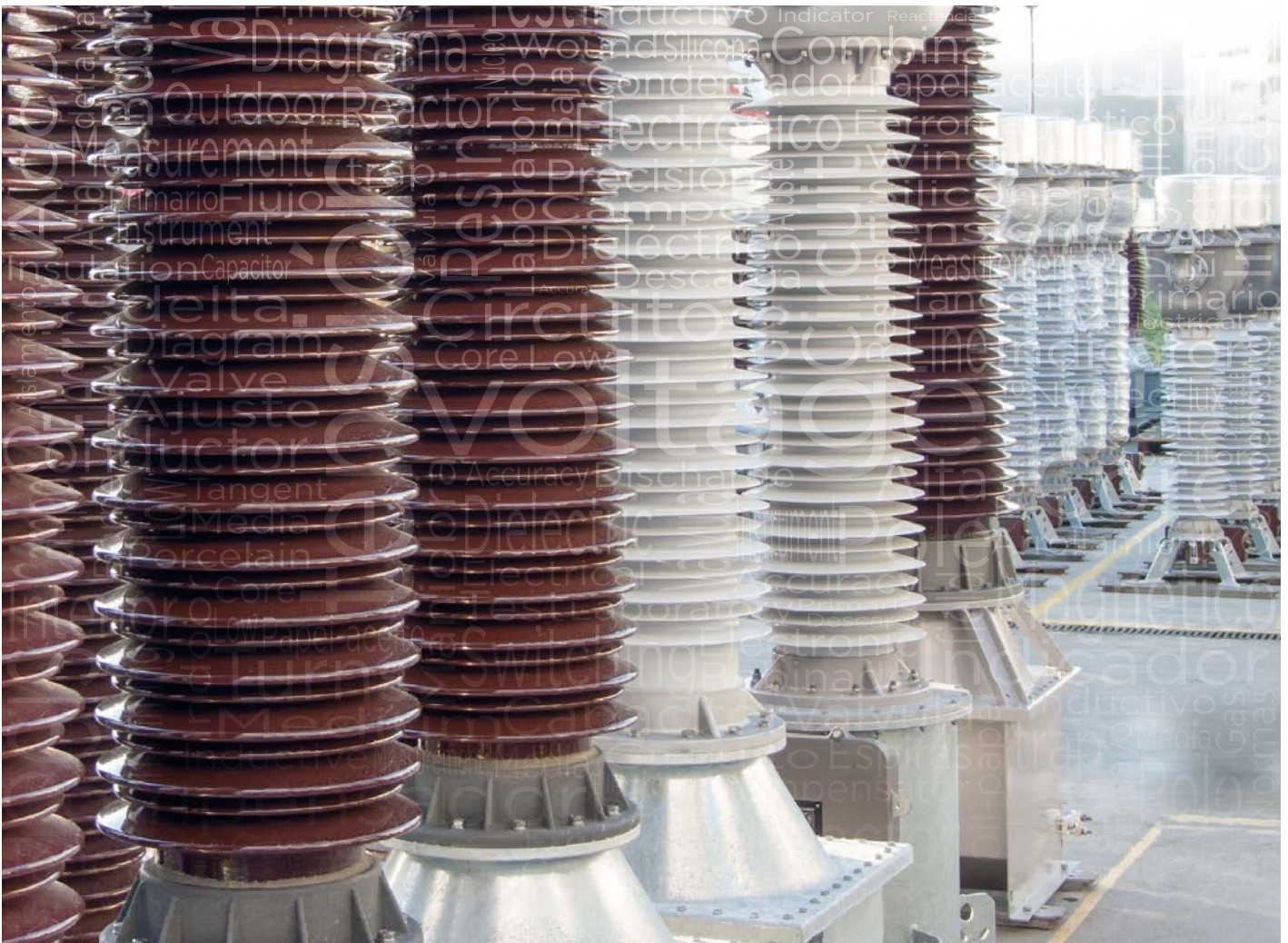


# INSULATION TECHNOLOGY IN INSTRUMENT TRANSFORMERS



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Contact ARTECHE to confirm the characteristics and  
availability of the products described here.

Jaime Berrostequieta  
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The bottom half of the page features a series of white, curved, overlapping lines that create a sense of motion and depth against the solid blue background. These lines sweep from the bottom left towards the right, with some lines curving upwards and others downwards, creating a dynamic, wave-like pattern.

# Moving together

# CONTENTS

1. Introduction | 4
2. Technical description | 5
  - 2.1. Outside Insulation | 5
  - 2.2. Oil-paper internal insulation | 6
  - 2.3. SF6 internal insulation | 10
3. Quality control & testing | 11
4. Inspection & cheking in the field | 13
  - 4.1. On commissioning | 13
  - 4.2. Checking in the field | 13
5. Conclusions | 14

# SUMMARY

Firts, the technology used nowadays to construct insulation in High Voltage instrument transformers is described. New materials are discussed as alternatives in design and likely trends for the future.

