Lecture # 13

High Voltage Testing

The fabrication and selection of insulation for a particular purpose is a subject of extreme importance in electrical engineering. For example, the winding insulation of rotating machines must provide electrical isolation between turns and the metal parts of the stator and rotor and in addition must have capability to withstand thermal and mechanical shocks due to vibrations. Transformer winding insulation must be thermally strong in order to sustain the high temperatures resulting from overloads and short-circuits. Besides, oil used in transformers must have cooling properties in addition to provide insulation. Overhead line insulators must provide electrical isolation and mechanical support to conductors. In this context, testing of insulation is an essential part of electrical power engineering practice, ensuring long-term reliability of power system components.

Withstand Test

Withstand voltage of insulator is referred to the voltage the insulation can sustain without breakdown. Electrical insulation in practice must be capable of withstanding normal operating voltages in addition to the occasional power-frequency and impulse overvoltages experienced during operation. Using suitable testing procedures, the withstand capability of insulation to such voltages can be determined. The essential objective of high voltage laboratories is the testing of insulators before being used to fulfill the required prime purpose and other, which include; thermal stability over wide ranges of temperatures and maintaining both chemical and physical properties during its entire service life. Since all equipment has to withstand a certain voltage without damage under operating conditions, all equipment are subjected to factor of safety. Therefore withstand-tests on insulation are usually performed with voltages applied that are more than the normal voltage, but less than the breakdown voltage.

Impulse withstand test: The insulator is mounted on a test bench and tested with lightning impulse. Thus a 1/50μs wave of the specified voltage (corrected for humidity, air density etc) is applied. Flashover or breakdown should not occur. The test is repeated five times for each polarity.

One-minute dry test: The insulator is cleaned and is mounted as specified and the prescribed voltage (corrected for ambient conditions) is applied at power-frequency under dry conditions and is gradually increased and maintained at a prescribed level for one minute. The insulation must withstand the test voltage without breakdown or flashover during the test. A factor of safety is often used which in most cases is 2.

One-minute wet test: The insulator is sprayed throughout the test with artificial rain drawn from a source of supply at a temperature within 10°C of the ambient temperature of the neighborhood of the insulator. The rain is sprayed at an angle of 45 degrees on the insulator at the prescribed rate of 3 mm/minute. The insulator is subjected to a voltage with a prescribed factor of safety and is maintained for one minute.

Dielectric Parameters

All insulating materials or dielectrics fail at some level of voltage. Thus all insulating materials have certain withstand capability, which is generally termed as its dielectric strength and is the voltage stress that a material can withstand before breakdown occurs. Test variables include electrode configuration, geometry of the test object, and the frequency and rate of application of the test-voltage.

All practical dielectric material have capacitance and insulation resistance and are therefore referred to as lossy dielectrics. A lossy capacitor is thus composed of dielectric capacitance C_S and a dielectric resistance R_S in series forming an Equivalent Series Circuit (ESC) as shown in Figure (1).

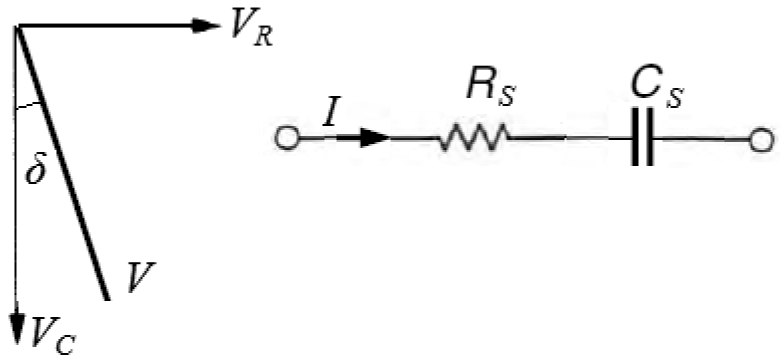

Figure 1: Equivalent Circuit of Dielectric

In a series circuit the current will be the same in both resistance and capacitor, but the voltage drops across each will be different; the capacitor voltage drop V_C lags the voltage drop across the resistance V_R by 90 degrees. The voltage V across the combination is then the resultant of the voltage drop across the capacitor and resistance. The loss angle is also defined by the angle between the voltage drop V_C across the capacitor and the total voltage V across the series combination of resistance and capacitance as illustrated by the vector diagram in Figure (1). However, when representing the electrical circuit parameters, the loss-tangent of a dielectric is equal to ratio between the real impedance vector of the circuit and the reactive impedance vector. From vector diagram of Figure (1), the loss-tangent is then given by:

