

Chapter-8

Measurement of High Test Voltages

Ravindra Arora

Professor (Retired)

Department of Electrical Engineering
Indian Institute of Technology Kanpur
Kanpur, Uttar Pradesh, India

Bharat Singh Rajpurohit

Associate Professor

School of Computing and Electrical Engineering
Indian Institute of Technology Mandi
Mandi, Himachal Pradesh, India

Objectives

- Principles and types of voltage dividers
- Methods of peak voltage measurement
- Voltage measurement with Sphere-gap
- Principle, construction and operation of electrostatic voltmeters

Introduction

- High test voltages generated in laboratories require special techniques for their measurement.
- Each type of high voltage namely; ac, dc and impulse can be suitably measured with more than one different techniques.
- The choice of the method of measurement in a laboratory is a *matter of convenience, cost* and the *accuracy* required for the measurement besides the safety.
- The complications in measurements increase with the magnitude of the voltage desired to be measured. The problems confine mainly with respect to the large structures of the device and the electric stress control techniques applied to *prevent PB and flash overs*.
- The high voltage equipments have large stray capacitances with respect to the grounded structures and hence large voltage gradients are set up.
- A person handling these equipments and the measuring devices must be protected against these over voltages.
- For this, large structures are required to control the electrical fields and to avoid flash over between the equipment and the grounded structures. Sometimes, these structures are re-quired to control heat dissipation within the circuits.
- Therefore, the location and layout of the equipments is very important to avoid these problems.
- Electromagnetic fields create problems in the measurements of impulse voltages and currents and should be minimised.
- The high voltage measurement *techniques in electric power systems are different*. These are not discussed in this course.

High Voltage Measurement Techniques

Table 1. High test voltage measurement techniques

Type of voltage	Method or technique
ac power frequency	(i) Primary side for low test voltage measurement (rms)
	(ii) Sphere gap (peak)
	(iii) Electrostatic voltmeter (rms)
	(iv) Series impedance and ammeter
	(v) Potential dividers and oscilloscope (resistive, capacitive or mixed dividers)
	(vi) Peak voltmeters with dividers
dc voltages	(i) Sphere gap, either polarity
	(ii) Series resistance and micro-ammeter
	(iii) Resistive potential divider
Impulse voltages (li & si) either polarity and other high frequency high voltages	(i) Sphere gap
	(ii) potential dividers, oscilloscope (capacitive, resistive & capacitive)
	(iii) Peak voltmeters with series capacitors and potential dividers

High Voltage Measurement Techniques

As it can be seen in this table, the *earliest technique of sphere gap* and the modern and *most accurate technique of potential divider* are applicable for the measurement of all the three types of voltages and both their polarities.

The *sphere gap technique*, used widely for over a century, is *not used* any more.

The disadvantages of this method are many. It does not provide a continuous measurement of the voltage and a flashover between the two spheres is essential. This measurement technique is not an accurate one. It may give error upto 3% in the measurement.

The *electrostatic voltmeter*, suitable for the measurement of ac (rms) and dc voltages, is one of the most accurate instrument. However, *due to its size, cost and adjustment problems*, it is not used very widely.

For the measurement of ac power frequency voltage, the simplest way is to *measure the voltage on the primary side* or at the low voltage side of the ac test transformer and *calibrate the dial of the low voltage voltmeter* by multiplication of the turns ratio to get the high output voltage.

However, this technique could give rise error in two ways.

First, in case of high capacitive loads, the leading current output from the test transformer results in higher actual voltage output than measured with the help of turns ratio at the primary side, the well known Ferranti effect .

Secondly, if the output voltage is not perfectly sinusoidal, the peak value is not times the rms value. To overcome this problem, measurement of peak value of the output voltage at the high voltage side is recommended.

Principle of Potential Dividers, Their Types, and Applications

- For the measurement of High Voltages of any type, the best technique is by dividing the high voltage in to a low voltage level suitable for the instrument or the measuring circuit, where it can be measured directly. .
- The HV potential divider arms could be pure capacitive, pure resistive or a combination of the two.
- The essential requirement is that the wave shape to be measured is correctly reproduced on the oscillograph with a known voltage reduction ratio.
- The general principle of potential divider technique is shown by the circuit diagram in Fig. 1.

