Measurements of high voltages and currents
Introduction:

• It is essential to measure the voltage and currents accurately, ensuring perfect safety to the personnel and equipment.

• Linear extrapolation of the devices beyond their ranges are not valid for high-voltage meters and measuring instruments, and they have to be calibrated for the full range.

• Electromagnetic interference is a serious problem in impulse voltage and current measurements, and it has to be avoided or minimized.
Measurement of High DC Voltages:

- Series Resistance meters and potential dividers cause current drain from the source and hence problems arise due to large power dissipation, leakage currents and limitation of voltage stress per unit length, change in resistance due to temperature variations.

- Generating Voltmeters are high impedance devices and do not load the source.

- Spark gaps such as sphere gaps are gas discharge devices and give an accurate measure of the peak voltage. Sphere gap measurement of voltages is independent of waveform and frequency.

- Atmospheric conditions like temperature and humidity and by the vicinity of earthed objects affects the measured values.
High Ohmic Series Resistance with Micrometer:

- High dc voltages are usually measured by connecting a very high resistance (few hundreds or Mega ohms) in series with a micro ammeter.

- Current I flowing through large calibrated resistance R is measured by Moving Coil Micro ammeter.

- Voltage drop in the meter is negligible, as the impedance of the meter is only few ohms compared to few hundred mega ohms of the series Resistance R.

- A protective device like a paper gap, a neon glow tube, or a zener diode is used in case the series resistance R fails or flashes over as shown in fig.1

![fig.1 Series resistance Micrometer](image)
• Voltage drop in each resistor element is chosen to avoid surface flashovers and discharges.

• Resistance chain is provided with corona-free terminations.

• The limitations in the series resistance design are:
  - power dissipation and source loading
  - temperature effects and long time stability
  - voltage dependence of resistive elements
  - sensitivity to mechanical stresses.
Resistance Potential Dividers:

- Influence of temperature and voltage on the elements is eliminated in voltage divider.

- With sudden changes in voltage, such as Switching operations, flashover of test objects or source short circuits, flashover or damage may occur to divider elements due to stray capacitance across the elements and due to ground capacitances.

- To avoid these transient voltages, voltage controlling capacitors are connected to linearize the transient potential distribution as in fig.3.
Generating Voltmeters:

• Direct connection to high-voltage source is avoided in Generating Voltmeters.

• A generating voltmeter is a variable capacitor electrostatic voltage generator which generates current proportional to the applied external voltage. (driven by external synchronous or constant speed motor and does not absorb power or energy from the voltage measuring source).
Principle of operation

- The charge stored in a capacitor of capacitance $C$ is given by $q = CV$. If the capacitance of the capacitor varies with time when connected to a voltage source of voltage $V$, the current through the capacitor is given by

$$i = \frac{dq}{dt} = V \frac{dC}{dt} + C \frac{dV}{dt}$$

- For dc voltages $\frac{dV}{dt} = 0$. Hence,

$$i = \frac{dq}{dt} = V \frac{dC}{dt}$$

- If the capacitance varies between the limits $C_0$ and $C_0 + C_m$ sinusoidally as

$$C = C_0 + C_m \sin \omega t$$

The current is

$$i = i_m \cos \omega t$$

where

$$i_m = VC_m \omega$$
• For a constant angular frequency $\omega$, the current is proportional to the applied voltage $V$. The generated current is rectified and measured by a moving coil meter.

• Generating voltmeter can be used for a.c voltage measurements also provided that angular frequency $\omega$ is the same or equal to half that of the supply frequency.

• Generating voltmeters employ rotating sectors for variation of capacitance.

• Fig.4 gives the schematic diagram of a generating voltmeter. The high voltage source is connected to a disc electrode $S_3$ which is kept at a fixed distance on the axis of the other low voltage electrodes $S_0, S_1$ and $S_2$.

• The rotor $S_0$ is driven at a constant speed by a synchronous motor at a suitable speed (1500, 1800, 3000, or 3600 rpm).

• The rotor vanes of $S_0$ cause periodic change in capacitance between the insulated disc $S_2$ and the hv electrode $S_3$.

• The shape and number of the vanes of $S_0$ and $S_1$ are so designed that they produce sinusoidal variation in the capacitance.
• The generated ac current through the resistance R is rectified and read by a moving coil instrument. An amplifier is needed, if the shunt capacitance is large or longer leads are used for connection to rectifier and meter. The instrument is calibrated using a potential divider or sphere gap.
• The meter scale is linear and its range can be extended by extrapolation.

![fig.4 Schematic diagram of a generating voltmeter (rotating vane type)](image)

![fig.5 Calibration curves for a generating voltmeter](image)
• **Advantages:**
  - No source loading by the meter
  - No direct connection to high voltage electrode
  - Scale is linear and extension of range is easy
  - A very convenient instrument for electrostatic devices such as Van de Graaff generator and particle accelerators.

• **Limitations:**
  - Require calibration
  - Careful construction is needed and is a cumbersome instrument requiring an auxiliary drive.
  - Disturbance in position and mounting of the electrodes make the calibration invalid.
DC Electric Field Strength (E):

- Electric fields exist in the near vicinity of very high voltage power lines.

- Development of electric field meters and measurement of electric fields are necessary due to their biological, and ecological effects and possible shock hazards.

- Electric field strength can be measured by using
  - variable capacitor probe or generating voltmeter
  - vibrating plate capacitor

- Basic principle of measurement is by measuring either the induced charges or currents sensed by the electrodes.
Variable Capacitor Field Meter:

• If a metallic electrode is kept in an electric field $E$, the total charge induced on its surface $A$ is

$$ Q = \varepsilon A E = \varepsilon \int E dA $$

• If the area of the sensing electrode varies and the variation of the area of the sensing electrode is periodic, then the current flowing through the measuring electrode to the ground is

$$ I = \frac{dq}{dt} = \frac{1}{T} \int \frac{dq}{dt} dt = \frac{q_{\text{max}} - q_{\text{min}}}{T} $$

Average value of electric field is

$$ E = \frac{q_{\text{max}} - q_{\text{min}}}{\varepsilon_0 A T} = \frac{q_{\text{max}}}{\varepsilon_0 A T} = \frac{i}{\varepsilon_0 A} \text{ if } q_{\text{min}} = 0 $$
• Arrangement of electrodes is shown in fig. 6
• Sensing electrode which is in the form of a circular disc is divided into sectors and shielded by a rotating shutter which rotates at an angular velocity $\omega$. The shutter is driven at a constant speed by a motor.
• Two opposite sectors of the sensing electrode are grounded and the other two are connected to ground through a measuring resistance $R$.
• The voltage across the resistance is measured and then electric field intensity $E$ is measured.
• The induced current signal (voltage) is rectified by a phase sensitive detector operating with suitable phase angle relative to the movement of shutter and is calibrated in terms of electric field $E$.
Vibrating Plate Field Meter:

- A vibrating plate or electrode is located below the fixed plate and is made to oscillate at a fixed rate by a driver motor and voltage is induced between the plates.

- The Electric field is proportional to voltage induced V.

Fig. 7 Vibrating plate field meter
AC Field Strength Meter:

- **Principle**: Electric field between the plates of the capacitor is proportional to the charge induced on the plates of the capacitor and varies because of the variation of the ac electric field, the capacitive current is a measure of the field.

- **Types of electrode for field probe:**

![Diagram](image)
• Charge Q induced on the surface of a conductor in an electric field $E$ for a Spherical electrode is $Q = 3\pi a^2 \varepsilon_0 E = K \varepsilon_0 E$

  Current through the probe $I = \frac{dq}{dt} = K \omega \varepsilon_0 E \cos \omega t$

  $K$ -> Determined by Type of probe electrode
  $I$ -> Rectified meter

• Accuracy of the instrument is about 0.5% .

• Accuracy depends on
  ➢ Harmonic content.
  ➢ Atmospheric conditions like temperature, humidity.
  ➢ Position and location of the meter in Electric field.
Measurement of Ripple Voltage in DC Systems:

- Ripple voltages are ac voltages of non-sinusoidal nature and if a resistance potential divider is used along with an oscilloscope, the measurement of small values of the ripple will be inaccurate.

- **Principle**: Measure the varying component of the ac voltage by blocking the dc component in C-R circuit. (condition to be satisfied is $\omega CR \gg 1$).
Measurement of Ripple with CRO:

- Switch ‘S’ must be closed when the CRO is connected to the source so that the CRO input terminal does not receive any high voltage signal while ‘C’ is being charged.

- Capacitance ‘C’ is rated for peak voltage and capacitance should be larger than the capacitance of the cable and input capacitance of CRO together.