Finally, various methods are described to assure manufacturing quality and the condition of transformers in service.

## 1. INTRODUCTION

Although the main purpose of a instrument transformer (IT) is to transform accurately voltage or current to standardized levels in both transient and established regimes, if it is connected to a high voltage line its electrical insulation function is also highly important.

Medium voltage (3.6 to 72.5 kV) must be distinguished from high voltage (72.5 to 800 kV) in terms of use and the insulation applied. The high voltage units are the main subject of this article.

There are three types of IT:

1. Current Transformers (CT) for transforming the current on the line to which they are connected in series (fig. 1).
2. Voltage Transformers, which may be magnetic (MVT) or capacitive (CVT) used to transform the voltage between the line and earth (fig. 2 & 3).

3. Combined Transformers (KT) made up of one CT and one MVT (fig. 4). Insulation differs considerably between these types, so they are analyzed separately here.

The IT is a static unit which in principle needs no maintenance throughout its lifetime, which may be as long as 25 years. However it is hard to know the condition of a IT, so that if it fails it does so unexpectedly and sometimes violently.

There has therefore been intense work recently aimed at finding ways of learning the status of the main insulation on these units.



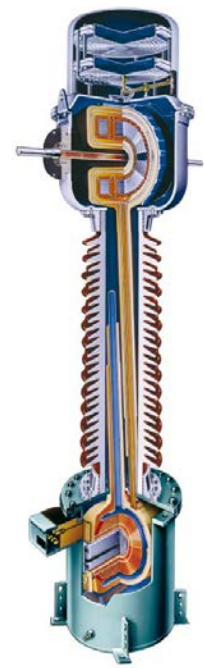
› Fig. 1. Current transformer



› Fig. 2. Inductive voltage transformer



› Fig. 3. Capacitive voltage transformer



› Fig. 4. Combined transformer



## 2. TECHNICAL DESCRIPTION

The appearance of epoxy type synthetic resins enabled the same material to be used for inside and outside insulation of medium voltage, indoor ITs (figs. 5).

Later, cycloaliphatic resins and materials such as butyl which behave better against surface electric arcs and UV rays enabled the same technique to be used in designs for ITs for outside use (fig. 6).

However in such cases the leakage path must be greater than that used in porcelain insulators because they are organic and therefore less resistant to the mentioned electric arcs.

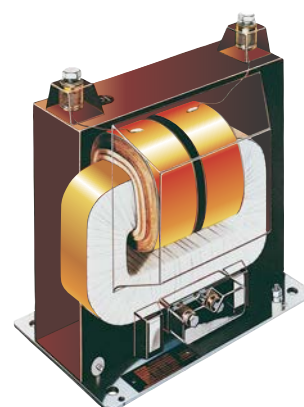
The manufacturing advantages of solid insulation can be combined with high outer strength in designs such as the one in fig. 7, where epoxy resin is combined with porcelain in a medium voltage IT.

In this case the leak-tightness of the chamber between the two parts must be ensured to prevent moisture getting in and causing an electric arc between the high and low voltage across the chamber.

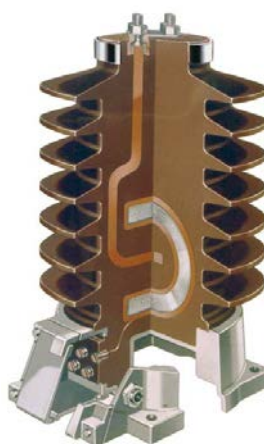
Various trials have been carried out with these materials in high voltage, but they have been found to be unsuitable for voltages of more than 72.5 kV. Oil paper is therefore still used in internal insulation, despite of the process being more laborious, and porcelain for the outside.



› Fig. 5a. Indoor current transformer; indoor service



› Fig. 5b. Indoor voltage transformer; indoor service



› Fig. 6. Current transformer; outdoor service; dry type,



› Fig. 7. Current transformer; outdoor service; epoxy+porcelain

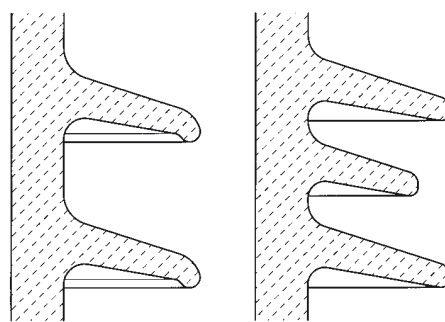
### 2.1. OUTSIDE INSULATION

As indicated above, porcelain is normally used for insulation at high voltages. To a lesser extent polymer insulators, with glass fiber body and silicone sheds, are used.

