

GOVERNMENT COLLEGE OF ENGINEERING, KALAHANDI



Lecture notes
on
HIGH VOLTAGE ENGINEERING
(Module III)



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Module-III
Generation of High Voltages and Currents

In the fields of electrical engineering and applied physics, high voltages (d.c., a.c., and impulse) are required for several applications. For example, electron microscopes and x-ray units require high d.c. voltages of the order of 100 kV or more. Electrostatic precipitators, particle accelerators in nuclear physics, etc. require high voltage (d.c) of several kilovolts and even megavolts. High a.c. voltages of one million volts or even more are required for testing power apparatus rated for extra high transmission voltages (400 kV system and above). High impulse voltages are required for testing purposes to simulate overvoltages that occur in power systems due to lightning or switching surges. For electrical engineers, the main concern of high voltages is for the insulation testing of various components in power systems for different types of voltages, namely, power frequency a.c., high frequency, switching or lightning impulse. Hence, generation of high voltages in laboratories for testing purposes is essential and is discussed in this chapter.

Different forms of high voltages mentioned above are classified as

- (i) high d.c. voltages,
- (ii) high a.c. voltages of power frequency,
- (iii) high a.c. voltages of high frequency,
- (iv) high transient or impulse voltages of very short duration such as lightning overvoltages, and
- (v) transient voltages of longer duration such as switching surges.

Normally, in high voltage testing, the current under conditions of failure is limited to a small value (less than an ampere in the case of d.c. or a.c. voltages and few amperes in the case of impulse or transient voltages). But in certain cases, like the testing of surge diverters or the short circuit testing of switchgear, high current testing with several hundreds of ampere is of importance. Tests on surge diverters require high surge currents of the order of several kiloamperes. Therefore, test facilities require high voltage and

high current generators. High impulse current generation is also required along with voltage generation for testing purposes.

4.1 GENERATION OF HIGH DC VOLTAGE

Generation of high d.c. voltages is mainly required in research work in the areas of pure and applied physics. Sometimes, high direct voltages are needed in insulation tests on cables and capacitors. Impulse generator charging units also require high d.c. voltages of about 100 to 200 kV. Normally, for the generation of d.c. voltages of up to 100 kV, electronic valve rectifiers are used and the output currents are about 100 mA. The rectifier valves require special construction for cathode and filaments since a high electrostatic field of several kV/cm exist between the anode and the cathode in the non-conduction period. The a.c. supply to the rectifier tubes may be of power frequency or may be of audio frequency from an oscillator. The latter is used when a ripple of very small magnitude is required without the use of costly filters to smoothen the ripple.

4.2 Half and Full Wave Rectifier Circuits

Rectifier circuits for producing high d.c. voltages from a.c. sources may be

- (a) halfwave,
- (b) full wave, or
- (c) voltage doubler type rectifiers.

The rectifier may be an electron tube or a solid state device. Nowadays single electron tubes are available for peak inverse voltages up to 250 kV, and semiconductor or solid state diodes up to 20 kV. For higher voltages, several units are to be used in series. When a number of units are used in series, transient voltage distribution along each unit becomes non-uniform and special care should be taken to make the distribution uniform. Commonly used half wave and full wave rectifiers are shown in Fig. 4.1.

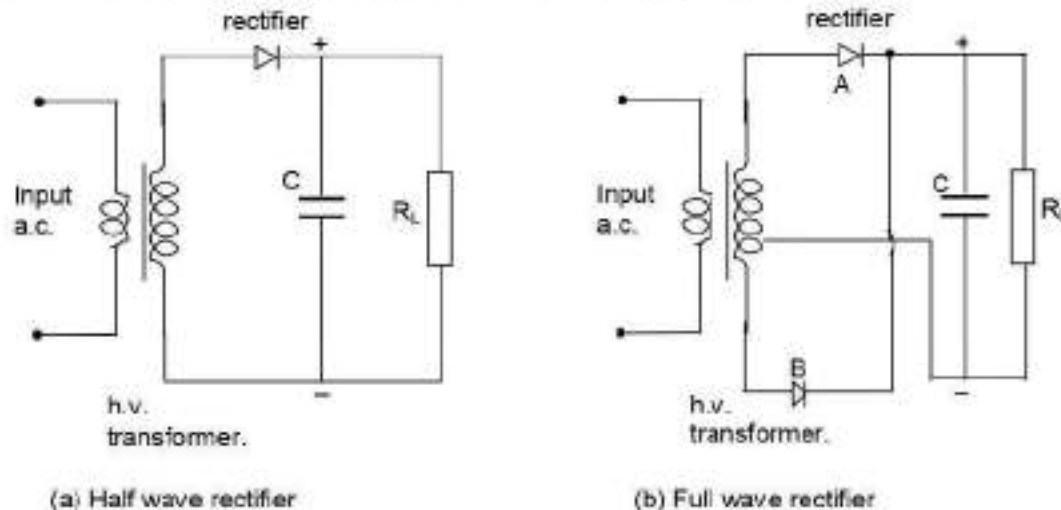


Fig.4.1 Full and Half wave rectifiers

In the half wave rectifier (Fig. 4.1a) the capacitor is charged to V_{max} , the maximum a.c. voltage of the secondary of the high voltage transformer in the conducting half cycle. In

the other half cycle, the capacitor is discharged into the load. The value of the capacitor C is chosen such that the time constant CR_L is at least 10 times that of the period of the a.c. supply. The rectifier valve must have a peak inverse rating of at least $2V_{max}$. To limit the charging current, an additional resistance R is provided in series with the secondary of the transformer (not shown in the figure).

A full wave rectifier circuit is shown in Fig. 4.1b. In the positive half cycle, the rectifier A conducts and charges the capacitors V_{max} , while in the negative half cycle the rectifier B conducts and charges the capacitor. The source transformer requires a centre tapped secondary with a rating of $2V$.