![Diagram of measurement setup](image)

*Fig. 9 Current arrangement for the measurement of ripple voltage*
High AC and Impulse Voltages:

- **Series Impedance Voltmeters:**
  - For power frequency ac measurements the series impedance may be a pure resistance or reactance and since resistances involve power losses, often a capacitor is preferred as a series reactance.

- **Problems with High resistances:**
  - Variation of resistance with temperature.
  - Residual Inductance of the resistance.
  - Stray Capacitances.
• At any frequency $\omega$ of ac voltage, the impedance of the resistance $R$ (shown in fig. 10) is

$$Z = \frac{R + j\omega L}{(1 - \omega^2 LC) + j\omega CR}$$

• If $\omega L$ and $\omega C$ are small compared to $R$,

$$Z = R[1 + j(\frac{\omega L}{R} - \omega CR)]$$

and the total phase angle is

$$\tan \phi \approx (\frac{\omega L}{R} - \omega CR)$$
• For extended and large dimensioned resistors, each elemental resistor has to be taken as a transmission line equivalent, for calculating the effective resistance.

• Equivalent circuit of a high voltage resistor neglecting inductance.

(a) Extended series resistance with inductance neglected

- $C_q$ — Stray capacitance to ground
- $C_s$ — Winding capacitance

fig. 11 Extended Series resistance with inductance neglected
• Ground or stray capacitance of each element influences the current flowing in the current and hence results error in the meter.

• Stray ground capacitance effects can be removed by shielding the resistor \( R \) by a second surrounding spiral \( R_s \), which shunts the actual resistor but does not contribute to the current through the instrument.

• By tuning the resistors \( R_a \), the shielding resistor and potentials may be adjusted w.r.t actual measuring resistor so that resulting compensation currents between the shield and the measuring resistors provide a minimum phase angle.

![Diagram](image)
Series Capacitance Voltmeter:

A series capacitor is used instead of a resistor for ac high voltage measurements.

- Current $I_c$ through meter is $I_c = j\omega CV$ ($V$ is applied ac voltage)
  
  If ac voltage contains harmonics, error due to changes in series impedance occurs. The rms value of voltage $V$ with harmonics is
  
  $$V = \sqrt{V_1^2 + V_2^2 + \ldots + V_n^2}$$

  Currents due to harmonics are
  
  $$I_1 = \omega CV_1$$
  $$I_2 = 2\omega CV_2$$
  $$I_n = n\omega CV_n$$

  **With a 10% fifth harmonic only, the current is 11.2% higher, and hence error is 11.2% in the voltage measurement.**

  **This method is not recommended when ac voltages are not pure sinusoidal waves**
Capacitive potential dividers:

- A standard compressed air or gas capacitor ($C_1$) is a three terminal capacitor and it is connected to any large capacitor ($C_2$) (mica, paper, or any low loss capacitor) through a shielded cable and $C_2$ is completely shielded to avoid any stray capacitances.

  **Applied Voltage $V_1$ is**
  
  $$V_1 = V_2 \left( \frac{C_1 + C_2 + C_m}{C_1} \right)$$

  $C_m$ - capacitance of meter, connecting cable and leads

- Capacitive voltage dividers with an electrostatic voltmeter is used to eliminate the errors due to harmonic voltages.

![fig.14 Capacitance potential divider](image)
Capacitive Voltage Transformers (CVT):

- CVT can be connected to a low impedance device like a wattmeter pressure coil or relay coil whereas Capacitance divider requires a high impedance meter like electrostatic voltmeter.

- $C_1$ is made of few units of high voltage capacitors, and the total capacitance will be around a few thousands picofarads as against a gas filled standard capacitor of about 100 pF.

fig.15 Capacitive voltage transformer
• A matching transformer (10-30kV/100-500V) is connected between the load or meter M and C₂.

• For Resonance, the value of tuning choke L is

\[
\omega(L + L_T) = \frac{1}{\omega(C_1 + C_2)}
\]

where

- L = Inductance of choke
- \(L_T\) = equivalent inductance of transformer ref. to hv side

• Capacitance divider with suitable matching or isolating potential transformer tuned for resonance condition is used in power systems for voltage measurements
CVT Phasor Diagram:

• The meter reactance, $X_m$ is neglected and is taken as a resistance $R_m$ when the load is connected to a voltage divider side. The voltage across the potential transformer $V_2 = I_m R_m$ and the voltage across the capacitor is $V_2 + T_m (R_c + jX_c)$.

• The phasor diagram is written taking $V_1$ as the reference phasor.
  
  $V_1 = V_{c1} + V_{c2}$ and total current $= I_m + I_{c2}$.

• With proper tuning $V_2$ will be in phase with $V_1$. The potential transformer resistance and reactance are included in $R_i$ and $X_i$, the resistance and reactance of tuning inductor.

• Voltage $V_2$ (meter voltage) will be in phase with the input voltage.

![Phasor diagram of CVT under resonance conditions](image)
• **Advantages of a CVT**
  - Simple design and easy installation.
  - Useful for voltage measuring device for meter and relaying purposes and also as a coupling condenser for power line carrier communication and relaying.
  - Frequency independent voltage distribution along elements as against conventional magnetic potential transformers which require additional insulation design against surges.
  - Provides isolation between high voltage terminal and low voltage metering.

• **Disadvantages of a CVT:**
  - Voltage ratio is susceptible to temperature variations, and
  - Problem of inducing ferro-resonance in power systems.
Potential Transformers (Magnetic Type):

- Magnetic potential transformers are the oldest devices for ac measurements.
- For very high voltages, cascading of the transformers is possible.
  \[ V_1 / V_2 = \alpha = N_1 / N_2 \]
  
- PT’s suffer from the ratio and phase angle errors caused by the magnetizing and leakage impedance of the transformer windings and these errors are compensated by adjusting the turns ratio with the tapping's on the high voltage side under load conditions.

- PT do not permit fast rising transient or high frequency voltages along with normal supply frequency, but harmonic voltages are usually measured with sufficient accuracy.

- With high voltage testing transformers, no separate potential transformer is used, but a PT winding is incorporated with the high voltage windings of the testing transformer.
• With test objects like insulators, cables, etc. which are capacitive in nature, a voltage rise occurs on load with the testing transformer, and the potential transformer winding gives voltage values less than the actual voltages applied to the test object.

• If the percentage impedance of the testing transformer is known, the following correction can be applied to the voltage measured by the PT winding of the transformer.

\[ V_2 = V_{20} (1 + 0.01v_x C / C_N) \]

- \( V_{20} \) = open circuit voltage of PT winding,
- \( C_N \) = load capacitance used for testing,
- \( C \) = test object capacitance (\( C << C_N \)) and
- \( v_x \) = % reactance drop in the transformer.
Electrostatic Voltmeters:

- **Principle**: In electrostatic fields between the electrodes of a parallel plate capacitor is

\[
F = \left| \frac{-\delta W_s}{\delta s} \right| = \frac{\delta}{2} \left( \frac{1}{C} V^2 \right) = \frac{1}{2} V^2 \frac{\delta C}{\delta s} = \frac{1}{2} \varepsilon_0 V^2 \frac{A}{s^2} = \frac{1}{2} \varepsilon_0 A(V)^2 = \frac{d^2}{2825} \left( \frac{V}{s} \right)^2 \text{gmwt}
\]

- When one of the electrodes is free to move, the force on the other plate can be measured by controlling it by a spring or balancing it with a counter weight.

- For high voltage measurements, a small displacement of one of the electrodes by a fraction of a millimetre to a few millimetres is usually sufficient for voltage measurements.

- As the force is proportional to the square of the applied voltage, the measurement can be made for ac or dc voltages.
• Electrostatic voltmeters are made with parallel plate configuration using guard rings to avoid corona and field fringing at the edges.

• An absolute voltmeter is made by balancing the plate with a counter weight and is calibrated in terms of a small weight.

• Electrostatic voltmeters have a small capacitance (5 to 50 pF) and high insulation resistance ($R > 10^{13} \Omega$).

• Upper frequency limit for ac applications is determined from the following considerations:
  - natural frequency of the moving system
  - Resonant frequency of the lead and stray capacitances with meter capacitance
  - R-C behavior of the retaining or control spring (due to fractional resistance and elastance)

• Accuracy for ac voltage measurements is better than 0.25% and for dc it is 0.1%
Construction:

• It consists of parallel-plate disc type electrodes separated by a small distance. The moving electrode is surrounded by a fixed guard ring to make the field uniform in the central region.

