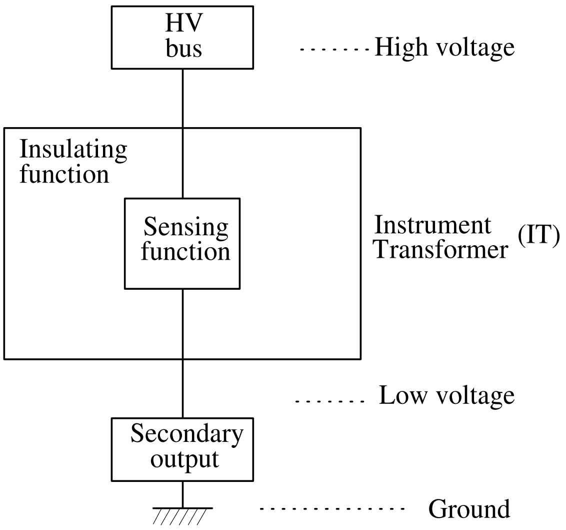


Figure 1.3: Functional diagram of an instrument transformer

The key features of a conventional IT are shown in the functional diagram of Figure 1.3. The main functions, namely the sensing function and the insulating function will now be described in general terms followed by a general description of common components and auxiliary parts of the conventional, freestanding IT. The special features of GIS-connected ITs will be then be described and finally, other types of ITs will be dealt with.

1.2.1 Freestanding Instrument Transformer Features

1.2.1.1 Sensing function

1.2.1.1.1 Magnetic cores and windings

The most widespread sensing principle is based on the magnetic coupling of windings wound on a ferro-magnetic core as shown in Figure 1.4. The use of multiple cores (Figure 1.4c) or windings with tappings (Figure1.4d) have led to several designs of instrument transformers for duplication of functions, increased reliability and reduced power loads. Magnetic principles are used equally for voltage and current sensing. Examples are given in Figure1.5 which shows winding circuits for both sensing functions.

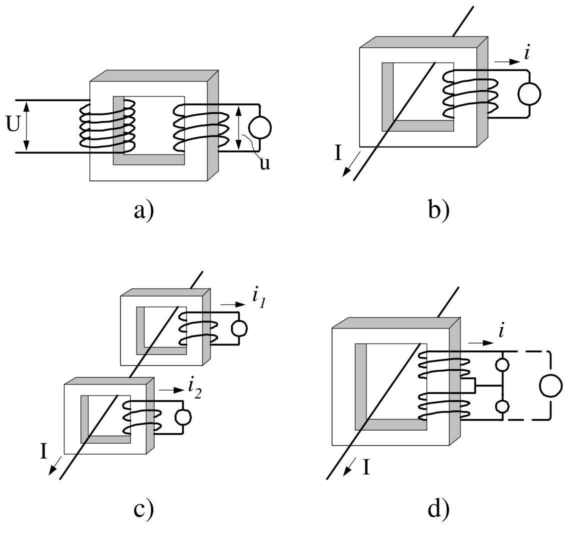


Figure 1.4: Schematic description of magnetic sensing principles

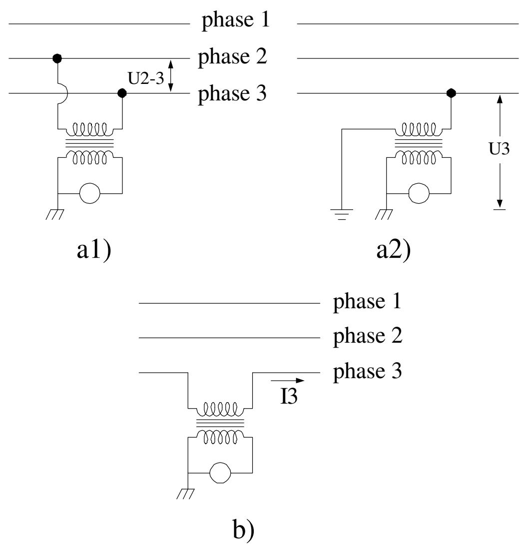
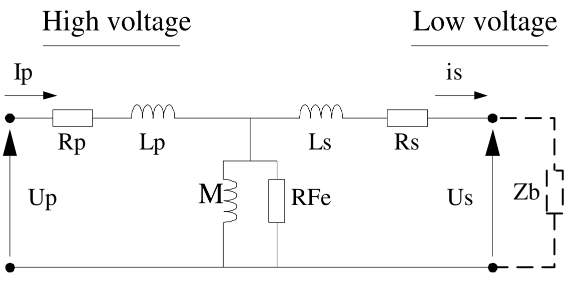


Figure 1.5: Winding circuits of (a) magnetic voltage and (b) magnetic current sensing

For current transformers (CT), the primary winding is connected in series with the line carrying the current to be measured. The CT operates with its secondary under low impedance conditions. The instruments connected to it, along with their cables and compensating elements are called the CT "burden". In general, burden values are very low, *i.e.* below 100 VA. CT transformer ratios are chosen such that they supply 1A or 5A at nominal primary current.

The magnetic voltage transformer (MVT) is quite similar in concept and behaviour to power transformer and is in marked contrast with the CT in many respects. The MVT may be pictured as a "parallel" transformer and the CT as a "series" transformer. The CT can be considered as operating under virtual short-circuit conditions whereas the MVT is functioning under virtually "no load" conditions. Under normal operating conditions of the power line, the voltage is nearly constant and thus the MVT magnetic excitation is fairly constant and varies over a restricted range. In contrast, the magnetic excitation of the CT varies significantly, over a wide range of current from normal line operating conditions to system faults. In general MVT ratios are designed such that their output delivers voltages in the order of 100V at nominal line voltage.

The basis for the electro-magnetic functioning of the core and winding arrangements of CTs and MVTs is the equivalent circuit of Figure 1.6



Ip : Primary current
is : Secondary current
Rp : Resistance of the primary conductor
Lp : Primary leakage inductance
M : Coupling inductance
RFe : Equivalent resistor for hysteresis and eddy losses in the core
Ls : Secondary leakage inductance
Rs : Resistance of the secondary windings
Zb : Impedance of the burden
Up : Primary voltage
Us : Secondary voltage

Figure 1.6: Equivalent circuit of the magnetic instrument transformer

Analysis of this equivalent circuit allows the following main observations to be derived for the current transformers:

a) R_p and L_p have no influence on the measurement functions of a CT.

b) R_p and L_p are negligible for the bar primary (live tank) CT design.

c) The short-circuit forces on the primary winding arrangements are a function of the current I_p and the primary winding loop inductance L_p. Some designs of CT are filled with quartz sand in addition to the insulation liquid to mechanically stabilise the primary winding.

d) The temperature rise in the CT is a function of $I_p^2 \cdot R_p$. Some CT designs employ a special cooling and primary conductor design using a laminated primary conductor for better oil circulation and for reduction of eddy current. Secondary and dielectric losses can significantly contribute to the temperature rise of the CT, the latter especially at higher voltage levels.

e) (I_p - I_s) is the excitation current of the core. For measurement applications, a core design where the value (I_p - I_s) remains low and within close limits is required in order to achieve good accuracy. This is achieved by avoiding air gaps in the core and by the use of special magnetic materials such as grain orientated steel or 'permalloy'.

   CT cores for measurement applications use a ring-core type construction made of strip magnetic material wound in spiral form (like a clock spring) and they can be fitted in most CT designs. For special CT designs such as the eye-bolt type illustrated in Figure 1.9c, epoxy reinforced cut ring cores are sometimes used and air gaps are minimised by grinding and lapping the surfaces as part of the manufacturing process.

f) The ring-core type construction for protection applications may have air gaps if special requirements are specified for the response of the CTs to asymmetrical fault currents. The gaps are filled with insulation material to ensure mechanical stability (Figure 1.7).

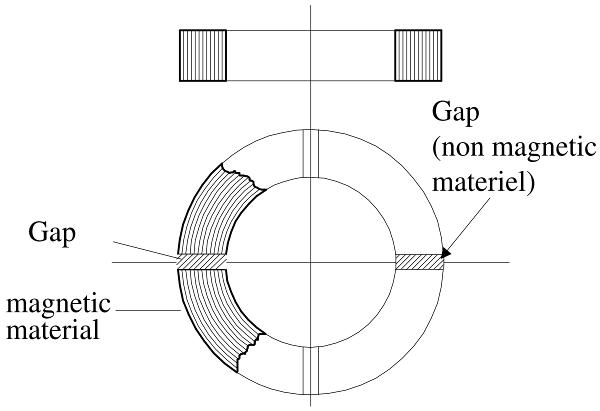
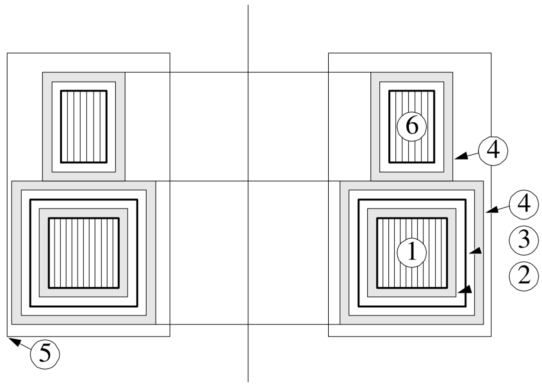


Figure 1.7: Ring-core type construction with air gaps

There are two possibilities:

– type TPY-cores, with very small air gaps intended only to reduce the remanence of the core;
– type TPZ-cores, with more and longer air-gaps allowing the use of practical core sizes whilst achieving an acceptable phase-angle error level (see transient behaviour of CTs -section 1.2.1.1.4).

A common arrangement of ring cores is shown in Figure 1.8.



1 : First core
2 : Insulation - core/secondary winding
3 : Secondary winding; one or more layers
4 : Insulation - secondary winding/earth shield and secondary winding first core/second core
5 : Earth screen or earth shield
6 : Second core

Figure 1.8: Ring-core with winding and insulation

g) Special attention must be paid to ascertain proper shielding between the internal winding insulation system and the main insulation of the CT.

h) The secondary leakage L_s should be very low to achieve good accuracy even during transient conditions. Such a "low leakage flux" CT can be achieved by applying the following design principles according to IEC:

- use of ring cores,
- evenly distribute the secondary windings over the circumference of the ring core. This also applies to the different tapping windings and to the air gaps in the core,
- use of a primary conductor as short as possible (the bar primary, live tank CT has a L_p near to zero!),
- balancing windings may be necessary for high current hairpin or eyebolt type CTs.

i) The resistance value R_s of a core is dependant on the number of secondary turns which is defined by the ratio of the CT. The time constant of the secondary circuit and the maximum heat dissipation are two further design criteria for the R_s value.

The primary winding of CTs may have only one or a few turns. If there is only one turn, the primary winding may consist of a straight bar conductor, as shown in the bar primary live tank CT (Figure 1.9a), or the primary conductor can be bent in the form of a "U" as in the hairpin type (Figure 1.9b) or in the form of an eye-bolt (Figure 1.9c). Hairpin and eye-bolt types are both classed as dead tank designs.

For the dead tank designs the cores are mounted around the insulated conductor at the bottom of the CT at earth potential. For the live tank bar primary CT, the secondary cores are mounted inside an insulated metal housing in the form of a toroid. Both the cores and the metal housing are effectively at earth potential.

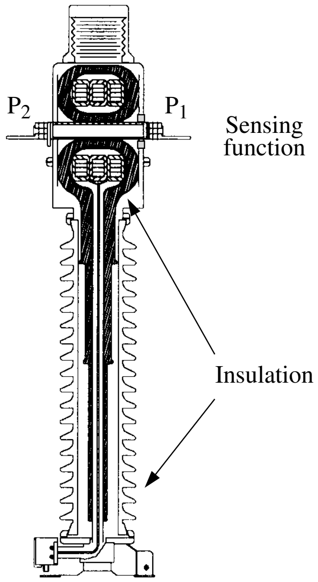


Figure 1.9a: Bar primary, live tank CT

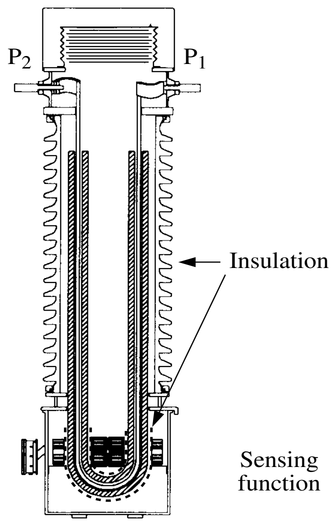


Figure 1.9b: Hair-pin type CT

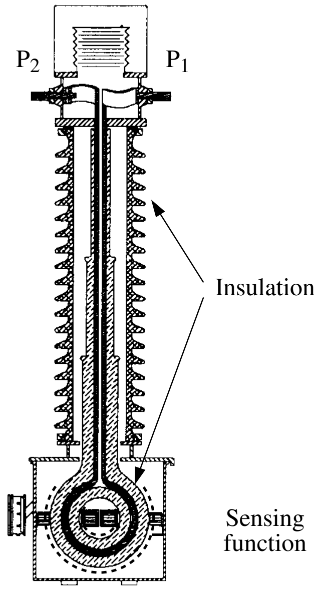


Figure 1.9c: Eye-bolt type CT design

For the live tank design which has a primary winding of more than one turn, the turns may be wound around the toroïd, either equally divided over the circumference or be composed of a number of rigid bars. In the hair-pin design a composite conductor is used with thin insulation between the strands. In all designs, the different turns can be connected in series or parallel or series/parallel offering the possibility of achieving a number of transformation ratios, for example 300/1A or 600/1A or 1200/1A. Various transformation ratios can also be achieved by means of tappings on the secondary windings, recognising that the accuracy and maximum rating will vary at different taps. Additionally, each tapping winding should be distributed over the full circumference of the core.

In CTs, the two functions of sensing and insulation are always completely separated: the primary is at HV-potential, the cores and secondary windings are at earth potential. Between these two components, the internal insulation accomplishes duty II, the insulation function.

In MVTs however, the sensing and insulation functions are not separate [3]. The primary winding is not only essential for the formation of the output signal, but the high potential at the HV-terminal gradually reduces along the winding to zero at the earth terminal. Therefore, in the primary winding both sensing and insulation functions are combined.

For MVTs which are connected between phase and earth, the insulation between primary and secondary windings is only dimensioned for a low test voltage, usually not higher than 10 kVac (or 19 kVac for outdoor units specified to ANSI/IEEE Standards). In MVTs, which are connected between phases, the insulation between primary and secondary windings should be dimensioned for a much higher voltage, because in normal service this insulation will be stressed continuously at: $\frac{1}{6} U_m \sqrt{3}$.

The core of MVTs is usually built up of grain orientated steel sheets or of 'permalloy' with a square section in the yokes and a section roughly approaching circular form in the wound limbs. In dead tank MVTs (Figure 1.10) only one limb will be provided with windings and the core will be at earth potential.

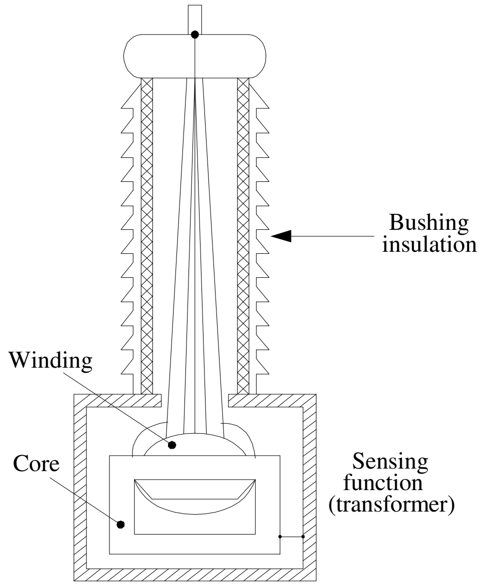


Figure 1.10: Dead tank MVT with one HV winding

In cascade MVT types however, both limbs are provided with windings and the core is at a potential of 50% of the phase voltage. The active part can be mounted inside the insulator porcelain enclosure (Figure 1.11a) or inside a metal tank (Figure 1.11b) which is also at a potential of 50% of phase voltage.

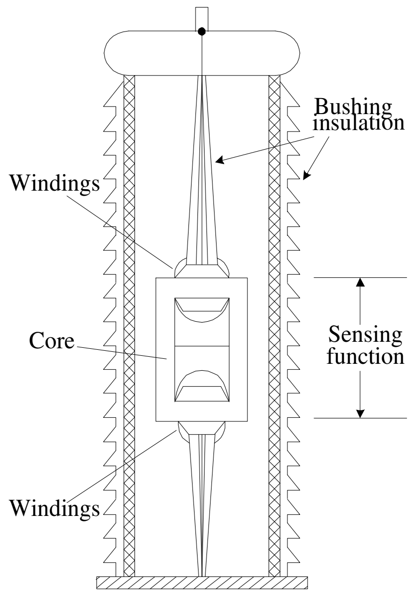


Figure 1.11a: Cascade-type MVT with two HV windings in series

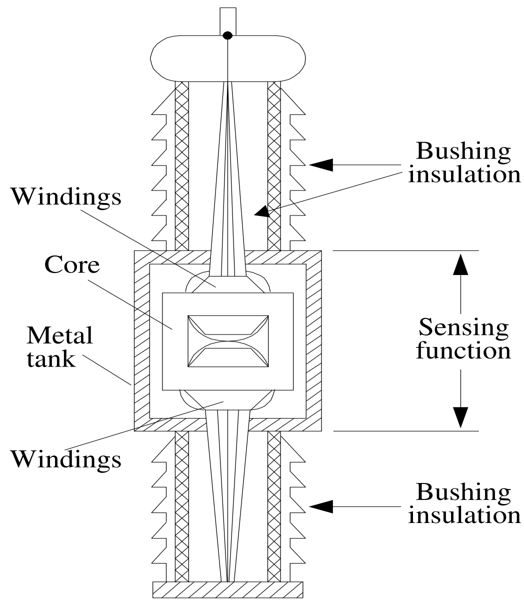


Figure 1.11b: Live tank cascade MVT with two HV windings in series

For extra high voltages, two cascades can be stacked and connected in series - The double cascade will have 4 wound limbs in total and the cores will then have potentials of 75% and 25% respectively of phase-to-earth voltage. Using the same principle some MVTs have been produced with 3 or more cascade units

The secondary and tertiary windings of MVTs are usually layer windings with one or a few layers, wound with paper-insulated or lacquered copper wire of circular or rectangular section. The windings are wound on a cylinder or coil former of resin impregnated paper or transformer board.

In cascade VTs, additional magnetizing windings are necessary for the exchange of magnetizing energy between the limbs of a core (M1 in Figure 1.12) or between the cores (M2), in double cascade connections. These windings have the same design as the secondary windings and have a rated voltage of 100 to 500 V. In single cascades they are located immediately on the core limbs and have the same potential as the core. In double cascades the magnetizing windings for the exchange of energy between the two cores are mounted on the outside of the second and third primary windings at a potential of 50% of phase voltage. Figure 1.12 shows the winding circuit of a double cascade MVT.

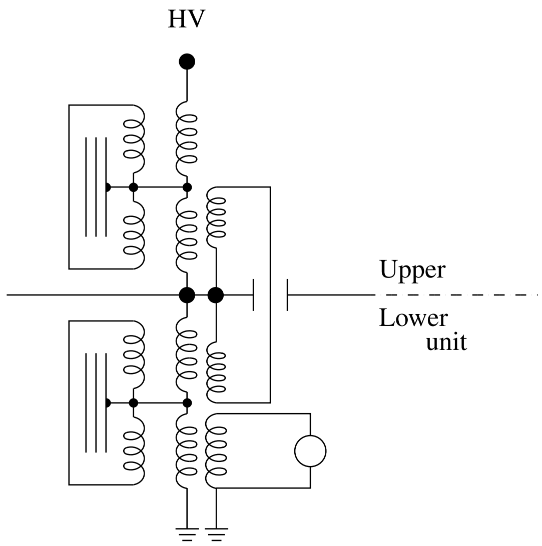


Figure 1.12: Winding circuit of double cascade type MVT

Many design concepts have been proposed that locate the magnetic sensing system at the high-voltage end of the IT leading to the so-called 'live-tank' (Figure 1.9a) whilst other ITs locate the sensing systems at the low voltage end of the IT and these are the 'dead-tank' designs (Figs. 1.9b, 1.9c and 1.10). Others designs position the sensing system at the mid-height of the unit such as the cascade MVTs (Figs. 1.11a and b) and cascade CTs (Figs. 1.21a and b).

1.2.1.1.2 Capacitor voltage sensing

Various methods of voltage sensing are possible using the basis of the capacitor voltage divider. The capacitor divider is often made as a stack of identical capacitor elements which straightforwardly gives a uniform voltage distribution.

The pure capacitor divider can be equipped with a tap at the bottom as shown in Figure 1.13 to provide a sensing signal of 100-120V, but this is only of use for voltage indication because the phase angle error will rise to unacceptable values at loads (burdens) exceeding 0.1-1W. To overcome this problem, the capacitor voltage transformer (CVT) and the amplifier voltage transformer (AVT) were developed.

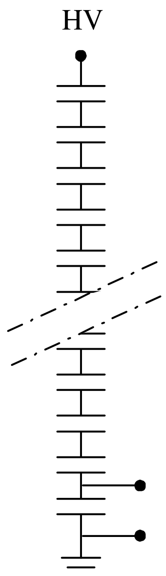


Figure 1.13: Capacitor voltage divider

Capacitor Voltage Transformer (CVT)

Capacitor voltage transformers consist of four main components, as seen in Figure 1.14, all of which contribute to the sensing function:

- capacitor voltage divider (C1 and C2),

– compensating reactor (L).
– intermediate voltage transformer (IVT) with its secondary winding (S),
– auxiliary circuits (F) for ferroresonance damping and (T) to achieve the required transient performance. the desired transient behaviour can sometimes be achieved without the use of auxiliary circuits..

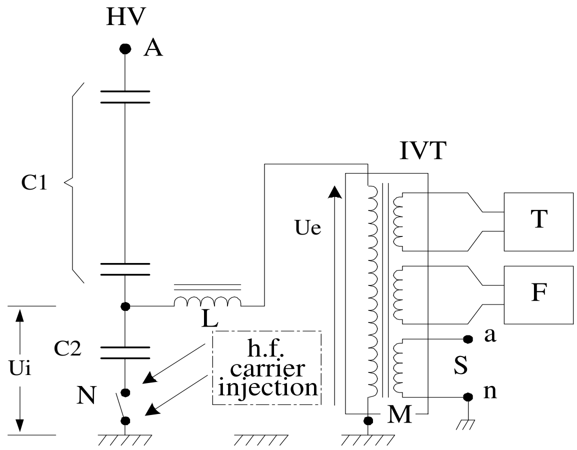


Figure 1.14: Electrical scheme of a CVT

The capacitor voltage divider has a tapping to provide an input voltage U_i which is usually 10 - 20 kV with respect to earth. If a burden was to be directly connected to the tapping point, the phase displacement of the voltage across it would change significantly with varying burden, for the reason described in 1.2.1.1.2. The inductance of the reactor (L) reduces this phase error variation to an acceptable specified value (virtually zero) for the input voltage U_e of the IVT.

Apart from the capacitor voltage divider, all the components are housed in a steel or aluminium tank at earth potential which is filled with transformer oil, although they may be air-insulated for lower intermediate voltages. The tank and its contents are called the electro-magnetic (EM) unit of the CVT and are mounted beneath the capacitor stack of the CVT in most cases (Figure 1.15a). Other solutions also exist in which the EM unit is situated separately from the CVT capacitor divider unit (Figure 1.15b) and historically, some CVTs were made using discrete capacitors in an open 'Christmas-tree' configuration, again with a separate EM unit (Figure 1.15c).

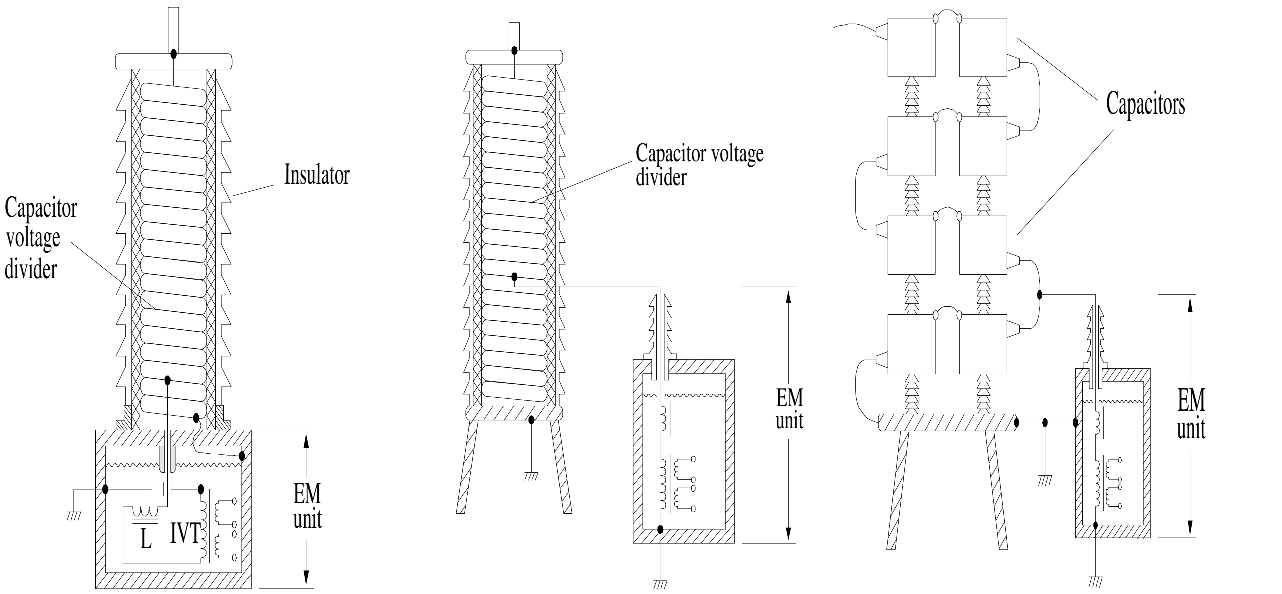


Figure 1.15a: Integrated-type CVT **Figure 1.15b: CVT with separate EM unit** **Figure 1.15c: Open configuration CVT**

As in the MVT, the capacitor voltage divider and the intermediate voltage transformer (IVT) both provide the sensing and insulation main functions. The design of the IVT is comparable to that of a MVT but has a lower rated voltage.

The reactor is provided with a core of transformer sheet steel and a layer winding of the same design as the secondary winding of an MVT. The core is at a potential of U_i to earth, the voltage drop across the reactor being 1-5kV at the full load of the CVT. In some IVT designs, the reactor L is connected between the neutral end of the primary winding of the IVT and earth thus making adjustment of the inductance easier because the reactor-core is at earth potential.

High-frequency (HF) carrier injection

The capacitor stacks of CVTs may also be used to connect a telecommunications signal to the HV line. For this application, an earth switch with a parallel choke (discharge) coil matching the characteristic impedance of the carrier wave cable is connected between capacitor C_2 and earth (Figure 1.14). The switch is closed during maintenance of the HF carrier equipment or when that equipment is out of service.

Amplifier Voltage Transformer (AVT)

Amplifier voltage transformers are in use in GIS. There are only two main components: the capacitor voltage divider and an electronic amplifier.

There are basically two functional principles used in AVT's:

a) "Passive" amplifier voltage transformer:

The high voltage is reduced by a capacitor voltage divider consisting of the high voltage capacitor C1 and the low voltage capacitor C2 to a lower voltage which is fed to the input of a high input impedance electronic amplifier (Figure 1.16a).

b) "Active" amplifier voltage transformer:

The low voltage capacitor C2 acts as the feedback capacitor of an operational amplifier. The input E of the amplifier has virtually earth potential. This makes the "active" amplifier voltage transformer almost independent of influences of the connecting lead between the low voltage terminal of the high voltage capacitor C1 and the input terminal of the amplifier (Figure 1.16b).

The high voltage capacitor C_1 is usually designed as a ring electrode around the primary conductor mounted inside the SF_6-gas filled housing and insulated from the metal wall of the vessel. Different techniques are used for the low voltage capacitor C_2. The sensitivity of the error of the measured voltage to temperature and pressure variations depends on the relative similarity in behaviour of the dielectrics of the capacitors C_1 and C_2.

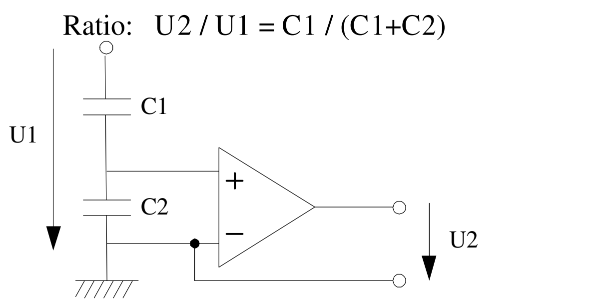


Figure 1.16a: Equivalent circuit of passive AVT

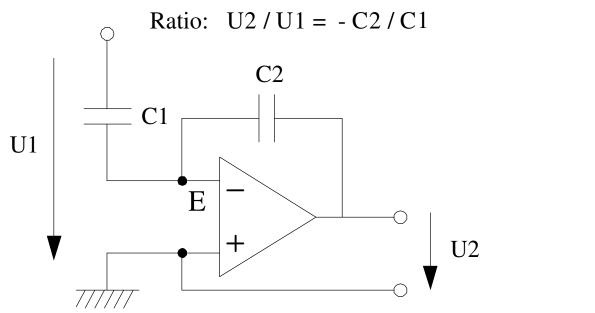


Figure 1.16b: Equivalent circuit of active AVT

1.2.1.1.3 Combined sensors

In some applications, dual function instrument transformers perform both current and voltage sensing (CT+MVT) in a single free-standing construction.. Combined ITs using SF6-gas and resin insulation respectively are shown in Figure 1.17a and b. In both designs, the top transformer is an MVT whereas the window type transformer underneath is the CT.

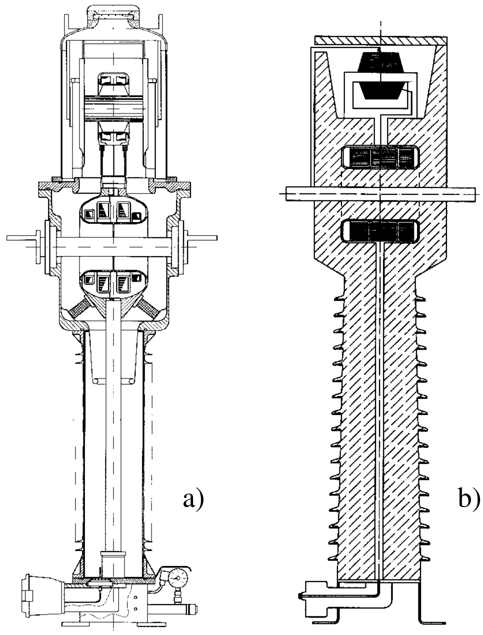


Figure 1.17: Combined IT: CT+MVT
a) SF_6 insulated and b) resin insulated

Typical paper/oil-insulated Combined ITs with a dead tank and an open core MVT are shown in Figs. 1.18a and b. respectively

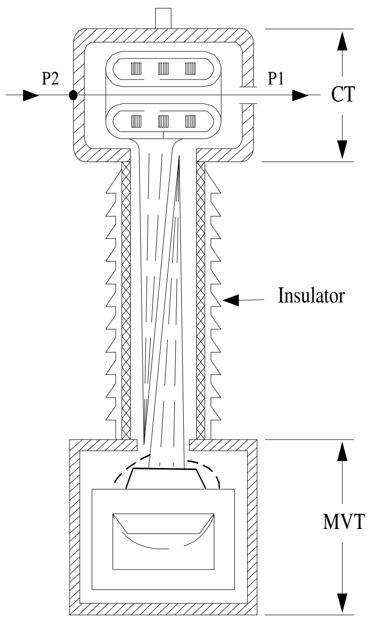


Figure 1.18.a Combined IT, paper-oil-insulated with dead tank MVT

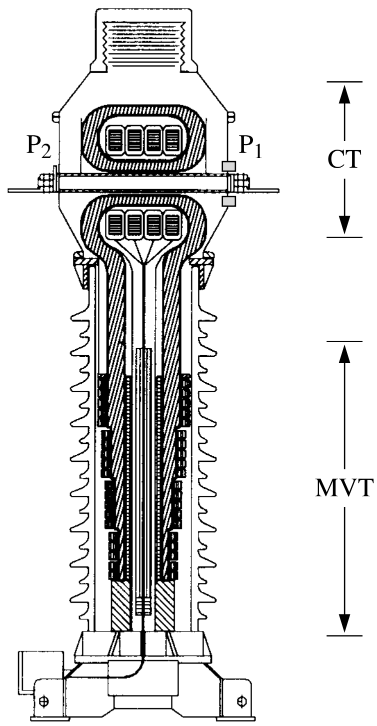


Figure 1.18.b Combined IT, paper/oil-insulated, with open core MVT

1.2.1.1.4 Secondary output signals

The output of a sensing system is always an analogue signal for conventional ITs and is an electrical (measurement) signal fed from the IT secondary. Non conventional ITs with optical or digital outputs are still in the development stage such that it is inappropriate to give clear statements on their behaviour. Therefore, consideration is restricted here to sensing systems with an electrical measurement signal.

The output signals should meet requirements of:

- Accuracy
- Transient behaviour
- Influence of system disturbances (ferroresonance)

Accuracy

For current as well as voltage transformers, the accuracy of an IT is defined by means of a maximum ratio error and a maximum phase displacement between the primary and the output signals. A number of accuracy classes are defined in IEC 60044-1 and 60044-2, the following classes usually applying:

- Class 0.5 for metering purposes (ratio error < 0.5%)
- Class 0.2 for tariff measurements (ratio error < 0.2%)
- Class 0.1 for tariff measurements of large amounts of electrical energy (ratio error < 0.1%).

Special protection accuracy classes exist for CT cores and the secondary windings of VTs supplying protection systems. For tariff metering, the IEC accuracy classes are valid between 1% or 5% to 120% of rated primary current or 80% to 120% of rated voltage over the range of 25% - 100% of rated burden. Outside these limits the errors will grow rapidly. In ANSI/IEEE Standards the accuracy classes for tariff metering are valid from 10% of rated current to maximum continuous current and for 90% to 110% of rated voltage, for the range of zero to rated burden. The accuracy classes are based on a system power factor of 60% ($\cos\varphi = 0.6$).

Normal values of rated secondary currents for CTs are 5 A and 1 A. Values of secondary voltages for VTs are $\frac{200}{\sqrt{3}}$, $\frac{110}{\sqrt{3}}$ or $\frac{100}{\sqrt{3}}$ V for phase to earth connected VTs and $\frac{200}{3}$, $\frac{110}{3}$ or $\frac{100}{3}$ V for VT tertiary windings to be connected in open delta.

Burdens are usually considered as a mixture of resistive and inductive load and are expressed in VA with a power factor of the burden = 0.8 lagging. For CT cores of the TPX, TPY, and TPZ-type the burden is considered purely resistive and given in Watts. Traditionally, burdens of 50 to 80 VA for CT cores and 200 VA for VTs were quite usual and necessary for the high power consumption of electro-mechanical protection relays and measuring instruments and because of the high losses in the long cables between the ITs and the central control-room of the substation. Moreover, there was a strong preference for 5 A as secondary current of CT-cores which resulted in high losses in the secondary wiring. A secondary current of 1 A was considered more sensitive to external influences and dangerous to personnel because of the occurrence of high voltages in the event of an open circuit in the secondary circuit.

Nowadays, the power consumption of electronic protection equipment is almost zero and the protection and metering equipment may be mounted in a relay cubicle near to the IT thereby reducing the power losses in the secondary wiring to a few Watts. A further reduction of wiring losses is possible by selecting a 1 A rated secondary current since the earlier problems have been solved. A rated secondary current of 1 A allows CT-cores to be smaller and lower weight.

When ordering new ITs, it is important that a realistic estimation of the total burden be made bearing in mind all the above-mentioned changes, and that this realistic value of burden be specified. However if the existing protection equipment is to be retained, the new IT should be specified (and will also be dimensioned) using the old, high burden values.

Where ANSI Standards are in use, utilities usually specify multiple ratio ratings and a 5 A secondary current for CT protection cores.

In substations where there is no public power supply available, the tertiary windings of MVTs are sometimes used to power auxiliary equipment. In such cases the thermal rating of the MVT should be higher in order to maintain the accuracy of the secondary signals within acceptable limits.

Transient behaviour of current transformers

Primary short circuit currents can contain large dc-components, the amount of dc-current being dependent on the moment of occurrence of the short-circuit. If the short-circuit occurs at a voltage zero, the dc-component will be maximum and equal to $\sqrt{2}$ times the rms value of the prospective short circuit current. Usually however, the dc-component of the current will be smaller because a short circuit at voltage zero is unlikely. The dc-component can be expressed in terms of the 'asymmetry-factor' which is defined as the ratio of the start value of the dc-component ('a' in Fig 1.19) to $\sqrt{2}$ times the rms value of the ac-component of short-circuit current.

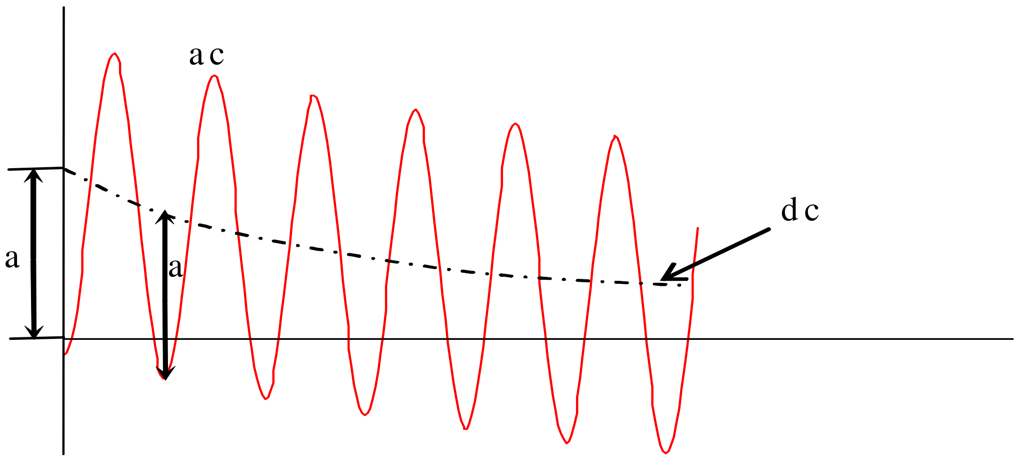


Figure 1.19: Asymmetric Short-circuit Current with AC and DC components

The primary dc-component will decay slowly with a time constant in the range 10 - 150 ms for substations remote from generators, but can reach values of 300 to 500 ms near a generator. The primary dc-component will be transmitted to the CT secondary winding only partially and slowly. The difference of the dc-components in primary and secondary current causes a dc-magnetization of the CT-core which grows to a maximum and then decays slowly to zero, the time to reach this maximum being determined by the primary and secondary circuit time constants. It is possible that the core could become saturated by the dc magnetization and consequently the ac-component of the output signal during primary short-circuit current conditions could be highly distorted. For CT cores used for protection applications, this could result in incorrect operation of the protection system. It is usually specified that the protection core should not saturate within a given time from the occurrence of the short circuit even under worst conditions. Within this time, usually 2 to 3 periods, the protection system should be able to detect the fault current correctly and initiate operation of circuit-breakers to clear the fault.

Accuracy requirements are sometimes specified such that the core should not saturate during the following switching sequence: first time delay (60 ms) - opening of the circuit breaker - rapid reclosure (after 300 ms) - second time delay (60 ms). The time delays given are only examples. The desired behaviour of these protection cores can be achieved by using transient performance TPY and TPZ cores which have non-magnetic core gaps (see section 1.2.1.1.1).

The dimensioning of the cores can be expressed by the Transient Dimensioning Factor (Ktd), which states the ratio of the error limiting induction of the core material to the rated induction (at rated current and burden). A specified transient performance can be achieved using TPZ cores at a much lower value of Ktd than by using cores without non-magnetic gaps, resulting in smaller dimensions and weight of the core but in largely increased phase angle errors.

In cores used for measurement applications, saturation of the core during primary short circuit events is considered an advantage since it can reduce the secondary response to the primary short circuit current, effectively protecting the connected measuring equipment against high overcurrents. The saturation behaviour is defined by the instrument security factor Fs, which states that at Fs times rated current the composite error of the core will be at least -10%, due to the onset of saturation.

Transient behaviour of voltage transformers

When a system earth fault or a three phase short circuit occurs, the voltage of the phase or phases involved will fall suddenly to almost zero. In the case of an earth fault, the voltage of the healthy phases will rise to the instantaneous value of the phase-to-phase voltage for resonant or non-effectively earthed or isolated neutral systems. For effectively earthed systems, the voltage rise will be less than 80% of the instantaneous value of the phase-to-phase voltage. The output (measuring) signal of VTs in the vicinity of the fault should follow this primary voltage drop or rise virtually without delay. this requirement is no problem for MVTs, but significant problems in meeting this demand are experienced by CVTs because of the capacitive energy stored in the capacitive divider and the magnetic energy stored in the reactor (see Figure 1.14) which prevent sudden changes in the output signal. For this reason the sensing system in CVTs is equipped with a special circuit, usually an additional burden, which allows for a more rapid adaptation of the charge of the capacitors to the new situation. Even then, the response of CVTs to an instantaneous 100% drop on the primary voltage will not be better than a decaying voltage at the secondary terminals, reaching 5 - 10% of the original value after one cycle of rated frequency.

Ferroresonance

Ferroresonance can occur in both MVTs and CVTs.

For MVTs, ferroresonance is always the result of the interaction of the non-linear inductance of its magnetic circuit with an external capacitance, for example the grading capacitors of a nearby circuit breaker.

In contrast, ferroresonance for CVTs is always the result of the interaction of internal components, specifically the nonlinear inductance and the parasitic capacitances of the HV-winding of the intermediate voltage transformer (IVT). CVT ferroresonance develops as follows: during a secondary short circuit, a large amount of magnetic energy (= 1/2 Li^2) is stored in the compensation reactor (see description of CVT in section 1.2.1.1.2). After interruption of the secondary short circuit current, this stored energy is released in the primary winding of the IVT and can cause saturation of the core of the transformer. When reaching saturation, high voltage peaks can develop and endanger the insulation of the IVT and the reactor and could eventually destroy these components. The voltage peaks will usually occur at subharmonic frequencies: 1/5, 1/4, 1/3 or 1/2 of rated frequency. (With MVTs, ferroresonance may also occur at rated frequency).

The disturbance of the output signal by ferroresonance voltage peaks is not usually considered as annoying and does not give sufficient reason for suppressing the ferroresonance. Nevertheless, in most cases, countermeasures against ferroresonance are taken for the purpose of preventing faults and destruction of the voltage transformer. In general, ferroresonance at rated frequency or higher harmonics can rapidly lead to dielectric failure of the unit, whereas subharmonic ferroresonance can cause a more slowly developing thermal failure.

For MVTs, suppression of ferroresonance is usually achieved by means of a damping resistor connected to the tertiary winding of the MVT or to the open delta connection of the tertiary windings of the three MVTs in a switching bay. The resistor can either be permanently connected or temporarily inserted by means of a saturable reactor in series with the resistor, the reactor effectively acting as a switch and closing at the occurrence of the voltage peaks. In some cases it is not possible to suppress rated frequency ferroresonance by means of a damping resistor and the occurrence of ferroresonance in such cases can only be prevented by judicious positioning of components in the substation (see 1.4.3.2). In principle, ferroresonance suppression devices connected to MVTs are not part of the IT's sensing system and are mentioned here only for the sake of completeness.

In CVTs however, ferroresonance damping devices are an integrated part of the IT sensing system, damping of ferroresonance being achieved in two ways:

a) by inserting an additional burden as described for MVTs with the burden resistor and its switching reactor being housed inside EM unit of the CVT, or
b) by peak-shaving of the voltage peaks, historically by means of an active-gap surge arrester or an external arc gap but nowadays by means of ZnO-arresters, thyristors or Zener diodes which are far better controlled and will short all voltage peaks rising above a well defined threshold value.

Gapped-type surge arrester had to be mounted under oil for electrical stress reasons, but a number of arresters proved not to be oil-tight, became useless in the long run and even dangerous to the proper functioning of the CVT. ZnO-arresters do not change their behaviour when they are immersed in oil. Thyristors and Zener-diodes can be mounted in air, for example in the terminal box and are therefore easily exchangeable; they are connected to an additional secondary winding of the IVT at 200 to 400V.

1.2.1.2 Insulating function

As mentioned in the Introduction the instrument transformer has to perform two duties. Duty II - to bring the measuring signal from HV-potential to virtually earth potential - is achieved by the presence of the main insulation system which, for most ITs, consists of the internal main insulation, including oil or SF_6-gas, and the external main insulation.

The internal main insulation is usually integrated in the active part: for CTs it is situated between the primary winding and the secondary cores and windings. For MVTs, it forms part of the primary windings (insulation between winding layers and turns) and for CVTs it forms part of the capacitor stack in the capacitor voltage divider. The internal main insulation also performs the voltage grading between the live parts of the IT and the base and other parts at earth potential. This voltage grading is particularly important at the outer surface of the insulator.

The external main insulation system forms part of the oil or SF_6 containment system, which for free-standing ITs is usually an insulator with metal tanks at top and bottom. The insulator also has the function to support the primary lead and the parts at the top of the IT which are at line-potential. It can be made of one of the following materials:

- porcelain
- glassfibre reinforced epoxy; often with silicone rubber insulator sheds (composite)
- cast resin, with cast-on insulator sheds for outdoor or a smooth surface for indoor application

For fully-resin-insulated ITs, a distinction cannot be made between internal and external insulation systems.

1.2.1.2.1 External insulation

General requirements

For outdoor free-standing ITs, porcelain or composite insulator housings are used for the external insulation and mechanical withstand functions [4]. The insulators are required to provide safe operation under specified service conditions like:

- mechanical stress
- SF_6-gas service pressure or oil volume and weight
- lightning impulse withstand voltage
  (for $U_m < 300$ kV)
- switching impulse withstand voltage, wet
  (for $U_m \geq 300$ kV)
- atmospheric pollution and/or contamination and rain.

The mechanical stress combined with the service pressure (gas or hydrostatic) determines the wall thickness and the flange design. The length (arcing and creepage distance) and the shed shape are dependent on the electrical and pollution requirements.

For voltages up to 145 kV epoxy and cycloaliphatic resin insulators are also in use, having both electrical and environmental performances that make them interesting contenders.

