Lecture # 12

Measurement of High Voltages

Direct measurement of high voltages is difficult because of high field involved and the accuracy that are difficult to achieve, mainly due to the stray capacitance and stray inductance. Besides, the size and rating of the measuring apparatus is often a limiting factor. Indirect methods of measurement are used depending on the type of high voltage; whether AC, DC or impulse.

High Voltage Measurement with Spark Gaps

We know that breakdown of a gap depends on the electric field, which is the function of voltage *V* and gap separation *d* and for uniform field gap is simply: V/d. This concept can be used for the measurement of voltages by means of gaps, commonly employing sphere and Rogowski electrodes. In the case of AC voltages, the frequency and time-dependency of the applied voltage also play an important role. Breakdown voltage of a spark gap is affected by several factors, which are:

1. Distance between the electrodes.
2. Shape of the electrodes and electrode symmetry (sphere, point, plane, rod, etc).
3. The type of dielectric gas.
4. The material of electrodes and surface conditions.
5. The temperature and pressure during measurement.
6. Alignment between the electrodes.
7. The type of voltage (DC, AC, or impulse).

For measuring voltage it is essential that the electric field is uniform over wide range of gap separation. The limitation in gap separation is essential to provide a fairly uniform field distribution so that no pre-ionization or corona appears prior to breakdown. The electrical field distribution within the high-field regions is controlled by the geometry of the electrode and the air density as well as its composition, which must be known, since air is composed of various types of molecules, which will influence the breakdown voltage. All these factors can be accounted for by the well-known breakdown criteria of gases besides the primary electron impact, whose presence is essential in this case. For this purpose, a mercury vapor lamp producing light in the UV range is used as a source of irradiating the gap to make sure that primary electrons are present. In some cases radioactive pellets having radiations of about 0.6 millicurie are inserted in the high-voltage sphere at the sparking points. However, studies of measurement of impulse voltage made by Cooper at the University of Manchester, UK revealed that irradiation of the gap practically produced no effect on the breakdown voltage.

Two types of electrode symmetries, based on uniform electric field are used for the measurement of high voltages. These are discussed in the following sub-sections.

Sphere Gap

For sphere gap the condition of uniformity of the gap is limited to separations that should not exceed the radius of the sphere and that the distance between nearby earthed objects including the walls and ceiling of the laboratory must be taken into account. A sphere gap arrangement is used for the measurement of the peak value of AC, DC and both polarities of impulse voltages.

Sphere gaps for measurement of high voltages are either arranged vertically or horizontally. Figure (1) shows a typical vertical and horizontal arrangement of sphere gaps used in high voltage laboratories for measurement of high voltages.

Figure 1: Photograph of a Sphere Gap arrangement

For alternating voltages and standard impulse voltage of 1/50 µs the gap separation between the two spheres must not exceed 0.5*D* and the breakdown values are accurate within ± 3%. The accuracy reduces for spacing: $d > 0.5D$. For measuring direct voltages, the values of breakdown voltages are accurate within ± 5% for gap spacing that does not exceed 0.4*D*. Tables of breakdown voltage can be obtained during calibration of the spark gap in the laboratory, which can be used when making measurements. Care must be taken to include the parameters of the laboratory conditions, such as humidity, temperature and pressure and electrode parameters during calibration for which a correction factor must then be employed for making measurements.

The effect of nearby earthed objects affects the breakdown voltage of the gap. When the radial clearance between the electrodes and an earthed metal cylindrical cage is reduced from 12.6*D* to 4*D*, the breakdown voltage of the gap reduces for the same gap separation, which fits into the relation:

$$\Delta V = m\log\left(\frac{d}{D}\right) + C \qquad 1$$

Where ΔV is the reduction in the breakdown voltage, and *m* and *C* are factors dependent on the ratio *d*/*D* (*d* is the gap separation and *D* is the diameter of the sphere) and *d* is the diameter of the cylindrical earthed cage surrounding the electrodes. It is therefore recommended to carry out measurements with sphere gaps in the laboratory well-away from other earthed objects in order to reduce the possibility of errors during measurements.