• The central torque is provided by balancing weight. The moving disc M forms the central core of the guard ring G which is of the same diameter as the fixed plate F. The cap D encloses a sensitive balance B, one arm of which carries the suspension of the moving disc.

• The balance beam carries a mirror which reflects a beam of light. The movement of the disc is magnified. As the spacing between the two electrodes is large, the uniformity of the electric field is maintained by the guard rings H which surround the space between the discs F and M. The guard rings H are maintained at a constant potential in space by a capacitance divider ensuring a uniform special potential distribution.
Electrostatic Voltmeter

(a) Absolute electrostatic voltmeter

(b) Light beam arrangement

- M — Mounting plate
- G — Guard plate
- F — Fixed plate
- H — Guard hoops or rings
- m — Mirror
- B — Balance
- C — Capacitance divider
- D — Dome
- R — Balancing weight

fig.17 Electrostatic Voltmeter
• The main differences between several forms of voltmeters lies in the manner in which the restoring force is obtained.

• For conventional versions of meters, a simple spring control is used, which actuates a pointer to move on the scale of the instruments. In more versatile instruments, only small movements of the moving electrodes is allowed, and the movement is amplified through optical means (lamp and scale arrangement as used with moving coil galvanometers).

• Two air vane dampers are used to reduce vibrational tendencies in the moving system, and the elongation of the spring is kept minimum to avoid field disturbances.

• Range of the instrument is easily changed by changing the gap separation so that V/s or electrical stress is the same for the maximum value in any range.

• With compressed gas or vacuum as medium, the meter is compact in size.
Peak Reading AC Voltmeters:

- Peak value of the ac waveform is necessary to obtain the maximum dielectric strength of insulating solids.

- When the waveform is not sinusoidal, rms value of the voltage multiplied by $\sqrt{2}$ is not correct, hence a separate peak value instrument is desirable in high voltage applications.
Series Capacitor Peak Voltmeter:

- **Principle:** When a capacitor is connected to a sinusoidal voltage source, the charging current is

  \[ i_0 = \int_0^t q dt = j \omega CV \]

- If a half-wave rectifier is used, the arithmetic mean of the rectifier current is proportional to the peak value of the ac voltage. The dc meter reading is proportional to the peak value of the value \( V_m \) or

  \[ V_m = \frac{I}{2\pi fC} \]

- This method is known as Chubb-Froscue method for peak voltage measurement.
• Diode $D_1$ is used to rectify the ac current in one half cycle while $D_2$ passes in the other half cycle.
• The charging current through the capacitor changes its polarity within one half cycle itself.

![Diagram](image)

**Fig. 18** Peak Voltmeter with a series capacitor
- This is suitable only of positive or negative half cycles and hence is valid only when both half cycles are symmetric and equal. This is not suitable when the voltage waveform is not sinusoidal but contains more than one peak or maximum.

- The shaded areas gives the reverse current in any one of the half cycles and the current within that period subtracts from the net current. Hence the reading of the meter will be less and is not proportional to $V_m$ as the current flowing during intervals $(t_1-t_2)$ will not be included in mean value.

fig. 19 Voltage waveform with harmonic content showing false maxima
• Pre-discharges currents within the test circuits cause very short duration voltage drops which introduce errors and this can be overcome by using a resistance $R$ in series with capacitor $C$ such that $CR<<1/\omega$

• Error due to resistance is

$$\frac{\Delta V}{V} = \frac{V-V_m}{V} = (1 - \frac{1}{1+\omega^2C^2R^2})$$

• The different sources that contribute to the error are
  
  - Effective value of the capacitance being different from the measured value.
  - Imperfect rectifiers which allow small reverse currents.
  - Non-sinusoidal voltage waveforms with more than one peak or maxima per half cycle.
  - Deviation of the frequency from that of the value used for calibration.
Digital Peak Reading Meter:

- Series capacitance peak voltmeter is not suitable for waveforms with more than one peak in each half cycle.

- In digital peak reading meter, instead of directly measuring the rectified charging current, a proportional analog voltage signal is derived which is then converted into a proportional mean frequency, $f_m$ as shown in fig.20.

- The ratio frequency $f_m/f$ is measured with a gate circuit controlled by the ac power frequency(f).
• A counter that opens for a adjustable number of periods $\Delta t = p/f$. During this interval, the number of pulses counted, $n$ is

$$n = f_m \Delta t = p \cdot \frac{f_m}{f} = 2pCV_mAR $$

$p$ – constant of the instrument

$A$ - conversion factor of ac-dc converter

• Reading of the voltage in kV can be obtained by suitable choice of the parameter $R$ and number of periods $p$ ($i_m$ is the rectified current through $R$)

$$A = \frac{f_m}{Ri_m} $$

• Total estimated error in this instrument was less than 0.35%.
fig. 20 Digital peak voltmeter
Peak Voltmeters with potential dividers:

- Voltage across $C_2$ is made use of in charging the storage capacitor $C_s$. $R_d$ is the discharge resistor employed to permit variation of $V_m$ whenever $V_2$ is reduced.
- $C_s$ is charged to a voltage proportional to the peak value to be measured. The indicating meter is either an electrostatic voltmeter or a high impedance VTVM.
- The discharge time constant $C_sR_d$ is designed to be about 1 to 10s. This give rise to a discharge error which depends on the frequency of the supply voltage.

![Diagram](image)

fig.21 Peak voltmeter with a capacitance potential divider and electrostatic voltmeter
• To compensate for the charging and discharging errors due to resistance, the circuit is modified as

fig.22 Peak voltmeter as modified by Haefely

• Rabus’ modification to compensate the charging errors

fig.23 Peak voltmeter with equalizing branch as designed by Rabus
Spark Gaps:

- A uniform field spark gap will always have a sparkover voltage within a known tolerance under constant atmospheric conditions. Hence a spark gap can be used for measurement of the peak value of the voltage.

- A sparkover voltage of 30kV(peak) at 1 cm spacing in air at 20°C and 760 torr pressure occurs for a sphere gap or any uniform field gap.

- Only sphere gaps are used for voltage measurements. In certain cases uniform field gaps and rod gaps are also used but their accuracy is less.

- The spark gap breakdown, especially the sphere gap breakdown, is independent of the voltage waveform and hence is highly suitable for all types of waveforms from dc to impulse voltage of short rise times.

- Sphere gaps can be used for radio frequency ac peak measurement(1 MHz)
• Sphere gaps can be arranged either
  ➢ Vertically with lower sphere grounded
  ➢ Horizontally with both spheres connected to the source voltage or one sphere grounded.

• In horizontal configurations, it is generally arranged such that both spheres are symmetrically at high voltage above the ground.

• The voltage to be measured is applied between the two spheres and the distance or spacing S between them gives a measure of the sparkover voltage.

• A series impedance is usually connected between the source and the sphere gap to (i) limit the breakdown current (ii) suppress unwanted oscillations in source voltage when breakdown occurs.
Sphere gap for voltage measurement

1 — Insulator support
2 — Sphere shank
3 — Operating gear and motor for changing gap distance
4 — H.V. connection
P — Sparking point
D — Diameter of the sphere
S — Spacing
A — Height of P above earth
B — Radius of the clearance from external structures
X — High voltage lead should not pass through this plane within a distance B from P

fig. 24 Vertical Arrangement of sphere gap
Horizontal Arrangement of Sphere Gap

fig. 25 Horizontal arrangement of sphere gap
Peak Value of Sparkover voltage in kV for a.c, d.c. voltages of either polarity

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<th>Sphere diameter (cm)</th>
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• In the case of ac peak value and dc voltage measurements, the applied voltage is uniformly increased until sparkover occurs in the gap. Generally, a mean of about five breakdown values is taken when they agree to within 3%.

• In the case of impulse voltages, to obtain 50% flashover voltage, two voltage limits, differing by not more than 2% are set such that on application of lower limit value either 2 or 4 flashovers take place and on application of upper limit value 8 or 6 flashovers take place respectively.

• The mean of these two limits is taken as 50% flashover voltage. In any case, a preliminary sparkover voltage measurement is to be made before actual measurements are made.
Sphere Gap Construction:

- Sphere gaps are made with two metal spheres of identical diameters $D$ with their shanks, operating gear, and insulator supports.

