Generation of High A.C. Voltages: Most of the present day transmission and distribution networks are operating on a.c. voltages and hence most of the testing equipment relate to high a.c. voltages. A single phase transformer is the most common form of HVAC testing equipment. It is generally an iron core transformer designed to operate at the same frequency as the normal working frequency of the test object. The word test includes research, experimental, development and routine testing work.

The design aspect of a testing transformer does not differ from that of a power transformer so far as regulation, thermal rating and kVA output is concerned but the insulation of a testing transformer is designed so as to withstand the surges or transient overvoltages arising out of the flashover of the object under test. Also the designer or the selector of a particular testing transformer unit must keep in mind the following characteristic requirements also termed as testing specifications of testing transformer:

a) It must maintain the rated test voltage under specified conditions of load.
b) It must have sufficiently low internal impedance so as not to cause voltage drop during test.
c) It must have the ability to withstand repeated short circuit upto the rated voltage.
d) The waveform should be as sinusoidal as possible (allowance in peak voltage allowed is ±/2 x 5%).
e) The test circuit should be arranged that transient voltage drops do not occur due to any streamer discharge.
f) It should be capable of supplying large currents at low power factor over long periods of time. This is necessary during cable testing as it involves long period tests for determining the temperature rise under operating conditions.

A high A.C. voltage is generated by using – (1) Cascaded Transformers (2) Resonance method (series resonance and parallel resonance).

Cascaded Transformer: For voltages higher than 400 kV it is desired to cascade two or more transformers depending upon the voltage requirements. Single unit testing transformers are available upto 750 kV but is has been found that the cost of test unit increases rapidly with voltage due to good insulation requirements. There is also problem of transportation and erection due to large size of bushings. To overcome these difficulties two or three units of same rating are cascaded whereby only the L.V. winding of the first unit is connected to the supply and H.V. winding of all the units are in effect connected in series. The fig.1 shows a schematic diagram for connecting three identical testing transformers in cascade. The primary of the first transformer T_1 is supplied from a low voltage 50 Hz supply P_1S_1, the tank of which is earthed.

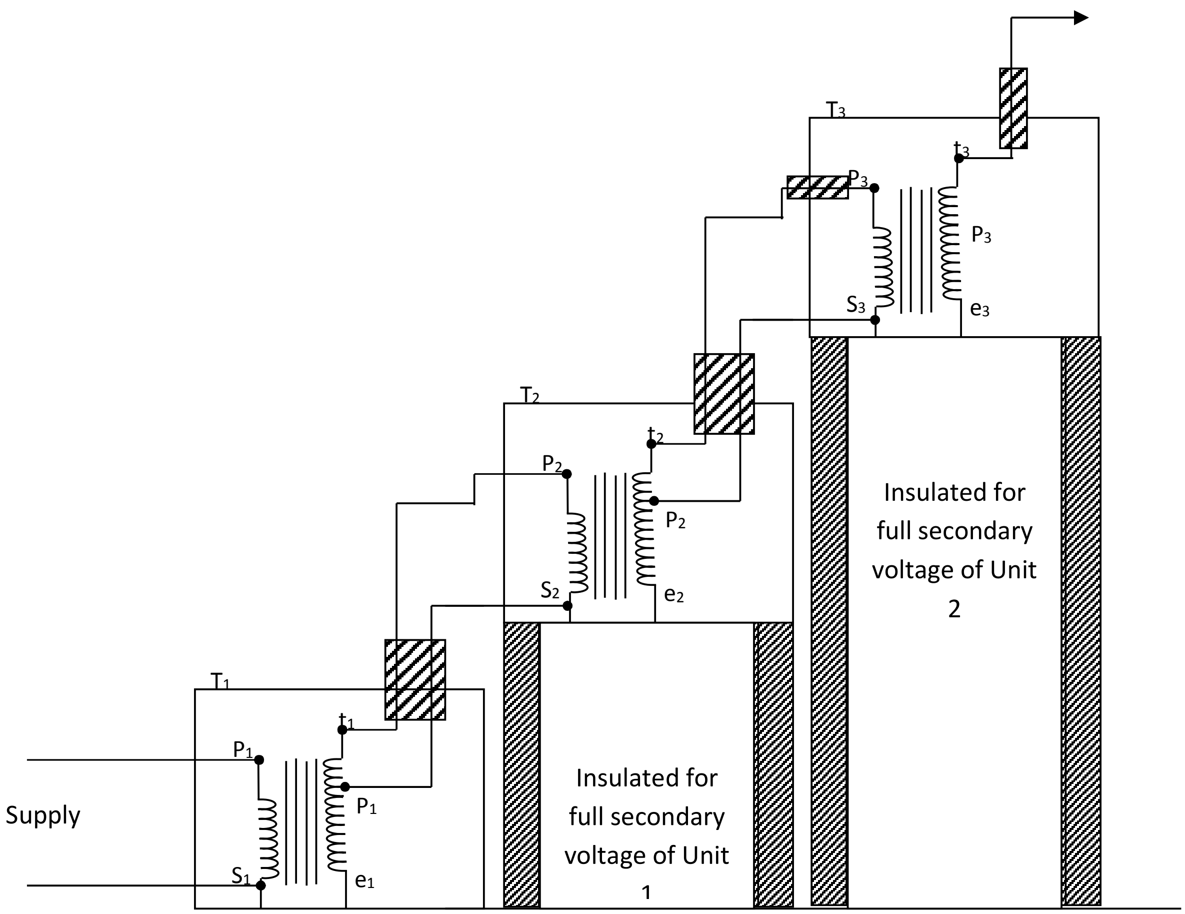


Fig.1 Three testing transformers connected in Cascade

t_1e_1 forms the secondary of this unit, the end e_1 of which is connected to the tank which is at earth potential. A tapping t_1P_1 is taken from the secondary of the transformer T_1 and it is made to supply the primary of transformer T_2 in such a way that the tapped voltage is equal to the primary supply voltage of T_1. e_2t_2 is the secondary of transformer T_2, the end e_2 being connected to the tank which is insulated from earth for the full secondary voltage of transformer T_1. In the same way transformer T_3 is energized, the end e_3 of which is connected to the tank which is insulated from the earth for the full secondary voltage of transformer T_2. The output voltage between the terminal t_3 and earth is approximately equal to the sum of three secondary voltages. Thus depending upon the test voltage required the number of units are cascaded.

Disadvantages of a single unit H.V. testing transformer: The following are the disadvantages of a single unit testing transformer:

1) A large quantity of good quality insulating material is required thus increasing the cost.
2) The size of the unit is big and so is the size of the bushings.
3) The electrical stress distribution is very uneven in the secondary winding.
4) Since there is only one large unit, reliability is not guaranteed and interchangeability is not possible.