Recent advances in insulator technology have allowed porcelain and solid insulation hollow tubes to be reinforced with glass-fibre shrouds or liners to prevent fire hazards and explosions in the event of internal arcing. Synthetic, or composite, insulators can have a built-in shroud to accomplish a similar function.

Porcelain insulator

Usually porcelain insulators are only applied with low pressure ITs (up to 2 bar abs.), but high strength porcelain insulators are in use for higher working pressures for SF_6-insulated bushings and some ITs. It is also possible to install an internal plastic tube, for instance made of glass fibre reinforced epoxy resin, to limit the volume of the pressurized gas in the space between the fibre tube and the porcelain insulator. The glass fibre tube may take the full internal pressure whereas the space between the porcelain insulator and the fibre tube is filled with a lower pressure gas. Alternatively a single pressure design is known where the fibre tube has appropriate openings to provide controlled and limited pressure relief.

The porcelain body normally consists of high strength aluminous porcelain according to IEC 60672 group C120 or better. For insulators longer than 1500 - 2000 mm, the body may be made of two or more parts which are connected by ceramic jointing or by jointing with epoxy glue. Air bubbles in the joints could cause partial discharge and care is exercised during the jointing operation to prevent this. In older units the parts are provided with metal flanges and connected by clamping (see Figure 1.34.a).

Composite insulator

Composite insulators are resistant to mechanical impacts and may be used for all internal pressures. They consist of three components:

- glass-fibre reinforced resin tube for the mechanical strength,
- weather sheds made of polymer or silicone rubber for the pollution withstand capability,
- metal flanges.

The sheds are moulded shed by shed with room temperature vulcanizing (RTV) material or cast in one piece (up to approx. 2000 mm) with high temperature vulcanizing (HTV) material. Longer insulators may be cast in two or more steps. The interface zone between tube and silicone rubber shed cover is most important regarding electrical strength because voids or bad bonding could create partial discharges (see Figure 1.35) [5] or flashovers in the bonding zone.

The pollution behaviour of new insulators is sometimes considered to be much better than the behaviour of porcelain insulators with the same creepage distance due to the water repellent property (hydrophobic) of the silicone rubber material. Long term service performance is not yet well documented.

Test procedures for composite insulators are described in IEC/TR 61462 "Composite insulators - Hollow insulators for use in outdoor and indoor electrical equipment - Definitions, test methods, acceptance criteria and design recommendations". In addition, IEC/TR 60815 "Guide for the selection of insulators in respect of polluted conditions" gives information concerning hollow composite insulators in part 3.

Solid-resin insulator

This type of IT family uses the same resin for both the internal and the external insulation, forming one block that also gives mechanical support. For solid-resin insulators, cast-on sheds are added for outdoor applications while ITs for indoor application may have smooth surfaces. The performance of resin as "internal" insulation will be treated later.

Safety issues

Failures are always possible despite the many controls and tests performed on the IT and, apart from disturbances to the power system caused by such failures, the risk of causing human injury must be reduced as far as possible. Measures have been taken to improve general safety, especially within the design process for ITs using porcelain insulators. Whatever the type of design or insulation, it is necessary that connections to ground or to HV-potential be dimensioned to carry the rated earth fault current of the system without melting and be able to withstand short circuit current forces and arcing overpressure without damage. This requirement applies to both CTs and MVTs.

In units with paper-oil insulation, creation of power arcing in the region of the porcelain insulator must be avoided because its resilience to internal arcing faults is low. According to the statistics available for ITs (see Chapter 4), the risk of major failures is extremely low and historically, most faults occur at the top or the bottom section of the transformer around the sensing part rather than within the bushing type insulation. According to laboratory tests, it is necessary to:

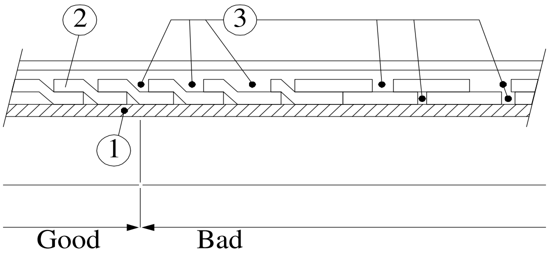
- prevent the pressure wave generated at the time of an internal fault travelling to the hollow porcelain insulator,
- limit the projection of insulator fragments to a few metres,
- reduce the quantity of outflowing oil in order to prevent fire.

In some designs, an internal arc will not usually lead to a catastrophic failure of the hollow porcelain insulator since an epoxy resin reinforced fibreglass tube (or other protection) is installed inside the insulator as discussed previously in order to reduce the effects of the pressure wave. Such a tube may also reduce the volume of oil flowing out after a failure.

1.2.1.2.2 Internal insulation

Paper/oil

The combination of oil-impregnated paper and fluid, mostly mineral transformer oil, is historically the most common and the most traditional of IT insulation concepts. The basis of this design is that the main insulation of the bushing part, consisting of layers of cable paper (‘Kraft’ paper (‘Kraftpapier’ in German)) and using elastic crepe cable paper for ‘problematic’ corners is totally impregnated with transformer oil. The paper is applied in the form of strips, where possible by winding machines, or in the form of sheets, mostly by hand. The withstand voltage capability of this construction in the plane perpendicular to the paper layers is very high. However, in the oil-filled channels longitudinal to the paper, the flashover voltage is much lower. It is therefore very important that the different layers of paper be wound with sufficient overlap to avoid continuous oil channels perpendicular to the layers over a distance of several layers (Figure 1.20), where partial discharge could develop and ultimately lead to the breakdown of the oil channel.



1. Metal tube
2. Paper strip
3. Oil channel

Figure 1.20: Insulation layer overlapping principle

The same principle applies to paper-insulated capacitor elements, where a minimum of three or four layers should be maintained to avoid the capillaries in the paper lining up and forming an oil channel between electrodes. The manufacturing process of this type of insulation is described in Chapter 2.

An important characteristic for all ITs is the position of the sensing part. The most common designs have already been shown in Fig 1.9 for CTs and Figs 1.10 and 1.11 for MVTs. Other designs can be found in older substations, for example the dielectric cascade CT (Figure 1.21a), the magnetic cascade CT (Figure 1.21b) and the open core MVT with disc windings of Fig 1.22 but nowadays these designs have almost been abandoned. A variant of the bar primary live tank CT (of Figure 1.9a), the support insulator CT (Figure 1.21c) is still in use with wound primary and the cores mounted with their centre line in a vertical position.

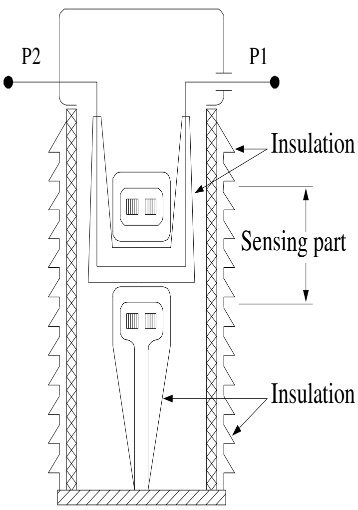


Figure 1.21a: Dielectric cascade-type CT

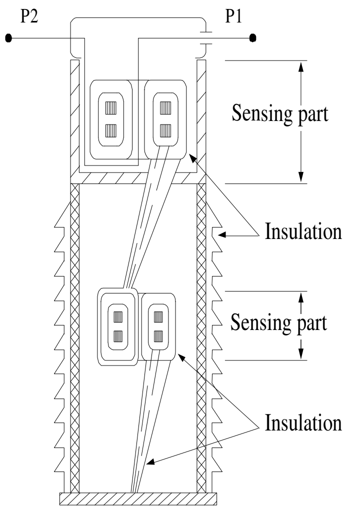


Figure 1.21b: Magnetic cascade-type CT

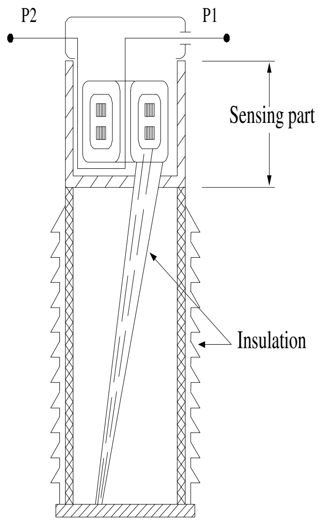


Figure 1.21c: Support insulator CT (core and windings mounted vertically)

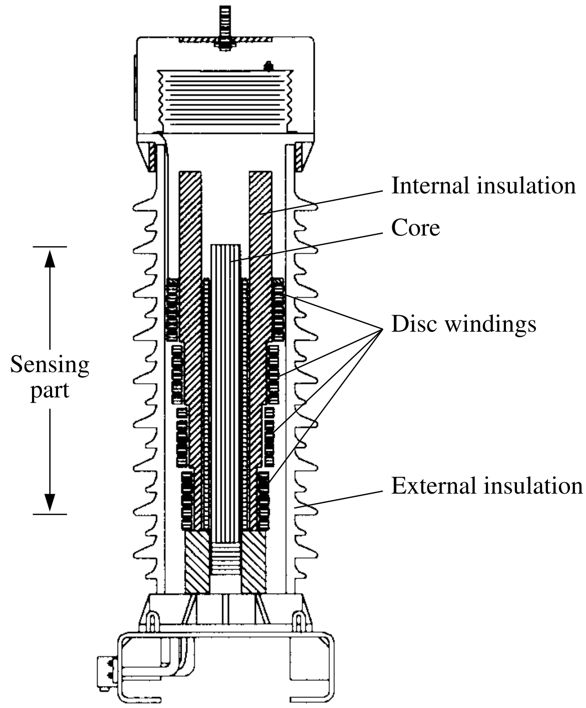


Figure 1.22: Open core MVT with disc windings

These various types of ITs illustrate how the position of the sensing part inside the insulator has led manufacturers to adopt a variety of paper/oil insulation designs.

The remaining space between internal insulation and external insulator is filled with oil. Different solutions exist to allow for expansion of the oil: free breathing, oil under pressure (hermetically sealed) or expansion by means of metal bellows or a rubber membrane of which more details are given in section 1.2.1.4.1. In one design of hairpin type CT, the oil is partially replaced by a filling of electrically inert quartz sand for greater rigidity of the internal primary busbar and insulation against short-circuit current forces.

Nowadays two types of CTs are mainly manufactured: the high-voltage insulation is concentrated either on the primary winding (hair pin or eye-bolt design, Fig 1.9b and c or on the secondary winding (bar primary design, Figure1.9.a. The first type of construction is interesting especially in terms of ease of manufacturing of the HV insulation. The second type offers several advantages:

- short-size primary circuit; this contributes to limiting temperature rise and reducing mechanical stresses during the period of the system fault current,
- symmetrical primary and secondary circuits, so that "a low leakage flux" current transformer is obtained, with consequently small errors even in the transient state and at high current.

In CTs, the common insulation between high voltage and earth potential consists of plain cable paper and/or crepe ‘Kraft’ paper. This insulation is obtained by the application of several layers of paper and insertion of a number of conducting equipotential shields (the number depending on the design) to promote a uniform distribution of the electric field within the head and the bushing type insulation.

The high dielectric strength paper is dried and degassed and vacuum impregnated with high-quality treated oil.

To guarantee the quality and reliability of the HV insulation, extra care is taken regarding:

- components, dimensions and assembly,
- absence of partial discharges at a voltage level far above the operating voltage,
- limited temperature rise during operation,
- shield behaviour in the presence of high frequency (HF) bursts,
- uniform voltage distribution within the insulation in the presence of HV surges,
- air/water-tightness and absence of internal underpressure.

Nowadays, three types of MVTs are manufactured:

– HV winding made from one coil,
– HV winding distributed over 2 or 4 coils.
– HV winding with multiple disc coils

The primary windings are designed with the anti-resonance winding technique to provide an excellent voltage distribution within the HV winding in the presence of steep-front HV surges. The primary winding of extra-high voltage MVTs is distributed over several coils. This "cascade" design offers several advantages - reduction of the electric gradient per coil and simplified coil insulation.

Two designs are in use for the insulation between the layers of the oil-impregnated layer winding:

– Insulation with layers of cable paper. The cooling of this winding can offer problems but the electric field configuration is good because the insulation layers can be bent to closely follow the equipotential surfaces. (Figure 1.23a)
– Barrier-insulation with oil ducts. This design offers good cooling but the electric field configuration at the end of the layers can cause problems in design and during manufacture. (Figure 1.23b)

Special attention has to be given to heating and electrical field concentration especially at the end of windings. Oil can be allowed to circulate by convection by the use of barrier-type insulation fitted with oil ducts as in Figure 1.23.b).

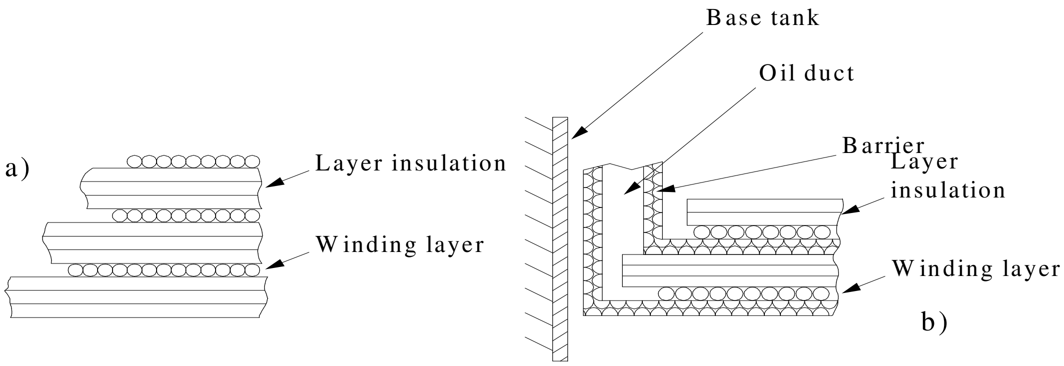


Figure 1.23: Oil impregnated layer winding:
a) without and b) with oil ducts

In CVTs, the HV capacitor and the intermediate capacitor consist of a number of capacitor elements connected in series. Each element is formed by winding together insulation sheets and aluminium sheets, which form the electrodes. Sometimes the edges of the sheets are folded back in order to reduce field concentration which occurs at the edges. The insulation design of the capacitor elements can be distinguished into two types:

a) Single element capacitor design (two electrodes) (Figure 1.24a)
b) Double element capacitor design (three electrodes) (Figure 1.24b)

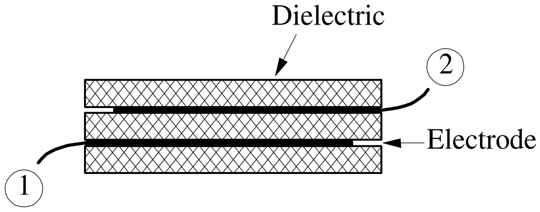


Figure 1.24a: Single element capacitor design (2 electrodes)

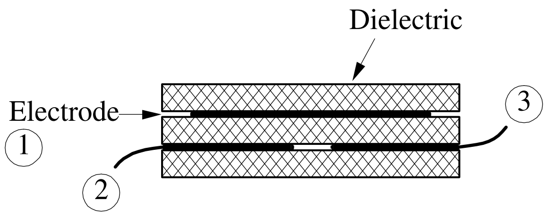


Figure 1.24b: Double element capacitor design (3 electrodes)

In both cases, the dielectric consists of oil-impregnated capacitor paper. Recently the so-called "mixed dielectric", consisting of sandwiched layers of capacitor paper and polypropylene foil has been introduced. In this design, the paper acts as a wick allowing rapid penetration of the oil between the polypropylene foils. The advantages of mixed dielectric media in combination with synthetic oil are as follows: low losses, constant capacitance over the whole temperature range of the CVT and low deterioration of the insulation because of the good gas absorption properties of the oil. The capacitance value may depend on the compression of the paper layers. Synthetic oil is used to allow for a higher capacitance value per volume. In some designs the oil is put under pressure (approx. 2 bars absolute) in order to achieve a higher partial discharge (PD)-inception voltage. The electrical contact between capacitor elements can be achieved by soldering (brazing) of contact strips or by pressing the contact strips together. In modern designs the contacts are made by riveting the electrodes together directly.

Each unit is dehydrated under heat and vacuum then impregnated with high-quality dielectric oil.

The operational quality of ITs depends mainly on the quality of the design (selection of components, process and manufacture) based on theoretical knowledge and field experience as well as on full control of the techniques used.

The choice of the different components and the tests performed on these components are important for the manufacture of high-quality ITs. Key design criteria concern:

- Characteristics and quality of the components defined by the IT manufacturer in the technical specifications.
- Operating temperature range.
- Chemical compatibility between the different components.
- Ageing tests: chemical - thermal - mechanical.
- Corrosion: influence of pollution and ozone.

IEC, ASTM and ISO standards specify the quality and the standard tests to be performed on various components such as enamel-insulated wires, magnetic cores, insulating paper, insulating oil, resins, porcelain and composite insulators, and gaskets. The IT manufacturer may also add more specific requirements and tests.

Apart from the particular points which demand special attention during design, component selection and manufacture, special tests (design tests) are recommended to check the quality of paper-oil insulation, especially in EHV current transformers.

In these units, the insulation is concentrated (one-stage HV insulation) so that the higher the voltage, the thicker the insulation. It is accordingly useful to check that:

- the thermal stability is correct at the rated voltage, frequency and temperature, at maximum current,
- the quality of the shields is correct to withstand steep-front HV surges (circuit-breaker or switching operation): > 200 impulses with chopped front 1×0.5 µs/0.6 U_{LI} with measurement of the gas content in the oil before and three days after the test,
- the voltage distribution is correct along the shields, between 50 Hz and 2 MHz, as HF bursts are generated during switching operations (1 to 3 MHz and 2 to $3 \times \frac{U_m}{\sqrt{3}} \sqrt{2}$).

U_{LI} is the lightning impulse withstand voltage. In MVTs and CVTs the HV insulation is more evenly distributed.

The paper/oil insulation is contained either in a sealed gas-saturated system or a sealed degassed system. Both systems are fitted with breathing and/or expansion devices. Therefore at any point in the insulation the oil-pressure is a function of gas pressure and the height of the oil column.

Paper-film/SF_6 gas

This type of internal insulation basically replaces oil as the bulk fluid in CT, MVT and CVT designs. The winding insulation and the capacitor insulation of individual elements are achieved by a dry-type dielectric such as paper and organic or synthetic films [6].

To obtain the desired dielectric strength and reliable insulation properties at rated operating pressure, extra care should be taken regarding:

- electrode surface quality and state,
- absence of particles inside the unit,
- control of humidity (allowable dew point always lower than minimum ambient),
- control of pure or gas-mixture partial pressures (density indicator) at reduced temperature and the control of leak-rate (typically < 1% per year),
- control of pressure relief features.

For paper-oil insulated ITs, the electrical field is controlled inside the paper insulation whereas for SF_6 insulated units the housing and other metallic parts of the instrument transformer are used as electrodes. Therefore surface roughness is one of the relevant factors for determining the allowable field strength. The other relevant factor for dimensioning is the gas pressure at which the IT is operated. An increase of the pressure essentially gives a higher insulation capability and therefore allows a higher field strength.

In GIS, the IT housings are part of the substation and the design pressure of the IT has to be adjusted to that of the substation. Basically the pertinent standards and safety precautions have to be observed in designing the housing. The design pressure of the substation results from its rated pressure at 20°C and represents the maximum pressure of the substation in operation.

For all SF_6-insulated free-standing and GIS-connected ITs, the pressure coordination could be, for example, in accordance with EN 50052 (see Figure 1.25).

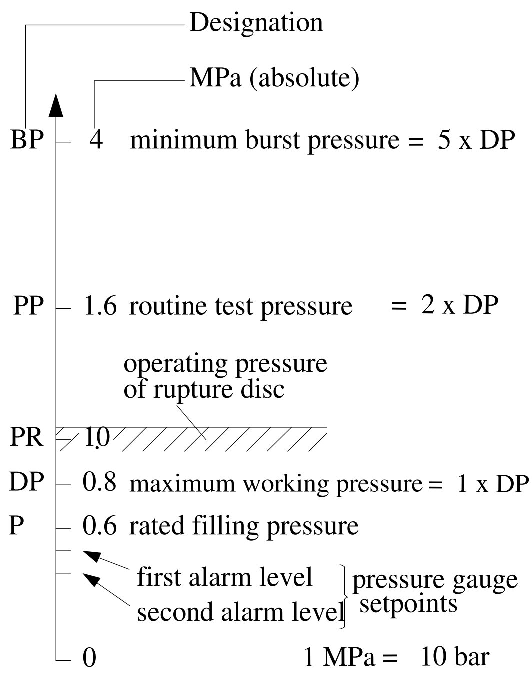


Figure 1.25: Gas pressure coordination for SF_6-insulated ITs

P) rated filling pressure P at 20°C
DP) maximum working pressure at maximum temperature = DP
PR) operating pressure of rupture disc
PP) routine test pressure RP for water pressure test = 2 × DP
BP) type test pressure *e.g.* for bursting test: burst pressure BP ≥ 5 × DP.

The working pressure for safety components (PR) such as a rupture disc is set between the design pressure and the routine test pressure. The routine test pressure is confirmed by stamps on the housing parts. Metal alloys are specified and have to be documented.

Usual values of the working pressure lie in the range 4 and 6 bars both for free-standing and GIS-connected units.

Dimensioning of the thickness of the housing walls is not only done in accordance with the pressure vessel standards - the burn-through time by arcing in the event of an internal fault to earth has also to be considered at critical points.

Temperature compensated pressure gauges are used for monitoring the gas density. They will be dealt with in the auxiliary parts section.

So-called 'absorption cartridges' can be used to ensure a constantly low dew point of the SF_6-gas over the total operating life which are filled with molecular sieves consisting of granulated sinter material which have a very large internal surface as a drying agent. Even in small quantities, molecular sieves are able to absorb and retain a lot of moisture.

Resin insulation

Figure 1.26 shows an MVT that uses the same resin for internal and external insulation, forming one block that also gives mechanical support. Primary and secondary windings are wrapped in such a way that they are able to absorb differences in expansion and contraction between the metal parts and the resin [7]. Cycloaliphatic resin properties are compatible with severe environmental conditions and Resin has a good characteristic of thermal dissipation.

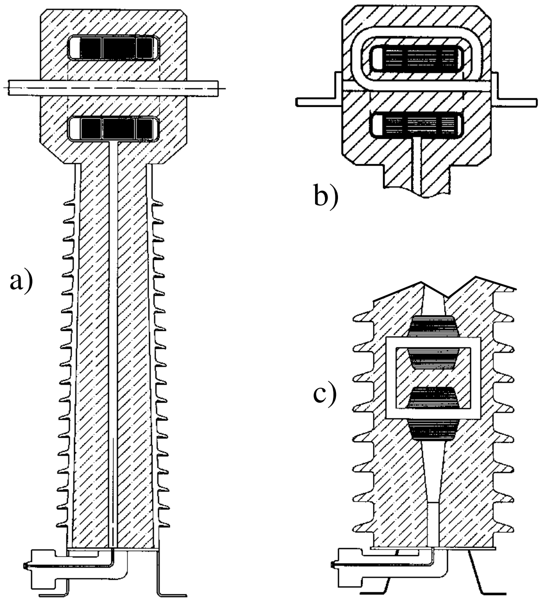


Figure 1.26: Solid insulation type IT: CTs with a) single and b) and multiple turns, and c) MVT design

The sensing parts, *i.e.* the core and the windings are typically located at the centre of the IT to improve the distribution of the electrical field on the external surfaces.

The IT can be stored and handled in any position - this gives more flexibility during transport and there is no need for maintenance before installation. The CT also has a high mechanical strength against primary short-time currents.

Figure 1.26a also shows a CT with the main internal insulation made from resin but with a separate external insulator. Primary terminals are located in the upper part of the head in straight bar (Figure 1.26a) or multiple turn configurations as shown in Figure 1.26b. The head of the IT may be covered with metal paint or provided with a metal screen cast in the resin just under the surface to obtain a better voltage distribution in the resin. For use in severe pollution environments, the whole sensing part may be pre-moulded in resin and a synthetic material added to give an improved exposed insulation surface. Other designs make use of cast sensing parts pre-moulded and fitted inside a gas containment or oil-filled containment structure. Finally, the pre-moulded part can be enclosed in another resin shell-structure that is moulded inside the external epoxy resin.

The operational reliability of a resin-based HV insulation is greatly affected on one hand by the choice of resin/hardener system and the type and percentage of filler and on the other by the production process items such as drying/degassing, mixing quality and the temperature cycle. The voltage gradient at rated voltage should not exceed 3 kV/mm and the creepage distance (insulators using cycloaliphatic resin) should be 25% higher than that of porcelain insulators. The PD level after dielectric tests should be < 10pC at 0.7 U_m.

Electric field stress grading

The most important point in the design of the main insulation of ITs is to achieve an equal voltage distribution over the external and internal surfaces of the insulator as well as over the surfaces of the internal main insulation and inside this insulation. The principle is that high electric field strength points should be avoided everywhere in the construction.

If the voltage distribution along the length of the internal insulation is homogeneous, the voltage distribution over the surface of the insulator will also be almost linear. Quite clearly this applies to capacitor stacks of CVTs on the condition that the insulator is completely filled with capacitor elements or, if not, that metallic spacers are inserted at regular distances between the capacitor elements. In CTs, a linear voltage distribution can be approached by the use of graded insulation made of paper insulation with screens of metal foil or carbonized paper inserted at regular intervals, in a similar way to the construction of the active part of HV bushings. The principle is that these screens are inserted in the paper insulation, being divided over the insulation thickness at such distances that the voltage difference between adjacent screens will be equal for all screens. Two solutions exist:

- with a few capacitive grading screens (Figure 1.27a), where grading rings (toroids) should be connected at the end of the screens to avoid concentrations of equipotential lines (high electric field stress),

or

- with a large number of screens at a potential difference of a few kV between the screens (Figure 1.27b). In this case grading rings at the end of the screens are not necessary because the electric field is uniform in these regions.

The HV primary conductor (at 100% voltage) is in the centre in these constructions.

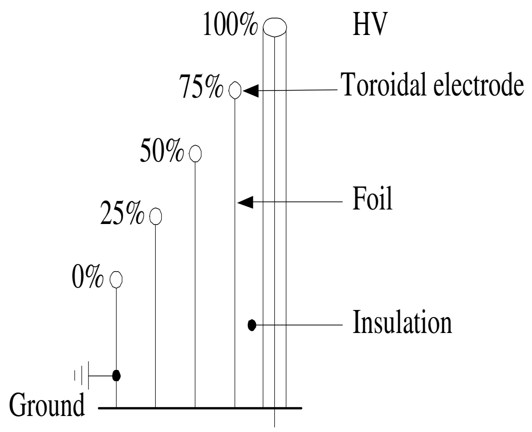


Figure 1.27a: Electric field stress relief concept with few capacitive grading screens and toroidal electrodes

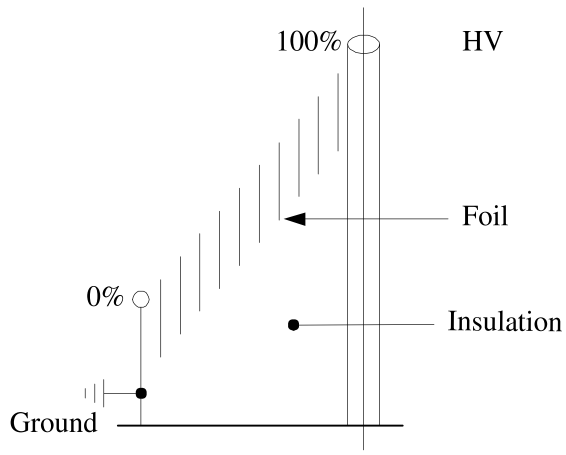
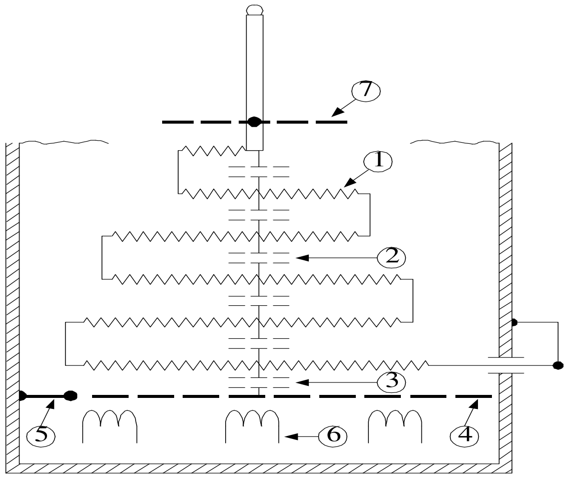


Figure 1.27b: Electric field stress relief concept using a large number of screens

For the bar primary live tank CT (reference to Figure 1.9.a), the bushing type insulation is applied to the "stem", which is the earthed tube housing the leads from the secondary windings to the terminal box. In this design, the tube in the centre is at zero (earth) potential and the outermost screen at 100% voltage: the paper insulation between the bar primary and the earthed toroid housing the cores also has a few screens.

For MVTs, the HV-layer winding is of trapezoid form with layer insulation as in Figure 1.23a and has an excellent voltage distribution which is controlled by the high-voltage and the earthed screens (item 7 and 4 in the equivalent circuit of Figure 1.28). The impulse behaviour is also very good due to the high natural capacitance between the winding layers. Moreover, this trapezoidal winding has an excellent mechanical stability if the insulation layers are folded back tightly and fixed properly.

It is very important that the shielding screen (item 4, Figure 1.28) between the last HV-winding layer and the secondary windings be earthed by means of a low impedance connecting lead. This will largely reduce the penetration of transient overvoltages from the HV-windings into the secondary windings.



1. Layer winding
2. Natural capacitance between two winding layers
3. Natural capacitance between the last winding layer and screen
4. Earthed screen
5. Low inductance earth connections
6. Secondary windings
7. HV screen

Figure 1.28: Equivalent circuit of layer windings in a MVT, showing earthed screens

Insulation design problems with MVTs could also arise in the construction of the insulation around the primary lead to the HV-winding. The principle of the design results in the stem being insulated by bushing type insulation but the screens are not connected to those of the HV winding insulation.

Field shaping is of paramount importance in SF_6 insulated designs. The distribution of the electric field is mainly determined by the shape of the HV- and LV-electrodes, the highest field strength usually occurring at the HV-electrode. The actual field strength distribution can be determined to very high accuracy using numerical field calculation methods like the charge simulation or the finite element method respectively.

To get a uniform field distribution along the high-voltage coil, intermediate electrodes may be used for system voltages in excess of 300 kV. This applies to free-standing transformers as well as to MVTs for GIS. Additionally a free-standing unit needs a sort of grading system to get an even distribution of the field stress along the insulator. For system voltages up to 300 kV this can normally be done by a carefully designed HV-electrode but an electrode with floating middle potential may be used for higher system voltages. Alternatively foil tube insulation with grading capacitor inserts may be used.

Figure 1.29 shows the critical points of careful field profiling in a dead-tank and a live-tank MVT using SF_6 as the main insulation. Similarly electric field stress relieving in CTs can be accomplished using smoothing electrodes or screens in solid, cast epoxy resin designs (Figure 1.30).

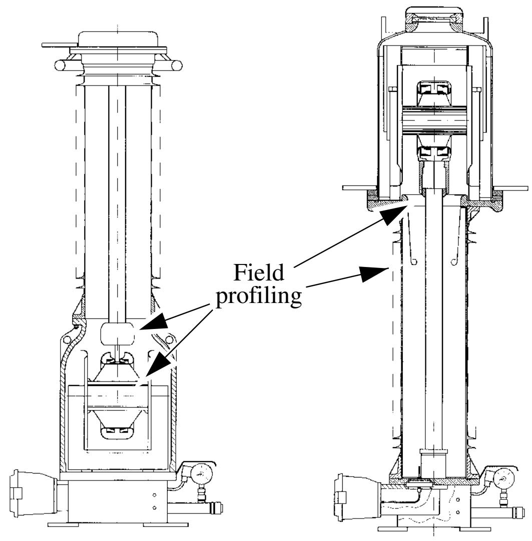


Figure 1.29: Field profiling designs for a dead-tank (left) and a live-tank (right) SF_6 insulated MVT

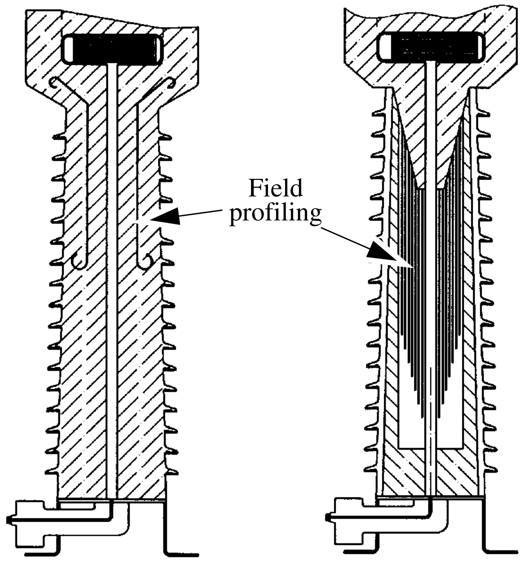


Figure 1.30: Field profiling designs for a resin insulated CT using a screen (left) and foil layers (right)

Environmental issues

Utilities and manufacturers have to comply with strict regulations concerning the handling, transportation and/or disposal of the great majority of insulating fluids and gasses. Regulatory bodies, for instance, are increasing their requirements with respect to reclaiming and re-cycling procedures of used insulating oil. In some cases, even the prevention of seepage into various soil types is regulated, whereby severe containment regulations are, of course, enforced. Specific procedures have been established for transporting used fluids and discarded insulating elements such as tanks, windings, bushings, etc. Strict company procedures are also commonplace regarding the maintenance and testing of ITs and power transformers with gaseous or liquid insulation. Recent regulations have, to all intents and purposes, banned fluids such as polychlorinated biphenols (PCBs) that may be potentially hazardous for humans, animals and/or the vegetation if burned in the atmosphere, spilled on the soil or released into underground water.

1.2.1.3 Common components

1.2.1.3.1 Tanks

The housing of free standing ITs has two main components: a base tank and a head tank, which are connected by the porcelain (or composite) insulator bushing.

Materials used for the design of the "base and head" tanks are:

– cast iron,
– welded steel,
– hot-dip galvanized welded steel,
– welded stainless steel
– cast aluminium
– welded aluminium
– cast resin.

The protection of the external surfaces against the atmosphere is well developed and the surfaces of the tanks are protected against corrosion by special technologies. However, there is little information available about gap corrosion between two parts joined by a sealing system and about protection against "gap corrosion".

Corrosion of the internal surface could be important as it may affect the lifetime of the IT. In cast-alloy housings an internal coating may be applied to provide oil-tightness and an internal coating can also be useful to prevent corrosion during the manufacturing process. Some varnish types used for the corrosion protection of internal metal surfaces can give off their solvents over a long time after application and these solvents can give the impression that an electric fault is developing in the unit when performing the first dissolved gas analysis (DGA) of the oil. Users need to be aware of this problem and manufacturers should avoid the use of such varnishes. A similar problem can arise if zinc-chloride from galvanised surfaces reacts with moisture in the oil causing the development of hydrogen.

1.2.1.3.2 Flanges and seals

Dielectric performance is intimately related to the quality and stability of the insulation fluid and to the mechanical integrity of bushing and tanks. The traditional porcelain and oil combination has recently become in competition with lighter and less fragile synthetic bushings that make good combinations with gas insulated ITs. Design principles equally apply to composite or synthetic insulators.

There are two main ways of fixing the porcelain insulator to the tanks: by clamping the bushing to the head and base flanges with the use of seals (Figure 1.31a) or by cementing the insulator in a metal flange or metal housing (Figure 1.31b). The latter method avoids stressing of the porcelain body due to grinding or local clamping.

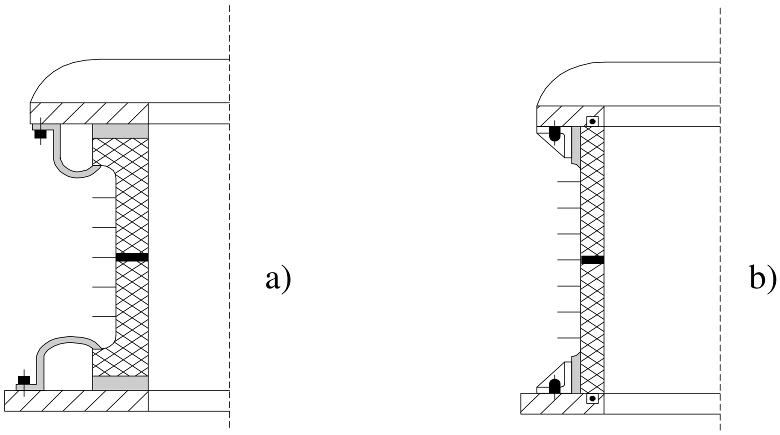


Figure 1.31: Design concepts of flange fixing to porcelain insulators, a) by clamping and b) by cementing

Composite hollow bushings are made of a shell and a separate soft insulating shroud. These bushings have their mechanical functions and their internal insulating functions performed by their internal tube. This reinforced tube is made of an epoxy resin impregnated synthetic fibre cloth. Both shrinking and material bonding techniques are used to attach the flanges - a combination of glueing and compression ensures gas and moisture tightness. Care is taken to provide the necessary stress relief at the various interfaces (Figure 1.32).

Three interfaces are indicated, namely:

- interface 1 between the flanges and the insulating tube,
- interface 2 between the flanges and the silicone rubber housing
- interface 3 between the insulating tube and the silicone rubber housing.

Sealing of the silicone rubber housing has to be validated by several moisture ingress tests which are performed along with ageing and pollution performance tests.

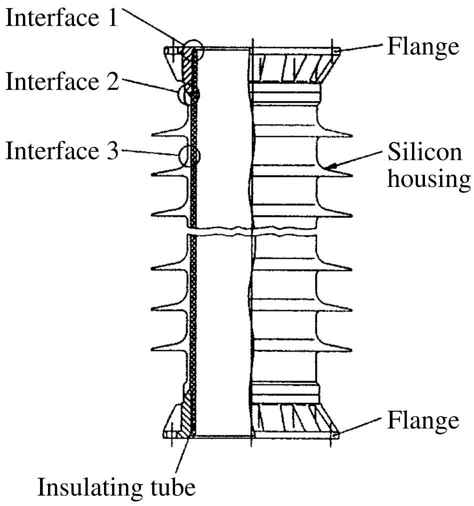


Figure 1.32: Design principles of synthetic insulators, showing various material interfaces and flange fixing

The length of the insulator (external insulation) is determined by the ac-power frequency withstand wet test for rated voltages < 245 kV and by the positive switching impulse wet test (SIL) for voltages ≥ 245 kV. In accordance with IEC recommendations, the probability of the flashover is < 10% for the SIL-withstand-voltage. The shape of the insulator sheds is important for polluted environments.

In order to keep leakage of the housing in gas insulated systems to minimum, recessed 'O' rings are used as gaskets. The surfaces of the sealing areas have to be of high quality. Cast housings should have a very dense, porosity free structure and welded housings require an appropriate welding procedure in order to have a high quality welding seam. A Helium leak test should be made on each housing before assembly and gaskets and flanges tested at operating pressure with a SF_6-leak-detection-device after assembly. For outdoor operation, gap corrosion has to be avoided by greasing flange gaps and only stainless steel screws should be used. External corrosion can be effectively avoided by using appropriate metal alloys and by applying modern varnishes.

1.2.1.3.3 Primary terminals

Primary terminals of CTs should be dimensioned for 1.2 × or sometimes 2 × rated current of the CT and should be able to withstand the rated short circuit current of the system mechanically and thermally. One terminal, in most cases P_2 at the busbar side, should be connected to the metallic head of the CT whereas P_1 on the line side should be insulated from the CT head. If needed the insulation gap of P_1 could be bridged by means of a LV-surge arrester. The CT terminals can be of different shapes, for example a cylindrical pin or disc provided with screw holes or a "flag" (a thick metal sheet in square or rectangular form provided with bolt holes). The terminal material can be aluminium, copper (silver-plated if necessary) or other material but should be compatible with the material of the HV connector in order to prevent corrosion between the two materials.

The dimensions of the primary terminal of MVTs and CVTs should suit the diameter of the connecting HV-outdoor conductor, which is determined by the requirement that the conductor should be corona-free. Moreover the primary terminals and the top housing should be able to withstand the rated earth fault current of the system during in the event of an external flashover of the unit.

1.2.1.3.4 Terminal boxes

The most common failures of secondary wiring and terminal boxes are conductor breakage, corrosion, insulation failures and leakage. These failures can be largely prevented by proper choice of materials and strict quality control during manufacturing.

The secondary terminals can be screws or bolts or wire connectors for wires up to 4 mm^2 and will usually be mounted in terminal boxes. It is advised that the terminal box should be provided with a copper earthing bar or strip to facilitate the earthing of the different secondary windings and the earth screens of the outgoing secondary cables. One terminal of each secondary winding of an IT must be earthed with one important exception - when secondary or tertiary windings of

VTs are connected in delta, only one corner of the delta might be earthed. The secondary earthing may be made in the terminal box. The terminal box can be built to meet different degrees of mechanical protection and can often be provided with anti-condensation heating. In some cases the box will also house terminals for tan-delta measurement of the main insulation, the earth switch of hf-carrier equipment for CVTs, or equipment for monitoring of the unit.

According to ANSI/IEEE Standards, CVTs should be provided with a potential grounding switch inside or near the terminal box for earthing of the EM unit.

The multiple conductor bushing bringing the secondary wires from the secondary windings out to the terminal box should be completely oil or SF_6 gas-tight even after 25 years service or more.

1.2.1.4 Auxiliary parts

1.2.1.4.1 Oil and gas containment

Leakage is the major problem in service for oil-insulated ITs (see Chapter 4) and could give rise to environmental pollution or endanger the internal insulation of the unit and cause failures if not detected in time. Therefore, good attention should be given to the design and manufacturing of all components where oil leakage could occur (flanges and seals, oil expansion devices etc.) and to the packing, transportation of the unit and the inspection and maintenance after installation.

Filling and monitoring

Oil and gas filling is usually done under controlled environments. Nevertheless, maintenance and operational procedures may require subsequent filling, although very rarely. The parts of the IT used for filling are thus very seldom used.

For checking and monitoring of ITs, the following devices can be installed:

- oil level indicators or minimum oil level alarms,
- bellows or membrane position indicators,
- oil pressure indicators, for hermetically sealed, oil-paper insulated ITs,
- gas density indicators for SF_6-insulated types, generally provided with alarm and emergency contacts,
- gas detection devices or gas relays, for paper-oil insulated types,
- oil sampling valves for dissolved gas analysis (DGA). Care should be taken that during sampling or after taking a number of samples, an equal volume of clean dry oil is refilled into the unit without allowing air bubbles or moisture into the oil of the IT,
- gas detection probes. One system is based on the molecular sieve and allows checks of the gas content (mainly hydrogen) of the oil at regular time intervals. The other system is based on the hydrogen/oxygen voltage cell and allows continuous surveillance of the oil and is used for power transformers and could possibly be adapted for use with ITs. However, the cost of gas detection probes should be considered in relation to the price of the IT.

All the above mentioned devices are usually built for visual inspection but are sometimes provided with alarm contacts.

GIS ITs usually have two valves: one valve is used as a connection to the density gauge and the other serves as a filling valve. Test samples may be drawn via this valve or, if necessary, gas may be refilled.

Oil expansion devices

Several solutions exist to accommodate expansion of the oil in paper-oil insulated ITs, working either with:

1. gas saturated oil

or

2. degassed oil

and with

a - constant pressure

or

b - temperature dependent pressure in the oil.

All combinations of 1. and 2. with a and b are possible.

1a1 - free breathing system where the oil is in contact with ambient air via an air dryer (silica gel type). This system is in use in older types and for lower rated voltages. The oil and the insulation will age more rapidly but this is not a severe problem in amply dimensioned insulation systems;

1a2 - hermetically sealed system with nitrogen cushion in contact with the oil, where the nitrogen can expand and contract in a rubber lung above the oil. There is a possibility of gas development in oil (see 1b below).

1b - hermetically sealed system with a nitrogen cushion in direct contact with the oil. The is a possibility that gas bubbles could develop in the oil during sudden drops of ambient temperature which could cause flashovers of the internal insulation or PD under service conditions;

2a - oil expansion system by means of a metal bellows or elastomer membrane. Bellows can either be of the positive type which are mounted on top of the head tank of the IT, or negative and sinking down into the head tank. Position indication is more difficult with negative bellows arrangements and leakage detection on the bellows is very complicated.

2b - sealed system with nitrogen cushion contained in metal bellows or a rubber lung immersed in the oil of the head tank. There is a possibility that gas will penetrate into the oil because the lung is not completely gas-tight.

In hermetically sealed systems there is a possibility that an underpressure occurs in the oil at low ambient temperature with the danger that humid ambient air can be sucked in through non-tight gaskets. Moreover, the partial discharge inception voltage can drop to dangerous values.

In ITs with oil expansion by means of bellows or membranes (type 2a), an oil drain valve and possibly an oil sampling valve is usually fitted in the base of the unit.

All oil expansion systems should be designed bearing in mind the specific ambient and environmental conditions in the country of destination or substation location in order to prevent inadvertent leakage and other problems such as corrosion of the bellows.

SF_6-gas protection devices

For gas insulated ITs, leakage is also the major problem found in service (in the same way as for paper-oil ITs). Temperature compensated pressure gauges are used in GIS ITs (See Figure 1.25). For remote monitoring two alarm contacts are used:

- first alarm level:
  first contact is activated if the pressure falls below a value P_1 which is the minimum pressure at which the unit should be able to withstand the test voltages. Routine and type tests should be performed at the pressure P_1,
- second alarm level:
  second contact is activated if the pressure falls below a value P_2, lower than P_1. At pressure P_2 the unit should be able to withstand normal service voltages for a short time, 15 min. for example. When the alarm for P_2 is activated, the part of the substation to which the affected unit is connected should be switched off.

The values of P_1 and P_2 are determined by the manufacturer.

Each pressure vessel should also have protection against overpressure to avoid bursting in the event of either filling errors or the pressure increase caused by an internal power arc. Since a rapid pressure increase occurs in event of a power arc, there has to be a sufficient cross section of the opening to achieve rapid gas expulsion. This requirement is met by rupture (bursting) discs or spring loaded valves having a large cross sectional opening. Normal pressure relief valves are not sufficient.

There are three kinds of design for rupture discs:

- convex metal rupture discs of nickel sheet
- metal rupture discs of sintered metal
- graphite rupture discs.