For application at high voltages of 50 kV and above, the rectifier valves used are of special construction. Apart from the filament, the cathode and the anode, they contain a protective shield or grid around the filament and the cathode. The anode will be usually a circular plate. Since the electrostatic field gradient are quite large, the heater and the cathode experience large electrostatic forces during the non-conduction periods. To protect the various elements from these forces, the anode is firmly fixed to the valve cover on one side. On the other side, where the cathode and filament are located, a steel mesh structure or a projective grid kept at the cathode potential surrounds them so that the mechanical forces between the anode and the cathode are reflected on the grid structure only.

Both full wave and half wave rectifiers produce d.c. voltages less than the a.c. maximum voltage. Also, ripple or the voltage fluctuation will be present, and this has to be kept within a reasonable limit by means of filters.

Ripple Voltage With Half Wave and Full Wave Rectifiers

When a full wave or a half wave rectifier is used along with the smoothing condenser C , the voltage on no load will be the maximum a.c. voltage. But when on load, the condenser gets charged from the supply voltage and discharges into load resistance R_L whenever the supply voltage waveform varies from peak value zero value. These waveforms are shown in Fig. 4.2. When loaded, a fluctuation in the output d.c. voltage δV appears, and is called a ripple. The ripple voltage δV is larger for a half wave rectifier than that for a full wave rectifier, since the discharge period in the case of half wave rectifier is larger as shown in Fig. 6.2. The ripple δV depends on (a) the supply voltage frequency f , (b) the time constant CR_L , and (c) the reactance of the supply transformer X_L . For half wave rectifiers, the ripple frequency is equal to the supply frequency and for full wave rectifiers, it is twice that value. The ripple voltage is to

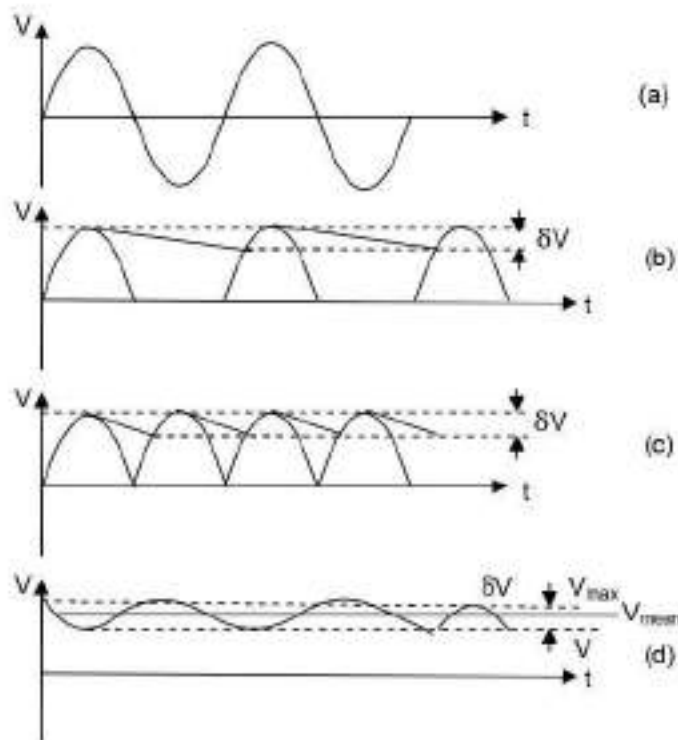


Fig.4.2 Input and output waveforms of half and full wave rectifiers
 (a) Input sine wave, (b) Output with half wave rectifier and condenser filter
 (c) Output with full wave rectifier and condenser filter, (d) V_{max} , V_{mean} and ripple voltage, δV with condenser filter of a full wave rectifier

be kept as low as possible with the proper choice of the filter condenser and the transformer reactance for a given load R_L .

4.1.2 Voltage Doubler Circuits

Both full wave and half wave rectifier circuits produce a d.c. voltage less than the a.c. maximum voltage. When higher d.c. voltage are needed, a voltage doubler or cascaded rectifier doubler circuits are used. The schematic diagram of voltage doublers are given in Figs. 4.3 a and b.

In voltage doubler circuit shown in Fig. 4.3 a, the condenser C_1 is charged through rectifier R to a voltage of $+V_{max}$ with polarity as shown in the figure during the negative half cycle. As the voltage of the transformer rises to positive V_{max} during the next half cycle, the potential of the other terminal of C_1 rises to a voltage of $+2 V_{max}$, depending on the time constant $C_1 R_L$ and the forward charging time constant. The ripple voltage of these circuits will be about 2% for $R_1/r \leq 10$ and $X/r \leq 0.25$, where X and r are the reactance and resistance of the input transformer. The rectifiers are rated to a peak inverse voltage of $2 V_{max}$, and the condensers C_1 and C_2 must also have the same rating. If the load current is large, the ripple also is more.