Rogowski Electrodes

The use of uniform field gaps is also extensively used for the measurement of high voltages. In the case of sphere gap, the breakdown voltage characteristics are generally uniform and almost linear for the gap separations that does not exceed 0.5*D*. The uniform field gaps based on Rogowski profile of the form shown in Figure (2) are also used for measuring voltage up to about 300 kV.

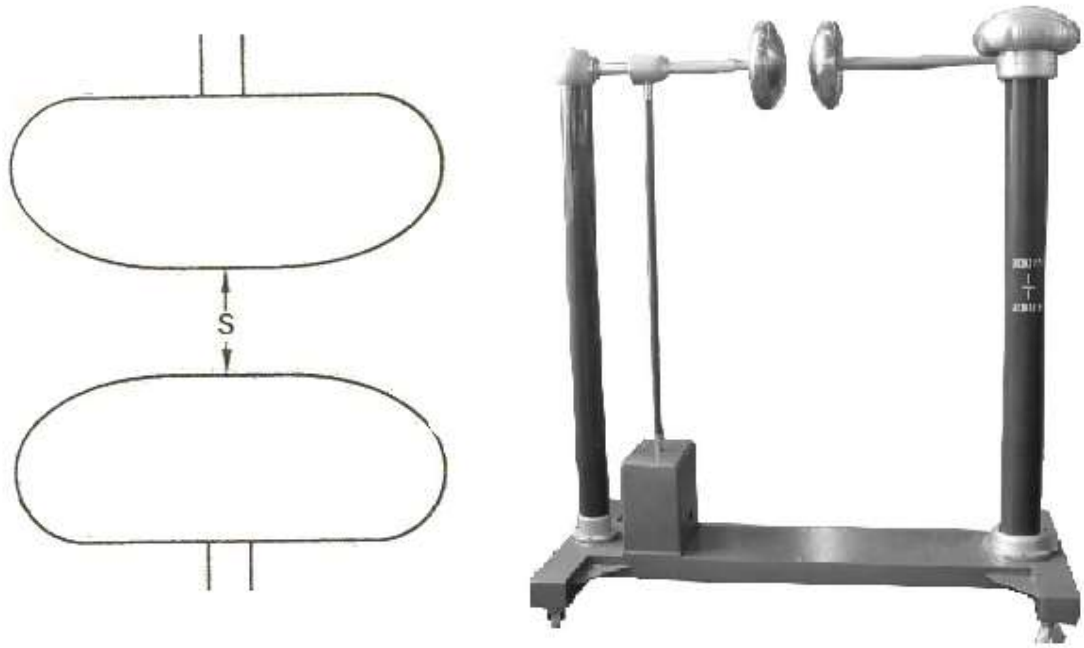

Figure 2: Rogowski Electrodes

An empirical formula for the breakdown voltage of the gap versus gap separation *d* is given by:

$$V_g = ad + b\sqrt{d} \qquad 2$$

Where *a* and *b* are constants. For laboratory conditions at the time of measurement, the air density correction factor is incorporated in Eq (2), giving:

$$V_g = a(\delta.d) + b\sqrt{(\delta.d)} \qquad 3$$

The air density correction factor δ is given by:

$$\delta = \frac{p}{p_0}\left(\frac{273+t_0}{273+t}\right) \qquad 4$$

Where p_0 air pressure at STP, p is air pressure at test conditions, t_0 is 25°C, t is temperature in degrees Celsius at test conditions. The air density correction factor δ is a slightly non-linear function.

Measurement Technique

The application of spark gaps for the measurement of high voltages is tedious and time consuming. The procedure usually consists of calibration and establishing a relationship between the breakdown voltage of gap, and the readings of a voltmeter or other measuring device connected in the circuit of the equipment. Alternatively, a voltage of some constant magnitude may be applied across the gap and the spacing between the spheres is gradually reduced until spark-over or breakdown occurs.