Advantages of Cascading: The following are the advantages of cascading over a single unit testing transformer:

1) The cost for cascaded transformer is less for a similar capacity as compared to a single unit testing transformer.
2) The height of the individual unit is less and also the bushings are small. The units maybe placed one over the other which reduces the space requirement although total height is increased.
3) Since the units are identical, therefore reliability is better and interchangeability is possible.

Limitations of Cascading: The following are the limitations of cascading of transformers:

1) The impedance goes on increasing rapidly and approximately as n^2 where n is the number of units cascaded, so the current in short circuit condition decreases. Thus the number of units to be cascaded is limited to 3 or 4 and never exceeds 5.
2) Iron and copper losses are quite high because the first unit has to supply the iron losses and copper losses of all other units in series and second one supplies to third and fourth unit.

Impulse Voltage: It is defined as a unidirectional transient voltage which rises rapidly to a maximum value without appreciable oscillations and then decays relatively slowly to zero. It is of two types – lightning impulse voltage (or lightning surge) generated due to charging of the clouds and switching impulse voltage (or switching surge) generated by the system itself. The impulse voltage is specified by the wave shape as shown in fig.1 The rising portion of the voltage time characteristic (portion OA in fig.1) is called wave-front. The duration of the wave-front is the total time occupied by the impulse voltage while rising from zero to peak value. The falling portion of the voltage time characteristic (portion AB in fig.1) is called wave-tail.

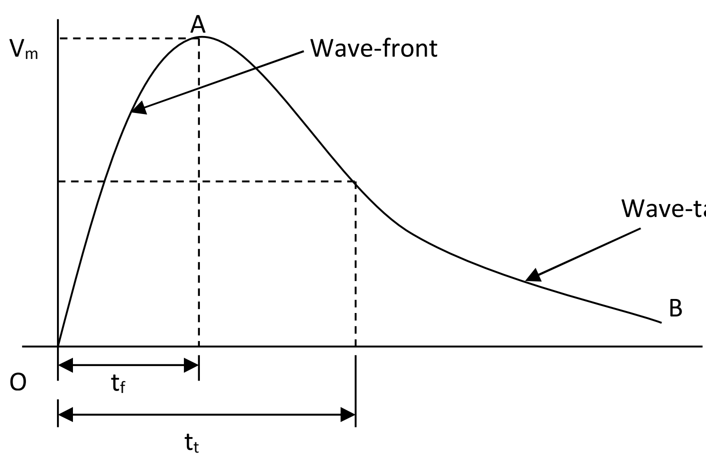


Fig.1 Wave shape of impulse voltage

An impulse voltage is specified by the following four things:

(i) **Polarity** – The switching surges have no negative polarity whereas the lightning surges can have both negative as well as positive polarity depending upon the charges on the clouds.
(ii) **Magnitude** – The maximum value of the impulse voltages called peak value.
(iii) **Front time (t_f)** – It is defined as the time taken for the impulse wave to reach to its peak value (maximum value) from zero value represented by t_f and expressed in microseconds.
(iv) **Tail time (t_t)** – It is defined as the time taken for the impulse voltage to reach to 50% of its peak value (maximum value) on the tail side from zero value represented by t_t and expressed in microseconds.

The following are the standard wave shape used for the testing of high voltage equipments.

Lightning surges

Indian Standard – 1.2 ± 20% /50 ± 30% μs

British Standard – 1/50 μs

American Standard – 1.5/40 μs

Switching surges

Indian Standard – 250 ± 20% /2500 ± 30% μs

The impulse voltage which results in flashover and puncture of insulation when applied to a piece of insulation sample is called chopped impulse voltage. If chopping of the wave occurs at the front part of the wave then it is called front chopped wave otherwise it is simply called a chopped wave.

Need for Generating Impulse Overvoltage and Current: In case of any electrical power system, its insulation is the weakest link. The design of the insulation depends upon the type of voltage it has to withstand. In case of EHV system and overhead transmission lines the insulation of the equipments are subjected to both the lightning and switching surges. These over voltages (lightning or switching) cause serious damages to the equipment insulation. Similarly over currents which may cause damage to the system equipments are generated by short circuit and lightning. Hence proper insulation is to be provided against these over voltages and over currents for protection of the system.

Therefore in order to design proper insulation for EHV system we have to test it for both over voltages and over currents. For this we need to generate impulse voltages and current to test the strength of insulation. The impulse voltages propagate as travelling waves which on reaching the terminal equipment may cause considerable damage to the equipment if not protected against such waves. In case of insulation, testing of voltage is important than the current since it is voltage which affects the insulation strength.

Generation of Impulse Voltage: The wave shape of an impulse voltage is given as shown in fig.2(a)

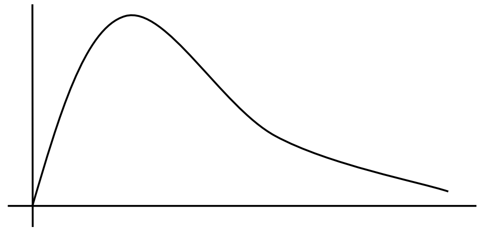


Fig.2(a) Wave shape of an impulse voltage

The impulse generators can be single stage or of multistage construction. The single stage circuits are mainly used for the generation of relatively low voltage impulses required for testing of dielectric sheets or non linear resistance discs for surge diverters. An impulse voltage wave shape can be represented as double exponential waves defined by the equation (as shown in fig.2(b))

$$V = V_o\,[e^{-\alpha t} - e^{-\beta t}]$$

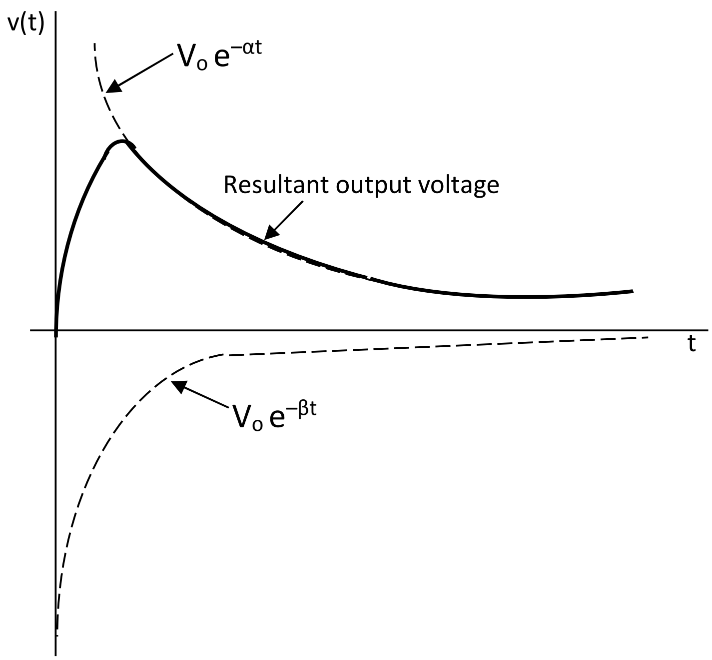


Fig.2 (b) Impulse voltage wave shape as a superposition of two exponential curves