The sheds are either all the same or alternate (fig. 8) with leakage paths of 20 mm/kV for average contamination and 31 mm/kV for heavy contamination. IEC standard 60815 goes into this matter in depth.

In the new designs the diameter of the porcelain parts has been reduced, with which the flashover voltage is increased, especially in the case of heavy pollution. By reducing the volume of oil the effects of any explosion and subsequent fire are also reduced.

Cemented flanges allow for much higher work coefficients in porcelain than clamps and enable excellent mechanical characteristics to be obtained in spite of the small diameter.



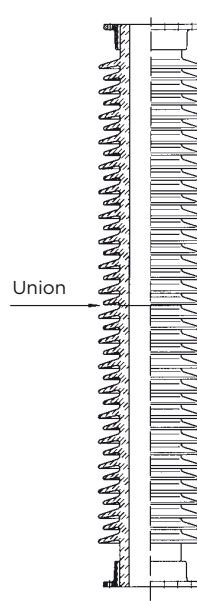
› Fig. 8. Porcelain sheds

## 2. TECHNICAL DESCRIPTION

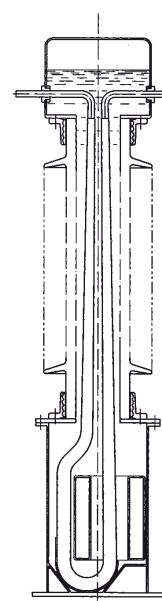
If the porcelain parts are very tall, they may need to be made in separate parts and then joined by ceramic adhesion (re-baking) or with epoxy glue (fig. 9).

When ITs are installed at altitudes of more than 1000 m above sea level, it must be taken into account that the lower air density makes it less electrically rigid, and taller porcelain units are needed to withstand the same voltages. Since the internal insulation is not affected by this problem, it does not need to be oversized. If the outside insulation is to be checked in a laboratory at normal altitude a reinforced prototype must be built so that higher voltages can be applied.

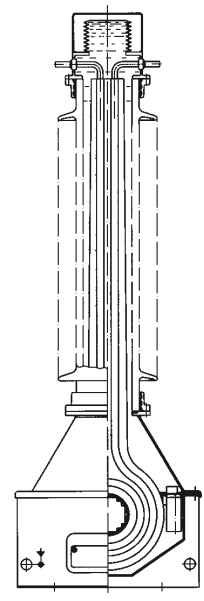
This is expensive: an alternative is to test the flashover voltage of the insulator, since this is not affected substantially when the internal parts are fitted.



› Fig. 9. Bonded porcelain



› Fig. 10. Hair pin type C.T.



› Fig. 11. Needle type C.T.

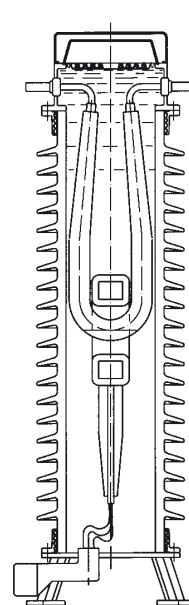
## 2.2 OIL-PAPER INTERNAL INSULATION

### A. MAIN INSULATING ELEMENT

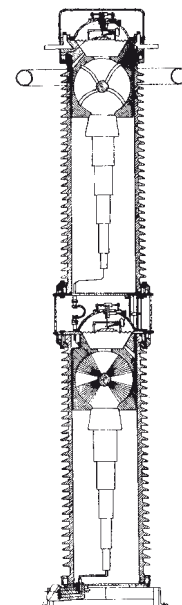
It consists of oil paper insulating assembly between the high and low voltage electrodes or screens.

In CTs this insulation can be on the primary, on the secondary or partly on each. If it is on the primary it can be hairpin type (fig. 10) with the primary having the appearance of an insulated cable, or needle type (fig. 11).

These are usually known as “dead tank” models, with those having the insulation on the secondary (fig. 1) being known as “live tank” models. Models with insulation shared between primary and secondary are seldom used (fig. 12).



› Fig. 12. Intermediate type C.T.



› Fig. 13. Cascade C.T.

Cascade type CTs (fig. 13) are a special case. Two CTs of one of the types indicated above are connected in series, with each bearing half the voltage. This voltage sharing is a function of the capacities of the transformers (500-1000 pF) and may vary due to strays or leakage current if there is heavy pollution.

## 2. TECHNICAL DESCRIPTION

Kraft and/or capacitor type paper is used. It is overlapped so that no easy paths are provided for electric arcs. There should be no gaps, because after impregnation they will contain only oil, with a dielectric constant which is half that of oil paper. This will lead to a big increase in gradient in an area which is already electrically weak.

MVTs can be made up of a single coil (fig. 2) or several coils on a single core (fig. 14) or on several cores (fig. 15). In this case voltage sharing is guaranteed inductively by auxiliary windings in each core and between cores.