For safeguarding personnel, it is imperative to provide an appropriate cover for the rupture disc arrangement to achieve a predetermined direction of the gas stream.

1.2.1.4.2 Capacitive taps

Capacitive taps (sometimes also known as ‘test taps’) on CTs are used for the measurement of voltage or the tan delta (tanδ) of the bushing part of the main insulation. The capacitive tap is connected to an insulated secondary terminal and is earthed when the CT is in normal service. (Note: see also section 1.2.2.3 dealing with capacitive taps designed for the provision of a voltage signal)

This tap allows tan delta measurements on two different parts of the main insulation:

1. Measurement of the tan delta of the insulation between the tapped screen and the adjacent earthed screen. This measurement is not very accurate, because the insulation between the two screens is not stressed electrically in normal service but it can give a warning of abnormally high moisture content in the insulation.
2. Measurement of the tan delta of the main insulation between the primary terminal and the tapped screen. This method has the advantage of measuring a well defined capacitance, but the disadvantage that the CT has to be disconnected from the line. It is, however, not necessary to isolate the base of the CT from ground.

The connection of the tap to the screen should be made very carefully, by soldering to a metal screen or pressing tightly to a carbonized paper screen. If this connection were to become loose, arcing could occur with subsequent damage to the CT.

A rough indication of changes of the tan delta value can be obtained by means of a device mounted in the base of the IT and consisting of an image capacitor which is made of the same materials as the main insulation. The tan delta of this capacitor can give an indication of high moisture content of the main insulation but not of any degradation caused by overstressing, overheating or influence of high frequency transients.

For CVTs, the connection between the tap on the capacitor voltage divider and the electromagnetic unit can be used for tan delta measurements but only if it is easily accessible.

These taps have also been used in order to facilitate on-line surveillance systems to detect any troublesome conditions that may develop in CVTs. Attempts to obtain knowledge of partial discharge (PD) signatures that could serve as indicators of conditions prior to failures have been made recently.

1.2.1.4.3 Safety devices

Earthing

Proper earthing of internal screens and electric field stress relieving layers has to be ensured throughout the lifetime of the IT. This is also true for the tie-point that ensures earthing of the IT equipment to the substation earth grid. These earthing points are designed in such a way as to ensure safety in the case of system faults in the immediate vicinity of the IT and to prevent overvoltages on the secondary signals. For earthing of secondary windings see 1.2.1.3.4.

Cables

The various secondary terminals have to feed multiple equipments in the control room. A number of procedures have to be standardized so as to assure low power losses and appropriate insulation levels throughout the length of the cables. Current loops have to comply with strict wiring requirements and systematic cable labelling within the control bay environment. The advent of novel techniques making use of fibre optic cables has alleviated the safety aspects significantly with respect to errors in handling of secondary terminal cables, which could lead to short circuits or overvoltages. However optical cable technology has yet to match the ruggedness of electrical cables in the substation environment.

Surge protection

A great number of auxiliary devices have to do with the protection of secondary outputs and capacitive taps. In essence they include spark-gaps, fuses and semiconductors in passive and active circuitry. Transient voltage suppressors have been added to existing ITs in addition to protection during steady-state operations because of increasingly demanding substation conditions. High-frequency transients and ferroresonance stresses are discussed under "Special Constraints". Historically, they have been the source of many IT failures.

1.2.1.4.4 Support structures

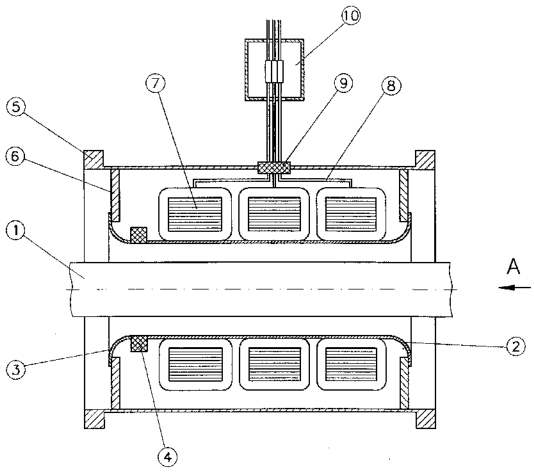
These structures ensure proper clearance within substations for safe operation of machinery and service vehicles. This hardware has to comply with similar standards regarding corrosion as, for instance, for line hardware. Seismic constraints call for extra care for the protection of key IT functions in some areas.

1.2.2 Special Instrument Transformer features

1.2.2.1 GIS connected IT

The typical design for CTs in GIS (Figure 1.33) consists of the cores (7) mounted on a cylindrical field electrode (2), (3) co-axially arranged around the primary conductor and assembled in a housing. This grading electrode controls the field distribution towards the primary conductor (1) and ends with large radii.

The grading electrode is fixed to the housing (5) by means of metallic supports (6) and has a defined insulation gap (4) in order to avoid a closed loop around the cores. The secondary leads (8) of the cores are brought out via a multipin bushing (9) to the secondary terminal box (10). Transient overvoltages are reduced to a minimum by appropriate screening of cores and secondary leads. The grading electrode and its metal support as well as the attachment of the cores onto the electrode should be dimensioned in such a way that they can resist mechanical stresses during transportation.



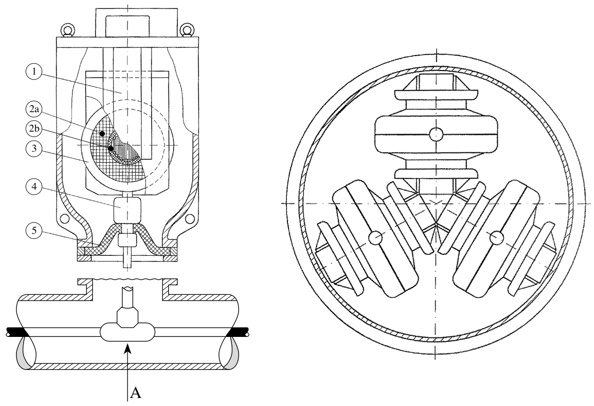
1. Primary conductor
2. Cylindrical electrode
3. Cylindrical electrode
4. Protective gap
5. Disc-type insulator
6. Metal support
7. Cores and windings
8. Secondary leads
9. Feedthrough bushing
10. Terminal box

Figure 1.33: Gas insulated single-phase CT design for GIS

Separation of the CT gas volume and the GIS gas volume is not usual. Gas monitoring or rupture discs are therefore not used in GIS CTs.

The sensing part of MVTs in GIS (Figure 1.34a) consists of a laminated core (1) in an upright position, within a profiled shell bearing the coils (2a-HV, 2b-LV). The secondary and primary windings are concentric. electrodes (3) with large radii and the coil shell fulfil the field-distribution requirements around the coils. The secondary leads and the neutral end of the primary winding are brought out from the MVT housing via a multipin bushing insulator. On the primary side, the electrode (4) of a disc type insulator (5) is connected by a well rounded conductor to the HV terminal. The disk type insulator also separates the MVT gas volume from the GIS gas volume.

In the three-phase MVT (Figure 1.34b), seen from the direction of arrow A in Figure 1.34a, the arrangement of the cores onto the grading electrode is the same as in the single phase design. The suspension of the electrode and core unit is more complex in the three phase system. The secondary terminal leads of the cores can either be fed through the housing phase by phase or bundled together through a multipin bushing.



Single-phase
(a)

Three-phase
(b)

Figure 1.34: MVTs for GIS

With the three-phase arrangement the sensing parts are arranged in a common housing. The same principles apply for the sensing parts and the housing as in the single-phase design. In the arrangement and design of the sensing parts the dynamic and mechanical stresses caused by line discharges have to be taken into consideration as will be seen later.

There are also CVT designs applied to GIS equipment. The schematic representation of such devices is shown in Figure 1.35. The capacitive coupling between C_1 and C_2 is accomplished by an insulated circular pick-up representing capacitor C_1.

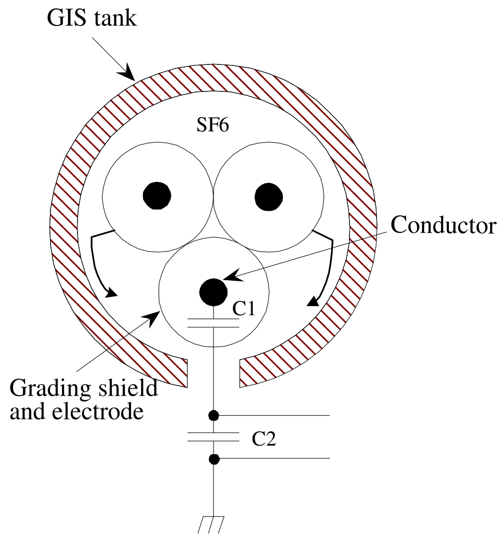


Figure 1.35: Schematic circuit of 3-phase CVT using SF_6 internal insulation

1.2.2.2 Bushing-mounted current transformer

This type of CT can be retrofitted over the bushings of power transformers, reactors, and dead-tank circuit breakers. The bushing-type CT is mounted externally over and at the lower end of the bushing and is placed on the tank cover of the apparatus at ground potential. These CTs are used primarily for protection but may also be used for metering and control. They are made of toroidal cores of grain oriented steel with single or multiple windings, with or without air-gaps. This type of CT is widely used in the USA and other countries with comparable design principles for substations, mostly mounted on dead-tank circuit breakers.

1.2.2.3 Capacitive tap on CTs

The internal main insulation of CTs is often of the bushing type, consisting of paper insulation with voltage grading screens inserted. With a right choice of insulation layer thickness it is possible to tap off a voltage signal, of up to a few kV only between the earthed screen and its adjacent screen because it is impracticable to produce a large spacing of the insulating layer between them. This voltage signal can be used as a voltage indication without amplification. If however equipment with higher power consumption and low burden impedance were connected, the insertion of an amplifier would be necessary to meet the demands of the load. Figure 1.36 illustrates the free-standing version of voltage measurement using a capacitive tap on a CT, where the voltage is obtained much in the same way as with a CVT.

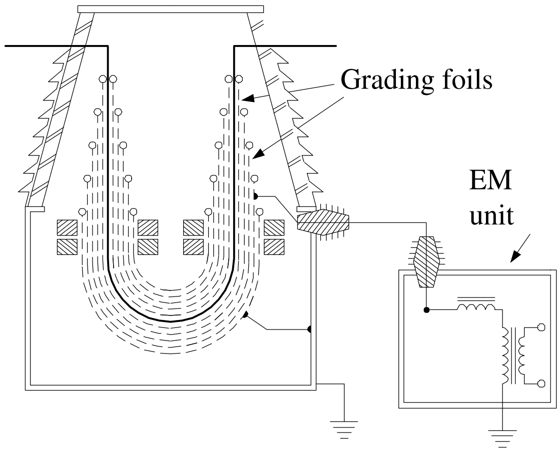


Figure 1.36: Illustration of a capacitive tap voltage transformer attached to a conventional hair-pin CT

1.3 Instrument Transducers

1.3.1 Optical transducer features

1.3.1.1 Nomenclature

The key features of a freestanding optical instrument transducer can be illustrated with the functional diagram given in Figure 1.37.

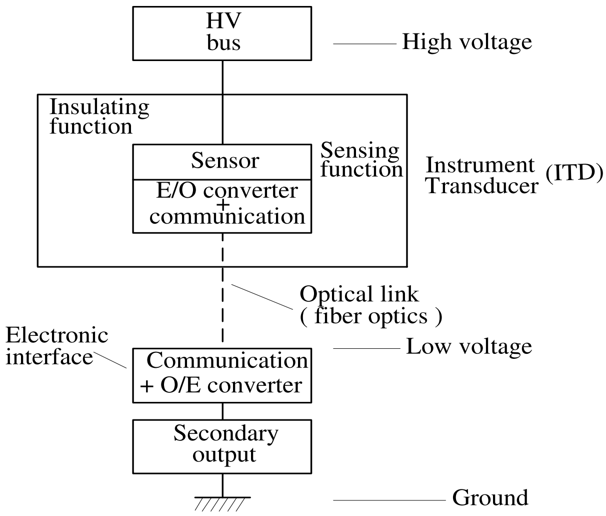


Figure 1.37: Functional diagram of instrument transducer

The main functions are the same as for a conventional IT, namely the insulating function and the sensing function. In this case however the link between the instrument transducer and the secondary output is no longer direct and "hard-wired". The link between the sensor and the low-voltage is achieved by optical converters and fibre channels. Moreover these converters need to communicate between each other. Many communication schemes can be used but only a general description is given here. The symbols E/O and O/E refer to the electrical-to-optical and the optical-to-electrical conversion of the sensor signals transferred via the communication link. Basically, the fundamental difference between an instrument transducer and a conventional IT is the electronic interface needed for its operation. This interface is required both for the sensing function and for adapting the new sensor technology to that of the secondary output currents and voltages [8, 9].

The simplest way to get acquainted with optical instrument transducers and conventional instrument transformers alike is to consider their basic similarities and their basic differences. In fact they share a number of parts, as shown in

Figure 1.38. This comparison of a double-sensor optical CT with a hairpin-type magnetic CT illustrates similarities between the two technologies. Multiplicity of functions and redundancies are achieved conventionally by using multiple secondary coils. For the optical CT, multiplicity of substation functions and added redundancies, for instance for reliability reasons, are achieved using multiple sensing units. Multiple outputs can be fanned out from each sensing unit or from each individual interface module in order to achieve several tasks, much like is done by looping relay coils from the individual hard-wired secondary cables. Optical cables can be made that contain several optical fibres, with quite rugged jacket material.

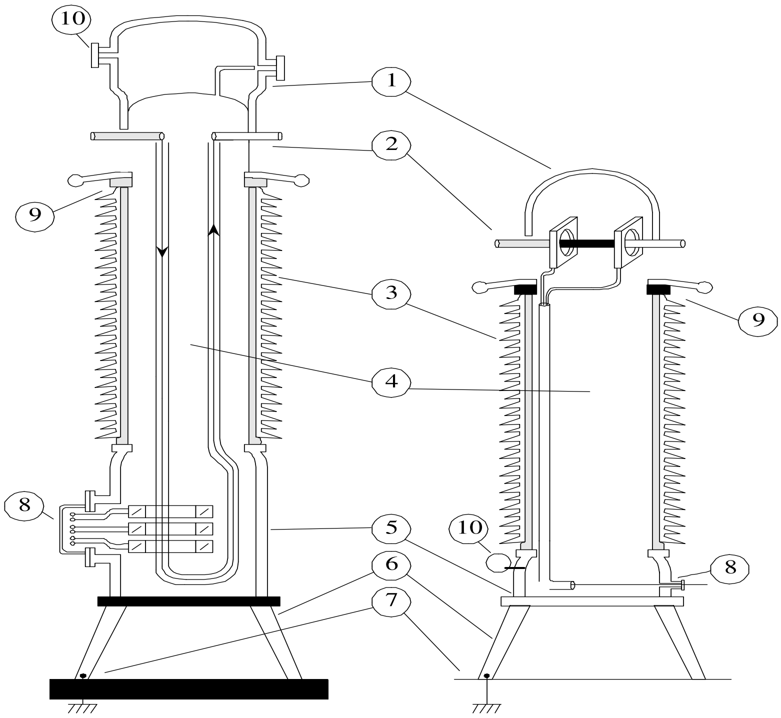


Figure 1.38: Design similarities between conventional free-standing IT concept and its optical counterpart

Non-conventional optical transducers actually lend themselves to smaller, lighter devices where the overall size and power-rating of the unit does not have any significant bearing on the size and the complexity of the sensor. With the advent of synthetic rubbers and silicone shed materials, lighter high-voltage insulators are becoming widespread. These insulator structures can be tailor-made to fit optical sensing devices in the sense that fibres can now be made an integral part of the insulator. The lighter sensors require much smaller and much lighter insulators. Some concepts can be conceived that will eventually be strung from under conductor bundles or busbars, or readily be part of the apparatus.

"Optical" transducers can be separated in two families: firstly the *hybrid* transducers, making use of conventional electrical circuit techniques to which are coupled various optical converter systems, and secondly the *genuine* transducers which are based on fundamental, optical sensing principles.

A hybrid combined IT is schematically described in Figure 1.39. This schematic representation shows a passive voltage sensor and dual passive current sensors, forming a combined optical CT and CVT. Recently prototypes of a combined optical CT and of a fully-optical voltage transducer have been proposed. This is shown schematically in Figure 1.40.

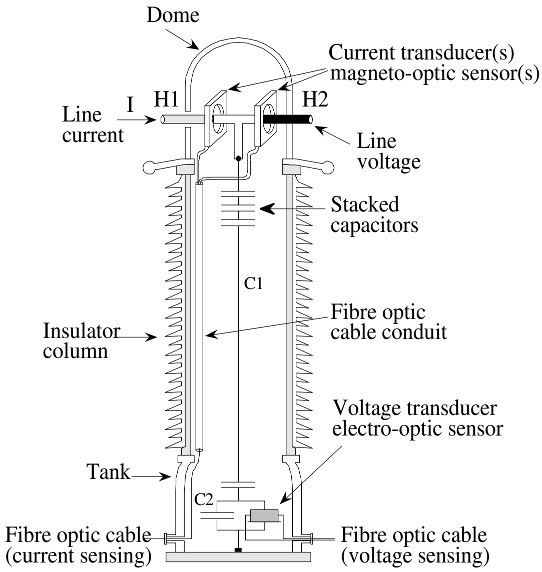


Figure 1.39: Combined optical IT (CT and CVT), using a conventional capacitor voltage divider concept

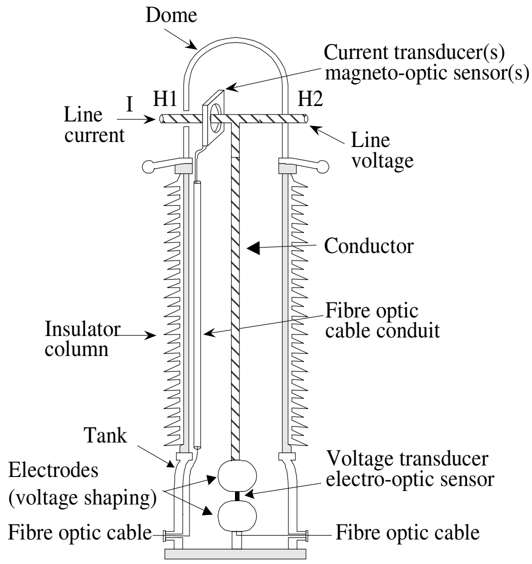


Figure 1.40: Combined optical CT and "all optical" voltage transducer

Finally, optical current transducers have been proposed for use in GIS (Figure 1.41).

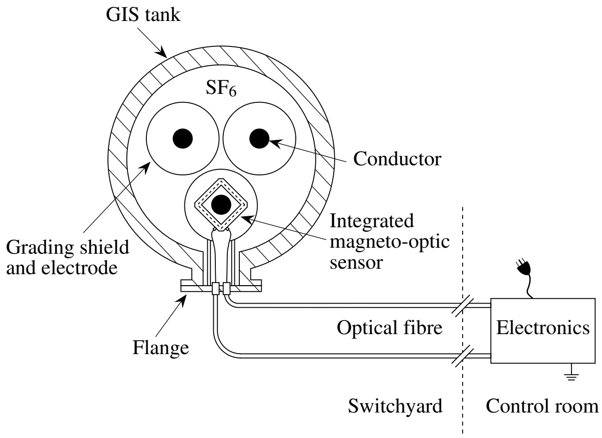


Figure 1.41: Design of an optical current sensor integrated into the GIS bus-bar of a 3-phase system

1.3.1.2 Optical sensor concepts

The scope of this document does not allow for an in-depth description of the sensors. Yet the first principles and the physical nature of the optical sensors most common to optical instrument transducers and commercially available are, in a sense, simple to understand. One only needs to know that optical sensing media (glass, crystals, plastics) show a sensitivity to electric and magnetic fields and that some properties of a probing light beam can be altered when passing through them. One simple optical transducer description is given here in Figure 1.42.

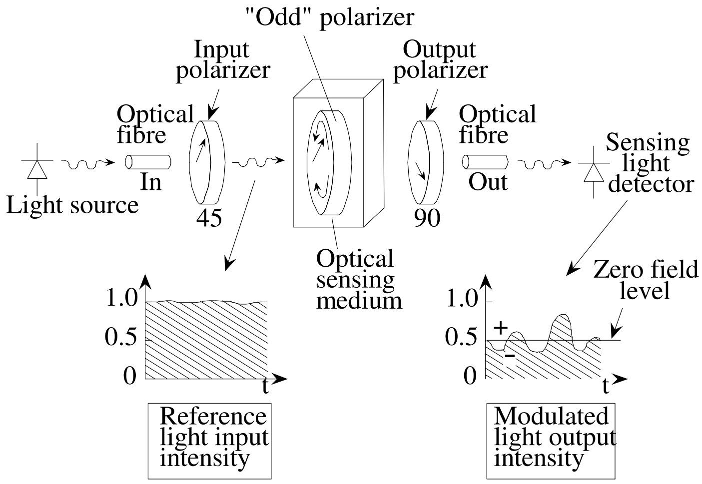


Figure 1.42: Schematic representation of the concepts behind the optical sensing of varying electric and magnetic fields.

Consider the case of a beam of light passing through a pair of polarizing filters. If the input and output polarizing filters have their axes rotated 45° from each other, only half the light will come through. The reference light input intensity is maintained constant over time. Now if these two polarizing filters remain fixed and a third polarizing filter is placed in between them, a random rotation of this middle polarizer either clockwise or counterclockwise will be monitored as a varying or modulated light output intensity at the light detector.

In a sense this is what happens when a block of optical sensing material (glass or crystal) is immersed in a varying magnetic or electric field. This sensing block plays the role of the "odd" polarizer. Changes in the magnetic or electric field in which the optical sensor is immersed are monitored as a varying intensity of the probing light beam at the light detector. The light output intensity fluctuates around the zero-field level equal to 50% of the reference light input. This modulation of the light intensity due to the presence of varying fields is converted back to time-varying currents or voltages. The same physical principle is also true for non-varying fields. In this case considerably more sophistication is needed in order to get an output that is a faithful replica of the applied dc current or voltage. There are also several other physical concepts that are put to use, but they will not be discussed here.

A transducer uses a *magneto-optic effect sensor* for optical *current* measuring applications. This reflects the fact that the sensor is not basically sensitive to a current but to the magnetic field generated by this current. Although "all-fibre" approaches are feasible, most commercially available optical current transducers rely on a bulk-glass sensor. Most optical voltage transducers on the other hand rely on an electro-optic effect sensor. This reflects the fact that the sensor used is sensitive to the imposed electric field. So far only a few electro-optic transducers have been developed for the power industry.

1.3.1.3 Hybrid transducers

The hybrid family of non-conventional instrument transducers can be divided in two types: those with active sensors and those with passive sensors. The idea behind the type of transducer with an active sensor is to change the existing output of the conventional instrument transformer into an "optically isolated" output. Therefore one achieves this conversion by merely adding an optical conversion system (Figure 1.43). This conversion system may require a power supply of its own: this is the active sensor type. The optical conversion can take place in the "live" part of the transformer or at the low voltage (secondary) end. The use of an optical isolating system serves to de-couple the instrument transformer output secondary voltages and currents from earthed or galvanic links. Thus the only link that remains between the control-room and the switchyard is a fibre optic cable.

Another type of hybrid non-conventional instrument transformer is achieved by retrofitting a passive optical sensing medium into a conventional "hard-wire secondary" instrument transformer. This can be termed as a passive hybrid type since no power supply of any kind is needed at the secondary level.

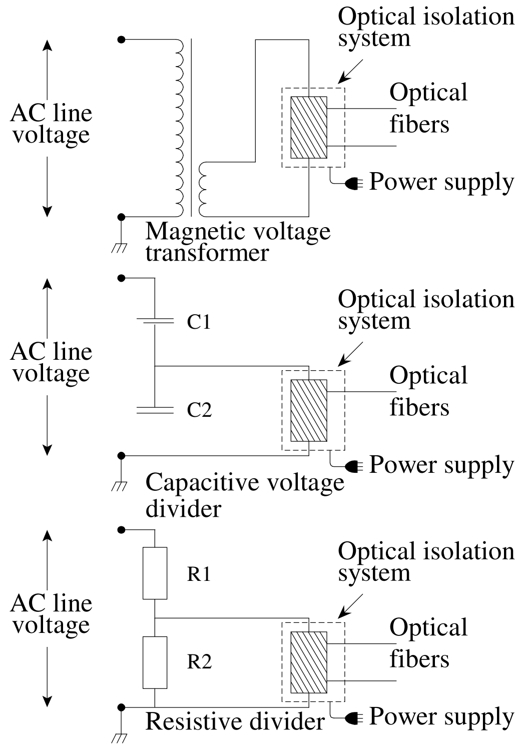


Figure 1.43: Equivalent circuits of hybrid-type optical conversion, using an MVT, a capacitor and a resistive voltage divider

1.3.1.4 Genuine transducers

This family of instrument transducers is clearly an offspring of novel optical sensors. Any new IT based on this type is fully passive. Referring back to the functional diagram of Figure 1.37, passive optical sensors imply no electrical-to-optical (E/O) stage at the sensor level. The sensing function is achieved directly by the sensing material and the communication is obtained by simple fibre optics which run from the base of the unit to the sensor location.

Both current and potential transducers or even combined current and voltage versions are being developed, which make use of optical sensing media. In these transducers the only link between the control room and the substation is of course again a fibre-optic cable. Indeed the only link between the power system voltages and currents and the control room is made through light channels. The sensing element is made of an optical material that is positioned in the electric or magnetic field to be sensed. In the case of a current measuring device the sensitive element is either located free in the magnetic field (Figure1.44a) or it can be immersed in a field-shaping magnetic "gap" (Figure 1.44b). In the case of a voltage sensing device (Figure 1.45a, b) the same alternatives exist, this time for elements that are sensitive to electric fields.

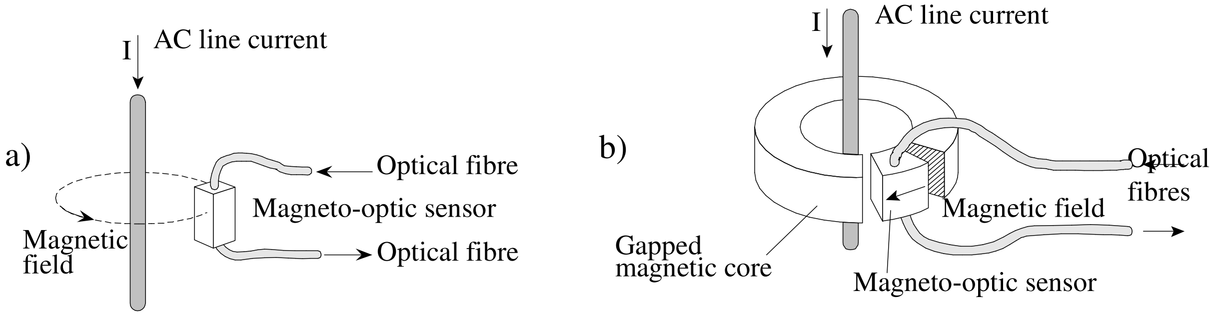


Figure 1.44: Optical current sensor based on the magnetic properties of optical materials showing "free-field" type (a) and a "field-shaping" type (b)

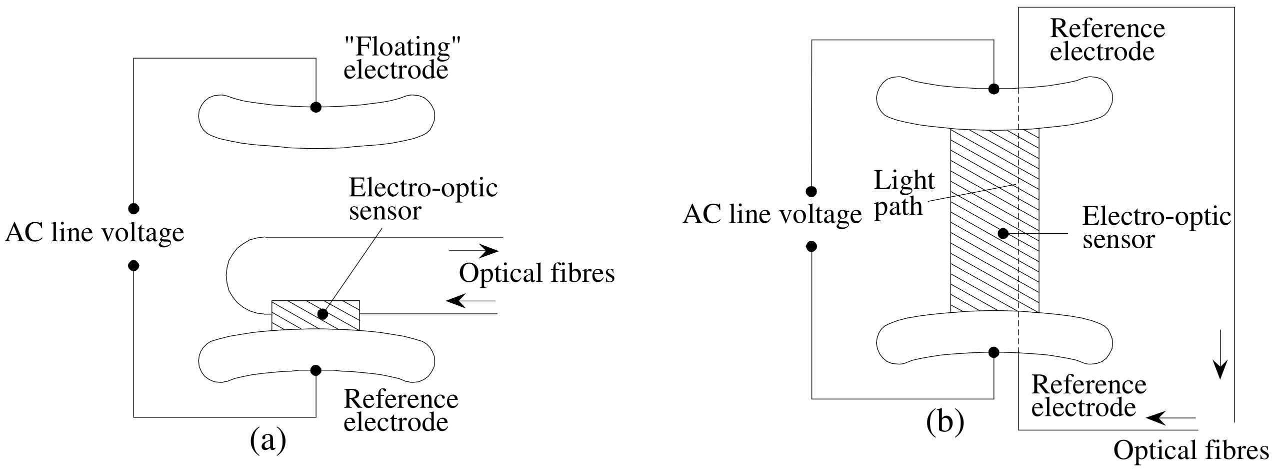


Figure 1.45: Optical voltage sensor based on the electric properties of optical materials showing a free-field" type (a) and a "field-shaping" type (b)

In all cases, there is an optical fibre that channels the probing reference light from a source into the medium and another fibre that channels the light back to an analysing circuitry. In sharp contrast with a conventional free-standing IT, the optical IT needs an electronic interface module in order to function. Therefore its sensing principle (the optical material) is passive but its operational integrity relies on the interface which is powered in the control room (Figure 1.46).

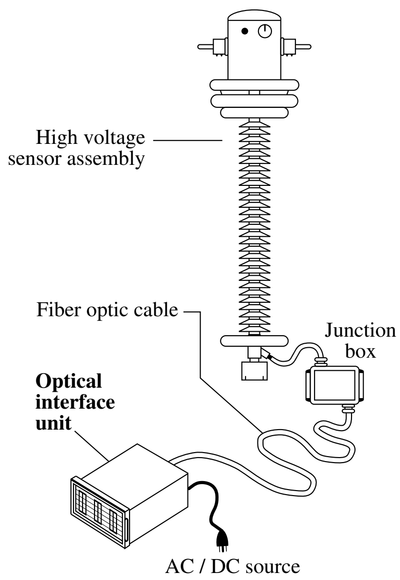


Figure 1.46: Novel instrument transducer concept requiring an electronic interface in the control room

Similar to conventional ITs, there are "live" tank and "dead" tank optical transducers. There are also combined current and voltage units much as with conventional ITs. Typically, current transducers take the shape of a closed loop of light-transparent material, fitted around a straight conductor carrying the line current (Figure 1.47). In this case a bulk-glass sensor unit is depicted (Figure 57a), along with an "all-fibre" sensor example, as shown in Figure 1.47b. Light detectors are basically very sensitive devices and the sensing material can thus be selected in such a way as to scale-up readily for larger currents.

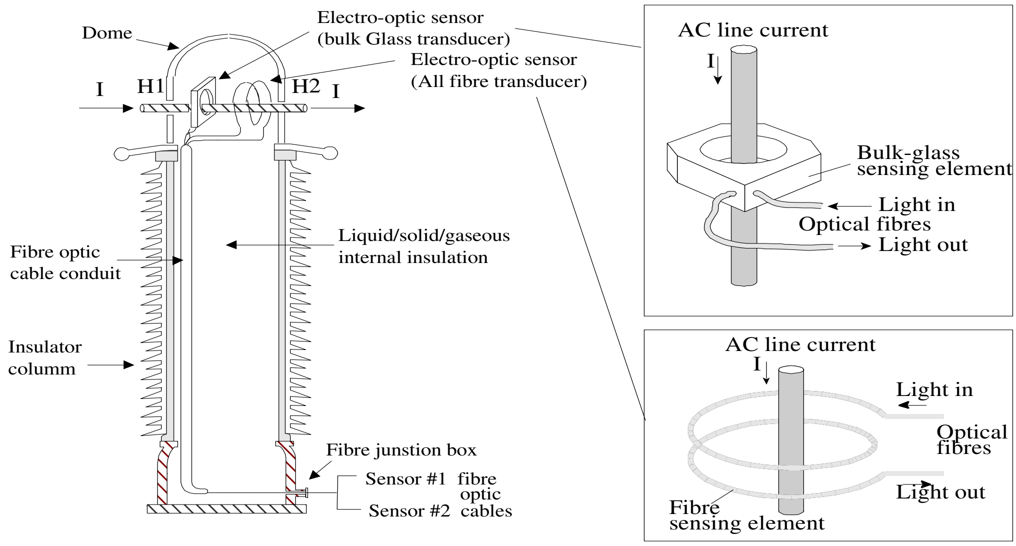


Fig 1.47: Conceptual design of a double-sensor optical CT. The inserts show a glass-ring sensor approach (a) and an "all-fibre" sensor concept (b)

Truly passive optical voltage transducers however do not lend themselves easily for increasingly higher and higher line voltages. This is simply because the dielectric strength of the optically transparent material is insufficient when subjected to an increasing electric stress across its surfaces. Precise field shaping constructions and materials with higher dielectric constants are needed. Most obviously gas insulation allows one to consider small bulk-material dimensions.

Typically, electro-optical sensitive materials can be made to withstand high power frequency voltage stresses of the order of 10 kV/cm in room-temperature SF_6 at atmospheric pressure. A live-tank and a dead tank version are shown schematically in Figure 1.48.

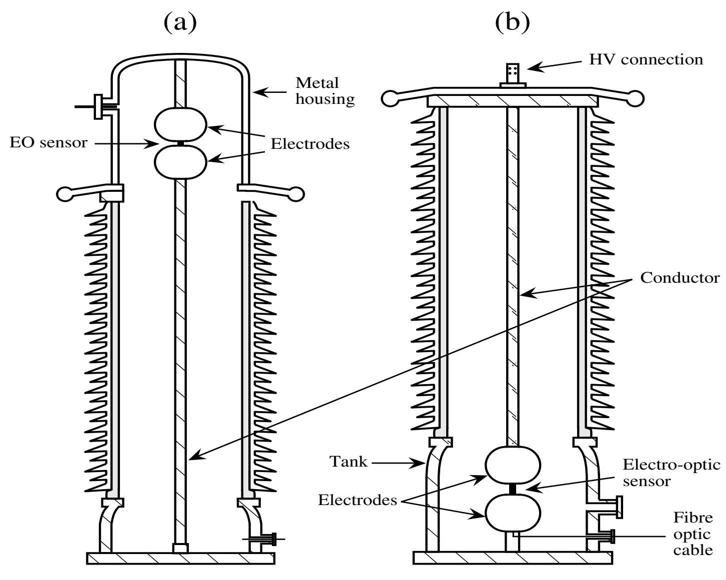


Figure 1.48: Live-tank (a) and dead-tank (b) optical voltage transducer concepts, using a "full-voltage" sensor (see Figure 1.45)

Although truly genuine optical ITs were introduced as power system contenders nearly 10-15 years ago, there are still only a few in service nowadays. This situation reflects in part the true conservative nature of the power industry and the utilities alike. With reason, the protective relaying functions and the control functions of ITs have always been kept within strict limits in such a way that standard practices could be widely used. Isolated failures, sometimes catastrophic, have occurred but conventional ITs overall have shown a rather consistent record of fidelity and reliability. As for metering functions, novel ITs should lend themselves in the coming years to a less conservative stance from users in the power business. However long term stability and consistency of the new transducers has yet to be demonstrated

Tariff metering also relies on well established tools with the result that no significant change has occurred in the IT world. This situation may evolve with the introduction by the power industry of more computer-based protection and control systems in substations. The same change may be prompted when standardizing bodies begin looking into ways of adding novel electronic techniques in order to achieve more demanding performances from ITs, such as faster response, immunity to transient surges and upgrading of existing line protection.

1.3.2 Other sensing systems

1.3.2.1 Zero-flux (Hall Effect) current transformer

In this case, the sensing element is a semiconducting wafer that is placed in the gap of a magnetic concentrating ring. This type of transformer is also sensitive to dc currents. The transformer requires a power supply that feeds from the line or from a separate power supply. The sensing current is typically 1/1000 times smaller than the current to be measured. In its simplest shape the Hall effect voltage is directly proportional to the magnetizing current to be measured. For more accurate and more sensitive applications the Hall sensor is placed in a gap as described but the sensing current is fed through a secondary, multiple-turn winding, placed around the magnetic ring in order to balance out the gap magnetic field. This zero-flux or null-flux version allows very accurate current measurements in both dc and high-frequency applications. A schematic representation of the sensing part is shown in Figure 1.49.

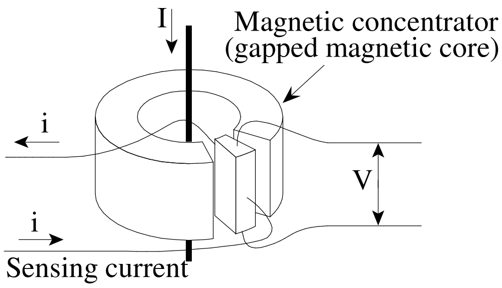


Figure 1.49: Conceptual design of a Hall-effect current sensing element fitted in a field shaping gap

1.3.2.2 Hybrid magnetic-optical sensor

This type of transformer is mostly used in applications such as series capacitive compensation of long transmission lines, where a non-grounded measurement of current is required. In this case several current sensors are required on each phase in order to achieve capacitor surge protection and balance. The preferred solution is to use small toroidally wound magnetic core transformers connected to fibre optic isolating systems. These sensors are usually active sensors in the sense that the isolating systems require a power supply. This is illustrated in Figure 1.50.

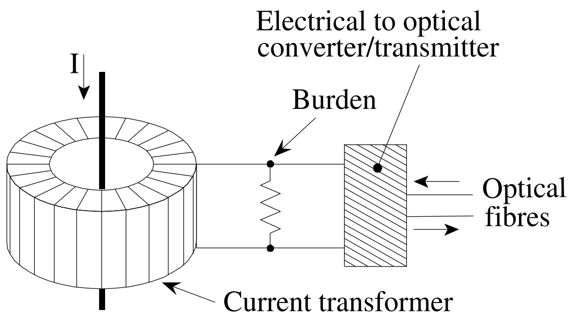


Figure 1.50: Design principle of a hybrid magnetic current transformer fitted with an optical transmitter

1.3.2.3 Rogowski coils

The Rogowski coil is based on the principle of a CT with a very high load impedance, where the ferro-magnetic core has been abandoned completely. The output signal is a function of the first derivation of the current. The secondary winding is wound on a toroid of insulation material. In most cases the Rogowski coil will be connected to an amplifier, in order to deliver sufficient power to the connected measuring or protection equipment and to adapt to the entrance impedance of this equipment. The schematic representation of the Rogowski coil sensor is shown in Figure 1.51.

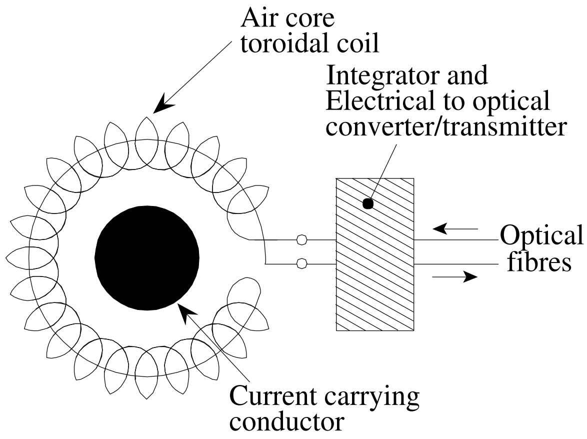


Figure 1.51: Schematic representation of a Rogowski coil, used for current sensing

1.3.2.4 Integrated transducers

This type of IT is relatively new, as it implies using optically de-coupled sensor solutions in such applications as CTs integrated to the line or to the power-station hardware. This is illustrated in Figure 1.52 a) and b). In this case one of the non-conventional sensors described previously is used in a "suspended" system where optical fibres are fitted in special insulators. A number of practical solutions are being developed for integrated systems that are fitted literally inside power apparatus such as power transformers, circuit breakers, shunt reactors, switches, etc. The apparatus sensor approach identified in Figure 1.52.c) opens up applications that will lead to much more compact equipment, such as in SF_6 insulated dead-tank breakers, where voltage and current measuring functions would be made internally inside the live parts or in a dead tank system. In a sense magnetic current transformers, known as bushing-mounted CTs and measuring equipment, developed for GIS could be considered as "integrated" conventional ITs.

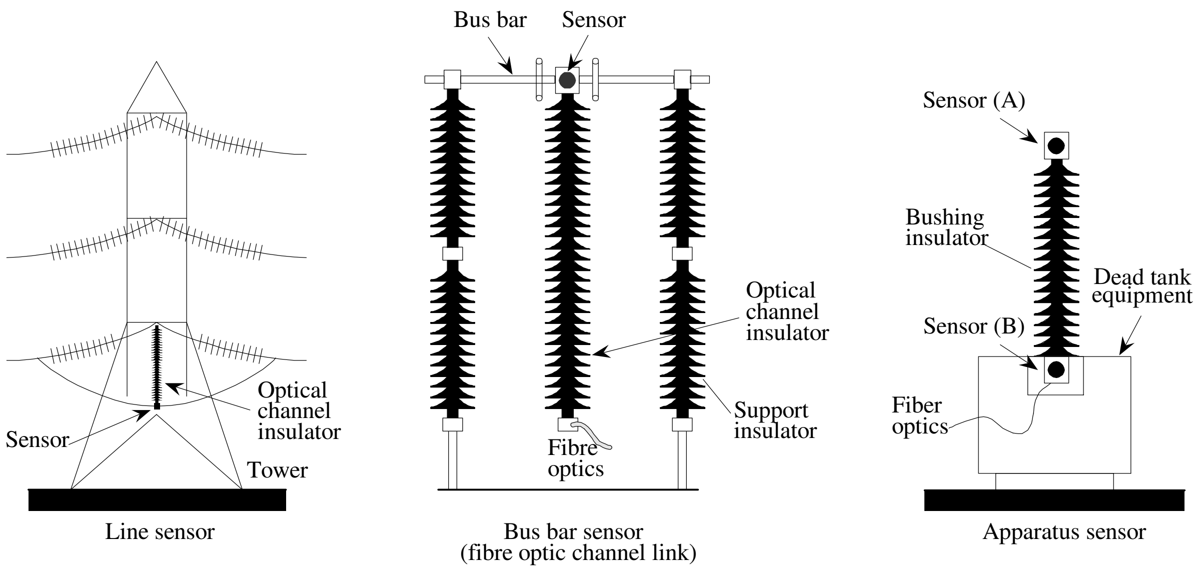


Figure 1.52: Concepts of integrated optical IT showing applications as a) line sensor b) bus bar sensor and c) apparatus sensor

1.4 Design considerations

1.4.1 Guidelines

As we have seen, ITs may differ widely in the technology concerning the sensing system and the insulation system. Although similar and more strictly standardized around mechanical or functional requirements, common components and auxiliary parts also differ in their ruggedness and field reliability records. In this respect general guidelines have been set and specific design constraints have been defined in order to achieve better performance.

1.4.2 Standard constraints

The IT should withstand a set of standard requirements, based on field conditions that have been recommended by standardizing bodies. These Standards will not be discussed in this context. We will only try to explain the impact of some of the basic constraints on a good design. The standard constraints occur during operation of the IT in its lifetime under service voltage, temporary overvoltages and transient overvoltages, as well as heating due to loads. A brief list is provided below.

– Service voltage, with maximum voltage $U_m/\sqrt{3}$ during the lifetime of the unit,

– temporary overvoltages during an earth fault in the grid, dependent on the earthing system of the grid and varying from

  - U_m (rms value) during a maximum of 4 to 8 hours or even longer, in resonant earthed or isolated neutral systems, to
  - U_m during 1 s or less, in non-effectively earthed systems, to
  - 0.8 U_m or less, during a maximum of 1 s in effectively earthed systems.

All voltages are phase-to-earth. At the start of the earth fault, transient overvoltages of higher peak values will occur, which will attenuate to the above-mentioned quasi-stationary effective values within a few periods.

– switching overvoltages,

– lightning overvoltages, full wave or chopped wave.

The ability of the insulation to withstand these constraints can be demonstrated by applying the standard dielectric tests, as described in Chapter 3. Chopped lightning tests should be performed if the lightning protection of the power system is achieved by means of spark gaps or similar. The choice of the test voltages can be made according to IEC 60044-1, 60044-2 and 60071 and eventually in accordance with IEC 60694 "Common clauses".

Hairpin and eye-bolt type CTs (Figs.1.9.b & c) will be extra stressed by lightning waves because the high inductivity of the primary loop will result in a high (lightning) voltage drop between the incoming and outgoing primary conductors. Faults at the top of the CT can be prevented by applying a small surge arrester between the primary terminals.

The internal main insulation will also be stressed by the heat from the Ohmic losses in the conductors and by its own dielectric losses. Appropriate heat run tests should demonstrate that the hot spot and top oil temperatures stay below the prescribed maximum values.

CTs will also be stressed by short duration currents (short-circuit currents), passing through the primary winding. These currents will cause heating of the primary conductor and mechanical forces in different parts of the CT construction. The ability to withstand these constraints can be demonstrated in short-circuit tests, but the heating of the primary can also be calculated, giving the mean temperature rise at the end of the process which is considered to be adiabatic (see clause 2.1.5 of IEC Publ. 60076-5).

1.4.3 Special constraints

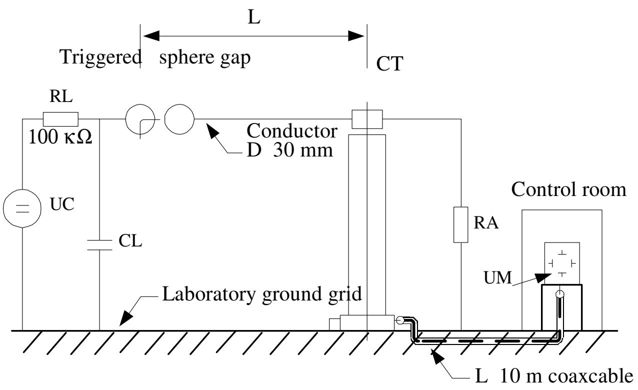
In certain applications, ITs have to withstand electrical and mechanical stresses which are not yet covered by or not fully defined in the IEC Standards. Certain stresses may cause significant damage to the ITs if the interactions of network and IT are not known or not considered. Some cases of non-standardized stresses on ITs are dealt with in the following sections.

1.4.3.1 High frequency stresses

Numerous restrikes occur during disconnector operations which will excite high frequency current oscillations in the capacitance of the ITs and the reactance and resistance of the loop concerned. During such oscillations, high frequency currents in the range of kA will flow through internal shields and connections of the IT and may cause local discharges which may finally destroy the insulation of the IT [10].

