TRANSFORMER INSULATION

This article introduces the electrical insulating systems adopted in power and instrument transformers, with particular reference to their types, the choices of the constituent materials, their short- and long-term behavior, and the design criteria. The definition of an electrical insulating system as per the IEC (International Electrotechnical Commission) Publication 505, prepared by TC 98 (1) follows:

> The insulation system is an insulating material, or an assembly of insulating materials, to be considered in relation with associated conducting parts, as applied to a particular type or size or part of electrical equipment. A single piece of electrical equipment may contain several different insulation systems.

Such a definition demonstrates that the properties of the adopted materials ("components") and the effects of their combination (including the compatibility problems) influence the overall characteristics of an insulation system. Especially when polymeric materials are present, the technology implemented to set up such components is another, even more important, factor that governs the overall performances of the insulation system and the relevant equipment.

The transformer insulation system consists of

- conductor insulation, interturn and intersection insulation, and insulation between coils of a single winding
- insulation between windings and between windings and grounded parts of the transformer (main insulation)

The main insulation is illustrated in Fig. 1 where a cross-section of a power transformer with concentric windings is shown schematically.

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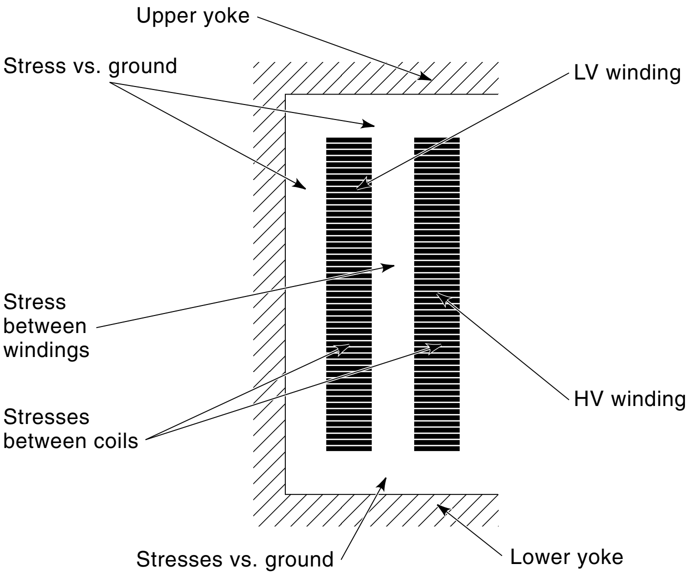

Figure 1. Schematic representation of the insulation of a power transformer with concentric windings. The main dielectric stresses are identified.

For all transformers, the choice of the most suitable insulation system can be influenced by several factors. Examples are:

- the rated voltage level, the service gradient, and the test gradients—These can indicate whether to adopt insulation systems having special features, that would affect both the short- and long-term behavior.
- safety requirements, especially with respect to fire resistance, for installations in a public site or in certain industrial sites—These could require the adoption of solid insulating systems (even if, this way, the transformer “active” materials would not be fully exploited).
- the need to interface SF6 insulated systems (gas insulated substation or gas insulated lines), together with fire resistance requirements—It would drive the adoption of SF6-impregnated insulating systems for voltage transformers and, sometimes, for power transformers.
- cost problems—In the absence of special requirements, the goal of achieving the minimum cost can render the adoption of insulation systems based on mineral oil both for cooling and for insulating purposes convenient, especially for distribution transformers.

Regarding power transformers, the solution of the cooling problems can heavily influence the choice of the insulation system. In fact, as the machine losses increase with the third power of the linear scale factor and the heat exchange surface increases with the second power of the same factor, it is clear that increasing the power of a machine requires the adoption of increasingly more sophisticated cooling techniques. For instance, over a certain power limit, it becomes necessary to

- adopt oil as an insulating and cooling medium
- improve the heat exchange between oil and active parts of the machine, assisting the oil circulation
- improve the heat exchange between the transformer “shell” and the surrounding ambient, forcing the oil through air (or water) heat exchangers

Clearly, the specific solutions implemented to satisfy the cooling needs of a transformer substantially modify the transformer morphology and its insulation system.

The insulation systems used at present for different types of power transformers and for various applications are summarized in Table 1. Additionally, a classification of the insulation systems adopted in instrument transformers is illustrated in Table 2.

From Tables 1 and 2, it appears that the main insulation systems are

- mineral (or synthetic) oil with polymer or cellulosic barriers
- polymeric papers or pre-pregs, impregnated by insulating varnish (dry type)
- polymeric papers or films embedded in thermosetting resins (cast resin)

DIELECTRIC STRESSES IN THE TRANSFORMER WINDINGS

Before examining in detail the insulation systems of power and instrument transformers, it is worthwhile to study the relevant selection criteria, which are related to the dielectric stresses.

Voltage is the first element that determines the dielectric stresses in these insulation systems. It can originate from normal and from anomalous service conditions or can be applied during standard tests performed in order to represent the service conditions. Because this factor is very wide-ranging, consult IEC publications (2–4) for details.

In the following, attention will be given to the following different stress situations:

- at power frequency
- at atmospheric impulse (lightning surge), simulated by 1.2 μs/50 μs (rise time/time-to-half-value) impulses
- at switching surge conditions, simulated by 250 μs/2000 μs (rise time/time-to-half-value) impulses

From a geometrical point of view, the present study, as evidenced in Fig. 1, is related to the dielectric stresses:

- between the windings and the ground
- between different windings
- between the coils of a single winding

Stresses Between the Windings and the Ground

Figure 1 illustrates that

- for each winding, the stresses between the single windings and the ground affect the insulation between the ends of each winding and the upper yoke or the lower yoke
- for the low voltage winding (generally the inner wind-

Table 1. Power Transformers Insulation Systems

Type	Cooling Fluid	Conductor Insulation	Main Insulation	Application
Dry	Air	Enamel	Nonimpregnated pressboard	Small transformers for home and industrial use. $P \leq 1$ kVA, $V \leq 500$ V.
		Enamel and kraft or polymeric paper	Insulating varnish, impregnated pressboard	Machines for naval (or industrial) use or for high safety level distribution. $P \leq 5$ MVA, $V \leq 15$ kV.
		Enamel, glass fiber	Cast resin	Machines for naval (or industrial) use or for high safety level distribution. $P \leq 20$ MVA, $V \leq 36$ kV.
	SF6	Enamel and kraft paper or polymeric paper	SF6-impregnated film or polymeric paper	Transformers for industrial use or for fire-resistant transformer stations. $P \leq 30$ MVA, $V \leq 130$ kV.
Fluid immersed	Synthetic oil (silicon oil or esters)	Enamel and kraft paper	Pressboard barriers and synthetic oil ducts	Transformers for industrial use or for distribution. $P \leq 10$ MVA, $V \leq 100$ kV.
	Mineral oil	Enamel and kraft paper	Pressboard barriers and mineral oil ducts	Transformers for industrial use or for transformer stations. The highest power and voltage levels are reached.

ing), the stresses versus ground affect the insulation between the inner winding itself and the magnetic core

- for the high voltage winding (outer winding), these stresses are “screened” by the inner winding

At power frequency, the highest stress situation is found—for the case of triangle connection or of star connection with isolated neutral—during the applied voltage test, when all the winding is at the same potential vs. ground (which is a condition quite different from the service condition). Transformers having windings star-connected with permanently grounded neutral (a condition that allows a reduced insulation vs. ground) are normally subjected to the induced overvoltage test. In these cases, the line ends are the most highly stressed regions.