Since in general the actual air density during a measurement differs from the reference conditions, the breakdown or flashover voltage of the gap will be expressed as:

$$V_g = kV_{g0} \qquad 5$$

Where V_{g0} corresponds to the tabulated experimental/test values that are obtained under controlled laboratory conditions (STP) and k is the correction factor. In order to obtain k, the air density correction factor is calculated from Eq (4). The values of k and δ are then compared for the same values of ambient temperature and pressure in Table (1).

Table 1: Typical Values of *k* and *δ*

δ	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10
k	0.72	0.76	0.81	0.86	0.90	0.95	1.00	1.05	1.09

When making measurements with AC and DC voltages, it is recommended to place a resistor of 100kΩ to 1MΩ in series with the gap. In the case of impulse voltage measurements, a non-inductive resistance of 500Ω is recommended to be included in series with the sphere gap arrangement. This is essential in limiting the high current resulting from breakdown. Furthermore, including of resistance allows the damping of superimposed oscillations. It is a recommended practice that when making measurements with AC or DC voltages, the applied voltage is increased gradually until the gap breaks down and generally three readings are taken from which a mean value is determined.

Example 1: Calculate the expected error in breakdown voltage of a sphere gap at 35ºC and humidity amounting to 780mm of Hg when the breakdown voltage of a gap at STP is 22kV (peak).

Solution:

Given that: the breakdown voltage at STP is V_{g0} = 22kV. The air density correction factor for given temperature and pressure is:

$$\delta = \frac{p}{p_0}\left(\frac{273+t_0}{273+t}\right) = \frac{780}{760}\left(\frac{273+25}{273+35}\right) = 0.99$$

It can be approximated from Table (13.1) that k = 0.99. The breakdown voltage of the gap at the given temperature and pressure is then:

$$V_g = kV_{g0} = 0.99 \times 22 = 21.78\,\text{kV (peak)}$$

The error is:

$$\frac{22-21.78}{22} \times 100 = \mathbf{1\%}$$

Potential Dividers

In the high voltage laboratories, most apparatus have voltage ratings, ranging from a few to several hundred kilovolts. The use of simple voltage divider network enables the measurement of several kilovolts on a digital voltmeter or a conventional analog voltmeter. A voltage divider or a potential divider is basically a combination of two components; resistances or capacitors in series and is based on the fundamental principle that the voltage drop across any component is determined in terms of voltage across the combination. Figure (3) shows a simplest form of resistance potential divider, a series combination of two resistances R_1 and R_2. In case of high-voltage dividers, the resistor R_1 is a high-voltage resistor, which takes the larger share of the applied voltage as a drop and R_2 is a low-voltage resistor, which takes a small share of the total voltage. The resistor R_1 thus constitutes the high-voltage arm and R_2 the low-voltage arm of the potential divider. If V is the voltage applied across the combination, then the voltage V_0 derived across the low-voltage arm of the divider is given by:

$$V_0 = V\frac{R_2}{R_1+R_2} = VN \qquad 6$$

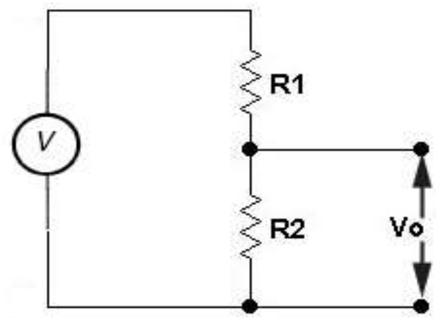

Figure 3: Simple Potential Divider

The term: $\frac{R_2}{R_1+R_2} = N$ in Eq (6) is the voltage divider ratio or simply divider ratio. The conventional low voltage instrument is connected across the low-voltage arm of the divider and the voltage drop across it is directly measured. The instrument can then be calibrated in terms of high voltage V by using Eq (6). For example, if V is the high voltage, say of magnitude 20 kV and it is desired that V_0 be low enough to be measured by conventional instrument (voltmeter) without being damaged. It is therefore required to choose appropriate resistances R_1 and R_2 to accomplish this. If a digital voltmeter of say maximum range of 300 volts is to be used. Then using a little tolerance to avoid full-scale deflection that 20 kV is likely to produce, it is assumed that 20 kV may read 200 volts on the instrument connected across the low-voltage arm. Then a compromise between choosing R_1 and R_2 can be accomplished by considering the standard commercially available suitable resistor R_1, since it is easier to choose and fabricate a low-voltage arm resistor. Furthermore, high-voltage resistors require special design considerations and are usually difficult to fabricate. High-voltage resistors are available in the range of values from 1kΩ to 100MΩ in multiples of 10. For special purposes 50Ω and 1000MΩ are also available.