High frequency transients during disconnector operations can also influence the secondary circuits of ITs and associated equipment and effective low inductance shielding within the IT is necessary to avoid this. The following test method may be used to prove the ability of such shielding to prevent disturbances from the secondary winding. The subject is also under consideration by IEC.

The circuit diagram is given in Figure 1.53.



Test set up

Highest system voltage	Um	123 kV	245 kV	420 kV
Distance L gap to CT	L	1.5 m	2.5 m	3.5 m
Charging capacitor	CL	1.5 nF	2.0 nF	2.0 nF
Load resistance for CT's	RA	60 MΩ	60 MΩ	60 MΩ

Component values

Figure 1.53: Schematic test set-up and circuit elements for testing the response of IT to switching surges

A capacitor C_L is charged with a voltage $U_c = U_m \sqrt{2} / \sqrt{3}$ and then discharged through the IT. The maximum peak value of the transient overvoltage U_M in each secondary winding has not yet been standardised but often a value of 1000 V is taken. If the available charging voltage during test is lower than the required above, the calculation of U_M is as follows:

$$U_M = \left(U'_M / U'_c\right). U_m . \sqrt{2} / \sqrt{3}$$

The test at reduced voltage U'_c may be performed only if it can be shown that there is a linear relation between the charging voltage U'_c and the measured overvoltage U'_M. This can be proven by measurements at three different values of the charging voltage. In the formulae the following symbols are used:

- U_m : highest system voltage
- U_c : charging voltage
- U'_c : charging voltage, if the test is performed at reduced voltage
- U_M : measured overvoltage in the secondary circuit at charging voltage U_c
- U'_M : measured overvoltage in the secondary circuit if the test is performed at reduced voltage.

For an effective reduction of the common mode induced voltages due to disconnector operation shielded cables should be used for the connection of the equipment to the IT. The shield of the cables may be earthed at both ends but since this could give rise to high currents in the shield during earth faults in the grid, the shield should be earthed at one end only. Special attention should also be given to the earthing of the internal shielding of the IT (capacitance (tan delta measuring) taps for example) which should be of the low inductance type and able to sustain high currents.

During the operation of disconnectors in GIS, similar high-frequency overvoltages can be generated but with very short rise times of the order of 5 - 10 ns and peak values up to 2.5 p.u. Because of the very short rise times, these VFTOs (very fast transient overvoltages) are very dangerous to ITs connected directly to a GIS. However, if there is a short length of outdoor conductor (with a characteristic impedance differing considerably from that of the GIS) between the GIS and the IT, the overvoltages will be reflected to a large degree and will not harm the CT. For test purposes these overvoltages can be best generated using a spark gap mounted in a compartment filled with pressurised SF_6-gas.

1.4.3.2 Ferroresonances

Ferroresonance in MVTs (See also section 1.2.1.1.4) is an oscillation between the earth capacity of the system and the saturable inductivity of the voltage transformer, leading to aperiodic saturation of the magnetic core with a harmonic or subharmonic of the rated frequency of the network.

Ferroresonance at rated or higher harmonic frequencies generally leads to a dielectric failure of the unit, whereas subharmonic ferroresonance leads to thermal failures.

Ferroresonance effects can be prevented by avoiding certain network configurations or reduced by the use of damping systems like saturation coils or resistors.

1.4.3.2.1 Ferroresonances with single-phase MVTs

The ferroresonance phenomena may be caused by switching operations in a network between the non-linear reactances of the MVTs and capacitances of the network which forms a resonant circuit.

The basic circuit is shown in Figure 1.54. Stable oscillations at power frequency and its lower and higher harmonics may occur during and after operations of switch S, due to the non-linear behaviour of the reactance. These oscillations are called ferroresonance and they may damage MVTs by over-heating and/or overvoltage stresses.

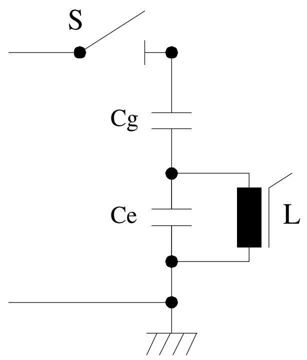


Figure 1.54: Basic circuit for development of MVT ferroresonance

Typical network configurations, which may lead to ferroresonance phenomena are as follows:

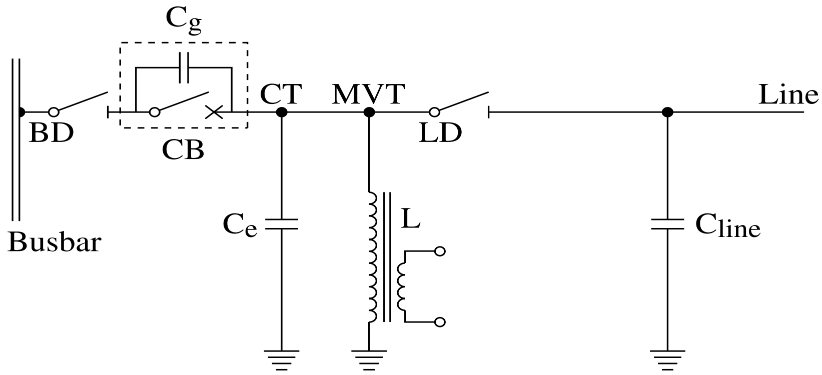
a) Single-phase ferroresonance in a configuration where an MVT is connected to a high-voltage line which is deenergised but running alongside another energised line.

b) Single-phase ferroresonance between an MVT and the HV/MV capacitance of a supply transformer.

c1) Single-phase ferroresonance between an MVT and the grading capacitance of an open circuit-breaker (Figure 1.55).

c2) Single-phase ferroresonance between MVTs installed on a busbar and the grading capacitances of circuit breakers tripped by a busbar protection scheme. (During a fault on the busbar, all circuit-breakers are opened by the busbar protection scheme and ferroresonance may occur between the grading capacitances of the open circuit-breakers working in parallel and the MVTs installed on the busbar).

d) Three-phase ferroresonance with MVTs connected to a system with isolated neutral (floating neutral) and very low zero sequence capacitance.



BD	=	busbar disconnector
LD	=	line disconnector
CB	=	circuit breaker, with
C_g	=	grading capacitance
C_e	=	capacitance to earth of CT and adjacent components
C_{line}	=	line capacitance
L	=	reactance of MVT

Figure 1.55: Equivalent circuit showing ferroresonance occurrence in case c1

In practice it is not always possible to avoid the configurations described above. Since ferroresonances occur only in unfavourable combinations of capacitances and the non-linear reactance of the MVTs it is important to recognize these configurations.

In many cases the ferro-resonance phenomena are detected by audible noise of the MVT in the substation or by the swinging of the pointers of voltmeters before the MVTs are destroyed. Nowadays this latter detection becomes more and more difficult since measuring signal converters are used in modern control installations in which the sub-harmonic component of the voltages is suppressed. The consequence is that sub-harmonic voltage oscillations cannot be observed by the operator and special detection equipment may be required to give an alarm on the occurrence of steady state ferro-resonance.

If ferroresonance occurs, the resonant circuit has to be detuned or damped. Detuning may be done for instance by switching a line on or off. Damping may be achieved for instance by a resistive load or a damping reactance coil. In the event of ferroresonances according to case d), a resistive load may be connected to the terminals of the open delta of the residual voltage winding.

The ferroresonance phenomena as given in a) may be avoided by changing the position of the phases on the line towers. This change may be done at the transition between line and substation. This modifies the coupling capacitance between energised and deenergised lines in such a way that ferroresonance does not occur.

Ferroresonances according to c1) will generally not occur if the resulting grading capacitance of the circuit-breaker is less than 250 pF and the capacitance to earth of the MVT and the associated CT is higher than 1000 pF. As a rough rule of thumb, ferroresonance at rated frequency will occur if the ratio of CB capacitance to parallel (shunt) capacitance is close to 1. Limiting of the value of the grading capacitance of a circuit-breaker is possible if this capacitance is used only for grading, but not if it is necessary to help breaking short line fault currents.

Ferroresonances with grading capacitances of circuit-breakers will not occur if the MVTs are connected directly to the line because the line capacitance is in parallel with the local MVT capacitance. This also occurs if, when deenergising a line by opening the circuit-breaker in the bay considered, the busbar disconnector (BD in Figure 1.55) is opened first and the line disconnector (LD) afterwards. When energising the line, the line disconnector should be closed first and then the busbar disconnector.

Special care should be taken with substation arrangements prone to ferroresonance when schemes for synchronising purposes are tested. In configuration c2), ferroresonances would be avoided if CVTs were used instead of MVTs. This can normally be possible because the VTs connected to the busbar are mainly used for synchronizing purposes and not for protection.

Countermeasures have to be taken to avoid the destruction of MVTs in all the ferroresonance cases considered. When an MVT fails and ferroresonance is suspected, care should be taken to prevent failures to other MVTs in the same configuration. There is only limited experience in detecting pre-damaged units. Since ferroresonance causes over-voltage stresses and/or overheating of the primary winding, tests for detecting such failures may be proposed such as dielectric tests with PD, tan delta and capacitance, and analysis of the oil by DGA (dissolved gas analysis).

It seems technically impossible to design a ferroresonance-free MVT. However, since the use of ferroresonance damping devices is widely recognised, it is not deemed relevant to provide additional dimensioning requirements to IEC 60044-2 on this subject. Recently however, a new core design has been introduced which is ferroresonance free under specified conditions.

1.4.3.2.2 Ferroresonance in CVTs

Ferroresonance may not only occur with MVTs but also with CVTs. CVTs consist of a capacitive divider and a compensation-reactor tuned to rated frequency in series with an inductive voltage transformer. Ferroresonance may occur during sudden changes of the primary voltage but, moreover, saturation of the burden may occur and result in ferroresonance with the capacitances of the CVT. Ferroresonance could also occur if the compensation-reactor becomes saturated, for instance during a short circuit of the burden. This phenomenon is covered by tests prescribed in IEC 60044-2.

Ferroresonance in CVTs normally causes no damage to the high-voltage capacitances but may lead to faulty operation of the protection system and/or to damage to the equipment of the secondary circuit. CVTs are fitted with damping devices to avoid ferroresonance. For fast protection systems it is required that the voltage performance of the CVT is not influenced by ferroresonance during the measuring time of the protection. The solution to this problem is the task of the CVT manufacturer.

1.4.3.3 Capacitive discharge

1.4.3.3.1 Line and cable discharging by MVTs

MVTs or CVTs and CTs for metering, measuring and protection purposes are connected at the terminations of HV lines and cables in a substation. One advantage of MVTs is the ability to discharge the phases of overhead lines which is especially important for three-phase auto-reclosing of circuit-breakers since the MVT can effectively reduce the level of overvoltages.

When switching off an unloaded line or cable circuit with a circuit-breaker, the circuit voltage is at its crest value at the moment of current interruption and the capacitance of the line remains charged at that voltage. If the line is fitted with MVTs at its terminals, line discharge takes place through the primary circuit of the MVTs and is governed by the non-linear magnetic reactance of the core and the resistance of the primary winding.

The discharge current of the line capacitance through the primary winding of the MVT takes the shape of a periodically or aperiodically damped oscillation. This current acts as a magnetizing current for the MVT and may saturate the core, thus changing the non-linear magnetic reactance of the core from a high to a low value. Ultimately, the current will be limited by the resistance of the primary winding only [11].

This discharge current leads to two kinds of stresses in the MVT:

a) temperature rise;

b) mechanical forces.

Under the worst conditions of high voltage, long line, large number and sequence of switching operations, these stresses may result in damage to the MVT.

a) Temperature rise

The trapped electrical energy in the capacitance of the line or cable will be absorbed by the primary winding of the MVT and be converted into heat. The consequence is that each de-energisation of the line or cable causes an incremental temperature rise of the primary winding of the MVT. Multiple line and cable discharging operations at short time intervals may cause overheating and damage to the primary winding and its surrounding insulation and ultimately cause failure of the MVT. Line and cable switching operations at short time intervals will usually only be performed during commissioning tests and during the testing of protection schemes.

b) Mechanical forces

The discharge current flowing through each turn of the primary winding produces a magnetic field which, in combination with the current in the winding, will cause forces on the individual turns. These electromagnetic forces, depending on the discharge current, the ampere-turns and the design of the MVT, act to compress certain regions of the primary winding and lead to high mechanical tension in the conductor of the primary winding.

In the worst case, the primary winding may be distorted and parts of the winding will be short-circuited if the winding or the layer insulation is damaged. In addition to the mechanical stresses in a single phase MVT, account has to be taken of the influences coming from the other phases. These influences can be important if the spacing between the MVTs is small as in GIS where, in some cases, the three units are installed in a single housing.

The levels of these thermal and dynamic stresses on the primary windings of MVTs depend on and increase with the following parameters of the network:

- system voltage;
- length of line or cable;
- number and sequence of switching operations.

To avoid any damage to MVTs by such discharge stresses, the manufacturer of the MVT should be consulted in any case if, for instance, the length of a 420 kV line is greater than 200 km and/or the desired number of switching operations exceeds 5 per hour. Precautionary consultation with the manufacturer should also be made for cable circuits and at other voltage levels where users suspect that the switching duties of the circuit may exceed the discharge capability of the MVT.

The behaviour of MVTs during line discharging has not been dealt with in IEC Publication 60044-2. Therefore it is proposed that the capability of line discharging of MVTs be coordinated using rated breaking currents of circuit-breakers for switching unloaded lines or cables. The requirements on circuit-breakers are given in IEC 60056: High-voltage alternating-current circuit-breakers, as "Rated line-charging breaking current" and "Rated cable-charging breaking current". The maximum values of line and cable capacitances according to IEC 60056 are given in Table 1. For 800 kV systems the line discharge current should be 900A.

Table 1

Rated voltage	Rated breaking current * for		Capacitance to be de-energised by MVT	
U kV	Line I A	Cable I A	Line C µF	Cable C µF
72.5	10	125	0.8	9.5
100	20	125	1.1	6.9
123	31.5	140	1.4	6.2
145	50	160	1.9	6.1
170	63	160	2.0	5.2
245	125	250	2.8	5.6
300	200	315	3.7	5.8
362	315	355	4.8	5.4
420	400	400	5.3	5.3
525	500	500	5.3	5.3
* IEC 60056, High-voltage alternating-current circuit-breakers.				

For MVTs connected to GIS, the recommended maximum value for capacitances to be discharged is 15 µF, *i.e.* 5 µF per phase for three-phase units.

1.4.3.3.2 Capacitor bank discharging by MVTs

MVTs are also used for this special purpose and the stresses on the MVT are the same as given in 1.4.3.3.1. For some applications it may be necessary to use a special design and it is recommended to contact the manufacturer on such occasions.

The discharging capability of a MVT may be demonstrated by testing with 10 de-energisations of a capacitance as given in Table I, charged to a voltage equal to the peak value of the phase-to-earth voltage. The MVT would pass the test successfully if the voltage error and the phase displacement, the partial discharge values and the frequency response before and after test are substantially the same.

Attention should be given to the fact that, when performing such discharge tests, large electrical energies are involved. If the MVT fails it may be destroyed and could be dangerous to the persons in the locality of the unit.

1.4.3.3.3 Line or cable discharging in GIS-connected MVTs

Discharge operations are:

- discharging of long, free running overhead lines
- discharging of the capacitor banks of compensation installations or HVDC-stations
- discharging of cables

The resulting stresses are described in the following.

During the above discharge operations the core of the MVT usually enters into saturation after a few milliseconds and the voltage measured at the secondary winding will be distorted due to this saturation.

For the actual discharge operation, only the remaining air inductance L and the resistance R of the voltage transformer primary coil have to be taken into consideration. The capacitance of the overhead line, the capacitor bank or the cable is given in a capacitance C. The equivalent circuit Figure 1.56.a applies for the discharge operation. The solution of the relevant differential equations results in a damped sinusoidal discharge or a damped aperiodic discharge, dependent on the values of C, L and R. For:

$$\frac{R^2}{4L^2} > \frac{1}{LC} \quad ; \quad \text{aperiodic discharge}$$

$$\frac{R^2}{4L^2} < \frac{1}{LC} \quad ; \quad \text{oscillating discharge}$$

The high resistance (some 10 kΩ) of the primary winding makes an oscillating discharge only possible with small capacitances and therefore the resulting discharge energies will be low. For that reason the more important discharge, from a technical point of view is the aperiodic damped discharge. Is this case the discharge current will be as shown in Figure 1.56b.

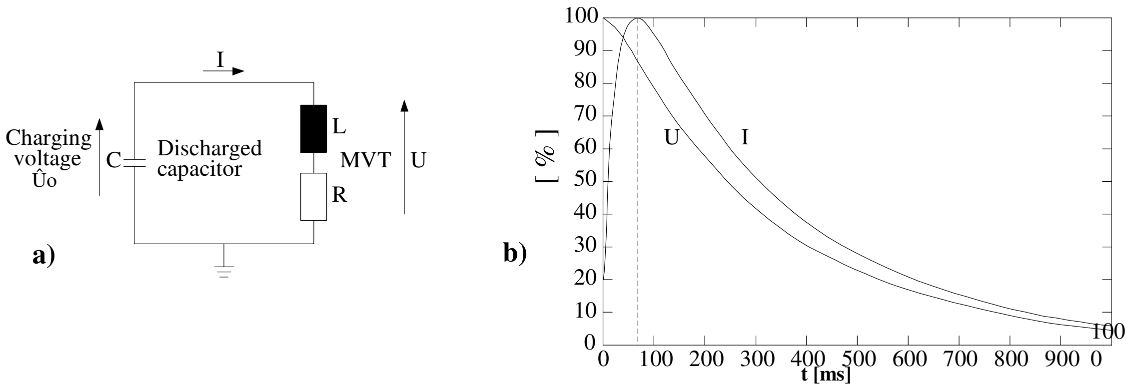
Two effects can become dangerous for voltage transformers during discharge and can cause damages:

1a - In freestanding MVTs or single phase GIS-connected MVTs the discharge current results in attracting forces of the primary turns.

1b - In three phase GIS-connected MVTs the discharge current results (additionally to 1a) in attracting or repelling forces between the primary coils.

2 - Each discharge results in a temperature rise of the primary winding.

The number of primary turns is usually around 50 000 and higher. Therefore, the forces under 1a and 1b can be very high as given in the example below. The coils and turns of the VT primary winding have to be sufficiently rigid to withstand these forces. It is therefore necessary to specify the line or cable capacitances and to test whether the primary winding, or the three primary windings in the case of three-phase GIS connected MVTs, withstand the resulting forces during discharge of the capacitances. To test the most critical case in a three phase unit, the current in the windings should flow in different directions.



145 kV - Magnetic Voltage Transformer (three phase MVT)
Temperature rise 12,3 C
Max. current, ëo = 4.7 A after 67 ms
Ûo = 123 kV, C = 15 mF, R = 21 kW, L = 506 H
N = 56000 turns

Figure 1.56: Aperiodic capacitive discharge simulation of GIS-connected MVT showing the circuit elements a), and the waveforms (V, I) in b)

The basis for the calculation of the temperature rise is the charging energy of the capacitor bank:

$$\text{Energy} = \frac{1}{2} C\hat{U}_{\circ}^{2}$$

This energy is converted during the discharge to heat, causing a temperature rise of the primary winding. If the time between discharges is too short the temperature steps of the discharges accumulate and the resulting temperature can exceed the specified temperature of the MVT. The number of discharges during a prescribed time interval must be restricted.

Figure 1.56b gives an example of a discharge curve. A capacitance of 15 µF is loaded with $U_{\circ}$ = 123 kV. The maximum current during discharge is 4.7 A.

The dynamic reaction of this current becomes apparent when taking into consideration that the primary winding in this case has N = 56 000 turns. Therefore, a force according to 263 200 Ampere turns reacts on the coil. The temperature rise per discharge reaches 12.3 K. The experimental result corresponds very well with the theory.

1.4.3.4 Mechanical vibrations

1.4.3.4.1 Transportation

ITs are subject to stochastic oscillations or shocks during transportation. Shocks can also occur at loading and unloading, making adequate packaging and crating essential.

Vibrations during transportation can cause the rupture of soldered connections and the loosening of screws and nuts. Metal bellows for the oil expansion are especially prone to damage and they should be very well padded in order to prevent rupture or leakage by the continuous friction of the bellows against the inside of the head tank wall if transported in the horizontal position.

During road transportation, average vertical acceleration values are about 1 g for frequencies up to 25 Hz, but peak values up to 4 g can be observed. Horizontal acceleration values are about 25% lower. At higher frequencies acceleration values are much lower. Acceleration values resulting from shocks are less than 5 g on normal roads, but far higher values up to 10 g can occur on unpaved roads or trails. In this case values of horizontal acceleration components are not much lower than the vertical ones.

IEC Publication 60077 specifies that equipment to be transported by rail is to be tested at an acceleration of 3 g for 2 hours at each noted resonance frequency within the range 1-50 Hz. If no major resonance occurs the equipment is to be tested at the acceleration of 3 g at 10 Hz for not less than 2 hours. Stresses during transportation by ship are generally lower. The same can be said of loading and unloading provided that the apparatus is carefully handled.

It is advisable to use some shock indicators or shock registration devices to check that limits agreed between manufacturer, user and shipping company are not exceeded.

Shock indicators are attached to the IT to indicate high shock stresses which might result in damage. The release acceleration of the indicator is given in units of g (g = 10 m/s^2). Indicators with release accelerations of 15/20/30.g are normally used. The sensitivity of the shock indicator should be selected according to the kind of packaging and dimensions of the device. For ITs, the shock indicators are glued in the secondary terminal box.

There are several kinds of shock indicators:

- Sphere indicator: Spheres located in a transparent plastic housing are held by springs in a fixed position. By arranging the springs crosswise different shock directions are sensed. When an impulse reaches the release acceleration value the spheres fall out of their fixed position.
- Fluid indicator: In a tube are two fluids of a different colour. The fluids are separated by their surface tension. The colour changes when a shock impulse exceeds the surface tension.
- Shock recorder: There are "mechanical" and "electronic" shock recorders. Accelerations are recorded in three axes. These recorders are very expensive.

1.4.3.4.2 Earthquakes

Earthquakes may cause damage to buildings and also to the equipment of electrical substations including ITs. For general purposes earthquake severities are classified using scales of intensity or magnitude.

Intensity scales are empirically determined. The modified Mercalli scale for example contains 12 levels of intensity in accordance with their observed effects. Magnitude scales give the measured energy content of an earthquake at a defined point from the epicentre with standardized seismographs. The magnitude scale is not limited at the upper end.

The use of these scales for setting up test procedures and values is limited because the scales may only roughly correspond with certain values of the ground acceleration and do not supply any other vibrational data for calculation or testing.

Earthquakes are of a stochastic nature and reach their highest values of acceleration in the horizontal directions while vertical accelerations are less than about 50% of the horizontal values. The duration of earthquakes is about 15 to 30 seconds; however the strong part of an earthquake lasts only a few seconds. The typical frequency range is from 1 to 30 Hz.

Response spectra are used for the purpose of designing and testing electrical equipment under seismic environmental conditions [12, 13]. These spectra give the response of oscillators with one degree of freedom, a fixed characteristic frequency and constant damping to the typical stochastic earthquake vibration recorded for a certain region. The response amplitude of an oscillator will be at a maximum if it is excited at its natural frequency. A record of a seismograph at the site where the ITs are to be installed is used to establish a response spectrum. In this way a so-called "Initial Response Spectrum" is obtained which reflects the seismic stresses provoked by the considered earthquake. A representative number of initial response spectra determined from different earthquakes describes the anticipated seismic stress for the site or area. An enveloping curve around the initial response spectra is called a Required Response Spectrum (RRS) because it marks the limits of vibrational requirements. This spectrum shows the relationship between frequency, amplitude (displacement, velocity or acceleration) and damping for testing purposes.

Qualification of electrical equipment to seismic requirements may be done by test or by a combination of test and analysis. Computer controlled hydraulic earthquake simulators are available for performing seismic tests on ITs.

ITs are mounted on support structures in open air substations and it must be ensured that the inputs from the earthquake are not unacceptably amplified by the support structures. Design guidelines are given in the literature. If the induced stresses from the specified earthquake exceed the physical strength of the IT, dampers between the support structure and the IT may be used for increasing the damping and reducing the amplification factor. During seismic events the damping properties of these devices should be fully retained.

It has been shown by testing and computation that live-tank and dead-tank IT designs both can fulfil the requirements regarding seismic stresses. The withstand capability of an IT to seismic stresses is strongly influenced by its weight and the height of its centre of gravity. These values are of similar order for both live and dead tank designs, noting that the design of the base for live-tank ITs and of the tank for dead-tank ITs is of great importance.

A Required Response Spectrum should be established if the substation is expected to be subjected to earthquake stresses. The purchaser should make these requirements part of his order to the IT manufacturer who will take them into account for the designing and testing of the ordered ITs.

In parallel, the substation designer has to design suitable support structures which will not unacceptably amplify the earthquake accelerations. An alternative method for verifying the behaviour of the combination of IT and support structure is to test the IT mounted on the same structure that is to be used in service. Furthermore, high voltage connections should be arranged in such a way that the mechanical interaction with other electrical equipment is limited.

In technical specifications for GIS, acceleration values of 0.5 g are often required for high risk earthquake areas. ITs have to pass tests at these values without damage and this can be ascertained by calculation or by direct test. Two possible test signals are allowed for the direct test:

a) Continuous sinusoidal test

   In this test a sinusoidal displacement with an acceleration of 0.5 g at the resonant frequency of the IT, for example for 15 periods, is used. Earlier specifications were even more stringent and required a continuous sinusoidal displacement for 1 minute.

b) Sine beat test (Figure 1.57)

   In this test, impulse bursts are used which correspond better to earthquake stresses than the stresses applied in test method a). The acceleration of the modulated sinusoidal displacement peaks to a maximum of 0.5 g at the resonant frequency of the IT. Each sine beat should contain 5 or 10 periods (5 or 10 pulse-sine-beat)

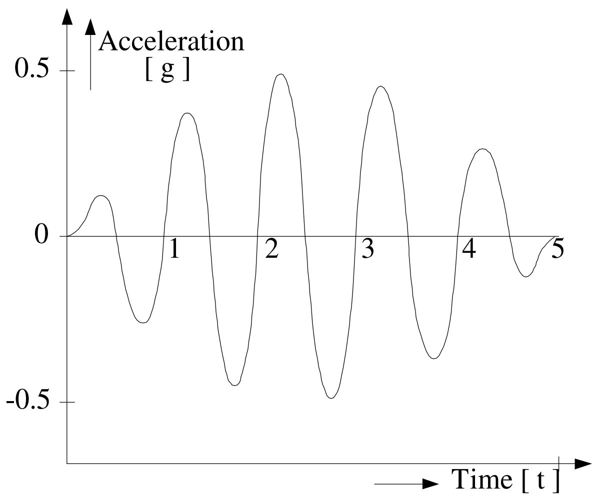


Figure 1.57: 5-pulse sine beat waveform for seismic testing

The test signals of the individual methods cause different stresses in the IT since the displacements of the table are amplified differently in the IT.

For SF_6-insulated ITs especially for outdoor operation, the inner support of the active part towards the outer shell has to withstand these stresses.

Tests show that live tank ITs are well suited to withstand the most severe earthquake tests without damping devices. However, special attention has to be given to the design of the base and it is advantageous to design an elastic base which is able to absorb more energy.

2 MANUFACTURE AND QUALITY

2.1 Introduction

The reliability of instrument transformers in HV substations is of particular importance. Indeed they should be energised for many years of service, without any operational failure, in spite of all the electrical and atmospheric disturbances in the power system. In such difficult situations they should provide precise information, in order that the protection relays can make the right decisions. Instrument transformer failure may accordingly cause serious disturbances in power systems as well as important material damage and be a hazard to the personnel.

This chapter provides details of the manufacturing process, of quality tests related to the design and of development tests, in order to deliver reliable ITs. The types of units under consideration are all ITs for Air Insulated Substations (AIS) and MVTs for Gas Insulated Substations (GIS) currently manufactured, which are as follows:

- CTs:
  - paper-oil: top core or bottom core ;
    and resin: eye-bolt or hair pin ;
  - SF6 gas: top core.
- MVTs:
  - paper-oil: HV winding in single coil or distributed in several coils ;
  - SF6 gas: HV coil winding in single ;
    and resin
- CVT:
  - paper/ film-oil : several capacitors in series in HV section.

The present range of technology for CTs and MVTs is:

- resin 72.5 to 145 kV
- paper-oil 72.5 to 765 kV
- SF6 72.5 to 765 kV.

For CVTs the present technology is mainly paper-polypropylene film + synthetic oil from 72.5 to 765 kV.

Considering the production process, the final quality of the IT depends on:

- quality of the design,
- choice of the components, materials and their quality,
- quality of the manufacturing process,
- quality assurance level.

The quality of the manufactured product is very important to assure the reliability of the IT, quality assurance playing an important role in all activities, from reception of the components to after-sales service; it involves all personnel, from the top management to the workers on the shop floor. Certification of the quality assurance system is a useful instrument, but alone it cannot guarantee absolutely "failure - free" production; a quality assurance system itself says nothing about the quality of the design, the manufacturing processes applied or the materials used; therefore education and training of the personnel at all levels is necessary to increase quality-consciousness and to achieve best results.

In the manufacturing process the most important points to obtain a good final product are:

- quality of the documents: technical information and drawings,
- quality of the equipment and tools,

– quality of the workers, training and technical assistance level on the shop floor.

2.2 Design and Quality Control

2.2.1 General requirements

The quality of the manufactured instrument transformers is already determined to a great extent during the design work. Experience shows that bad design is an important cause of failures. The design engineering work should be carried out by qualified and experienced personnel to ensure that design, tests, approval and issue of design documents are executed in a satisfactory manner. Development work should also be based on theoretical knowledge and field experience, as well as on full control of the techniques used. Design review should be carried out with the participation of qualified manufacturer's personnel or independent engineers, who can influence and critically examine the selected technical solutions.
In the event of changes in design, the same rules should be applied as to the original design work. All modifications should be examined and approved by qualified personnel, and validated by appropriate tests.

During design of all types of ITs, special precautions should be taken in order to ensure operational safety.

Examples of special points that should be taken into account as part of design control are:

– compatibility between materials, especially between oil and rubber (gaskets), enamel, varnish, paint, for the whole temperature range of the IT,
– shielding of the secondary winding against high frequency influences and fault current to earth inside the unit,
– coordination of withstand strength between different parts of the HV insulation system especially during HV surges or bursts,
– low and high temperature behaviour of the oil expansion system i.e. metal bellows and gaskets,
– mechanical, thermal and seismic stresses,
– accuracy requirements during operation and transient conditions, for all specified burdens,
– special constructions for transportation and storage.

The routine, type and special tests are carried out on the first manufactured units in order to verify the correctness of the selected design. The result of these tests should be recorded in written reports. The documentation should also define the technical requirements to be met in production, inspection, and packaging of the products.

2.2.2 Manufacturing documents

- *Drawings and technical notes:*

These documents should describe the instructions and requirements for each activity concerned. The allocation of responsibility for formulation, review, approval and issue of documents must be established:

  – the documents must be available at the right place at the right time,
  – all changes are examined and approved by the responsible engineer who improved the original design.

- *Process control documents for the manufacturing process:*

Documents must be established specifying method, sequence, instruments, gauges, etc, to be used for inspection, as well as the measurements with their appropriate tolerances. They must be completed by the worker and checked by the quality control operator.

2.2.3 Purchasing of components and materials

The quality of an instrument transformer is greatly influenced by the quality of components and materials used such as enamel-insulated wires, magnetic material, insulating paper, plastic films, insulating oil, SF6 gas, resin hardener and filler, insulators (porcelain or composite), gaskets, etc.... Relevant instructions, type and routine tests should ensure that purchasing is properly planned and carried out. However this presumes that goods and services are purchased from suppliers who can provide the desired quality.

The necessary requirements regarding the quality system of suppliers are determined after an evaluation and classification of products obtained. IEC and ISO standards can be used to specify the quality and the tests to be performed on various components and materials: type, routine or incoming tests. The manufacturer may also add specific requirements or tests to the International Standards, dependent on the IT design, the type of ITs or the service conditions: compatibility, ageing, thermal behaviour, etc. The quality of external components has to comply with the environmental requirements. Special attention has to be paid to the compatibility of the components with liquid or gaseous insulating materials.

Examples of components which may critically affect the quality of an instrument transformer are listed together with their most critical properties:

- *oil:* electrical, physical and chemical properties,
- *paper or film:* dimensions, electrical, mechanical and chemical properties,
- *insulators:* appearance, dimensions, porosity (porcelain), ageing due to environment (synthetic), electrical and mechanical strength,
- *bellows:* material quality, tightness, withstand pressure, volume, thermal behaviour,
- *gaskets:* material quality, appearance, dimensions, compatibility, temperature range,
- *core material:* magnetic properties, dimensions and appearance,
- *housing:* dimensions, appearance, porosities in cast housings, mechanical strength, surface treatment (against corrosion), tightness (take care that the type of internal treatment or paint will not cause chemical reaction resulting in any gas development),
- *resin mixture:* weathering properties. water diffusion, erosion resistance,
- *SF6 gas:* purity of gas, according to IEC 376.

Supplier evaluation should be made when a new supplier is contacted or in the case of special requirements. The evaluation will include financial, commercial and technical assessments.

The purchase technical documentation normally contains the following:

- Procedures to test and to control the quality of products supplied.
- Procedures for the dealing with non-conforming products or components.
- The right to monitor quality and test procedures of the supplier.
- Requirements for packaging and storage.

2.2.4 Process control

Control of activities which are part of the production and assembly process should be carried out in accordance with a documented system. The manufacturing specification is an important document of the production department during the manufacturing process. The specification contains details of the sequence of operations, production methods, materials and special tools required. All special requirements, for cleanness, ventilation, temperature, air humidity,... should be stated in the instructions; an example of these requirements is the cleanness of rooms for the production of capacitors or SF6 gas insulated ITs.

Special tools should be tested for functioning at fixed intervals. If a tool is found to be defective whilst in use, the work should immediately be interrupted and the tool adjusted, repaired or replaced.

All checklists must be completed by the workers and checked by the quality control operator.

2.2.5 Product identification and traceability

A system must be used which ensures that components are easily identified in the production documentation at all stages. Requirements for the identification marking of purchased items are specified in the purchase documents. The receiving department is responsible for identifying incoming goods:

- Magnetic cores are identified by dimensions and quality.

- Insulators are identified by drawing reference on the first shed.
- Oil, paper, resin, etc, are identified by supplier references.
- All mechanical pieces are identified by the drawing number.
- During the manufacturing process, each IT and each document are identified by the order number.

2.2.6 Quality records

A system should be applied to control the handling and filing of quality records. "Quality Records" means written reports, issued in connection with the implementation of the quality system as well as test reports, which demonstrate that the products supplied fulfill the stated quality requirements. Quality records include results of inspections and tests, materials certificates and any reports on non-conformity, audit reports, procedures and testing reports. Documents issued in connection with tests must include the date of the test, the name of the test engineer, the results of the test and information on how the applicable requirements have been satisfied. If the test results deviate from the applicable requirements, the non-conformances are described and accompanied by a note on the action required to rectify them.

The quality records should not be limited to the final electrical tests, but extended to all the other technical departments; as for example:

- Research and Development: design review of new special processes and apparatus.
- Purchasing: homologation of the suppliers.
- Resources and Human: recording of the training of the personnel.
- Quality Assurance: rejection and rework notes, corrective actions files, internal quality audits, calibration certificates of measuring instruments, statistical results, follow-up of special processes, quality plans.
- Technical-commercial: manufacturing cards with the endorsements, orders files.

2.3 Main manufacturing processes

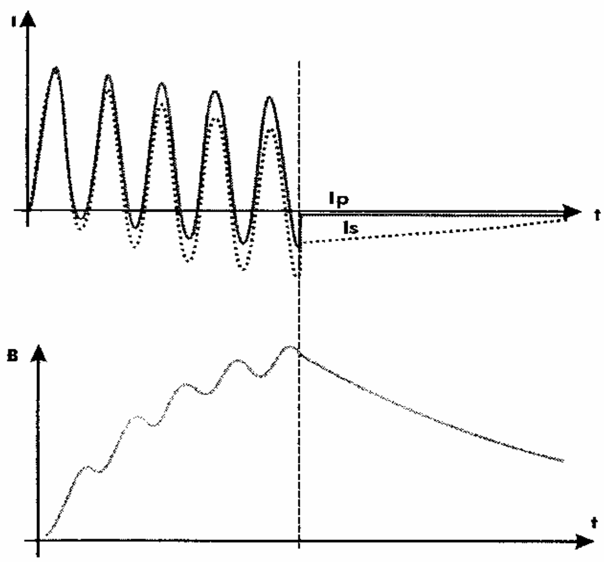
2.3.1 Active part

2.3.1.1 Design and calculation

Instrument transformer steady state accuracy, according to the Standards or the clients requirements can be calculated by computer programme; also its transient performances can be predicted (Figure 2.1). Electrical (internal or external) stresses, thermal and mechanical stresses, can be calculated from tables or computer programmes based on test results. An example of computed voltage distribution is given in Figure 2.2. As part of the manufacturing process, tests and checks may be made at a number of stages to verify that the accuracy or performance of cores and windings is within specified tolerances. For instance:

- check of the magnetic characteristics of cores,
- accuracy checks on the transformer after winding and assembling, for CTs and for MVTs,
- check on the capacitance values of the capacitor stack for CVTs, before and after drying and oil impregnation.

Reduced insulation properties (before impregnation) have to be taken into account during any dielectric checks made before impregnation.



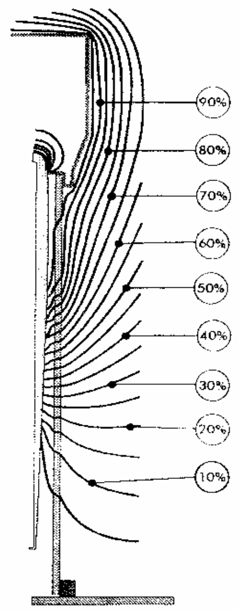


Figure 2.1: Transient response of CT TPZ class - cycle CO (according to IEC 44-6).

Figure 2.2: Voltage distribution along CT insulator.

2.3.1.2 Assembly

The LV windings are shielded by an earth screen able to protect the active part against HF surges or bursts and to conduct earth fault current in case of an internal arc.

2.3.2 High-voltage insulation

2.3.2.1 Insulation concepts

An insulation programme exists in detail for each type of CT, MVT or CVT, which defines the type and dimensions of each component to be used. The programme and the components should be such that the density and homogeneity of paper or film are the same in all parts of the HV insulation. Several screens may be used to limit the voltage gradient to the calculated values. Control tables specifying the sequence, dimensions or instruments, winding machine settings, etc, to check the conformity and quality of HV insulation will be used; these documents must be completed by the worker for each IT.

2.3.2.2 Drying process for oil insulation

During insulation drying, the heating and vacuum programme (temperature-vacuum-time) should be adapted to each unit depending on the thickness and type of insulation, in order to reach a residual water content in paper or film appropriate to the required dielectric losses. The main points, for the paper or paper/film insulation are:

- Before the drying process, the insulation paper contains between 7 and 10 % (weight) of water, under normal conditions of pressure and temperature.
- To get a good paper or paper-film/oil insulation (high dielectric strength and low dielectric losses), it is necessary to have between 0.1 and 0.2 % (depending on type of insulation) of water in paper or in film. Figure 2.3 indicates a typical relationship between dielectric strength and moisture content in paper.
- The water contained in the paper or film is in equilibrium with the partial vapour pressure for water around the insulation. Therefore, to extract the water, heat, vacuum and time are needed.
- During the drying process, it is necessary to reach a temperature of at least 100°C at atmospheric pressure, before starting the vacuum; if the temperature is too low or the drying process is too fast, ice can form in deeper parts of the insulation.
- During the drying process of the paper, the maximum temperature should not exceed 120°C in order to avoid thermal degradation. Vacuum must be maintained to prevent paper degradation at this temperature.

– During the drying process there will be temperature and pressure gradients inside the insulation; for example: in a CT with 50 mm of insulation thickness and 110°C/1 Pa at the insulation surface, the temperature and pressure will be ≈ 100°C/5 Pa in the heart of the insulation. Then to reach the same level of drying everywhere in HV insulation, it is necessary to adjust the heating time and vacuum duration at the type of insulation (thickness, type of paper, design,…).

Figure 2.4 indicates the relationship between moisture content in non impregnated paper and tan δ. Note that reducing the moisture content below 0.1 % does not result in a further reduction of the tan δ.
Figure 2.5 indicates the process conditions necessary to achieve drying to the required moisture content of 0.1 % in the paper: typical values are 110°C and 1 Pa. The time, in days, depends on the thickness of the insulation.

2.3.2.3 Impregnation with oil

- *Quality of oil:*

Since the normal ageing processes that affect the insulation of paper-oil ITs are closely related to the properties of the oil, it is essential to select carefully good quality oil. It has been found that some crudes or refining processes may leave undesirable polar compounds which can affect the electrical strength, tan δ and other characteristics of the insulating oil. Choice of poor quality oil or inadequate processing can significantly reduce the service life of ITs.

- *Impregnation:*

The impregnating oil should be dried (water ≤ 5 ppm) and degassed (gas < 0.3 %), in order to obtain good insulation quality, high dielectric strength and low dielectric losses (IEC 296 or IEC 867).
For impregnation, the process instructions which include control of temperature, vacuum and time, must be followed precisely for each type of IT. In new ITs, typical values of water and gas in oil are: water ≤ 10 ppm, gas ≤ 1%

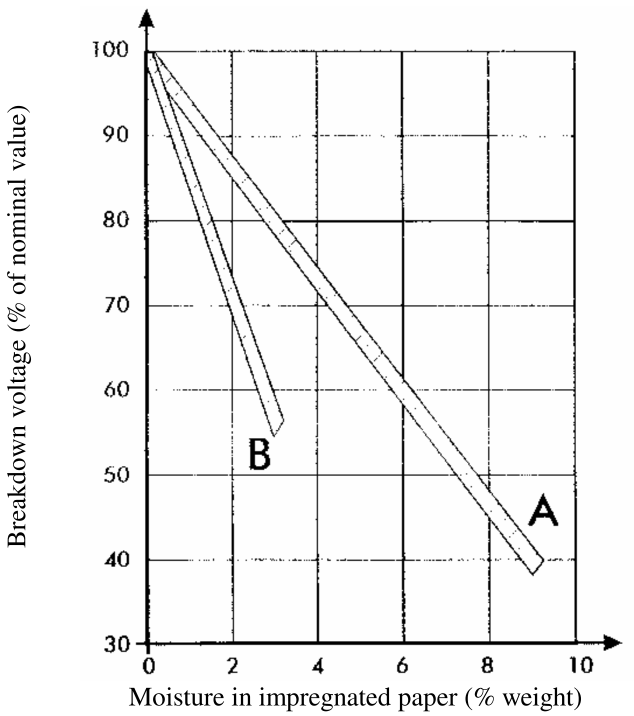


Figure 2.3: Breakdown voltage in relation to moisture in impregnated paper

A = Power frequency - B = lightning impulse

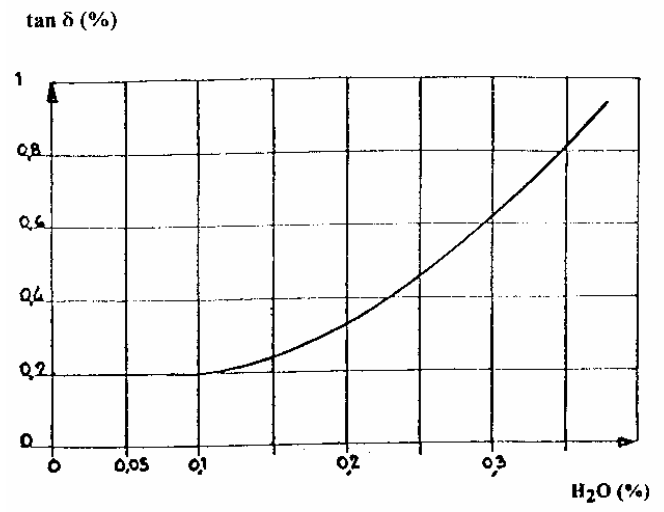


Figure 2.4: tan δ at 90 °C versus water content, for non impregnated paper

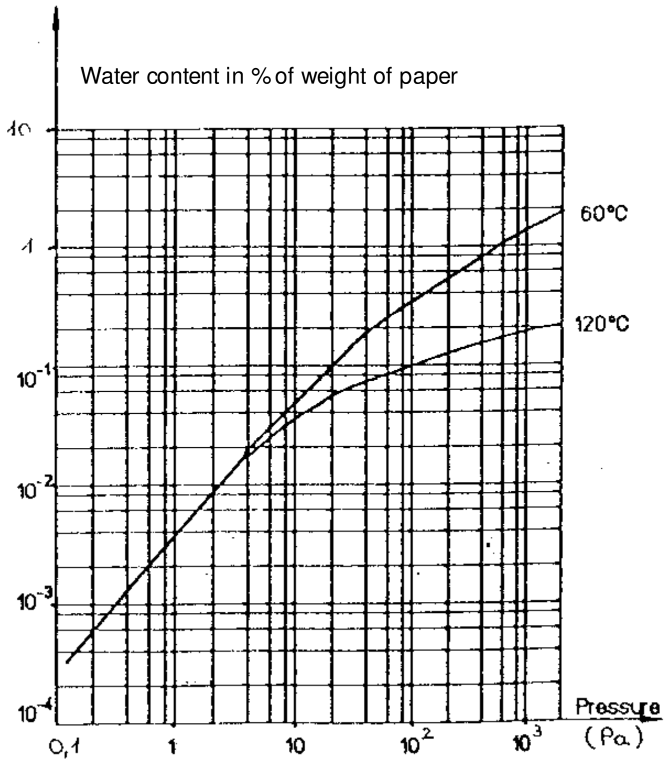


Figure 2.5: Drying of paper : equilibrium water content versus temperature and vacuum

To guarantee the quality and reliability of the HV insulation in CTs, MVTs and CVTs, special attention should be given regarding:

- partial discharges,
- temperature rise,
- good behaviour of the shields and good voltage distribution within the insulation, even in the presence of HV surges, lightning impulses or HF bursts,
- air and water tightness, prevention of internal underpressure in paper/film-oil insulation.

The low PD level and the lightning impulse withstand requirements are met by good design and good quality of components and manufacturing process assuring good homogeneity and density of the paper-oil or paper/film-oil insulation.
In EHV insulation, the dielectric losses and the behaviour of voltage grading screens are important parameters.

