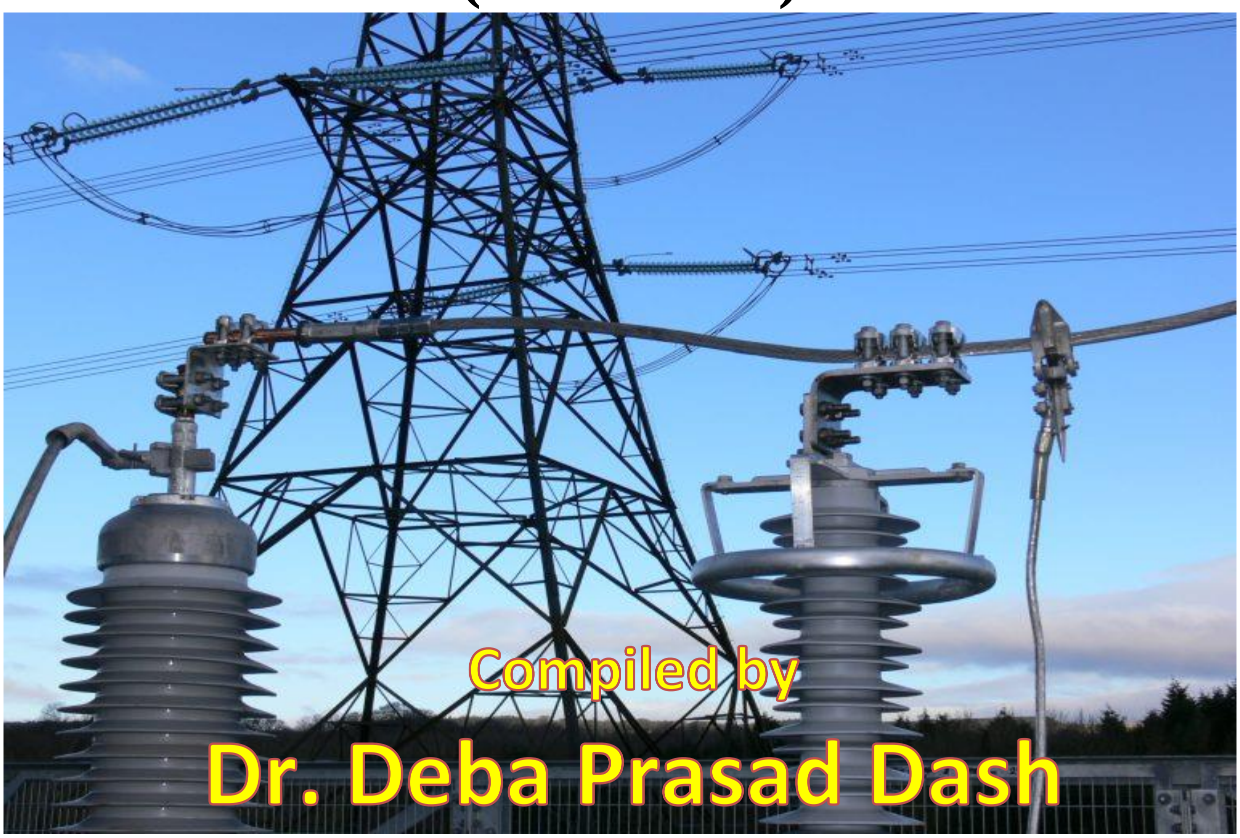
GOVERNMENT COLLEGE OF ENGINEERING, KALAHANDI

Lecture notes

on

HIGH VOLTAGE ENGINEERING

(Module IV)



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Disclaimer

MODULE_IV

8.NON-DESTRUCTIVE TESTING OF MATERIALS AND ELECTRICAL APPARATUS

In order to ensure an economic power-supply system with a high level of reliability, it is important to be able to monitor the dielectric parameters of the various insulations being utilized – when new and in service. Present power systems are ageing significantly and in many cases 40 per cent of the equipment is older than the conventional 'design life' of 25 years.