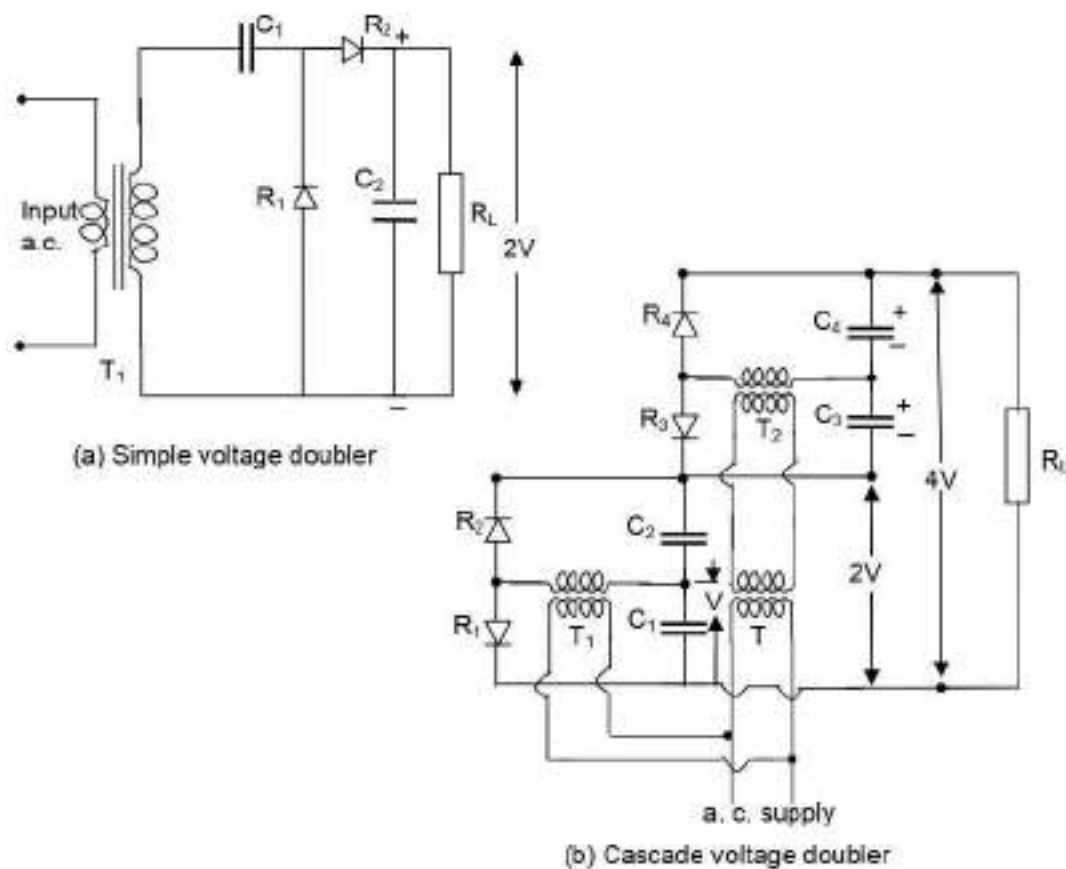


Fig.4.3 Voltage doubler circuits

T_1, T_2 – h. v. transformers; R_1, R_2, R_3, R_4 – rectifiers;

C_1, C_2, C_3, C_4 – condensers; R_L – load resistance; T – isolating transformer

Cascaded voltage doublers are used when larger output voltages are needed without changing the input transformer voltage level. A typical voltage doubler is shown Fig. 4.3b. The rectifiers R_1 and R_2 with transformer T_1 and C_1 and C_2 produce an output voltage of $2V$ in the same way as described above. This circuit is duplicated and connected in series or cascade to obtain a further voltage doubling to $4V$. T is an isolating transformer to give an insulation for $2V_{max}$ since the transformer T_2 is at a potential of $2V_{max}$ above the ground. The voltage distribution along the rectifier string R_1, R_2, R_3 and R_4 is made uniform by having condensers C_1, C_2, C_3 and C_4 of equal values. The arrangement may be extended to give $6V, 8V$, and so on by repeating further stages with suitable isolating transformers. In all the voltage doubler circuits, if valves are used, the filament transformers have to be suitably designed and insulated, as all the cathodes will not be at the same potential from ground. The arrangement becomes cumbersome (large and heavy therefore difficult to carry) if more than $4V$ is needed with cascaded stages.

4.1.3 Voltage Multiplier Circuits

Cascaded voltage multiplier circuits for higher voltages are cumbersome and require too many supply and isolating transformers. It is possible to generate very high d.c. voltages from single supply transformers by extending the simple voltage doubler circuits. This is simple and compact when the load current requirement is less than one milliampere, such as for cathode ray tubes, etc. Valve type pulse generators may be used instead of conventional a.c. supply and the circuit becomes compact. A typical circuit of this form is shown in Fig. 4.4a.