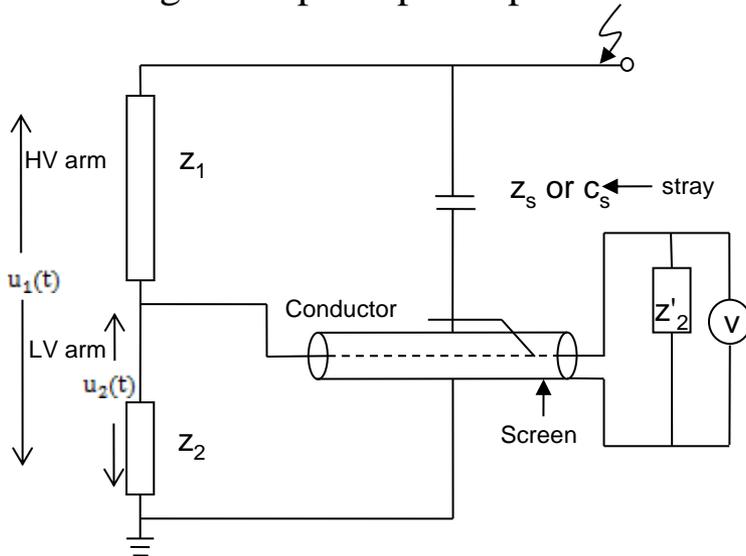


Fig. 1. The principle circuit for voltage dividers

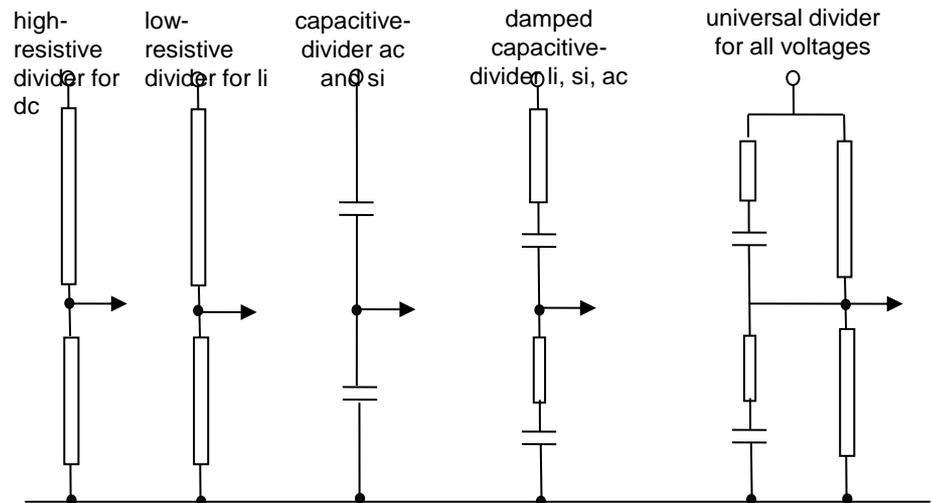


Fig. 2. Schematic describing the principle of the five types of potential dividers

Principle of Potential Dividers, Their Types, and Applications

$$\frac{U_1}{U_2} = \frac{Z_1 + Z_2}{Z_2} \approx \frac{Z_1}{Z_2}$$

Z_1 - the high voltage arm of the divider.

It could be pure C, pure R or combination of R and C as per requirement.

- Values of Z_1 and Z_2 are chosen such that the potential across Z_2 is around 100 V.
- The voltage division ratio can be given as;

$$\frac{Z_1}{Z_2} \gg 1 \quad Z_2 = \left(\frac{1}{Z_2'} + \frac{1}{Z_2''} \right)^{-1}$$

where

Z_2'' = terminal impedance of oscilloscope

- This technique of potential dividers is **most accurate**.
- It provides a continuous measurement of all the types of applied high voltages i.e. **dc, ac and impulse**.
- The suitability of the type of divider depends upon not only the type of voltage, but also upon the range of magnitude of the voltage to be measured. Basically, there are five types of potential dividers in use, shown in Fig. 2.
- These are pure high resistance dividers suitable for the measurement of high dc, pure low resistance dividers for li impulse voltages, pure capacitive dividers for ac and si voltages, damped capacitive dividers suitable for ac, li and si and the so called, universal divider, a combination of capacitances and resistances, which is suitably applicable for all the types of high voltages in a laboratory.

Principle of Potential Dividers, Their Types, and Applications

➤ Pure Capacitive Voltage Dividers

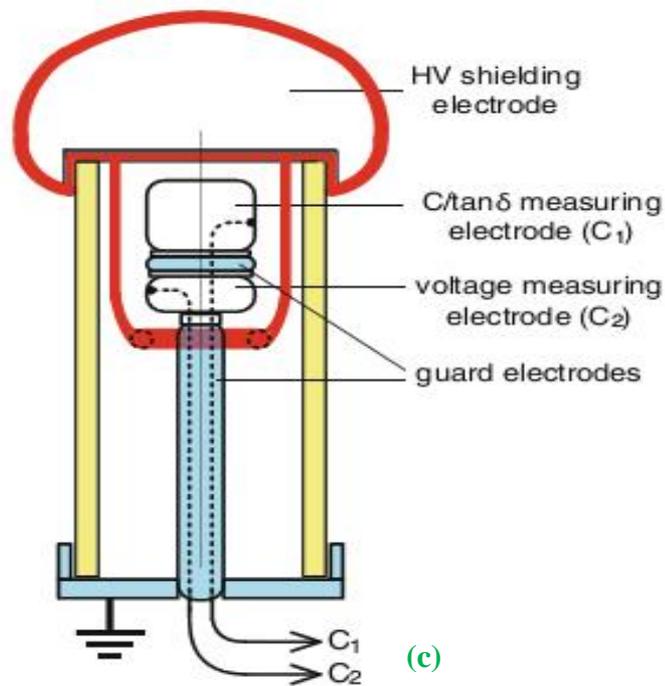
- Usually having their capacitance in pF range, are commonly compressed gas or vacuum capacitors.
- Comprise a number of nF range HV capacitors, made out of polypropylene or paper filled with oil, built in a stack and connected in series.
- Pure capacitive voltage dividers are suitable for the measurement of high power frequency and impulse voltages, especially si.



