

High Reliability Instrument Transformers with Oil-Paper Dielectric

by Dave Keshavdas



Instrument transformers with oil-paper insulation is a proven technology that has provided service since more than seven decades. As the technology has matured, it is even more important today to understand this technology to bring cost effective and reliable transformers to the market.



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Photo: ITC

Oil-Paper Dielectric

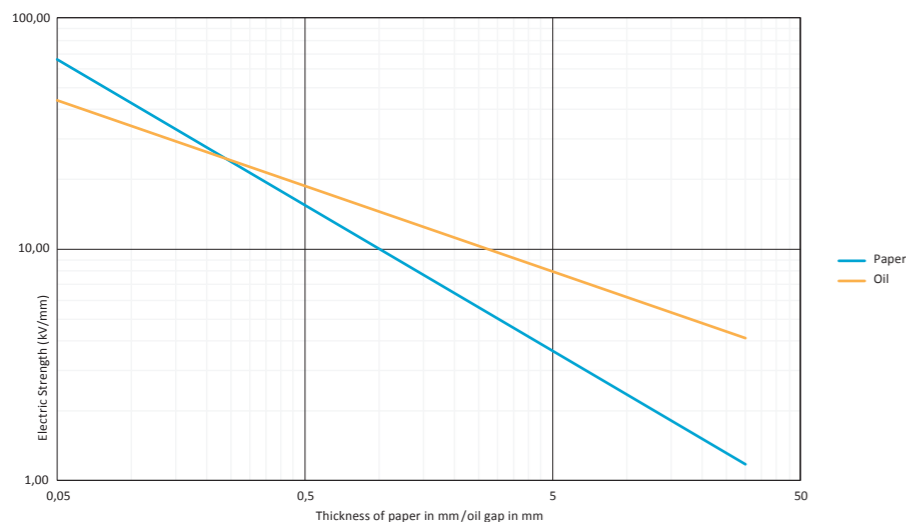
Any insulation either partially or completely loses its insulating behavior when the electric stress exceeds the electric strength of the insulating material. Such a loss can be temporary or permanent, which corresponds to self-healing and non-self-healing insulation. Due to the statistical nature of insulation breakdown, a different value of breakdown voltage occurs for every event of electric stress.

In practice, however, what does not lead to breakdown is easier to determine. This "withstand stress" must be capable of being determined strictly from the dimensions and the nature of the insulating materials. In an oil-paper insulation, it is of the form $E_0 d^{-b}$ kV/mm for a dielectric of thickness d (mm), where E_0 and b are constants determined empirically. See Figure 1. For very small thicknesses, the electric strength is not large because of the presence of weak spots, voids, holes, etc. in the individual sheets of papers. With the increase in the number of sheets (6-10), mutual overlapping of these weak spots reduces the probability of their occurrence in the same place.

Electrical Design

Designing the insulation for the LI voltage is a common pitfall in high voltage design. It is incorrectly believed that the short duration transients such as the impulse voltage creates the maximum damage to the insulation.

Figure 1: Electric Strength of oil and paper



Although the peak dielectric stress during the LI voltage is high, the breakdown strength of oil-paper insulation, as well as oil-gaps is significantly higher with impulse than during AC voltage test.

Generally, about 2.5 times higher strength can be assumed for LI voltages compared to 1 min AC test voltage. Due to its higher energy content, a long duration AC voltage does more damage to the insulation than an extremely short duration impulse voltage. Moreover, a long duration AC voltage applied at a lower level can also do more damage than 1 min AC test voltage. It is generally accepted that the lifetime of the oil-paper insulation follows an exponential relationship with respect to the breakdown strength as follows:

$\log t + n \log E_b = \text{constant}$
 n is about 30-40 and depends on the type of material.



For $t = 1$ min and $E_b = 15$ kV/mm as the limiting stress for the dimensioning voltage, this limits the electric stress at no more than 8.6 kV/mm at operating rms voltage for a design life of 30 years. In practice, the electric stress is designed not to exceed 3.5 kV/mm at operating rms voltage.

Electro-thermal Design

Due to the Arrhenius effect, thermal breakdown is a more serious problem than higher electric stress. The Montsinger effect suggests that only 8 K rise in temperature halves the life of the paper insulation between the temperature of 80°C and 140°C.

The dielectric losses in an instrument transformer become important as the system voltage increases, as the losses are proportional to the square of the system voltage. The losses increase the temperature of the dielectric, with the risk of overheating, eventually leading to thermal breakdown. Given the relative



temperature by about 10 K without any reduction in the life. Paper winding by machine or application by hand should be carried out with adequate tensioning such that there is no reduction in the mechanical strength on heating. This can be quality controlled using, for example, hardness tests before and after drying.