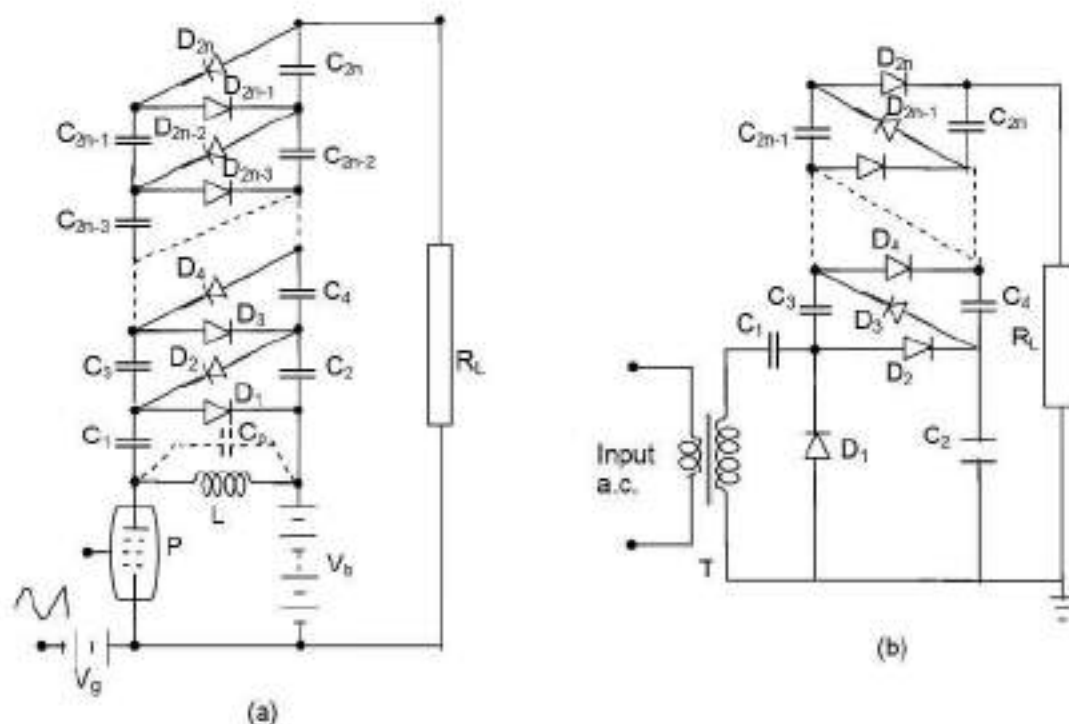


Fig.4.4 (a) Cascade rectifier unit with pulse generator, (b) Cockcroft-Walton voltage multiplier circuit. P – Pulse generator, V_b – D.C. supply to pulse generator, V_g – Bias voltage

The pulses generated in the anode circuit of the valve P are rectified and the voltage is cascaded to give an output of $2nV_{max}$ across the load R_L . A trigger voltage pulse of triangular waveform (ramp) is given to make the valve switched on and off. Thus, a voltage across the coil L is produced and is equal to $V_{max} = I_{max} \sqrt{L/C_p}$, where C_p is the stray capacitance across the coil of inductance L. A d.c. power supply of about 500 V applied to the pulse generator, is sufficient to generate a high voltage d.c. of 50 to 100 kV with suitable number of stages. The pulse frequency is high (about 500 to 1000 Hz) and the ripple is quite low (<1%). The voltage drop on load is about 5% for load currents of about $150 \mu A$. The voltage drops rapidly at high load currents.

Voltage multiplier circuit using the Cockcroft-Walton principle is shown in Fig. 4.4b. The first stage, i.e. D1, D2, C1, C2, and the transformer T are identical, as in the voltage doubler shown in Fig. 4.3a. For higher output voltage of $4, 6, \dots, 2n$ of the input voltage V , the circuit is repeated with cascade or series connection. Thus, the condenser C_1 is charged to $4V_{\text{max}}$ and C_{2n} to $2nV_{\text{max}}$ above the earth potential. But voltage across and individual condenser or rectifier is only $2V_{\text{max}}$.

-Ripple in Cascaded Voltages Multiplier Circuits

With load, the output voltage of the cascaded rectifiers is less than $2nV_{\text{max}}$, where n is the number of stages. The ripple and the voltage regulation of the rectifier circuit may be estimated as follows.

Let f = supply frequency,
 q = charge transferred in each cycle,
 I_1 = load current from the rectifier,
 t_1 = conduction period of the rectifiers,
 t_2 = non-conduction period of rectifiers, and
 δV = ripple voltage.

Referring to Fig. 4.3a, when load current I_1 is supplied from condenser C_2 to the load during the non-conduction period t_2 is q , and is related as follows.

$$I_1 = \frac{dq}{dt} \approx \frac{q}{t_2}$$

$$t_1 (t_2 \text{ and } t_1 + t_2 = \frac{1}{f} \text{ (i.e. the period of the a.c. supply voltage),}$$

$$t_2 = \frac{1}{f}$$

Since Also, $q = C_2 \delta V$

$$\text{Hence, } \delta V = \text{the ripple} = \frac{I_1}{fC_2}$$

At the same a charge q is transferred from C_1 to C_2 during each cycle of $x = \frac{1}{fC_1}$.

Hence Regulation = mean voltage drop from $2V_{\text{max}}$

$$= \frac{I_1}{f} \left[\frac{1}{C_1} + \frac{1}{2C_2} \right] \quad (6.1)$$

Therefore, the mean output voltage = $2V_{\text{max}} - \frac{I_1}{f} \left(\frac{1}{C_1} + \frac{1}{2C_2} \right)$

For the cascade circuit, on no load, the voltage between stages is raised by $2nV_{\max}$ for n stages.

Referring to Fig. 4.4b, to find an expression for the total ripple voltage, let it be assumed that all capacitances C_1, C_2, \dots, C_n be equal to C let q be the charge transferred from C_n to the load per cycle. Then the ripple at the condenser C_n will be $\frac{I_1}{fC}$. Simultaneously, C_{n-2} transfers a charge a charge q to the load and to C_{n-1} . Hence, the ripple at the condenser C_{n-2} is $\frac{2I_1}{fC}$. Similarly, C_{n-4} transfers a charge q to the load, to C_{n-3} , and to C_{n-2} . Therefore, the ripple at condenser C_{n-4} is $\frac{3I_1}{fC}$. Proceeding in the same way, the ripple at C_2 will be $\frac{nI_1}{fC}$. Hence, for n stages the total ripple will be

$$\delta V_{\text{total}} = \frac{I_1}{fC} [1 + 2 + 3 \dots + n] = \frac{I_1}{fC} \frac{n(n+1)}{2} \quad (6.2)$$

It can be seen from the above expression that the lowest capacitances (C_2, C_4 , etc.) contribute most for the ripple. If these capacitances are increased proportionately, i.e. C_1 and C_2 are made equal to nC , C_3 and C_4 are made equal to $(n-1)C$ and so on, the total ripple will be only $\frac{nI_1}{fC}$.

-Regulation or Voltage Drop on Load

In addition to the ripple δV there is a voltage drop ΔV , which is the difference between the theoretical no load and the on load voltage. From the analysis of the ripple voltage, it may be seen that the condenser C_1 is not charged to $2V_{\max}$ but only to $\left(2V_{\max} - \frac{2nI_1}{fC}\right)$.