(a)



(b)



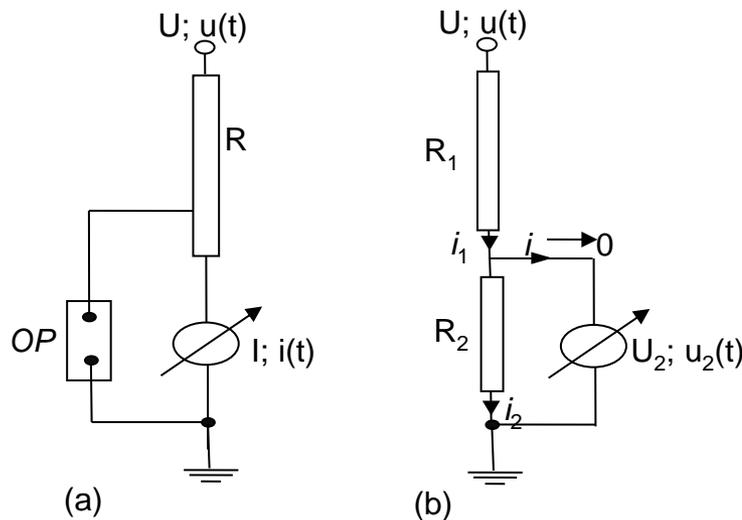
(c)

Fig. 3. (a) Standard (compressed gas) capacitor of 1600 kV rms, 20pF , Courtesy Himalayal China (b) SF6-filled standard capacitor for 800 kV, nominal capacitance 100 pF.

Principle of Potential Dividers, Their Types, and Applications

➤ Pure Resistive Potential Dividers

- The high potential drop across a resistive arm by simple Ohm's law is used to reduce the voltage to a measurable quantities, circuits for such measurement are shown in fig. 4.
- Pure resistive arm or divider can be used for the measurement of dc, ac, and impulse voltages.
- The wave forms of **ac and impulse** voltages could also be recorded with the **help of an oscilloscope**.
- While measuring very high voltages, the resistive arm **inductance and stray capacitance** cause **large error in the accuracy** of measurement.
- **To overcome the error** caused due to inductance of the wire **wound resistors**, **thin film resistors** are now used.



- Ammeter in series with resistor R ;
- Voltage divider R_1, R_2 and voltmeter of negligible current input.
- OP, Over voltages protection.

Fig. 4. Measurement of high dc and ac voltages by means of
(a) ammeter in series with a resistor R ; OP: Overvoltage protection
(b) Voltage divider R_1, R_2 , and a voltmeter of negligible current input.

Principle of Potential Dividers, Their Types, and Applications

- **Mixed Resistive and Capacitive Dividers or Universal Dividers**
- The problem caused by the stray capacitance in resistive voltage divider is over come by placing actual capacitors in parallel with the resistor units of the HV arm.
- This gives rise to a mixed resistive and capacitive divider used for highest voltage range of **impulse voltage measurement**. These are also known as 'damped capacitive divider' or RC divider.

R' = Resistance of single element of the HV arm

where a number of them are in series.

C'_p = Capacitance across each of such element.

C'_e = stray capacitance to earth of the element \forall

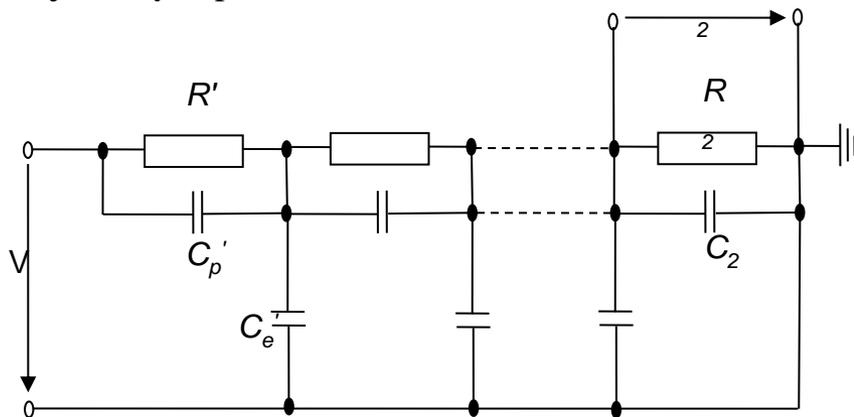


Fig. 4. Simplified equivalent circuit for parallel-mixed resistive-capacitive (RC) divider