The condition of high voltage electrical insulation systems used in power cables, power transformers and generators is influenced by a number of manufacturing and operating variables which affect performance and failure

Nondestructive testing - NDT - use test methods to examine an object, material or system without impairing its future usefulness. Non-destructive testing is often required to verify the quality of a product or a system. Commonly used techniques are

AET - Acoustic Emission Testing
ART - Acoustic Resonance Testing
ET - Electromagnetic Testing
IRT - Infrared Testing
LT - Leak Testing
MT - Magnetic Particle Testing
PT - Dye Penetrant Testing
RT - Radiographic Testing
UT - Ultrasonic Testing
VT - Visual Testing (VI - Visual Inspection)

Impedance measurements are a basic means of evaluating electronic components and materials. Every material has a unique set of electrical characteristics that are dependent on its dielectric or insulation properties. Accurate measurements of these properties can provide valuable information to ensure an intended application or maintain a proper manufacturing process.

8.1Measurement of dc insulation resistance, volume resistance, and surface resistance.

From such measurements and the geometric dimensions of specimen and electrodes, both volume and surface resistivity of electrical insulating materials can be calculated, as well as the corresponding conductances and conductivities

The dc resistance test is used to measure the direct-current (dc) resistance of resistors, electromagnetic windings of components, conductors, etc..

When a dielectric is subjected to a steady state static electric field E the current density J_c is given by
$J_c = \sigma E$
Assuming a cuboid of the insulating material with thickness d and area A, then
Current $I = J_c A$ and power loss = $VI = VJ_c A = V \sigma EA = V\sigma AV/d = \sigma E^2$. Volume.
Therefore, specific dielectric loss = σE^2 Watts/m3.
The conductivity of the insulating materials viz liquid and solid depends upon the temperature and the moisture contents. The leakage resistance R_0 (σ) of an insulating material is determined by measuring the current when a constant d.c. voltage is applied. Since the current is a function of time as different mechanisms are operating simultaneously, so to measure only the conduction current it is better to

measure the current about 1 min after the voltage is switched on. For simple geometries of the specimen (cuboid or cube) specific resistivity ($p = 1/\sigma$) can be calculated from the leakage resistance measured. If I is the conduction current measured and V the voltage applied, the leakage resistance is given by $R=V/I=d/\sigma A$, where d is the thickness of the specimen and A is the area of section.

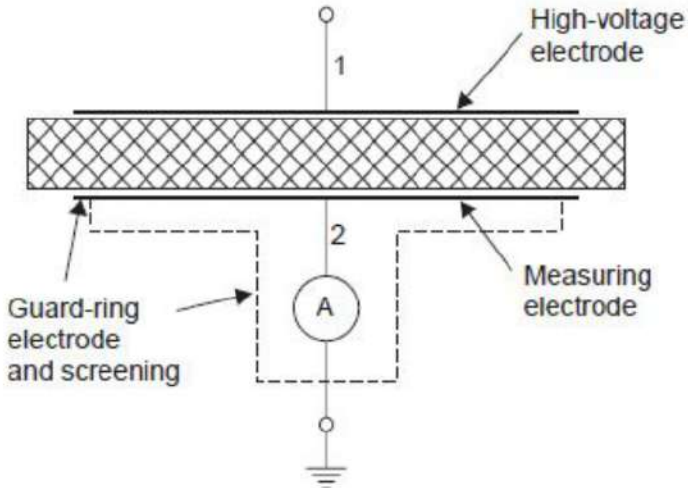

Fig. 8.1. Simple arrangement for measurement of resistivity of the insulating material.

The d.c. voltage of 100 volt or 1000 volt is applied between electrode 1 and the earth. The measuring electrode 2 is earthed through a sensitive ammeter. The third electrode known as guard ring electrode surrounds the measuring electrode and is directly connected to ground so as to eliminate boundary field effects and surface currents. The width of the guard electrode should be at least twice the thickness of the specimen and the unguarded electrode (1) must extend to the outer edge of the guard electrode. The gap between electrode 2 and 3 should be as small as possible. A thin metallic foil usually of aluminium or lead of about 20 μm thickness is placed between the electrodes and specimen for better contact. The specific conductivity for most of the insulating material lies in the range of 10^{-16} to 10^{-10} S/cm, which gives currents to be measured of these speciemen to be of the order of picoampers or nanoamperes.The measuring leads should be appropriately and carefully screened. The measurement of conduction current using d.c. voltage not only provides information regarding specific resistivity of the material but it gives an idea of health of the insulating material. If conduction currents are large, the insulating properties of the material are lost. This method, therefore, has proved very good in the insulation control of large electrical machines during their period of operation.