As concerns the impulse stresses (5), note that the atmospheric impulses (lightning impulses) mainly affect transformers connected to overhead lines, whereas the switching

Table 2. Types of Instrument Transformers Insulation Systems

Type	Installation	Rating Voltage	Insulation System
Voltage transformers	Indoor	$V_n < 1000$ V	Dry type Cast resin
		1 kV $< V_n <$ 60 kV	Cast resin Oil–paper
	Outdoor	1 kV $< V_n <$ 60 kV	Oil–paper
		$V_n >$ 60 kV	Cast resin (cycloaliphatic epoxy) Oil–paper
	GIS (gas insulated substation)	1 kV $< V_n <$ 60 kV	Dry type
		$V_n >$ 60 kV	Cast resin (toroidal type)
Current transformers	Indoor	$V_n < 1000$ V	Dry type
		1 kV $< V_n <$ 60 kV	Cast resin
	Outdoor	1 kV $< V_n <$ 60 kV	Cast resin Oil–paper
		$V_n >$ 60 kV	Oil–paper SF6–paper
	GIS (gas insulated substation	1 kV $< V_n <$ 60 kV	Dry type Cast resin
		$V_n >$ 60 kV	Dry type Cast resin (toroidal type)

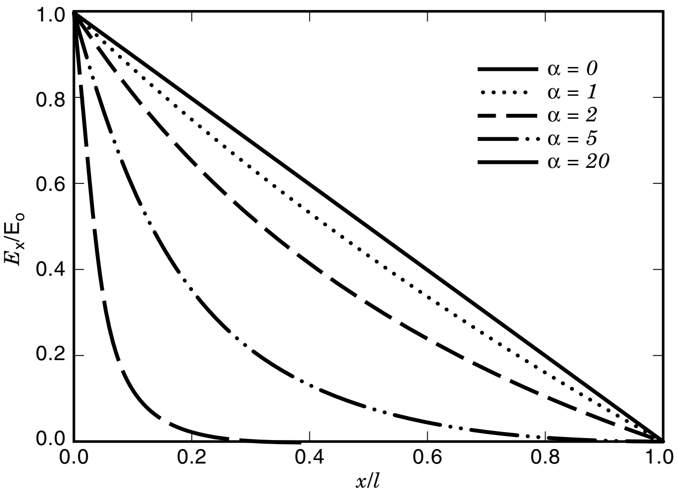

Figure 2. Parametric diagram of the normalized potential difference (E_x/E_0)—between one coil at distance x from the winding end and the winding end itself—versus the normalized distance (x/l) of a coil from the winding end where l is the whole winding length and the ratio α is the parameter.

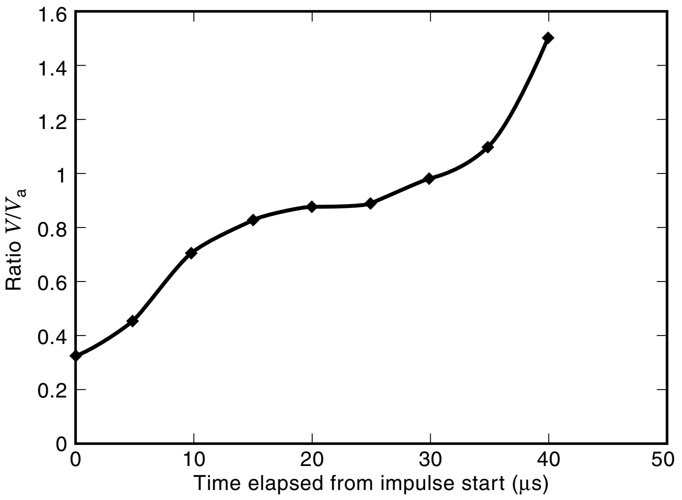

Figure 3. Ratio between actual voltage V and the peak of the applied voltage V_a, measured on a winding at a normalized distance x/l = 0.8 versus elapsed time since the impulse start (up to 40 μs).

surges affect all the machines that are in presence of switchgears that are not perfectly set or of switchgears with a high K (overvoltage ratio):

$$K = \frac{E_{\max}}{\sqrt{2}E_n} \tag{1}$$

where E_n is the root-mean-square (rms) value of the nominal voltage and $E_{\max}$ is the maximum value of the transient recovery voltage (TRV). A clear example of the latter situation is offered by the case of "vacuum" switchgears, which are often accompanied by surge arresters, to cope with overvoltages caused by the interruption of currents lower than a critical value.

In the presence of impulse overvoltages, the initial distribution of potential along the winding is related to the value of the capacitance distributed between coils and toward the ground (Fig. 2); the most stressed coils are the ones nearest to the line end.

At each point along the winding, it is important to consider the variation of potential with time. Because of the reflections of the impulse at the ends of the winding, it is possible, as shown in Fig. 3, that, at certain points of the winding and in certain instants, the potential vs. ground reaches values higher than the initial voltage at the line end.

Finally, it is worthwhile to recall that the impulse breakdown voltage is related to the rise time (time to crest) and to the time required by the voltage pulse to drop to half of its crest value (time-to-half-value). Figure 4 illustrates a particular case where the breakdown takes place at the front of the impulses.

Stresses Between the Different Windings

The situation regarding the dielectric stresses between the windings is similar to the situation existing between the windings and the ground. In this case, too, at power frequency, the maximum stress is reckoned during the applied voltage tests; an exception is made for the case of the windings star-connected with permanently grounded neutral, where the above made considerations still hold.

The stresses caused by impulses depend on the level of the voltage waves capacitively transferred from a winding to the other; therefore, they depend on the relative capacitance. The transferred waves can diminish the potential difference between two windings, but they can make more critical the withstand capability versus ground of the "target" winding.

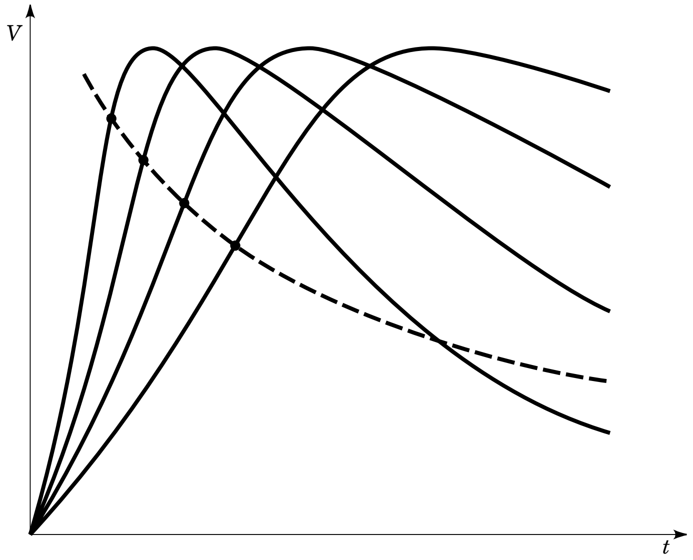

Figure 4. Voltage–time curves representing the breakdown voltage (and the relevant time delay) related to impulses with different rise times.

Stresses Between Coils of a Single Winding

At power frequency, in service conditions and during the induced overvoltage test, between the coils of a winding, there is a potential difference on the order of some dozen volts or, for large transformers, on the order of some hundred volts.