- Spheres are generally made of copper, brass, or aluminium; the latter is used due to low cost.
Factors Influencing the Sparkover Voltage of Sphere Gaps:

(i) nearby earthed objects
(ii) atmospheric conditions and humidity
(iii) irradiation, and
(iv) polarity and rise time of voltage waveforms.
Effect of Nearby Earthed Objects:

- The Effect of nearby earthed objects was investigated by Kuffel by enclosing the earthed sphere inside an earthed cylinder. It was observed that the sparkover voltage is reduced.
- The reduction was observed to be

\[ \Delta V = m \log \left( \frac{B}{D} \right) + C \]

where \( \Delta V \) = percentage reduction

- \( B \) = diameter of earthed enclosing cylinder,
- \( D \) = diameter of the spheres,
- \( S \) = spacing, and \( m \) and \( C \) are constants.
- The reduction was less than 2\% for \( S/D \leq 0.5 \) and \( B/D \geq 0.8 \). Even for \( S/D \approx 1.0 \) and \( B/D \geq 1.0 \) the reduction was only 3\%. Hence, if the specifications regarding the clearances are closely observed the error is within the tolerances and accuracy specified.
- The reduction in voltage is within the accuracy limits, if \( S/D \) is kept less than 0.6A , A is the distance from sparking point to horizontal ground plane.
Influence of ground plates on Sparkover voltage

fig. 26 Influence of ground planes on sparkover voltage
Effect of Atmospheric Conditions:

- The sparkover voltages of a spark gap depends on the air density which varies with the changes in both temperature and pressure.

- If the sparkover voltage is $V$ under test conditions of temperature $T$ and pressure $p$ torr and if the sparkover voltage is $V_0$ under standard conditions of temperature $T=20^\circ C$ and pressure $p=760$ torr, then
  \[ V = kV_0 \]
  where $k$ is a function of the air density factor $d$, is given by
  \[ d = \frac{p}{760} \left( \frac{293}{273+T} \right) \]

- Relation between correction factor $k$ and air density factor $d$

<table>
<thead>
<tr>
<th>d</th>
<th>0.70</th>
<th>0.75</th>
<th>0.80</th>
<th>0.85</th>
<th>0.90</th>
<th>0.95</th>
<th>1.0</th>
<th>1.05</th>
<th>1.10</th>
<th>1.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>0.72</td>
<td>0.77</td>
<td>0.82</td>
<td>0.86</td>
<td>0.91</td>
<td>0.95</td>
<td>1.0</td>
<td>1.05</td>
<td>1.09</td>
<td>1.12</td>
</tr>
</tbody>
</table>
• The sparkover voltage increases with humidity. The increase is about 2 to 3% over normal humidity range of 8 g/m$^3$ to 15 g/m$^3$.

• Humidity effect increases with the size of spheres and is maximum for uniform field gaps.

• The sparkover voltage increases with the partial pressure of water vapour in air, and for a given humidity condition, the change in sparkover voltage increases with the gap length.

• The influence of humidity on sparkover voltage of a 25cm sphere gap for 1 cm spacing is shown in fig…….
Effect of irradiation:

- Illumination of sphere gaps with ultra-violet or X-rays aids easy ionization in gaps.
- The effect of irradiation is pronounced for small gap spacings.
- A reduction of about 20% in sparkover voltage was observed for spacings of 0.1 D to 0.3 D for a 1.3 cm sphere gap with dc voltages.
- The reduction in sparkover voltage is less than 5% for gap spacings more than 1 cm, and for gap spacings of 2 cm or more it is about 1.5%.
- Hence, irradiation is necessary for smaller sphere gaps of gap spacing less than 1 cm for obtaining consistent values.
Effect of Polarity and Waveform:

- It has been observed that the sparkover voltages for positive and negative polarity impulses are different.

- For sphere gaps of 6.25 to 25 cm diameter, the difference between positive and negative dc voltages is not more than 1%.

- For smaller sphere gaps (2 cm diameter and less) the difference was about 8% between negative and positive impulses of 1/50 μs waveform.

- The wave front and wave tail durations also influence the breakdown voltage.

- For wave fronts of less than 0.5 μs and wave tails less than 5 μs the breakdown voltages are not consistent. Hence the use of the sphere gap in this case is not recommended for voltage measurement.
Uniform Field Electrode Gaps:

• Sphere gaps, have only limited range with uniform electric field. It is not possible to ensure that the sparking always takes place along the uniform field region.

• Rogowski presented a design for uniform field electrodes for sparkover voltages up to 600kV, given by

\[ V = AS + B\sqrt{S} \]

where A and B are constant, S is the gap spacing in cm.

• The constants A and B were found to be 24.4 and 7.50 respectively at a temperature T=250°C and pressure =760 torr.

• Sparking potential is a function of air density (air density factor ‘d’) sparkover voltage is modified as

\[ V = 24.4dS + 7.50\sqrt{dS} \]
Uniform field electrodes

AC, EF — Flat portion (≥ S)
Curvature A to B and C to D ≥ 108
Curvature B to E and D to F continuously increasing

(a) Electrodes for 300 kV (rms) spark gap

AB — Flat portion
BC — Sine curve
CD — arc of a circle with centre at O
XY — OC sin \( \left( \frac{\pi}{2} \cdot \frac{BX}{BO} \right) \)

(b) Bruce profile (half contour)

fig. 28 Uniform field electrode spark gap
• Bruce made uniform field electrodes with a sine curve in the end region.

• According to Bruce, the maximum voltage for electrodes of different voltages are given as below:

<table>
<thead>
<tr>
<th>Diameter Of Electrode (inches)</th>
<th>4.5</th>
<th>9.0</th>
<th>15.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Voltage (kV)</td>
<td>140</td>
<td>280</td>
<td>420</td>
</tr>
</tbody>
</table>

• For the Bruce profile, the constants A and B are respectively 24.22 and 6.08.

• Sparkover voltage increases with humidity and it is modified as

\[ V = 6.66\sqrt{dS} + [24.55 + 0.41(0.1e - 1.0)]dS \]

where, \( V \) = sparkover voltage, \( kV_{\text{peak}} \) (in \( kV_{\text{dc}} \)),
\[ e = \text{vapour pressure of water in air ( mm Hg).} \]

• Constants A and B differ for ac, dc, and impulse voltages.
A comparison between sparkover voltages (in air at a temperature of 20°C and a pressure of 760 torr) of a uniform field electrode gap and a sphere gap is given as below:

<table>
<thead>
<tr>
<th>Gap spacing (cm)</th>
<th>Sparkover voltage with uniform field electrodes as measured by</th>
<th>Sphere gap sparkover voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ritz (kV)</td>
<td>Bruce (kV)</td>
</tr>
<tr>
<td>0.1</td>
<td>4.54</td>
<td>4.50</td>
</tr>
<tr>
<td>0.2</td>
<td>7.90</td>
<td>7.56</td>
</tr>
<tr>
<td>0.5</td>
<td>17.00</td>
<td>16.41</td>
</tr>
<tr>
<td>1.0</td>
<td>31.35</td>
<td>30.30</td>
</tr>
<tr>
<td>2.0</td>
<td>58.70</td>
<td>57.04</td>
</tr>
<tr>
<td>4.0</td>
<td>112.00</td>
<td>109.00</td>
</tr>
<tr>
<td>6.0</td>
<td>163.80</td>
<td>160.20</td>
</tr>
<tr>
<td>8.0</td>
<td>215.00</td>
<td>211.00</td>
</tr>
<tr>
<td>10.0</td>
<td>265.00</td>
<td>261.1</td>
</tr>
<tr>
<td>12.0</td>
<td>315.00</td>
<td>311.6</td>
</tr>
</tbody>
</table>
Rod Gaps:

- A rod gap is also sometimes used for approximate measurement of peak values of power frequency voltages and impulse voltages. IEEE recognized that this method gives an accuracy within $\pm 8\%$.

- The rods will be
  - Either square edged or circular in cross-section.
  - Length of the rods may be 15-75 cm
  - Spacing varies from 2 to 200 cm.

- The sparkover voltage, as in other gaps, is affected by Humidity and Air density.