8.2Measurement of Dielectric Constant

The measurement of dielectric constant, also known as relative permittivity of a material, is one of the most popular methods of evaluating insulators such as rubber, plastics, and powders. It is used to determine the ability of an insulator to store electrical energy. The complex dielectric constant consists of a real part (k'), which represents the storage capability and an imaginary part (D), which represents the loss.

Dielectric constant measurements can be performed easier and faster than chemical or physical analysis techniques making them an excellent material analysis tool

8.3Measurement of Dissipation Factor

Dissipation factor (D) is defined as the ratio of an insulating materials resistance to its capacitive reactance at a specified frequency. It measures the inefficiency or loss of the material, is always greater than 0, but usually much smaller than the dielectric constant. D measurements are an excellent means of quality control which can yield indication of contamination or deterioration. For example, if we wanted to check the purity of epoxy or some raw material for consistency in a production run why not just measure the D. Excessive moisture would increase the dissipation factor value telling us something has changed as compared to previously established values.

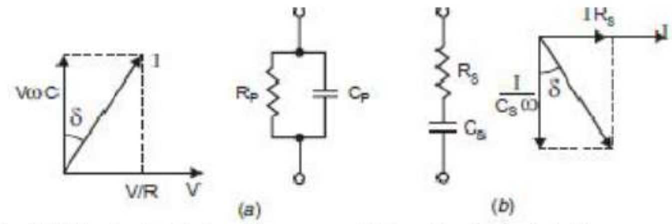

Fig.8.2 Equivalent circuit representation for dielectric loss

The dielectric conductivity takes into account all the three power dissipative processes including the one which is frequency dependent. Fig. 8.2 shows two equivalent circuits representing the electrical behaviour of insulating materials under a.c. voltages, losses have been simulated by resistances.

Normally the angle between V and the total current in a pure capacitor is 90°. Due to losses, this angle is less than 90°. Therefore, δ is the angle by which the voltage and charging current fall short of the 90° displacement.

$\tan\delta = 1/(\omega C_p R_P)$

whereas for series circuit $\tan\delta = (\omega C_s R_s)$

8.3.1 HIGH VOLTAGE SCHERING BRIDGE

The bridge is widely used for capacity and dielectric loss measurement of all kinds of capacitances, for instance cables, insulators and liquid insulating materials. We know that most of the high voltage equipments have low capacitance and low loss factor. This bridge is then more suitable for measurement of such small capacitance equipments as the bridge uses either high voltage or high frequency supply. If measurements for such low capacity equipments is carried out at low voltage, the results so obtained are not accurate.

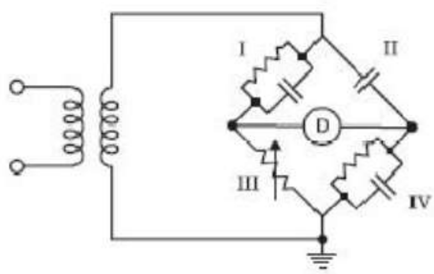

Fig.8.3 High Voltage Schering Bridge

Special features of the bridge

1.High Voltage supply

2.Screened Standard Capacitor

3.Large impedance of arm I &II

4.Null Detector

5.Automatic Guard Potential Regulator

The bridge is balanced by successive variation of R_1 and C_2 until on the oscilloscope (Detector) a horizontal straight line is observed.

$\tan\delta = (\omega C_2 R_2)$

$C_p = \cos^2\delta \; C_s R_2 / R_1$.

Problem

1.A 33kv 50Hz HV Schering bridge is used to test a simple insulation. The various aims have the given parameters on balance. The standard capacitance 500pf, the resistive branch 800 ohms and branch with parallel combination of resistance and capacitance has 180 ohms and 0.15μF. Determine the value of the capacitance of this sample, its parallel equivalent loss resistance, power factor and power loss under these test conditions.

8.4 Partial Discharges

Partial discharge is defined as localised discharge process in which the distance between two electrodes is only partially bridged *i.e.,* the insulation between the electrodes is partially punctured. Partial discharges may originate directly at one of the electrodes or occur in a cavity in the dielectric. Some of the typical partial discharges are: (*i*) Corona or gas discharge. These occur due to non-uniform field on sharp edges of the conductor subjected to high voltage especially when the insulation provided is air or gas or liquid(cf.Fig.8.4a) (*ii*) Surface discharges and discharges in laminated materials on the interfaces of different dielectric material such as gas/solid interface as gas gets over stressed ϵ_r times the stress on the solid material (where ϵ_r is the relative permittivity of solid material) and ionization of gas results(cf.Fig.8.4b & c) (*iii*) Cavity discharges: When cavities are formed in solid or liquid insulating materials the gas in the cavity is over stressed and discharges are formed (cf.Fig.8.4d) (*iv*). Treeing Channels: High intensity fields are produced in an insulating material at its sharp edges and this deteriorates the insulating material. The continuous partial discharges so produced are known as Treeing Channels(cf.Fig.8.4e)