where α and β are constants dependent on the specifications of the wave. The rapid rise and slow decay can be generated by discharging circuits with two energy storage elements as the wave shape $(e^{-\alpha t} - e^{-\beta t})$ may be composed by the superposition of two exponential functions. One storage element will be the capacitance of insulation to be tested (known as load). The other element may be a capacitor or an inductor. However for lightning impulses we do not prefer inductances because a fast discharge through a pure inductor is impossible and it will be invariably associated with oscillations. A suitable fast discharge impulse generator circuit is always built up essentially with two capacitors.

The basic circuit used for the generation of impulse voltage is Marx's circuit as shown in fig.5 (a) and (b). The capacitance C_1 is called source or impulse capacitance C_S, C_2 is called load capacitance C_L, R_1 is called front time resistance R_f and R_2 is called tail time resistance R_t. The source capacitor is charged via a high charging resistance to the direct voltage and then discharged by breakdown of the spark gap SG. The desired impulse voltage appears across the load capacitor C_2. The most significant parameter of an impulse generator is the energy stored within the discharge capacitor C_1 i.e. (1/2) $C_S V_O^2$ and determines mainly the cost of a generator and is used as one of the ratings of an impulse generator. When the gap SG breaks down, the capacitor C_1 charges the load capacitor C_2 through the resistance R_1. During this period the voltage across C_1 decreases and that across C_2 increases. After the peak value V_m has been attained, both C_1 and C_2 discharge through the resistance R_2.

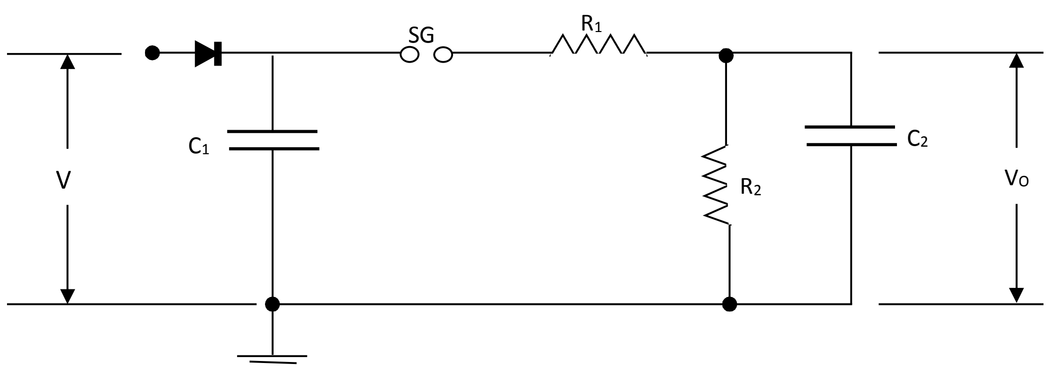


Fig.5 (a) Basic Marx's circuit for impulse voltage generation

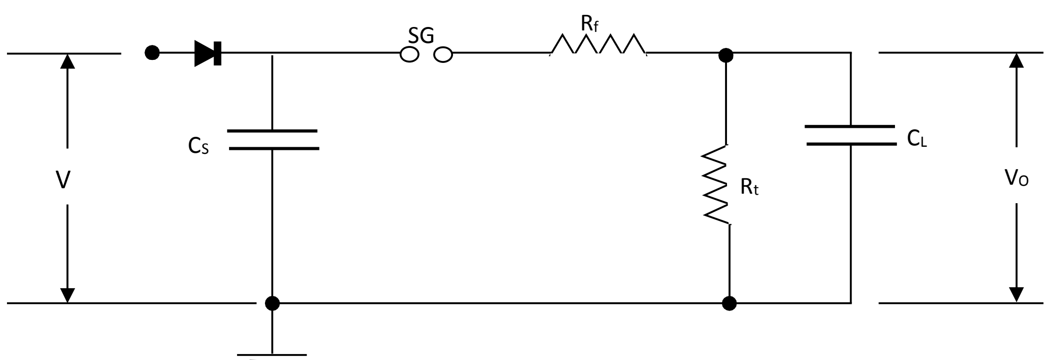


Fig.5 (b) Basic Marx's circuit for impulse voltage generation

For the analysis of basic Marx circuit, the following assumptions are made:

i. There is no inductance in the circuit.
ii. There is no stray capacitance.
iii. The total current initially passes through the source capacitance (C_2 or C_S)
iv. R_2 >> R_1 and C_1 >> C_2 (which holds true in practical cases and hence R_2 can be neglected when considering t_f and t_t in terms of circuit parameters)

The front time and tail time can be determined as follows

$$t_f = 3R_f \frac{C_S C_L}{C_S + C_L} \quad \text{and} \quad t_t = 0.7\,(R_f + R_t)(C_S + C_L)$$

Multistage Impulse Voltage Generator: The important components of an impulse generator are the impulse capacitor C_S, the load capacitor C_L, the wavefront shaping resistor R_f and the wavetail shaping resistor R_t. In some cases Rf is connected in between high voltage output terminal and the terminal common to test object and voltage divider. For obtaining higher and higher impulse voltages a single stage circuit is inconvenient for the following reasons:

(i) The physical size of the circuit elements becomes very large.
(ii) High d.c. charging voltage is required.
(iii) Suppression of corona discharges from the structures and leads during the charging period is difficult.
(iv) Switching of very high voltages with spark gaps is difficult.

To generate very high impulse voltages Marx suggested a multiplier circuit. The fig.7 shows a practical impulse generator with several stages which are cascaded. The capacitors are first charged in parallel through resistors RS and then discharged in series through spark gaps. The spark gaps lie in the same vertical plane to ensure that ultraviolet radiations in first gap will irradiate the other gaps. The distances between various sphere gaps are adjusted such that the first gap is only slightly less than the next gap and so on. The gaps are set such that they do not sparkover at charging voltage.