- Humidity correction for rod gap sparkover voltages:

<table>
<thead>
<tr>
<th>Vapour pressure of water (torr)</th>
<th>2.54</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correction factor %</td>
<td>-16.5</td>
<td>-13.1</td>
<td>-6.5</td>
<td>-0.5</td>
<td>4.4</td>
<td>7.9</td>
<td>10.1</td>
</tr>
</tbody>
</table>
• The power frequency breakdown voltage for 1.27 cm square rods in air at 270°C and at a pressure of 760 torr with the vapour pressure of water of 15.5 torr is given below:

<table>
<thead>
<tr>
<th>Gap spacing (cm)</th>
<th>Sparkover voltage (kV)</th>
<th>Gap spacing (cm)</th>
<th>Sparkover voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>26</td>
<td>30</td>
<td>172</td>
</tr>
<tr>
<td>4</td>
<td>47</td>
<td>40</td>
<td>225</td>
</tr>
<tr>
<td>6</td>
<td>62</td>
<td>50</td>
<td>278</td>
</tr>
<tr>
<td>8</td>
<td>72</td>
<td>60</td>
<td>332</td>
</tr>
<tr>
<td>10</td>
<td>81</td>
<td>70</td>
<td>382</td>
</tr>
<tr>
<td>15</td>
<td>102</td>
<td>80</td>
<td>435</td>
</tr>
<tr>
<td>20</td>
<td>124</td>
<td>90</td>
<td>488</td>
</tr>
<tr>
<td>25</td>
<td>147</td>
<td>100</td>
<td>537</td>
</tr>
</tbody>
</table>

• In case of impulse voltage measurements, the IEC and IEEE recommend horizontal mounting of rod gaps on insulators at a height of 1.5 to 2.0 times the gap spacing above the ground. One of the rods is usually earthed.
• Corrections for humidity for 1/5 μs impulse and 1/50 μs impulse are given below:

• Sparkover voltages for impulse waves are given below:

<table>
<thead>
<tr>
<th>Gap length (cm)</th>
<th>1/5 μs wave (kV)</th>
<th>1/50 μs wave (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>66</td>
</tr>
<tr>
<td>10</td>
<td>101</td>
<td>111</td>
</tr>
<tr>
<td>20</td>
<td>179</td>
<td>208</td>
</tr>
<tr>
<td>30</td>
<td>256</td>
<td>301</td>
</tr>
<tr>
<td>40</td>
<td>348</td>
<td>392</td>
</tr>
<tr>
<td>50</td>
<td>431</td>
<td>475</td>
</tr>
<tr>
<td>60</td>
<td>513</td>
<td>557</td>
</tr>
<tr>
<td>80</td>
<td>657</td>
<td>701</td>
</tr>
<tr>
<td>100</td>
<td>820</td>
<td>855</td>
</tr>
</tbody>
</table>
Impulse Voltage Measurement:
Potential Dividers:

- Potential or voltage dividers for high-voltage impulse measurements, high frequency ac measurements, or for fast rising transient voltage measurements are usually either resistive or capacitive or mixed element type.
- The low voltage arm of the divider is usually connected to a fast recording oscillograph or a peak reading instrument through a delay cable.
- $Z_1$ is usually resistor or a series of resistors in case of a resistance potential divider, or a single or a number of capacitors in case of a capacitance divider or a combination of both resistors and capacitors.
• When a step or fast raising voltage is applied at the high voltage terminal, the voltage developed across the element $Z_2$ will not have the true waveform as that of the applied voltage. The cable can also introduce distortion in the waveshape.

• Different Errors in the measurements:
  i. Residual Inductance in the elements.
  ii. Stray Capacitance occurring
    a. between the elements,
    b. From sections and terminals of the elements to ground, and
    c. From the high voltage lead to the elements or sections;
  iii. The impedance errors due to
    a. Connecting leads between the divider and test objects, and
    b. Ground return leads and extraneous current in ground leads; and
  iv. Parasitic oscillations due to lead and cable inductances and capacitance of high-voltage terminal to ground.
Resistance Potential Dividers:
Very Low Impulse Voltages and Fast Rising Pulses:

• A simple resistance potential divider consists of two resistances $R_1$ and $R_2$ in series ($R_1 \gg R_2$).
• The attenuation factor of the divider is given by

$$a = \frac{V_1(t)}{V_2(t)} = 1 + \frac{R_1}{R_2}$$

• The divider element $R_2$, in practice, is connected through a coaxial cable to the oscilloscope. The cable will generally have a surge impedance $Z_0$ and this will come in parallel with oscilloscope input impedance.

fig. 31 Resistance potential divider with surge cable and oscilloscope terminations
• For high frequency and impulse voltages (since they also contain high frequency fundamental and harmonics), the ratio in the frequency domain will be given by

\[ a = \frac{V_1}{V_2} = 1 + \frac{R_1}{(R_2 / 1 + j\omega R_2 C_m)} \]

• Hence, the ratio is a function of the frequency. To avoid the frequency dependent of the voltage ratio, the divider is compensated by adding an additional capacitance \( C_1 \) across \( R_1 \). The value of \( C_1 \), to make the divider independent of the frequency, may be obtained from the relation,

\[ \frac{R_1}{R_2} = \frac{C_m}{C_1} \]

• This compensation is used for the construction of high-voltage dividers and probes used with oscilloscopes.

• Usually, probes are made with adjustable values of \( C_m \) so that the value of \( C_m \) can include any stray capacitance including that of a cable.
• Compensated resistance potential divider

![Diagram of compensated resistance potential divider]

fig.32 Compensated resistance potential divider

• Output of compensated resistance voltage divider.

![Graph showing waveforms]

(i) Overcompensated  (ii) correctly compensated  (iii) Undercompensated

fig.33 Output of compensated resistance potential divider for different degrees of compensation
• For the exponential slope or for the rising portion of the wave, the time constant

\[
\tau = \left[ \frac{R_1 R_2}{R_1 + R_2} \right] (C_1 + C_m)
\]

• The time constant will be too large when the value of \( C_1 \) is greater than that required for correct compensation and hence an overshoot with an exponential decay occurs as shown in fig.33(i)

• For undercompensation, the charging time is too high and as such an exponential rise occurs as shown in fig.33(iii)
Potential dividers for High-Voltage Impulse Measurements

- For voltages above 100 kV, $R_1$ is no longer small in dimension and is usually made of a number of sections. Hence the diameter is no longer a small resistor of lumped parameters, but has to be considered as an equivalent distributed network with its terminal to ground capacitances and intersectional series capacitances as shown in fig.34.

- The total resistance $R_1$ is made of $n$ resistors of value $R_1'$ and $R=nR_1'$. $C_g$ is the terminal to ground capacitance of each of the resistor elements $R_1'$, and $C_s$ is the capacitance between the terminals of each section.

- The inductance of each element ($L_1'$) is usually small compared to the other elements.
• This divider produces a non-linear voltage distribution along its length and also acts like an R-C filter for applied voltages.

• The output of divider for various values of $C_0/C_s$ ratio is shown in fig.35

By arranging guard rings at various elemental points, the equivalent circuit is modified using Capacitive Voltage divider.
Capacitance Voltage Dividers:

- Capacitance voltage dividers are ideal for the measurement of fast rising voltages and pulses.

- The capacitance ratio is independent of frequency, if their leakage resistance is not high enough to be neglected. But usually the dividers are connected to the source voltage through long leads which introduce lead inductances and residual inductances.

- The capacitance used for very high-voltage work is not small in dimension and hence cannot be considered as a lumped element.

- Therefore, the output of the divider for high frequencies and impulses is distorted as in the case of resistance dividers.
fig. 36 Equivalent circuit of a resistance potential divider with shield and guard rings
Pure Capacitance Dividers:

- A pure capacitance divider for high voltage measurements and its electrical equivalent network without stray elements is shown in fig.37

\[ a = \frac{V_1(t)}{V_2(t)} = 1 + \frac{C_2}{C_1} \]
• Capacitance $C_1$ is formed between the hv terminal of the source (impulse generator) and that of the test object or any other point of measurement.

• The CRO is located within the shielded screen surrounding capacitance $C_2$ ($C_2$ includes the capacitance used, the lead capacitance, input capacitance of the CRO)

• The advantage of this connection is that the loading on the source is negligible; but a small disturbance in the location of $C_2$ or hv electrode or the presence of any stray object nearby changes the capacitance $C_1$, and hence the divider ratio is affected.

• In many cases, a standard air or compressed gas capacitor is used which has coaxial cylindrical construction.
• Design frequently used is to make $C_1$ to consist of a number of capacitors $C_1'$ in series for a given voltage $V_1$.
• Equivalent circuit is similar to that of a string insulator unit used in transmission lines.

![Diagram of Distributed Network](image)

fig. 38 Capacitance voltage divider
• Voltage distribution along the capacitor chain is non-linear and hence causes distortion of the output wave. But the ratio error is constant and is independent of frequency as compared to resistance dividers.

• A simplified equivalent circuit is shown in fig.39 which can be used if \( C_1 \ll C_2 \) and \( C_g \ll C_1 \). The voltage ratio is

\[
a = \frac{V_1(t)}{V_2(t)} \approx \left[1 + \frac{C_2}{C_1}\right]\left[1 + \frac{C_g}{6C_1}\right]
\]

• The ratio is constant and gives an error of less than 5% when \( C_1 = 3C_g \). This equivalent circuit is satisfactory up to 1 MHz.
Field Controlled Voltage Dividers:

- The electrostatic or capacitive field distribution of a shield or guard ring placed over a resistive divider to enforce a uniform field in the neighborhood and along the divider may be adopted for high voltage measurements.