In the case of impulse stresses, the potential difference between coils depends on the ratio α (between the distributed capacitance versus ground C and the capacitance between coils c), which, for l = length of the winding, is

$$\alpha = l\sqrt{\frac{C}{c}}$$

If x is the coordinate along the winding and E_0 is the potential at the line end, the voltage between coils E_x becomes

$$E_x = E_0 \frac{\sinh \alpha \left(1 - \frac{x}{l}\right)}{\sinh \alpha}$$

With respect to the first coils, for $\alpha > 5$, it is possible to write

$$\left(\frac{dE}{dx}\right)_{(x=0)} \cong \frac{E_0}{l}\alpha$$

so that at the line end of the winding the coil-to-coil potential difference is α multiplied by the value that would be present in case of linear distribution. Figure 2 illustrates the curves of the ratio E_x/E_0 versus x (parameter α), whereas a simple helically wound winding would have a value of α higher than 5, adopting special arrangements of turns (“interleaved windings”) or suitably alternating winding sections it ensures to attain $\alpha = 1$ (linear distribution of the potential difference) conditions or even to reach $\alpha < 1$ situations.

Other Types of Stresses

The increasing diffusion of power electronic devices (solid state rectifiers, converter/inverter, etc.) which require the presence of a transformer suggests that also the effects, on the relevant insulation, of the stresses due to the presence of periodic nonsinusoidal voltage waveforms or to the presence of dc components in sinusoidal voltage waveforms should be considered here. In such situations, an optimal design of the transformer topology and of its insulation system is needed to avoid premature failures. However it is not possible, here, to deal with the design criteria both because of limited space and because they are still object of research.

OIL–SOLID BARRIERS INSULATING SYSTEMS

As reported in Tables 1 and 2, the insulating system most widely used in high-power (and high-voltage) transformers is made by cellulosic paper impregnated by mineral oil (oil–paper insulation). The introduction of the oil–paper insulation has been an important step in the evolution of transformers because it opened the way to substantial power and voltage increases for such machines. In fact, the mineral oil in a transformer plays a double role: it is the cooling fluid and it is part of the insulation system.

The oil–paper insulation system belongs to the more general category of insulation systems made by an insulating liquid in series to solid barriers. Two different configurations dominate the practical applications.

1. *Oil-Impregnated Cellulosic Paper (or Polymeric Paper).* If this solid barrier were immersed in air, it would show modest dielectric performances because of its porosity. Because it is immersed in an insulating liquid, such performances are higher than in air. Besides the presence of paper causes a “blocking” effect (Garton effect), which limits the possibility of moving impurities. In general, as the dielectric performances of an insulating liquid are negatively influenced by the presence of mobile impurities, in this case the oil performances (dielectric strength) are highly increased because of the paper. These effects grant to the insulation system better dielectric properties than its components, if separately considered. Additionally, the compatibility between oil and polymeric (or cellulosic) papers is carefully checked because it can heavily influence the reliability of the insulation. This insulation system, with cellulosic paper, is widely adopted for power machines, for both medium voltage (MV) and high voltage (HV) applications (from 0.1 MVA upward) and for HV instrument transformers (> 60 kV).
2. *Oil-Impregnated Polymeric Films.* In this case, the solid component (polyester or polypropylene film) has properties comparable or better than those of the insulating oil. The solid barriers are made by several thin tapes (or sheets), which sometimes are microcorrugated on one or both sides. Several oil layers and film barriers are alternated and are arranged in different ways to form the insulation system. The beneficial effect of these solid barriers is twofold: they act as elements blocking (Garton effect) impurity particles—although less efficiently than paper in the oil–paper systems—and they enable to increase the insulation system withstand voltage because of their high dielectric strength. Also, in this case, the compatibility between oil and polymer is carefully checked because the insulation reliability heavily depends on it. This insulation system, which is typical of capacitors, is also used, albeit rarely, for instrument transformers in the MV and HV ranges.

In all unused oil–solid barriers insulation systems, the treatment of component materials is particularly important. The insulating liquid is to be dried, filtered and degassed, whereas the solid barriers are to be dried. Such treatments are carried out up to a level that depends on the voltage of the transformer: the oil–paper systems for the highest voltage (and power) levels are to be treated with special care.

High-power machines are dried within their own tank and rendered pressure- and vacuum-tight; generally instrument transformers and distribution transformers are subjected to such treatments while hosted in suitably large autoclaves.

In oil-insulated distribution transformers (hundreds of kVA), the high-voltage windings can be realized using enamel-insulated conductors, and the solid barriers for ground insulation can be made by nonimpregnated (or bakelized) pressboard (for electric purposes). In such cases, the enamel compatibility with the oil is checked in advance.

Materials Employed in Oil–Paper Insulating Systems

Here are considered, in detail, the key characteristics of the main materials employed in insulation systems with solid (paper) insulating barriers immersed in a liquid dielectric.

Liquid Insulating Materials

The liquid insulating materials usually (6) employed in transformers are the following:

- mineral oil, derived from distillation of crude oil
- silicon oil, derived from silicon organic chemistry processes
- organic esters, for transformers, usually obtained through synthetic processes
- PCB fluids (also named askarels)

Actually the use of the PCB fluids (polychlorinated biphenyls) in transformers is presently internationally banned for ecological reasons. PCB fluids were introduced because they were highly fire resistant and they beneficially influenced global cost (manufacturing, installation, and maintenance) of transformers. PCB-insulated transformers were used widely until their potential to damage the ecosystem was recognized, originating an international ban.

Among the other three fluids, mineral oil is the most widely adopted because of both its good dielectric properties and its cost. The silicon oils and the esters have been introduced as substitutes of PCB fluids in order to satisfy special requirements of fire resistance; however, their high cost limits their use in transformers intended for industrial or civil installations where stringent safety and reliability requirements must be met. Silicon oils are also particularly well suited to impregnate polymeric papers or microcorrugated films. In this way, high service temperature insulation systems (F or H thermal class) can be formed.

Mineral Oil. Mineral oils are obtained from crude oil (more precisely from crude petroleum), which, as per ASTM D288 (7), is defined as follows:

> A naturally occurring mixture, consisting predominantly of hydrocarbons, which is removed from the earth in liquid state or is capable of being removed. Crude petroleum is commonly accompanied by varying quantities of extraneous substances such as water, inorganic matters and gas. The removal of such extraneous substances alone does not change the status of the mixture as crude petroleum. If such removal appreciably affects the composition of the oil mixture then the resulting product is no longer crude petroleum.

There are several types of crude oil (or crude petroleum), which have different compositions and which can be basically grouped as based on paraffin hydrocarbons or as based on naphtene hydrocarbons (or of intermediate type).

Table 3. Density, Viscosity, and Pour Point of Class I, II, and III Mineral Oils

Insulating Oil	Density at 20°C–(kg/m^3)	Viscosity at 20°C–(cSt)	Pour point (°C)
Class I	888	70	−30
Class II	879	32	−45
Class III	872	6.5	−60

The characteristics of a mineral oil are influenced by the original crude oil from which it is derived. Several properties, even nonelectric ones, contribute to characterize an insulating liquid. They can be grouped as physical, chemical, and electrical properties.

The *physical properties*—density, viscosity, "pour point," and flammability characteristics (described by flash point, fire point and auto-ignition temperature)—are of particular interest and are interrelated. With reference to the latter properties, it is possible (8) to classify mineral oils in view of the transformer installation site environmental temperature. As reported in Table 3, Class III oils are more suitable to operate in cold climates than Class I oils. In fact, as illustrated in Fig. 5, at the cold winter temperatures typical of northern countries, the viscosity of Class I and Class II oils would be so large that oil circulation in a machine that is about to be started would be difficult. At the opposite environmental temperature ranges, the use of medium- or high-viscosity oils is preferred because the adoption of low-viscosity oils would increase the risk of fire. Actually, as shown in Fig. 6, low-viscosity oils are characterized by a higher flammability: the short average length of their molecules implies a high density of molecule-ends, which are the most reactive sites, and it is, in the end, a basic cause of the high flammability.