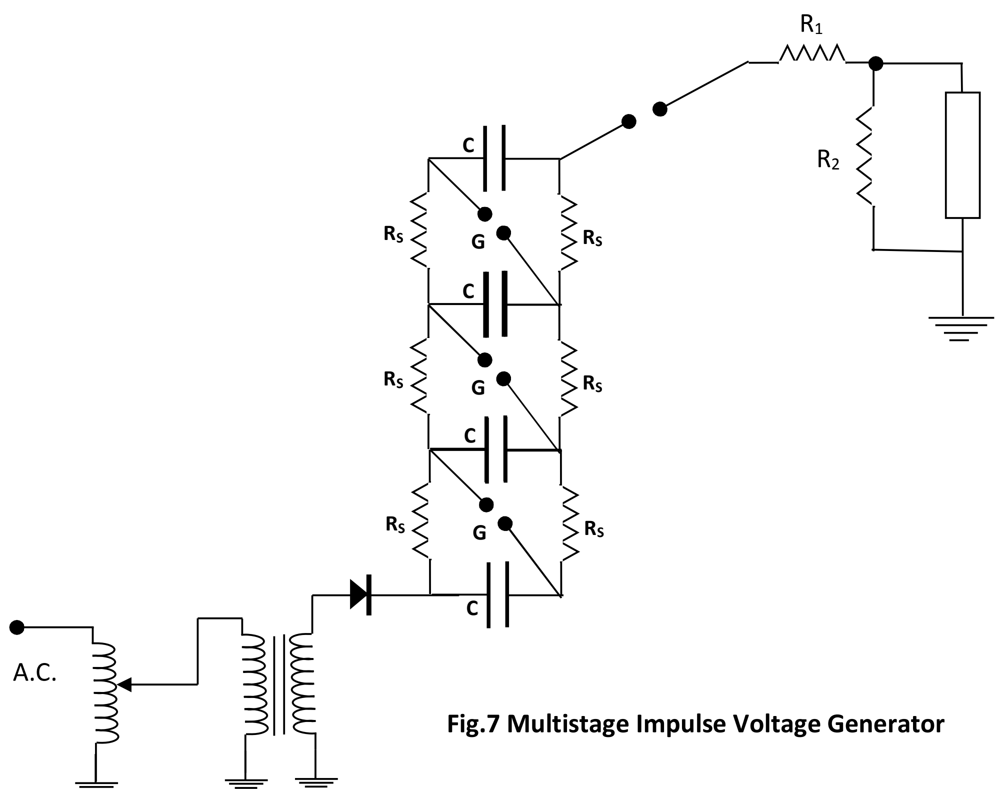


Fig.7 Multistage Impulse Voltage Generator

The capacitors are charged in parallel such that the higher stages acquire charge slowly but finally all stages acquire the same final voltage. Then the lowest spark gap is triggered which results in the breakdown of all other spark gaps resulting in all the capacitors being connected in series and are discharged thereby generating a very high voltage. A three electrode arrangement known as trigatron is used for initiating the triggering of the lowest spark gap.

Resonant Transformers: The fig.1 (b) shows the equivalent circuit of a high voltage testing transformer (shown in fig.1 (a)) which consists of the leakage reactance, the shunt capacitance across the output terminal due to the bushing of the high voltage terminal and also that of the test object. It may be seen that it is possible to have series resonance at power frequency ω if $\omega(L_1+L_2) = 1/\omega C$. With this condition, the current in the test object is very large and is limited only by the resistance of the circuit.

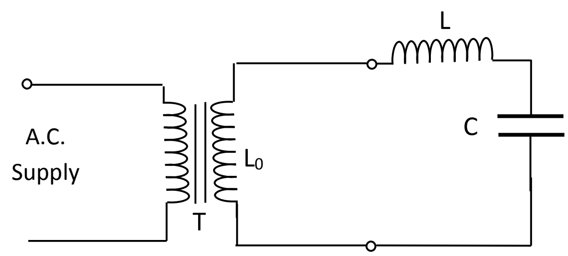


Fig. 1(a) Transformer

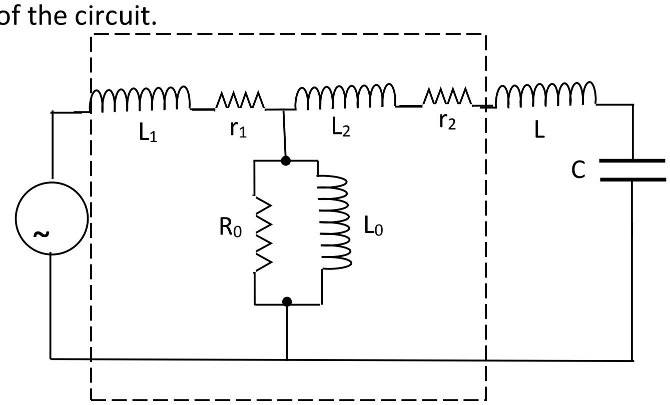


Fig.1 (b) Equivalent Circuit of testing transformer

From the fig.1 (a) and 1(b) we have

- T – Testing transformer
- L – Choke
- C – Capacitance of H.V. terminal and test object
- L_0 – Magnetizing Inductance
- L_1, L_2 – Leakage inductances of the transformer
- r_1, r_2 – Resistances of the transformer windings
- R_0 – Resistance due to core loss

The waveform of the voltage across the test object will be purely sinusoidal and its magnitude is given by

$$V_C = \left|\frac{-jVX_C}{R + j(X_L - X_C)}\right| = \frac{V}{R}X_C = \frac{V}{\omega CR}$$

Where R is the total series resistance of the circuit. The quality factor Q of the circuit is given by $X_C/R = 1/\omega CR$ which gives the magnitude of the voltage multiplication across the test object under resonance conditions. Therefore the input voltage required for excitation is reduced by a factor 1/Q and the output kVA required is also reduced by a factor 1/Q. The secondary power factor of the circuit is unity.

The resonant testing method for generating high a.c. voltage is basically used for testing purposes which require both high voltage as well as high current such as cable testing, dielectric loss measurements, partial discharge measurements etc. In this method a transformer with 50 to 100 kV voltage rating and a relatively large current rating is connected together with an additional choke if necessary. The test condition is set such that

$\omega(L_e + L) = 1/\omega C$ where L_e is the total equivalent leakage inductance of the transformer including its regulating transformer. The main advantages of generating high a.c. voltage using resonance are as follows:

a) It gives an output of pure sine wave.
b) Power requirement is very less (only 5 to 10 % of total kVA required.
c) There is no high power arcing and heavy current surges occur if the test object fails as resonance is lost at the failure of the test object.
d) Cascading is possible for very high voltages.
e) The test arrangement is quite simple and compact.
f) There is no repeated flashover in case of partial failure of the test object and insulation recovery.