Design and Manufacturing for Reliability

The electric field in an instrument transformer is mostly non-uniform. An important characteristic of the non-uniform field is unequal distribution of the field between the electrodes. When the electrodes have identical profiles, the field is maximum on the surface of the electrodes and minimum in the middle. For dissimilar electrodes, the highest electric intensity occurs on the

permittivity of the dielectric and $\tan \delta$ measurement, it is possible to calculate the critical voltage leading to thermal breakdown at any given operating temperature. As the ambient temperature rises there is a theoretical limit to which an instrument transformer can be operated safely under conditions of high voltage and high ambient temperature.

The $\tan \delta$ value can be reduced through the process of drying. Extensive drying, however, can cause premature ageing and damage to the paper insulation due to depolymerization. A low DP value, measured indirectly through furan analysis of the oil, reduces the life of insulation. A well dried paper insulation is considered as having a residual moisture content of 0.3% - 0.5%.

To reduce the damages from thermal effects, the use of high strength thermally upgraded kraft and crepe papers allows a higher operating

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electrode with the smaller curvature and the minimum on the opposite electrode.

Insulation for Voltage Transformer

The primary winding of an inductive voltage transformer should be

done with an adequate number of turns to allow a low flux operation at the working voltage. A magnetic field flux density of up to 0.8 T is recommended at 1.2 times the working voltage. To overcome the stresses during the lightning impulse each winding layer acts as a capacitance foil while the inductance of the coil has a negligible effect. The winding layer capacitances can be made approximately uniform by reducing the winding lengths at the higher voltage layers. An appropriately dimensioned high voltage electrode in a voltage transformer will reduce the stress significantly. Similarly, the electrode earthed in service will confine the voltage distribution in the space between the electrodes and eliminate spurious discharges from the earthed core sharp edges. To reduce the surface discharges from the high voltage electrode, it is necessary to wrap it with semi-conductive or insulation paper. In free oil gaps between any areas of high potential difference, impurities in the oil reduces the dielectric strength of oil substantially and increases the probability of a complete breakdown. To avoid this, free oil gaps can be prevented by inserting papers perpendicular (barriers) to the field.

Insulation for Current Transformer

A carefully shaped core housing in live tank CT will make the insulation

profile such that the boundary surfaces follow the equipotential surfaces, and the tangential stresses are minimized. With increasing service voltage, it is necessary to increase the inner diameter of the housing proportionately.

Field analysis should be carried out to determine the stresses in

the diagonal direction for the core housing. A design without any intermediate shields is possible up to the system voltage of 550 kV which is also convenient to manufacture.

Capacitive Grading for Bushing Tube

The bushing tube is capacitively graded with single sided insulation shields or screens inserted at certain positions to give a uniform axial or radial distribution. To reduce the effects of field enhancement, the free oil gaps in the insulation must be minimized.

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The boundary discharges on the paper are more likely due to surface level impurities and moisture. Therefore a design with uniform axial distribution and minimal axial stress is superior. The axial field strength limit is 1 kV/mm at the dimensioning voltage. The radial field strength can be allowed to vary but has to be kept well within the breakdown limit of 15 kV/mm at the dimensioning voltage.

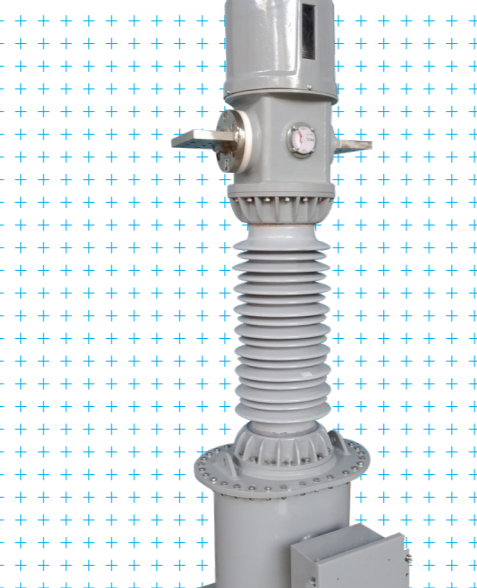
Oil Impregnation

After drying of the paper insulation, instrument transformers are filled with oil under vacuum of less than 0.5 mbar. The air remaining in the gaps of the paper is evacuated during this vacuum phase.

Degassed, vacuum filtered mineral oil, with residual moisture at less than 5 ppm, at a temperature of 60-75°C is filled in the transformer. The oil penetrates the voids in the paper through capillary action. Once the vacuum is released and air is let in, the voids in the paper creates a partial vacuum which lead to absorption of the oil. The air exerts a positive pressure and contributes together with capillary action in filling the voids with oil.

The most important factor that influences the ingress of oil is the capillary structure, the geometry of the capillaries and their accessibility. The gaps in the paper layers influence the ingress of oil especially for very tightly wound kraft paper layers, where the flow of oil can only be in a direction

parallel to the layers. The residual air in paper strongly affects its permeability as it slows down the speed of oil impregnation. When the oil penetrates a capillary, the residual air inside becomes compressed by the capillary forces and hence the internal pressure builds up. For this reason, to reach a faster ingress of oil it is very important to have less air inside. The efficiency of removal of trapped air is dependent on the vacuum level.