Then, the oxidation stability and the gassing characteristics, at high temperature and in the presence of a high electric field and of ionization (silent discharges), can be regarded as the most important *chemical properties* of a mineral oil. They offer indications about the aging characteristics of an oil in normally stressed conditions (in the presence of oxygen and electric fields) and abnormally stressed conditions (in the

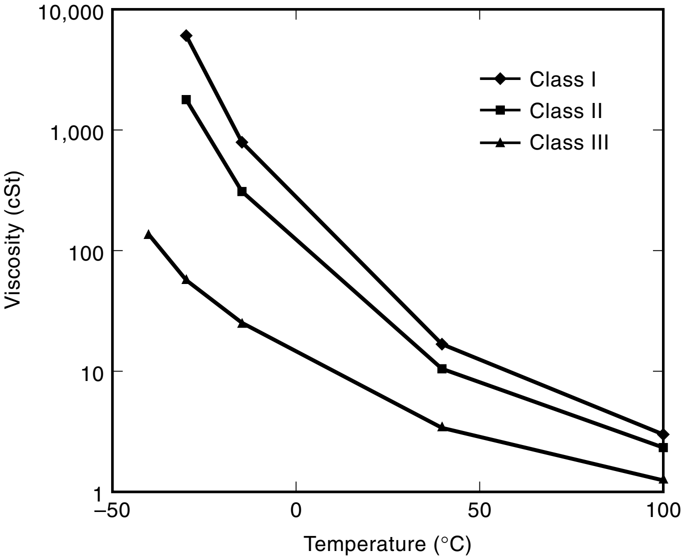

Figure 5. Viscosity versus temperature relevant to three different classes of mineral oil (as per Publication IEC 296).

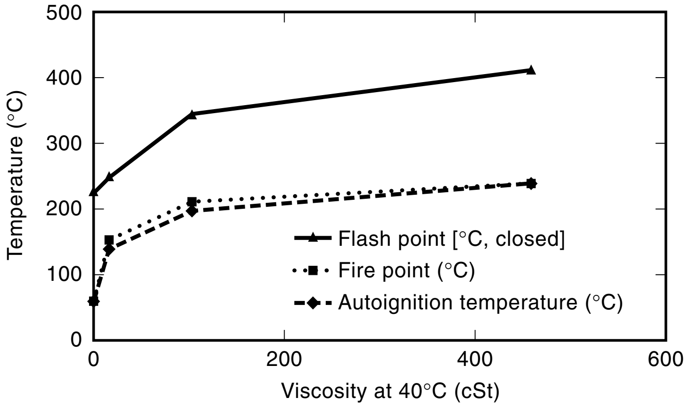

Figure 6. Flash point, fire point and autoignition temperatures for oils with different viscosity at 40°C.

presence of discharges). These topics are covered by the International Electrotechnical Commission (IEC), which has selected and validated tests to evaluate the oxidation stability of insulating oils in controlled and repeatable conditions and to characterize the gassing phenomena (9,10).

IEC also issued Publications 567 (11) and 599 (12), which propose a methodology for sampling and analyzing the gases (products of degradation) dissolved in oil and illustrate the relevant results interpretation criteria. The latter techniques allow us to determine the type of stress present when gases are dissolved in oil—on the grounds of their type and quantity—thus providing a simple and reliable diagnostic tool of the insulation system.

This tool, if correctly used, can assist in the preparation of maintenance schedules or can help avoid unpredicted failures, which would be particularly relevant in the case of instrument and of power transformers for > 100 kV voltages (12). An example of such diagnostic tool application (13) is reported in Table 4 for oil–paper insulation. In fact, Table 4a shows the acceptable concentration levels (in parts per million) of the main dissolved gases for different types of equipment, whereas Table 4b indicates the influence of the ratio CO_2/CO on the value of C_2H_4 corresponding to an equally critical (dangerous) situation in power transformers.

Additionally, the chemical properties carrying information about the content of the impurities (e.g., water and nitrogen content, sulphur staining and corrosion) can be interesting. In particular, the water content noticeably influences the insulating properties of the liquid and of the insulation system.

As the solubility of water in oil, which amounts to 30–80 ppm at 20°C in an unused oil, increases as the aging (oxidation) level advances, the water content in oil can represent a further diagnostic parameter to monitor/evaluate the state of the insulation.

Table 4a. Acceptable Levels of the Main Dissolved Gases in a Mineral Oil Insulation for Different Types of Equipment (A = power transformer; B = measurement transformer; C = tap changer communicating with the main tank)

Type of Equipment	C_2H_2 (ppm)	C_2H_4 (ppm)	H_2 (ppm)
A	20	500	200
B	200	500	250
C	40	40	500

Table 4b. Pairs of Values of C_2H_4 Content (in parts per million) and of the Ratio CO_2/CO Corresponding to an Equally Dangerous Level in Power Transformers

CO_2/CO	<6	<3	<2	<1
C_2H_4	400	150	100	20

Obviously, as far as applications are concerned, the *electrical properties* are the most interesting ones, especially

- the breakdown voltage (see dielectric strength) at power frequency;
- the impulse breakdown voltage;
- the volume resistivity (ρ_v), measured in dc;
- the loss factor (tang δ);
- the relative dielectric permittivity (ϵ_r).

Even though typical values of such properties for mineral oil are reported in Table 5, some comments follow:

- All the preceding properties, excluding the ϵ_r, are largely influenced by either the presence of water or ionic impurities in oil.
- The dielectric strength is the most interesting property. Its value is critical to the design of an insulation system and to the maintenance of the transformer. Such a value depends also on the presence of conducting or of insulating particles, which, forming "bridges" between the electrodes, can easily lead to the dielectric breakdown of the oil (14). For example, the presence of just 20 ppm of water in oil can considerably decrease the machine's ability to withstand voltage. Very high values of dielectric strength are required for oils to be used in HV transformers (where, because of dimensional limits, the voltage gradients are highest). Finally, because the measurement of this property (15) on machines is an easy and low-cost procedure (it simply involves taking a sample out of the transformer tank and performing a standard breakdown test), the maintenance operations can be efficiently planned by simply monitoring this property variation with time. Used oils are periodically, according to the transformer maintenance plans, subjected to a reconditioning treatment (filtering, degassing, drying) that are apt to increase their dielectric strength.

Table 5. Typical Electric Properties of a Mineral Oil

Property	Typical Values
Alternating current (50 Hz) breakdown voltage (kV)	30–60
D = 2.5 mm, IEC spherical electrodes	
Impulse breakdown voltage (kV)	
D = 12.5 mm, negative	120–190
positive	65–90
Tan δ at 90°C	$1–6 \times 10^{-3}$
Resistivity at 90°C (TΩ · m)	0.02–2
Relative permittivity at 90°C	2.1–2.5

- The measurements of ρ_v, ϵ_r, and tang δ are rather critical (16) and require good cleaning standards (especially with respect to the test cell) in order to avoid the influence of extraneous agents. Nevertheless, such measurements are a powerful diagnostic tool to evaluate the quality of an unused oil and to determine whether the service conditions have modified the oil-insulating properties up to a critical level.

Synthetic Oils. Several types of synthetic oils that can be used in very different applications are available. Essentially, there are two reasons for introducing such products: (a) the need to find liquid dielectrics that have surely controlled and highly repeatable characteristics for particularly critical applications (e.g., high-voltage cables); (b) the need to find a substitute for the chlorinated oils (PCB), both to get insulating liquids with high ϵ_r values (4–6)—for applications as capacitors—and to get a low flammability material—for applications as high-safety distribution transformers.