The disadvantage of this method is that additional variable chokes which are capable of withstanding the full test voltage and full current rating are required. There following are three types of circuits used for generating high voltage a.c. at power frequency using resonance principle:

i. Series resonance circuit.
ii. Parallel resonance circuit.

Single unit resonant test systems are built for output voltages upto 500 kV, while cascaded units for outputs upto 3000 kV are available.

Series Resonance Circuit: The equivalent circuit of a single stage test transformer alongwith its capacitive load is shown in fig.2 (a) where L_1 represents the inductance of voltage regulator and transformer primary, L_2 represents inductance of transformer secondary, L is the exciting inductance of transformer and C is capacitance of the load. Normally $L >> L_1$ and $L >> L_2$, hence its shunting effect can be neglected.

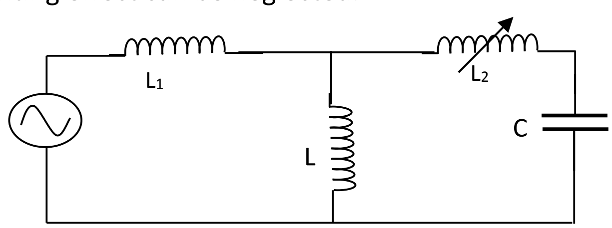


Fig. 2 (a) Equivalent circuit of single stage test series resonant transformer

Therefore the inductances L1 and L2 get connected in series with the load capacitance C forming a series LC circuit. In general the load capacitance is variable but while generating high voltage using resonance the load capacitance remains fixed. Hence we introduce a variable reactor in the transformer primary so that it becomes possible to have resonance at power frequency by making the inductive reactance become equal to capacitive reactance. At resonance the current in the circuit is only limited by the value of resistance circuit (which in general for resonant test transformer is very small). The fig.2 (b) shows a series resonant test transformer circuit.

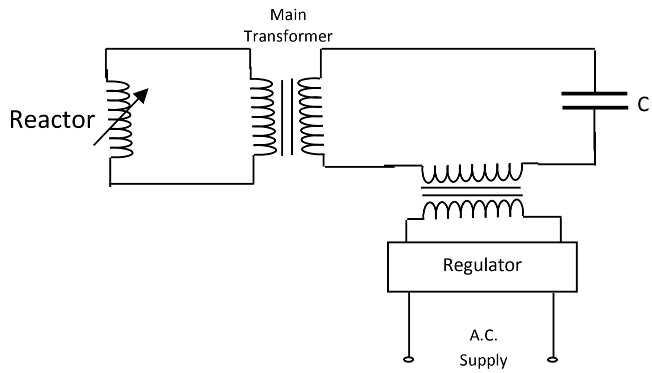


Fig. 2(b) Series Resonant Test Transformer Circuit

The development of series resonance circuit for testing purpose has been widely welcomed as it helped in overcoming resonance problem faced in testing transformer while testing short length of cables. It consists of a continuously variable reactor connected in the low voltage winding of the step up transformer whose secondary is rated for the full test voltage. For certain setting of reactor, the inductive reactance of the circuit becomes equal to the capacitive reactance at power frequency which will result in resonance. Thus the reactive power requirement of the supply becomes zero and it has to supply only the losses of the circuit. However, the transformer has to carry the full load current on H.V. side which is a disadvantage of this method. The inductors are designed for high Q factor. The feed transformer therefore only supplies the losses of the circuit.

However now a new technique is being used to generate high voltage using series resonance in which a split iron core is used in the construction of H.V. continuous variable reactor which results in omission of testing step up transformer as shown in fig. 2(c)

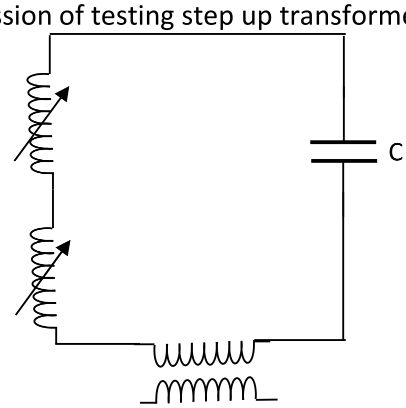


Fig. 2(c) Series Resonant circuit with variable H.V. reactors having split iron core

The inductance of these inductors can be varied over a wide range depending upon the capacitance of the load to produce resonance. The following are the advantages of a series resonant circuit:

i) The power requirement of the feed circuit is very small.
ii) It suppresses harmonics and interference to a large extent.
iii) In case of flashover /breakdown of test specimen during testing on H.V. side, the resonant circuit is detuned and the test voltage collapses immediately. The short circuit current is limited by the reactance of the variable reactor.
iv) In this case no compensating reactor’s are required which results in a lower overall weight.

v) In case of testing of SF_6 switchgear there is no special protection required against transients as there are no multiple breakdowns in high transients.
vi) Any number of units can be connected in series without any impedance problem which is very severely associated with cascaded test transformer.

Parallel Resonant Circuit: The fig. 3 shows a schematic of a typical parallel resonance circuit. In this the variable reactor is incorporated into the high voltage transformer by introducing a variable air gap in the core of the transformer. In this circuit the variation in load capacitance and losses cause variation in input current only whereas the output voltage remains practically constant. In case of single stage design, the parallel resonant method offers optimum testing performance.

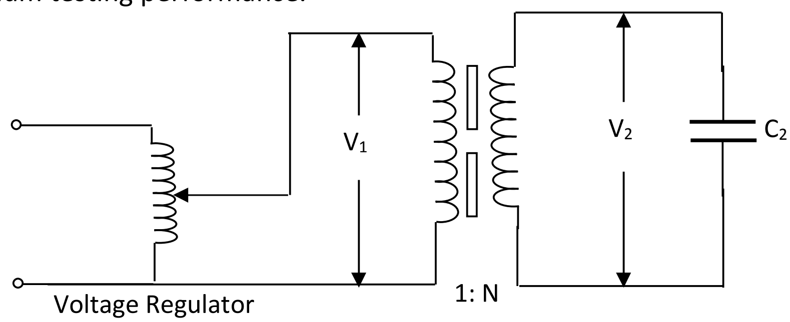


Fig.3 Parallel Resonance Circuit

Series – Parallel Resonant Circuit: The fig. 5 shows testing circuit which utilizes the advantages of both series resonant circuit and parallel resonance circuit.