Taking this into consideration, for example; for a voltage of 20 kV across a normal 0.5 Watts resistor, it is therefore necessary to stay within the specified limits of the 0.5 Watts resistor and use at least 20,000/500 = 40 resistors in series for this voltage level. In addition, the high-voltage resistor must be able to limit the current in the case of accidental breakdown. The value of the high-voltage arm resistor must be high-enough to limit the current to a few milliamperes or cautiously to a few amperes in worst cases. According to the specifications of 500 volts DC and 0.5 Watts, the value of a single resistor will be 0.5MΩ. The use of 40 similar resistors will produce a complete unit of 20MΩ. Using Eq (6) for V = 20 kV and V_0 of 200 volts to give deflection up to 200 volts for 20 kV, yields the value of R_2 to be about 200 kΩ.

It is also important to properly bond the low-voltage arm to the mains ground, especially when a digital voltmeter or an oscilloscope is employed. The low-voltage arm must be protected from the high voltage that may appear due to the failure of the high-voltage arm. A spark gap or a protector tube can be connected across the low-voltage arm so that in the event of failure of the high-voltage arm, the spark gap or protector tube discharges so as to collapse the voltage without causing damage to the low-voltage arm, instrument and the operator.

In case of measuring AC voltages, the stray capacitances are also to be considered, especially when stacks of resistors are used to form the high-voltage arm of the divider. The actual divider ratio N is determined by the following formula:

$$N = \frac{R_2}{R_1}\sqrt{\frac{(1+\omega^2 C_{S2}{}^2 R_2{}^2)}{(1+\omega^2 C_{S1}{}^2 R_1{}^2)}} + 1 \qquad 7$$

Where ω is the frequency of the voltage to be measured and C_{S1} and C_{S2} are the stray capacitances of high-voltage arm and low-voltage arm respectively. For high-voltage AC measurements, a capacitance potential divider as shown in Figure (4) is preferred. The advantage of a capacitance potential divider is the relative simplicity in design over resistance potential dividers.

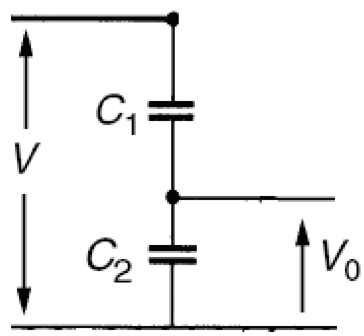

Figure 4: Capacitor Voltage Divider

The capacitor C_1 is generally standard air capacitor and forms the high-voltage arm and C_2 is the capacitance of the low-voltage arm. The voltage V_0 across the low-voltage arm capacitor is related to the applied voltage V and capacitance C_1 of the high-voltage arm by the expression:

$$V_0 = V\frac{C_1}{C_1 + C_2} = VN \qquad 8$$

The major advantage of using standard air capacitor in the high-voltage arm is the ease with which it can be constructed and shielded to minimize the effect of stray capacitance and the absence of heating.

It must be remembered that when the supply voltage across the divider is removed, the capacitors are still charged, which depends on the point on the voltage wave where the system is switched off. In determining voltage, the effect of residual charges on the plates of the capacitors must therefore be considered.

Example 2: Select a capacitor required for the low-voltage arm of a capacitive potential divider to provide a peak-voltage of 200 volts on the oscilloscope when the high-voltage arm of the divider has capacitance of 1nF and the voltage of 1MV peak is to be measured. Neglect the surge impedance of the cable.