![Diagram of field-controlled resistance divider with a damping resistor](image)

fig. 40 Field-controlled resistance divider with a damping resistor
• The shield is in the form of a cone. \( R_1 \) is a non-linear resistance in the sense the resistance per unit length is small and hence loading effect is reduced.

• The main advantage is that the capacitance per unit length is small and hence loading effect is reduced. Sometimes the parallel resistance \( R_2 \) together with the lead inductance and shunt capacitances cause oscillations as shown in fig.41(a). The oscillations can be reduced by adding a damping resistor \( R_d \) as shown in fig.40.

• These dividers are constructed for very high voltages (up to 2MV) with response times less than 30 ns.

• Resistance column is made of woven resistance of 20 k\( \Omega \).

• The step response of such a divider is shown in fig.. With and without damping resistor. With a proper damping resistor \((R_d)\) the response time is much less and the overshoot is reduced.
fig. 41 Step response of field controlled voltage divider

(a) $R_d = 0$ and long lead
(b) $R_d = 0$ and short lead of 14' long with low inductance
(c) $R_d = 500 \, \Omega$ and long lead
Mixed R-C Potential Dividers:

- Mixed potential dividers use R-C elements in series or in parallel.

- A better construction is to make an R-C series element connection and these dividers are made up to rating of 5 MV with response time less than 30 ns.

- The Equivalent circuit is shown in fig.42

- The low voltage arm R₂ is given “L peaking” by connecting a variable inductance L in series with R₂. The step response of the divider and the schematic connection is shown in fig.43

- For a correctly designed voltage divider L peaking will not be necessary.
(a) Equivalent circuit

\[ R'_1 = \frac{R_1}{n} \]
\[ C'_1 = nC_1 \left( 1 - \frac{C_g}{6C_1} \right) \]

\( C_g \) = ground capacitance
\( C_1 \) = total series capacitance
\( R_1 \) = total resistance
\( R_1C_1 = R_2C_2 \)

(b) Step response determined with low voltage step pulse

fig. 42 Equivalent circuit of a series R C voltage divider and its step response
fig. 43 L peaking in low voltage arm and step response of the divider with L peaking.
R-C Potential Dividers for 2 MV Rating and above:

- Voltage dividers used for measuring more than one million volt attenuate the measuring signal to value in the range of 100V to few hundreds of volts.

- The criteria required to assess the dividers are

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i)</td>
<td>Shape of voltage in the test arrangement should be transferred without any distortion to the LV side.</td>
</tr>
<tr>
<td>(ii)</td>
<td>Simple determination of transfer behavior should be ensured.</td>
</tr>
<tr>
<td>(iii)</td>
<td>Should be suitable for multipurpose use (for use with ac power frequency voltages, switching impulse voltages as well as with lightning impulse voltages.)</td>
</tr>
</tbody>
</table>
• The dividers should have broad bandwidths. The above requirements are generally met by
  a) Optimally damped R-C dividers.
  b) Under damped or low-damped R-C dividers
• The high-voltage arm of such dividers consists of series R-C units while the secondary arm is usually an R-C series or parallel circuit.

### Optimally Damped Dividers

| (i) | \( R_1 = 4\sqrt{L_1 / C_g} \) Where  
|     | \( L_1 \) is the inductance of the high-voltage lead and HV portion of divider.  
|     | \( C_g \) is the equivalent capacitance to ground.  
|     | \( R_1 \) is in the range of 400-1000 ohms. |

(ii) Step Response is shown in fig.44 Because of large time constant\((R_d + R_1)C_1\), the optimal damped divider affects the voltage shape at the test object. Standard lightning impulses sometimes cannot be generated to the correct standard specifications. R-C potential dividers are not suitable for measurements with test objects of very low capacitance.
## Underdamped R-C divider

(i) \( R_1 \) will be equal to 0.25 to 1.5 times \( \sqrt{\frac{L}{C_1}} \)

where \( L \) is inductance for complete measuring loop

\( C_1 \) is the capacitance of HV part of divider.

Normal value of \( R_1 \) lies between 50 and 300 ohms.

(ii) Acts as a load capacitance and is suitable for applications over a broad bandwidth, i.e., ac, switching impulses, lightning impulses, chopped waves, etc. These are also suitable for measurement of steep fronted impulse waves. Even though the step response is poor in this case, they can be used to measure the standard impulse wave to a better accuracy.
(i) Optimally damped

Response time : 50 n sec
Front time : 50 n sec
Overshoot : = 3%
Parameters : $R_1 = 1000 \, \Omega$
$C_1 = 360 \, pF$

Damping resistance : 500 \, \Omega
$(R_d + R_1) \, C_1 = R_2 \, C_2$

(ii) Underdamped

Response time : 4 n sec
Front time : 110 n sec
Overshoot : = 30%
Parameters : $R_1 = 256 \, \Omega$
$C_1 = 400 \, pF$

Damping resistance : 0 \, \Omega
$R_1 \, C_1 = R_2 \, C_2$

fig.44 Step Response of a 4 MV R-C divider
Fig. 45 Record of the front portion of a lightning impulse wave with underdamped (curve A) and optimally damped (curve B) dividers for a negative polarity wave when both dividers are connected in parallel.
Different Connections employed with Potential dividers:

- Possible errors are
  
  i. \( R_2 \neq Z_0 \) (surge impedance of the cable)
  
  ii. Capacitance of the cable and CRO shunting R2 and hence introducing distortion
  
  iii. Attenuation or voltage drop in surge cable \( Z_0 \).
  
  iv. Ground capacitance effect.

- To avoid reflections at the junction of the cable and R2, R2 is varied to give the best possible step response. When a unit step voltage is applied to take a fraction of the voltage \([C_1/(C_1+C_2)]\) into it and cause reflections at the input end.

- In the beginning of the cable acts like a resistance of value = \( Z_0 \) the surge impedance, but later behaves like a capacitor of value equal to total capacitance of the cable.

- Introduced distortion is compensated by using a split capacitor connection as shown ….with \((C_1+C_2)=(C_3+C_k)[C_k=\text{capacitance of the cable}]\).
(a) Resistance potential divider with surge cable and CRO

(b) Capacitance divider with surge cable and CRO

(c) Split capacitor arrangement $R = Z_0$

(d) Resistance potential divider with surge cable and CRO. Voltage ratio, $V_1/V_2 = 1 + (R_1/R_2) + (R_1/R'_2)$ where $R_2/Z_0$

fig. 46 Potential Divider arrangements
Mixed Potential Dividers:

- Arrangement for mixed potential dividers are shown in fig.47 is modified and improved in the arrangement of fig.47(b)

\[ R_1 C_1 = \frac{C_2 Z_0 (C_1 + C_2 + C_k)}{(C_1 + C_2)} \]

\[ Z_0 = R_3 + \left( \frac{R_1 R_2}{R_1 + R_2} \right), \text{ and } R_1 C_1 = R_2 C_2 \]

- The response is greatly improved. The arrangement shown in fig.47(c) is simple and gives the desired impedance matching.
(a) R-C series divider

(b) Modified connection of R-C divider

(c) Impedance matching with R-C divider

fig. 47 Mixed potential divider arrangements
Peak Reading Voltmeters for Impulse voltages:

- It is enough if the peak of an impulse voltage wave is measured; its waveshape might already be known or fixed by a source itself.
- The basic circuit along with its equivalent circuit and the response characteristic is shown in fig. 48. The circuit consists of only rectifiers.

fig. 48 A peak reading voltmeter and its equivalent circuit (R-C approximation)
• Diode D conducts for positive voltages only. For negative pulses, the diode has to be connected in reverse.

• When a voltage impulse \( v(t) \) appears across the low voltage arm of the potential divider, the capacitor \( C_m \) is charged to the peak value of the pulse.

• When the amplitude of the signal starts decreasing the diode becomes reverse biased and prevents the discharging of the capacitor \( C_m \).

• The voltage developed across \( C_m \) is measured by a high impedance voltmeter (an electrostatic voltmeter or an electrometer).

• As the Diode D has finite forward resistance, the voltage to which \( C_m \) is charged will be less than the actual peak of the signal, and is modified by the R-C network of the diode resistance and the measuring capacitance \( C_m \).

• The error is shown in fig. The error can be estimated if the waveform is known. The actual forward resistance of the diode D (dynamic value) is difficult to estimate, and hence the meter is calibrated using an oscilloscope.
• Peak voltmeters for either polarity employing resistance and potential dividers are shown in fig.49

• The voltage of either polarity is transferred into a proportional positive measuring signal by resistive or capacitive voltage divider and a diode circuit.