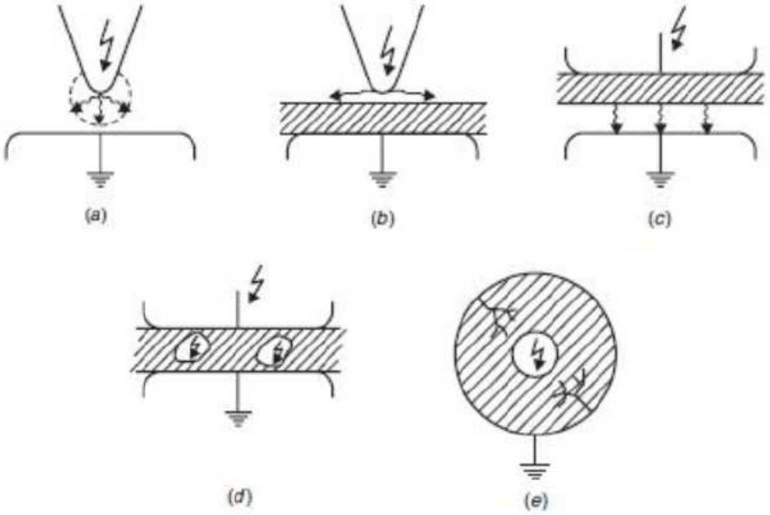

Fig. 8.4Various Partial Discharges

External partial discharge is the process which occurs external to the equipment e.g. on overhead lines, on armature etc.

Internal Partial Discharge

Internal paratial discharge is a process of electrical discharge which occurs inside a closed system (discharge in voids, treeing etc). This kind of classification is essential for the PD measuring system as
external discharges can be nicely distinguished from internal discharges. Partial discharge measurement have been used to assess the life expectancy of insulating materials. Even though there is no well defined relationship, yet it gives sufficient idea of the insulating properties of the material. Partial discharges on insulation can be measured not only by electrical methods but by optical, acoustic and chemical method also. The measuring principles are based on energy conversion process associated with electrical discharges such as emission of electromagnetic waves, light, noise or formation of chemical compounds. The oldest and simplest but less sensitive is the method of listening to hissing sound coming out of partial discharge. A high value of loss factor tan δ is an indication of occurrence of partial discharge in the material. This is also not a reliable measurement as the additional losses generated due to application of high voltage are localised and can be very small in comparison to the volume losses resulting from polarization process. Optical methods are used only for those materials which are transparent and thus not applicable for all materials. Acoustic detection methods using ultrasonic transducers have, however, been used with some success. The most modern and the most accurate methods are the electrical methods. The main objective here is to separate impulse currents associated with PD from any other phenomenon.

8.4.1 *The basic PD test circuit*

For the evaluation of the fundamental quantities related to a PD pulse we simulate the test object, as usual, by the simple capacitor arrangement as shown in Fig. 8.5(a), comprising solid or fluid dielectric materials between the two electrodes or terminals A and B, and a gas-filled cavity. The electric field distribution within this test object is here simulated by some partial capacitances, which is possible as long as no space charges disturb this distribution. Electric field lines within the cavity are represented by C_c and those starting or ending at the cavity walls form the two capacitances C_b' and C_b'' within the solid or fluid dielectric. All field lines outside the cavity are represented by $C_a = C_a' + C_a''$. Due to realistic geometric dimensions involved $C_b = C_b' C_b''/(C_b' + C_b'')$ the magnitude of the capacitances will then be controlled by the inequality $C_a \gg C_c \gg C_b$.