Fig. 16 shows the construction of a MVT coil with sheets of 0.04 mm capacitor paper placed between the turns of fine copper wire so that capacitive and inductive voltages are maintained at different frequencies.

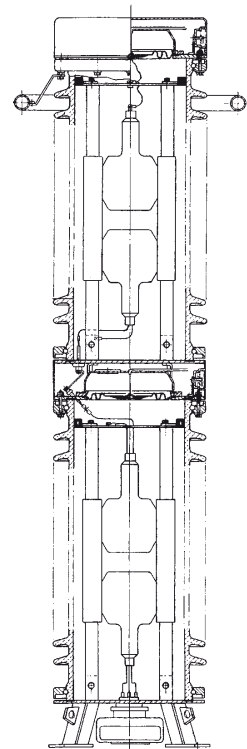
Since the distance between layers of the wire is small, the working gradients of the insulation are far higher than those used in CTs, and can be as much as half the levels used in CVTs.

The CVTs insulation comprises of flat capacitor units connected in series, fitted inside the porcelain. Each unit is made by winding two sheets of aluminium and various sheets of paper on a cylindrical mandrel and then impregnating them with mineral oil (fig. 17). Polypropylene is also used with a sheet of paper to improve the impregnation of the whole assembly. With polypropylene the value of  $\tan \delta$  of the capacitor is reduced considerably.

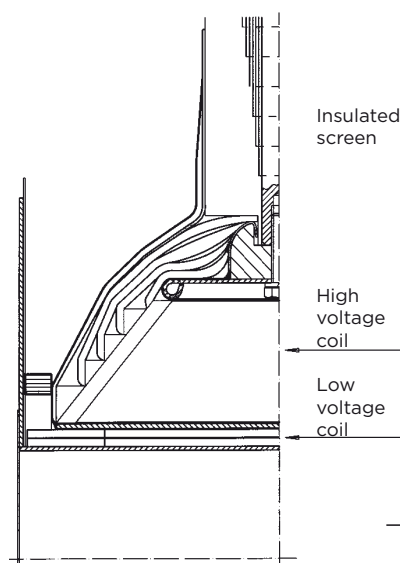
However, bear in mind that MTs age due to partial discharges and not thermal effects, the significance of the value of  $\tan \delta$  relative and is only comparable when the same materials are used.



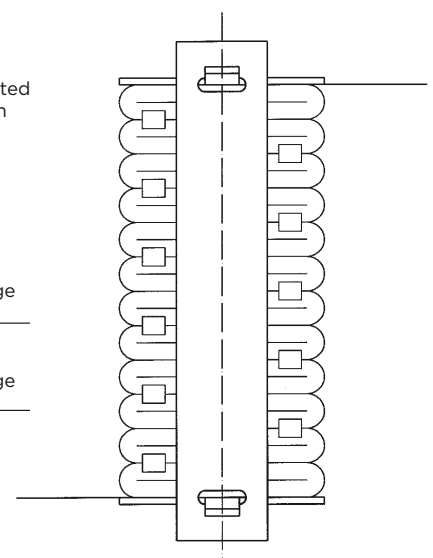
➤ Fig. 14. Cascade M.V.T.



➤ Fig. 15. Cascade M.V.T.



➤ Fig. 16. M.V.T. coil



➤ Fig. 17. Capacitor stack

## 2. TECHNICAL DESCRIPTION

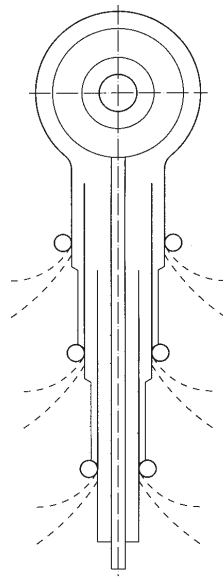
### B. TRANSITIONAL AREA

This is the gap between the high and low voltage electrodes along the surface of the main insulator in contact with the oil. If this area is properly designed the flashover voltage can be raised both inside the MT and in the air. Normally screen electrodes (fig. 18) or capacitor screens (fig. 19) are used.

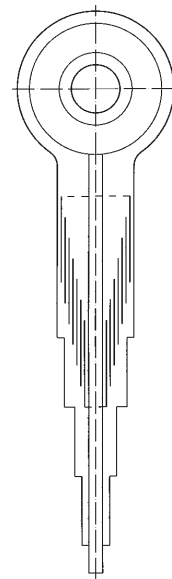
With the first of these systems less screens are used, but they must have rounded ends to reduce the axial gradient.

When capacitor screens are used, similar to those used in bushings, it is advisable to use a high number of screens to reduce the edge effect.

In some cases, it is necessary to interpose short screens, that don't affect the capacitive voltage distribution, but reduce the gradient at the ends of main screens.