- *Thermal stability:*

To obtain a good thermal stability in EHV/CTs with paper-oil insulation, it is necessary to limit the dielectric dissipation factor "tan δ" at operating temperature. The origin of the dielectric losses are colloidal (glue) or polar (water or ageing products from oil) or ionic (conductive particles) contaminants in HV insulation.

- The specific dielectric losses in an alternating electric field are:

$$p_o = \omega\, \varepsilon_o\, \varepsilon_r \tan \delta_\theta\, 10^6 \left[\frac{W}{cm^3} \Big/ \left(\frac{kV}{cm} \right)^2 \right]$$

where: $\omega = 2\pi f$, $\varepsilon_o = \frac{1}{3{,}6\pi} 10^{-12}$ F/cm, $\varepsilon_r \approx 3$,

$\tan \delta_\theta$ = dielectric loss factor at reference temperature (room temperature)

p_o is the specific dielectric loss, per unit of volume at reference temperature θ, at an electrical stress of 1 kV/cm and at nominal frequency.

- Tan δ is temperature and electrical stress dependent (chapter 3, figures 3.1 and 3.2), therefore the dielectric losses per unit of volume at nominal frequency, operating temperature and operating electrical stress are:

$$p_{(\theta - E)} = p_0 e^{\alpha(\theta 2 - \theta 1)} E^2 \left[\frac{W}{cm^3} \right]$$ at operating conditions.

E = electrical stress [kV/cm].

" α " is the temperature coefficient: $\alpha = \frac{\ln(\tan \delta_{\theta 2}) - \ln(\tan \delta_{\theta 1})}{\theta_2 - \theta_1} [1/K]$.

θ_2 and θ_1 are two temperatures in °C in the operating temperature range (e.g.: 90°C and 20°C).

- The power dissipated in the total insulation as a result of the dielectric losses, in an alternating field, at operating temperature θ and voltage U (same electrical stress in each part of the insulation) is given by: $P = \omega C U^2 \tan \delta_\theta$ [W]

For example: CT = 1000 pF/60 Hz and $\tan \delta_\theta = 0.003$
for 245 kV - P ≈ 20 Watts and for 765 kV: P ≈ 210 Watts.
In CTs, the dielectric loss parameter becomes more critical with increasing voltage and therefore thermal stability should be tested in EHV/CTs.
Thermal stability is reached, when the quantity of the heat, produced by dielectric losses and Joule effect in the active part, is less than the heat that can be dissipated by conduction through the solid HV insulation
NB: In EHV/MVTs or CVTs, where the HV insulation is distributed in several coils or capacitors, there is no problem of thermal stability.

- *Screens behaviour:*

in EHV/CTs, it is important to check the behaviour of the screens and the voltage distribution within the insulation in the presence of HV surges. That is carried out by chopped front waves impulses according to IEC requirements (> 200 front chopped waves 1 x 0.5 μs/ 0.6 LI).

Figures 2.6b and 2.6c show the behaviour, with two designs of HV screens, predicted by computer when a front chopped impulse 1/0.2 μs = " U " is applied on the HV connection. This design approach is valid for the high voltage screen, but also for the intermediate screens used to reduce the voltage stress in the insulation (head + bushing).
In figure 6b, the HV impulse " U " is directly transfered from the HV connection to the first HV screen: " U_1 " follows " U " without delay; the same transfer, without delay, is achieved for " U_2 ", " U_3 " and " U_4 ". In this case the voltage distribution is correct (the voltage distribution is a pure capacitive voltage distribution).
In figure 6c, the HV impulse " U " is transfered from the HV connection to the HV screens with a delay and the voltage distribution is not correct.
Therefore to obtain a good behaviour in HV/CTs it is necessary to design all screens with a low inductance. In a "top core CT", this is achieved for the LV earth screen by installing an aluminium core box.

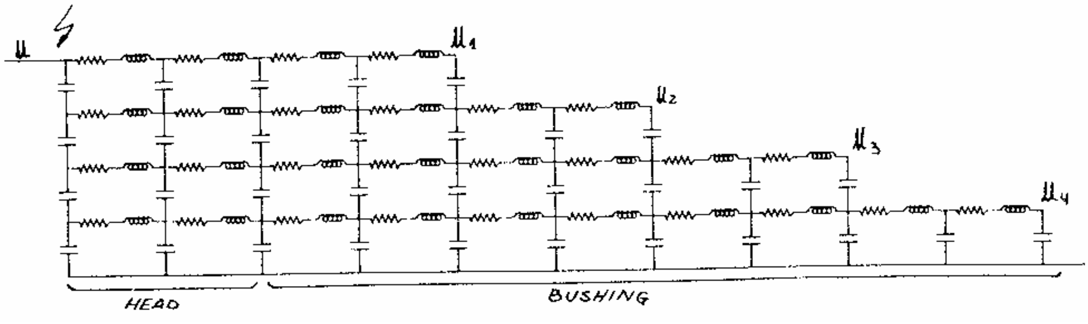


Figure 2.6a: example of equivalent electrical circuit of HV screens.

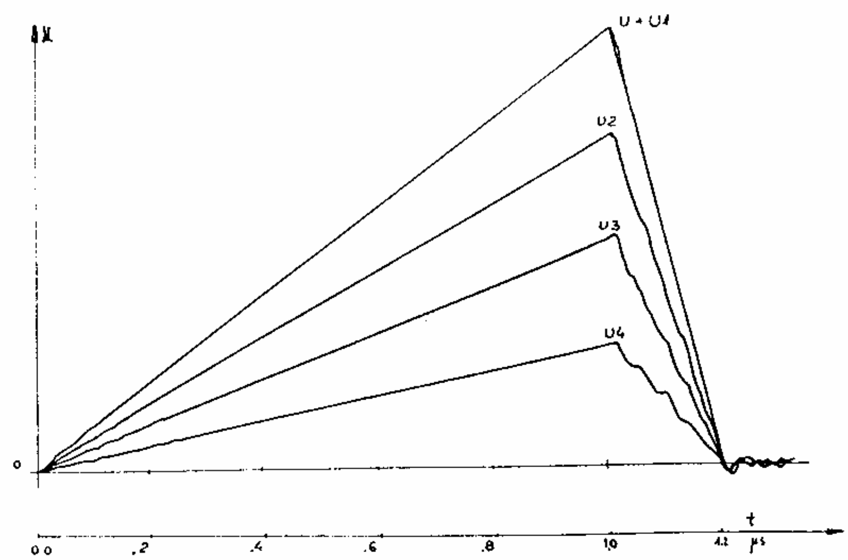


Figure 2.6b: Impulse 1 x 0,2 µs: HV screen with a good behaviour

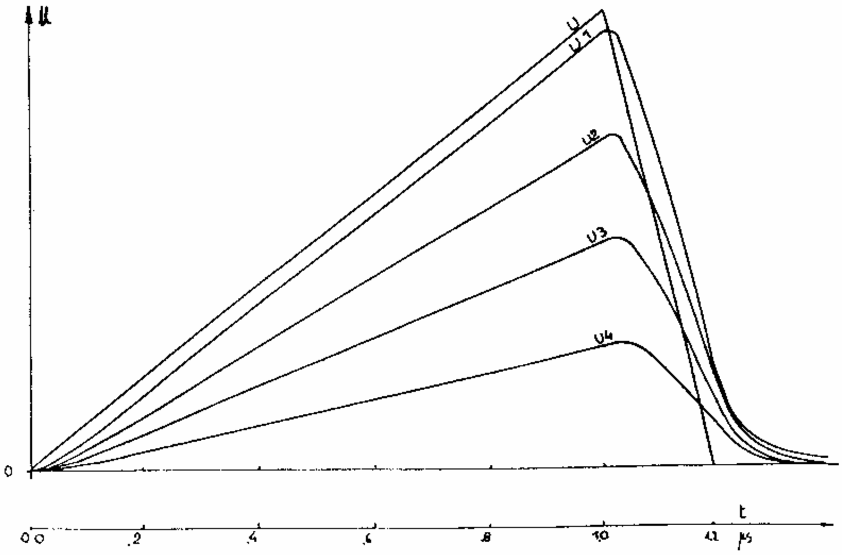


Figure 2.6c: Impulse 1 x 0.2 µs: HV screen with a bad behaviour

2.3.2.4 SF_6 insulation.

To guarantee the quality and reliability of the SF_6 gas insulated CTs and MVTs, extra care should be taken on the following points :

- The SF6 gas quality should be in accordance with IEC 376.
- Tightness (housing and sealing).
- Smoothness of the HV electrodes (roughness: e.g ≤ 1.6 µm) and the absence of dust.
- Epoxy resin supports: partial discharges should be according to IEC 60044-1.
- Moisture: the dew point should be lower than - 5°C, as specified in IEC 694.

To reach the value required for the moisture content, it is necessary to dry the components used inside of the SF_6 gas insulated ITs. Because the drying process is carried out on completely assembled units, the temperature limit is determined by the components. The drying process, performed before filling with SF_6 gas, consists of a well defined heating, vacuum and time cycle; this process is specially important in MVTs with polyester film, where the water content in the film should be reduced from 0.5 % to 0.3 %. The dew point is measured when an equilibrium is established between moisture and dry SF_6 gas. When giving proper attention to the above-mentioned points, a good lightning impulse behaviour can be achieved over the full operating life.

In order to keep leakage to a minimum (≤ 1 % gas leakage per year), aluminium cast housings must have a dense and porosity-free structure. The surfaces of the sealing areas must be smooth (roughness e.g. ≤ 1.6 µm) and "O-ring" gaskets should be used. For outdoor operation, corrosion can be avoided by greasing the flange gaps.

Each SF6 gas insulated IT should be equipped with:

- a temperature-compensated SF_6 gas density monitoring system to detect gas leakage,
- a humidity absorber, to ensure a low dew point,
- a rupture disc, to limit the overpressure in case of an internal power arc.

2.3.2.5 Cast resin insulation.

The choice of the resin/hardener system and the type/percentage of filler (silica filler for sheds for outdoor type) together with the drying/degassing, the mixing quality and the temperature cycle of the components, greatly affect the operational reliability of cast resin in HV insulation. Mechanical stresses should be avoided during manufacture of units insulated with epoxy resin; such stresses are caused by:

- high exothermy during the chemical reaction,
- high thermal and unevenly distributed shrinkage,
- inserts not suitable or not properly treated.

To prevent these three causes of mechanical stresses:

- A low chemical reactive resin should be used.
- The percentage of filler should be increased (from 2.5 to 3 x resin weight) in order to increase the thermal conductivity and to decrease the thermal expansion coefficient.
- All important metal parts should be coated.

During processing, before pouring the resin mixture, the temperature and vacuum of the mixture and the active part of the IT are checked. Temperature and time are recorded during the polymerisation process.

The correct selection of electrical and temperature gradients ensures the desired behaviour in service. The electrical stress at operating voltage should be less than 3 kVrms/mm. The partial discharge level obtained after power frequency dielectric tests should be according to IEC 60044-1 / 60044-2; partial discharge tests allow detection of voids, mechanical stresses and micro-cracks. The operating temperature is according to class E; the glass transition temperature is always higher than 90°C. Finally, for ITs with resin sheds, the creepage distance is typically 25 % higher than with porcelain insulators.

2.3.2.6. External insulation.

The type of insulator (arcing and creepage distance) should be defined correctly based on the operating conditions specified by the client and the voltage distribution in the bushing. The quality of the external insulation may be checked according to the standards:

IEC 60815:	Guidelines for selecting insulators in a polluted environment
IEC 60044-1/60044-2:	Current respectively Voltage Transformers" - clauses on wet tests for outdoor ITs.
IEC 61462:	Composite insulators
IEC 60-1/2:	HV tests
IEC 506:	Switching impulse tests on HV insulators
IEC 507:	Pollution tests on HV insulators for AC networks

2.3.3 Special processes.

The term "special processes" refers to processes and methods the outcome of which may not easily be checked upon completion. Such processes include heat treatment, oil or SF6 impregnation, welding, soldering, inorganic and organic surface treatment, resin mixture pouring, and crimping connections. The use of special processes in the production and testing of products should be regulated by proven and well-documented methods ensuring that the final product has the characteristics intended.

A full verification of some of these processes may often require destructive inspection of the IT. Special processes such as welding and soldering should be carried out by authorized, trained personnel. Training and periods of practice are also necessary for tasks which do not require authorization.

Examples of special processes in instrument transformer manufacturing which have a critical influence on quality are:

- Taping of main insulation (paper or film), where training of personnel is particularly important;
- paper or film drying, where control of process parameters : time, temperature and vacuum level are important;
- oil impregnation, where temperature, vacuum and time are important parameters;
- resin mixture process, active part conditionning and mixture pouring;
- SF6 impregnation;
- making of internal electrical connections using crimping, welding or soldering, which must be made according to instructions by personnel having appropriate training. Four parameters are essential for the reliability of connection systems using crimping techniques:
  - the splice sleeve must have a correct diameter relative to the diameter of the non-insulated wire,
  - the correct crimping tool with a correct code mark must be used
  - the assembly of the splice and wires must be done according to appropriate drawings,
  - instructions for the verification steps must be followed.

The random tests should include check of the crimping tool and test of tensile strength of finished connections.

2.3.4 Training

Qualified, experienced personnel are a key resource in implementing high quality in all operations. It is essential that competent personnel carry out the various tasks. Planned and documented training must be provided and periodically repeated to ensure that the basic requirements are fulfilled. Examples of operations needing specially trained personnel are the application of paper insulation to CTs or MVTs, and the handling of plastic film in capacitor manufacturing.

2.4 Inspection and testing

2.4.1 Planning

The inspection and test plan which is a part of the quality plan summarizes the inspection and tests which precede the final approval of the instrument transformers before delivery. This plan, drawn up separately, refers to the documentation to be used for inspection. The requirements to be met, and the manner in which the results are to be recorded, are outlined in mandatory technical specifications, inspection cards and requests for tests additional to normal procedures.

Test requirements and approval criteria are widely dependent on the specific instrument transformer design and are therefore determined by the unit responsible for development and design. Inspection and test plans may also be established for products purchased from external suppliers. However, if possible, products bought externally are inspected in accordance with plans formulated by the supplier and based on relevant Standards or product specifications.

2.4.2 In-coming goods inspection and testing

Instructions and regulations should be applied to ensure that incoming goods are inspected in accordance with documented procedures. The inspection documents contain instructions on what is to be inspected, how and to what extent the inspections should be carried out and requirements for inspection records. Requirements regarding marking and identification of goods should be made clear to the supplier in the purchase order. The receiving department should be responsible for identification, tests, recording of arrival date, and for the supply of complete documentation, covering all areas specified in the purchase order.

Example: external supplies can be sorted into two different categories:

- *cat. A*: strategic products (oil, resin, paper, film, SF6 gas, insulator, wires, magnetic material, bellows, etc). For each component of this strategic category, a specification must be made. This category needs a high degree of inspection, and high reliability of the processes of the approved suppliers. Regular checks of the quality of these "strategic" approved suppliers should be carried out. For each batch, the manufacturer delivers a test certificate.
- *cat. B*: products for which specification, inspection instructions or drawings are available (mechanical pieces).

  This category needs only sample inspection or dimensional verification.

Non-conforming goods should be treated in accordance with paragraph 2.4.7.

2.4.3 In-process inspection and testing

In order to ensure that the instrument transformers are in accordance with the specified requirements, they must be inspected during manufacturing and assembly. The extent and execution of the necessary inspections plans, instructions and specifications are supervised by the Quality Department.

Examples of tests that are sometimes used as in-process checks are:

- low voltage insulation tests;
- check of number of turns on cores;
- capacitance and tan δ measurement;
- expansion volume check;
- quality of oil, resin or SF6;
- water and tan δ at 90°C in oil;
- dew point of SF6 gas;
- chemical exothermy of resin mixture.

When special processes are implemented, for which verification by testing is difficult, the equipment used should be checked and the following process parameters should be monitored:

- heating, vacuum and time during the drying of the paper or film,
- heating and vacuum during the mixing of the components in the resin process.

The manufacturer should establish effective inspection control to stop the use, further processing, assembly or dispatch of products until satisfactory results have been obtained from the stipulated inspections and tests and until there is no doubt about the interpretation of these results.

2.4.4 Final inspection and testing.

The instrument transformer should undergo the final inspection at the end of the manufacturing process, in order to ensure that the characteristics and performances comply with specified requirements. As a rule, final inspection consists of visual and functional inspections in accordance with inspection cards, instructions and specifications. Final inspection and testing can include different checking and monitoring activities. The most important of these activities are regulated by International Standards.

Data obtained from final inspection and testing should be recorded, if possible, in a way that allows comparison with data obtained later in service. In this way, it is possible to evaluate changes in such data which might affect reliability.

2.4.5 Test status.

A system should be used to indicate product inspection and test status with regard to stipulated inspection operations. Inspection and test status should be indicated by marking after each inspection, either directly on the product or on a special document which accompanies the product. Only products which, at inspection, have been found to be in accordance with specified requirements or with approved deviations will be permitted to progress or to storage, further processing operations or dispatch as appropriate:

- in the MV range: green label for acceptable and red label for reject are used,
- in HV range: an identification card follows each HV/IT, this card contains the results of:
  - the accuracy after winding and assembling "active part" or the capacitance value of the capacitor stack,
  - the inspection during the HV paper insulation process or during the drying process.
- The final inspection and the final electrical tests results are written in the final report.

2.4.6 Measuring and test equipment.

Measuring devices, electrical instruments and test equipment should be regularly calibrated in order to ensure that measuring and test results are sufficiently accurate. The calibration system covers all equipment used for the inspection and testing of products as well as equipment used for the control and monitoring of important parameters within the manufacturing process, where faults may adversely affect quality. Certain types of production tools are also covered by this system. New measuring equipment and tools should be given an identification number and should be checked prior to use. Equipment and tools which are in use should undergo periodic calibration against certified equipment traceable to recognized standards. If there are no such references, the calibration is carried out in accordance with established methods and the results are documented.

The results of measuring equipment or tools inspections should be recorded. Test equipment and tools which have been approved at the periodic tests have a label or a colour coded sticker attached, stating the date of the next calibration.

2.4.7 Control of non-conforming products.

Instructions and rules should exist for the handling of non-conforming products. "Non-conformity" means that the requirements set out in the order or in the production documentation have not been fulfilled, or that the product cannot be considered a piece of good workmanship. Products with demonstrated non-conformities are segregated from the materials flow in order to prevent them from being used by error. This is done either by marking the products or storing them in specially assigned places, pending a decision on further action.

Permission to repair a defect or for "use-as-it-is" is granted by the quality department in consultation with the unit responsible for design and development. After such measures as re-working or repair, another inspection is carried out. It would be suitable to develop statistical follow-up of the non-conforming products in order to analyse the different reasons for rejection (example: by "Pareto analysis"), to evaluate the different costs and to analyse the different causes of rejects. These measures should be applicable for the incoming rejects, and for the production rejects and reworks.

2.4.8 Corrective actions.

When defects are discovered, a system for implementation of corrective action has to be applied. Any employee of the company who discovers a defect should be responsible for reporting it. Thereafter, the department responsible for the product in question is informed in accordance with the system and should subsequently take corrective action. If it is considered necessary, the causes of the defect are analyzed and the corrective actions subsequently taken are reported to the heads of the departments involved. If a defect is discovered by the user either at commissioning, inspection or in-service monitoring, the manufacturer should be contacted. In such a case the causes of the defect should be analysed and corrective actions be agreed between the user and the manufacturer. If the analysis shows that the defect may recur, the relevant design department or the quality department should take the necessary preventive actions. This system of corrective action should be extended to the supplier, in order to improve the reliability of the incoming goods and components.

2.4.9 Quality audits.

In order to determine whether the quality system is functioning efficiently, periodic quality audits of all functional units should be carried out. The frequency of these internal audits should be stated in an activity plan which is prepared annually by the quality department. These audits should be carried out by the quality department, assisted if required by specialists. The quality auditors should not have any direct responsibility for the units being audited. Quality audits can also be performed by external independent organizations or, in case of major contracts, by personnel from the customer organization. In addition to the periodic system audits, product and process audits are also carried out in order to determine whether stipulated quality requirements are met.

If any discrepancies are discovered during the audit, corrective action has to be taken. When discrepancies have been rectified, another audit is carried out if deemed necessary, covering those areas which were the subject of the corrective action.

Auditing of important suppliers should be carried out in conjunction with supplier assessment and when circumstances indicate the need.

2.5 Handling, storage and delivery.

In the handling, transport and storage of products, regulations and supplier procedures should be applied which ensure that the products are not damaged or suffer any other deterioration of quality, and that inappropriate usage of the products is prevented. During handling and transport, special attention should be paid by manufacturer and client to limit shocks to < 4 g in vertical and horizontal directions: use of trucks with special suspension, handling with care, indications on packing, instructions, etc. For certain ITs, shock indicators can be used. Instrument transformers kept in store should be checked periodically. These checks are intended to reveal storage problems such as oil leakage, low oil levels and instances where the permitted storage time has been exceeded. Restrictions on storage time and storage position depend on the design of the instrument transformer. Bellows can be damaged if the storage time is exceeded with the IT stored in the horizontal position. Long time storage without removing the packing material can cause corrosion if water absorbing materials have been used for packing. Packaging, marking, booking of transport and final dispatch are carried out in compliance with the relevant documentation, such as drawings and packing instructions.

Inspection, in compliance with stipulated requirements, should be carried out regularly by the packaging foreman or supervisor. In such instances, cleaning, special protective measures, packaging and marking are given special attention. The manufacturer should deliver the IT in proper packaging or crating with clear hoisting according to the handling instructions. The marking of the position in which instrument transformers are to be transported is of vital importance. Transportation in the wrong position is most likely to damage the windings of MVTs, and the main insulation of CTs.

The following is an example of a "special transport test":

- According to the "international" statistics, the shocks during the normal handling and truck transport are less than 4g.
- On "active part": in the laboratory it is possible to test the "active part" on a shock machine with "4 g at 5 to 10 Hz" for 2 hrs. The criteria should be: no visual deterioration, no leakage, to withstand the LV power frequency test (3 kV/50 Hz) and accuracy tests.
- On the complete IT, with its packing and in normal transport position (Figure 2.7): a "transport test" by road over a distance of approximately 1000 km can be carried out.

After the transport test, the electrical routine test programme should be performed on the IT, and should not reveal any deficiencies.

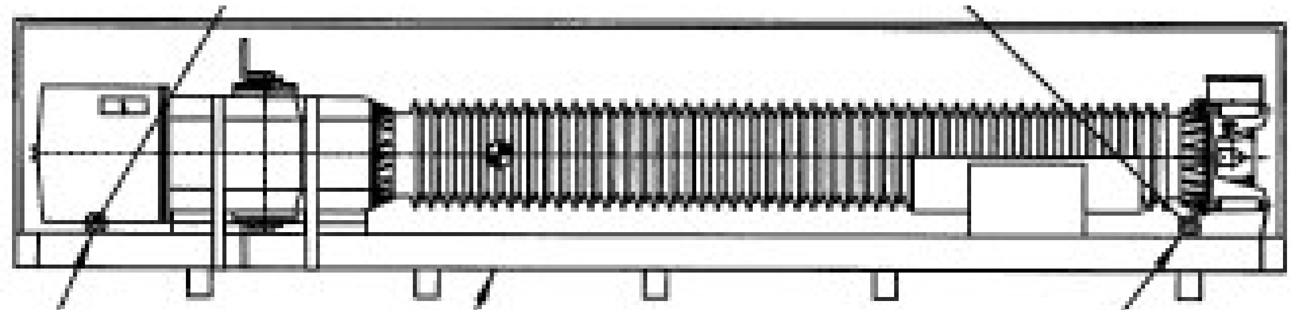


Figure 2.7: Example of a packing of an EHV/CT in transport position

3 TESTS

3.1 Introduction

This chapter identifies all tests necessary to verify the quality of an instrument transformer (IT) with regard to the following items:

- **Design** to verify that the instrument transformer can withstand and endure various stresses and environmental conditions during it's service life.
- **Construction** to verify the quality of materials as well as the manufacturing process.
- **On commissioning** to verify that the instrument transformer is fit for service after transportation, to verify that the installation work is acceptable and to provide an initial maintenance record before energisation.
- **In service** to verify that the instrument transformer remains in a suitable condition and fit for further service. To identify the type and extent of ageing and degradation in order to estimate the safe remnant asset life of the instrument transformer.

Type, Routine and Special tests are performed in the factory to verify the quality and performance of the instrument transformer in design and construction as well as production quality. Type and Special tests may alternatively be performed in an independent laboratory.

Commissioning and in-service tests are performed on site.

In-service tests and diagnostic applications are further described in Chapter 5 of this Report.

3.2 Factory Tests to Verify Design, Construction and Production Quality

Tests performed in the factory are classified and specified in IEC Standards and are listed in 3.2.1.1 to 3.2.3.3 below. Tests to other Standards such as ANSI or IEEE may also be applied. Proposals for tests, which are additional to IEC, are mentioned in Section 3.3 and are included for information. It should also be remembered that many countries impose additional tests or variations from the tests in these Standards because of special local requirements and experience.
Reference is made to current IEC Standards at the time of preparation of this Report, although it is recognised that they are subject to ongoing revision.

3.2.1 Type tests

The purpose of type tests is to assure by testing that:

(i) the instrument transformer can withstand and endure various in-service stresses, and to prove that the transformer is suitable for the specified system conditions (i.e. is specified in accordance with the User's requirements for earthing system, fault current, etc.),

(ii) the production quality of the instrument transformer meets the required Standards,

(iii) to form a benchmark for subsequent production units.

All dielectric type tests are performed on the same transformer, unless otherwise specified in the Standards or agreed by the customer.

Type tests according to the Standards are mandatory.

3.2.1.1 Type Tests for Current Transformers

These are performed according to IEC 60044-1 and are:

a) Short-time current test.

b) Temperature-rise test.

c) Lightning impulse test (including chopped wave).

d) Switching impulse test ($U_m \geq 300$ kV).

e) Wet test for outdoor type
   - power frequency voltage for Um < 300 kV
   - switching impulse voltage for Um ≥300 kV.
f) Determination of errors.

In addition, protective current transformers for transient performance may be tested in accordance with IEC 60044-6 (1992). For current transformers class TPS, TPX, TPY and TPZ, the additional type tests are:

g) Measurement of peak instantaneous error current.
h) Determination of Factor of Construction (F_c).
   (See comments in Section 3.3.1.8)

3.2.1.2 Type Tests for Voltage Transformers

These are performed according to IEC 60044-2 for MVTs and to IEC 60044-5 for CVTs and are:

a) Short-circuit withstand capability test.
b) Temperature-rise test.
c) Lightning impulse test (including chopped wave).
d) Switching impulse test (U_m ≥300 kV).
e) Wet test for outdoor type
   - Power frequency voltage for CVTs and MVTs (Um <300 kV)
   - Switching impulse for Um ≥300 kV.
f) Determination of errors.
g) Ferro-resonance tests on CVTs.
h) Transient response test on CVTs.
i) Discharge test on capacitive parts of CVTs.
j) High frequency capacitance and equivalent series resistance measurement on CVTs.
k) Stray capacitance and conductance measurement of low voltage terminal on CVTs.
l) Determination of the temperature coefficient (only for the capacitive part of CVTs).

3.2.1.3 Type Tests for Combined Transformers

These are performed in accordance with IEC 60044-1 for the current transformer part and IEC 60044-2 for the voltage transformer part. Temperature rise performance and the mutual influences between the current and voltage parts are also measured in accordance with IEC 60044-3.

3.2.2 Special Tests

Special tests are normally performed on instrument transformers by agreement between the manufacturer and the user. The following tests are already included in the Standards.

3.2.2.1 Special tests for Current Transformers

These are performed according to IEC 60044-1, and IEC 60044-6 and are:

a) Chopped lightning-impulse test.
b) Measurement of capacitance and tan δ (dielectric loss angle).
c) Multiple chopped impulse (MCI) test on the primary insulation (primary winding).
d) Verification of low leakage flux design (protection cores for transient performance only).

e) Mechanical (Cantilever) tests.

3.2.2.2 Special Tests for Voltage Transformers

These are performed according to IEC 60044-2 or to proposed IEC 60044-5 (for CVTs) and are:

a) Chopped lightning-impulse test.

b) Measurement of capacitance and tan δ.

c) Mechanical (Cantilever) tests.

3.2.2.3 Special Tests for Combined Transformers

These may be performed as specified in the Standards for current and voltage transformers. IEC 60044-3 does not specify additional special tests.

3.2.3 Routine tests

The purpose of routine tests is to verify the quality of construction, materials and manufacturing process. The tests are normally performed on complete units, apart from some tests for CVTs.

3.2.3.1 Routine Tests for Current Transformers

These are performed according to IEC 60044-1 and IEC 60044-6 and are:

a) Verification of terminal markings

b) Power frequency withstand test on secondary windings to earth

c) Power frequency withstand test between the secondary windings

d) Inter-turn overvoltage tests on the secondary windings

e) Power frequency withstand test on the primary winding

f) Partial discharge measurement

g) Determination of errors

Transient performance protection cores are tested in accordance with IEC 60044-6 as follows:

h) Determination of turns ratio error (TPS only)

i) Determination of steady state ratio error and phase displacement (TPX, TPY, TPZ)

j) Determination of secondary winding resistance (All classes)

k) Determination of secondary excitation characteristic

l) Determination of remanence factor (K_r for TPY only)

m) Calculation of secondary loop (circuit) time constant (T_s for TPY and TPZ)

3.2.3.2 Routine Tests for Voltage Transformers

These are performed according to IEC 60044-2 for MVTs or to IEC 60044-5 for CVTs, and comprise:

a) Verification of terminal markings

b) Capacitance and tan δ for the capacitive part of CVTs

c) Voltage withstand test

- Power frequency voltage test on primary and secondary windings, and between sections, for MVTs
- Power frequency voltage test on capacitive part(s) and electromagnetic unit for CVTs
- (Capacitance and tan δ should be measured on the capacitive part before and after the voltage test according to IEC 60358)
- Bias test (A.C. superimposed with three switching impulses), combined with partial discharge measurement, as an alternative for the capacitive part of CVTs with Um ≥ 300 kV according to IEC 60358, 1990.

d) Partial discharge measurement

For the capacitive part of CVTs with Um $\geq$ 300 kV, the test may be performed using the A.C. test or bias test (A.C. superimposed with three switching impulses) as a pre-stress level. (See item 3.3.3.7 for comment)

e) Determination of errors

f) Sealing test (for capacitive parts of CVTs and for SF_6 insulation)

3.2.3.3 Routine Tests for Combined Transformers

These are performed in accordance with IEC 60044-3 and are the same as for CTs and VTs described above.

3.2.4 IEEE Standard Tests for Instrument Transformers

Requirements for testing of instrument transformers are contained in:

– IEEE Standard C57.13-1993 'IEEE Standard Requirements for Instrument Transformers'

and

– ANSI C93.1 - 1990 'American National Standard for Power-Line Carrier Coupling Capacitors and Coupling Capacitor Voltage Transformers (CCVT) requirements.

The tests in IEEE (and ANSI) Standards are very similar in the type of test and test method to those in IEC Standards. The main differences between IEC and IEEE requirements are the number of tests required, the values of the dielectric tests, and which tests should be routine, type or special tests. The other differences in testing are outlined below.

3.2.4.1 Type Tests

For CTs, IEEE Std. C57.13-1993 requires that protective CTs in which the leakage flux in the core has an appreciable effect on the ratio within the specified limit, a typical overcurrent ratio curve shall be given on rectangular coordinate paper plotted between primary and secondary current over the range from 1 to 22 times the rated primary current, for all the standard burdens up to the overcurrent which causes a ratio correction of 50%.

For CTs and VTs IEEE Std. C57.13-1993 requires that routine tests be passed before and after the type tests.

For CVTs, ANSI C93.1-1990 requires that the following tests are included:

a) Radio Interference Voltage (RIV) test

b) Cantilever load test

c) Measurement of minimum creepage distance

d) Short-time overvoltage test (140% of performance voltage applied to the HV terminal for 1 minute with the maximum burden for the most stringently rated accuracy class applied to one secondary winding).

3.2.4.2 Special Tests

For CTs:

a) Measurement of open-circuit secondary voltage magnitude

b) Radio Interference Voltage test

c) Partial discharge test

For VTs:

d) Tests to verify voltage transformer capabilities at 125%, 140% and 173% of rated line to earth voltage

e) Radio Interference Voltage test

f) Partial discharge test

3.2.4.3 Routine Tests

For protective CTs, IEEE Standard C57.13-1993 requires the knee of the excitation curve to be shown. For CTs with non-gapped cores, the knee is defined as the point where the tangent is at an angle of 45 degrees to the abscissa (when the scaling factors of the IEEE Standard are applied). For gapped core CTs in which the leakage flux in the core does not have an appreciable effect on the ratio within the specified limit, the knee is defined as the point where the tangent is at 30 degrees to the abscissa. The exciting current is not to exceed 125% of the typical curve value below the knee point.

3.3 Tests Additional to IEC Standards

The tests listed below are suggested by the experience of manufacturers and users and are proposed for consideration in future IEC Publications. In summary they are:

Type Tests:
3.3.1.1 Periodic Refreshment of type test
3.3.1.2 Application of Routine Tests before and after type tests
3.3.1.3 Oil and SF_6 Gas Quality
3.3.1.4 Measurement of capacitance and tan δ (dielectric loss angle)
3.3.1.5 Multiple chopped impulse (MCI) tests for ITs
3.3.1.6 External insulation
3.3.1.7 Pressure, sealing and leakage tests for SF_6 and paper-oil ITs
3.3.1.8 Factor of construction and verification of low leakage flux design (comment)
Special Tests:
3.3.2.1 Thermal stability test for paper-oil CTs
3.3.2.2 Internal arcing test for free standing instrument transformers
3.3.2.3 Ferroresonance test on MVTs
3.3.2.4 Capacitive energy discharge test for MVTs
3.3.2.5 Seismic performance
Routine Tests:
3.3.3.1 Lightning impulse test
3.3.3.2 Capacitance and tan δ measurement of primary insulation
3.3.3.3 Measurement of insulation resistance
3.3.3.4 Excitation curve for MVTs
3.3.3.5 Pressure, sealing and leakage tests for SF_6 and paper-oil ITs
3.3.3.6 Partial Discharge test for complete CVTs
3.3.3.7 Bias test for CVTs (Comment)

3.3.1 Type Tests (additional to IEC Standards)

3.3.1.1 Periodic Refreshment/Revalidation

The Standards do not stipulate a validity period for type tests and, in principle, type tests are performed once only and are valid so long as materials, construction and processing of the instrument transformer remain unchanged. Significant changes to the manufacturing process invalidate the appropriate type tests, but minor changes may not. It is the responsibility of the manufacturer to judge whether type tests have become invalid.

In practice, manufacturers and utilities also perceive that there is a need to refresh the type tests periodically. Repetition (refreshment) of type tests is justifiable where:

- considerable time has passed since the original type tests
- traceability of the current production design to the type tested design cannot be positively established
- there have been a number of small, but overlapping changes, say to materials or to process, where the manufacturer did not consider it necessary to perform type tests following each change.

For various reasons it seems reasonable to perform some type tests more frequently than others. For example, the integrity of the internal major insulation may be seriously affected by a gradual reduction in factory quality over periods of years. Dielectric (lightning impulse) type tests, which verify internal insulation quality, should be performed more frequently than, say, the short-time current or temperature rise test.

To avoid adverse effects on the costs of ITs, it is proposed that the validity of type tests, for the same design of instrument transformer, should last for a maximum of ten years and that all type tests should be repeated automatically after this period. Lightning impulse type tests should remain valid for a maximum of two years only.

An additional proposal is for a statement to be prepared by the manufacturer at the end of five years after the type tests, declaring the status of the design.

3.3.1.2 Application of Routine Tests before and after Type Test

For all ITs it is good practice to perform all the Routine tests mentioned in Section 3.2.3 before and after the Type tests. The comparison of Routine test results before and after tests provides evidence of verification of the Type tests, i.e. that the instrument transformer is undamaged.

For SF_6 type instrument transformers, the routine power frequency voltage withstand test on the primary winding together with partial discharge measurement should be performed just before and after the impulse test. The purpose of power frequency test before the application of impulses is to provide conditioning as well as pre-stressing. For paper-oil and resin ITs, the final withstand test may be performed at a reduced voltage, as allowed in the Standards.

To evaluate the thermal ageing of insulating materials, it is also useful to perform a tan δ (dielectric loss) measurement on the complete unit before and after the temperature-rise test.

For paper-oil type instrument transformers, it is useful to perform oil sampling before and three days after all type tests for chromatographic analysis of dissolved gases to provide additional information that the transformer has successfully withstood the tests. In principle there should be no change in DGA levels before and after type tests. For chromatographic analysis of oil after type tests, DGA values are typically:

CO	100 ppm	CO_2	200 ppm
H_2	≤10 ppm	CH_4	5 ppm
C_2H_6	5 ppm	C_2H_4	2 ppm
C_2H_2	0 ppm (none measurable)		

The interpretation of the levels of the dissolved gasses, and their comparison before and after type tests must be treated with care, because they can be influenced by the performance of the oil laboratory. For this reason it is necessary to appreciate the sensitivity, repeatability of oil sampling and analysis, and reproducibility between laboratories. Account must also be taken of the low volume of oil in the IT when interpreting the significance of changes in dissolved gas levels. (See also Section 3.3.1.5.1).

To prevent the formation of bubbles and penetration of foreign materials into the oil, oil sampling has to be made carefully according to the manufacturer's procedures, including oil filling which may be needed.

Some users now specify DGA after routine tests on oil filled CTs and MVTs as a quality check of manufacture, and to provide baseline information for maintenance purposes. The levels given above may be appropriate in these circumstances. However, DGA adds to manufacturer's (and purchaser's) costs and may not be considered to be necessary in all cases.

3.3.1.3 Oil and SF_6 Gas Quality

The need for good quality oil of consistent standard is outlined in Chapter 2. A test report for mineral oil according to IEC Publication 60296 is required. Also, the following properties for new oil, which are additional to IEC, are recommended:

- Conductivity at 90°C $< 10^{-11}$ S/m
- Conductivity at 20°C $< 10^{-12}$ S/m
- Maximum tangent delta (50 Hz) at 90°C 0.30%
- Maximum tangent delta (50 Hz) at 20°C 0.05%

  (The ratio of tangent delta at 90°C to 20°C should not exceed 10)
- Impulse breakdown strength (ASTM D3300) >145 kV
- PCB content (ASTM D4059) < 2 ppm

Similarly, for equipment using SF_6 gas, the gas must be of good quality and of consistent standard. A test report according to IEC publication 60376 and its supplements is required.

3.3.1.4 Measurement of the Capacitance and Tan δ (Dielectric loss angle)

Measurement of capacitance and tan δ as a <u>type test</u> should record their dependence upon temperature and voltage. The tests may be applied to all types of insulation but the introduction of new primary insulation materials makes it essential that it be performed certainly for paper-oil insulated ITs. For new paper-oil instrument transformers, the value of tan δ is typically 0.2 - 0.4% at ambient temperature and generally increases with increasing voltage. The variation in value of tan δ with voltage for capacitively graded (or condenser type) insulation should be small: the increase of tan δ should not exceed 0.05% over the voltage range, kV Um/√3 when measured at ambient temperature (20°C ±10°C). If the value of tan δ decreases with voltage, it can be an indication of excess moisture, contamination of the insulation or incompatible materials.

Typical curves of the temperature and voltage dependence of tan □ for a new capacitively graded paper-oil 420 kV CT are given in Figures 3.1 and 3.2 respectively. Similar curves can be obtained for other paper-oil ITs.

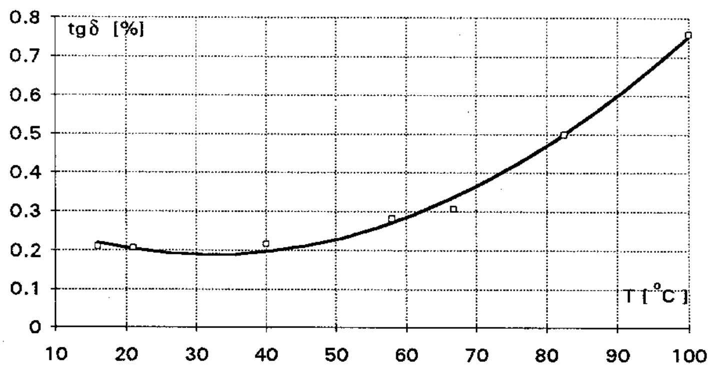


Figure 3.1: Temperature dependence of tan for a typical 420 kV live tank CT (with graded insulation).

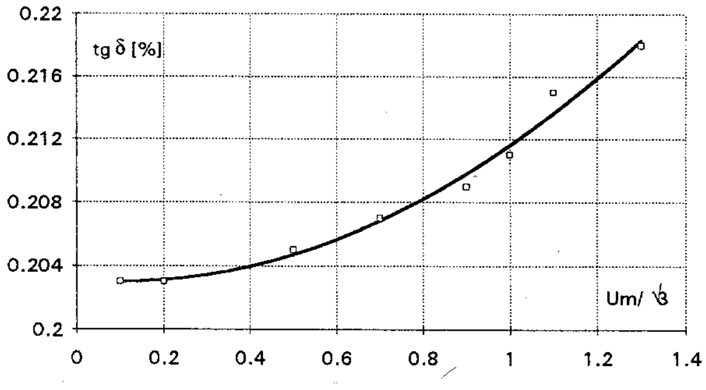


Figure 3.2: Voltage dependence of tan for a typical 420 kV live tank CT (with graded insulation).

The tan δ of a new MVT with paper-oil insulation may typically be higher than that of CTs because of the differing designs of MVTs. For guidance the tan δ should generally be in the range 0.2 to 0.5%. For resin insulation, the value should be less than 2%.

In general, the measured value of tan δ is an average for the insulation system within the test 'envelope'. Thus some parts of the insulation may have much higher localised tan δ levels and these may not be readily detected by the overall measurement at ambient temperature. Care must also be taken with different designs of ITs to ensure that the highest electrically stressed areas of insulation, which are most at risk, are included within the test envelope. For instance, for some designs of CTs, measurement of capacitance and tan δ at the test tap may result in the measurement of only a (small) part of the CT insulation. For MVTs, a number of separate measurement arrangements may be necessary depending on their construction. (See Section 3.3.3.2.2)

Capacitance and tan δ tests are described further in Section 3.3.3.2.

3.3.1.5 Multiple Chopped Impulse Test (MCI) for Instrument Transformers

High frequency transients are generated during disconnector closing and opening operations due to the repeated restriking of the arc between the contacts of the disconnector. Disconnector arcing (restriking) is known to have caused progressive degradation and failure of some designs of paper-oil insulated type current transformers. [22]. The MCI test [14], was therefore proposed primarily for post type paper-oil current transformers, and is now included in IEC Publication 60044-1 as a Special Test. The test effectively searches for design and constructional defects which give internal electrical discharge or arcing under high frequency conditions. The test circuit is defined as in Figure 3.3, and is arranged to produce chopped lightning impulse waves, by means of an air insulated chopping gap (E). Between 100 and 600 impulses of negative polarity chopped near the crest are applied. Rise time and collapse time of the impulse, from zero to chopping and from chopping to zero respectively, should be between 1.2 and 0.5 µs. The amplitude of test voltage should be about 2/3 of rated lightning impulse withstand voltage. The amplitude of the first opposite polarity oscillation should have a value between 30 to 50% of the chopped impulse crest value. The test voltage should be applied between the high voltage terminal and earth at the rate of one impulse per minute.

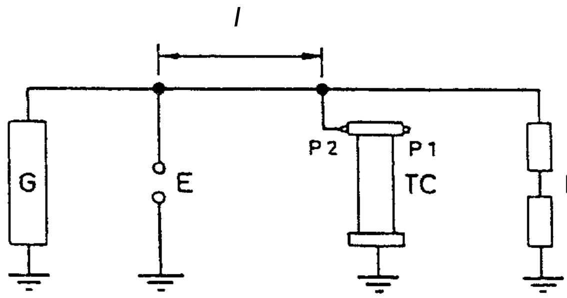


Figure 3.3: Multiple chopped impulse (MCI) test circuit.

3.3.1.5.1 Paper-oil Current Transformers

The acceptability (pass) criteria are established primarily by means of gas-in-oil levels (Dissolved Gas Analysis - DGA). In principle, the test as proposed does not allow for an increase in dissolved gas content before and after the MCI test. In practice the criterion is not so easy to fulfil and due regard must be paid to:

(1) Volume of oil within the equipment which influences the apparent (measured) dissolved gas levels. Measured levels of dissolved gas generated by the same type of fault may be different in equipment of different rating, and oil volume.

(2) Accuracy of DGA results due to variability of sampling and different detection limits (sensitivities) and uncertainties of different test laboratories.

(3) Ability to extract representative oil samples from remote or separate sections of the equipment.

In transformer diagnosis by DGA, some gases are considered as typical for identification of a kind of incipient fault (key gases).

Gases such as H_2, CH_4, C_2H_6, (without C_2H_4 and C_2H_2) are produced at low energy levels and are representative of:

- numerous weak partial discharges occurring in gas pockets, voids, bubbles of air, nitrogen, water vapour. In this case, the ratio H_2/CH_4 is higher than 3 [compared with IEC599: >10]
- thermal effect at low temperature (less than 300^{O}C). In this case, the H_2/CH_4 ratio is close to 1 [IEC599: < (1 - 0.33)].

The evolution of both of these incipient faults is very slow and it takes a long time to reach significant gas concentration levels (typically 1 year or more).

Gases such as C_2H_4 and C_2H_2 are produced at a local high energy level. These gases are representative of:

- hot spots at mean or high temperature (300 to 1100^{O}C). In this case the ratio C_2H_2/C_2H_4 is lower than 1 [IEC599: <0.1]
- high energy partial discharges due, for instance, to floating potential pieces or sparking on a screen etc. with the C_2H_2/C_2H_4 ratio greater than 1. [IEC599: (0.1 - 3)]

So, in a new instrument transformer, the key gases corresponding to low level energy phenomena may often be present at very low concentrations (close to the detection limits.) In these circumstances, they have to be considered as process residues (gases evolving from paints, varnishes, enamels, papers, zinc etc.) They may also be due to catalytic effects at the metal-oil interface, for instance by oil contact with steel or zinc. Consequently the gases produced at low-level concentrations cannot be used to identify typical faults produced by multiple chopped impulse tests on the primary insulation.