Practically, the insulating liquid that best meets the safety requirements of transformers is the silicon oil, although some esters have been satisfactorily employed. However, the costs of both solutions make their use impracticable for high-power machines. Another obstacle is the need for ad hoc treatment systems when specific applications require very high dielectric properties.

Silicon oils have a very good chemical stability—below their flash point—and a good flame resistance, although the latter is lower than that for the askarels. A typical silicon oil for transformers has flash point $\geq$285°C and fire point $\geq$340°C, whereas the self-ignition temperature is $\geq$490°C. The relevant curve of viscosity vs. temperature is reported in Fig. 7. Note that at 20°C the viscosity value is intermediate between a Class I and a Class II mineral oil, whereas 100°C its value is quite high, definitely higher than any mineral oil employed in transformers.

The dielectric properties of a typical silicon oil for transformers are reported in Table 6. Comparing it with Table 5 (mineral oil) shows that the dielectric strength is similar, although, after the first breakdown, the silicon oil dielectric strength drops. The discharge produces solid particles that form interelectrodic semiconducting bridges and facilitate the following discharge processes. Even though silicon oils have very good values of tang δ and ρ_v, lower and higher, respectively, than the mineral oil ones, their dielectric strength remains constant up to a water content of 60 ppm, and their thermal stability is particularly high.

Table 6. Electric Properties of a Silicon Oil for Transformers

Property	Typical Values
AC (50 Hz) breakdown voltage (kV)	
D = 2.5 mm, IEC SPHERICAL ELECTRODES, first discharge	35–60
AC (50 Hz) BREAKDOWN VOLTAGE [kV]	
D = 2.5 mm, IEC SPHERICAL ELECTRODES, second-sixth discharge	10–16
Impulse breakdown voltage (kV)	
D = 12.5 mm, negative	270
positive	80
Tan δ at 90°C	1×10^{-4}
Resistivity at 90°C (T$\Omega \cdot$ m)	0.5–1
Relative permittivity at 90°C	2.7

Silicon oils can be used in as-received conditions, whereas mineral oils for HV and ultra-high-voltage (UHV) transformers are to be subjected to treatments (drying, degassing, and filtering) before being used in order to achieve dielectric strength values much higher than the ones reported in Table 5. Finally, the high thermal stability of silicon oil enables us to assemble insulating systems of a thermal class higher than the Class A (e.g., introducing also silicon enamels and aramidic papers that have service temperatures between 180° and 220°C).

Cellulosic Paper

In traditional transformer insulation, the solid barriers are made by particularly pure cellulosic paper. Even though the conductors are paper-tape wound, the main insulation of the coil versus ground and the insulation of the coil connections versus ground is made by thick paper or paperboard elements (as visible in Fig. 8).

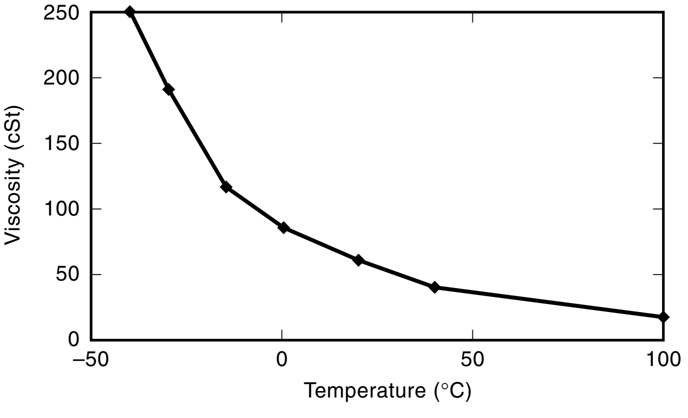

Figure 7. Viscosity versus temperature diagram of a silicon oil for transformers.

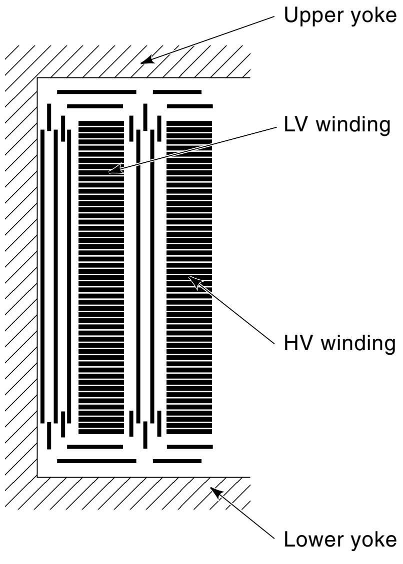

Figure 8. Schematic example of insulation versus ground and of insulation between windings in a power transformer with concentric windings.

The coils and the straight connections are insulated with Kraft paper, which is defined by IEC Publication 60554 (17) as "paper made entirely from soft pulp manufactured by the sulphate process." The curved elements are insulated by means of crêpe paper, that is "Paper that has been subjected to crêping," where crêping is "a process of imparting an irregular close crimp to the paper to increase its thickness and its extensibility in the machine direction." In transformer insulation, Kraft paper about 50 μm thick, with 45 g/m^2 grammage (i.e., apparent density in the range of 0.85 g/cm^3 to 0.95 g/cm^3) and dielectric strength (in dry conditions) ranging between 7 kV/mm and 9 kV/mm is adopted.

Paper is also characterized by its chemical properties [e.g., the ash content (0.5% to 1%), the conductivity ($\leq$4 mS/m to 10 mS/m) and the pH (6.0–8.0) of the extracted water. Although such properties are interesting because they monitor the paper pureness (which is a precondition to avoid the possible alteration of the impregnating oil), the mechanical characteristics of the paper tapes are of interest because they influence the manufacturing process of the transformer coils insulation.

As shown in Fig. 8, the axial and radial insulation of the windings are generally made by plain or corrugated paperboard for electric purposes (18), with thickness ranging between 0.3 mm and 8 mm.

In special cases, when mechanical and electrical properties higher than the ones of usual paperboards are required, calendered or pressed paperboards are also used. Their higher density (about 1.25 g/cm^3) and their highly intertwined fiber structure are responsible for their improved performances. However, in general, the introduction of several thinner barriers, instead of a single thick barrier, is preferred. In this way, a higher dielectric can withstand voltage, and a better cooling system and a lower risk of presence of defects in the paperboard are achieved.

Because the overall performances of the insulation system depend on the impregnating oil, the dielectric properties of dry and nonimpregnated paper are of little relevance. But such properties can be important because they reveal the presence of moisture in the paper. The water content in the paper will progressively transfer to the oil until an equilibrium condition (which depends also on the temperature) is reached, and it will cause a decrease of the insulation system dielectric strength. For this reason, the drying process is particularly important when setting up the paper insulation, even more so as regards the paperboards, because of their noticeable thickness.

Figure 9 reports a schematic diagram of the drying process, for an hygroscopic paper (HP) and for a nonhygroscopic paper (NHP). When decreasing the moisture content, three different phases are encountered.

- In the first phase, the moisture leaves the paper surface (evaporation) at a uniform speed.
- When the paper surface becomes dry, the second phase takes place. The water vapor generated inside the paper bulk reaches the outer surface through the pores created during phase 1, and the drying speed progressively decreases.
- During the third phase, in the NHP case (dashed line curve), the drying speed is limited by the attractive forces (caused by secondary bonds acting between water and paper molecules), which cause a resistance to the flow of moisture. The same mechanism is active in the case of hygroscopic paper (full line curve), but its effects are particularly intense. In fact, the energy required to overcome these forces is so high, even at medium-level moisture content, that the drying speed rapidly decreases to zero. At this point, an equilibrium moisture level is established, and no additional water molecules are released.