► Fig. 18. Rounded screens



► Fig. 19. Capacitor screens

### C. OIL COMPENSATOR

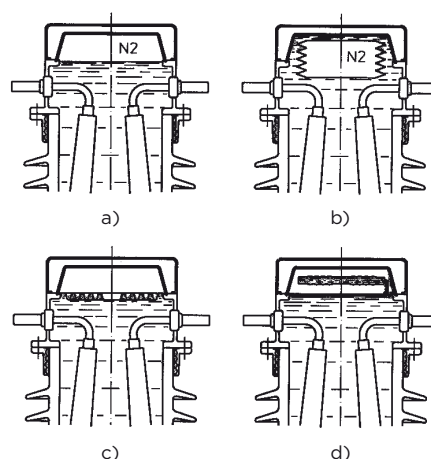
Although it is an auxiliary element in the IT, it influences decisively in the behavior of the insulation system.

ITs, like other electrical equipment, formerly used oil in contact with the atmosphere, meaning that they were saturated with gas and water. In some cases a silica gel drying filter was used, but since these filters were located in high voltage areas they were not changed and after a while became ineffective.

This design is valid up to a certain voltage level, provided that the insulation is properly sized, but in the case of very high voltages, e.g. 420 kV, the high level of the  $\tan \delta$  of this insulation causes considerable heating. CTs with very thick insulation are hard to cool, so the transformer may age prematurely.

At present, all ITs are built with an oil volume compensator so that the oil is not in direct contact with the air. This maintains the high dielectric characteristics of the oil paper assembly, obtained by careful manufacturing with vacuum drying at more than 0.02 Torr. for 5-15 days. In final electrical testing these ITs have not partial discharges, and their  $\tan \delta$  is lower than 0.5%.

There are many versions of compensator designs, but most are covered as shown in fig. 20.



- a. Nitrogen cushion
- b. Gas balloon
- c. Rubber membrane
- d. Metal bellows

► Fig. 20. Compensators



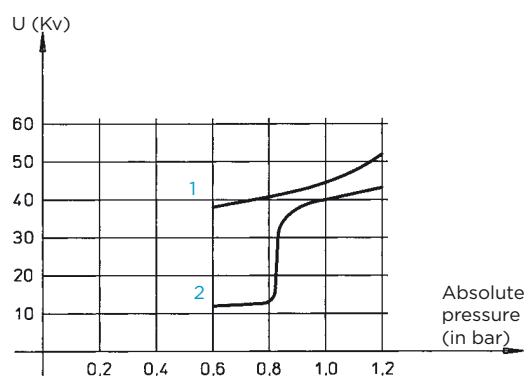
## 2. TECHNICAL DESCRIPTION

### 1. Nitrogen Cushion

The oil is saturated with gas. The amount it contains is the result from the pressure and temperature. At low temperatures the reduction in pressure causes bubbles to form in the oil. They rise to the top chamber, leading to partial discharges. Experiments have shown that in gas saturated oil with pressures of less than 0.8 bar absolute, the voltage at which partial discharges appear drops drastically (fig. 21).

To prevent this, transformers are usually built with a slight overpressure at ambient temperature (20°C). However the leak-tightness of the seals must be ensured to prevent overpressure from causing gas leaks under maximum heating conditions.

Another hazard of this design is the possibility that water lying on the surface of the transformer in contact with the seal area may get inside if the seals do not work properly, because at low temperatures there will be underpressure.



➤ Fig. 21. Inception voltage of partial discharges

- 1. Without N2 in contact with oil (cases b, c, d)
- 2. With N2 chamber (case a)

### 2. Gas Balloon

This is an improved variant of the above. The gas is not in contact with the oil and the oil is therefore not saturated.

Oil pressure also varies with temperature here, with consequential risks should the seals fail.

### 3. Rubber Membrane

In this case the oil pressure is constant due to the great elasticity of the membrane. If the correct material is used the permeability of the compensator can be reduced and oil can be kept in good condition for years.

### 4. Metal Bellows

This solution is similar to the previous one, but metal (e.g. stainless steel) is used as the elastic element.

If the compensator is built of welded plates the whole assembly is highly elastic and no pressure is produced in the oil as the volume varies. The welding is highly delicate and requires great care, because the steel involved is very thin.

In the case of bellows manufactured by shaping (no welds in the main body) pressure must be applied to make a change in volume, which means that the oil does not work at constant pressure. On the other hand, compensators of this type can deteriorate if sudden changes of volume occur at low temperatures.