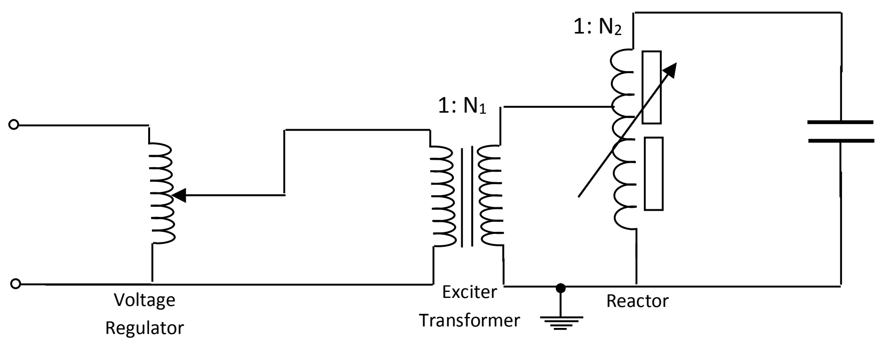


Fig. 5 Series Parallel Resonance High Voltage System

The following points need to be kept in mind while considering a series-parallel resonant circuit:

- ✓ The output voltage is achieved by auto transformer action and parallel compensation is achieved by the connection of the reactor.
- ✓ For a certain gap opening uncontrolled overvoltage of test sample results in case of parallel connected test system and if test set is allowed to operate for a long time resulting in heating and damage to the reactor.
- ✓ Experimentally it has been observed that complete balance of ampere turns takes place when the system operates under parallel resonance conditions. However under all other settings of variable reactor, an unbalance in AT forces large leakage flux into the surrounding metallic tank causing large circulating currents resulting in hot spots which adversely affects dielectric strength of oil in the tank.

- ✓ So instead of using only series resonant or only parallel resonant circuit, it is recommended to use a series – parallel resonant mode for testing purposes. For a single stage system upto 300 kV, series resonance method is strongly recommended and beyond that parallel resonance method.

Generation of High Frequency A.C. High Voltages: A high frequency high a.c. voltage is not only required for d.c. power supplies but also for testing electrical apparatus for switching surges. This requires high voltage high frequency transformer. The advantages of these high frequency transformers are:

(i) The high frequency resonant transformers do not use iron core which results in saving in cost and size.
(ii) These transformers give pure sine wave output.
(iii) The voltage build up is slow over a few cycles and hence there is no damage due to switching surges.
(iv) The voltage distribution is uniform across the winding coils due to subdivision of coil stack into a number of units.

The most commonly used high frequency resonant transformer is Tesla coil which is a doubly tuned resonant circuit whose equivalent circuit is shown in fig.6

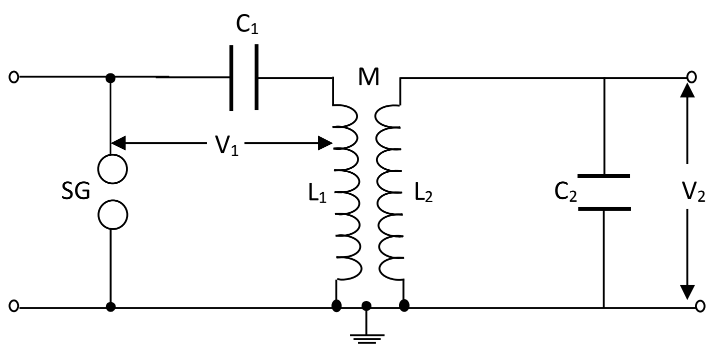


Fig. 6 Equivalent Circuit of Tesla Coil

The primary voltage rating is 10 kV and the secondary maybe related to as high as 500 to 1000 kV. The primary is fed from a d.c. or a.c. supply through the capacitor C_1. A spark gap SG connected across the primary winding is triggered at the desired voltage V_1 which induces a high self – excitation in the secondary. The primary and secondary windings (having inductance L_1 and L_2) are wound on an insulated former having air core immersed in oil. The windings are tuned to a frequency of 10 to 100 kHz by means of the capacitors C_1 and C_2.

The output voltage V_2 is a function of the parameters L_1, L_2, C_1, C_2 and mutual inductance M. Usually the winding resistance being small contributes only for damping oscillations. The output voltage is given by

$$V_2 = V_1\sqrt{\eta\frac{C_1}{C_2}}$$

Where η = efficiency of transformer. If the coupling K = M/L_1L_2 is large then for large values of winding resistances the output voltage waveform may become a unidirectional impulse instead of a sinusoidal waveform.

Advantages of high voltage high frequency transformer: The following are the advantages of a high voltage high frequency transformer:

(i) There is saving in cost and size due to the absence of iron core.
(ii) The output wave obtained is purely sinusoidal.
(iii) There is no damage due to switching surges as voltage build up is slow over few cycles.

Introduction to High Voltage Measurement – It is essential to measure the voltages and currents accurately ensuring perfect safety to the personnel and equipment in industrial testing and research laboratories. The location and layout of the devices are important as the person handling the equipment must be protected against overvoltages and also against any induced voltages due to stray coupling. The different used for high voltage measurements may be classified as in table 1 and table 2

Table 1 High Voltage Measurement Techniques

(a) D.C. Voltages	(i) Series resistance microammeter (ii) Resistance potential divider (iii) Generating voltmeter (iv) Sphere and other spark gaps
(b) A.C. Voltages (power frequency)	(i) Series impedance ammeters (ii) Potential dividers (resistance or capacitance type) (iii) Potential transformers (electromagnetic or CVT) (iv) Electrostatic voltmeters (v) Sphere gaps
(c) A.C. High frequency or voltages, impulse and other rapidly changing voltages	(i) Potential dividers with a cathode ray oscillograph (resistive (ii) Peak voltmeters (iii) Sphere gaps

Resistance Potential Dividers for d.c. Voltages – A resistance potential divider with an electrostatic voltmeter is shown in fig.2 The influence of temperature and voltage on the elements is eliminated in the voltage divider arrangement. The high voltage magnitude is given by $[(R_1 + R_2)/R_2]V_2$ where V2 is the d.c. voltage across the low voltage arm R2. With sudden changes in voltages, such as switching operations, flashover of the test objects or source short circuits, flashover or damage may occur to the divider elements due to the stray capacitance across the elements and due to ground capacitances. To avoid these transient voltages, voltage controlling capacitors are connected across the elements. A corona free termination is necessary to avoid unnecessary discharges at high voltage ends. Potential dividers are made with 0.05% accuracy upto 100 kV, with 0.01% accuracy upto 300 kV