Fig. 5. Damped capacitive-resistive voltage divider (on the left) the measurement of 4.5 MV impulse voltage (generator on right), courtesy Siemens (now High Volt), Dresden, Germany

Peak Voltage Measurement

- Behaviour of a dielectric is strongly dependent on the electric stress it is subjected to.
- The intensity of electric stress depends upon the peak magnitude of the voltage of a time varying waveform.
- Unlike power frequency voltage, for impulse voltages of different wave shapes, where single pulses are produced repeatedly with a time gap, the concept of rms voltage is irrelevant.
- The techniques developed for the measurement of peak voltages therefore gained importance.

Peak Voltage Measurement

➤ Chubb-Fortescue Method

A simple, yet accurate, method for the measurement of peak values of ac power frequency voltage was proposed by Chubb and Fortescue in 1913. The circuit diagram for this method is shown in Fig. 6.

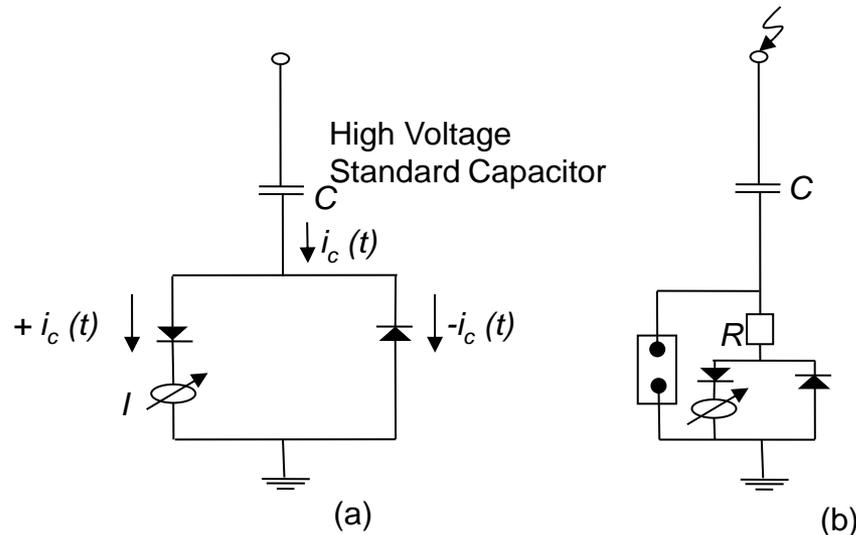


Fig. 6. The ac peak voltage measurement by Chubb and Fortescue. (a) Fundamental circuit. (b) Recommended circuit

The measuring instrument in this circuit, an ammeter, reads the magnitude of charge per cycle or the mean value of the current

$$i_c(t) = C \frac{dU(t)}{dt}$$

Peak Voltage Measurement

Hence,

$$I = \frac{1}{T} \int_{t_1}^{t_2} i_c(t) dt = \frac{C}{T} \int_{t_1}^{t_2} dU = \frac{C}{T} (|U_{+max}| + |U_{-max}|)$$

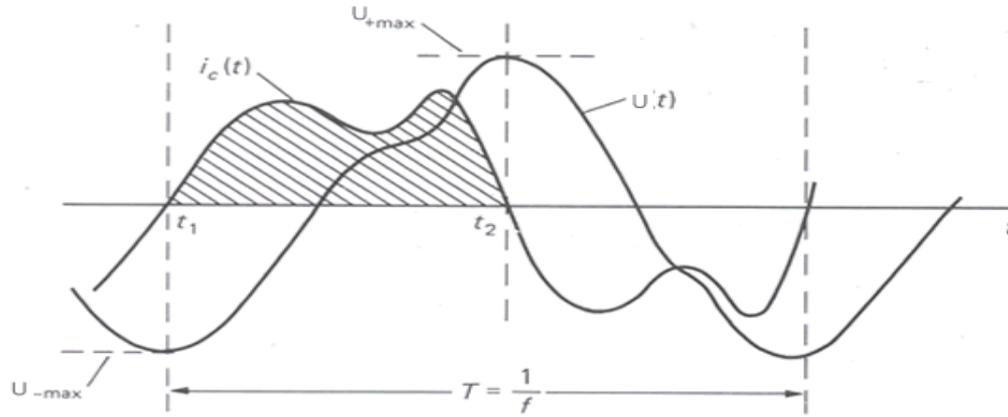


Fig. 7. Diagram of possible voltage $u(t)$ and current $i_c(t)$ forms in the circuit in Fig. 6