## 2. TECHNICAL DESCRIPTION

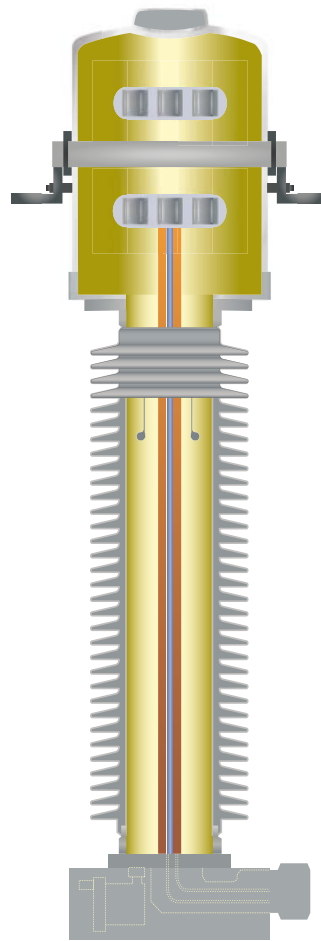
### 2.3. SF6 INTERNAL INSULATION

IT using SF6 gas as their main insulator have existed for many years.

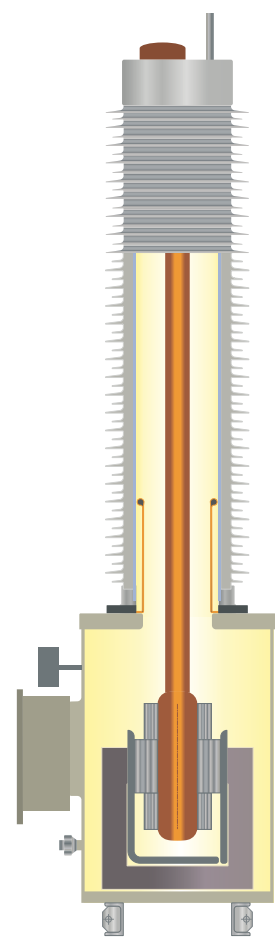
Figs. 22 shows a construction of this type, where oil paper insulation and supplementary oil have been replaced by SF6, resulting a simple assembly. An intermediate screen is used in order to optimize the distribution of the field along the insulator.

This material is well known due to its use in GIS (gas insulated substation) substations. It usually runs at 3.5 - 4.5 bar absolute, since its dielectric characteristics improve considerably with increased pressure, but care must be taken to prevent condensation from forming at low temperatures. This is important in ITs because they are installed outdoors, where they may have to contend with temperatures of -25°C or even lower.

The MVT in GIS substations are generally also insulated with SF6. The insulation between layers may be paper, but if so, proper drying must be ensured, as any moisture in an atmosphere of SF6 and electric arcs can produce corrosive compounds. For this reason polypropylene is normally used as an insulator, as it does not absorb water.



➤ Fig. 22a. SF6 insulated C.T.



➤ Fig. 22b. SF6 insulated V.T.

➤ GIS substation with voltage transformers



# 3. QUALITY CONTROL & TESTING

There are regulations governing instrument transformers (IEC 61869, IEEE C57-13, etc.) that stipulate various routine and type tests for establishing the quality of apparatuses.

However these tests must be supplemented by others to provide the best possible guarantees as to the overall manufacturing quality. ISO standard 9000 on Quality System lays down the processes or aspects of manufacturing to be tested in accordance with the selected level. These include design, documents, suppliers, process inspection and records.

Below we will discuss of some final tests whose characteristics are being studied, and some conditions that are required for ITs but not included in the standards.

## A. ROUTINE DIELECTRIC TESTING

Since a power frequency withstand test puts a strain on the transformer, there is a tendency to reduce the level but measuring partial discharges immediately afterwards, without reducing voltage to zero.

For CVTs a PD test with switching waves overlapped to power frequency is under study.

## B. LIFETIME TESTING

As indicated above thermal aging does not usually take place in ITs. However, if it is considered convenient a thermal stability test can be performed. Measuring  $\tan \delta$  after a heating test is not sufficient to check this phenomenon.

Electrical aging is caused by partial discharges, so accelerated testing must be based on voltage/time curves with the same probability of partial discharges. These curves have the following form:

$$U = C t^{-\gamma}$$

where C and  $\gamma$  are constants.

## C. HIGH-FREQUENCY TRANSIENTS

When disconnectors or circuit breakers are used, high-frequency oscillations (0.1 - 10 MHz) are produced with voltages up to 3 times the rated level. Waves of this type cause short-duration currents in TM screens of up to 1000 A, sometimes causing the transformer to fail.

To analyze the behaviour of ITs in respect of this phenomenon, IEC has a method in which at least 100 pulses chopped at the crest are applied, and the comparison with the values of gas content before and after test is analyzed.

The increases in gases dissolved in the oil are being discussed in the IEC working groups.

## D. LINE DISCHARGE

When a line is opened under no load, maximum voltage is obtained. If this is not discharged there may be an overvoltage on reconnection.