$$\tan\delta = \frac{R_S}{X_C} = \omega C_S R_S \qquad 1$$

Dielectric resistance, capacitance and loss tangent are important parameters in the specification of any insulation and all these are inter-related. They have a profound impact on the performance of the insulator and can govern the types of application for which the insulation may be used. Capacitors with dielectric resistance will naturally need to dissipate power as heat. For some circuits with only low values of current, this may not be a problem. However, in many cases where current levels are high, the power levels dissipated by the dielectric may result in a significant temperature rise. This needs to be within the operational bounds for the capacitor otherwise damage may result, and this is essential to be incorporated within the design of circuits. It is found that when the temperature of a capacitor rises, then generally the dielectric resistance increases, although in a non-linear fashion. Increasing frequency also has a similar effect.

The losses in the dielectric are measured by tanδ when AC voltage is applied. Loss Analysis (DLA) and tanδ evaluation are well-established tests and have been used for many years, especially to determine the condition of insulation used in electrical machines. Sometimes insulators after manufacture are found to contain defects in the form of voids or cavities. These defects (due to non-homogeneity) have lower breakdown strength than the material itself, and if present would gradually deteriorate and cause ultimate breakdown after some time, the time may range from days to years.

Voids are also formed when the cable insulation is subjected to cyclic voltage stresses far less than the intrinsic strength of insulation. The long-term exposure of insulation to such stresses causes gradual deterioration of insulation over a passage of time, which may extend to years. The deterioration, in many cases is un-noticeable and the cable may perform normally. However, degradation gradually builds up to a stage where defects such as micro-cracks and voids that are of sufficient size to sustain gaseous discharges causing ultimate failure with time. Both dielectric loss energy and loss-tangent are affected by the void content of the insulation, the higher the void content the higher the loss-tangent and dielectric loss. The higher the void content, the higher is the loss-tangent and dielectric loss. The measurement of dielectric loss in insulating materials is thus very important, as it provide a good indication of the dielectric strength and quality of insulating materials. In the case of cable, dielectric loss measurements are now generally recognized as the most reliable guide to the quality and condition of the cable, and the manufacturers usually quote figures of loss-tangent at different temperatures and frequencies. Dielectrics having low values of loss-tangent indicates low power loss and are therefore regarded as better insulating materials. Moreover, high insulation resistance means less leakage current, which also is an indication of better insulating materials.

The Schering Bridge (Non-destructive Testing)

The dielectric loss and insulation resistance is most reliably and conveniently measured with the help of Schering Bridge, which is considered to be the most important apparatus for high voltage testing laboratories. Besides dielectric loss and insulation resistance, parameters such as dielectric capacitance can also be determined by using Schering bridge without destroying the specimen. Measurements of parameters of the insulating material made with Schering Bridge usually do not destroy the material as in the case of withstand tests; the method of using Schering Bridge is commonly referred to as non-destructive testing technique.

A Schering Bridge is an electrical bridge circuit, which is generally used for measuring an unknown capacitance and insulation resistance of a dielectric material. Form these parameters, the tanδ can be measured. The loss-tangent is the measure of the deviation of the phase angle between capacitor voltage and current, this difference being caused by the dielectric loss within the capacitor.

A Schering Bridge as shown in Figure (2) is a four-arm bridge circuit. The specimen of insulation for which measurements are to be performed, represented by a series resistance–capacitance (R_1 and C_1) combination, is connected in the arm BC of the bridge.

