Practices of Insulating Materials in Instrument Transformers

A. Masood, M.U. Zuberi, M.S. Alam, E. Husain, M.Y. Khan

I. INTRODUCTION

The study of insulating material selection, behavior and performance are important aspects to be considered for designing any electrical instrument, machine or device. Apart from conductors, insulator forms the backbone of any electrical system. Though insulators form the backbone, they are also the weakest link in the system. Hence, maximum care and attention is needed while choosing insulating materials for a given application so that it gives the desired performance under worst working conditions. This paper addresses the problem of selection criteria, test specifications and material treatment to justify the use of various dielectrics/insulating materials used for insulating high voltage instrument transformers i.e. CTs and PTs.

While in use, insulating materials are subjected to various electrical, mechanical, thermal stresses and partial discharges. Therefore, criteria for selection of these materials is, that, they must withstand these stresses without or with such rate of deterioration such that their performance is not affected throughout the life expectancy of the equipment, which is considered approximately 25-30 years.[1]

For instrument transformers, selection and tests for insulating materials are major considerations. The governing standards of the current transformer is IS: 2705, IEC: 185 and for the voltage transformer is IS: 3156, IEC: 186. The requirements of instrument transformer are specified in terms of service conditions, ratings and special features such as limiting dimensions etc. Performance is evaluated by various type tests, routine tests and some optional tests for checking special features not generally covered by type test or routine tests

The various types of tests carried out on both CTs and PTs affecting their dielectric medium are given in Table I.

<table>
<thead>
<tr>
<th>Type of Test</th>
<th>Applied on</th>
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<tbody>
<tr>
<td>Short Time Current Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Temperature Rise Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Lightning Impulse Voltage Withstand Test</td>
<td>Yes</td>
</tr>
<tr>
<td>H.V. Power Frequency Wet Withstand Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Routine Test</td>
<td></td>
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<tr>
<td>H.V. Power Frequency Dry Withstand Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Test on Primary Winding</td>
<td></td>
</tr>
<tr>
<td>H.V. Power Frequency Dry Withstand Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Test on Secondary Winding</td>
<td></td>
</tr>
<tr>
<td>Over-Voltage Inter-turn Test</td>
<td>Yes</td>
</tr>
<tr>
<td>Partial Discharge Test</td>
<td>Yes</td>
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</tbody>
</table>

The temperature rise of winding when subjected to continuous thermal current or voltage as applicable to instrument transformer at the rated frequency and current/voltage output determines the class of insulation or dielectric surrounding the winding. Having determined the class of insulation or dielectric, the consideration is based on the mechanical/electromagnetic stress generated in windings and in the dielectrics surrounding it, due to dynamic short time current condition. Mechanical stress may occur during normal handling during manufacture, transportation and erection in case of CT and PT.

Besides, mechanical stress, the dielectric has also to withstand electrical stress during lightning impulse and power frequency voltage applications under wet as well as dry conditions. Partial discharge test is an indicator of i) presence of air pocket in dielectric and/or ii) loose electric contact and/or iii) external corona discharge. This is subject to the condition that the properties of insulating material are in conformance to the specifications/requirements.

One basic requirement for all materials used in oil immersed transformers is that they should be compatible with insulating oil and should not react with or deteriorate the oil. Out of the three broad categories of insulation, namely, solid, liquid and gaseous; solid and liquid insulation materials have been discussed.

Tests for different insulation components used in CT/PT are performed according to Indian Standards as mentioned in Table II.
II. BRIEF DESCRIPTION OF INSULATING MATERIALS

A. TRANSFORMER OIL

Petroleum based mineral insulating oil is used in transformer as a dielectric medium as well as a coolant. Transformer oil [1] which belongs to Class A insulation mainly consists of four generic classes of organic compounds, namely, paraffins, naphthenes, aromatics and olefines. Paraffins and naphthenes are saturated hydrocarbons while aromatics and olefines are unsaturated hydrocarbons. For better stability of low viscosity type fresh insulating oil, it is desirable to have more of naphthenes or paraffins, less of aromatics and none of olefines. Such an optimum balance is achieved by a carefully controlled refining process. An oil is known as naphthenic base or paraffin base oil depending upon the dominance of naphthenes or paraffins. Naphthenic base oils are more in use as dielectrics in colder countries since they do not consist of wax type constituent which increases their viscosity at very low temperatures. Due to cost consideration, in a country like India having moderate climate, it is advisable to use paraffin base oil.

Insulating paper being hygroscopic [5], the incipient moisture is dried in heated vacuum chambers. The degree of dryness is monitored by measurements of loss tangent on the major insulation. When optimum values of measurements are obtained during the drying cycle, instrument transformers are impregnated with dried and degassed transformer oil or else the design and operation of the equipment is limited by the occurrence of partial discharges either at the interface or in voids. It is possible that under electrical stress and working condition, a slow change in material may lead to localized variations in physical properties, generally towards their degradation [4].