In contrast, the presence of C_2H_2 or C_2H_4 even at very low level of concentration should be considered as the result of very high temperature hot spot or partial discharges due to floating potential or local sparking. This latter fault is the only one that may be produced by multiple chopped impulse test on the primary winding. Consequently, if after this test, C_2H_2 and/or C_2H_4 are not detectable, the other gases are not significant at low concentration levels. Typical values are: H_2 ≤10 ppm, CH_4 ≤5 ppm, C_2H_4 ≤5 ppm, C_2H_2 ≤ not measurable. With respect to (3) above, the construction of some paper-oil equipment mitigates against the uniform dissipation of dissolved gases and access may not readily allow extraction of representative oil samples, for example, from equipment with granulated fillers in the oil.

Some evidence exists that deterioration of internal connections and screen materials may not have progressed to the point of failure (and discharge) before the end of the MCI test sequence. Such failures may therefore remain undetected by DGA and also by the traditional electrical tests for insulation integrity (tan δ and partial discharge). For these reasons, some internal connections and screen failures may only be found by physical examination of the active part, which necessitates dismantling the equipment.

3.3.1.5.2 Other Instrument Transformers

SF_6 and resin insulated CTs are used at the same locations as paper-oil CTs, and will be subjected to the same high frequency stress conditions due to disconnector switching. However, there is no evidence as yet of failures of SF_6 insulated CTs due to high frequency transient voltages and their construction would appear to be immune to insulation degradation. Failure evidence for resin insulated equipment is not yet forthcoming, but it seems prudent to perform MCI tests on CTs of this design given the difficulty in predicting their performance in advance.

Other paper-oil instrument transformers, notably CVTs (and perhaps MVTs and Combined Transformers) are sometimes located in service at line-end positions adjacent to disconnectors. Evidence is needed to demonstrate their ability to withstand the effects of potentially life-limiting high frequency transient voltages.

GIS-connected MVTs can be located close to GIS disconnectors and are exposed to disconnector transients. GIS disconnectors produce similar high frequency arcing effects during operation as air-insulated disconnectors, but with very much faster rise times, of the order of 5-10 ns, and peak values to 2.5 pu. An MCI test for GIS-connected MVTs is proposed, adopting the same principles and test methodology specified for air-insulated instrument transformers, but where the GIS-connected MVT and the chopping gap are connected in the same SF_6 filled enclosure. This test is not appropriate to GIS-connected CTs.

It is proposed that instrument transformers of rating 72.5 kV and above, including resin insulated equipment should be subjected to MCI tests at the type-test stage. Free standing SF_6 CTs and GIS-connected CTs should be excluded. Acceptability criteria for paper-oil CTs may be applied to paper-oil MVT's, Combined Transformers and CVTs. General acceptability criteria for the other categories of instrument transformer are proposed as follows:

- no change in partial discharge characteristics, tan δ level and DGA levels before and after the MCI test.
- no change in measurement error before and after the test (for all instrument transformers).
- visual inspection of internal components and insulation confirms the absence of arc or discharge activity during the MCI test.

Experience at cast-resin type instrument transformers reveals that MCI or even normal chopped impulse can cause deterioration of ungraded insulation of this type. On resin insulation, inadequate screen design can be detected by pd measured after only 100 impulses. In some cases partial discharge measurement just after the chopped impulse test may give a satisfactory value, but the test 1-2 days afterwards may show a worse result. Insulation puncture is sometimes found on bar primary live tank cast resin CT's during the application of the chopped impulse test.

3.3.1.6 External Insulation

For free-standing porcelain type instrument transformers intended to operate in a polluted environment of specified contamination level, the tests may include power frequency withstand under artificial pollution according to IEC 60507. Creepage distances for specified pollution classes may be chosen according to IEC 60815.

Instrument transformers using a composite insulator (resin bonded glass fibre tube with elastomeric shedded external part) or using resin insulation exposed to the atmosphere should be subjected to the "Ageing test under operating voltage simulating weather conditions" according to Annexe C of IEC 61109. The purpose is to verify the dielectric performance under pollution, intense solar or ultraviolet radiation and frequent temperature inversions with condensation. Additionally for non-ceramic insulators, one utility requires that instrument transformers with external insulation of composite or resin type should undergo artificial pollution tests according to IEC 60507 (in the absence of published IEC Standards for non-ceramic insulators) followed by exposure to severe natural pollution conditions for a minimum period of two years.

Test and acceptability criteria for composite insulators for outdoor use are currently the subject of CIGRE WG 33-04.

3.3.1.7 Sealing, Tightness and Bellows Tests

Chapter 4, 'Failure Modes', indicates that the technical life of approximately 40% of ITs, both paper-oil and SF_6 filled designs, may end prematurely because of oil or unacceptable gas leakage. Type and Routine tests for sealing integrity and durability have not been uniformly specified in the Standards, neither do the Standards specify cyclic tests for expansion or bellows arrangements. However, many manufacturers perform endurance tests, especially on metallic bellows constructions. It is proposed that this situation be addressed, by the Standards bodies leading to the adoption of Standardised test procedures. Test procedures should also include tests at the specified extremes of ambient temperature.

3.3.1.8 CT Factor of Construction 'Fc' and Verification of Low Leakage Flux Design (Comment)

Current Transformers are very accurate and long lasting, reliable equipment, which therefore will be exposed to different service conditions during their lives. However, their transformation characteristics are different under different service conditions. Strictly speaking, to predict the actual behaviour of a CT under any service condition, it should be of the «Low Leakage Flux», or of the «Low Secondary Leakage Reactance» design. That means that the secondary leakage reactance «X_s» should preferably be zero.

There is a relationship between the design parameters of the core and the leakage flux, i.e. «X_s», but also between its magnetic properties, permeability and therefore flux density. Further, external effects, eg magnetic fields from return or neighbouring conductors, will also influence the value of «X_s». A current transformer, unlike a power or voltage transformer, functions from very low induction values to almost saturation. When the flux density approaches the knee-point of the magnetising curve, the permeability will decrease rapidly, causing the core material to have higher magnetic resistance, i.e. the core becomes less attractive to the magnetic field lines, resulting in increased leakage flux and «X_s». The ratio between the theoretically induced e.m.f. «E» and the practically available one, «E_{av}.» is the so called «Factor of Construction, F_c». According to the IEC 6044-6, the Factor of Construction, F_c is defined from the ratio:

$$F_c = \frac{U_{alc}}{E_{alc}}$$

where:

- U_{alc} - equivalent secondary accuracy limiting voltage defined as r.m.s. value of sinusoidal voltage of rated frequency which, if applied to the secondary winding of a current transformer with open primary winding, would result in an excitation current corresponding to the maximum permissible error current.
- E_{alc} - equivalent secondary accuracy limiting e.m.f. defined as r.m.s. e.m.f. of rated frequency determined during a direct test when the observed error current corresponds to the maximum permissible error current.

It must be mentioned that the error current is an absolute and unique value based on the specified primary symmetrical short-circuit value which means that U_{alc} is a constant value for a given transformer. U_{alc} may also be different from core to core, because it depends on the cross sectional area of the core, air gap length, winding resistance and secondary winding arrangement (stacked secondaries). All are subject to tolerances. However, there is an opinion, [23] that «F_c», strictly relates to the test conditions only, and should not be quoted or applied at other values of current. Moreover, «F_c» may not be a constant for the same design of core within a CT because of interaction with return conductors etc. «F_c» is not a measure of whether the CT core is a «low leakage» type or not.

IEC 60044-6 specifies a method of determining «F_c» which is by direct test. An example is attached as Appendix 1. As described below, this may be time consuming and expensive. With respect to verification of low leakage flux design, IEC 60044-6 Standard confirms that the «Factor of Construction» is not adequate to verify whether a CT is, or is not, of the «Low Leakage» type. Therefore, Standard IEC 60044-6 Clause 7.4 recommends special tests to verify a low leakage flux design. The Clause states: «Direct tests to verify that a current transformer will satisfy the basic requirements of a low leakage flux design shall be made at a sufficiently large number of energising current, duty cycle and burden combinations as can reasonably establish that the deviation between the theoretical equivalent secondary e.m.f. and the measured value does not exceed 10%. Assuming that three different currents, duty cycles and burden combinations are sufficiently large numbers, the test will mean at least 27 separate test conditions and the verification of low leakage type might take three days testing in a high power laboratory.

Nowadays consulting engineers, manufacturers and utilities are in the possession of computer programs to calculate, (estimate) the CTs' transient performance. If it is necessary to use the CT under different service conditions, the best way is to list the parameters of (1) Current levels, (2) Duty cycles and (3) Burdens, compute the most onerous condition, and that will be the specified condition for direct testing. If the CT passes the test, then it will be good enough for all the other service conditions. In theory this method means a single test application, or at most two days work in practice.

In summary, there is a variance between experts on the value of determining «F_c» which requires international resolution.

3.3.2 Special Tests (additional to IEC Standards)

3.3.2.1 Thermal stability test for paper-oil CTs

The self-heating effects resulting from dielectric losses are significant only for paper-oil CTs of higher voltage ratings. For example, comparison of dielectric losses for 245 kV and 765 kV CTs (1000 pF/0.3% tan δ at 60 Hz, independent of voltage) are 20 watts and 220 watts respectively. A test of thermal stability may only be appropriate for CTs of the higher voltage ratings, and is especially justifiable for CTs intended for use in high ambient temperatures, and where maximum circuit load may also occur simultaneously (eg hot countries, with a high air conditioning load). Thermal stability testing may also be useful in determining the continuing operational suitability of aged CTs. [24] Test conditions should take into account the highest ambient temperature, solar gain, rated current and maximum rated voltage.

A form of 'temperature inversion' type test, in which the CT is energised at rated voltage and subjected to a number of temperature inversion cycles, may also be applicable to gas cushion CTs, or as a diagnostic investigation test for aged CTs. Alternatively, temperature inversion may be simulated by reducing the internal pressure of the CT. Partial discharge activity during the test may indicate an unsuitable or aged CT.

3.3.2.2 Internal Arcing Test for Free Standing Instrument Transformers

In Chapter 1, we have examined what can be done to improve the behaviour of paper-oil ITs in case of internal arcing. According to the statistics the risk of faults within the bushing portion (adjacent to the insulator) are extremely low; faults occur in the active part at the top or the bottom where the voltage gradient is highest. In most cases the fault current is eliminated after 100 ms (see requirements for TPY or TPZ CT cores), and the test duration could be limited to 200 ms. Should a test be required, the fault should normally be located at the position in the active part where the voltage gradient is at a maximum.

For paper-oil and resin ITs, there should be no projection of fragments of porcelain; for SF_6 ITs, the transformer should withstand the test without explosion. The main objective is to design an IT to avoid breakage of the porcelain insulator during internal arcing. (Some utilities do not accept breakage of the porcelain). An important feature is that the internal earth bonding connections of the CT should be able to withstand internal fault current without failure.

Requirements for the gas filled enclosures of GIS - MVTs are implicit in IEC 60517.

The specification for these tests is subject to current IEC consideration.

3.3.2.3 Ferro-resonance Test on MVTs

To avoid single-phase ferroresonance between an MVT and the grading capacitance of an open circuit breaker, it is useful to make a test to determine the critical range for the occurrence of ferroresonances as a function of grading capacitance and line-to-ground capacitance (capacitance of MVT including line and associated equipment). Care must be taken to limit the temperature rise of the HV winding of the MVT. It should be noted that this test can be very expensive and does not give the guarantee that the MVT under real system conditions is also free from ferroresonances.

3.3.2.4 Capacitive Energy Discharge Test for MVTs

The thermal and mechanical forces to be endured by the primary winding of a MVT during discharge of lines, cables and capacitor banks is described fully in Chapter 1.

The discharge capability of a MVT may be demonstrated by testing with 10 de-energisations of a capacitance as given in Chapter 1, Table 1 charged at a voltage equal to the peak value of the phase-to-earth voltage. The MVT will have passed the test successfully, if comparison of voltage error and the phase displacement, the partial discharge values and the frequency response before and after test are substantially the same. Gas in oil quantities may also be analysed for paper-oil MVTs. (Acceptability criteria are not available at this time).

Attention has to be paid to the fact, that, when performing such discharge tests large electrical energies are involved. The total time for the test, and the rest time between application of successive de-energisations, must be such that an unacceptable temperature rise of the winding does not inadvertently result. If the MVT fails it may be destroyed at once. Care must similarly be applied during commissioning of long lines and cable circuits which employ MVTs, to prevent the repetition of many auto-reclose and circuit switching test operations in close succession.

For 3-phase arrangements of GIS-connected MVTs in the same GIS enclosure, test conditions should take into account the effects of electromagnetic forces between windings of different phases. This means that one could not simply test with the windings of the different phases in parallel. For GIS-connected MVTs, the recommended maximum value of capacitance to be discharged is 15 μF for single phase MVTs, and 5 μF for each single phase MVT of a 3 phase MVT assembly (such that the sum of the three capacitances is 15 μF).

3.3.2.5 Seismic Performance

Chapter 1 deals with the specification and design of ITs for use in earthquake areas. Computer controlled hydraulic earthquake simulators are available to test the specified performance of the complete IT and associated damping arrangements where supplied. International Standards have been agreed for testing of Circuit-breakers [25]. It is suggested that a similar Standard should be established for ITs.

3.3.3 Routine Tests (additional to IEC Standards)

This Section describes tests which are extra to the Routine Tests currently stated in IEC Publications. Proposal of these tests results from the experience of manufacturers and users.

3.3.3.1 Lightning impulse test

Lightning impulse tests provide additional confidence in the verification of correct insulation build quality, insulation thickness and correct placement of voltage grading foils. Some users already specify these tests as routine tests.

3.3.3.2 Measurement of Capacitance and tan δ.

The need for capacitance and tan δ type tests is described in Section 3.3.1.4.

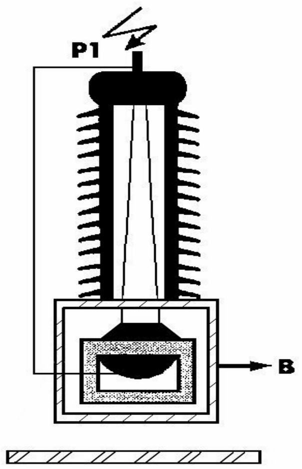
Capacitance variation between instrument transformers of the same design may indicate poor control over dimensional quality or internal damage of primary insulation. Tan δ measurement is a quality check for insulation dryness of paper-oil ITs and the absence of contaminants. A secondary purpose of performing capacitance and tan δ routine tests is to make reference measurements for maintenance purposes. The voltage dependence of tan δ should be verified over the range 10 kV to $Um/\sqrt{3}$. The value of the ambient temperature during the test should be recorded.

3.3.3.2.1 tan δ measurement of CTs.

The test of the high voltage insulation should be performed according to Clause 21 of IEC 60044-1 and at ambient temperature. For paper-oil CTs, the tan δ of the high voltage insulation at $Um/\sqrt{3}$ should generally be less than 0.4%. The tan δ value of a new resin insulated unit should be less than 2%. Capacitance or tan δ measurements are readily performed on CTs. Capacitance and tan δ tests are not appropriate for gas filled CTs. There is insufficient information to give guidance for capacitance and tan δ criteria of SF_6 gas impregnated polymeric insulation (CTs and VTs).

3.3.3.2.2 tan δ measurement of MVTs and Combined Transformers

For MVTs, the primary winding may consist of a single coil (Figure 3.4a), or several coils connected in series (cascade type Figure 3.4b).



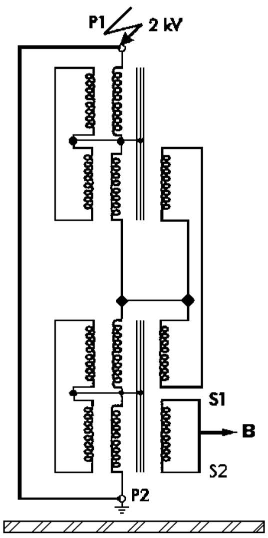


Figure 3.4a: Single primary coil type MVT

Figure 3.4b: Schematic of Cascade type MVT with four primary coils

Built-in screens or shields, some with earth bonding connected internally to the base tank, or via external connection, may be incorporated in the design. The neutral-end of the primary winding may also be electrically accessible for test purposes. (See example of Figure 3.4 (c) for the single primary coil design).

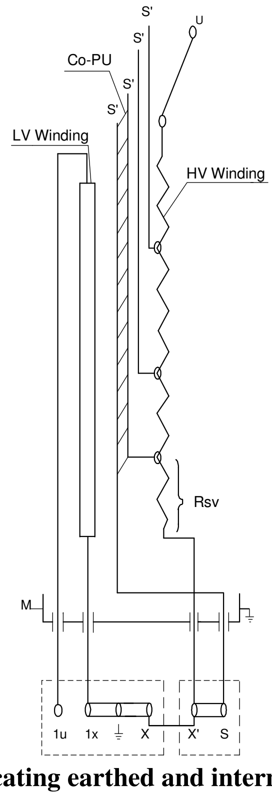


Figure 3.4c: Single coil MVT indicating earthed and intermediate screens and external links.

The different constructions and winding arrangements of MVTs make it possible to perform a variety of measurements of tan δ, albeit that some will be restricted to low levels of test voltage. Each arrangement may test a different part of the insulation system.

For the single primary coil design, the tan δ of the overall insulation can be measured (at low voltage), from the primary terminal P_1 to the tank B, with the neutral end of the primary winding disconnected from the base tank and connected to the voltage source (Figure 3.4a). The test voltage is limited by the insulation voltage of the neutral connection. Similarly, HV winding to LV winding insulation and/or winding to screen measurements can be made. For MVTs, equipped with a measuring terminal at the screen between HV and LV windings the tan δ of the overall insulation can be measured with induced voltage (neutral end of HV winding earthed), up to rated voltage.

For multi-coil (cascade) designs where several coils are connected in series on a number of separate cores, it is not possible to measure the tan δ and capacitance of the whole main insulation. As for the single coil design, HV to LV winding and winding to earth screen, measurements can be made but this will cover only the insulation of the final cascade stage. As a minimum, the test arrangement of Figure 3.4b allows measurement of the HV to LV winding insulation, at low test voltage.

Similar difficulties will be experienced for the separate MVT and CT elements of paper-oil Combined Transformers. Some users and manufacturers specify that earth bonding screens be connected externally via links solely for the purpose of making tan δ measurements on the respective parts.

All methods have different advantages; high voltage arrangements allow the MVT to be stressed as it would be in service whereas the low voltage arrangements may allow a more detailed assessment of the different parts of the MVT insulation.

3.3.3.2.3 tan δ measurement of CVTs

The capacitance and tangent delta of a CVT should be performed on:

- each capacitive part
- the electromagnetic part
- the complete unit

The measurement of capacitance and tan δ on the capacitor parts (capacitor units) according to IEC 358 is performed before assembly onto the electromagnetic part. Since individual parts of CVTs cannot be separated on site, the tan δ measurement on a complete CVT can provide a reference value for later maintenance. Tan δ measurement on the complete CVT should be performed over a voltage range from 10 kV to Um/√3. The low voltage terminal of the capacitive part should be connected, together with the earth potential side of the primary winding of the intermediate voltage transformer to the measuring bridge. The secondary terminals of the electromagnetic part should be left open. The tank should be earthed. This measurement can provide a fingerprint value for easy checks during later maintenance in the substation.

To measure only on the electromagnetic part, the earth potential side of the transformer should be disconnected from the low voltage terminal of the capacitive part (which is separated from the tank) and a voltage of 2 kV should be applied to this earth potential terminal. The short-circuited secondary terminals of the transformer part should be connected to the isolated tank and to the bridge. The tan δ of the low voltage insulation (oil-to air bushing, insulated base plate, terminal plate, etc.) which is known to have caused failures of some CVTs can be measured using this arrangement.

The tan δ value of each capacitor unit gives information on dielectric loss only and is therefore normally very low. However, Watts losses in both the electromagnetic unit and the ferroresonance suppression devices increase the value of measured tan δ. Typical values of tan δ are suggested as following:

paper-oil insulation

- capacitor unit 0.3%
- electromagnetic unit 1.0%
- complete unit 1.0%

For capacitors using paper-film (mixed) dielectric and synthetic insulating oils, the dielectric loss angle (tan δ) may typically be 0.02%. Typical curves showing variation of capacitance and loss angle with temperature, for new CVT capacitors are shown in Figures 3.5 and 3.6.

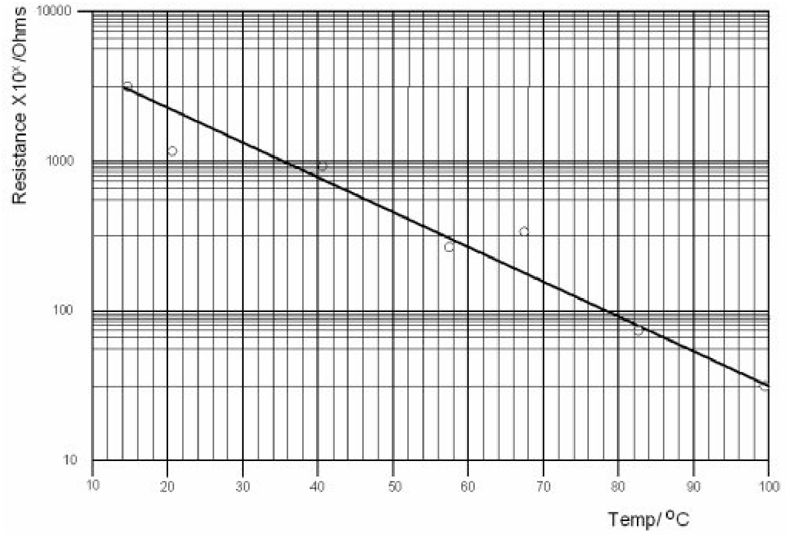


Figure 3.5: Capacitance variation with temperature

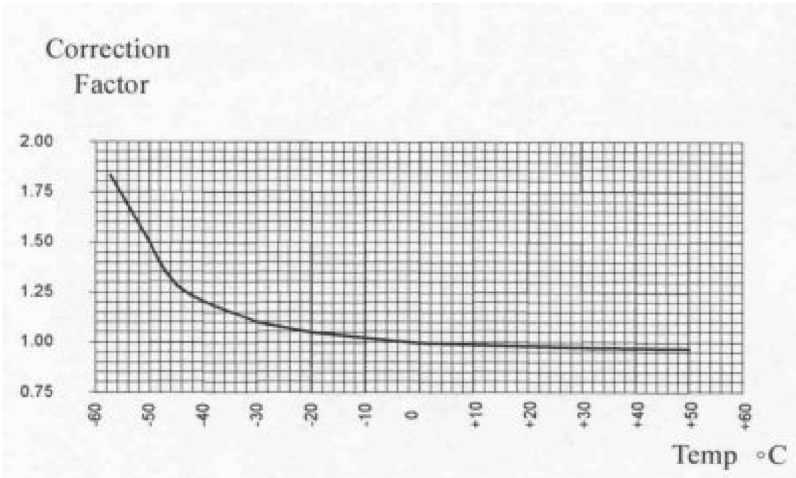


Figure 3.6: Tan δ variation with temperature

3.3.3.3 Measurement of insulation resistance

Insulation resistance measurement is applicable only to paper-oil transformers and is used to check the condition of the insulation, the uniformity of production and to obtain a reference value for maintenance purposes. The value of the insulation resistance is measured using direct voltage (D.C.), for example at 1000 V by the U-I method. The measurement of the insulation resistance should be performed after the power frequency withstand test. Of most interest is an insulation resistance test of the main insulation.

For CTs, the test voltage should be applied to one of the primary terminals. Generally the short-circuited secondary winding(s), any screen, metal casing and one end of the current measuring device should be connected together and to the earth. The direct voltage source is unearthed. For MVTs, the test arrangement is practically the same as for measurement of tan δ according to the methods in 3.3.3.2.2. The ambient temperature and temperature of the equipment under test shall be in the range from 10 to 30^{o} C. Ambient temperature should be recorded and the measured insulation resistance value be corrected to 20^{o} C.

The insulation resistance value is obtained as the quotient of the applied voltage and corresponding current measured ten minutes (or one minute) after applying voltage. Recommended value of insulation resistance for a new transformer should be 800 GΩ for CTs and 200 GΩ for MVTs (ten minute values). The insulation resistance is dependent on the temperature and typical dependence for a 420 kV live tank CT is given in Figure 3.7. [24].

For some applications, a polarization index by which the dryness of the paper-oil can be assessed can be calculated as the ratio of two insulation resistance readings. Usually, the polarization index is defined as the ratio of the 1 minute/15 seconds readings but also the ratio of the 10 minutes/1 minute reading is used.

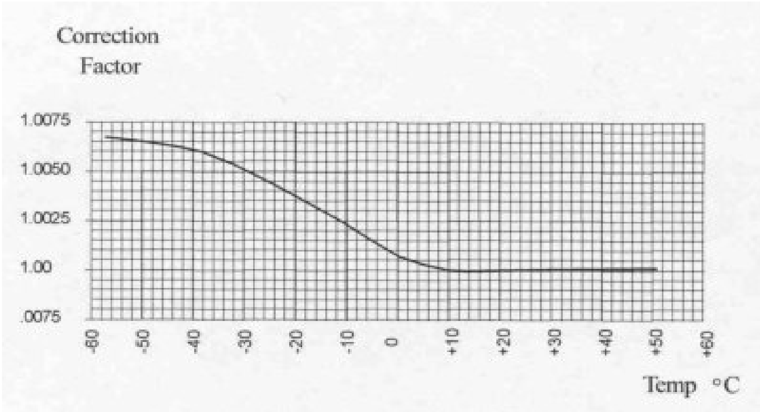


Figure 3.7: typical temperature dependence of insulation resistance for a 420 kV live tank CT (10 minute value)

3.3.3.4 Excitation curve for MVTs

For MVTs, an excitation curve such as given in Figure 3.8 should be provided as a reference for future diagnostic testing in the event of fault. The characteristic derived from this test is a combination of the inductance and capacitance of the transformer. It is not the same as the magnetisation characteristic of the core material.

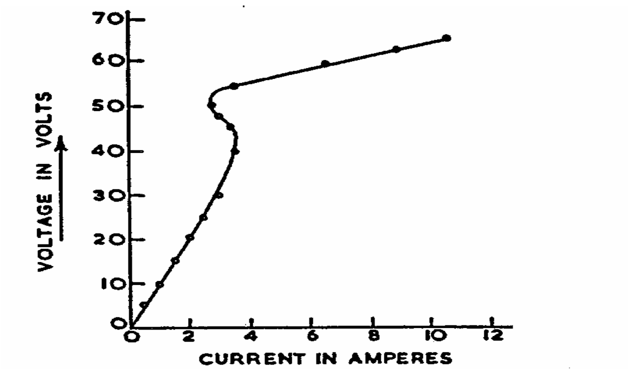


Figure 3.8: Typical excitation characteristic for MVTs.

3.3.3.5 Pressure, Sealing and Leakage tests for SF_6 and Paper-oil Instrument Transformers

Pressure and leakage tests for free-standing gas filled transformers should be performed as for GIS metal enclosed equipment. It is recommended that the leakage rate for all gas filled instrument transformers should be no more than 0.5% per year. Test methods should be subject to agreement between the manufacturer and the user, for example the method given in IEC 68-2-17 for SF_6 filled switchgear.

Sealing tests are also applicable to paper-oil ITs. Test methods must take into account the effects of bellows arrangements. Many manufacturers perform a form of sealing test as part of the oil impregnation and filling processes. However, there is a need to reach agreement on a standardised test procedure.

3.3.3.6 Partial Discharge Test for Complete CVTs

The partial discharge test requirements and procedures of IEC 60044-5 usually result in the IVT and capacitor sub-components being tested separately and the performance of the interface connections of the complete CVT may therefore not be established. Routine and type tests of partial discharge on the complete CVT are therefore proposed to overcome this shortfall.

3.3.3.7 'Bias Test' for Partial Discharge, and for Routine Voltage Test for CVT Capacitors (Comment)

IEC 358 Clause 9 specifies that the capacitors may be pre-stressed using a procedure where three switching impulses are applied to the capacitor, which is simultaneously energised at a specified power frequency voltage ('bias test'). The impulses are synchronised to the peak of the power frequency voltage. Justification for the test procedure originated from experience that capacitor partial discharge could be ignited by transient voltages, the discharge sustained thereafter at the normal continuous voltage level.

In IEC 358, the 'bias' test is specified as a type test for partial discharge and as an option for the routine voltage tests. Experience from manufacturers is that the test is extremely difficult (if not impossible) to perform in most high voltage laboratories. There is danger to test transformers and difficulty in obtaining the partial discharge free background conditions at the required level (<5pC) since the impulse generator is normally capacitively coupled to the test capacitor by a spark gap. Consequently, the test is universally ignored and the alternative test procedure specified in IEC 358 is usually adopted. It is expected that any revision of IEC 358 (at the first issue of the proposed IEC 44-5 (IEC 38/183/CD(1997)) will exclude specification of the bias test.

3.4 Tests for Optical Instrument Transformers

Tests for optical instrument transformers are given in IEC 60044-7 and 60044-8. Optical ITs generally include a high voltage (HV) part, a low voltage (LV) part, an optical fibre link and an optical fibre insulator. Tests mentioned in the draft Standards are as followings:

3.4.1 Tests on the low voltage part

a) Dielectric test according to IEC 60255-5

b) Conducted and RF interference emission to EN55022 class A

c) Impulse voltage test to IEC 255-5, 5 kV 0.5 J

During the tests, the following performance should be checked:

d) Susceptibility to RFI to IEC 60255-22-3 class III test method A

e) Power frequency interference non-maloperate.

f) The test voltage between terminals should be 250V and between terminals and earth should be 500V.

g) High frequency disturbance test to IEC 255-2-1, severity class III.

h) Fast transient test to IEC 60255-22-4, severity level IV.

i) Shock and bump test to IEC 60255-21-2 severity class 1

j) Seismic test to IEC 60255-21-3 severity class 1

k) Low temperature non-maloperate to IEC 60068-2-1

l) Dry heat non-maloperate to IEC 60068-2-2.

m) Vibration and endurance test to IEC 60255-21-1 severity class 1

n) Supply variation non-maloperate

o) Supply interruption non-maloperate

p) Electrostatic discharge test to IEC 60255-22-2 severity class III

3.4.2 Tests on High Voltage Part

For accuracy tests on digital output ITs, a suitable method for comparing the digital output with a reference measurement is required. The tests should consist of:

a) Accuracy as a function of temperature.

b) Accuracy as a function of rapid temperature variation (only applicable to Faraday, Pockels sensor based devices)

c) Accuracy as a function of measured voltage or current including maximum fault current

d) Susceptibility to 50 Hz magnetic field applied in all axes, min 15 mT rms

e) Susceptibility to RFI to IEC 60255-22-3 class III test method A. Greater test severity may be required dependent on application i.e. for circuit breaker mounted devices

f) Temperature rise at continuous maximum current to IEC 60694

g) Radio interference voltage test to IEC 60694

h) Test for enclosure environmental protection to IEC 60529. IPX6 level required for water wash duty

3.4.3 Tests on the Optical Fibre Insulator

Typically, optical ITs incorporate polymeric insulation for which comprehensive national or international Standard are not applicable. Prior to the following tests, polymeric insulators may be subjected to accelerated ageing tests at a coastal testing station for a number of years.

a) Dielectric tests to IEC 60694.

b) Radio interference voltage test to IEC 60694

c) Artificial pollution test to IEC 60507 (conventional insulation) or IEC1109 (polymeric insulation).

3.4.4 Tests on the Optical Fibre Link

a) OTDR test (commissioning test)

b) Attenuation measurement (commissioning test)

3.4.5 Tests on the Complete System

a) Accuracy as a function of vibration. (The LV part is covered in Clause 1.12).

For the HV part and optical fibre insulator, the vibration level and frequency range will be dependent on application. For circuit breaker mounted devices measurements at the circuit breaker indicate a requirement of 40g from 3Hz to 3kHz in all axes. For this test the HV part should be connected to the optical fibre to simulate the normal installation method. The optical fibre link may be tested for vibration to IEC 60255-21-1 severity class 2 and for shock and bump to IEC 60255-21-2 severity class 2. Note that where a digital PCM, or similar fibre transmission signal is used it is not necessary to test the optical fibre insulator or optical fibre link for vibration.

b) Loss of optical fibre link non-maloperate. The optical IT should not cause inadvertent relay tripping.

c) Bandwidth test. Accuracy at ‘n’ th harmonic dependent on application.

d) Waveform distortion. Using a 50 Hz sinusoid input, the output signal should be analysed for harmonic distortion. Permitted levels will be dependent on application.

3.5 Tests Performed on Commissioning

Commissioning tests verify that the internal state of instrument transformer is fit for service after transportation, accept the installation work, and obtain the first maintenance record before energisation. The following tests are given for guidance and may be performed at the discretion of the utilities. The extent of the tests may depend on the completeness of routine test information available from the manufacturer.

In-service tests may use the techniques described here, and are given in Chapter 5.

3.5.1 Visual Inspection

Visual checks of equipment after transportation such as porcelain cracks, deformation of primary terminals, any abnormalities inside secondary terminal box, any mechanical damages, deformation or abnormalities of expansion devices (bellows in case of oil type, or rupture disc for gas type), traces of dampness or moisture such as rust or corrosive metal parts.

- Checks of loose connection, presence of fuses, etc.
- Oil level or traces of oil leakage (oil type)
- Pressure of gas for possible gas leakage (gas type)
- Inspection of shock indicators (GIS MVT)

3.5.2 Electrical Tests

Tests available are:

Transformation ratio check for CTs: Performed at zero burden (no load condition) by injection of rated current, or 200 A minimum, whichever is practicable.

Polarity Test for CTs: By inductive kick by direct current or electric battery. The CT must be demagnetised before and after the test. Portable instruments to measure both ratio and phase angle error are available, the ratio test and polarity test can therefore be combined.

Winding resistance for CTs and MVTs: The d.c. resistance of each individual winding should be measured

Excitation test for protective class CTs: Made for each secondary CT winding

Measurement of circuit total burden: The sum of the internal burden of the instrument transformer and all external connected burden.

Insulation resistance measurement for all ITs: To check for possible undesirable damage or deformation inside the transformer during transportation, only measurement of the insulation resistance by a magneto ohmmeter is recommended. The test should be performed by applying D.C. voltage between each winding (with terminals short-circuited) and the earthed metallic tank. The test duration should be about 1 minute. Insulation resistance measurement on commissioning using the methods of 3.3.3.3 is not recommended.

On-site tan δ measurement: Site measurement of tan δ for instrument transformers which are equipped with capacitive test taps is performed as it is in the factory. For other instrument transformers without test taps, the base of instrument transformer is always earthed and cannot be isolated. Thus the same measurement of tan δ as performed in the factory or in the laboratory usually may not be applied.

Field test instruments are available with facilities to compensate for external leakage current. The test voltage of this particular equipment is normally 10 kV for HV insulation and about 2.5 kV for LV insulation. The test arrangement is similar to the connection of instrument transformer during insulation resistance measurement. Tan δ and capacitance measurement can also be made on site by the use of other low voltage test bridges, and high voltage transportable test equipment capable of measurement at voltages up to rated voltage. The choice and application of various test equipments is at the discretion and experience of the user.

Site testing for tan δ may be susceptible to variation from factory tests due to the following factors:

1. the test equipment type and the measurement voltage level.
2. atmospheric conditions (ie high humidity, rain)
3. temperature of the test object.
4. induced voltages in the test object from adjacent live equipment.

Experience indicates that different measured values of tan δ may sometimes be obtained on the same IT from different test equipment, test arrangements and test conditions. [24]

3.5.3 Ferroresonance tests on MVTs

Tests may be performed on VTs which are be susceptible to ferroresonance (from tests in item 3.3.2.3) in order to verify that ferroresonance does not occur, or to verify the effectiveness of installed damping devices. Sufficient switching operations covering point on wave energisation and de-energisation, and all possible combinations of circuit-breaker and parallel capacitance to be encountered in service should be performed. Even then, these tests may not cover all situations as explained in Chapter One. Damping devices should normally be expected to suppress ferroresonance within ten cycles. Care must be taken to avoid instances of fundamental frequency resonance which can lead to failure of the VT winding within a short period of time. It should also be recognised that substations may be commissioned in sections and not as a whole. Thus MVTs may be initially energised in circuit arrangements that do not occur once the whole circuit or substation is commissioned.

3.5.4 Post-energisation checks

Check for abnormal noise and deviation of voltage and current values. (Safety precautions must be observed).

4 RESULTS OF FAILURE SURVEY

4.1 Summary

The results of the second international survey on the failure modes of high voltage instrument transformers are analysed and presented, and where possible compared with the results of the first enquiry performed by CIGRE WG 23.07 and published in CIGRE Technical Report 57, 1990.

4.2 Scope of survey

The scope of the survey was limited to Instrument Transformers (ITs), that is Current Transformers (CTs), Magnetic Voltage Transformers (MVTs), Capacitor Voltage Transformers (CVTs) and Combined Transformers (Combi's), rated at 60kV and above, which use of paper-oil, resin or SF6 gas insulation systems. The participants contributing towards this second survey were restricted to utility organisations only. This was not the case in the first survey, which also included data received from some manufacturers.

The period covered by this survey is between 1985 and 1995.

4.3 Organisation and participation of the survey

This second survey questionnaire was designed along similar lines to the first enquiry to collect as much data as possible about the population of installed instrument transformers, the type of failures experienced, and the actions taken by the user to maintain or monitor the equipment before or after failure occurred. A total of 22 utilities from 14 countries answered the second survey and a total of 3004 failure reports were received.

A supplementary survey was also designed to specifically identify any actions or strategies developed by the utility to further improve the reliability of the equipment. A total of 16 utilities answered the supplementary questionnaire. Participants to this survey came from Australia, Austria, Canada, England, France, Mexico, Netherlands, New Zealand, Portugal, South Africa, Spain, Thailand, Ukraine and USA.

Some questions within the survey were not answered by all the participating utilities as some did not keep sufficiently detailed records and others just did not know the answers. Therefore the analysis of the responses contained within this Report only used data that was submitted for that particular question.

Copies of this second and supplementary survey questionnaire are attached as Appendix 2 to this Report.

4.4 Population survey results

The sample size of installed instrument transformers as at July 1995 for the purpose of this survey is a total of 131,207 units. The distribution of the Instrument Transformer population against their rated voltages and the type of major internal insulation used in the design is shown in Table 2. As not all utilities identified specific instrument transformers contained within their SF6 Gas Insulated Switchgear (GIS), the data reported in Table 2 in the SF6 column is a combination of both free standing post type units and units contained within GIS.

It is recognised that there is a significant technology change between resin MVTs rated above and below 72kV. However, because of the relatively small numbers reported to this survey, all resin ITs are combined in one category below 220kV.

Comparison of the first and second surveys shows:

- The total Instrument Transformers population contained in the second survey (131,207 units) is almost the same as it was in the first survey (136,033 units).
- The total population of this second survey contained 15.7% of units rated at 300kV and above, while the first survey contained only 10%.
- All other factors remained very similar.

Table 2: Population of ITs by type and system voltage ratings

Type of IT	60kV<U<220kV	220kV≤U<380kV	380kV≤U	Total
CTs				
- Paper Oil	29,051	22,270	9,018	60,339 (46%)
- Resin	2,691	0	0	2,691 (2%)
- SF6	279	688	1,193	2,160 (1.7%)
				Total= 49.7%
MVTs				
- Paper Oil	13,784	2,604	2,382	18,770 (14.3%)
- Resin	27	0	0	27 (0%)
- SF6	182	162	74	418 (0.3%)
				Total= 14.6%
CVTs				
- Paper Oil	5,230	12,637	4,917	22,784 (17.4%)
- Resin	0	0	0	0
- SF6	0	0	0	0
				Total = 17.4%
Combi's				
- Paper Oil	22,301	1,713	0	24,014 (18.3%)
- Resin	0	0	0	0
- SF6	4	0	0	4 (0%)
				Total = 18.3%
Totals	73,549 (56%)	40,074 (31%)	17,584 (13%)	131,207 (100%)

4.5 Failure reports

For this survey, failures were categorised into three specific types:

- **Major Failures**, which were sudden explosive events that caused an immediate emergency system outage or trip.
- **Minor Failures**, which were non-violent but still, required an urgent system outage within, for instance, one hour.
- **Defects**, which required a non-urgent (planned) outage to repair or replace the unit.

The above definitions of Failures and Defects were considered to be more appropriate to Instrument Transformers and were therefore chosen in preference to definitions used by CIGRE WG 13.06 for Circuit-breakers. The definition of Major Failures was relatively clear and is consistent with the first survey where they were called Violent Failures. Minor Failures and Defects were not consistently reported by all utilities and therefore cannot be directly linked or compared between the two surveys unless they are added together, as they were in the first survey, and called Non-Violent Failures.

The failure reports received from this second survey are condensed in the Table 3. The data are given firstly as the number of reported failures and then a percentage figure is given in brackets ( ) which provides the Relative Failure Rate. This is obtained by dividing the number of failures reported by the total population of that type of IT as at 1995.
Note: The percentage figure is the failure rate set to ten years period.

Table 3: Failure report summary

Type of IT	Major Failures	Minor Failures	Defects
CTs	261 (0.40%)	126 (0.19%)	637 (0.98%)
MVTs	85 (0.44%)	38 (0.20%)	414 (2.16%)
CVTs	60 (0.26%)	150 (0.66%)	414 (1.82%)
Combi's	54 (0.23%)	101 (0.42%)	664 (2.77%)
Total of all ITs	460 (0.35%)	415 (0.32%)	2129 (1.62%)

From the data contained in Table 3, it cannot be readily concluded that one type of instrument transformer is more reliable than another.

A further analysis of Major Failures for CTs only, for different voltage ratings and major insulation groups is shown in Table 4.

Table 4: CT Major Failures versus voltage ratings

Type of CT	60kV<U<220kV	220kV≤U<380kV	380kV≤U
Paper-oil CTs	62 (0.21%)	95 (0.43%)	57 (0.63%)
Resin CTs	47 (1.75%)	Not Applicable	Not Applicable
SF6 CTs	0 (0.0%)	0 (0.0%)	0 (0.0%)
Total of all CTs	109 (0.34%)	95 (0.41%)	57 (0.56%)

Table 4 shows an increase in relative failure rate as the voltage of the paper-oil CTs increases, also a high failure rate of resin designs, and no Major Failures for SF6 designs. Insufficient information was available to distinguish between the relative failure rates of the different types of paper-oil CT designs.

An analysis of Major Failures for MVTs only, for the different voltage ratings and major insulation groups is shown in Table 5.

Table 5: MVT Major Failures versus voltage ratings

Type of MVT	60kV<U<220kV	220kV≤U<380kV	380kV≤U
Paper-oil MVT	68 (0.49%)	9 (0.35%)	3 (0.13%)
Resin MVTs	2 (7.41%)	Not Applicable	Not Applicable
SF6 MVTs	0 (0.0%)	2 (1.23%)	1 (1.35%)
Total of all MVTs	70 (0.5%)	11 (0.40%)	4 (0.16%)

Table 5 shows a decrease in relative failure rate as the voltage of paper-oil MVTs increases, an increase in failure rate for SF6 designs as the voltage increases, and again a high failure rate for resin designs. It must be noted however that the relatively small number of resin MVTs reported in the survey may have the effect of exaggerating the relative failure rate for this type of equipment.

An analysis of Major Failures for CVT's only, for the different voltage ratings, is shown in the Table 6.

Table 6: CVT Major Failures versus voltage ratings

Type of CVT	60kV<U<220kV	220kV≤U<380kV	380kV≤U
Paper-oil CVT	11 (0.21%)	35 (0.28%)	14 (0.28%)

Table 6 shows a relatively constant failure rate for CVTs of all voltages.

An analysis of Major Failures for Combi's only, for different voltage ratings, is shown in the Table 7.

Table 7: Combi's Major Failures versus voltage ratings

Type of Combi's	60kV<U<220kV	220kV≤U<380kV	380kV≤U
Paper-oil Combi's	54 (0.24%)	0 (0.0%)	Not Applicable
Resin Combi's	No Data	Not Applicable	Not Applicable
SF6 Combi's	0 (0.0%)	No Data	Not Applicable
Total Combi's	54 (0.24%)	0 (0.0%)	No Data

Table 7 shows a higher failure rate for the lower voltage Combi's.

From all data received, the overall failure rate for each year of the ten-year period of the survey (1985 to 1995) is displayed in the Figure 4.1. It has been assumed that the total population of instrument transformers within the ten-year period has remained constant at 131,000 units since the actual in-service population for individual years is not known. The effect of this assumption is considered not critical to the trend of the results.

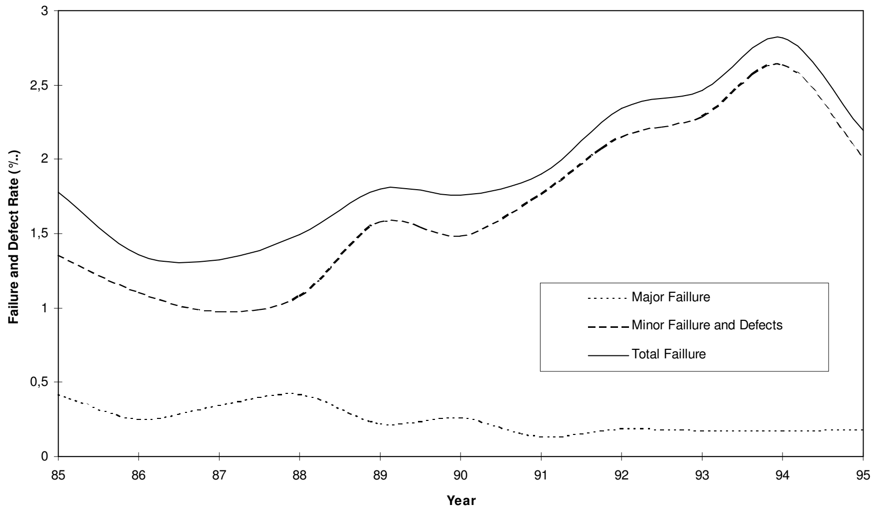


Figure 4.1: Failure and Defect Rate

The data of Figure 4.1 show a sustained reduction in Major Failure rate since 1991 which was accompanied by an increase in the rate of Minor Failures and Defects during the same period. This relationship may indicate the recent successes, that utilities are having by identifying and removing defective units before they develop into Major Failures. The apparent reduction of the Minor Failure and Defect rate after 1994 may also suggest that the majority of defective units have been identified and appropriate action taken. The results of future surveys will confirm if this conclusion is correct.