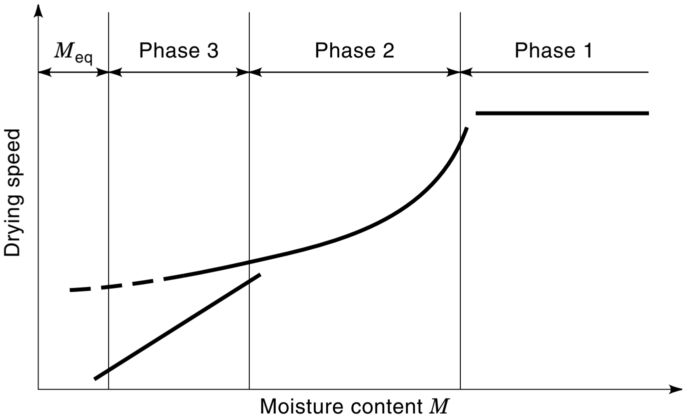

Figure 9. Diagram of the drying speed versus moisture content of papers for transformer insulation. The dashed line represents nonhygroscopic paper and the solid line, hygroscopic paper.

Therefore, to complete a drying process in the shortest possible time, it is necessary to supply heat (in order to transform water in vapor and to overcome the attractive forces already described) and to add vacuum treatments (in order to assist the extraction of vapor from the paper).

DRY TYPE AND CAST RESIN TRANSFORMER INSULATING SYSTEMS

About a century ago, the first transformers on high-voltage machines were insulated with organic textiles impregnated with shellac or other natural varnishes. Later on, such insulation systems were replaced by oil–paper systems. When the ban on PCB fluids was issued, dry transformer insulation, regained interest because it was considered an alternative to silicon oil–paper and to liquid ester-paper insulating systems for MV applications (24 kV to 36 kV nominal voltage, up to 10 MVA to 15 MVA service power) where especially high safety and reliability levels (19) are required.

In fact, the availability of modern materials allowed the development of transformers having Class F (cast resin) or Class H (dry-type) insulation and excellent fire-resistance properties. The latter properties were essentially related to the introduction of a high quantity of mineral filler in the resin (in cast resin systems) or to the presence of a small quantity of special insulating materials (in dry-type systems).

Dry-Type Insulation Systems

Dry-type insulation can be considered a direct upgrade of the insulation adopted in the first transformers. The new and modern insulating materials allowed designers to modify the insulation system structure substantially, while extending its reliability and thermal life properties. The HV windings structure is quite similar to the one used in the case of oil-insulated machines: disc or layer winding subsections have been adopted, although copper or aluminum conductors can be used. To reach a service temperature of about 200°C, the conductors are insulated by a double layer of enamel or by an insulating tape. The insulation is selected on the basis of the performances required to the machine. Such tape can be a pre-preg epoxy (or polyester) fiberglass tape or a pre-preg mica tape, or (more frequently) it can be obtained from aramidic paper. The winding is then impregnated in a autoclave with a polyurethane or silicon varnish. Employing aramidic paper and silicon varnish, insulations with 180°C nominal service temperature levels can be produced, although their actual service temperatures generally will be kept at a lower level in order to increase the machine's reliability.

As shown in Fig. 10, the low-voltage windings of these machines are often obtained from metallic sheets, whereas the coils are insulated with aramidic paper or resin-impregnated fiberglass textile. As in the case of HV windings, the winding is eventually impregnated by means of an insulating varnish.

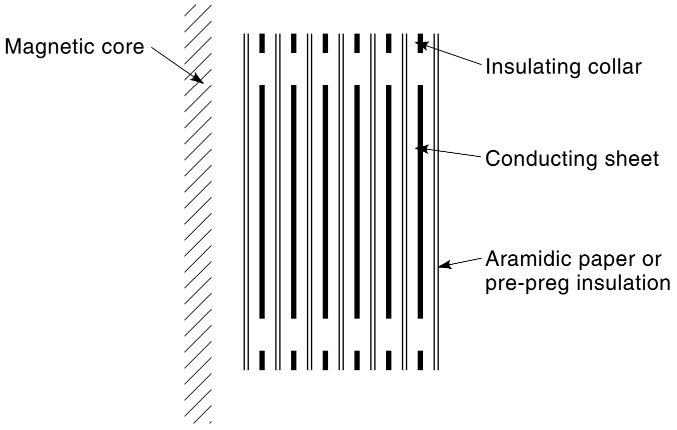

Figure 10. Schematic view of a typical low-voltage winding for dry-type transformers. Metal sheets form the coils and the coil insulation is provided by aramidic paper or prepreg.

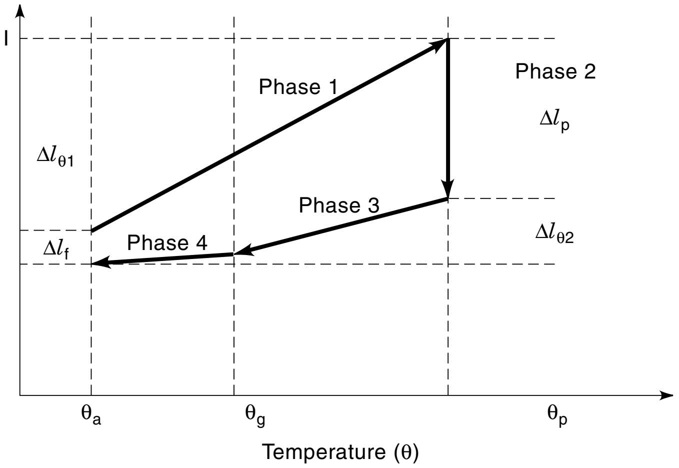

Figure 11. Expansion and shrinking of an epoxy resin during the curing process θ_a = ambient temperature; θ_g = glass transition temperature; θ_p curing temperature; $\Delta l_{\theta 1}$ = thermal expansion of the liquid resin; Δl_p = shrinkage due to the crosslinking process $\Delta l_{\theta 2}$ = thermal shrinkage of the cured resin; Δl_f = residual shrinkage at the end of the process.

Cast Resin Insulating System

From 1960, cast resin (usually epoxy resin) medium voltage instrument transformers and MV small-power transformers entered the market. The partial discharges level of such machines often was quite high and was the cause of their short electric lives; besides, the shrinkage effects caused by the resin-curing process (see Fig. 11) was the origin of very high internal mechanical stresses, whose presence, on one hand, blocked the development of larger dimension power transformers and, on the other hand, caused, in the instrument transformers (especially in the current transformers), unacceptable errors because of the mechanical effects of the resin shrinkage (forces) acting on the magnetic core.

Today, the continuous evolution of the casting techniques, the introduction of low-shrinkage (or high-flexibility) polyurethane and epoxy systems, and the possibility of adopting mineral fillers that enable the resin systems to reach the linear expansion coefficient of copper ($\Delta l/l = 18 \times 10^{-6}$) or of aluminum ($\Delta l/l = 24 \times 10^{-6}$) permit to manufacture all the types of measurement and of MV power transformers listed in Table 1.