Solution:

Given that: V_0 = 200 volts and V = 1MV = 1 x 10^6 Volts. Capacitance of the high-voltage arm C_1 = 1 nF.

If V_0 is the voltage across the low-voltage arm of the divider, C_1 is the capacitance of the high-voltage arm and C_2 is the capacitance of the low-voltage arm, then:

$$V_0 = V\left(\frac{C_1}{C_1 + C_2}\right)$$

The required divider ratio is: $N = \frac{V_0}{V}$, therefore:

$$N = \frac{200}{1000000} = 2\times10^{-4}$$

Substituting the value of C_1 in the above expression and rearranging gives:

$$C_2 = \frac{1\times10^{-9} - 2\times10^{-13}}{2\times10^{-4}} = \mathbf{5\ \mu F}$$

Example 3: Design a capacitive potential divider for a voltage of up to 100kV (RMS) to be measured with a conventional low voltage (0 – 300 volts) voltmeter to give a full-scale deflection of up to 200 volts for the full RMS value of high voltage to be measured.

Solution:

Given that: V = 100 kV = 100 x 10^3 volts and V_0 = 200 volts (full-scale deflection). Therefore:

$$N = \frac{C_1}{C_1 + C_2} = \frac{V_0}{V} = \frac{200}{100\times10^3} = 2 \text{ x } 10^{-3}$$

Choosing the high-voltage arm as series combination of high-voltage capacitor shown in Figure (4), rated at 10 kV and having capacitance of C = 6 pF. In the present example, 10 similar capacitors will be required for 100 kV. Since these are connected in series then we have:

$$\frac{1}{C_1} = \sum_{n=1}^{10}\frac{1}{C_n} = \frac{10}{C}$$

Therefore: $$C_1 = \frac{C}{10} = \frac{6\times10^{-12}}{10} = 0.6\text{pF}$$

And $$\frac{0.6\times10^{-12}}{0.6\times10^{-12} + C_2} = 2\times10^{-3}$$

From which:

$$C_2 = \mathbf{0.3\ nF}$$

Ammeter in series with High Impedance

The simplest and convenient method of measuring voltage is to know the current flowing through known impedance. The method of measurement of voltage is based on simple Ohms law; according to which the voltage is determined from the product of current recorded by ammeter and the value of impedance connected in series with the ammeter. A simple arrangement for the measurement of high voltage by this method is illustrated in Figure (5). The ammeter resistance r is generally very small (of the order of few Ohms) as compared to the impedance Z (of order of MΩ) connected in series with the ammeter and can therefore be neglected in making measurements. Therefore:

$$V = i(r + Z) \approx iZ \qquad 9$$

Where i is the current recorded by the ammeter and V is the unknown voltage to be measured, which is applied across the combination as shown in Figure (5). For measurement of direct voltages, a moving-coil type meter is used provided that the superimposed AC ripple is less than 10%. The accuracy of the method depends on the proper selection of the high-voltage impedance

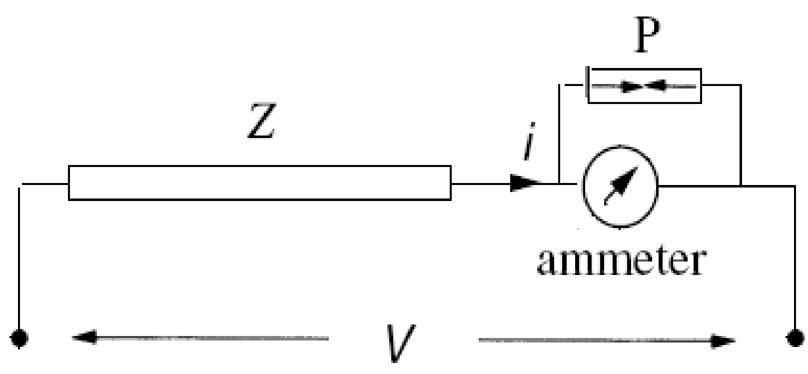

Figure 5: Ammeter in Series with High Impedance

In most applications a resistor having resistance of the order of mega-Ohms is used. The resistor can be a single unit or a number of similar units stacked together in series to form a vertical column. These resistors must have negligible resistance-temperature coefficient and chances of corona discharge must be minimized. Since the currents are of order of mA, non-inductively wire-wound resistors are generally used. Wire-wound metal resistors made from Cu–Mn, Cu–Ni and Ni–Cr alloys or similar compositions, which have very low temperature coefficients (typically approximating to 10^{-5}/ºK) provide adequate accuracy in measurement.