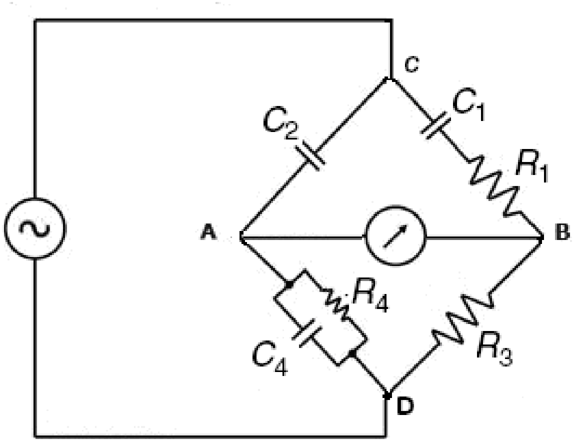

Figure 2: Schering Bridge

In the Schering Bridge shown in Figure (2), the resistances R_3 and R_4 are known, while the resistance R_1 is unknown. The capacitance C_2 and C_4 are also known, while the capacitance of C_1 is to be measured. In practice R_3 is a variable and is usually in the form of a decade box and its maximum value is limited to about 100kΩ in order to keep the effects of any stray capacitance relatively small. R_4 is made constant and in general realized as a multiple of (1000/π)Ω thus making possible a direct reading of tanδ, provided a constant value of the frequency is indicated. The coordinated adjustment of elements R_3 and C_4 are necessary to balance the bridge. The capacitor C_4 is generally a standard laboratory variable capacitor. A good range for this is usually between 0.1μF and 0.1nF. To measure R_1 and C_1, the values of C_2 and R_4 are generally fixed, while the values of R_3 and C_4 are adjusted until the current through the ammeter between points A and B becomes zero. This happens when the voltages at points A and B are equal, in which case the bridge is said to be "balanced". The balance condition for any AC bridge is similar to that of Wheatstone bridge, except that complex impedances rather than resistances are used in the expression for balance condition that is:

$$\frac{Z_{CA}}{Z_{AD}} = \frac{Z_{BC}}{Z_{DB}} \qquad 2$$

For the Schering Bridge shown in Figure (2), the impedances of the arms are as follows:

$$Z_{CA} = \frac{1}{j\omega C_2}$$

$$Z_{AD} = \frac{R_4}{1 + j\omega C_4 R_4}$$

$$Z_{BC} = R_1 + \frac{1}{j\omega C_1} = \frac{1 + j\omega C_1 R_1}{j\omega C_1}$$

And $$Z_{DB} = R_3$$

Substituting all the above impedances in the balance condition as depicted in Eq (2):

$$\frac{1/ j\omega C_2}{R_4 /(1 + j\omega C_4 R_4)} = \frac{(1 + j\omega C_1 R_1)/ j\omega C_1}{R_3}$$

Rearranging and simplifying, we obtain:

$$\frac{R_3}{j\omega C_2} = \frac{1 + j\omega C_1 R_1}{j\omega C_1} . \frac{R_4}{1 + j\omega C_4 R_4}$$

Cross-multiplying and simplifying, we obtain:

$$C_1 R_3 + j\omega C_1 C_4 R_3 R_4 = C_2 R_4 + j\omega C_1 C_2 R_1 R_4 \qquad 3$$

Equating real and imaginary terms separately on both sides of Eq (3) will provide the values of unknowns in terms of the known values. Thus equating the real parts on both sides of Eq (3):

$$C_1 = C_2 \left(\frac{R_4}{R_3} \right) \qquad 4$$

Equating the imaginary terms on both sides of Eq (3):

$$R_1 = R_3 \left(\frac{C_4}{C_2} \right) \qquad 5$$

The detector used to certify balance conditions is generally a vibration galvanometer or oscilloscope (digital or cathode-ray). The Schering bridge network is grounded at the low-voltage end of the high-voltage testing transformer. Under balance conditions, both sides of the detector are at the same potential, but the shield is grounded. Therefore stray capacitances appear across the branches CA and BC, and depending upon the length of the connecting cables to C_2 and C_1, these stray capacitances can assume values over a wide range.

Example 1: A Schering bridge is to be used for the measurement of unknown parameters of a piece of dielectric material at power frequency consists of a standard capacitor of 0.1μF, 10 kV and a fixed resistance of 10kΩ in arm AD. At balance, the capacitor in arm AD has a value of 10nF and resistance in arm DB is 300kΩ, determine the capacitance, insulation resistance and loss-tangent of the dielectric material.

Solution:

Given that:

$C_2 = 0.1\ \mu F$
$R_4 = 10\ k\Omega$
$C_4 = 10\ nF$
And $R_3 = 300\ k\Omega$

Using:

$$C_1 = C_2\left(\frac{R_4}{R_3}\right)$$ for the unknown capacitance:

$$C_1 = 0.1\times10^{-6}\times\left(\frac{10}{300}\right) = \mathbf{3.33\ nF}$$

And $$R_1 = R_3\left(\frac{C_4}{C_2}\right)$$ for the unknown resistance:

$$R_1 = 300\times10^{3}\times\frac{10\times10^{-9}}{0.1\times10^{-6}} = \mathbf{30\ k\Omega}$$