If both, the +ve and -ve, peak values are equal, the expression for the charging current of the HV capacitor can be written as,

$$I = CfU_{pp} = 2CfU_{max}$$

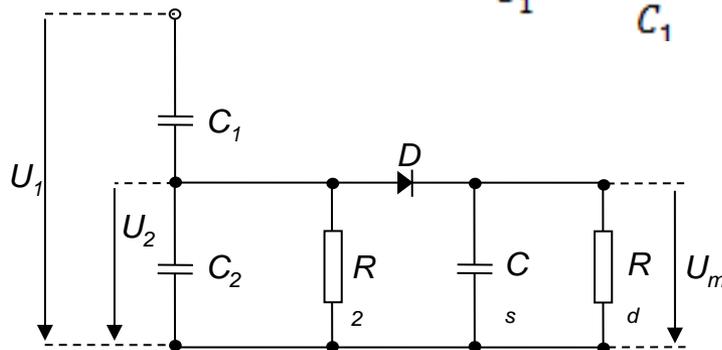
With *knowledge of exact value of f and C* , the value of dc current measured gives $2U_{max}$, the actual peak to peak value of the ac voltage.

Peak Voltage Measurement

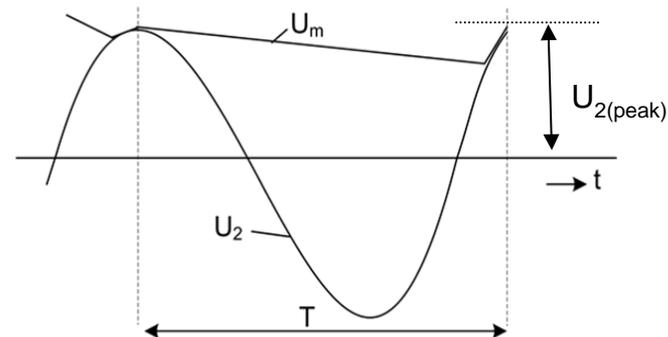
➤ Peak voltage measurement with Capacitive Voltage Divider

- The measuring capacitors C_m is charged to the peak value U_2 , the lower arm voltage of the capacitive voltage divider.
- If U_2 is decreased, C_m will hold the charge and the voltage across it *will not change*. Because of the reverse bias current of the diode, there is a danger that U_2 will gain negative dc component over the time.
- Hence U_m will no longer follow the change in U_2 . Therefore, discharge resistors R_2 and R_d must be included in this circuit.
- The time constant $R_d C_m$ should be between **0.5 - 1 sec** to obtain a good response. When the circuit response conditions are taken care, the peak value of the voltage to be measured is given by the relation

$$\hat{U}_1 = \frac{C_1 + C_2}{C_1} \hat{U}_m$$



(a)



(b)

Fig. 8. (a) Simple peak voltmeter circuit for ac voltage measurement, according to Davis, Bowdler and Standring
(b) Voltage waveforms in the circuit

Peak Voltage Measurement with Sphere Gap

➤ Construction of sphere gap and its effects

- A sphere gap consists of two adjacent metal spheres of equal diameters whose separation gap distance is variable. The ability to respond to peak values of impulse voltages, if the time to *peak is not too short* (1-3 μsec), is governed by a short statistical time lag or the delay in time required for the availability of an electron to initiate an electron avalanche and hence the breakdown.
- Within the limited gap distance between the spheres, *a weakly nonuniform field exists*, hence no PB or corona appear before the complete breakdown or flashover.
- For a given dimension of the diameter/radius of the spheres and a gap distance between them, the magnitude of the voltage at which the breakdown occurred is read from the *standard calibrated tables available for different types of voltages and for both their polarities*.
- This technique is adopted for the measurement of all the types (dc =, ac ~ and impulse λ) high voltages of either polarity.
- The field between two identical spheres is a *classical example of "weakly nonuniform" field*. The breakdown characteristic of such a gap is linear for the *gap distances not greater than the radius* of the spheres.

Peak Voltage Measurement with Sphere Gap

- Measurement voltage is made as a function of minimum distance at which it can **flash over or spark over**.
- The breakdown voltage of the gap does **not depend** upon the **duration** of application of voltage and also not upon its **variation with time**.