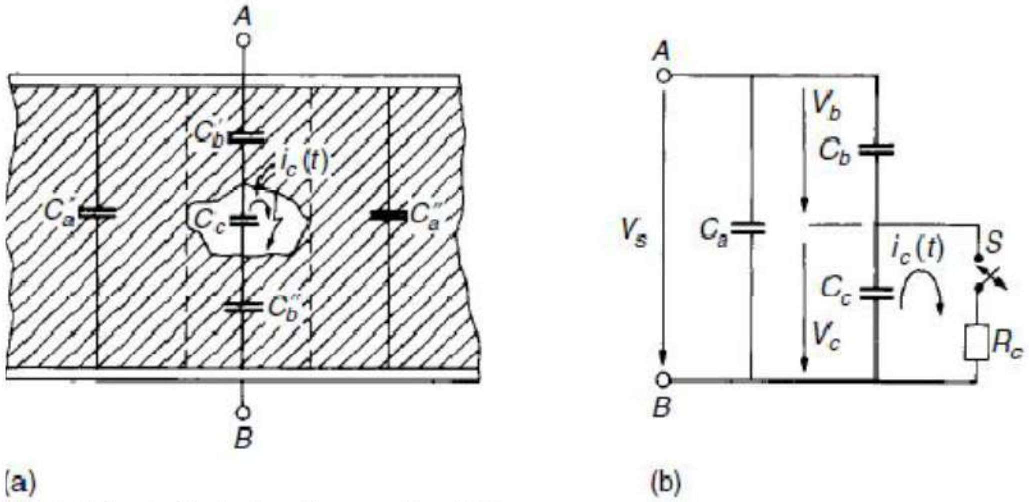

Fig.8.6 Equivalent circuit reprenting PD.

9.High Voltage Testing of Electrical Apparatus

Electrical equipment must be capable of withstanding overvoltages during operation. Thus by suitable testing procedure we must ensure that this is done. High voltage testing can be broadly classified into testing of insulating materials (samples of dielectrics) and tests on completed equipment. The tests carried out on samples of dielectric consist generally of the measurement of permittivity, dielectric loss per unit volume, and the dielectric strength of the material. The first two can be measured using the High Voltage Schering Bridge. The tests carried out on completed equipment are the measurement of capacitance, the power factor or the total dielectric loss, the ultimate breakdown voltage and the flash-over voltage. The breakdown voltage tests on completed equipment is only done on a few samples since it permanently damages and destroys the equipment from further use. However since all equipment have to stand up to a certain voltage without damage under operating conditions, all equipment are subjected to withstand tests on which the voltage applied is about twice the normal voltage, but which is less than the breakdown voltage.

In alternating voltage system, a careful choice of the characteristics of the testing transformer is essential. It is known that the flash over voltage of the insulator in air or in any insulating fluid depends upon the capacitance of the supply system. This is due to the fact that a voltage drop may not maintain preliminary discharges or breakdown. It is, therefore, suggested that a capacitance of at least 1000 pF must be connected across the insulator to obtain the correct flash over or puncture voltage and also under breakdown condition (a virtual short circuit) the supply system should be able to supply at least 1 amp for clean and 5 amp for polluted insulators at the test voltage.
There are some difficult problems with impulse testing equipments also especially when testing large power transformers or large reactors or large cables operating at very high voltages.

9.1 TESTING OF OVERHEAD LINE INSULATORS

High voltage testing of electrical equipment requires two types of tests: (*i*) Type tests, and (*ii*)

Routine test. Type tests involves quality testing of equipment at the design and development level *i.e.* samples of the product are taken and are tested when a new product is being developed and designed or an old product is to be redesigned and developed whereas the routine tests are meant to check the quality of the individual test piece. This is carried out to ensure quality and reliability of individual test objects.

High voltage tests include (*i*) Power frequency tests and (*ii*) Impulse tests. These tests are carried out on all insulators.

(*i*) 50% dry impulse flash over test.
(*ii*) Impulse withstand test.
(*iii*) Dry flash over and dry one minute test.
(*iv*) Wet flash over and one minute rain test.
(*v*) Temperature cycle test.
(*vi*) Electro-mechanical test.
(*vii*) Mechanical test.
(*viii*) Porosity test.
(*ix*) Puncture test.
(*x*) Mechanical routine test.

If the test is carried out under artificial rain, it is called wet flash over test. The insulator is subjected to spray of water of following characteristics:

Precipitation rate 3 $\pm$ 10% mm/min.
Direction 45° to the vertical
Conductivity of water 100 micro siemens $\pm$ 10%
Temperature of water Ambient +15°C

The insulator with 50% of the one-min. rain test voltage applied to it, is then sprayed for two minutes, the voltage raised to the one minute test voltage in approximately 10 sec. and maintained there for one minute. The voltage is then increased gradually till flash over occurs and the insulator is then flashed at least four more times, the time taken to reach flash over voltage being in each case about 10 sec. The flash over voltage must not be less than the value specified in specifications.