The dielectric loss given by loss tangent is:

$$\tan\delta = \omega C_1 R_1 = \omega C_4 R_4$$

Since the test is performed at power frequency and assuming that power frequency is 50Hz, the loss tangent is:

$$\tan\delta = 2\pi\times50\times10\times10^{-9}\times300\times10^{3} = \mathbf{0.942}$$

Example 2: The known components of a Schering bridge at power-frequency test voltage are follows:

C_4 is variable between 10^{-9} and 10^{-6} F
R_4 is variable between 0 and 5kΩ
C_2 has a value of 500pF and is a standard air capacitor
R_3 is fixed at 1kΩ

Calculate the maximum value of the unknown capacitance that can be measured. If on balance the value of capacitance of the dielectric is measured as 190pF with C_4 adjusted to 9nF, calculate the loss-angle of the dielectric.

Solution:

For maximum value of capacitance to be measured, the maximum value of the resistor R_4 of the bridge must also be adjusted to maximum. Using Eq (4), the maximum value of unknown capacitance that can be determined will be as follows:

$$C_1 = 500\times10^{-12}\times\left(\frac{5000}{1000}\right) = \mathbf{2500pF}$$

In order to calculate the loss angle of the dielectric whose capacitance under balance conditions is measured to be 190pF with C_4 adjusted to 9nF, it is required to find the value of the insulation resistance R_1 of the dielectric material. Therefore using Eq (5):

$$R_1 = 1\times10^3 \times \frac{9\times10^{-9}}{500\times10^{-12}} = 18\text{k}\Omega$$

The loss-tangent is:

$$\tan\delta = \omega C_1 R_1 = 2\pi\times50\times190\times10^{-12}\times18\times10^3 = 1.07\times10^{-3}$$

Form which:

$$\delta = \arctan(1.07\times10^{-3}) = \mathbf{0.06\ degrees}$$

Measurement of Dielectric Constant

Schering Bridge can also be used to determine the dielectric constant (relative permittivity) of insulating materials by comparing the geometrical similar capacitors with air as a dielectric and with the material of interest as dielectric. The process of measurement of capacitance is the same, which is used as a standard procedure on Schering Bridge for the measurement of unknown capacitance and resistance under balanced condition. In order to measure the dielectric constant the insulation under test is machined to give a reasonable cylindrical shape with diameter *D* and thickness *d*. The dielectric is then sandwiched between two identical disc-shaped metal electrodes. Care must be taken that the diameter of electrodes is same as that of the cylindrically shaped dielectric material and are applied with no resulting spacing at the interface. The object is then connected across arm BC of the bridge and the capacitance is determined from Eq (4) by balancing the bridge by the procedure described earlier. Once the capacitance is known then:

$$C_1 = \frac{\varepsilon A}{d} = \frac{\varepsilon_0\varepsilon_r\pi D^2}{4d}$$

Or

$$\varepsilon_r = \frac{4dC_1}{\pi\varepsilon_0 D^2}$$

Or

$$\varepsilon_r = \frac{0.144\times10^{-10}\,dC_1}{D^2} \qquad 6$$

Power Loss in Dielectric

The knowledge of power loss in a dielectric or insulating material is essential in the design and selection of material for a particular application. The dissipation factor or the loss-tangent does not provide actual power losses that occur in a dielectric material subjected to electric field. The average power loss is given as:

$$P_C = \frac{1}{2}\omega C V_m{}^2 \tan\delta \qquad 7$$

If the maximum electric field within the dielectric material is $E_m = V_m / d$, and the relative permittivity is considered as simply ε_r, then the power loss per unit volume of dielectric is:

$$W_C = \omega E_m{}^2 \varepsilon_0 \varepsilon_r \tan\delta \qquad 8$$

It is clear that tanδ is a direct measure of losses and that losses increase with the frequency of applied voltage.

Example 3: Calculate the average power loss in the dielectric in Example (2) if a voltage of 2kV (RMS) is applied across the dielectric.

Solution:

Given that: applied voltage of 2kV (RMS) is applied across the dielectric. The capacitance and loss tangent determined in Example (2) are 190pF and 1.07 x 10^{-3} respectively. Considering a power frequency of 50Hz and using:

$$P_C = \frac{1}{2}\omega C V_m{}^2 \tan\delta$$

We have:

$$P_C = \frac{1}{2}\times 2\pi\times 50\times 190\times 10^{-12}(2000\sqrt{2})^2\times 1.07\times 10^{-3}$$

Or $P_C = \mathbf{0.25\ mW}$