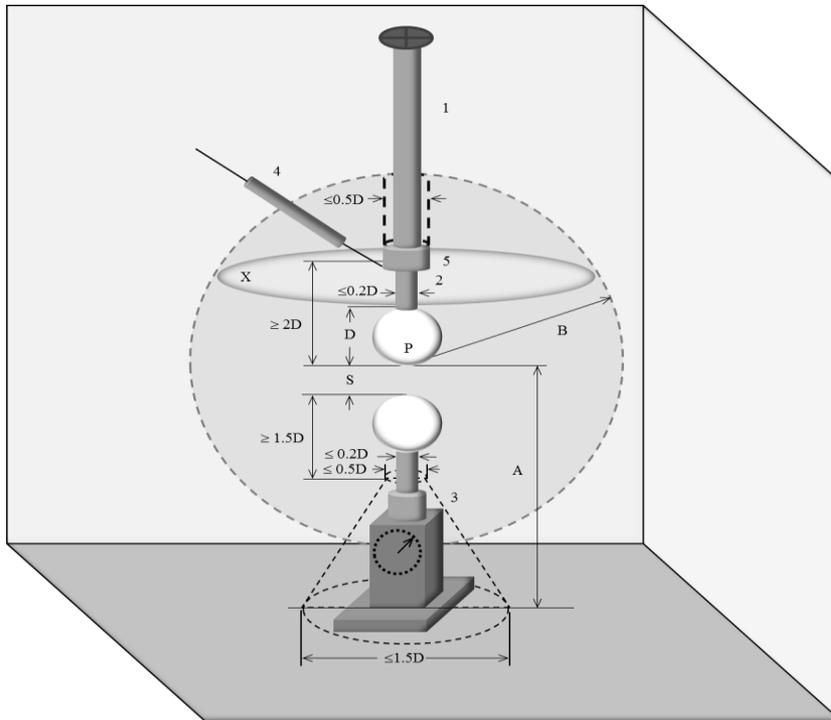


Fig. 9. A vertical sphere gap set, 1. Insulating support 2. Metallic Sphere supporting shaft 3. Sphere moving gear housing 4. Series resistor for high-voltage connection 5. Stress control toroid ring



Fig. 10. A 1 m diameter sphere gap in HV Laboratory at TU Dresden, Germany

Peak Voltage Measurement with Sphere Gap

➤ Correction Factor

- Since in general the actual air density during measurements differ from the reference conditions.
- The breakdown voltage of the air gap is given as

$$U_b = K_d U_{b0}$$

Where

U_{b0} corresponds to the table values ;

K_d = correction factor related to air density.

- The actual relative air density (RAD) is given in general terms by

$$\delta = \frac{p}{p_0} \frac{273 + t_0}{273 + t} = \frac{p T_0}{p_0 T}$$

Where

p_0 = air pressure for standard conditions; p = air pressure at the test conditions

$t_0 = 20$ °C; t = temperature in °C at the test conditions.

- The correction factor K_d , given in table below for increasing values of RAD are slightly non linearly. However, it can be seen from the table that the correction factor k_d is almost equal to RAD, δ .

Peak Voltage Measurement with Sphere Gap

Table 2 Air density correction factor

Relative air density RAD δ	Correction factor K_d
0.70	0.72
0.75	0.77
0.80	0.82
0.85	0.86
0.90	0.91
0.95	0.95
1.00	1.00
1.05	1.05
1.10	1.09
1.15	1.13

Disadvantages:

- 1.** For the measurement, breakdown in the gap has to take place.
- 2.** Continuous measurement of the voltage is not possible.
- 3.** This method is not very accurate.

Electrostatic Voltmeter, Their Working Principle and Construction

- Electrostatic Voltmeters produced upto 1000 kV rated voltage are suitable for the measurement of **ac power frequency, higher frequency rms voltages and dc voltages.**
- For higher voltage range compact voltmeters with SF₆ gas or vacuum insulation gap are also produced.
- These voltmeters were suggested by Kelvin in 1884 for the measurement of rms value of power frequency voltage. They are developed to follow the Coulomb's law which defines the static electric field as a field of force.
- The field produced between two parallel plate electrodes with shaped profile brims, is a **uniform field.**
- If the voltage applied across these parallel plates having a gap distance 'X' is U, then the uniform field produced in the gap between them will have an intensity E equal to U/X.
- The attracting *force F between the plates on area A of the electrodes is equal to the rate of change of stored electrical energy W_{el} per unit distance* in the capacitance formed between the plates.