4.6 Primary causes of the failures

For further analysis The Primary Causes of Failure were divided into the following seven broad categories:

- **Design Faults**, which included the electrical or mechanical design of the unit as well as the choice of materials, used in the construction and hence can affect most units within a particular design.
- **Inadequate Quality Control during Manufacture** which affected the electrical or mechanical integrity of random, or batches of units within a proven design, and included problems such as incorrect application of insulation systems, contaminated insulation, defects in assembly and also random moisture ingress, oil or gas leaks and corrosion problems.
- **Ageing** which normally affected units over 25 years old that exhibited a general decrease of reliability.
- **Lightning** and Overvoltages caused by thunderstorms.
- **Operation outside Specification** such as ferroresonances, capacitance discharges, abnormal service conditions, earthquakes, failures of adjacent equipment and other environmental conditions for which the units were not designed.

– **Inadequate Maintenance** by utilities also including incorrect installation or erection procedures.

– **Unknown**, which means unexplained failures and may be due to combinations of other causes.

The Primary Causes of all Failures and Defects reported in this survey are shown in Tables 8 to 12. The results are given as a percentage of the total number of faults within that failure category.

For CTs, the primary causes of failure are summarised in the Table 8.

Table 8: CAUSES OF FAILURE FOR CURRENT TRANSFORMERS

Primary Cause of Failures	**Major Failure** (Total = 261)	**Minor Failure** (Total = 126)	**Defects** (Total = 637)
Design Fault	34.5%	24.6%	55.9%
Inadequate Quality during Manufacture	17.2%	16.7%	22.3%
Ageing	10.3%	15.1%	4.7%
Lightning	8.4%	2.4%	0.0
Operation outside Specification	3.1%	24.6%	4.5%
Inadequate Maintenance	0.4%	0.8%	0.6%
Unknown	26.1%	15.9%	11.8%

For MVTs the primary causes of the failure are summarised in Table 9.

Table 9: CAUSES OF FAILURE FOR MAGNETIC VOLTAGE TRANSFORMERS

Primary Cause of Failures	**Major Failure** (Total = 85)	**Minor Failure** (Total = 38)	**Defects** (Total = 414)
Design Fault	54.1%	34.2%	51.9%
Inadequate Quality at Manufacture	7.1%	7.9%	17.4%
Ageing	1.2%	10.5%	3.9%
Lightning	17.6%	0.0	0.2%
Operation outside Specification	13.0%	28.9%	4.6%
Inadequate Maintenance	1.2%	5.3%	2.4%
Unknown	5.9%	13.2%	19.6%

For CVTs the primary causes of failure are summarised in Table 10.

Table 10: CAUSES OF FAILURE FOR CAPACITIVE VOLTAGE TRANSFORMERS

Primary Cause of Failures	**Major Failure** (Total = 60)	**Minor Failure** (Total = 150)	**Defects** (Total = 414)
Design Fault	43.3%	44.7%	69.1%
Inadequate Quality at Manufacture	16.7%	14.0%	10.8%
Ageing	26.7%	18.7%	3.1%
Lightning	3.3%	2.0%	0.0
Operation outside Specification	3.3%	4.0%	3.9%
Inadequate Maintenance	0.0	0.0	1.7%
Unknown	6.7%	16.0%	11.4%

For Combi's the primary causes of failure are summarised in the following Table 11.

Table 11: CAUSES OF FAILURE FOR COMBINED TRANSFORMERS

Primary Cause of Failures	Major Failure (Total = 54)	Minor Failure (Total = 101)	Defects (Total = 664)
Design Fault	59.3%	70.3%	80.9%
Inadequate Quality at Manufacture	0.0	1.0%	5.1%
Ageing	0.0	0.0	0.0
Lightning	29.6%	3.9%	0.8%
Operation outside Specification	9.2%	12.0%	3.2%
Inadequate Maintenance	0.0	0.0	0.2%
Unknown	1.8%	11.9%	9.9%

For further analysis of the Primary Cause of Failures all the results obtained from the survey are now summarised in Table 12. The category "Design Fault" is further divided into the actual subcategories of Electrical, Mechanical, Material Faults and Leak. Also the Primary Cause category "Inadequate Quality at Manufacture" is further divided into the actual subcategories of General Quality, Moisture Ingress, Oil Leak, Gas Leak and Corrosion faults.

Table 12: ANALYSIS OF FAILURES CATEGORIES

Primary Cause of Failure	Major Failure (Total 460)	Minor Failure (Total 415)	Defects (Total 2129)	All Defects and Failures (Total 3004)
Design Fault:				
- Electrical	40.0%	15.9%	12.2%	17.0%
- Mechanical	2.0%	10.5%	11.1%	9.6%
- Material	0.2%	2.5%	7.0%	5.3%
- Oil Leaks	0.0%	15.0%	35.2%	27.0%
Total	42.2%	43.9%	65.5%	58.9%
Inadequate Quality at Manufacture:				
- General Quality	4.3%	1.4%	1.3%	1.8%
-Moisture Ingress	3.3%	0.5%	1.8%	1.9%
-Oil Leaks	5.7%	8.9%	6.3%	6.5%
-Gas Leaks	0.0%	0.0%	0.8%	0.6%
-Corrosion	0.0%	0.3%	3.6%	2.5%
Total	13.3%	11.1%	13.8%	13.3%
Ageing	9.6%	12.3%	2.8%	5.1%
Lightning	12.0%	2.4%	0.3%	2.4%
Operation outside Specification	5.7%	14.7%	4.0%	5.7%
Inadequate Maintenance	0.4%	0.7%	1.0%	0.9%
Unknown	17.0%	14.7%	12.6%	13.6%

Significant results from Table 12 are;

- Of the 3004 failures reported a total of 1081 (36%) were attributed to oil leaks, gas leaks and moisture ingress problems. No Major Failures were directly attributed to Design Fault Oil Leaks, what suggests that some utilities may not have realised that some Major Failures could have been directly caused by this type of fault. On the other hand, it may be that oil leaks are usually readily detectable by inspection and therefore do not lead to Major Failures.
- It is difficult to differentiate between Major Failures attributed to lightning (12 %), and those attributed to ageing. A key-question for the future instrument transformers survey is to know at least if the transformer failed

immediately after a lightning stroke.

Also because ITs are more effectively protected by surge arresters than by spark gaps, the utilities insulation coordination practices could affect the failure rate of IT's.

4.7 Service life of instrument transformers

From the 2636 reports received concerning the age of the failed unit, the actual number of failures reported versus age is shown in Figure 4.2.

Figure 4.2: Number of failed units versus age at failure

Figure 4.2 indicates a gradual reduction in the number of Major Failures and Total Failures as the units get older. This phenomenon could be due either to the fact that there are fewer units of that age still in-service, or that units that are retired from service were not reported as failures in the survey. The graph for number of Units Scrapped versus Age shows a significant increase beyond the 20 years age mark, which suggests that the practical life of Instrument Transformers lies between 20 and 30 years.

In order to evaluate further the data in Figure 4.2, the primary cause of the 2636 failures has been analysed in terms of age of the IT at failure. This analysis is shown in table 13.

Table 13: Age of the IT failure

Primary Cause of Failures	**Failures in first 3 years of service** (Total 445 of 2636 = 17%)	**Failures in first 10 years service** (Total 1242 = 47%)	**Failures between 11 to 30 years** (Total 1130 43%)	**Failures after 31 years** (Total 264 = 10%)
Design Fault	67.0%	67.9%	56.1%	43.6%
Inadequate Quality at Manufacture	7.2%	7.7%	16.0%	25.6%
Ageing	0.0%	0.3%	5.0%	8.3%
Lightning	2.7%	2.3%	1.6%	0.8%
Operation out side of Spec.	2.5%	3.9%	5.6%	9.8%
Inadequate Maintenance	0.4%	0.6%	1.5%	0.0%
Unknown	20.2%	17.2%	14.1%	11.7%

A significant result from Figure 4.2 is the relatively large number of Minor Failures and Defects that occurred in the first 10 years of service, the greater proportion of which were subsequently repaired and the units returned back to service. From the report on which information in Tables 12 and 13 are based, it appears that a large proportion of these Minor Failures and Defects were caused by design defects mainly associated with seals and gaskets and which resulted in oil leaks. From Table 13 it appears that the primary causes of all failures within the first three to ten years of service remain basically the same, and that Inadequate Quality during Manufacture becomes more apparent as the units begin to fail in their later years of service.

4.8 Action taken on failed units

The responses received to this issue varied significantly because of the complexity of the faults and defects encountered; the age of the affected unit and its performance to date; the expertise or facilities of the utility involved; and the availability of spare parts or the original manufacturer, but in general the actions taken on failed units may be summarised by:

- All Major Failures resulted in the unit being scrapped.
- For Minor Failures and Defects, if the unit can be economically and satisfactorily repaired on site or returned to the workshop or manufacturer then this is done as often as possible. However if the unit is older than 20 years and the repairs are not simple then these units are normally scrapped.

From the 3004 reports received in the survey, 965 (32%) indicated that the failed or defective unit was scrapped, 1777 (60%) indicated that the unit was repaired and returned to service, and for 262 (8%) the action taken was not known.

4.9 Maintenance and monitoring techniques in use

From the 3004 reported failures the type of Maintenance Strategy or Monitoring System used prior to the Failure may be summarised as follows:

- Regular Visual Inspection reported 2916 times (95% of the 3004 reports)
- Checking of Oil Level Indicators and/or Pressure Gauges reported 1885 times (61%)
- Secondary Voltage Monitoring (for CVTs only) 459 times (15%)
- Insulation Resistance checks reported 330 times (11%)
- Dissolved Gas Analysis and/or Moisture of Oil reported 221 times (7%)
- Thermovision Inspection reported 131 times (4%)
- Tan δ measurements reported 56 times (2%)

It appears that most utilities use one or more of the above mentioned monitoring systems to check the condition of their transformers.

In response to the survey question on how the reported fault in the instrument transformer was initially detected the following replies were received:

- 63.3% was Planned Visual Inspection and Maintenance
- 13.3% was System Trip
- 10.9% was Monitoring System Alarm
- 7.7% was Other Methods
- 3.9% was Failure of similar equipment
- 1.3% was Unplanned Site Inspection.

From the above data, most of the "System Trips" were associated with Major Failures, and likewise "Monitoring System Alarms" were mainly associated with CVT failures. Therefore, it is clear that the main form of detection of almost all Minor Failures and Defects within CTs, MVTs and Combi's is by the Planned visual Inspection and Maintenance.

The survey did not provide specific data relating to the frequency of any inspections, the type of work performed, the criteria to determine what monitoring systems were adopted for particular IT designs, and the limits used to determine if the unit was serviceable or not. This information should be requested in the next survey.

4.10 Results from supplementary survey

The Supplementary Survey contained 16 responses, which are summarised in the Table 14;

Table 14: Supplementary survey

Supplementary Survey Question	Summary of Responses Received
What is the number of Major Failures occurred over past 5 years.	- Six responses had 1 to 2 per year - Seven had 3 to 5 per year - Three responses had none
Has the Major Failure rate changed over the past few years?	- Seven claimed it had decreased. - Four claimed it had increased. - Five claimed it had remained the same.
Has the Minor Failure rate changed over the past few years?	- Nine responses claimed it had increased. - Four responses claimed it had decreased. - Three responses claimed it had remained the same.
Can you identify why your Major Failure rate is lower than other utilities.	- Seven responses claimed it was due to improved levels of Maintenance, diagnostic tests, or In-service Monitoring Systems. - Five responses claimed it was due to purchasing from only a limited number of approved manufacturers. - Four responses claimed other reasons such as improved specifications, more conservative stress levels, more detailed inspections and factory tests.
Have you introduced any recent changes to further improve the reliability of Instrument Transformers?	- Six responses introduced improved maintenance strategies. - Six responses claimed the development of more effective diagnostic tests or in-service monitoring systems to detect incipient faults. - Five responses changed the type of designs or constructions purchased. - Five responses required more type or routine testing. - Four responses changed manufacturers or became more selective on who to accept. - Five improved their purchase specifications and quality requirements from manufacturers.
With respect to the recent changes introduced has there been an improvement in the reliability of the equipment.	- Eight responses claimed yes. - Four responses claimed it was too early to tell. - Two responses claimed no. - Two did not know.

4.11 Comparison of results between first and second surveys

The comparison of relative failure rates obtained in the first and second surveys are summarised in Table 15. As the first survey was performed over a period of 17 years (1970-1986), and the second survey was performed over a period of 10 years (1985-1995), to accurately compare the results between the two surveys there is a need to normalise them as follows:

- Relative failure rate = 100*(Number of failures between 1970 to 1986) / (Number of units of that type in 1986)
- Failure rate based on Transformer Service Years = 100*(Number of failures between 1970 to 1986) / (Number of units of that type in 1986 *17 Years)
- Relative failure rate = 100*(Number of failures between 1985 to 1995) / (Number of units of that type in 1995)
- Failure rate based on Transformer Service Years = 100*(Number of failures between 1985 to 1995) /

(Number of units of that type in 1995 *10 Years)

Table 15: Comparison between first and secondary survey

Type of Transformer and type of Failure	**Results of First Survey**		**Results of Second survey**	
	Relative failure Rates	Failure Rate Based On Transformer Service Years	Relative failure Rates	Failure Rate Based On Transformer Service Years
	Note 1	**Note 2**	**Note 3**	**Note 4**
Current Transformers				
(a) Major Failure	0.23 %	0.014 %	0.40 %	0.04 %
(b) Minor Failure	N/A	N/A	0.19 %	0.019 %
(c) Defect	N/A	N/A	0.98 %	0.098 %
Combine (b)+(c)	0.12 %	0.025 %	1.17 %	0.117 %
Combine (a)+(b)+(c)	0.65 %	0.039 %	1.57 %	0.157 %
Magnetic Voltage Transformers				
(a) Major Failure	0.32 %	0.019 %	0.44 %	0.044 %
(b) Minor Failure	N/A	N/A	0.20 %	0.020 %
(c) Defect	N/A	N/A	2.16 %	0.216 %
Combine (b)+(c)	0.49 %	0.029 %	2.36 %	0.236 %
Combine (a)+(b)+(c)	0.61 %	0.048 %	2.8 %	0.280 %
Capacitor Voltage Transformers				
(a) Major Failure	0.082 %	0.005 %	0.26 %	0.026 %
(b) Minor Failure	N/A	N/A	0.66 %	0.066 %
(c) Defect	N/A	N/A	1.82 %	0.182 %
Combine (b)+(c)	0.49 %	0.033 %	2.48 %	0.248 %
Combine (a)+(b)+(c)	0.64 %	0.038 %	2.74 %	0.274 %
Combined Transformers				
(a) Major Failure	0.1 %	0.006 %	0.23 %	0.023 %
(b) Minor Failure	N/A	N/A	0.42 %	0.042 %
(c) Defect	N/A	N/A	2.77 %	0.277 %
Combine (b)+(c)	0.38 %	0.022 %	3.19 %	0.319 %
Combine (a)+(b)+(c)	0.48 %	0.028 %	3.42 %	0.342 %

N/A = not available.

All results contained in Table 15 indicate a significant increase between the first and second surveys in the Major Failure Rates for all types of transformers. It must also be realised that the results of the second survey could again be much higher than quoted in this report if they included the other ITs that were also removed from service because they were of a suspect design.

While the population size and spread between the two surveys was very similar, as was the majority of participating countries, the main difference between the two was that the first survey included data from a number of manufacturers while this second survey only contained data from utilities which obviously must have access to more information from their network. The total number of failure reports received to this second survey was 3004 as compared with only 864 from the first survey. The second survey also contained data for resin and SF6 designs. Hence the results from this second survey are considered to be more accurate and representative of the total in-service instrument transformer population.

4.12 Other data available from the survey.

4.12.1 Special Type or Routine Tests (additional to IEC) performed on the failed unit or design when it was purchased to improve its performance.

The majority of respondents indicated that special tests were not performed above the IEC Standard requirements. However the few respondents that did know of special tests performed listed routine impulse testing; the multiple chopped impulse type (MCI) test; and reflected wave impulse type test which in effect applies an impulse with a higher than normal peak value which may occur if spark gaps are used to protect equipment.

4.12.2 Following the particular failure was there any action taken by the utility to change maintenance philosophies.

A large proportion of respondents indicated they had changed the practices particularly after Major Failures and included:

- The introduction of regular DGA and moisture testing on selected units and more frequent DGA testing on suspect units;
- More frequent Tan δ testing on selected designs;
- More frequent and detailed physical inspections;
- Regular thermovision checks;
- More regular secondary voltage checks of CVTs;
- Checking of CVT ferroresonance performance during commissioning.

4.12.3 As a result of the particular failure was any action taken to change future purchasing specifications, design or factory test requirements.

The majority of respondents indicated that the change had not been made, but some utilities that did respond yes included:

- Routine impulse testing;
- More stringent quality assurance compliance by the manufacturer;
- Statistical quality control to limit the routine test variations for partial discharge,
- The introduction of tan δ and capacitance measurements before and after dielectric tests;
- DGA of oil samples before and after routine dielectric tests;
- Routine ferroresonance tests for CVTs;
- Salt fog contamination type tests;
- Mechanical endurance type tests to prove the reliability of oil expansion devices;
- Multiple chopped lightning impulse type test;
- Long duration accelerated electrical aging tests;
- In some cases utilities specifically excluded certain types of designs or constructions.

4.13 Comments on quality of data received in the survey

A number of critical observations can now be made on the quality of data reported in this survey which have to be examined before any future surveys on this topic may be considered. These comments are summarised as follows:

- It appears that many utilities do not keep any form of database containing details of their Instrument Transformer populations, number of units in-service, types of constructions used, details of insulation and sealing systems, the date of manufacture, date when put into service, any service history and the date of removal from service and the reason.

- There also appears to be a lack of specific knowledge on the Type or Routine Tests performed when the units were manufactured. Also the possibilities that Type Tested units, which were subsequently put into service were more or less reliable than other units within that contract or design cannot be evaluated.
- Upon investigating the primary causes of any Major Failure, Minor Failure or Defect a number of utilities appear to have a sound understanding of the processes involved in the technical investigation or mechanism of a failure within Instrument Transformers. This is apparent with the large proportion of causes being attributed simply to "Design faults", even in some cases where the unit was over 30 to 40 years old. Another widely reported primary cause of failure was "Unknown" even for units that were only involved in Minor Failures or Defects for which all the evidence for the cause of the failure must be available.
- It appears that many utilities take actions to improve the reliability of their Instrument Transformers in-service only after obvious defects are observed or Major Failures occur. Future surveys could explore further the maintenance strategies and policies in use by the utilities to manage effectively their assets.

4.14 Future surveys

The significance of data received in this second survey, the clear requirement to develop and utilise additional monitoring techniques and the need to include the newer types of Instrument Transformer technologies indicate a need to repeat another survey within six to eight years.

The future surveys should be targeted towards Major Defects and Failures only, causes of these failures, maintenance and monitoring strategies, and therefore should again be completed by utilities only. Since many utilities found difficulty in collecting and reporting the specific data required by this survey it is recommended that CIGRE establishes a Working Group to define the format and information requirements of future surveys. This new format should consider using a common computer database to be issued to all participating utilities as soon as possible in order to obtain consistent and better quality data.

4.15 Conclusions

- Results of survey are realistic and informative.
- Major Failures continue to occur and most utilities had experienced at least two or more Major Failures per year for the past five years.
- The high number of utilities which reported large numbers of Major Failures in the first five years of this survey (1985 to 1990) was unexpected and differed significantly from the previous survey. This may have been due to the fact that the first survey was answered by a large number of manufacturers who might not have been aware of the problems the utilities were experiencing.
- The reduction in the number of Major Failures during the last five years of this survey (1990 to 1995) may indicate the success of the diagnostic and maintenance systems introduced by most utilities to detect suspect units before they develop into Major Failures. Consequently there has been an expected significant increase in the Minor Failures and Defects reported during this period.
- The relatively small quantity of resin and SF6 units reported to this survey has limited the amount of information available and reservation exists about the accuracy of reliability statistics for these designs.
- Analysis of the Primary Cause of Failures with respect to the age of the failed units did not show any dramatic differences throughout the lifetime of the unit. However the large proportion of failures or defects due to leakage is of great significance and needs to be investigated further.
- Existing maintenance, monitoring and diagnostic methods and practices do not appear to prevent Major Failures completely. When applied specifically to a design with a known failure characteristic some selective monitoring methods can detect other faulty units before they turn into a Major Failure. There appears to be a need for reasonably priced continuous on-line monitoring systems, which can effectively detect incipient failures within instrument transformers, particularly in CTs. Continuous secondary voltage monitoring of CVTs has been successfully developed and proved by many utilities to be very effective in preventing Major Failures of CVTs.
- It continues to appear that relatively small faults or defects can be repaired economically. Most faulted units over 20 to 25 years old and all major failures are normally scrapped.
- The Supplementary Survey has identified that most utilities are facing similar challenges to improve the overall reliability of Instrument Transformers. The highest priorities being to pay more attention to the quality of design,

manufacture and testing of new equipment, followed by improved maintenance and monitoring strategies for equipment already in-service.

5 MAINTENANCE, DIAGNOSTICS, AND CARE

5.1 Introduction

This chapter deals with maintenance, diagnostics, and care of ITs in service in order to maximize their life economically, ie to keep the units in reliable and safe operation for the expected life (generally above 25 years). Ideally the maintenance, diagnostics, and care program should detect any slow and gradual degradation of the equipment, occurring normally in service. Detection of defects at the early stages of development can keep the unit in reliable service, help to determine end-of-life and facilitate a timely replacement of the unit before a major failure occurs. An effective program should also be able to detect any fast developing faults and defects, which sometimes can lead to explosive failures, creating risk to the safety of personnel and equipment in close vicinity. In general the maintenance, diagnostics, and care of the ITs is intended to prevent unexpected premature failures, improve safety and quality of service, and also impact on the profitability through avoided costs involved in clean up after explosive failures. Usually, there is no intention to extend the service life of the IT, for instance by reconditioning. Various actions, which can be undertaken practically for maintenance and care of ITs during their operation, and their effectiveness and limitations, are described here.

5.2 General Components of Maintenance, Diagnostics and Care

Reliable service of ITs depends on various factors starting with:

- detailed specifications
- design
- quality control in the manufacturing process, assessed by successful factory tests,
- safe transportation
- installation of the unit as verified by commissioning tests,
- and finally the in-service maintenance and care of the unit, which generally includes surveillance, diagnostic tests and remedial actions, if any.

The program has to be cost effective. Compared to power transformers, ITs have low capital costs and their failure rates are generally low, as shown in Chapter 4. Often the decisions for diagnostics and maintenance of ITs are made on the basis of economic considerations rather than technical merits. An economic compromise dictates frequency and extent of various actions. Concerns for the safety of personnel working in the substation also influence the policies used by utilities.

Some utilities have practically no maintenance program for ITs or act only when a family of ITs starts showing problems, while some others have regular diagnostic and maintenance program. Maintenance may require periodic replacement of minor components, e.g., gauges, switches etc., which have a shorter life than their ITs. Sometimes an IT is withdrawn from service because of changes in service requirements, operating regime, voltage and/or current which exceed the values for which the IT was designed.

5.2.1 Existing Prior Data

For an effective maintenance and care program, records of data from specification, factory tests, commissioning tests, and previous in-service tests and any remedial actions should be kept properly. Also similar data on all other similar units should be available for comparison. Such historical data can be helpful in developing a cost-effective methodology for condition monitoring and to anticipate and prevent problems. Also an effective program can be developed only after understanding the aging processes relevant to the specific units. The various aging processes under different service stresses are briefly described in the next section.

5.3 Ageing Stresses and Processes

New equipment is designed to withstand operating stresses likely to occur in service. These stresses can be thermal, electrical, mechanical, and/or environmental and may be present alone or in combination. The stresses, which may be continuous or transient in nature, degrade or age the equipment gradually until its capability (strength or withstand) falls below the operating stresses, leading to its failure. The insulation system and the components other than the insulation system (ie, connections, seals, ceramic or polymeric insulators, etc.) are degraded under operating stresses. The utility survey (Chapter 4) attributes few IT failures directly to insulation aging and most failures to the design or manufacturing defects. Hence only a brief description the aging stresses is given in Appendix 3 (and references 27-38) to help interested persons in understanding premature failures and defects caused by rapid aging.

5.4 Remaining Life Estimation Vs Condition Assessment

An equipment reaches the end of life when it can not withstand the stresses in service. However, to define end of life in terms of physically measurable parameters is quite difficult. For paper-oil insulation, there have been some attempts to define the end of life from studies in laboratories and on insulation systems from old transformers [39]. For example, a drop in the degree of polymerization of paper to 250 (or even 150) has been suggested as one way to define the end of life. The suggested end of life characteristics for paper-oil insulation in transformers is also under study by a CIGRE task force (15.01.02). At present there is no agreement between experts on the definition of end of life. Ideally a substation maintenance engineer would like to know the remaining life of equipment. This seems to be impossible from a single set of measurements with the present state of art. Several utilities have replaced groups of ITs after failures of units from the group mainly because of environmental and safety concerns but, in itself, this should not be considered as a recommended end of life policy for ITs.

Present diagnostic techniques determine any degradation trend in the condition of the equipment. By trending over a certain period and then comparing with historical or family data in similar service, a decision about the serviceability of the specific equipment can be made. Some critical parameter values have been suggested and used as a guide for removing the equipment from service. However, the main goal of diagnostic tests described in the next section is to assess the condition of the equipment rather than its remaining life.

5.5 In-service Tests for Maintenance, Diagnostics, And Care

5.5.1 Selection of Tests

ITs, just like any other equipment, age under various stresses in service and produce changes in physical and chemical properties, some of which can be measured as diagnostic parameters. Diagnostic tests are performed to determine the condition of the equipment and also to decide on removal from service. The choice of tests and their frequency of application varies widely among different utilities from almost no in-service test to well planned programs, and depends on costs involved in the tests, their perceived effectiveness, available equipment and facilities, and the experience of the utility. The most commonly used tests are described below, first for paper-oil insulation and then for other insulation systems. Wherever possible the frequency of tests, their effectiveness and limitations, as generally accepted, are given.

The frequency of test applications varies widely from utility to utility and those stated in the following sections indicate general utility practice and should not be treated as recommendations. Test frequencies should be adjusted for a given family of ITs, and will be higher for suspect or problem units, and lower for units with no history of problems. The frequency of tests may also be increased for older units. In case of a problem, several different tests are often performed in combination.

Tests are divided into several categories: general inspection, periodic off-line tests, periodic on-line tests, continuous on-line tests and oil diagnostics. In the following sub-sections, many of the tests are described first with reference to ITs with paper-oil insulation, and then with reference to the other types.

5.5.2 General Visual Inspection

Visual inspection is done once or twice a month. The checks are as follows:

- signs of oil leaks and position of oil level indicator
- state of the bellows, as described in Table I
- state of the high-voltage insulator surface
- state of the anti-corrosive protection
- earthing of the instrument transformer

For ITs with a gas cushion, the gas should have positive pressure under all service conditions. Hence it is necessary to check it from time to time, or better by a permanently installed manometer on the top or bottom of the IT. In the latter case, the pressure has to be corrected for the height of the oil level. Cases of under-pressure, or over pressure, and differences of pressure in comparison with the other ITs in the same bay, may be an indication of a faulty unit and the IT has to be taken out of service for inspection. Depending on the scale of the manometer (not only red and green) a change of gas pressure of 0.1 to 0.2 bar can normally be detected.

For SF_6 gas-filled ITs, the gas pressure has to be checked regularly for possible gas leakage due to aging of the sealing system.

Surfaces of composite insulator housings should be checked for chalking, erosion, treeing or tracking which indicate an irreversible degradation.

Table 15: Inspection of bellows for paper-oil ITs

No.	Bellow's State	Conclusion	Action
1	All transformers in same bay exhibit approximately the same amount of bellows extension.	Transformer in good condition	No Action
2	Bellows extension at approx. halfway between minimum and maximum at temperature of about 20 °C.	Transformer in good condition	No Action
3	Transformers from the same batch exhibit widely differing bellows extensions	1. Possible oil loss 2. Overpressure 3. Bellows not able to move freely	De-energise if possible and keep transformer under continuous observation Inform manufacturer
4	Bellows extension independent on temperature	1. Sealing system (bellows) leaks or 2. Bellows not able to move freely	Inform manufacturer
5	Bellows fully contracted below permissible minimum	Possible oil loss	Check transformer for oil loss Inform manufacturer
6	Bellows extended beyond permissible maximum	Overpressure in transformer due to gas production or overheating	De-energise immediately Inform manufacturer

Note - Some ITs have a bellows indicating system with a 'dead zone'

5.5.3 Periodic Off-line Tests Measurements

These tests are done periodically usually at 3 to 6 year intervals with the IT disconnected from high voltage.

5.5.3.1 Oil analysis

Most paper-oil ITs are provided with a valve which allows oil samples to be taken and analyzed for dissolved gases and other properties, as described below. The maximum volume of oil which can be removed from an IT due to sampling is quite small and should be stated by the manufacturer. Replenishment will be required when the limit is reached. Taking oil samples from ITs is not free from risks. Precautions should be taken during the oil sampling as prescribed by the manufacturer. A reduction of the oil volume or an inadvertent introduction of air or moisture during the replenishment process can lead to a premature failure. Also the unit must be properly sealed after sampling of oil. Utilities must have procedures that restrict oil sampling to trained or experienced personnel. Oil sampling points should also be fitted with seals or locks to prevent unauthorized access. Oil sampling is not possible or recommended for certain designs, eg, CVT capacitors, unless they are especially equipped with oil sampling devices.

5.5.3.1.1 Dissolved Gas-in-oil Analysis (DGA)

The amount and composition of gases (degradation products) in oil are measured. The results are interpreted using similar methods (ie absolute levels, and ratios of different gas concentrations) as those for power transformers [40-43]. Generally a slow increase in the gas concentration is expected with normal aging in service. However, in some cases, dissolved gases (H_2, CO_2, hydrocarbons) may be present in the oil of new ITs, even before the application of voltage, due to diffusion from solid insulation or from solvents in internal painting or gluing agents. Some guidance is given in Chapter 3.

Some utilities take an oil sample within six to twelve months after commissioning, and later once in three to six years. Often utilities restrict oil sampling to diagnostic purposes. The use of DGA is recommended after a serious lightning incident on or near an IT, especially if adjacent equipment has been damaged. Additional analyses may be required if abnormal gas levels are found. For normally aging transformers the concentration levels of different gases in oil have been suggested. Typical acceptable values and threshold values for taking corrective action are given in Table 16, also IEC 599 (1997) gives similar values.

It should be noted that some Instrument Transformers have been found in service without explosion with gas in oil levels very much higher than those given in Table 16. Low intensity partial discharges produce large amounts of H_2 and small amounts of alkanes (CH_4 and C_2H_6 etc.). High energy discharges (sparking) produces C_2H_2.

Excessive heating of paper produces CO. If CO and CO_2 are found, thermal degradation of paper cellulose has to be considered. In a sealed system, with the seals intact, only CO levels may increase and CO_2 levels will be small. Thermal aging of paper in presence of moisture and oxygen produces both CO and CO_2. Also at temperatures not much higher than the ambient temperature, only CO_2 is formed. Moisture influences the formation of CO_2 and not CO.

A summary of the probable causes of gas generation is shown in Table 17.

Note should also be made of different oils being used by different manufacturers. In some cases, gas absorbing oils were replaced by low aromatic oils about 15 years ago. Different acceptable gas levels may be appropriate for different types of oils, but IEC 599 or the values in Table 16 may be used in the absence of more precise information.

There is limited experience of acceptable gas-in-oil levels for non-mineral oils, e.g., synthetic fluids used in some CVT capacitors.

Table 16: Maximum admissible values of Dissolved Gases for Paper-oil ITs

Gas [ppm]	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6	CO	CO_2
Nothing to do	300	30	2 *	10	50	300	900
Remove	>1000	>200	>10	>100	>500	No data available	No data available

* Indicates measurement threshold; ideally it should be zero.

Table 17: Generation of gas in oil-filled electrical equipment

Type of Gas		Overheating						Discharge of high energy / arcing		Partial discharge with low energy density	
		150 – 400 °C		400 – 900 °C		> 900 °C					
		Oil	Oil + paper	Oil	Oil + paper	Oil	Oil + paper	Oil	Oil + paper	Oil	Oil + paper
Hydrogen	H_2			o	o	•	•	•	•	•	•
Methane	CH_4	•	•	o	o	o	o	o	o	o	o
Ethane	C_2H_6	•	•	o	o						
Ethylene	C_2H_4			•	•	•	•	o	o		
Acetylene	C_2H_2					•	•	•	•		
Propane	C_3H_8	•	•								
Propylene	C_3H_6			•	•	•	•	o	o		
Propadiene	C_3H_4					•	•	•	•		
Propyne	C_3H_4					•	•	•	•		
Carbon monoxide	CO		o		•		•		•		o
Carbon dioxide	CO_2		•		•		•		o		o

• dominating gas o accompanying gas

5.5.3.1.2 Moisture content and tan δ in oil

Moisture in oil content (both free water and dissolved water) should be measured the by Karl Fischer method (IEC 422). The normal value for new units is 5 - 10 ppm and should remain at this level for metallic bellows sealed units during its normal life. For other sealed units and older designs, the value can be higher. Above 25-30 ppm level, the moisture may not be soluble in oil and the dielectric performance can decrease due to the presence of free water, especially at low ambient temperatures.

The measurement of tan δ of oil at 20 °C and 90 °C, in accordance with IEC 296, gives information of both ionic contamination (conducting particles) and polar deterioration products (peroxide, water, alcohols, ketones, acids). In sealed type ITs in good condition, very few contamination and deterioration products are formed. These products may increase as the sealing system ages and admits moisture.

This analysis is not normally made as a routine maintenance check and its use is more appropriate in diagnosis of suspect ITs.

5.5.3.1.3 Furans and other aging products

Overheating of paper produces furans or furanic compounds. Among several furan derivatives detected, 2-furfuraldehyde is the most important and sensitive even for an IT where the amount of paper is small compared to that in a power transformer.

Furan analysis is performed by HPLC (High Performance Liquid Chromatography) or by GC-MS (Gas Chromatography-Mass Spectrometry). The maximum concentration of 2-furfuraldehyde detected by HPLC for a thermally aged CT is about 0.2 μg/g when the measured CO concentration in oil is about 700 ppm.

Tan δ of oil and furan analysis are used widely for power transformers. However, the experience with their use for ITs is limited and they should be used only for diagnosis of a suspect unit.

Oil may also be checked for other properties like acidity, surface tension, and dielectric strength, etc.

5.5.3.2 Insulation resistance

The method and test procedure for this measurement in service is the same as described in Chapter 3 (Section 3.5.2.4). Depending on the IT design, insulation resistance between the high and a low voltage winding or the high voltage winding and earth should be measured. For the service measurement, full attention should be paid to the preparation of the transformer to be tested. All the insulators, particularly the surfaces of the HV insulator, must be clean and dry. This is particularly important for testing of insulation of instrument transformer with built-in capacitive shields in the insulation. The measured results should be corrected to 20 °C, and should be compared with those obtained at the factory. If the insulation resistance values (1 minute after applying the voltage) are lower than 50 GΩ for CTs, remedial steps may be necessary.

For MVTs the measurement of insulation resistance raises the same problems and restrictions as for measurement of tan δ (See Chapter 3). The results and efficiency of the test are dependent on the design of the MVT and the test arrangements.

Experience with insulation resistance measurement is limited to porcelain clad paper-oil ITs only. Guidance is not available for paper-oil or SF_6 insulated ITs which use composite insulators.

5.5.3.3 Capacitance and tan δ for paper-oil ITs

A bridge capable of testing both earthed and unearthed test objects is recommended for measurement of the capacitance and tan δ of ITs. For CTs and CVTs, the measuring voltage should be at least 10 kV and the results should be compared with factory measurements. For MVTs, the measuring voltage may be applied to the neutral terminal. In this case a voltage lower than the withstand voltage of the neutral terminal must be applied. For new ITs the tan δ value is approximately 0.3 % for CTs, somewhat higher for some MVTs, and much lower in CVTs with polymeric film insulation (see Chapter 3, Sections 3.3.4, 3.5.2.1 to 3.5.2.3). Generally tan δ values higher than 1% indicate poor condition of IT; any IT with tan δ above 1% should be taken out of service. Frequency of test (period) is normally about six years. For added guidance, the tan δ of an IT, measured at ambient temperature, should not normally exceed twice the as-new value.

For in-service paper-oil CTs and MVTs, it is worth noting that one user reports experiences with more than 700 CTs and MVTs and has measured tan δ values of <0.3% when the insulation is without defects. [37]

If tan δ measurements are made at different voltages up to 1.0 U or 1.2 U (U = rated line to ground voltage, see also 5.5.3.4), the variation in dissipation factor from 0.1 U to 1.0 U should be less than 0.0025 and the value at U less than 0.005. Also, the value of C should not change from the initial or new value by any significant amount; a capacitance change equal to the breakdown of the single grading layer, or of one capacitor element in CVTs, means a serious problem.

Investigations [44] have been made on the tan δ of new (and aged) CTs at elevated temperatures to determine the value of the temperature coefficient "α" of the insulation. It is considered that tan δ is an exponential function of the temperature θ, and the temperature coefficient "α" of the insulation can be given by

$$\alpha = \frac{\ln(\tan \delta_2) - \ln(\tan \delta_1)}{\theta_2 - \theta_1}$$

where $\tan \delta_1$ and $\tan \delta_2$ are the dielectric loss angles of the insulation measured at θ_1 and θ_2 respectively.

Figure 5.1 compares the relationship between tan δ and temperature, for a number of typical new CTs with graded and non-graded insulation respectively, with the temperature coefficient "α" indicated.

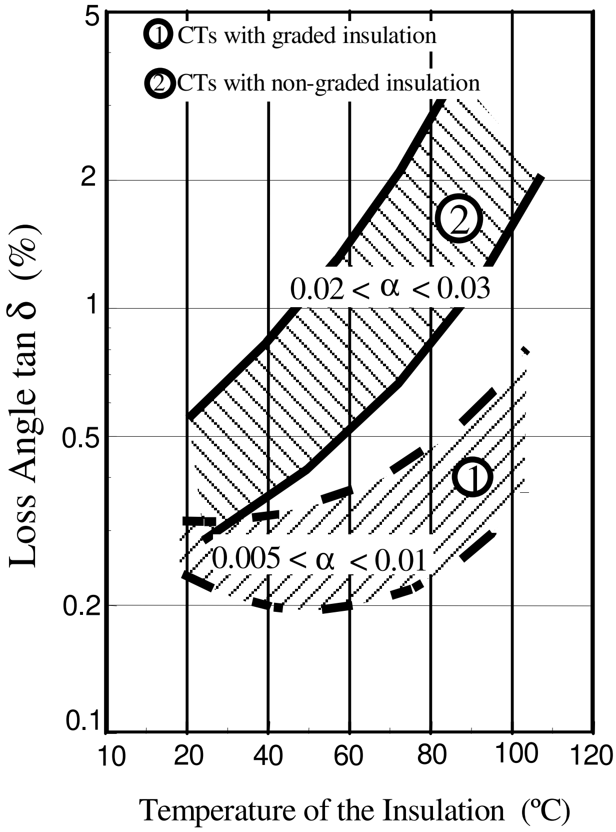


Figure 5.1: tan δ (dielectric loss angle) versus temperature for new graded and non-graded insulation CTs (reference [44])

The tan δ of instrument transformers with non-graded insulation is appreciably influenced by temperature, as shown in Figure 5.1. This behaviour is described (in reference [44]) to the presence of high electrical gradients having a direction that is not radial to the paper layers. Therefore the influence of the oil becomes more apparent. Generally, the CT can be considered to be in acceptable condition if α is <0.02 for graded insulation, and <0.03 for non-graded insulation. For comparison, Figure 5.2 shows the relationship of tan δ versus temperature for CTs with graded insulation of varying condition. The description is as follows:

Area 1	Insulation in good condition
Area 2	Insulation affected by contamination
Area 3	Insulation affected by heavy moisture absorption (2-5% water by weight)
Area 4	Insulation affected by strong partial discharges and hot spots.

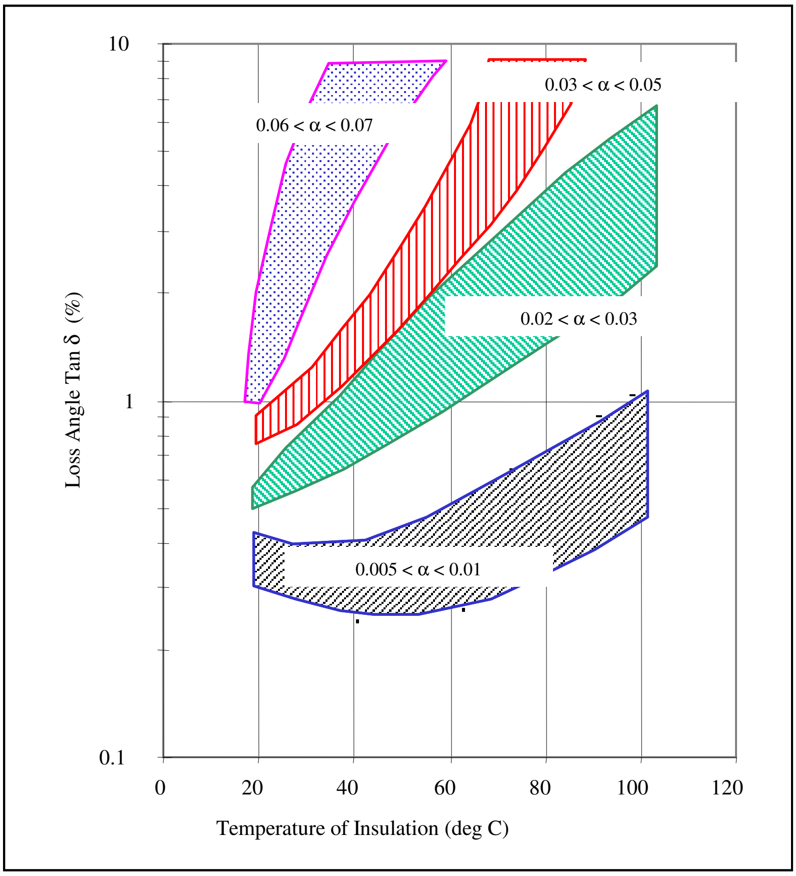


Figure 5.2: tan δ (dielectric loss angle versus temperature of the insulation for new and graded CTs (reference [44])

Figure 5.2 also shows that correct conclusions about the condition of the insulation may be made only from measurement of the tan δ of the insulation at ambient temperature and at higher temperature (for instance 90°C). The tan δ of the IT at elevated temperatures always gives a good indication of the quality of manufacture of CTs [44]. However, this requires heating of the entire CT. Using this method, values of "α" were obtained for more than 40 CTs suffering from high moisture. Figure 5.3 displays this data plotted as a Gumbel distribution. In this case α lies between 0.03 and 0.06.

Measurement of the tan δ of the oil at 25°C has also been found to correlate to the tan δ of the CT at ambient temperature, (Figure 5.4) greater correlation being observed for highly abnormal CTs where the insulation tan δ is > 1% [45]. The accuracy and the degree of difficulty of this test depend on the design of the ITs. Care must be taken with on-site measurement of tan δ, which is greatly influenced by environmental conditions and the cleanliness of the external insulation.

The application of tan δ tests to resin ITs is of little practical value. Better reliance may be offered by other test techniques, e.g., partial discharges.

C and tan δ tests are not applicable to gas insulated ITs.

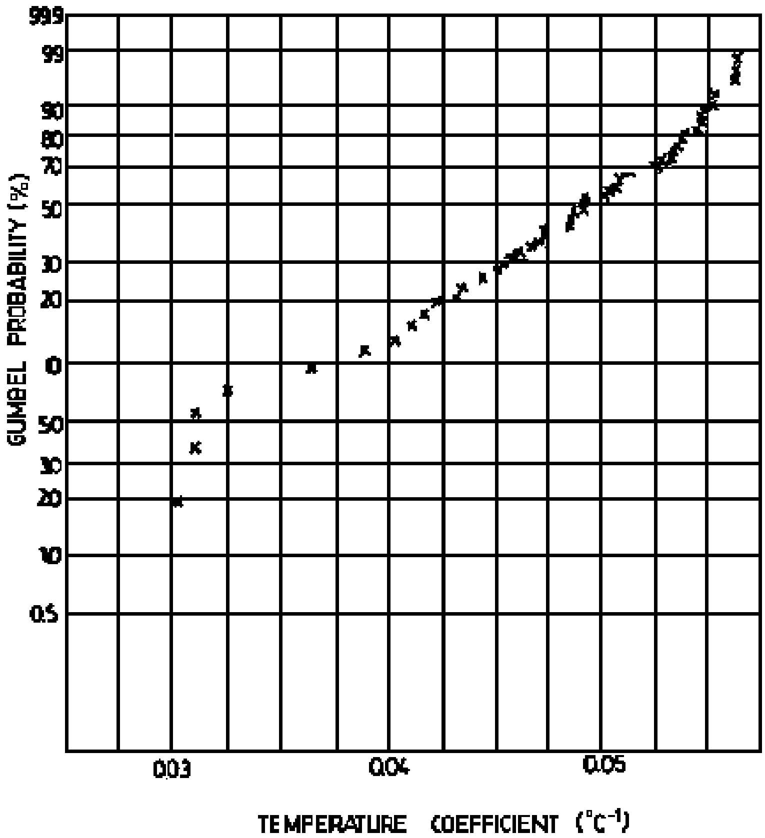


Figure 5.3 Gumbel distribution of «α» for 40 CTs suffering from moisture absorption (reference [45])

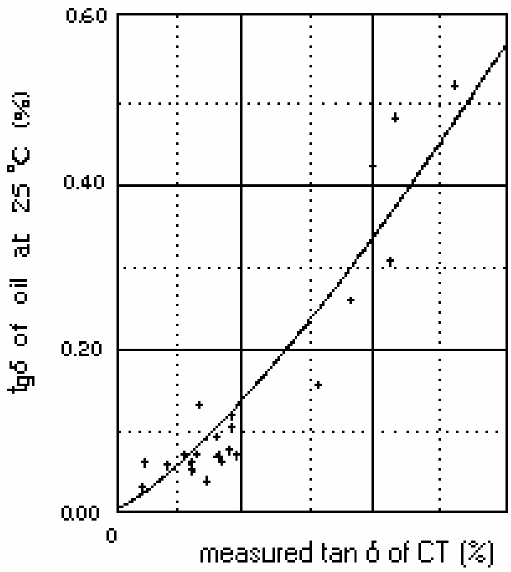


Figure 5.4 Relationship between tan δ of oil and tan δ of CT (reference [45])

5.5.3.4 High voltage withstand tests

Tests may be applied using rated frequency and/or impulse voltage at 65 to 75 % of the factory test values to check the integrity of the insulation system. Care should be taken for MVTs and combined ITs; a higher frequency test voltage (up to 200 Hz) may be required to avoid core saturation and overheating of the winding. This test is a simple withstand test and is not intended to give a qualitative assessment. The IT will have to be replaced in the event of a test failure.