MVTs are suitable for discharging lines, since their impedance drops rapidly when the core is saturated with the transient current. However, this high current causes thermal and dynamic stresses in the winding, and can even destroy the transformer if it is not prepared to support them.

The same thing can happen to MVTs used to discharge banks of capacitors.

## E. FERRO-RESONANCE

This phenomenon is not frequent, but it is highly dangerous, as the VT is generally destroyed by overheating.

Depending on the characteristics of the circuit, ferro-resonance may be in series or parallel, though the latter only occurs in lines with an insulated neutral and is therefore not found in high voltage situations.

Apart from the well known case of CVT, ferro-resonance in series can also be found in MVTs connected to a voltage line through distributing capacitors of a circuit breaker or through the capacity between lines when one is live and the other is not.

There are ways of avoiding this phenomenon, such as the use of an auxiliary secondary in an open delta connection on a resistor.

### 3. QUALITY CONTROL & TESTING

#### F. TRANSPORTATION & SEISMIC TESTING

The number of incidents in loading, transit and unloading is important. Malfunctions may also be caused which are not detected and which cause the transformer to fail when it is put into service.

It has been shown that truck and rail transportation is harder on equipment than sea transportation, reaching values even greater than 10 g.

With this, there is the need to establish maximum values so that on one hand, we are designing the packaging that can withstand these values and on the other ensure that the transport does not exceed these accelerations. There are device indicators which could be incorporated into the packaging to verify this data.

ITs can also be mechanically destroyed by earthquakes, since they are slim and fragile. It must be calculated properly if the installation site is prone to tremors.

Various companies have established specifications which include proper design criteria as well as test. Experience has shown that ITs manufactured to those requirements can withstand major earthquakes

In some cases, especially with very high voltages, dampers may need to be used.





# 4. INSPECTION & CHECKING IN THE FIELD

## 4.1 ON COMMISSIONING

First, check the condition of the packaging and the transformers carefully on arrival at their destination. They may have suffered damaging knocks or vibrations even if the packaging appears to be in good condition.

In transformers with oil level indicators, check that they are similar to other transformers from the same batch. Also carry out a detailed inspection of the seal area, checking for oil, especially after long periods of storage.

If a CT placed horizontally develops leaks the main insulation loses its oil and the unit must not be put into service.

As to electrical checking, it is advisable to measure the insulation between secondaries and between each secondary and earth.

Finally, when voltage is applied, any unusual noise may be an indicative of a malfunction in the transformer.

## 4.2 CHECKING IN THE FIELD

### A. VISUAL INSPECTION

It is advisable to run regular visual inspections on transformers, e.g. every three months to check oil indicators, etc. and check for oil leaks. As above, check also for any unusual noises.

### B. OIL ANALYSIS

After 5 - 10 years of service, samples should be taken of the transformer oil to check its condition. This can be checked via dissolved gas, tg  $\delta$  and moisture tests.

By analyzing the gases dissolved in the oil, the condition of the transformer can be known, and the causes of any deterioration. Usually  $H_2$ ,  $CH_4$ ,  $C_2H_4$  and  $C_2H_6$  are measured, though in ITs the most important are  $H_2$  (which indicates the presence of low energy partial discharges) and  $C_2H_4$  (which indicates larger electrical discharges).

This method is widely used in power transformers, but it has been shown that the same criteria cannot be used for ITs, as the results depend largely on the type of construction. Research is ongoing regarding this matter, and it is hoped that the phenomenon will be better known within a few years. As a guideline, the limit levels for dissolved gases in ITs are indicated in the IEC 60599 standard.

Experiments are being done to facilitate this test by placing detectors inside ITs, and the possibility of continuous monitoring is also being studied. The reason behind this is that ITs which have been in service for many years can age very quickly if partial discharges appear.

The tg  $\delta$  level of oil at 90°C indicates the degree of contamination, but is hard to relate this to the condition of the main insulation. With levels of more than approx. 6% the oil can be assumed to be in poor condition.

It is also important to measure the amount of water in the oil, as water passes from the oil to the paper, thus deteriorating the main insulation. By analyzing the oil in this way we can, even without testing the whole transformer at tg  $\delta$ , estimate whether it has become wet.

Furfuraldehyde in oil is measured to detect aging due to phenomena other than arcs. Though this is one of the parameters used in power transformers, it is not significant in ITs.

### C. ELECTRICAL TESTING

Partial discharge and tg  $\delta$  test on transformers are additional suitable means of learning the condition of the insulation, but in general they can only be performed in a laboratory.

There are portable units for measuring tg  $\delta$  at 10 kV, but the test is complicated because the ITs has to be disconnected from the line and the insulator cleaned. The measurements can vary greatly if this is not done carefully. On CTs it is advisable for an insulated connection point to be used for this test.

### D. OTHER METHODS

Thermovision equipment can be used to detect defects in the primary connections of CTs, excessive heating in CVTs, etc. This is a simple, very sensitive method and is recommended from experience.