Electrostatic Voltmeter, Their Working Principle and Construction

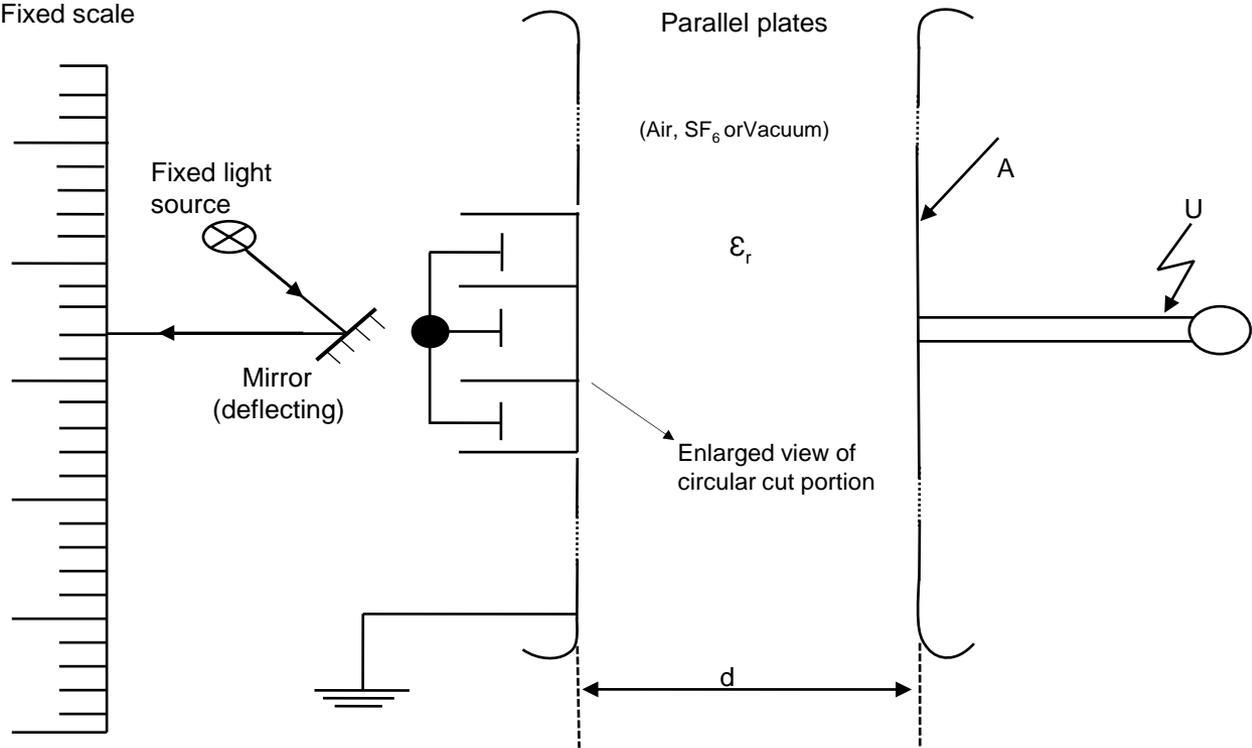


Fig. 11. Schematic of an electrostatic voltmeter

Electrostatic Voltmeter, Their Working Principle and Construction

$$F = -\frac{\partial W_{el}}{\partial X}$$

$$\text{or } |F| = \frac{dW_{el}}{dX} = \frac{d}{dX} \left(\frac{1}{2} C U^2 \right)$$

$$= \frac{1}{2} U^2 \frac{dC}{dX} = \frac{1}{2} U^2 \epsilon_0 \frac{d}{dX} \left(\frac{A}{X} \right) \quad (\text{Since } \epsilon_r = 1)$$

$$= \frac{1}{2} \epsilon_0 U^2 \frac{A}{X^2}$$

$$\text{or } |F| = \frac{1}{2} \epsilon_0 A E^2$$

Where ϵ = permittivity of the insulating medium

X = gap distance between the parallel plate electrodes of area A .

Then the mean value of the force is used to measure the rms value of the voltage.

$$\frac{1}{T} \int_0^T F(t) dt = \frac{\epsilon_0 A}{2X^2} \cdot \frac{1}{T} \int_0^T U^2(t) dt = \frac{\epsilon_0 A}{2X^2} (U_{rms})^2 \dots\dots\dots(a)$$

where T is a proper integration time.