In Figs. 12(a,b), two typical morphologies of winding for cast resin MV transformers are reported. The design illustrated in Fig. 12(a) involves a winding made by discs, which are made of metallic (copper or aluminum) ribbon and have a double polyethylene terephtalate ribbon (higher than the metallic ribbon) interleaved to the conductors. Such discs are piled introducing spacers made by the same resin used for casting, and the whole winding is embedded in epoxy resin (or, less frequently, in polyurethane resin) by means of a traditional gravity vacuum casting technique. The final product is a one piece cylindrical object. The resin layer around the outer winding is some millimeters thick, and, in part, its value depends on the achievable accuracy in centering the mold. Besides, Fig. 12(b) illustrates a design solution often adopted for low-power machines (up to 200 kVA to 300 kVA). The winding is divided in groups of enameled wire layers, where the wires often have a circular section and the interlayer insulation is made by aramidic paper (or by pre-preg textile). In this case too, the single elements are separated by spacers made by the same resin used for casting, whereas the winding is embedded using the aforementioned techniques. Note that, in this case, the resin penetration between layers is more difficult; therefore, the final presence of some voids is almost inevitable. For this reason, the layer voltage should be lower than the partial discharges inception voltage: layer voltage levels of 100 V to 200 V could be fairly acceptable for this purpose.

Finally, note that, although it is possible to manufacture cast resin low-voltage windings, the previously described designs are certainly more suitable to fulfill the needs of MV windings. The optimal design solution for low voltage windings should rather involve sheet conductors and dry type insulation.

Insulation Systems for Instrument Transformers

Usually the instrument transformers for indoors use, up to 36 kV, are of cast resin type. Besides, the adoption of cycloaliphatic epoxy resins allows the production of instrument transformers for outdoors use. These transformers have environmental performances similar to those of traditional transformers, where porcelain housings (or bushings, depending on the design) are present.

Although cast resin instrument transformers have winding structures similar to those of cast resin power transformers, they also have some differences.

- They are particularly compact; therefore, the electric gradients are high and the potential distribution must be closely studied. Often it is necessary to introduce such electric field control as semiconducting (or conducting) shields, which are often obtained from conducting powder-filled polymeric or natural paper.
- They require special care to eliminate surface spots of high electric field because such areas, in the presence of dew, can originate tracking and/or tangential partial discharges phenomena, which would progressively damage the resin surface (eventually leading to breakdown).
- In these transformers, the effects (on the core) of internal mechanical stresses caused by the cure of the resin are often avoided employing thermosetting resins with a glass transition temperature (TG) of about 30° to 50°C and with acceptable characteristics at high temperature. Alternatively, it is possible to protect the magnetic core by means of a soft solid material (if necessary, covered by conductive paper) and to adopt a thermosetting resin with a TG of 80° to 100°C.
- In the voltage transformers, the need to have a layer voltage lower than the partial discharges (PD) inception voltage can require that the MV winding be divided in two sections and that the relevant cost increase be accepted. A European manufacturer has solved the problem by introducing SF6 gas inside the resin shell of the device, thus increasing the PD inception voltage.

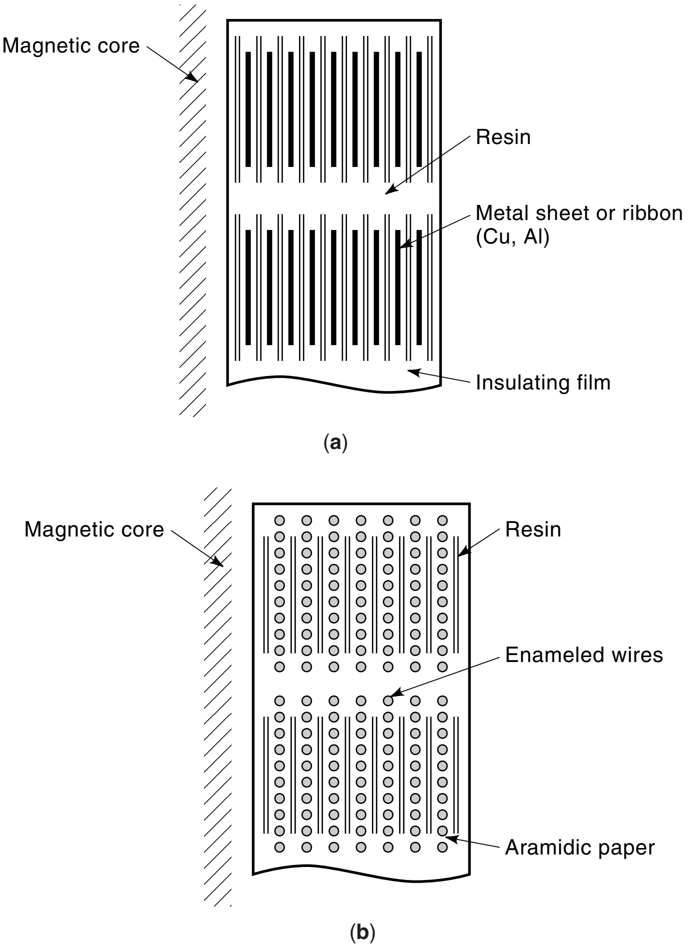

Figure 12. (a) Schematic view of a cast resin insulation for a high-voltage winding obtained from metal ribbons; the coil insulation is made of polyester film. (b) Schematic view of a cast resin insulation for a high-voltage winding obtained from enameled wires; the layer insulation is made of aramidic paper.

Solid Insulating Materials Employed in Air Transformers

The insulating barriers adopted in air transformers are examined here in detail.

- In the coil insulation, the following materials can be present:
  - polyester film [PET (polyethylene terephtalate) or PEN (polethylene naphtalene)]
  - aramidic paper
  - aramidic paper/polyester film bonded sheet
  - polyimide (PI) film
  - pre-preg fibreglass
- In the ground insulation, the following materials can be present:
  - epoxy resin with mineral filler
  - polyurethane resin filled by double carbonate (Ca and Mg) powder (dolomite)
  - aramidic paper impregnated by silicon or by polyurethane varnish
  - pre-preg fiberglass textile

Among polymer films, the case of PI or PEN films is to be noted. When adopting the latter films, it is necessary to employ resins with a high TG (90° to 100°C), in order to exploit their potential for a long thermal life. This fact requires a high percentage of suitable mineral fillers to be introduced in order to achieve a linear expansion coefficient similar to that of the metallic conductors, which is a condition to keep the internal mechanical stresses at an acceptable level.

Aramidic Paper. The aramidic paper is made by two types of an aromatic polyamide: short fibers flocks and light fibrous long particles. When the same manufacturing processes used in the case of natural (cellulosic) paper are applied to such components, it is possible to obtain sheets (which can be subsequently calendered at high temperature) of a synthetic flexible paper that has excellent thermal and mechanical properties as well as acceptable electric characteristics. This paper is a polar material and possesses dielectric properties highly dependent on temperature and frequency. Its main and typical characteristics are reported in Table 7.

Table 7. Properties of a Typical Calendered Aramidic Paper

Property	Values	Standard
Available thickness	0.05–0.76 mm	—
Density	0.7–1.1 g/m^3	—
Tensile strength/calendering direction	74–130 N/mm^2	ASTM D 828
Elongation at break	8–23%	ASTM D 828
Oxygen index	0.24–0.28	ASTM D 2863
Dielectric strength (0.05 mm thick)	21 kV/mm	
(0.30 mm thick)	34 kV/mm	ASTM D 149
(0.76 mm thick)	28 kV/mm	
Dielectric constant (1 kHz)	2–3.4	ASTM D 150
Loss factor (1 kHz)	7–20 × 10^{-3}	ASTM D 150
Temperature index (electrical and mechanical)	220°C	IEC 216

The information reported in Table 7 can be summarized as follows:

- As the calendering process produces more compact sheets from thicker input paper, this material density increases with its final thickness.
- For the same reason, higher-thickness calendered aramidic papers have higher tensile strength and longer elongation at the break.
- The dielectric strength of these paper sheets increases with thickness up to about 0.3 mm values. (In this range, the positive effect of the calendering process compensates and overcomes the well-known negative effect caused by the thickness increase). For sheets thicker than about 0.3 mm, the dielectric strength decreases because the latter effect dominates.
- The effects of calendering cause noticeable variations even with respect to the loss factor and to the dielectric constant, which are higher for higher thickness values.