9.2TESTING OF CABLES

High voltage power cables have proved quite useful especially in case of HV d.c. transmission. Underground distribution using cables not only adds to the aesthetic looks of a metropolitan city but it provides better environments and more reliable supply to the consumers.

A cable is subjected to following tests:

(*i*) Bending tests.
(*ii*) Loading cycle test.
(*iii*) Thermal stability test.
(*iv*) Dielectric thermal resistance test.
(*v*) Life expectancy test.
(*vi*) Dielectric power factor test.
(*vii*) Power frequency withstand voltage test.
(*viii*) Impulse withstand voltage test.
(*ix*) Partial discharge test.

High Voltage Schering Bridge is used to perform dielectric power factor test on the cable sample. The power factor is measured for different values of voltages *e.g.* 0.5, 1.0, 1.5 and 2.0 times the rated operating voltages. The maximum value of power factor at normal working voltage does not exceed a specified value (usually 0.01) at a series of temperatures ranging from 15°C to 65°C. The difference in the power factor between rated voltage and 1.5 times the rated voltage and the rated voltage and twice the rated voltage does not exceed a specified value. Sometimes the source is not able to supply charging current required by the test cable, a suitable choke in series with the test cable helps in tiding over the situation.

Partial discharge measurement of cables is very important as it gives an indication of expected life of the cable and it gives location of fault, if any, in the cable. When a cable is subjected to high voltage and if there is a void in the cable, the void breaks down and a discharge takes place. As a result, there is a sudden dip in voltage in the form of an impulse.

This impulse travels along the cable as explained in detail in Chapter VI. The duration between the normal pulse and the discharge pulse is measured on the oscilloscope and this distance gives the location of the void from the test end of the cable. However, the shape of the pulse gives the nature and intensity of the discharge. In order to scan the entire length of the cable against voids or other imperfections, it is passed through a tube of insulating material filled with distilled water. Four electrodes, two at the end and two in the middle of the tube are arranged. The middle electrodes are located at a stipulated distance and these are energized with high voltage. The two end electrodes and cable conductor are grounded. As the cable is passed between the middle electrode, if a discharge is seen on the oscilloscope, a defect in this part of the cable is stipulated and hence this part of the cable is removed from the rest of the cable.

9.3 TESTING OF BUSHINGS

Bushings are an integral component of high voltage machines. A bushing is used to bring high voltage conductors through the grounded tank or body of the electrical equipment without excessive potential gradients between the conductor and the edge of the hole in the body. The bushing extends into the surface of the oil at one end and the other end is carried above the tank to a height sufficient to prevent breakdown due to surface leakage. Following tests are carried out on bushings:

(i) Power Factor Test

The bushing is installed as in service or immersed in oil. The high voltage terminal of the bushing is connected to high voltage terminal of the Schering Bridge and the tank or earth portion of the bushing is connected to the detector of the bridge. The capacitance and p.f. of the bushing is measured at different voltages as specified in the relevant specification and the capacitance and p.f. should be within the range specified.

(ii) Impulse Withstand Test

The bushing is subjected to impulse waves of either polarity and magnitude as specified in the standard specification. Five consecutive full waves of standard wave form are applied and if two of them cause flash over, the bushing is said to be defective. If only one flash over occurs, ten additional applications are made. If no flash over occurs, bushing is said to have passed the test.

(iii) Chopped Wave and Switching Surge Test

Chopped wave and switching surge of appropriate duration tests are carried out on high voltage bushings. The procedure is identical to the one given in (*ii*) above.

(iv) Partial Discharge Test

In order to determine whether there is deterioration or not of the insulation used in the bushing, this test is carried out.

(v) Visible Discharge Test at Power Frequency

The test is carried out to ascertain whether the given bushing will give rise to ratio interference or not during operation. The test is carried out in a dark room. The voltage as specified is applied to the bushing (IS 2099). No discharge other than that from the grading rings or arcing horns should be visible.

(vi) Power Frequency Flash Over or Puncture Test

(*Under Oil*): The bushing is either immersed fully in oil or is installed as in service condition. This test is carried out to ascertain that the internal breakdown strength of the bushing is 15% more than the power frequency momentary dry withstand test value.