Similarly, C_2 is charged to only $\left[\left(2V_{\max} - \frac{2nI_1}{fC}\right) - \frac{(2n-1)I_1}{fC}\right]$, as it gives a charge of

$\frac{(2n-1)I_1}{fC}$ during the non-conduction period to the load and to the next condenser. Hence,

the total voltage drop at various condenser stages will be

$$\Delta V_2 = \frac{I_1}{fC} [2n + 2(n-1) + \dots + 2.2 + 1]$$

$$\Delta V_4 = \frac{I_1}{fC} [2n + 2(n-1) + \dots + 2]$$

$$\Delta V_{2n-2} = \frac{I_1}{fC} [2n + n - 1]$$

$$\Delta V_n = \frac{I_1}{fC} n$$

Addition of all the n voltage drops gives

$$\begin{aligned} \Delta V &= \frac{I_1}{fC} \left[n + 2n + (n-1) + 2n + 2(n-1) + n - 2 + \dots \right] \\ &= \frac{I_1}{fC} \left[\frac{2}{3}n^3 + \frac{1}{2}n^2 - \frac{1}{6}n \right] \end{aligned} \quad (6.3)$$

Here also, it is seen that most of the voltage drop is due to the lowest stage condensers C_1, C_2 etc. Hence, it is advantageous to increase their values proportional to the number of the stage from the top.

For large values of $n (\geq 5)$, $\frac{n^2}{2}$ and $\frac{n}{6}$ terms in Eq. (4.3) will become small compared to $\frac{2}{3}n^3$ and may be neglected; then the optimum number of stages for the minimum voltage drop may be expressed as

$$n_{optimum} = \sqrt{\frac{V_{max} f C}{I}} \quad (6.4)$$

..... I is the load current.

Thus, for a multiplier or a cascaded circuit with $f=50$ Hz, $C=0.1 \mu F$,

$V_{max} = 100$ kV and $I=5$ mA, the number of stages $n \approx 10$.

The regulation can be improved by increasing f , but an upper limit is set by the high voltage appearing across the inductances and high capacitor current which are considerable. At present, the Cockcroft - Walton type voltage multipliers are available using selenium rectifiers and a.c. supply frequencies of 500 to 1000 Hz for output voltages of more than one million volts and load currents of 30 mA.

Van de Graaff Generator

Preliminary Questions

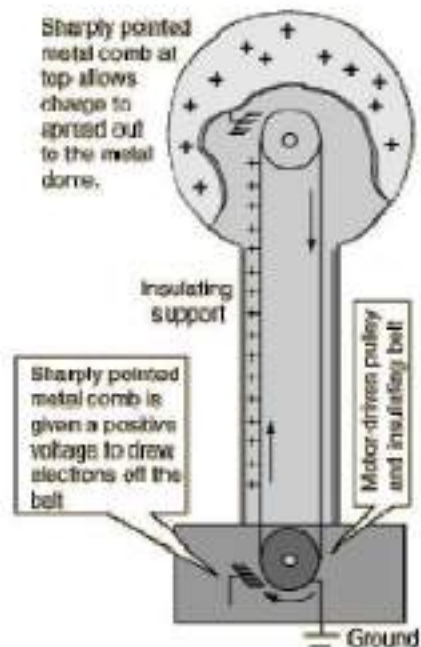
1. A small sphere of radius r and charge q is enclosed by a spherical shell of radius R and charge Q . Show that if q is positive, charge q will necessarily flow from the sphere to the shell (when the two are connected by a wire) no matter what the charge Q on the shell is. (NCERT PHYSICS).

2. There are three concentric and conducting spheres of radius R , $2R$ and $4R$ respectively. Innermost sphere A and the outermost sphere C are connected by a conducting wire while the intermediate sphere is uniformly charged to $+Q$. Find (a) charges on conductors A and C (b) potential of A and B . (c) If the spheres A and C are earthed,

A machine to make charges was invented in 1931 by a young American called Dr. Robert J. Van de Graaff. Huge machines, some over 30 m high, based on his ideas have been built to produce extremely high voltage (10MV).

A Van de Graaff generator operates by transferring electric charge from a moving belt to a terminal. The high voltages generated by the Van de Graaff generator can be used for

accelerating subatomic particles to high speeds, making the generator a useful tool for fundamental physics research.



Working of the generator is based on two principles:

(a) Discharging action of sharp points, i.e., electric discharge takes place in air or gases readily, at pointed conductors.

(b) If the charged conductor is brought in to internal contact with a hollow conductor, all of its charge transfers to the surface of the hollow conductor no matter how high the potential of the latter may be.

Theory behind construction:

If we have a large conducting spherical shell of radius ' R ' on which we place a charge Q , it spreads itself uniformly all over the sphere. The field outside the sphere is just that of a point charge Q at the centre, while the field inside the sphere vanishes. So the potential outside is that of point charge and inside it is constant.

The potential inside the conducting sphere = $\frac{1}{4\pi\epsilon_0} \frac{Q}{R}$

Now suppose that we introduce a small sphere of radius 'r', carrying a charge q, into the large one and place it at the centre. The potential due to this new charge has following values.

Potential due to small sphere of radius r carrying charge $q = \frac{1}{4\pi\epsilon_0} \frac{q}{r}$

Potential at the surface of large shell of radius R = $\frac{1}{4\pi\epsilon_0} \frac{q}{R}$

Taking both charges q and Q in to account we have for the total potential V and the potential difference given by,

$$V(R) = \frac{1}{4\pi\epsilon_0} \left(\frac{Q}{R} + \frac{q}{R} \right)$$

$$V(r) = \frac{1}{4\pi\epsilon_0} \left(\frac{Q}{R} + \frac{q}{r} \right)$$

$$V(r) - V(R) = \frac{q}{4\pi\epsilon_0} \left(\frac{1}{r} - \frac{1}{R} \right)$$

Now assume that q is positive. We see that, independent of the amount of charge Q that may have accumulated on the larger sphere, it is always at a higher potential: the difference $V(r) - V(R)$ is positive. The potential due to Q is constant upto radius R and so cancels out in the difference.