TRANSFORMERS WITH OIL-PAPER DIELECTRIC

The viscosity of the oil and surface tension at the oil-gas interface also affect the capillary rise and the flow rate in paper. The volume of the oil that enters inside the capillary is inversely proportional to the viscosity. The viscosity of the oil decreases when the temperature increases, therefore the rate of impregnation is faster at higher temperature. At 40°C, complete oil impregnation in paper requires about 7 days, whereas at 70°C, it can be achieved within 48 hours.

Corrosion Proof Body

To ensure longevity of the instrument transformer, the tank body should be absolutely corrosion proof throughout its lifetime. The tank if made of mild steel material should be hot dip galvanized to ISO 1461. In case the end-user requires high aesthetics, a duplex system can be adopted. Alternatively, the body can be of powder coated stainless steel AISI 304/316 or powder coated marine grade aluminum alloy 5083. All hardware should be made of stainless steel to AISI 304/316.

Hermetic Sealing

The various terminals of the instrument transformers as well the tank surfaces should be machined and sealed with high quality hydrogenated nitrile or viton rubber seals suitable for up to 160°C or higher. The transformer should be

leak tested at a positive pressure of 1.5 bar without and with oil at the manufacturing stages before and after oil filling, respectively.

High Safety Features

Stainless Steel Bellow

Mineral oil expands at a rate of approximately 4 liters for every 100 liters at a temperature difference of 50°K. Hence, an expansion device, such as a stainless-steel bellow becomes necessary. Gasses (especially hydrogen) evolved due to high moisture or partial discharges also expand the bellow. Such a stainless-steel bellow should be designed with a sufficient inner diameter so that speed of its expansion is higher.

When the bellow is connected to the high voltage tube of the instrument transformer, any abnormal expansion of the bellow can be used to disconnect it from the tube connected at high voltage. This will lead to its de-energizing and the transformer can then be taken out of service for diagnostics. Hence, the stainless-steel bellow serves a very important function to relieve the excessive pressure build up in oil and could prevent premature explosion.

Oil over-pressure switch

In case of a fault due to electrical discharges inside the transformer, or

an internal arc fault, the oil pressure will rise. In most cases, the rise is usually a slow event which can take from few minutes to even few days. If the excess pressure can be detected, the transformer can be de-energized and taken for examination before it can lead to an explosion.

Depending on the height of the instrument transformer, a suitable oil overpressure switch is fitted at the bottom of the transformer. This detector is provided with Normally Open/Closed (N.O./N.C.) contact at the normal, predefined hydrostatic pressure of the oil. In case of excessive pressure rise in the oil beyond the set point of the detector, the detector will close with one end connected to the metal tank body which is grounded in service. The potential contact of the detector could be connected to the visual and/or audio alarm to allow the operator to de-energize the instrument transformer.

Composite Insulators

Composite insulators are an alternative to porcelain insulator for the external insulation and are manufactured with a high strength inner FRP tube and external silicone rubber sheds. The physical properties of the FRP tube material does not allow it to shatter like porcelain. In the event of any fault, expected failure mode is rupturing or bursting which eliminates the

occurrence of hazardous condition to personnel and surrounding equipment.

Equipment using hollow core composite insulators can withstand seismic acceleration stresses up to 1 g without damage due their lower weight, high damping factor and high strength design characteristics. The hydrophobic properties of the silicone rubber sheds have a better electrical performance in contaminated condition.

Water on the surface of hydrophobic materials forms water beads, so the conductive contamination dissolved within the water beads is discontinuous. This condition results in lower leakage current flow and the probability of dry band formation, which in turn requires a higher impressed voltage to cause flashover. The higher resistance of silicone rubber helps to limit the arcing and minimizes the flashover.

Oil with Negative Gassing Tendency

Due to thermal or electrical stress through partial discharges, the oil-paper insulation can be degraded and release various gases, such as hydrogen. Since mineral oil is gas-evolving, the gases could accumulate and make partial discharges persistent. This could eventually lead to an explosion of the transformer and the risk of fire. By adding 3-10% of Mono/dibenzyltoluene (M/DBT) to the mineral oil, it can become gas absorbing from gas evolving. Such an oil is modified to behave with negative gassing tendency which helps eliminate the gaseous channels and thus suppress the probability of discharge occurrence.

Conclusion

Not only are better materials for both oil and paper available today, but the knowledge gained in insulation design over the past decades is also of advantage to implement stress optimized designs. Despite introductions of dry type instrument transformers, the advantages of oil-paper insulation are too difficult to ignore and will remain relevant for the foreseeable future.