• An active network with feedback circuit is employed in commercial instruments, so that the fast rising pulses can also be measured.

• Instruments employing capacitor dividers require discharge resistance across the low-voltage arm to prevent the build-up of dc charge.

fig.49 Peak reading voltmeter for either polarity with (a) resistance divider (b) capacitance divider
Measurements of High Currents:

- In power systems, it is often necessary to measure high currents, arising due to short circuits.

- For conducting temperature rise and heat run tests on power equipments like conductors, cables, circuit breakers, etc., measurement of high currents are required.

- During lightning discharges and switching transients also, large magnitudes of impulse and switching surge currents occur, which require special measuring techniques at high potential levels.

- High magnitude direct currents are measured using a resistive shunt of low Ohmic value.

- High current resistors are usually oil immersed and are made as three of four terminal resistances.
Hall Effect for DC measurements:

• If an electric current flows through a metal plate located in a magnetic field perpendicular to it, Lorentz forces will deflect the electrons in the metal structure in a direction normal to the direction normal to the direction of both the current and the magnetic field. The charge displacement generates an emf in the normal direction, called the “Hall voltage”.

• The Hall voltage is proportional to the current I, the magnetic flux density B, and the reciprocal of the plate thickness d, the proportionality constant R is called the ‘Hall coefficient’.

\[ V_H = R \frac{B_i}{d} \]

• For metals, the Hall coefficient is very small, and hence semi-conductor materials are used for which the Hall coefficient is high.
• In large current measurements, the current carrying conductor is surrounded by an iron cored magnetic circuit, so that the magnetic field intensity \( H = (1/\delta) \) is produced in a small air gap in the core.

• The Hall elements is placed in the air gap (of thickness \( d \)) , and a small constant dc current is passed through the element. The schematic arrangement is shown in fig.50

• The voltage developed across the Hall element in the normal direction is proportional to the dc current \( I \).

• Hall coefficient \( R \) depends on the temperature and the high magnetic field strengths, and suitable compensation has to be proved when used for measurements of very high currents.

• Hall generators can be used for measurement of unidirectional ac and impulse currents also with proper design of \( H \).
Hall Generator for measuring high dc currents

![Diagram of Hall Generator](image)

\[ V_H = R \cdot \frac{Bi}{d} ; R = \text{Hall coefficient} \]

(a) Hall effect  
(b) Hall generator

**fig.50** Hall generator for measuring high dc currents
Measurement of High-power Frequency Alternating Currents:

- Measurement of power frequency currents are normally done using current transformers only, as use of current shunts involves unnecessary power loss.

- Uses of Current transformers:
  - a) They provide electrical isolation from high voltage circuits in power systems.
  - b) Current transformers used for extra high voltage (EHV) systems are quite different from the conventional designs as they have to be kept at very high voltages above the ground.

- Current transformers introducing Electro-optical technique is shown in fig. 51.

- A voltage signal proportional to the measuring current is generated and is transmitted to the ground through an electro-optical device. Light pulses proportional to the voltage signal are transmitted by a glass-optical fiber bundle to a photodetector and converted back into an analog voltage signal.
• Accuracies better than \( \pm 0.5\% \) have been obtained at rated current as well as for high short circuit currents.

• Required power for the signal converter and optical signal are obtained from suitable current and voltage transformers.

![Diagram of current transformer with electro-optical signal converter for EHV systems.](image)
Measurement of High Frequency and Impulse currents:

- High impulse currents occur in lightning discharges, electrical arcs and post arc phenomenon studies with circuit breakers, and with electric discharge studies in plasma physics.

- The current amplitudes may range from few amperes to few hundred kiloamperes. The rate of rise of such currents can be as high as $10^6$ to $10^{12}$A/s, and rise times can vary from few microseconds to few nanoseconds.

- The methods that are frequently employed such that the sensing device should be capable of measuring the signal over a wide frequency band are
  i. Resistive Shunts
  ii. Magnetic Potentiometers or Probes
  iii. Faraday and Hall Effect Devices

- Accuracy of measurement varies from 1 to 10%.
Resistive Shunts:

• The most common method employed for high impulse current measurements is a low ohmic pure resistive shunt is shown in fig.52(a) and its equivalent circuit is shown in fig.52 (b)

• The current through the resistive element $R$ produces a voltage drop

$$v(t) = i(t)R$$

• The voltage signal generated is transmitted to a CRO through a coaxial cable of surge impedance $Z_0$. The cable at oscilloscope end is terminated by a resistance $R_i=Z_0$ to avoid reflections.

• The resistance element, because of its large dimensions will have a residual inductance $L$ and terminal capacitance $C$. The inductance may be neglected at low frequencies ($\omega$), but becomes appreciable at higher frequencies.
• Normally L and C become significant above a frequency of 1 MHz. The resistance value usually ranges from $10\mu\Omega$ to few milliohms, and the voltage drop is usually about a few volts. The value of the resistance is determined by the thermal capacity and heat dissipation of the shunt.

• Voltage drop across the shunt in the complex frequency domain is

$$V(s) = \frac{(R + Ls)}{(1 + RCs + LCs^2)} I(s)$$

• With the value of C neglected, voltage drop is

$$V(s) = (R + Ls)I(s)$$

fig. 52 Calibrated low ohmic shunt and its equivalent circuit for impulse current measurements
To reduce the stray effects, the resistance shunt is usually designed in the following manner:

a) Bifilar flat strip design
b) Coaxial tube or Park’s shunt design
c) Coaxial squirrel cage design.

a) Bifilar Strip Shunt:

i. Bifilar design consists of resistor elements wound in opposite directions and folded back, with both ends insulated by a Teflon or other high quality insulation.

ii. Voltage signal is picked up through a ultra high frequency coaxial connector. The shunt suffers from stray inductance associated with the resistive element, and its potential leads are linked to a small part of the magnetic flux generated by the current that is to be measured.

iii. To overcome these problems, coaxial shunts are chosen.
(a) Schematic arrangement

1. Metal base
2. Current terminals ($C_1$ and $C_2$)
3. Bifilar resistance strip
4. Insulating spacer (teflon or bakelite)
5. Coaxial UHF connector
   $P_1$, $P_2$ — Potential terminals

(b) Connection for potential and current terminals

fig. 53 Bifilar flat strip resistive shunt
b) Coaxial Tubular or Park’s Shunt:

i. In the coaxial design the current is made to enter through an inner cylinder or resistive element and is made to return through an outer conducting cylinder of copper or brass.

ii. The voltage drop across the resistive element is measured between the potential voltage drop across the resistive element is measured between the potential pick-up point and the outer case.

iii. The space between the inner and the outer cylinder is air and hence acts like a pure insulator.

iv. The maximum frequency limit is about 1000 MHz and the response time is a few nanoseconds.

v. The upper frequency limits is governed by the skin effect in the resistive element. The equivalent circuit to the shunt is given in fig.55 The step response and frequency response are shown in fig.56
1. Current terminals
2. Coaxial cylindrical resistive element
3. Coaxial cylindrical return conductor (copper or brass tube)
4. Potential pick up lead
5. UHF coaxial connector

fig. 5.4 Schematic arrangement of a coaxial ohmic shunt
fig. 55 Simplified and exact equivalent circuits of a co-axial tubular shunt.

(a) Exact equivalent circuit

- $L_0$ — Inductance
- $R_0$ — d.c. resistance
- $n$ — Number of sections per unit length

(b) Simplified circuit

$$L' = 0.43 L_0$$

fig. 56 Step and frequency responses of a coaxial tubular shunt.

(a) Step response

(b) Frequency response

$B = \text{Band width}$

$f_C = \text{Maximum frequency limit}$.
• Inductance $L_0$ is shown in fig.55 is

$$L_0 = \frac{\mu dl}{2\pi r}$$

where $d =$ thickness of cylindrical tube

$l =$ length of cylindrical tube

$r =$ radius of cylindrical tube

• Effective Resistance is given by

$$R = \frac{V(t)}{I_0} = R_0\theta(\omega t)$$

where $R_0 =$ the dc resistance ; $L_0 =$ inductance for dc currents and

$\theta(\omega t)$ is the theta function of type 3 and is equal to

$$[1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp(-n^2 \omega t)]$$

where $\omega = \frac{\pi^2 R_0}{L_0}$ $v(t)$ is the signal developed and $I_o$ is step current.
• The effective impedance of the shunt for any frequency $f$ according to Silsbee is given by

$$Z = \frac{R_0(1 + j)\delta}{\sinh[(1 + j)\delta]}$$

where $R_0 = \text{dc resistance } \Omega$,

$$\delta = 2\pi d \sqrt{f \mu / \rho}$$

$\rho = \text{resistivity of the material ,}\, \Omega\cdot\text{cm}$, $d = \text{thickness of the tube, cm}$, $f = \text{frequency , Hz}$, and $\mu = \text{permeability}$.