This means that if we connect the smaller and larger sphere by a wire, the charge q on the former will immediately flow on to the latter, even though the charge Q may be quite large. The natural tendency is for positive charge to move higher to lower potential. Thus, provided we are somehow able to introduce the small charged sphere into the larger one,

we can in this way pile up larger and larger amount of charge on the latter. The potential of the outer sphere would also keep rising, at least until it reaches the breakdown field of air.

Construction:

A simple Van de Graaff-generator consists of an endless belt of silk/rubber/Teflon, or a similar flexible dielectric material, running over two vertically mounted metal pulleys, upper one of which is surrounded by a hollow metal sphere. The belt is run by an electric motor. Two electrodes, in the form of comb-shaped rows of sharp metal points, are positioned respectively near to the bottom of the lower pulley and inside the sphere, over the upper pulley. Upper Comb is connected to the sphere, and lower comb to the ground.

The positive terminal of a high tension source (HT) is connected to the lower comb. Charges are accumulated at the pointed ends of the comb, the electric field increases and ionizes the air near them. The positive charges in air are repelled and get deposited on the belt due to corona discharge. The charges are carried by the belt upwards as it moves. When the positively charged portion of the belt comes in front of the upper collecting comb, by the same process of action of points and corona discharge occurs and the metal sphere acquires positive charges. The positive charges are uniformly distributed over the surface of the sphere.

The uncharged portion of the belt returns down collects the positive charge from lower comb which in turn is collected upper comb. The charge transfer process is repeated. As more and more positive charges are imparted to the sphere, its positive potential goes on rising. Leakage of charges in the belt and load puts a limit to generation. If the potential goes beyond this, insulation property of air breaks down and the sphere gets discharged.

Since a Van de Graaff generator can supply the same small current at almost any level of electrical potential, it is an example of a nearly ideal current source. The maximum achievable potential is approximately equal to the sphere's radius multiplied by the e-field where corona discharges begin to form within the surrounding gas.

Can we accelerate negative charges in a Van-de-Graff generator?

Yes, to accelerate electrons, the spherical metallic globe should be at negative potential. For this the polarity of the generator is reversed.

Prob.

Calculate the rate in rise of voltage for such electrostatic generator using SF₆ gas at 10 atmospheric pressure with C= 1000pF, belt width = 3m, belt speed= 200 m/min, charge density= 14×10^{-6} coul/sq. m.

5.1 GENERATION OF HIGH ALTERNATING VOLTAGES

When test voltage requirements are less than about 300kV, a single transformer can be used for test purposes. The impedance of the transformer should be generally less than 5% and must be capable of giving the short circuit current for one minute or more depending on the design. In addition to the normal windings, namely, the low voltage windings, a third windings known as meter windings is provided to measure the output voltage. For higher voltage requirements, a single unit construction becomes difficult and costly due to insulation problems. Moreover, transportation and erection of large transformers become difficult. These drawbacks are by series connection or cascading of the several identical units of transformers, where in the high voltage windings of all the units effectively come in series.

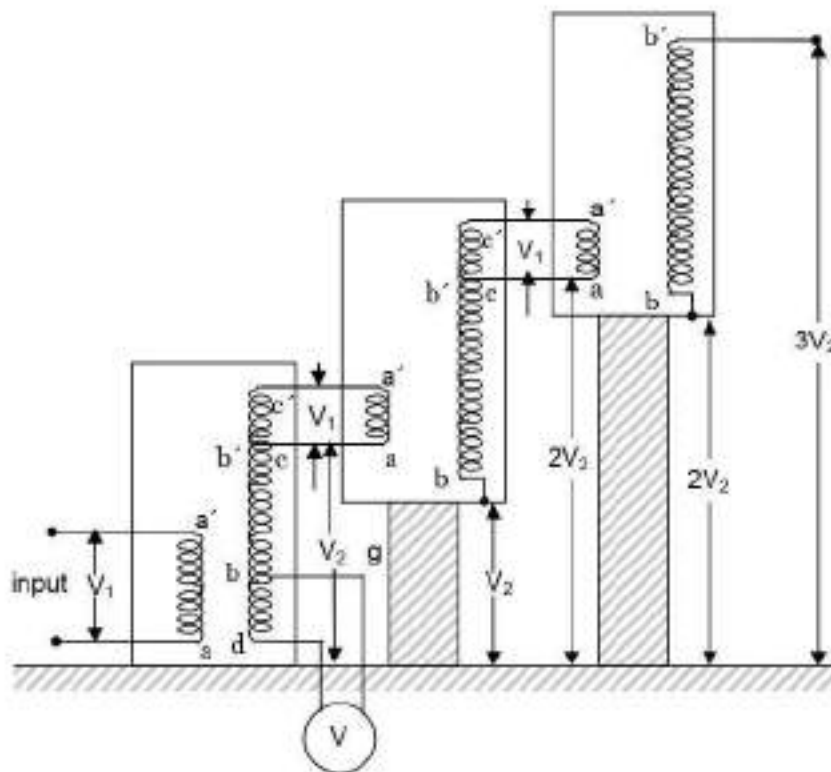


Fig.5.1 Cascade transformer connection (schematic)

V_1 – Input voltage; V_2 – output voltage; aa' - L.V. primary winding;
 bb' - H.V. secondary winding; cc' - Excitation winding; dd' – Meter
 winding (200 to 500); g – Insulation (pillars or post insulators);
 V - Voltmeter

5.1.1 Cascade Transformers

Figure 5.1 shows the cascade transformer units in which the first transformer is at the ground potential along with its tank. The second transformer is kept on insulators and maintained at a potential of V_2 , the output voltage of the first unit above the ground. The high voltage winding of the first unit is connected to the tank of the second unit. The low

voltage winding of this unit is supplied from the excitation winding of the first transformer, which is in series with the high voltage winding of the first transformer at its high voltage end. The rating of the excitation windings is almost identical to that of the primary or the low or the low voltage winding. The high voltage connection from the first transformer winding and the excitation winding terminal are taken through a bushing to the second transformer. In a similar manner, the third transformer is kept on insulators above the ground at a potential of $2V_2$ and is supplied likewise from the second transformer. The number of stages in this type of arrangement are usually two four, but very often, three stages are adapted to facilitate a three-phase operation so that $\sqrt{3}V_2$ can be obtained between the lines.