In addition, the distributed stray capacitance-to-ground causes a strongly non-uniform voltage distribution along a resistor column and overstresses the individual elements during a sudden load-drop originated by voltage breakdown of a test object. Use of toroidal electrode or guard-ring would make the voltage distribution along the resistor column more or less uniform. However, provision of corona shields as such will increase the self-capacitance of the resistor units and the arrangement therefore is regarded unsuitable for the measurement of power-frequency AC voltages.

Measurement of Impulse Voltage

Impulse voltage measurement generally incorporates an oscilloscope with a resistance or capacitance potential dividers or in some cases a combination of both resistors and capacitors forming a potential divider. Since impulse voltages are characterized by steep voltage-rise, the measurement of impulse voltages even of short duration presents no problems, if the amplitudes are low of the order of few kV range. The essential requirement is the reproduction of wave shape of impulse on an oscilloscope, from which the voltage can be measured by reduction ratio adjusted on time and amplitude from oscilloscope.

An arrangement of an oscilloscope for the measurement of impulse voltage incorporated with voltage dividers is shown in Figure (6) and is the common and most adequate layout of impulse voltage measuring circuit, which is often used for the measurement of lightning impulses if an accurate measurement of full and chopped voltages is desired.

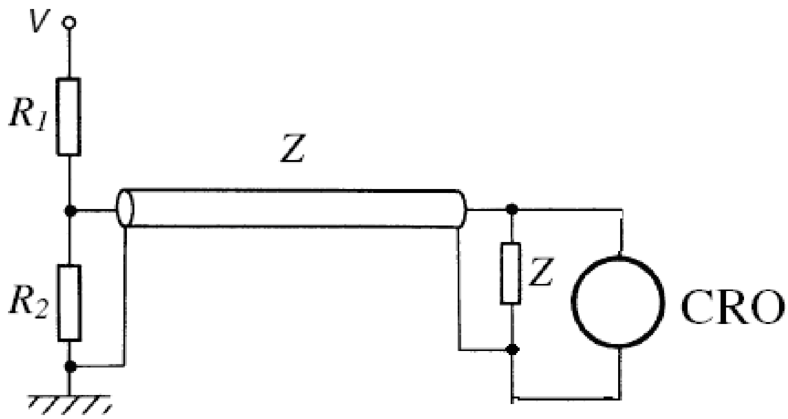

Figure 6: Arrangement for Measuring Impulse Voltages

Referring to Figure (6) the voltage *V* to be measured is applied across a potential divider, a combination of R_1 and R_2. The resistance R_1 of the high-voltage arm must be high to limit current during breakdown. The measuring system starts at the terminals of the low-voltage arm of the divider and comprises a connecting lead to the voltage divider and a recording instrument. The signal from the low-voltage arm of the divider passes through a matched coaxial cable, represented as impedance *Z*.

Effect of stray capacitance

Careful construction can result is very small self-inductance, which in most cases can be neglected. When resistor voltage dividers are used for the measurement of impulse voltages, the effect of stray capacitance must be considered. The effect of stray capacitance is illustrated in Figure (7).