In practical applications, the impregnation of aramidic paper (especially of calendered paper) by varnishes is difficult; therefore such varnishes should be considered just a general protection and a barrier against moisture.

Finally the special case of the bonded products, such as polyester film-aramidic paper, is to be evidenced; such products can add the good mechanical characteristics (including the shear strength) of the aramidic paper to the excellent dielectric properties of this polymeric film.

Polymer Films. The most widely used polymer film is the polyethylene terephtalate (PET), obtained from a reaction between terephtalic acid and polyethylene glycol. PET film is transparent. It becomes translucid for high thickness values. Its main properties are reported in Table 8.

In the cast resin transformer insulations, 25 μm to 30 μm thick PET films are usually adopted; double or multiple layers are often introduced to increase the insulation reliability.

Because the PET, like all polymer films, is easily damaged by cutting edges, such critical spots must be carefully eliminated from the metallic conductors.

In addition, note that the PET thermal aging characteristics vary with the insulation set-up conditions. In fact, the presence of air oxidates the film (especially at high temperature), increasing its fragility (i.e., decreasing its mechanical and electrical performances). In the cast resin insulating systems, the resin protects the film from the action of oxygen/air; therefore, it improves the actual film performances with reference to the outcome of laboratory thermal aging tests, which are normally carried out in air-filled ovens.

The alternative adoption of other polymer films must be carefully examined on a case by case basis. In fact, the introduction of the PEN or PI films would cause cost increases relevant to the material, which would not be justified, espe-

Table 8. Properties of a Polyethylene Terephtalate Film

Property	Values	Standard
Available thickness	6–100 μm	—
Density	1.365 g/m^3	—
Tensile strength at 25°C	100–200 N/mm^2	ASTM D 882-645
Elongation at break	120%	ASTM D 882-645
Water absorption at 23°C	<0.8%	ASTM D 570
Dielectric strength (25 μm) at 25°C	280–300 kV/mm	ASTM D 149
at 150°C	34 kV/mm	
Dielectric constant (60 Hz) at 25°C	3.3	ASTM D 150
at 150°C	3.7	
Loss factor (60 Hz) at 25°C	2.5 × 10^{-3}	ASTM D 150
at 150°C	6.4 × 10^{-3}	
Temperature index (electrical)	130–150°C	IEC 216

cially in the case of PI, at least until suitable Class H or Class 220 casting resins are available. However the introduction of the PEN films, which presently cost less than the PI films, appears interesting already because it allows the coil insulation (which is the most critical one) to be upgraded to Class H. This allows the cast resin temperature index to remain in the range of 150°C: a higher reliability insulation can be realized in this way.

Casting Resins. In the cast resin transformer insulation systems, the resins' role is twofold: they have an insulating function, and they protect the transformer's active parts from the action of external agents. Actually, such resins could be more appropriately named resin systems because they are made of base resin, hardener, mineral filler(s), and additives. The epoxy system is the most widely used resin system. The polyurethane resin system was frequently adopted in the past, because it requires a low-energy input in the casting stage and offers a good flexibility (as concerns its low TG types). Presently, it is used only for instrument transformers.

The epoxy systems employed in cast resin transformers for indoors service are based on bisphenol A or F resins, which offer the required mechanical and electrical characteristics and permit a structural modification of the resin flexibility through a variation of the hardener content. TG values ranging between 50°C and 100°C can be reached in this way. As previously noted, transformers for outdoors service require the adoption of a different type of epoxy resins, the cicloalyphatic ones.

A complete and correct embedding of all the active parts requires that the resin system possess a low viscosity (e.g., 1000 mPa · s at 40°C) at the casting temperature; such viscosity depends essentially on the resin and on the type, shape, and dimensions of the filler powder particles. For example, the presence of fillers having small particles and/or fiberlike shapes can move the resin system viscosity toward very high values.

The hardener is the basic component that crosslinks the resin in order to attain the optimal properties of the cured system. The hardeners usually employed in these cases are liquid organic anhydrides, normally low viscosity (200 mPa · s at 40°C) ones.

Because of its low cost and excellent performance, the most widely adopted mineral filler is the quartz powder. Other mineral fillers, such as the zirconium oxide, allow a lower linear expansion coefficient of the crosslinked system to be achieved, while powders of silane-treated quartz or aluminum hydroxyde are adopted in applications for outdoors service.

A typical bisphenol A quartz-filled epoxy system is composed of

- resin: 22% in weight
- hardener: 18% in weight
- mineral filler: 60% in weight

This composition offers a viscosity of the filled system, at 40°C, of about 30,000 mPa · s, which becomes 6000 mPa · s, at 70°C. Its pot-life, at 40°C, is 10 h to 12 h, and the linear expansion coefficient is $30–35 \times 10^{-6}$.

The crosslinking process causes a shrinkage of the resin, which is responsible for internal mechanical stresses. The basics of such a process are presented in Fig. 11, where it is shown that

- during Phase 1, the resin system, still liquid, undergoes a thermal expansion, while its temperature reaches the crosslinking temperature θ_p;
- during Phase 2, the formation of crosslinks between the macromolecules causes a decrease of the resin system volume, lowering the relevant linear dimensions by an amount Δl_p;
- during Phases 3 and 4, when the temperature decreases, the resin further shrinks. These phases are separated by the TG point, where the shrinking slope becomes lower. The Δl_f variation of linear dimensions (referred to the initial value) represents the residual shrinkage of the resin system after curing.

CONCLUSIONS

This article reviewed the main insulating systems employed in power and instrument transformers. Because of the available space, it could not be as exhaustive and fully detailed as the subjects deserve. For instance, the specialized subject regarding the shapes adopted in the design of insulation systems could not be properly covered, particularly in terms of oil–paper transformers.

Then other important, but less frequently used, insulating systems could not be considered here and their description is left to the specialized literature. The following insulating systems are an example of such missing topics.

- *The Insulation for SF6 Transformers.* SF6 in the transformer insulation can be adopted at different levels. The simplest level involves the use of components (dry-type or cast-resin-insulated transformers) enclosed in SF6-filled vessels, where suitable bushings are located. In this way, it is possible to increase the insulation reliability, especially in severely polluted environments. More interesting solutions involve, practically, the substitution of the insulating oil with SF6 and the parallel introduction of suitable modifications to the solid insulation. The latter design, for instance, is widely adopted in current transformers for HV applications and has guided the development of fireproof power transformers, especially in Japan (20,21). Finally, it is worthwhile noting that, in some transformer prototypes, the cooling functions have been attributed to liquid perfluorocarbons, whereas the insulating functions have been left to the gas SF6.
- *Transformers with Superconducting Windings.* These machines have been reconsidered recently because of the availability of high-temperature superconductors, which would allow the adoption of liquid nitrogen, as cooling medium and as insulating medium. However, the research (and development) efforts currently available to produce superconducting wires that have critical magnetic field and critical current density values sufficiently high to allow their use inside an electromagnetic machine have not yet been successful.

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