9.4 TESTING OF POWER TRANSFORMERS

Transformer is one of the most expensive and important equipment in power system. If it is not suitably designed its failure may cause a lengthy and costly outage. Therefore, it is very important to be cautious while designing its insulation, so that it can withstand transient over voltage both due to switching and lightning. The high voltage testing of transformers is, therefore, very important and would be discussed here. Other tests like temperature rise, short circuit, open circuit etc. are not considered here. However, these can be found in the relevant standard specification.

Partial Discharge Test

The test is carried out on the windings of the transformer to assess the magnitude of discharges. The transformer is connected as a test specimen similar to any other equipment and the discharge measurements are made. The location and severity of fault is ascertained using the travelling wave theory technique. The measurements are to be made at all the terminals of the transformer and it is estimated that if the apparent measured charge exceeds 10^4 picocoulombs, the discharge magnitude is considered to be severe and the transformer insulation should be so designed that the discharge measurement should be much below the value of 10^4 pico-coulombs.

Impulse Testing of Transformer

The impulse level of a transformer is determined by the breakdown voltage of its minor insulation (Insulation between turn and between windings), breakdown voltage of its major insulation (insulation between windings and tank) and the flash over voltage of its bushings or a combination of these. The impulse characteristics of internal insulation in a transformer differs from flash over in air in two main respects. Firstly the impulse ratio of the transformer insulation is higher (varies from 2.1 to 2.2) than that of bushing (1.5 for bushings, insulators etc.). Secondly, the impulse breakdown of transformer insulation in practically constant and is independent of time of application of impulse voltage.

Impulse testing consists of the following steps:

(*i*) Application of impulse of magnitude 75% of the Basic Impulse Level (BIL) of the transformer under test.

(*ii*) One full wave of 100% of BIL.

(*iii*) Two chopped wave of 115% of BIL.

(*iv*) One full wave of 100% BIL and

(*v*) One full wave of 75% of BIL.

During impulse testing the fault can be located by general observation like noise in the tank or smoke or bubble in the breather. If there is a fault, it appears on the Oscilloscope as a partial of complete collapse of the applied voltage. Study of the wave form of the neutral current also indicated the type of fault. If an arc occurs between the turns or form turn to the ground, a train of high frequency pulses are seen on the oscilloscope and wave shape of impulse changes. If it is a partial discharge only, high frequency oscillations are observed but no change in wave shape occurs.

9.5TESTING OF CIRCUIT BREAKERS

An equipment when designed to certain specification and is fabricated, needs testing for its performance. The general design is tried and the results of such tests conducted on one selected breaker and are thus applicable to all others of identical construction. These tests are called the type tests. These tests are classified as follows:

1. Short circuit tests:

(*i*) Making capacity test.

(*ii*) Breaking capacity test.

(*iii*) Short time current test.

(iv)Operating duty test

2. Dielectric tests:

(*i*) Power frequency test:

(*a*) One minute dry withstand test.

(*b*) One minute wet withstand test.

(*ii*) Impulse voltage dry withstand test.

3. Thermal test. 4. Mechanical test

9.6Tests on Lightning arrestors or surge diverters

For the normal or operating power frequency voltages, the lightening arrestor has to be a non conductor. It should behave as a short circuit for transient over-voltages of impulse character, discharge the heavy current, and recover its insulation without allowing the follow-up of the power frequency current.

The surge diverters need to be tested at the following current ratings.

Diverter Class	Diverter Rating	Impulse current rating(8/20μs)

A	230V-600V	1500-2500Amp
B	400V-33kV(distribution Class)	5kA
C	Station Type	10kA

Tests on surge diverters
Power frequency spark over test (Routine test)
Hundred percent standard impulse spark-over test
Front of wave spark-over test
Residual voltage test

The power frequency spark-over test is conducted using a series resistor(for current limitation in use of flashover) at 1.5 times the rated value for five successive applications under both dry and wet conditions.
The arrestor should operate when a lightening occurs. To ascertain it standard impulse voltage of specified magnitude is applied. The arrestor has to spark-over every times in each time of the ten successive applications both under positive as well as under negative polarity impulse. This is hundred percent standard impulse spark-over test.
Fromt of wave spark-over test- for steep fronted impulse wave with rate of rise 100kV/μs, for 12kV rating.
The arrestor must spark –over every time. The time to spark-over is also measured using oscilloscope and camera. The volt-time characteristics of the divider is plotted and the intersection of V-T ch. And the line with the slope of virtual steepness of the front give the front of wave spark-over voltage.
Residual voltage test: the residual voltage is the voltage developed across the non-linear resistor units during the flow of surge current. Standard impulse current of rated magnitude are applied and the voltage is measured by CRO and divider. The magnitude of currents are approximately 0.5, 1.0 and 2.0 time the rated value.