IS:335, gives various min./max. values of characteristics ensured by oil manufacturers. Test certificate is furnished along with the supply stating the exact values. These sixteen characteristics are - appearance, density, kinematic viscosity, interfacial tension, flash point, pour point, neutralization value, oxidation stability, ageing characteristics after accelerated ageing, presence of oxidation inhibitor, water content and SK values.

On receipt of oil at the works, few quality tests are performed, namely, electric strength (BDV), tan δ, specific resistance, oxidation stability, ageing characteristics after accelerated ageing, presence of oxidation inhibitor, water content and SK values.

II. MATERIALS

<table>
<thead>
<tr>
<th>TABLE II</th>
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<tbody>
<tr>
<td>MATERIAL</td>
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<tr>
<td>Liquid dielectric</td>
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<td>Insulating Kraft &amp; Crepe Paper, Class Y insulation, are one of the earliest forms of composite dielectrics used in high voltage engineering since the end of the 19th century. Paper as such has very poor dielectric properties, but when impregnated with oil, the properties of the composite dielectric improve considerably. Paper is a product of 'Cellulose' obtained from soft wood pulp.</td>
</tr>
</tbody>
</table>
of mainly pine or spruce found in Scandinavia[1]. Cellulose is a complex carbohydrate, which forms the chief constituent of the cell walls of plants. The cell walls contain lots of contaminants like lignin and resins which are removed by the sulphate process treatment and careful water washing.

Normal thickness of paper available in the market are 15, 20, 25, 50, 65, 75, 100, 125, 160, 200 or 250 micrometers. It forms an excellent insulation between primary and secondary windings. Additional strength is provided during taping process so as not to allow presence of air pockets, which are trapped between layers. This additional strength is provided by use of crepe paper. Crepe paper is made of Kraft insulating paper by a process, which imparts irregular close crimps to it, thus increasing its thickness as well as extensibility in the machine direction[2]. Crepe paper normally available has nominal values for elongation break at 50%, 80%, 120% and 200% etc. with coarse, medium or fine creeping.

On impregnating the paper with transformer oil after drying and degassing, the voids in paper are filled-up with oil expelling the air. Drying process of paper takes place in a warm vacuum chamber. In order to avoid damage to cellulose, slow drying is performed within a temperature of 120° C on achieving vacuum of 0.01 Torr, oil is impregnated at the reduced temperature of about 60° C.

In the composite insulation, the dielectric properties are improved considerably. Electric strength improves from 10 or 11 kV/mm to 60 or 70 kV/mm. tanδ decreases from 0.1 or 0.2 to 0.004 to 0.006 at approximately 90°C. Standard values of relative permittivity, loss tangent and electric strength of paper impregnated with oil at 20° C are 3.5 - 3.9, 0.0026 – 0.003 and 60 - 70 kV/mm.

Above results are considerably affected by the presence of moisture and ‘Service electric stress’. To give trouble free life to equipment, it is advisable to process and impregnate the paper with transformer oil carefully and keep the maximum ‘Service stress’ under 2 kV/mm.

C. PRESS PAPER

Press paper, Class E insulation, is made of insulating Kraft paper. A large no. of thin papers having thickness of the order of 30-micro-meter are pressed together by a hot press method in the desired form. A glossy finish is provided to the surface. In the absence of binding material, electrical properties of these boards are near that of high quality paper. When impregnated with oil, its dielectric properties become equivalent to those of insulating Kraft paper.

D. BAKELITE

Bakelite, Class E insulation, is available in the form of a board. It is produced by polymerization of phenol and formaldehyde resins, [1] which are subsequently cross-linked under pressure. When dried, degassed and impregnated with oil, its relative permittivity becomes 4.2 and electric strength becomes 40 - 50 kV/mm.

E. UNIMPREGNATED DENSIFIED LAMINATED WOOD

Wood based laminates, Class A insulation, are manufactured from selected veneers (mostly 2 mm thick) obtained from various timbers. The veneers are dried and partially impregnated with neutral phenol formaldehyde and then densified under heat and pressure. Alternate veneers with grain orientation at right angles to each other are placed so as to obtain high mechanical strength.

In areas, which require higher mechanical and moderate electric strength, this material is used extensively, for example, in core clamps and vertical supports. As its moisture absorption capacity is high, wood is assembled with core and coil etc. and then dried, degassed and impregnated with transformer oil so that moisture is replaced with the oil. Wood yields compressive strength as high as 185 MPa and electric strength as high as 60 kV/mm edge wise.

F. COTTON TAPE

Cotton tape, Class Y insulation, is manufactured from cotton yarn, which is reasonably free from reps, slubs, knots and kinks etc. Tapes are evenly woven. They are singed, brushed and calendered. Its use is limited to low tension areas, like taping core etc. It is available in 20-30 mm width of 50 – 100 meter roll lengths. As its breaking load is approx. 10 Kg, it can provide moderate clamping strength. Its pH value is between 6.0 and 8.5, chloride content is 10 ppm (max.) and conductivity of aqueous extract is 50 micro-mhos/cm. Therefore, it should be dried alongwith the assembly and then impregnated with resin in dry type transformers or with oil in oil immersed transformers.