Supply to the units can be obtained from a motor-generator set or through an induction regulator for variation of the output voltage. The rating of the primary or the low voltage windings is usually 230 or 400 V for small units up to 100 kVA. For larger outputs the rating of the low voltage winding may be 3.3 kV, 6.6kV or 11 kV.

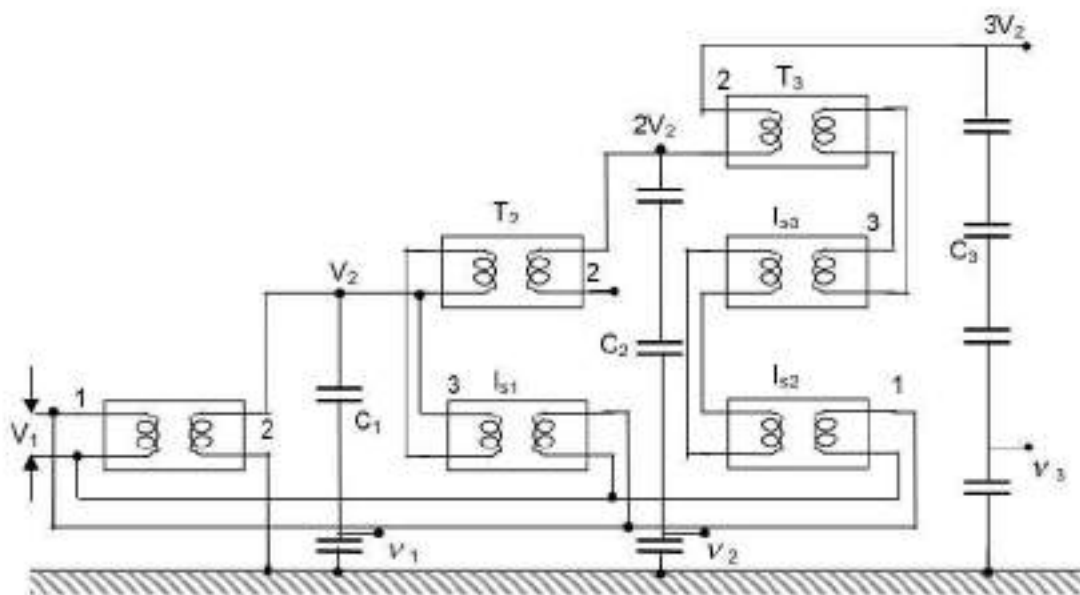


Fig. 5.2 Cascade transformer unit with isolating transformer for excitation

T_1, T_2, T_3 - Cascade transformer units

I_{s1}, I_{s2}, I_{s3} - Isolating transformer units

C_1, C_2, C_3 - Capacitance voltage dividers for h.v. measurement after 1st, 2nd and 3rd stages

V_1, V_2, V_3 - For metering after 1st, 2nd and 3rd stages

1. Primary (l.v. winding), 2. h.v. winding, 3. excitation winding.

In figure Fig. 5.2, a second scheme for providing the excitation to the second and the third stages is shown. Isolating transformers I_{s1}, I_{s2} and I_{s3} are 1:1 ratio transformers and are meant for supplying the excitation for the second and the third stages at their tank

potentials. Power supply to the isolating transformers is also fed from the same a.c. input. This scheme is expensive and requires more space. The advantage of this scheme is that the natural cooling is sufficient and the transformers are light and compact. Transportation and assembly is easy. Also the construction is identical for isolating transformers and the high voltage cascade units. Three phase connection in delta or star is possible for three units. Testing transformers of ratings up to 10 MVA are cascade connection to give high voltages up to 2.25 MV are available for both indoor and outdoor applications.

In order to reduce the size and cost of the insulation, sometimes transformers with a centre tap on high voltage windings earthed or connected to the tank are used. This connection results in a cheaper construction, and the high voltage insulation now needs to be designed for $V_2/2$, that of second transformer at $3V_2/2$, and that of the third transformer at $5V_2/2$.

All the cascade transformer units which are meant for the supply of excitation to the next stage have large leakage between the primary (or the low voltage winding) and the excitation windings. Hence, they are invariably provided with compensating windings.

5.1.2 Resonant Transformers

The equivalent circuit of a high voltage testing transformer consist of the leakage reactances of the windings, the windings resistances, the magnetizing reactance, and the shunt capacitance across the output terminal due to the bushing of the high voltage terminal and also that of the test object. This is shown in Fig 5.3.