9.7 RADIO INTERFERENCE MEASUREMENTS

Many electrical apparatuses like transformers, line conductors, rotating machines, etc. produce unwanted electrical signals in the radio and high frequency (television band, microwave bands, etc.) ranges. These signals arise due to corona discharges in air, internal or partial discharges in the insulation, sparking at commutators and brush gear in rotating machines, etc. It is important to see that the noise voltages generated in the radio and other transmission bands are limited to acceptable levels, and hence the radio interference voltage measurements are of importance. It has been found that the surface conditions of the overhead conductors subjected to high voltage stresses and varying atmospheric conditions greatly influence the magnitude of the noise voltage produced. In case of solid insulators, the bonding between the porcelain and the metal pin, the binding of high voltage conductor and the insulator surface, and the surface pollution were found to be the sources of this noise.
The noise generated in the radio frequency band as a result of corona or partial discharges in high voltage power apparatus may be measured

(i) by the radio frequency line to ground voltage known as the radio influence voltage or RIV, and
(ii) as an interfering field by means of an antenna known as the radiated radio interference voltage or RI.

Normally, the tests and measurements done in the laboratories are RIV measurements, whereas field investigations with portable radio receivers are RI measurements.
A radio noise meter (consisting of a portable radio receiver with a local oscillator, a radio frequency amplifier, a mixer, an intermediate frequency amplifier, and a detector similar to that of a standard radio receiver) is used in the laboratory and operates in the frequency range 150 kHz to 30 MHz. In addition, the radio noise meter has multiinput circuits to accommodate a number of pick-up devices, attenuators, calibrators, and output circuits containing special detectors and meters. The detector circuit consists of a diode detector in series with a series resistance R_S, charging a parallel R-C circuit. The detector circuit is provided with a measuring device to measure either (a) the average value, (b) the peak value, or

(c) quasi-peak value (the quasi-peak value of the impulse noise is equal to the rms value of the sine wave at the centre frequency of the pass band which produces the same deflection in the meter scale as that of the impulse). The voltmeter provided at the end of the detector has an input impedance of 50 to 75 ft.

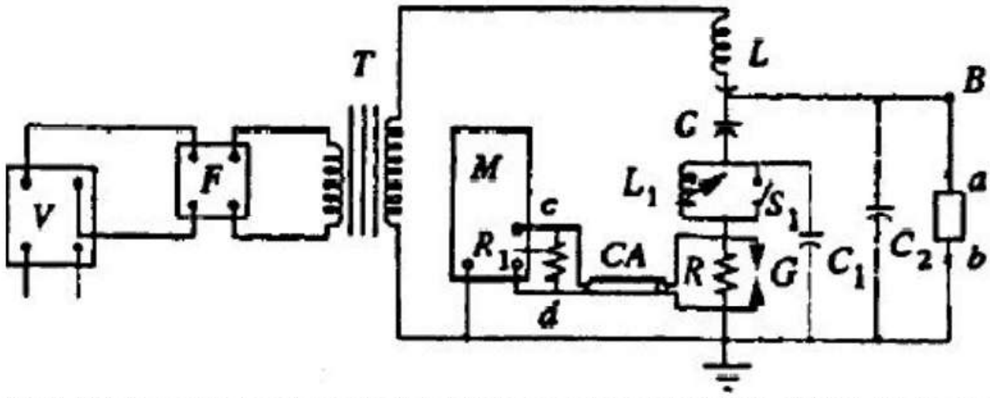

Fig.8.7 Schematic diagram of circuit for measurement of RIV of high Voltage apparatus in 150kHz to 30MHz frequency range.
F-Voltage control unit, V-Voltmeter, T-High Voltage Transformer, L-Radio frequency choke, C-Coupling condenser, R_1-Meter input impedance, M-Radio Noise Meter, A,b-Test apparatus, CA-Co-axial cable, G-Protective Gap, S_1-Shorting Switch C_1C_2-Stray capacitances, L_1-Tuning choke, R-Measuring impedance.