5.5.3.5 Partial discharges

Development work is in progress to measure partial discharges on site using an external power source at rated voltage. Any significant change from earlier readings or a reading above the background value should be a cause for concern. Reducing the background noise always present in the field to levels below acceptable pd levels (about 2 pC) is a major problem; on-site background pd levels may only be reduced to a few hundred pCs by the use of conventional measurement techniques. Balanced bridge techniques are becoming available to overcome this problem.

5.5.3.6 Polarization or recovery voltage

Several authors have reported a polarization technique to detect degradation of insulation in power transformers [46-49]. DC voltage is applied to the insulation for a charging time t. The insulation is then short-circuited, for another definite period of time T. Then the open circuit recovery voltage is monitored as function of time. It is believed that the water generated in degradation of the insulation causes a charge build-up at the interfaces and changes the recovery voltage curve. There is limited experience with this technique applied to ITs.

5.5.3.7 Ratio checks

For VTs the transformation ratios may be measured and a deviation which exceeds the specified error of the VT, also taking into account the error of the test equipment, must be investigated further. In CVTs, a deviation of more than 2 % in voltage measurement may indicate a faulty capacitor element and must be investigated further.

5.5.3.8 Meters and gauges

Periodic calibration and functional tests are required to ensure that all meters and gauges continue to indicate and operate correctly. The usual period for testing is at least 6 years but utility local experience may vary this period.

5.5.4 Periodic On-line Tests

The following periodic tests are performed with the IT in service (i.e., at full voltage). No outages or external power supplies are needed. These measurements are normally made once a year.

5.5.4.1 Thermo-vision check

Thermovision check is very effective in detecting hot spots or overheated parts due to defective contacts, loose connections and also dielectric losses. Thermovision can be used for all types of ITs.

In one case, overheating of the capacitive part of paper-oil type CVTs was detected, the cause being later ascribed to contamination produced by mishandling of the paper during the manufacturing process. The contaminant increased the value of tan δ (and dielectric losses) at the operating voltage. Several tens of CVT's of the same batch were also checked using thermovision, but found to be acceptable.

Another utility reports that the checking of a few hundred CVTs revealed the presence of overheating caused by internal insulation discharges in evolution, but not the detection of totally short-circuited elements. When the hot spots were found, the temperature increase of the porcelain in the region of the failure ranged from 10 to 30 °C. However, a hot spot temperature rise of 3-4 degrees may be significant.

5.5.4.2 Partial discharges

Reference [50] describes the measurement of on-line partial discharges (pd) by an Australian utility. The principal parts of the system are a high voltage capacitor probe, a pair of matched transducers (one of which is a clip-on device) and an electronic detection unit. A sophisticated system of filters and differential amplifiers are used to minimize the substation noise interference. Sensitivity levels can approach those in a laboratory under favorable conditions. A different method has been described by Lemke and Schmiegel [51].

Some utilities perform ultrasonic measurements of pd for dead tank CTs and MVTs. An ultrasonic detector is fixed on the outside of the tank with magnets. The measurements are performed in normal service condition with the transformer energised. However, sensitivity depends on local conditions, weather, etc., and other confirmatory diagnostic tests, such as DGA, should also be applied to suspect units.

5.5.5 Continuous On-line Monitoring

The periodic off-line or on-line tests can detect gradual degradation of bulk insulation. However, certain types of fast evolving faults (for instance resulting from lightning strikes or where rapid degradation of the equipment could occur over a period of weeks or months) are unlikely to be anticipated by periodic tests. On-line continuous monitoring of the ITs is the only way to detect such faults. Various monitoring systems have been reported in literature as described below. It must be emphasized that these systems are mostly in the development stages, some are in limited or trial application and are still to be proven to be technically effective. Also such systems are costly, but their use may be justifiable in critical stations and also as part of general station monitoring schemes.

5.5.5.1 Tan δ

Continuous tan δ monitoring systems for instrument transformers have been reported [52, 53]. The tan δ indicates the average condition of the bulk insulation; its measurement alone may not be able to detect a fast developing localized severe degradation.

5.5.5.2 Insulation leakage current

A coupler placed on the external ground lead connection can be used to measure the insulation leakage current to ground. A significant increase in the leakage current can be expected to occur immediately before the final breakdown of the insulation and attempts have been made to predict impending failures of CTs by detecting this increase. [54]. The technique has not yet seen wide-spread use, pending validation of its reliability in terms of immunity from false alarms and the adequate warning times. The effect of transient currents during switching has to be suppressed.

5.5.5.3 Partial discharges

Both localized degradation and bulk degradation of paper-oil insulation can be expected to produce partial discharges (pd) before the final failure. Experiments on laboratory models have shown that intense pd activity occurs for a significant period just before the failure of the insulation system [55]. Interference from external noise is the biggest problem in on-line pd monitoring in the field. For reliable continuous on-line pd measurements, discrimination between pd and external noise is essential.

Several methods have been reported for eliminating or minimizing interference from external noise in pd measurements. External electrical or acoustic noise can be discriminated from the pd signal by combining the electrical detection with acoustic detection [56-58]. One utility has developed an innovative and patented technique for noise elimination based on the direction or polarity of the pd pulse current [59-61] in several CTs connected to the same power line phase. This system has been implemented on current transformers in two 230 kV substations and shown to produce no false alarms. However, none of the monitored units has failed or indicated problems. A different technique has been reported by another utility [62, 63].

5.5.5.4 Oil probes

On-line systems to measure dissolved hydrogen in oil have become available [64]. These systems are usually used on power transformers. In one application, a CT was removed from service after an increase in H_2 from 100 ppm to 1000 ppm in four hours. These systems require installation of the gas sensors in contact with oil, hence require addition of some pipework to the existing equipment. Therefore the technique is inherently intrusive in nature and the sensor should ideally be installed close to the gas generating or accumulating region. Therefore the gas monitoring systems may be suitable for power transformers with circulating oil but for instrument transformers with stagnant oil, their usefulness is inherently limited and their cost usually prohibits widespread application.

Some utilities have reported the use of electro-optical free gas detection relays in MVTs, which have detected faults, which would inevitably have lead to catastrophic failure. However, even for 420 kV equipment, such systems are 5 - 10 % of the capital cost of the IT and may also be subject to lower reliability than the IT.

Fiber optic sensors embedded within the winding can be used as on-line indicators of temperature [65, 66] and moisture [66]. However the method is intrusive by nature and may not probe the worst point in the insulation. Also the fragility of optical fibers is still an unsolved problem [68]. The fibre optic sensors have been used in power transformers, but their use in ITs may not be worthwhile.

5.5.5.5 Zero sequence voltage

Zero sequence voltage has been used on CVTs where degradation of a capacitor unit produces a slow variation of the secondary voltage. To detect the existence of a faulty CVT, a test device measures the zero sequence voltage across the secondaries of a set of three CVTs. When this voltage reaches a threshold, an alarm is given after a time delay, which is necessary to avoid generating alarms due to the presence of induced voltages when the line is de-energised. Such devices have been installed on all CVTs on entire networks and there is good experience from two utilities using this technique. The threshold value, in the region of 5% of the assigned voltage, makes it possible to take action while the evolution of the phenomenon is still slow, thereby avoiding the generation of accidental alarms due to unbalancing of the network. It is estimated that at this value, two or three capacitive elements are deteriorated whereas the capacitor is capable of supporting ten or so defective elements.

5.5.6 Multiple Tests and Comparison with Other Units

It should be emphasized that a single diagnostic test may not provide sufficient information on the condition of a particular IT. Often more than one test is performed to assess the condition of an IT and to decide if the IT should be removed from service. Also the acceptable values of a specific diagnostic parameter may be different for ITs of different types, of different manufacturer, and different service history. Comparison of test results on the same type of ITs on different phases in the same bank, or same type of ITs from the same manufacturer installed in different locations, and comparison with earlier tests in the factory or in the station will help in determining the degree of degradation. This way one can assess if an individual IT is faulty, or if all ITs of the same manufacture and from the same batch have a generic fault.

5.5.7 SF_6 Instrument Transformers

Few major failures of SF_6 filled instrument transformers have been reported. Degradation of the primary gas insulation does not occur, but excessive gas leakage, moisture ingress and water deposition on insulating surfaces could lead to insulation flashover. Presence of any metallic particles also lowers the dielectric strength significantly. Operation of the equipment below its minimum operating gas density must be avoided because the insulation performance, especially under system switching and lightning overvoltages, may lead to internal flashover.
At present, a gas leakage rate of < 1% is specified in the Standards for SF_6 insulated power transmission equipment. Data from utilities for GIS equipment generally suggests that substantially lower levels of leakage occur on most equipment; the annual leak rate is < 0.5% for equipment made before approximately 1985 and < 0.1% for recent equipment. For some very early CTs, made in the 1960s, one utility report that the reason for removal from service was unacceptable gas leakage caused by seal face corrosion or hardening of seal materials. Gas leakage can typically exceed 20% per year for such older equipment.

SF_6 gas in ITs performs mainly an insulating function. The amount of gas decomposition products is therefore extremely low and presence of such products indicates an internal sparking. Consequently the standard electrical tests applied to paper-oil and resin insulation systems are not appropriate and maintenance consists mainly of gas pressure monitoring, leakage rate assessment and leak location, gas quality and moisture content tests. Gas quality tests for humidity, acidity and decomposition products are usually performed periodically (for instance at 6 year intervals).

Humidity can be conveniently measured in terms of the condensation temperature, or dewpoint, at atmospheric pressure and calculated for the operating pressure of the equipment. For insulation integrity, it is important only that the dewpoint is below 0 °C at the minimum operating gas density so that moisture is not condensed onto insulating surfaces. At temperatures below 0 °C, non-conducting ice is formed. IEC 694 recommends a maximum dewpoint temperature of –5 °C. Dewpoint measurement apparatus is commercially available. An increase in humidity may indicate saturation of the molecular sieve.

Decomposition products can be measured by using a tracer gas detector sensitive to SO_2. Detectors calibrated for HF are also available but are less sensitive and use more gas. Detection of decomposition products may be obscured if internal adsorbers have been fitted to the SF_6 plant and caution must therefore be applied to the use and interpretation of this test.

SF_6 concentration is usually measured for indication of adequate gas filling procedures, but can also indicate air (and thereby moisture) ingress. SF_6 percentage (concentration) can be measured as a percentage using analysers that compare the speed of sound of the measured SF_6 gas mixture with calculated values. The analysers are set up for measuring the mixtures of SF_6 with air or nitrogen.

At present the life of the ancillary equipment, for instance gas density gauges, rupture discs etc., is less than the life of the ITs and replacement of the ancillary equipment may be required during the life of the ITs. As SF_6 is a 'greenhouse gas', care should be taken to limit any release to the atmosphere during any gas monitoring operations and to recover all gas during major evacuations.

5.6 Corrective Actions

If an IT is found to be faulty, it can either be repaired or refurbished or has to be removed from service. Minor external problems, like dirty insulators, loose contacts, defective meters and gauges, broken secondary terminal blocks, and minor oil leaks etc. can be corrected on-site. However, if the problem is too serious or costly to correct, the faulty IT must be removed from service. Because of the low capital cost of ITs, most utilities do not consider major corrective actions or refurbishment of ITs to be justifiable. Site reprocessing of paper-oil insulated ITs is impractical because of the need for special processing facilities and the testing requirements to establish the quality of the unit. Factory treatment is usually ruled out by economic considerations. One exception is the replacement of oil in the electromagnetic units of CVTs.

If an IT is found to be faulty because of a design or quality defect, it is the usual practice to check all other ITs of the same type or manufacture.

International agreement has prohibited the supply of insulating oils containing polychlorinated biphenols (PCBs) but older ITs may contain contamination levels which exceed the allowed values. Special precautions and personnel protection are required during the handling of ITs known to be contaminated and their disposal at end of life is strictly regulated to prevent PCBs entering the environment.

5.7 Conclusions

This chapter has summarized the various practices used by utilities for the maintenance, diagnostics, and care of the ITs. Although there is no consistency in practices of different utilities, steps, which can be taken to assure safe and reliable operation of the units, have been described above.

Maintenance of ITs is normally targeted at preventing catastrophic or sudden failure, rather than seeking to improve condition or extend the life of the IT. Maintenance policies are a balance of risk and safety, judged against economic cost.

Maintenance practices may be combinations of:

a) Periodic visual inspections and surveys.

b) Periodic off-line tests/measurements.

c) Periodic on-line tests and checks.

d) Continuous on-line monitoring.

The condition of an IT is best assessed with regard to trend information and comparison with other ITs of the same family and age.

It does not seem possible to give accurate predictions of end-of-life for ITs from single characterization parameters and a number of criteria must be used to give an assessment of condition. It is recognized that paper-oil equipment may sometimes exhibit slow degradation and then rapidly degrade to failure.

End of life may be determined by factors other than insulation degradation, for instance oil leakage or excessive SF_6 gas loss.

On-site repair, or factory reconditioning of paper-oil ITs is usually only considered for ITs which are less than 20 years old. Major failures always result in the scrapping of the unit. On-site reconditioning of degraded ITs may not be viable or cost justifiable.

Care and maintenance, performed by routine visual inspection, together with diagnostic testing to assess condition is the most often performed practice. Consequently, most defects of ITs are discovered during such inspections.

It is good practice to avoid regular intrusive maintenance where possible. For paper-oil ITs, risks are attached to regular oil sampling and attention must be paid to strict control of oil sampling to avoid contamination of the oil volume. Reduction of the IT oil below the limits prescribed by the manufacturer is prohibited. Local practice and the condition and age of the equipment determine the period of oil sampling. Older and suspect families may require more sampling.

Difficulty has been experienced with on-site tests for partial discharge and tan δ testing. Utility practices vary, and periodicity of off-line tests and assessments are at the experience of the user. Tan δ and IR tests of MVTs are not standardised and the test connection and applied measurement voltage must be considered with the manufacturer. On-site monitoring of SF_6 filled ITs is restricted to gas leakage and gas condition monitoring. Resin ITs appear to attract almost no condition assessments.

On-line condition monitoring techniques for CTs are not mature although a number of trials are in progress. For CVTs, continuous secondary voltage monitoring has been successfully applied. For MVTs some utilities report failures saved by free gas detectors. However, the cost of on-line monitoring equipment is significant and widespread continuous monitoring may not be justifiable except in certain circumstances. Thermovision surveys have successfully found overheating problems in CVTs.

Appendix 1: Comment on Factor of Construction, F_c

According to the IEC 60044-6 Factor of Construction, F_c is defined from the ratio:

$$F_c = \frac{U_{alc}}{E_{alc}} \qquad (1)$$

where :

U_{alc} - equivalent secondary accuracy limiting voltage defined as r.m.s. value of sinusoidal voltage of rated frequency if applied to the secondary winding of a current transformer, with open primary winding, would result in an exciting current corresponding to the maximum permissible error current

E_{alc} - equivalent secondary accuracy limiting e.m.f. defined as r.m.s. e.m.f. of rated frequency determined during a direct test when the observed error current corresponds to the maximum permissible error current.

It must be mentioned that the error current is an absolute and an unique value based on specified primary symmetrical short-circuit current value what means that U_{alc} is, for a given transformer, constant value.

According to the given definition, determination of Factor of Construction is as follows:

1. During the direct type test, error current and secondary voltage integral have to be measured (Figure A1.1. and Figure A1.2.)

2. The accuracy limiting secondary exciting current I_{al} is calculated from equation

$$I_{al} = 0.1 x \sqrt{2} x I_{sn} x K_{ssc} \qquad (2)$$

For example:
If rated secondary current is 1 A and rated symmetrical short-circuit factor equal to 20 then I_{al} equals 2.83 A.

3. The time when the accuracy limiting secondary exciting current I_{al} is reached can be read from error current oscillogram (for our example see Figure A1.1).

4. At the same instant, from corrected measuring values of secondary voltage integral corresponding to accuracy limit flux M_{alc} can be read (for our example see Figure A1.2).

5. From that number equivalent secondary accuracy limiting e.m.f. E_{alc} can be easily calculated by formula:

$$E_{\mathrm{alc}} = 2\pi f \times \Phi_{\mathrm{alc}} / \sqrt{2} \qquad (3)$$

6. With the rated power frequency voltage, U_{alc} has to be to found out.

7. Using equation (1) Factor of Construction F_c can be easy calculated

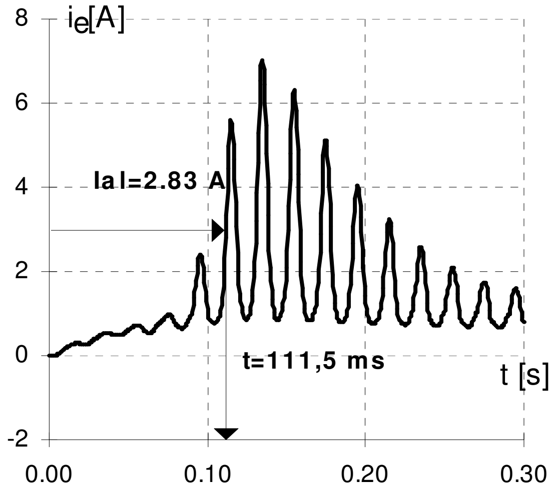


Figure A1.1: This needs a title

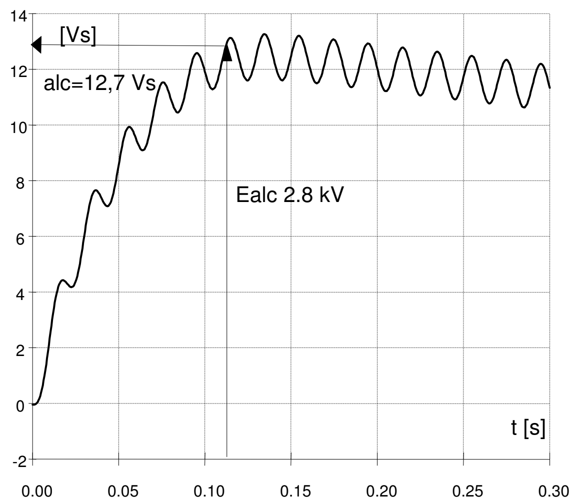


Figure A1.2: So does this!

During the routine test, Factor of Construction F_c determined in this way is used as factor by which rated equivalent excitation limiting secondary voltage U_{al} has to be multiplied. At so obtained voltage $F_c \times U_{al}$, the magnetising current from secondary side excited current transformer, should be less than accuracy limiting secondary exciting current I_{al}.

Appendix 2: The Second Survey and Supplementary Survey Questionnaires

CIGRE WG 12.16 INSTRUMENT TRANSFORMER FAILURE REPORT

Important Note: If a specific question cannot be answered with complete accuracy then the best answer possible will suffice rather than leaving the item blank.

COUNTRY:

UTILITY: REPORT No. [ ][ ][ ]

DATE OF FAILURE: [Year / Month] 19_____ / _________

TYPE OF FAILURE:

(1) Major Failure (Catastrophic - violent explosion) emergency system outage.

(2) Minor Failure (Non-catastrophic - loss of function) requires urgent system outage.

(3) Defect not resulting in major or minor failure but still requires planned system outage. .... [ ]

TYPE OF TRANSFORMER:

[(1) CT; (2) MVT; (3) CVT; (4) CombTx] [ ] **Rated Voltage kV** [ ][ ][ ]

TRANSFORMER CHARACTERISTICS:

Year of Manufacture: _________ **Years in Service before failure** : ___________

Type of Tank used:

[(1) Live Tank; (2) Dead Tank; (3) No Tank (all secondary cores within porcelain)].. [ ]

Primary Arrangement:

For CT's (1) Hairpin; (2) Eye Bolt; (3) Bar Primary; // (A) Single Turn; (B) Multiple Turns;
For MVT's (1) Single Primary; (2) Cascade Primary; (3) Double Cascade;
For CVT's (1) Single Capacitor Section; (2) Multiple Sections; (3) Christmas Tree Type;
For Comb.Tx's - CT arrangement (from above) // VT arrangement (from above) ;.................. [ ]

Major Insulation :

[(1) Oil-Paper; (2) Oil-Paper-Film; (3) All Film - Oil; (4) Resin; (5) SF6 Gas; (6) Other] .... [ ]

Fluid Insulation (if any):

……………………………………………………………………………………….

[(1) Mineral Oil; (2) Synthetic Oil] ....

{Brand or type of Mineral or Synthetic Oil used if known ....} [ ]

SPECIAL TESTS: These questions are asked so we can examine whether instrument transformer performance is being improved by the application of special Type and Routine tests, additional to the IEC Standards.

- Has this design been subjected to any special Type Tests at Factory or other Testing Institute, (for example has DGA been used to prove performance during type tests; or the 600 chopped lightning impulse test for CTs - linked to disconnector high frequency induced failures; or combining switching impulse and power frequency partial discharge tests; or a test to prove the design is "explosion proof")

[Do not know / No / Yes - give details] ....

....

- Has this equipment been subjected to any special Routine Tests at Factory or Testing Institute.

[Do not know / No / Yes - give details]

....

....

TYPE OF MONITORING USED PRIOR TO FAILURE (more than one may be chosen) :

[(1) Regular Visual Inspection ; (2) Thermovision Inspection ; (3) Oil Level Indicators ; (4) Pressure Gauges ; (5) Dissolved Gas Analysis of Oil ; (6) Acoustic Measurements ; (7) Secondary Voltage Monitoring ; (8) Partial Discharge Measurements ; (9) Tan delta Measurements ; (10) Nothing at all ; (11) Leakage Current Monitoring ; (12) Moisture Content ; (13) Oil Quality ; (14) Other Techniques, give details…………………………………………………………………………………………………….. [ ]

HOW FAULT DETECTED:

[(1) System trip; (2) Monitoring system alarm; (3) Unplanned site visit; (4) Planned maintenance; (5) Failure of similar equipment; (6) Other, give details]

....……………………………………………………………………………

CAUSE OF FAILURE: (Choose only the primary cause of the failure)
[(1) Design Fault ; (2) Lightning ; (3) Inadequate Quality Control during Manufacture ; (4) Abnormal Service Conditions ; (5) Ferroresonance ; (6) Capacitance energy discharge ; (7) Earthquake ;
Moisture Ingress ; (9) Oil Leak ; (10) Gas Leak ; (11) Failure of Adjacent Equipment ; (12) Ageing ; (13) Operation outside Specification ; (14) Environmental Conditions outside Specification ; (15) Inadequate Maintenance ; (16) Damage to porcelain insulator ; (17) Corrosion ; (18) Unknown Reasons ; (19) Other Reasons - give details]
....…………………………………………………………………………………………….

ACTION TAKEN ON FAILED UNIT:
[(1) Removed from service & scrapped; (2) Repaired & returned to service (3) Other Action, provide details]..................……........……........
……
…………….

OTHER UNITS OF SAME DESIGN:
- Were families of instrument transformers similarly affected [Yes / No]
- Numbers of instrument transformers removed from service as a result of this one type failure ...

AS A RESULT OF THIS FAILURE WAS ANY ACTION TAKEN BY THE UTILITY TO CHANGE MAINTENANCE PHILOSOPHIES [Do not know / No / Yes - give details]
....

AS A RESULT OF THIS FAILURE WAS ANY ACTION TAKEN TO CHANGE PURCHASING SPECIFICATIONS, THE DESIGN OR FACTORY TEST REQUIREMENTS [Do not know / No / Yes - give details]..

REPORT PREPARED BY : DATE :

Important Notes :

1. *Within this Survey the term Major Failure is defined as a catastrophic explosive failure which results in an emergency system outage, and the term Minor Failure is defined as a non- catastrophic loss of function failure which requires an urgent system outage.*

2. If a specific question cannot be answered with complete accuracy then the best answer possible will suffice rather than leaving the item blank.

1. **COUNTRY**:……

2. **UTILITY**:…….

3. **Has your utility responded to the Failure and Population Survey {WG 12.16 (Galea) 04}** -- [Yes / No]

4. **Approximately how many Major Failures of Instrument Transformers have occurred within your utility over the past 5 years**

   [(1) No Failures at all
   (2) On average between one and two per year
   (3) On average between three and five per year
   (4) On average between five and ten per year
   (5) On average more than ten per year]...

5. **Comparing your Utility's Major Failure Rate of say twenty years ago, ten years ago and say the last few years, has the Major Failure Rate**
   [(1)Increased; (2)Decreased; (3)Stayed the same; (4) Do not know]..

6. **Comparing your Utility's Minor Failure Rate of say twenty years ago, ten years ago and say the last few years, has the Minor Failure Rate..**
   [(1)Increased; (2)Decreased; (3)Stayed the same; (4) Do not know] ....

7. **As some utilities have experienced on average more than ten Major Failures per year, can you identify why your Utility's Major Failure rate is lower** (if more than one answer is chosen, put in order of high priority first) ; [(1) Do not know; (2) Better and more detailed Purchase Specifications used; (3) Requested more Type Tests that required by IEC - give details; (4) Required more Routine Tests than required by IEC - give details; (5) Purchased from only limited number of approved manufacturers; (6) Only purchased well proven mature designs; (7) Enforced higher Quality Standards on manufacturers; (8) Improved level of In-service Monitoring systems has identified units to be removed before they fail; (9) Other Reasons - give details …………………………………… ………………………………………………………………… …

8. **Has your utility introduced any recent changes (within the last five years) to specifically further improve the reliability of Instrument Transformers, that is to reduce both Major and Minor Failures.** [Do not know / No / Yes - give details (1) Improved purchase specifications ; (2) Increased manufacturer's factory warrantee period ; (3) Changed the type of designs or constructions purchased - give details; (4) Introduced design accreditation system before allowed to Tender; (5) Changed manufacturers or became more selective on who to accept; (6) More Type Tests required to be performed ; (7) More Routine Tests required to be performed; (8) Improved Quality requirements from manufacturers; (9) Improved maintenance strategies for instrument transformers; (10) Developed more effective in-service monitoring systems to detect incipient faults ; (11) Other, give details] ……
   ....

9. **With respect to the changes outlined in question 8 above, have you noticed any improvements in the reliability of the equipment purchased. ....**
   [Yes / No / Too early to tell / Do not know]

PREPARED BY: DATE:

Appendix 3: Aging Stresses and Processes

The stresses and environmental conditions responsible for the degradation of ITs have been reviewed in various papers and are described briefly here. The following discussion often makes reference to paper-oil insulation systems which are used in most ITs in operation today (see Chapter 4). However, it can be used for other components/insulation systems with some modifications.

Thermal Stress

Heat is produced mainly through ohmic heating of the current carrying conductors and the magnetic (hysteresis and eddy current) losses in the iron cores. For a good new insulation system, the dielectric losses (dissipation) are relatively small. However, with aging the dielectric losses increase and may become very large just before the failure of the insulation system.

Thermal aging or degradation is produced by various physico-chemical reactions in the insulation system. In paper-oil insulation [27-29], high temperatures cause scission of the polymer chains of cellulose molecules in paper, and oxidation and decomposition of oil molecules. The result is a reduction in the degree of polymerization (DP) and mechanical strength of paper, and production of many reaction by-products, including gases (carbon monoxide, carbon dioxide, hydrocarbons) and water molecules. Various furfuraldehydes, collectively called furans, are a specific product of the thermal degradation of paper. Also high temperatures may cause increased polymerization of oil molecules, producing sludge that reduces the efficiency of oil as a thermal convective medium.

Thermal stress may also have an indirect effect on the degradation of the insulation system. Different coefficients of thermal expansion for different components and different temperatures in different parts of the same component produce mechanical stresses. In paper-oil, gases generated by thermal degradation or vaporization of water molecules may produce bubbles or voids and initiate partial discharges in the presence of operating electric fields.

Thermal aging of insulation systems has been studied since 1930 [30]. In 1948 Dakin recognized that thermal degradation results from chemical changes and used a relation similar to Arrhenius equation to describe the rate of thermal degradation [31, 32]. Also the thermal aging rate is significantly increased by the presence of impurities, specially water, oxygen, and metallic ions. [29]

Electrical Stress

The insulation system has to withstand electrical stresses produced by the operating voltage as well as transient voltages with relatively short duration but magnitudes much higher than the normal operating voltages. The electrical stresses age the insulation system through complicated electro-chemical reactions. The aging of insulation system under electrical stress E is often expressed through two empirical formulas [33, 34], an inverse power law $t = A\ E^{-n}$, and the exponential law $t = B\ e^{-CE}$. (t is the life of the insulation system under stress E; A, B, C and n are constants for the insulation system.) These relations are normally applicable for all insulation systems. However, the values of the constants vary over wide range for different insulation systems and even for the same insulation system in different designs. The above relations are best applied for the estimation of life of the bulk insulation system under electrical stresses close to the normal operating value.

In addition to the bulk aging of the insulation system described above, the electric stress may produce partial discharges in the insulation system where the local electrical stress may exceed the local dielectric strength. In some cases the dielectric strength may decrease from local fast degradation of the insulation system, for example near the hottest spot in a transformer. On the other hand the local stress may be enhanced by the presence of sharp points on the conductors or by the generation of small gas volumes or voids, or by transient overvoltages. The transient voltages may be produced by power system overvoltages, lightning, switching of the equipment or other closely connected devices, and/or failure or reclosure of other equipment connected to the same power bus. Transient voltages may have magnitudes up to 3 pu and frequencies in 100 kHz-10 MHz range. High frequency overvoltages can produce local discharges in LV and HV shields and also damage secondary windings (between turns). Once initiated under the transient overvoltages, the partial discharge activity may continue under normal operating voltages at the damaged sites.

Partial discharges degrade paper and oil and the degradation products are gases and 'X'-wax molecules. If the gases are dissolved in oil or diffuse to areas of lower electrical stress, the pd activity may stop. If the products of partial discharge activity are not removed from the site by diffusion or dissolution, they may accelerate further the pd activity resulting in degradation of the insulation system at a relatively faster rate. The level of pd activity and the rate of degradation of the insulation system depend on various factors like electrical field, gas solubility in oil, temperature and pressure.

In general, under partial discharges, synthetic polymeric materials degrade at a much faster rate than the paper-oil insulation system.

Mechanical Stress

ITs are subjected to mechanical stresses in service. The electromagnetic forces between different current carrying conductors in an IT produce mechanical stresses. Changes in temperature of the transformer with changes in ambient conditions and in load produce differential expansion and contraction of different components resulting in large mechanical forces. Large system fault or short circuit currents also subject an IT to electromagnetic forces which can sometimes affect the structural integrity of the unit [35]. Excessive mechanical stresses cause damage to structural parts as well as to the insulation system of the equipment.

Environmental Stress

The insulation system as well as other components of ITs are degraded by the environmental conditions in service. Humidity and pollution may compromise the integrity of insulators. Organic materials are prone to degradation by exposure to UV radiation, oxygen and ozone, nitrogen oxides, humidity and industrial pollution. Corrosion affects metallic components. Various seals including gaskets may become brittle after long exposure to ambient conditions. The insulation systems have many impurities, which are either natural (like lignin in paper) or added during manufacturing to modify properties (like anti-oxidants in oil, fillers in resin). Some dissolved metallic ions and metallic and non-metallic particles may also be present. Moisture and other gases may ingress into the insulation system from the environment. The insulation system will also contain various products from the degradation process. These contaminants may reduce strength of the insulation system (like moisture or metallic particles) or may participate directly in chemical reactions causing degradation of the insulation system (like oxidation in presence of oxygen). Some contaminants may speed up the rate of chemical degradation indirectly under suitable conditions. For example, the presence of excessive moisture enhances the rate of thermal degradation of paper very significantly [27,29].

Combined Stresses

In a transformer in service, the insulation system is rarely subjected to a single stress. Almost always the thermal, electrical, mechanical, and environmental (contamination) stresses are present simultaneously. Often the presence of one stress may influence the aging process caused by another stress quite significantly. Because of the synergetic effects of different stresses, the aging of any insulation system under multiple stresses is quite complicated. No easy and acceptable relations are available to explain the multi-stress aging of insulation systems.

Most Important Stresses for Different Types of ITs

A particular stress may be more degrading, and hence more important, for one type of insulation system than for others. For example, overheating and moisture degrade the paper-oil insulation very quickly. Partial discharges created by temperature inversion may be more important a factor for units with gas cushions than for other units. For resin insulated ITs, the thermal stresses are the most important as they tend to produce micro cracks through differential expansion and contraction of various components. For SF_6 insulated systems, the important degrading factors are moisture and metallic particles.

In Service Failure Scenario

In service an insulation system ages slowly for many years. When the insulation degradation reaches a critical stage, the degradation products may accelerate the aging process leading to a runaway condition and eventual failure of the insulation system. For example, initially the moisture in paper in new transformers is below 0.5 % by weight. Slow aging in service (and possible diffusion of moisture from environment in some transformers) may gradually and slowly increase the moisture content in paper. If the moisture reaches a critical value, the degradation rate under thermal stress increases very significantly [27-30]. More moisture causes higher dielectric losses. This may lead to more heating of paper, producing more water and more heating. If free gas bubbles are formed in the process, partial discharge may also be initiated. The pd activity may further degrade paper and oil, producing more water and gases. If the products of degradation move or diffuse away from high stress areas, the rate of the degradation process may remain constant or even decrease. At some stage the degradation process may become self- accelerating. The runaway condition may lead to a rapid failure of insulation. In some cases, the final failure of paper-oil insulated equipment may be preceded by a quick buildup of excessive pressure [36, 37] in the porcelain insulators, resulting in an explosion. Such explosive failures have been experienced in instrument transformers [38].

Normal aging of the equipment (and the bulk insulation system) under service conditions is a relatively slow process and the equipment is expected to provide reliable service for 25 to 40 years. However, in some cases the equipment fails prematurely because of the fast-localized degradation in some critical region of the insulation system. This may be caused by some initial local weakness or manufacturing defect in the insulation system or local enhancement of stress (e.g., by metallic particles, bubbles, sharp points, blockage of oil flow path), or under high frequency transient voltages. A premature failure is often a relatively fast process caused by localized degradation as compared to normal failures caused by slow aging of the bulk insulation system.

Bibliography

1. CIGRE 23.07, Report 57; the Paper-oil Insulated Measurement Transformer, 1990.
2. H.J. Vorwerk : Service experience gained with instrument transformers 100 kV and conclusions. SEV Bulletin, vol. 72 (1981) No 1, pp. 27-34.
3. P. Matthiessen and U. Weigel : Voltage transformers for high voltage switchgear with capacitive dividers and electronic instrumentation amplifiers. SEV Bulletin, Vol. 71 (1980), No. 9, pp. 450-455.
4. P. Minder : Operation reliability of high voltage instrument transformers. SEV Bulletin, Vol. 76 (1985), No 9, pp. 509-512.
5. CIGRE WG 22.10 : Technical basis for minimal requirement for composite insulators. Electra No 88, May 1983, pp. 89-114.
6. CIGRE WG 23.03 : Nouveaux principes de mesure du courant, de la tension et divers aspects de leur application aux postes blindés, Electra, No 121, pp. 70-75.
7. M. Paris, C. Caillot, J. Perret : Tenue aux intempéries et au rayonnement U.V. des matériaux isolants. Journées d'études SEE, Isolants électriques. 6-7/3/1985 Gif-sur-Yvette.
8. CIGRE 34.03 : Non conventional current and voltage transformers, Electra No 59, pp. 91-122, 1978.
9. EPRI EL-5431 : Optical Power Line Voltage and Current Measurement Systems, Vol. 1 and Vol. 2, Project 2748, Sept. 1987.
10. M. Gailly, H. Chorel : Les réducteurs de mesure et les perturbations à fréquence élevée. Revue Générale de l'Électricité, no 10/1979.
11. R. Amsinck, Entladung von Hochspannungskabein über induktive metall-gekapselte Spannungwandler, Electrizitatswirtschaft-80 (1981), 950-955.
12. IEC, TC 17 A (Sec) 174 : Draft, Guide for Seismic Qualification of High Voltage Alternating-Current Circuit-Breakers.
13. Guide for Seismic Design of Substation Equipment, Japan Electric Association Guide : JEAG 5003-1980.
14. CIGRE WG23.07: The paper-oil insulated Measurement transformer, Brochure no. 57, 1990.
15. IEC Publication «IEC 60044-1: Instrument Transformers - Part 1: Current Transformers".
16. IEC Publication "IEC 60044-2: Instrument Transformers - Part 2: Inductive Voltage Transformers".
17. IEC Publication 60044-3 "Instrument Transformer Part 3: Combined Transformers".
18. IEC Publication 60044-6 "Instrument Transformer Part 6: Requirements for protective current transformers for transient performance".
19. IEC Publication 358 "Coupling capacitors and capacitive dividers", 1990.
20. IEEE Std C57.13,1993 "IEEE Standard requirement for Instrument Transformers".
21. ANSI C 93.1-1990 "American National Standard for Power-Line Carrier Coupling Capacitors and Coupling Capacitor Voltage Transformer (CCVT) requirements".
22. Poljak, B. Bojani_ : A contribution to explanation of behaviour of HV current transformer in service. IEEE/PES Winter Meeting, New York, 1991, 91WM023-2PWRD.
23. Korpanay: Problematische Stromwandler-Typenprufung Bull SEV/USE 87 (1996) 1, p.39-43
24. Poljak, B. Bojani_ : Test for estimation of behavior of HV current transformer in service, IEEE/PES Winter Meeting, New York, 1991, 91WM024-2PWRD.
25. IEC 1166:1993, Guide for seismic qualification of high-voltage alternating current circuit-breakers
26. P. Aggarwal, N S Saxena, B S Sharma, Shalindra Krishan: Failure of Electromagnetic Voltage Transformer due to Sustained Over-voltage on Switching - An in depth Field Investigation and Analytical Study. IEEE: PES 81 SM 317-7
27. Febre, J., and Pichon, A., Deterioration Processes and Products of Paper in Oil Applications to Transformers, CIGRE Report No. 137, 1960.
28. Fallou, B., Synthesis of Work Carried out at LCIE on the Paper-Oil Complex, Rev. Gen. Electr., 1970, Vol. 79, pp. 645-661 (in French).

29. Shroff, D.H. and Stannett, A.W., A Review of Paper Ageing in Power Transformers, IEE Proc., Vol. 132, Pt. C, No. 6, November 1985, pp. 312-319.

30. Montsinger, V.M., Loading Transformers by Temperature, Trans. AIEE, Vol. 49, 1930, pp. 776-792.

31. T.W. Dakin, Electrical Insulation Deterioration Treated as a Chemical Rate Phenomenon, AIEE Trans. Vol. 67, 1948, pp. 113-122.

32. Nelson, W., Analysis of Accelerated Life Test Data - Part I: The Arrhenius Model and Graphical Methods, IEEE Trans. On Electrical Insulation, Vol. EI-6, No. 4, December 1971, pp. 165-181.

33. Nelson, W., Graphical Analysis of Accelerated Life Test Data with the Inverse Power Law Model, IEEE Trans. on Reliability, Vol. R-21, No.1, February 1972, pp. 2-11.

34. Kiersztyn, S.E., Formal Theoretical Foundation of Electrical Aging of Dielectrics, IEEE Trans. on Power Apparatus and Systems, Vol. PAS-100, No. 11, November 1981, pp. 4333-4338.

35. McNutt, W.J., and Patel, M.R., The Combined Effects of Thermal Ageing and short-circuit Stresses on Transformer Life, IEEE Trans. on Power Apparatus and Systems, Vol. PAS-95, July/August 1976, pp. 1275-1286.

36. Barkan, P. et al, Overpressure Phenomena in Distribution Transformers with Low Impedance Faults: Experiment and Theory, IEEE Trans. on Power Apparatus and Systems, PAS-95, No. 1, January/February 1976, pp. 37 - 48.

37. EPRI Workshop on "Failed High Voltage Instrument Transformers", Electric Power Research Institute, Palo Alto, California, September 24-26, 1990; Workshop Proceedings, EPRI TR-100205, Project 3320, January 1992.

38. H. Yoshida, Y. Ishioka, T. Yanari, T. Teranishi, and T. Suzuki, Degradation of Insulating Materials of Transformers, IEEE Trans. on Electrical Insulation, Vol. EI-22, Dec 1987, pp. 795-800.

39. P.J. Griffin, Criteria for the Interpretation of Data for Dissolved Gases in the Oil of an Insulation, STP 998, ASTM, 1988, pp. 89-106.

40. C.E. Lin, J.M. Ling, and C.L. Huang, An Expert System for Transformer Fault Diagnosis using Dissolved Gas Analysis, IEEE Trans. on Power Delivery, Vol. PWRD-8, 1993, pp. 231-238.

41. IEEE Standard C57.104-1991, IEEE guide for the Detection and Determination of Generated Gases in Oil Immersed Transformers and Their Relation to the Serviceability of the Equipment.

42. IEC Publication 599, 1978, Interpretation of the Analysis of Gases in Transformers and other Oil Filled Electrical Equipment in Service.

43. G. Gorlini, W. Mosca, M. Tellarini: The evaluation of aging conditions of High Voltage Current transformer. CESI Publication no. 76/11.

44. Bhumiwat, S., Srihatajati, S., Ageing insulation study of Instrument Transformers in EGAT System after several years in service. CIGRE Symposium, Berlin 1993, Paper 110-12

45. Bognar, A., L. Kalocsai, G. Csepes, E. Nemeth, J. Schmidt, Diagnostic Tests of High Voltage Oil-Paper Insulating Systems (in Particular Transformer Insulation) Using DC Dielectrometrics, CIGRE, International Conference on Large High Voltage Electric Systems, paper 15/33-08, 1990.

46. Bognar, A., G. Csepes, L. Kalocsai, I. Kispal, Spectrum of Polarization Phenomena of Long Time-Constant as a Diagnostic Method of Oil-Paper Insulating Systems, Proceedings of the 3rd International Conference on Properties and Applications of Dielectric Materials, pp. 723-726, 1991.

47. Darveniza, M., T.K. Saha, D.J.T. Hill, T.T. Le, Assessment of Insulation in Aged Power Transformers by Interfacial Polarization Spectrum and its Correlation with Chemical Properties, 6th International Conference on Dielectric Materials, Methods and Applications, pp. 233-236, 1992.

48. Kachler, A.J., Baehr, R., Zaengl, W. S., Breitenbauch, B., Sunderman, U., Critical Comments on the Measurement of Humidity in Transformers using the Voltage Recovery Method, Electrizitats Wirtschaft. Vol 95 (1996) no. 19 pp. 1238 - 1245

49. Allan, D., Blundell, M., Boyd, K., Hinde, D., New Techniques for Monitoring the Insulation Quality of In-service HV Apparatus, IEEE Transactions on Electrical Insulation, Vol. EI-27, No. 3., pp. 578-585, 1992.

50. E. Lemke and P. Schmiegel, Experience in PD Diagnosis Tests on Site Based on the PD Probe Technique, Report of 3rd Workshop and Conference on EHV Technology, August 2-4, 1995, IISC, Bangalore, India, pp. 199-203.

51. Cummings, H.B., J.R. Boyle, B.W. Arp, Continuous, Online Monitoring of Free Standing, Oil-Filled Current Transformers to Predict Imminent Failure, IEEE Transactions on Power Delivery, Vol. PWRD-3, No.4, pp. 1776-1783, 1988.

52. P. Vujovic, R.K. Fricker, J.A. Ehrich, and A.R. Young, Development of an On-line Continuous Tan δ Monitoring System, Conference Record of the 1994 International Symposium on Electrical Insulation, Pittsburgh, PA, USA, June 5-8, 1994, IEEE Publication 94CH3445-4, pp. 50-53.

53. Altman, M.S., Installation of Insulation Monitoring System on Free Standing Current Transformer, EPRI Workshop on "Failed High Voltage Instrument Transformers", Electric Power Research Institute, Palo Alto, California, September 24-26, 1990; Workshop Proceedings, EPRI TR-100205, Project 3320, January 1992.

54. Failure Anticipation in Oil-Paper Insulation, B.K. Gupta, Presented at, and published in the conference record of, 1984 IEEE International Symposium on Electrical Insulation, Montreal, Canada, June 11-13, 1984, IEEE Publication 84CH1964-6-EI, p 339.

55. Kawada, H., M. Honda, T. Inoue, T. Amemiya, Partial Discharge Automatic Monitor for Oil-Filled Power Transformer, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, No.2, pp. 422-427, 1984.

56. Van Haeren, R., G.C. Stone, J. Meehan, M. Kurtz, Preventing Failures in Outdoor Distribution-Class Metalclad Switchgear, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, No. 10, pp. 2706-2712, 1985.

57. Blackburn, T.R., R.E. James, Q. Su, T. Phung, R. Tychsen, J. Simpson, An Improved Electric/Acoustic Method for the Location of Partial Discharges in Power Transformers, Proceedings of the 3rd International Conference on Properties and Applications of Dielectric Materials, pp. 1132-1135, 1991.

58. Kurtz, M. and Stone, G.C., Fault monitoring by Detecting a Polarity Difference, US Patent No. 4385271, May 1983.

59. M. Kurtz, G.C. Stone, P. Daechsel, and B.K. Gupta, Fault anticipator for Substation Equipment, IEEE Trans. on Power Delivery, Vol. PWRD-2, No.3, July 1987, pp. 722-724.

60. B.K. Gupta and G.C. Stone, Partial Discharge Monitoring in Instrument Transformers, Presented at EPRI Workshop on "Failed High Voltage Instrument Transformers", Electric Power Research Institute, Palo Alto, California, September 24-26, 1990, and published in the Workshop Proceedings, EPRI TR-100205, Project 3320, January 1992.

61. Boisseau, C., T. Fortin, V. Hilario, Instrument Transformers Partial Discharges Measurement as a Monitoring Method, EDF Annual Report 1992.

62. Boisseau, C., Tantin, P., Despiney, P., and Hasler, M., Instrument Transformer Monitoring, CIGRE Symposium, Berlin, 1993, Paper 110-13

63. Belanger, G., Field Testing of Hydran 101 and 201 for Dissolved Hydrogen in Transformer Oil, Doble Conference, 1985, pp. 801-814.

64. Allen, P.H.G. and Havlicek, K., Hottest Spot Technique for Better Transformer Utilization, Electrical Review, pp. 647-650, 1974.

65. McNutt, W.J., J.C. McIver, G.E. Leibinger, D.J. Fallon, K.A. Wickersheim, Direct Measurement of Transformer Winding Hot Spot Temperature, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, no. 6, pp. 1155-1162, 1984.

66. Gupta, B.K., Field Measurement to Determine Moisture Content in Solid Transformer Insulation, Canadian Electrical Association (CEA) Project 301 T 638, Final Report, December 1993.

67. Aubin, J., Gupta, B.K., and Polovick, G., Transformer Thermal Behavior under Emergency Overloading, Canadian Electrical Association (CEA) Project 355 T 822, Final Report, November 1994.