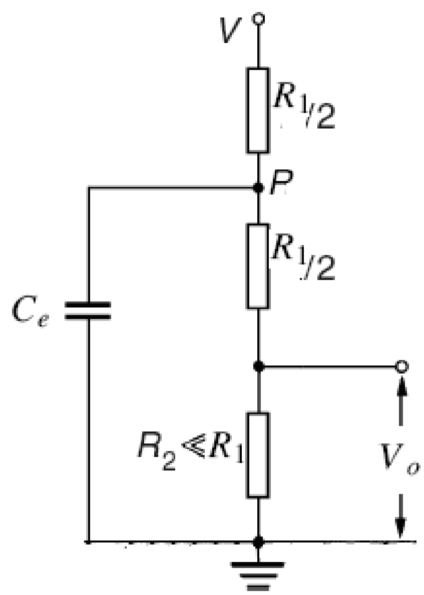

Figure 7: Stray capacitance distribution along the divider

The stray capacitance-to-earth will be distributed uniformly along the entire length of the high-voltage resistor since the resistor R_1 is often a wire-wound resistor. The value of this stray capacitance will vary in accordance with the distance of a point on the length of the resistor from the ground. The average value of this capacitance will be somewhere located at approximately mid-length on R_1. According to Figure (7), the total capacitance C_T and the stray capacitance to earth C_e is related as:

$$C_e = \frac{2}{3} C_T \qquad 10$$

The total resistance of the potential divider is ($R_1 + R_2 \approx R_1$), since R_1 is much larger than R_2. As shown in Figure (7), point P where the effect of stray capacitance-to-earth is averaged, divides the total resistance R_1 into two equal resistances each having a value of $R_1/2$, which forms a parallel combination giving equivalent resistance equal to $R_1/4$. Since R_2 is much smaller than R_1, the time constant T of the distributive capacitance-to-earth C_e along the length of R_1 is:

$$T \approx \frac{R_1 C_e}{4} \qquad 11$$

Considering the capacitance-to-earth C_e from Eq (10) and substituting in Eq (11), we have:

$$T \approx \frac{R_1 C_T}{6} \qquad 12$$

If the rise-time of the impulse voltage to be measured fall within the time constant as defined in Eq (12), then the impulse can easily be reproduced. In general, for a vertical cylindrical arrangement of resistors, the total capacitance C_T ranges between 15 to 30pF/m. The stray capacitance to earth C_e can be approximated by assuming that the stacked capacitor units are cylindrical in shape with a diameter d forming a metal vertical column of height h with a distance y from the ground given according to the expression (W. Zaengl):

$$C_e = \frac{2\pi\varepsilon_0 h}{\ln\left(\frac{2h}{d}\sqrt{\frac{4y+h}{4y+3h}}\right)} \qquad 13$$

Since y is very much smaller as compared to height h of the divider, so that the term of the square root can be approximated to $1/\sqrt{3}$, then Eq (13) takes the form:

$$C_e \approx \frac{2\pi\varepsilon_0 h}{\ln\left(\frac{1.15h}{d}\right)} \qquad 14$$

The stray capacitance-to-earth is generally in the range of 10 to 15pF/m. The residual inductances are, however, negligibly small within the frequency range of 100 kHz to 1 MHz and their effect can therefore be neglected.

Example 4: Design a potential divider for a 1MV, 1.2/50μs lightning impulse voltage from using standard resistors available with value 40kΩ and length of 0.5m.

Solution:

Given that the impulse wave 1.2/50μs of peak value 1MV has to be re-produced through a measuring circuit of potential divider. Choosing *T* to be equal to 1.2μs and considering capacitance to ground of 30pF/m, then each 40kΩ resistor mounted vertically will constitute a capacitance to ground of 15pF. The resistor value can be determined from using Eq (12), which on re-arrangement yields:

$$R_1 = \frac{6T}{C_T} = \frac{6 \times 1.2 \times 10^{-6}}{15 \times 10^{-12}} = 0.48 \text{ x } 10^6\ \Omega$$

Since standard available resistors are 40kΩ of 0.5m length, then the number of resistor units *n*, required are:

$$n = \frac{480 \times 10^3}{40 \times 10^3} = \mathbf{12}$$

The length of the divider is considerable that is 6m. In case of limitation regarding height of ceiling of the laboratory, the resistors may be arranged vertically outdoor or may be arranged in helical form in the laboratory to reduce the height of the divider.