To detect failures in condenser units of CVTs, open delta voltage can be used, as capacitor failures normally occur gradually.

Ultrasonic methods have also been tried to detect internal discharges, but at the moment the sensitivity levels attained are not sufficient.



## 5. CONCLUSIONS

The classical oil paper insulation system is still normally used in ITs. Improvements in material quality and design have enabled dielectric characteristics to be considerably improved.

New materials are being used, especially SF6 gas in ITs for GIS substations and for normal uses.

The tests laid down in standards are considered insufficient, and need to be supplemented to ensure correct transformer operation in service.

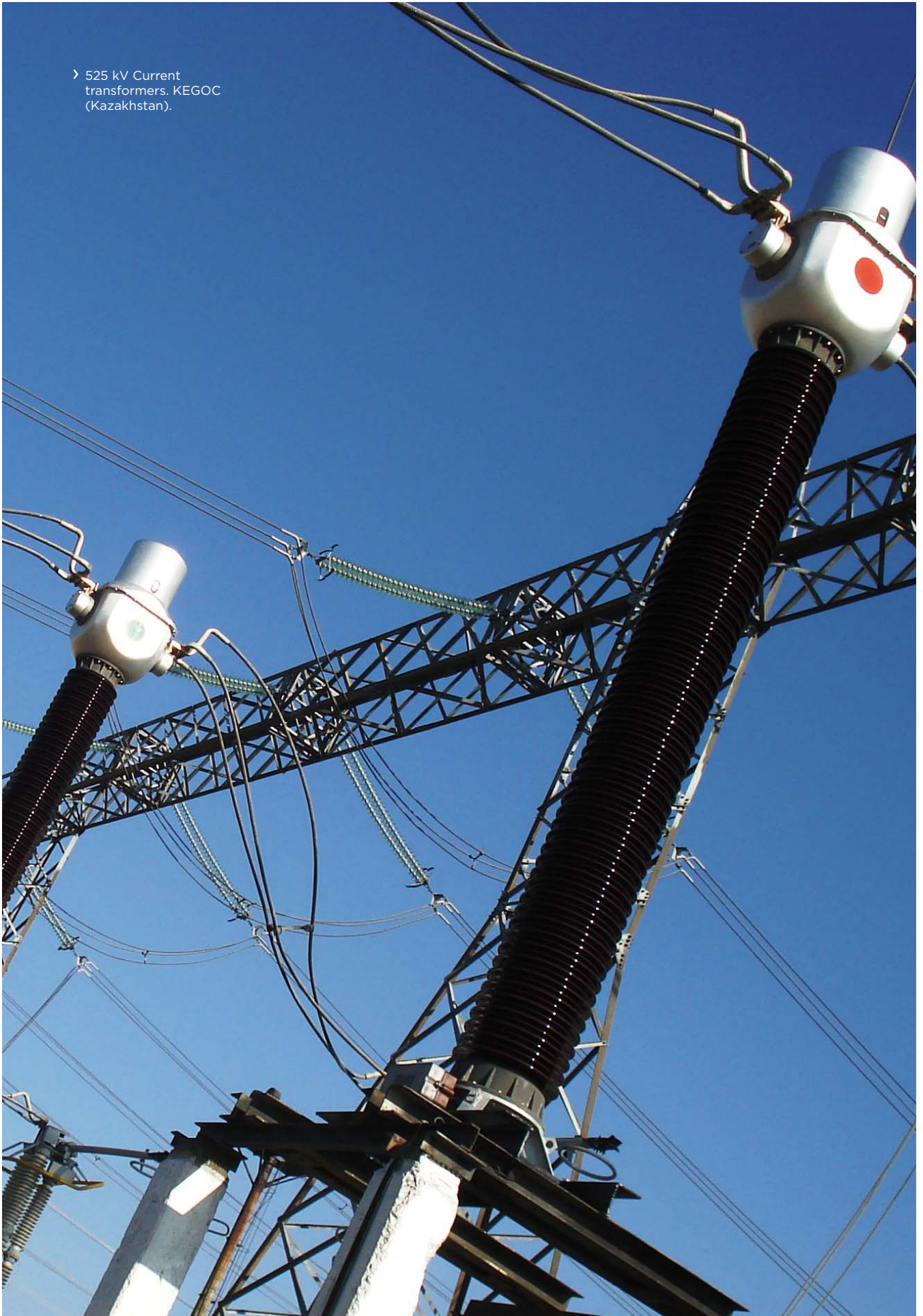
Although there are various methods to know the state of insulation in IT with many years in service, at the moment, there is no method sufficiently reliable and clear.

➤ 145 kV current and voltage transformers. Argentina.





› 525 kV Current  
transformers. KEGOC  
(Kazakhstan).





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