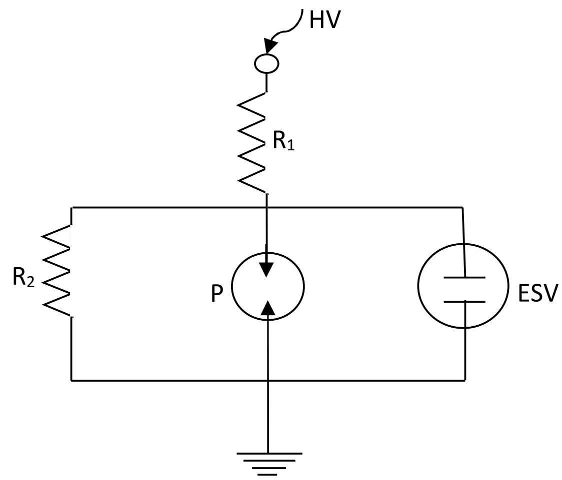


Fig.2 Resistance Potential Divider

ESV – Electrostatic Voltmeter P – Protective Device

Capacitance Voltage Transformer – A capacitance voltage transformer (CVT) is basically a capacitor divider used with a suitable matching or isolating potential transformer tuned for resonance conditions. A CVT can be connected to a low impedance device like a wattmeter pressure coil or relay coil which is in contrast to a simple capacitor divider which requires a high impedance meter like a TVM or electrostatic voltmeter. The fig.4 shows the schematic diagram of CVT with its equivalent circuit as shown in fig.5

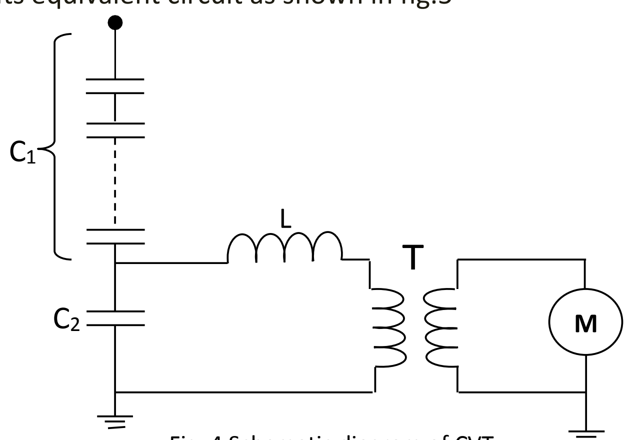


Fig. 4 Schematic diagram of CVT

The capacitor C_1 is made of a few units of high voltage capacitors such that the total capacitance is of few thousand picofarads. A matching transformer is connected between the load or meter M and C_2. The transformer ratio is chosen on economic grounds and the H.V. winding rating maybe 10 or 30 kV with the L.V. winding rated from 100 to 500 V. The value of the tuning choke L is chosen to make the equivalent circuit of the CVT purely resistive. The resonance condition is achieved when the following condition is satisfied:

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

where L = inductance of the choke

LT = equivalent inductance of the transformer referred to H.V. side

The meter reactance Xm is neglected and is taken as a resistance load Rm when the load is connected to the voltage divider side.

Advantages of CVT: The following are the advantages of a capacitance voltage transformer:

i. Simple design and easy installation.
ii. Can be used both as a voltage measuring device for meter and relaying purposes as well as coupling condenser for power line carrier communication & relaying.
iii. The voltage distribution along the elements is frequency independent as against conventional potential transformers which requires additional insulation design against surges.
iv. Provides isolation between the high voltage terminal and low voltage metering.

Disadvantages of CVT: The following are the disadvantages of capacitor voltage transformer are:

i. The voltage ratio is susceptible to temperature variations.
ii. The problem of inducing ferro – resonance in power systems.
iii. **Sphere Gap:** It is considered as one of the standard methods for the measurement of peak value of d.c., a.c. and impulse voltages and is used for checking the voltmeters and other voltage measuring devices used in H.V. test circuits. When an electric field across a gap exceeds the static breakdown strength of the gap it results in complete breakdown of the gaseous gap having uniform field. A uniform electric field is created in the gaseous gap between two spherical electrodes of equal diameter, if the electrodes are separated by a distance much smaller than the electrode radius. It can be used for measurement of impulse voltage of either polarity provided that the impulse is of standard waveform having wavefront time atleast 1 μs and wavetail time 5 μs. The sphere gaps can be arranged either vertically with lower sphere grounded, or horizontally with both spheres connected to source voltage or one sphere grounded. The two spheres used are identical in shape and size. The fig. 6(a) and 6(b) shows the schematic arrangement.