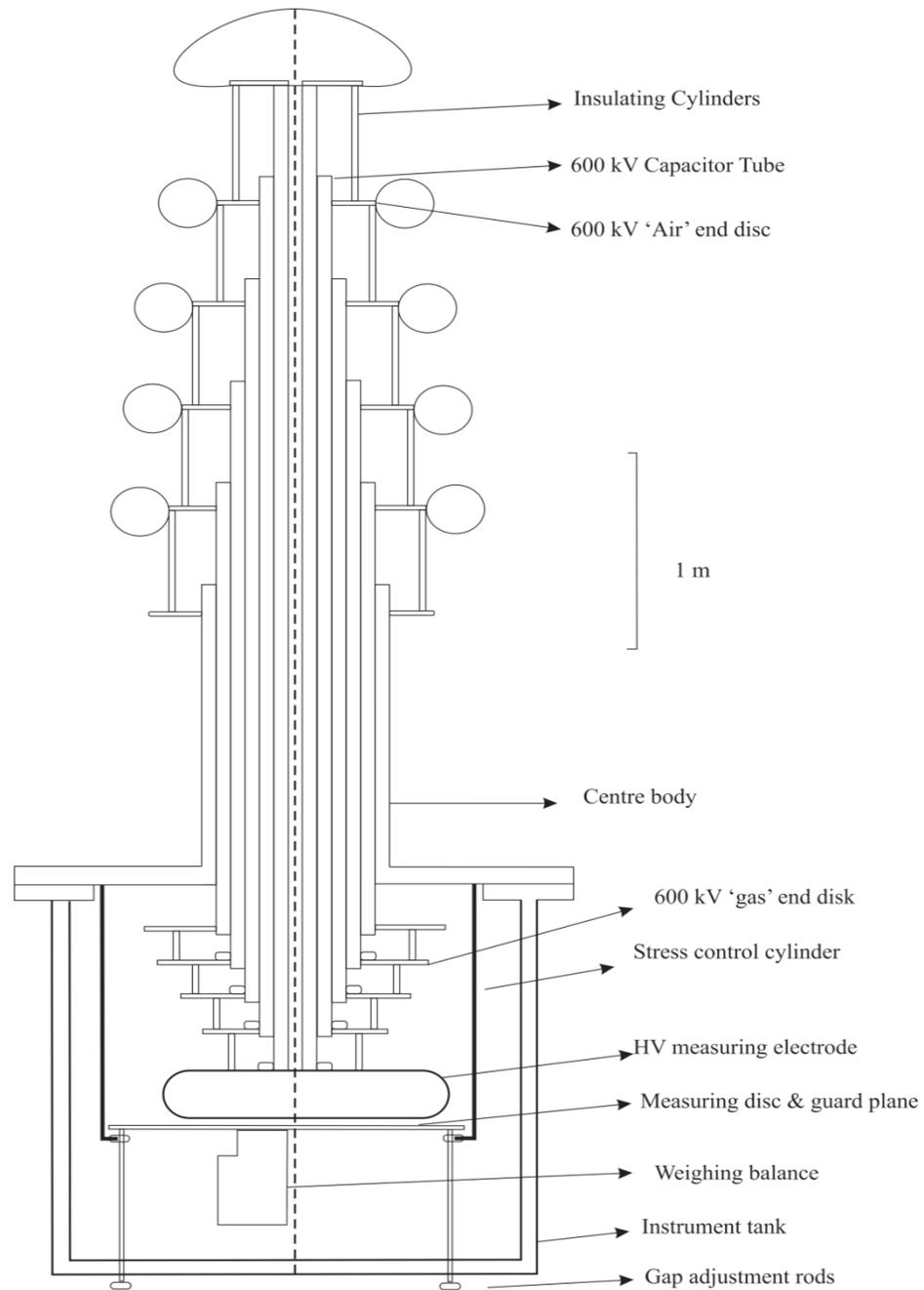


Figure 8.14 Sectional view of 1000 kV electrostatic voltmeter.

Electrostatic Voltmeter, Their Working Principle and Construction

- Electrostatic voltmeters are arranged such that one of the electrodes or a part of it is allowed to move.
- Thus electrostatic voltmeters are rms indicating instruments if the force integration and its display follows equ.(a).
- Various voltmeters developed differ in their use of different methods of restoring forces required to balance the electrostatic attraction.
- This can be achieved by suspension of the moving electrode on one arm of a balance or its suspension on a spring or the use of a pendulous or tensional suspension.
- The small movement is generally transmitted and amplified by a spot light and mirror system, but many other systems have also been used.
- The electrostatic measuring device can be used for absolute voltage measurements since the calibration can be made in terms of the fundamental quantities of the gap length and forces.
- For a **constant electrode separation 'X'** the integrated forces increase with $(U_{rms})^2$ and thus the **sensitivity** of the system for **low ranges** of the rated voltages of the instrument is **small**.
- This disadvantage is overcome, however by varying the gap length in appropriate steps.
- The high pressure gas or even high vacuum between the electrodes provide very high resistivity, therefore the **low active power loss**.
- The measurement of voltages lower than about **50V** is not possible as because the forces become too small.
- The load **inductance** and the electrode system capacitance, however, form a series resonant circuit which must be damped, thus limiting the frequency range.

Summary

- Unlike the measurement of high voltages in power system, the measurement of high test voltages in the HV laboratories require altogether special techniques.
- The high ac and dc test voltages are desired to be measured continuously and accurately at the output side of the test voltage generation equipment when applied on a test object while increasing or decreasing.
- In order to take adequate care of the deviations in the wave form delivered by the test equipment, the best method found is the measurement of peak value/magnitude with the help of ‘voltage dividers’.
- In case of the measurement of high impulse voltages, besides the magnitude, the wave form is also very important to be recorded to ensure distortions within permissible limits.
- The old and classic technique of the measurement of all the types of high voltages, ac, dc and impulse, with the help of ‘sphere gaps’ is not adopted any more due to its limitations.
- In this chapter, principles of measurement of all types of high test voltages in the HV laboratories have been discussed, for example, sphere-gap, potential dividers, electrostatic voltmeters, etc.

Thank You & References

- Ravindra Arora and Bharat Singh Rajpurohit, "Fundamentals of High-Voltage Engineering" Wiley India, 2019.
- High Voltage and Electrical Insulation Engineering, By R. Arora, W. Mosch, IEEE Press, August 2011.
- High Voltage Insulation Engineering: Behaviour of Dielectrics ; Their Properties and Applications by R. Arora, W. Mosch, New Age International, 1995