G. SELF ADHESIVE POLYESTER FILM TAPE

This tape, Class B insulation, is available with backing of polyester film in two thickness of 50 and 80 micro-meter with non corrosive thermosetting adhesive coating. It provides excellent service in areas requiring adhesive strength of 3.0 N/cm as well as electric breakdown capability of 5 kV (for 50 micro-meter thick tape)/8 kV (for 80 micro-meter thick tape). It withstands temperature upto 130° C with ease. It is also oil resistant. The firmness of the tape increases on heating at 150° C for 1 hour or 130° C for 2 hours and remains so on cooling; it does not soften appreciably on subsequent re-heating. The initial heating of the thermost adhesive improves the solvent resistant and increases the softening temperature.

H. PVC TAPE

PVC, Class Y insulation, is a polymer product of the monomer Vinylchloride derived from ethylene. PVC, a polar dielectric, is very hard, brittle and thermally unstable product. Therefore, other substances are added to make it suitable for the use. Tanδ of PVC compounds is high, which restricts its use only for low voltage application. ‘Working stress’ is limited to 3 kV/mm[1]. It works safely upto 90° C beyond which it begins softening. It is available in various colors, various tape width 15 mm to 30 mm and roll lengths of 25 meters to 50 meters.
I. ENAMELED ROUND WINDING WIRE

High conductivity annealed round copper conductor has uniform covering of durable and flexible synthetic enamel suitable for elevated temperatures [1]. The enamel (Terephthalate polyester based) has a smooth surface free from embedded particles of dust and other deleterious material. This enamel, Class H insulation, shows no cracks even at working temperatures up to 180° C. The wire is available in fine and medium covering from 0.02 mm up to 5.00 mm. Wire showing abrasion resistance from load 5 N to 8 N on nominal conductor diameter from 0.8 mm to 2.5 mm makes it ideal to wind on a former or core either manually or by machine. Electric breakdown voltage of approximately 4 to 5 kV on medium covering wires makes it safe to employ in suitable layer windings in high voltage applications in PTs and CTs.

J. HOLLOW INSULATOR

Ceramics, Class C insulation, also known as porcelain in one of its forms, are widely used for insulators and bushings in outdoor applications owing to their non-hygroscopic nature and high mechanical strength. It constitutes of clay, aluminum oxide, feldspar and quartz. Ceramics [1] requiring high mechanical strength and low dielectric losses contain alumina. Tanδ values of porcelain is high i.e. 20x10^{-3} at 20° C, it increases with temperature and becomes 40x10^{-3} at 50° C, thereby, increasing the dielectric losses. Breakdown strength is also less compared to other materials, i.e. 20 kV/mm but remains stable up to 120° C.

K. EPOXY RESIN

The word epoxy refers to a compound containing more than one epoxide group per molecule, i.e., an oxygen atom united with two carbon atoms joined already in some other way. Resin is a substance obtained from plant, it is also a substance obtained from man-made processes. Epoxy Resins, Class F insulation, being thermosetting plastics exhibit hardening quality in their molecules and so it is high i.e. 20x10^{-3} at 20° C, it increases with temperature and becomes 40x10^{-3} at 50° C, thereby, increasing the dielectric losses. Breakdown strength is also less compared to other materials, i.e. 20 kV/mm but remains stable up to 120° C.

III. MAJOR INSULATION LAYING AND PROCESSING

Since partial discharge has been prescribed as a routine test (Table I), on all CTs and PTs of 132 kV and above rating, the processing of insulation has to be done carefully to avoid any occurrence of discharge, which may affect the life as well as the accuracy of measurements.

The primary winding is insulated with electrical grade kraft insulation paper. The insulation is laid over the region enveloping the secondary cores and over the straight portion leading to the primary terminals. In the region around the secondary cores, a shield is provided to protect the secondary from the high voltage system. Grading of insulation by using metallic screens with shaped contours ensures a homogeneous radial stress distribution, besides regulating the stress distribution axially in the air porcelain system as well.

After laying of the insulation, the coil is conditioned under high humidity in a humidity chamber with a relative humidity of about 90%. The changes in electrical properties (capacitance C, insulation resistance R, and tanδ) are measured with time and the process is continued till these properties become practically constant. Figure 1 shows the measurement of C, R and tanδ for a typical sample.

As soon as the conditioning is over, the coil is transferred to a heated vacuum chamber connected to a sophisticated vacuum system to achieve a very high degree of vacuum during processing. The degree of dryness is monitored by measurements of C, R and tanδ. Figure 2 shows the variation of the measured quantities during drying. When optimum values of measurements are obtained during the drying cycle, the insulating paper is impregnated with dried and degassed transformer oil.

Finally, we keep in mind that no universal law is available to interpret and understand the insulating material behavior; each one will fix the rule according to the stress condition[3-4].
IV. REFERENCES


Fig. 1. Conditioning of coil sample at 92% relative humidity and at 32°C.

Fig. 2. Drying characteristics of coil sample