• The rise time is given by

$$T = 0.237 \frac{\mu d^2}{\rho}$$

• Bandwidth is given by

$$B = \frac{1.46R}{L_0} = \frac{1.46\rho}{\mu d^2}$$
(c) Squirrel-Cage Shunts:

i. In post arc current measurements, high ohmic value shunts which can dissipate larger energy are required.

ii. Tubular shunts are not suitable due to their limitations of heat dissipation, larger wall thickness, and the skin effect.

iii. To overcome these problems, the resistive cylinder is replaced by thick rods or strips, and the structure resembles the rotor construction of double squirrel-cage induction motor.

iv. The equivalent circuit for squirrel-cage construction is different, and complex.

v. The shunts show peaky response for step input, and a compensating network has to be designed to get optimum response.

vi. Step response (fig.57(a)) and frequency response (fig.57(b)) characteristics are given. Rise times of better than 8 ns with bandwidth more than 400 MHz were obtained for this type of shunts.

vii. A typical R-C compensating network used for these shunts is shown in fig.58
fig. 57 Response of squirrel vage shunt for different number of rods

(i) number of rods too small
(ii) ideal number of rods
(iii) number of rods too high
\[ R \quad \text{— Shunt resistance} \]

\[ r_1 - r_6 \quad \text{— Resistors and capacitors in compensating double T network and } C_1 - C_6 \]

fig. 58 Compensating network for squirrel cage shunts
(d) Material and Technical Data for the Current Shunts:

i. The important factor for the materials of the shunts is the variation of the resistivity of the material with temperature.

ii. Physical properties of some materials with low temperature coefficient, which can be used for shunt construction are given.

iii. Importance of the skin effect has been pointed out in the coaxial shunt design.

iv. The skin depth for a material of conductivity $\sigma$ at any frequency is given by

$$d = \frac{1}{\sqrt{\pi f \mu \sigma}}$$
### Properties of Resistive Materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Constantan</th>
<th>Manganin</th>
<th>Nichrome</th>
<th>German silver</th>
<th>Ferro-alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity $\rho$ at 20°C (Ω-m)</td>
<td>$0.49 \times 10^{-6}$</td>
<td>$0.43 \times 10^{-6}$</td>
<td>$1.33 \times 10^{-6}$</td>
<td>$0.23 \times 10^{-6}$</td>
<td>$0.49 \times 10^{-6}$</td>
</tr>
<tr>
<td>Temperature coefficient per °C($10^{-6}$)</td>
<td>30</td>
<td>20</td>
<td>20</td>
<td>$\approx 50$</td>
<td>40</td>
</tr>
<tr>
<td>Density at 20°C kg/litre</td>
<td>8.9</td>
<td>8.4</td>
<td>8.1</td>
<td>$\approx 7.5$</td>
<td>8.8</td>
</tr>
<tr>
<td>Specific heat kilo calories/kg °C</td>
<td>0.098</td>
<td>0.097</td>
<td>0.11</td>
<td>$\approx 0.1$</td>
<td>$\approx 0.1$</td>
</tr>
</tbody>
</table>
• Skin depth $d$, is defined as the distance or depth from the surface at which the magnetic field intensity is reduced to ‘1/e’ of the surface value for a given frequency $f$.

• Materials of low conductivity $\sigma$ (high resistivity material) have large skin depth and hence exhibit less skin effect.

• Low ohmic shunts of coaxial type or squirrel cage type construction permit measurement of high currents with response times less than 10 ns.
Rogowski Coils:

- If a coil is placed surrounding a current carrying conductor, the voltage signal induced in the coil is $v_i(t) = M \frac{dI(t)}{dt}$ where $M$ is the mutual inductance between the conductor and the coil, and $I(t)$ is the current flowing in the conductor.

- The coil is wound on a nonmagnetic former of toroidal shape and is coaxially placed surrounding the current carrying conductor.

- The number of turns on the coil is chosen to be large, to get enough signal induced. The coil is wound cross-wise to reduce the leakage inductance. Usually an integrating circuit (see fig. 59) is employed to get the output signal voltage proportional to the current to be measured.

- The output voltage is given by

$$V_m(t) = \frac{1}{CR} \int_0^t v_i(t) = \frac{M}{CR} I(t)$$
Rogowski coils with electronic or active integrator circuits have large bandwidths (about 100 MHz). At frequencies greater than 100 MHz the response is affected by the skin effect, the capacitance distributed per unit length along the coil, and due to the electromagnetic interferences.

\[ V_i(t) = \text{Induced voltage in the coil} = M \frac{d[k(t)]}{dt} \]

- \( Z_0 \) — Coaxial cable of surge impedance \( Z_0 \)
- \( R-C \) — Integrating network

**Fig. 59** Rogowski coil for high impulse current measurements
Magnetic Links:

- Magnetic links are short retentivity steel strips arranged on a circular wheel or drum. These strips have the property that the remanent magnetism for a current pulse of $0.5/5\mu s$ is same as that caused by a dc current of the same value.

- Hence, these can be used for measurement of peak value of impulse currents. The strips will be kept at a known distance from the current carrying conductor and parallel to it.

- The remanent magnetism is then measured in the laboratory from which the peak value of the current can be estimated.

- These are mainly useful for estimating the lightning currents on the transmission lines and towers.

- The rate of rise of impulse currents can be measured using the magnetic links by placing them within the magnetic field of inductors which carry the main current to be measured.
• The inductors are connected in series with different values of resistances giving different time constants. Hence the magnetic links record the peak currents whose values are different.

• Knowing the time constants of the resistance –inductance combination, the mean rate of rise of the current in the main circuit is estimated.
Other techniques for Impulse current Measurements:

1. Hall Generators
2. Faraday Generator or Ammeter
3. Current Transformers
Hall Generators:

- Hall generators can be used for ac and impulse current measurements.

- The Bandwidth of these devices was found to be about 50 MHz with suitable compensating devices and feedback.

- The saturation effect in magnetic core can be minimized, and these devices are successfully used for post arc and plasma current measurements.
Faraday Generator or Ammeter:
• When a linearly polarized light beam passes through a transparent crystal in the presence of a magnetic field, the plane or polarization of the light beam undergoes rotation.

• The angle of rotation is given by:

\[ \alpha = VBI \]

where

\( V = \) a constant of the crystal which depends on the wavelength of light.

• To measure the waveform of a large current in an EHV system an arrangement shown in fig….. will be employed.

• A beam of light from a stabilized light source is passed through a polarizer \( P_1 \) to fall on a crystal \( F \) placed parallel to the magnetic field produced by the current \( I \).

• The light beam undergoes rotation of its plane of polarization. After passing through the analyzer, the beam is focused on a photomultiplier, the output of which is fed to CRO.
• The output beam is filtered through a filter $M$, which allows only the monochromatic light. The relation between the oscillograph display and the current to be measured are complex but can be determined.

• The advantages of this method are that
  i. There is no electrical connection between the source and the device.
  ii. No thermal problems even for large currents of several kiloamperes.
  iii. As Signal Transmission is through n optical system, no insulation problems or difficulties arise for EHV system. However, this device does not operate for dc currents.
fig. 60 Magneto-optical method for measuring impulse currents
Current Transformers:

- Measurement of high frequency currents such as fault currents in power systems, switching current transients and impulse currents during impulse testing of transformers can be measured using current transformers with an air core or a ferrite core.
- The transformer will have torroidal core with central bar primary or wound primary with single turn.
- The secondary side of the current with \( N_1 \) primary and \( N_2 \) secondary turns is given by
  \[
  I_2(t) = \frac{N_1 I(t)}{N_2}
  \]
- Usually, the secondary winding is terminated by a resistance \( R_2 \) and a CRO will be connected through a cable of surge impedance \( Z \) terminated by a resistance \( R \) equal to surge impedance.
  \[
  I_3(t) = \frac{R_2}{R + R_2 + Z_0} I_2(t)
  \]
  \[
  V(t) = \left[\frac{RR_2}{R + R_2 + Z_0}\right] I_2(t)
  \]
  \[
  I_2(t) = \frac{N_1 RR_2}{N_2 R + R_2 + Z_0} I_1(t)
  \]