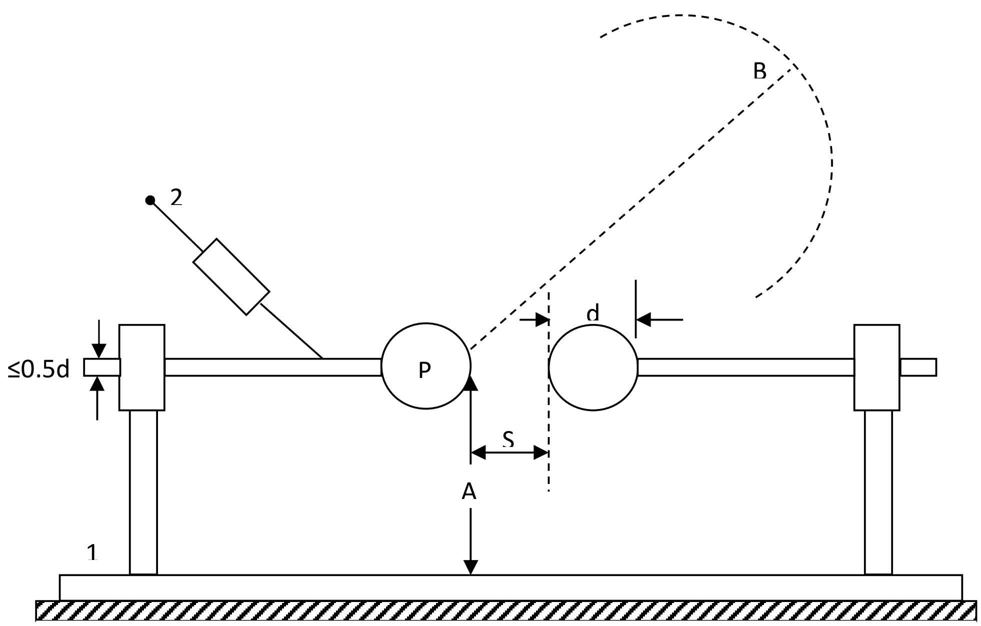


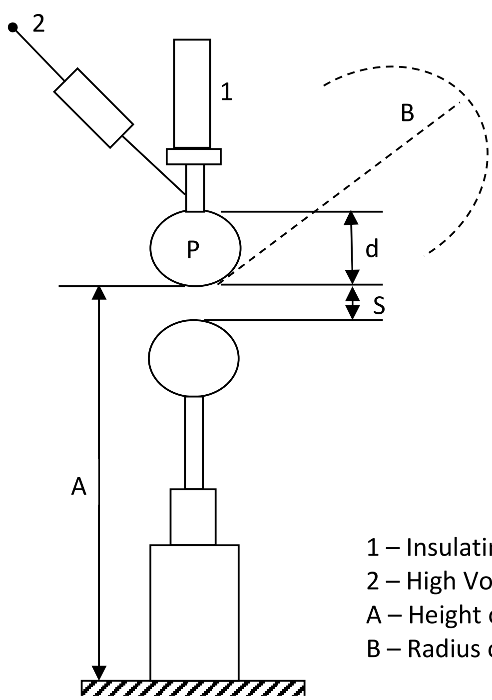
Fig. 6(a) Horizontal Arrangement of Sphere gap

iv.

v. The horizontal arrangement is usually preferred for sphere diameters d < 50 cm. This arrangement is used for measurement at lower voltage ranges. With larger spheres the vertical arrangement is chosen where the lower electrode is earthed. In both the arrangements one of the spheres is static and the other is movable so that the spacing between them can be adjusted. A minimum clearance around the spheres must be available within which no external objects such as walls, ceilings, transformer tanks, impulse generators or supporting framework for the spheres are allowed. The minimum clearance is dependent on the gap spacing.

vi. The height of the sparking point P above the horizontal ground plane A, minimum clearance B are related to sphere diameter d and gap spacing S respectively. The voltage to be measured is applied between the two spheres and the distance between the gap gives a measure of the sparkover voltage. A series resistance is usually connected between the source and the sphere gap to (i) limit the breakdown current and (ii) to suppress unwanted oscillations in source voltage when breakdown occurs. The value of the series may vary from 100 Ω to 1000 kΩ for a.c. and d.c. voltages but not more than 500 Ω in the case of impulse voltages.

vii.



1 – Insulating Support
2 – High Voltage Connection with series resistor
A – Height of sparking point P above the ground plane
B – Radius of space free from external structures

Fig. 6(b) Vertical Arrangement of Sphere gap

viii.

ix. The spheres are made of copper, brass or aluminium. The standard diameters for the spheres are 2, 5, 6.25, 10, 12.5, 15, 25, 50, 75, 100, 150 and 200 cm. The spheres are carefully designed and fabricated so that their surfaces are smooth and the curvature is uniform. The surfaces should be free from dust, grease or any other coating. Irradiation of gap is needed when measurements of voltage are less than 50 kV are made with sphere gaps of 10 cm diameter or less.

Factors Influencing Sparkover Voltage of Sphere Gaps: There are various factors that affect the sparkover voltage of a sphere gap like nearby earthed objects, atmospheric conditions and humidity, irradiation, polarity and rise time of voltage waveforms.

(a) **Influence of nearby earthed objects:** The effect of nearby objects was investigated by Kuffel by enclosing the earthed sphere inside an earthed cylinder. It was observed that there was reduction in breakdown voltage given by the empirical formula.

$$\Delta V = m \ln \frac{B}{D} + C$$

Where ΔV = reduction in breakdown voltage
B = diameter of earthed enclosing cylinder
D = diameter of spheres
m and C = factors depending on S/D ratio
S = spacing between spheres

The relation was less than 2% for S/D ≤ 0.5 and B/D ≥ 0.8. The reduction was only 3% for S/D ≈ 1.0 and B/D ≥ 1.0

(b) **Influence of humidity:** Kuffel studied the effect of humidity on breakdown voltage by using spheres of 2 cm to 25 cm of diameter and uniform field electrodes. It was concluded that the sparkover increases with the partial pressure of water vapour in air, and for a given humidity condition, the change in breakdown voltage increases with the gap length. This is due to water particles which readily attach with free electrons thus forming negative ions. These ions therefore slow down and are unable to ionise neutral molecules under field conditions in which electrons will readily ionize. It has been observed that within the humidity range of 4 to 17 g/m^3 the relative increase of breakdown voltage is found to be between 0.2 to 0.35 % per gm/m^3 for the largest sphere of diameter 100 cm and gap length upto 50 cm.

(c) **Influence of dust particles:** The presence of dust particles between the gap results in erratic breakdown in homogeneous or slightly homogeneous electrode configurations. The dust particle comes in contact with one electrode getting charged to polarity of that electrode when d.c. voltage is applied. It then gets attracted by the opposite electrode due to field forces triggering early breakdown. The gaps subjected to a.c. voltages are sensitive to dust particles but the probability of erratic breakdown is less.

(d) **Influence of atmospheric conditions:** The breakdown voltage of a spark gap depends on the air density which varies with the changes in both temperature and pressure. If the breakdown voltage is V under test conditions of temperature T and pressure p , if sparkover voltage is V_O under standard conditions of temperature and pressure then V = k V_O where k is a function of d where

$$d = \frac{p}{760}\left[\frac{293}{273+T}\right]$$

The following table gives the relation between k and d

d	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15
k	0.72	0.77	0.82	0.86	0.91	0.95	1.00	1.05	1.09	1.12

(e) **Influence of irradiation:** The illumination of sphere gaps with ultraviolet or X rays aids easy ionization in gaps. It was observed that for spacings of 0.1D to 0.3D for a 1.3 cm sphere gap with d.c. voltages there was reduction of 20% in breakdown voltage. The reduction in breakdown 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% Thus irradiation is necessary for smaller sphere gaps of gap spacing less than 1 cm for obtaining consistent values.

(f) **Influence of polarity and waveform:** It has been observed that the breakdown voltages for positive and negative polarity impulses are different. It has been experimentally investigated that for sphere gaps of 6.25 cm to 25 cm diameter, the difference between positive and negative d.c. voltages is not more than 1%. For smaller sphere gaps (2 cm or less diameter) the difference is 8% between negative and positive impulses of 1/50 μs waveform. For the wavefronts of less than 0.5 μs and wavetails less than 5 μs the breakdown voltages are not consistent. Hence the use of sphere gap is not recommended for voltage measurement in such cases.