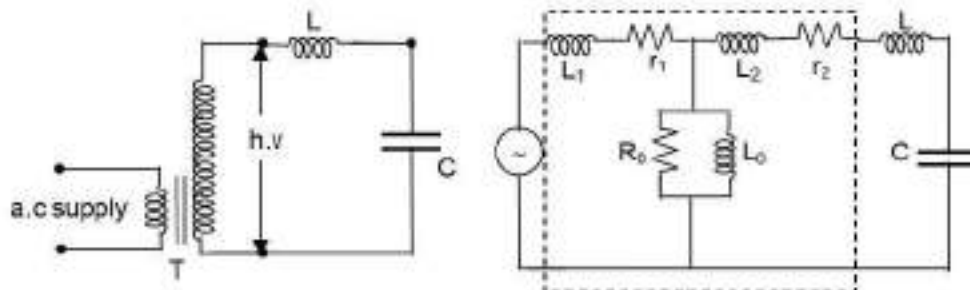


Fig.5.3 Resonant transformer and equivalent circuit. T – Testing transformer;
 L – choke; C – Capacitance of a h.v. terminal and test object;
 L_0 – Magnetizing inductance; L_1, L_2 – Leakage inductance of the transformer; r_1, r_2 – resistance of the windings; R_0 – Resistance due to core loss

It may be seen that it is possible to have series resonance at power frequency $\omega, (L_1 + L_2) = 1/\omega C$. With this condition, the current in the tests object is very large and is limited only by the resistance of the circuit. The waveform of the voltage across the

test object will be purely sinusoidal. The magnitude of the voltage across the capacitance C of the test object will be

$$V_c = \left| \frac{-jVX_c}{R+j(X_L-X_c)} \right| = \frac{V}{R} X_c = \frac{V}{\omega CR} \quad (6.8)$$

where R is the total series resistances of the circuit.

The factor X_c/R is the Q factor of the circuit and 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.

This principle is utilized in testing at very high voltage and on occasions requiring large current outputs such as cable testing, dielectric loss measurements, partial discharge measurements, etc. 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 chief advantages of this principle are:

- a) it gives an output of pure sine wave,
- b) power requirements are less (5 to 10% of total kVA required),
- c) no high power arcing and heavy current surges occur if the test object failed, as resonance ceases at the failure of the test object,
- d) cascading is also possible for very high voltage,
- e) simple and compact test arrangement, and
- f) no repeated flashovers occur in case of partial failures of the test object and insulation recovery. It can be shown that the supply source takes Q number of cycles at least to charge the test specimen to the full voltage.

The disadvantages are the requirements of additional variable chokes capable of withstanding the full test voltage and the full current rating.

5.2.3 Generation of High Frequency a.c. High Voltages

High frequency high voltage are required for rectifier d.c. power supplies as discussed. Also, for testing electrical apparatus for switching surges, high frequency high voltage damped oscillators are needed which need high voltage high frequency transformers.

The advantages of these high frequency transformers are:

- i) the absence of iron core in transformers and hence saving in cost and size,
- ii) pure sine wave output,
- iii) slow build-up of voltage over a cycles and hence no damage due to switching surges, and
- iv) uniform distribution of voltage across the winding coils due to subdivision of coil stack into a number of units.

The commonly used high frequency resonant transformer is the Tesla coil, which is a doubly tuned resonant circuit shown schematically in Fig. 5.4a.

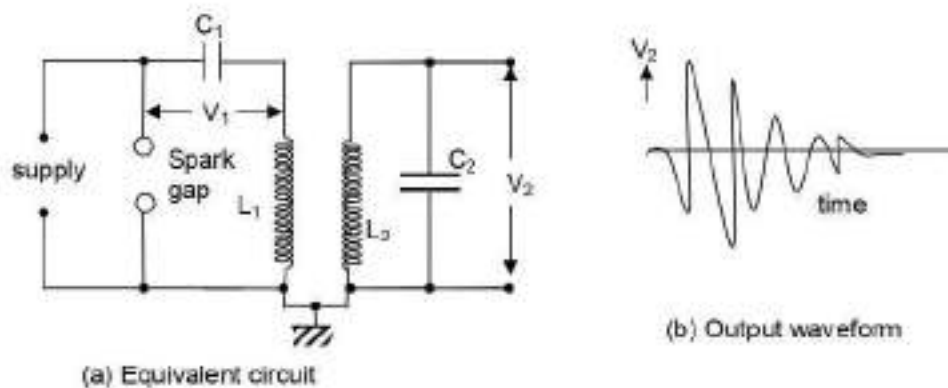


Fig.5.4 Tesla coil equivalent circuit and its output waveform

The primary voltage rating is 10 kV and the secondary may be rated to as high as 500 to 1000 kV. The primary is fed from a d.c. or a.c. supply through the condenser C_1 . A spark gap G connected across the primary is triggered at the desired voltage V_1 which induces a high self excitation in the secondary. The primary and the secondary windings (L_1 and L_2) are wound on an insulated former with no core (air cored) and are immersed in oil. The windings are tuned to a frequency of 10 to 100kHz by means of the condensers 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 the mutual inductances M . usually, the windings resistance will be small and contribute only for damping of the oscillations.

The analysis of the output waveform can be done in a simple manner neglecting the winding resistance. Let the condenser C_1 be charged to a voltage V_1 when the spark gap is triggered. Let a current i_1 flow through the primary windings L_1 and produce a current i_2 through L_2 and C_2 .

Then,

$$V_1 = \frac{1}{C_1} \int_0^t dt + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \quad (6.9)$$

$$\text{and, } 0 = \frac{1}{C_2} \int_0^t dt + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}$$

The Laplace transformed equations for the above are,

$$\frac{V_1}{s} = \left[L_1 s + \frac{1}{C_1 s} \right] I_1 + M s I_2 \quad (6.10)$$

$$\text{and, } 0 = [M s] I_1 + \left[L_2 s + \frac{1}{C_2 s} \right] I_2$$

where I_1 and I_2 are the Laplace transformed values of i_1 and i_2 . The output voltage V_2 across the condenser C_2 is

$V_2 = \frac{1}{C_2} \int_0^t i_2 dt$; or its transformed equation is

$$V_2(s) = \frac{I_2}{C_2 s} \quad (6.11)$$

where, $V_2(s)$ is the Laplace transform of V_2 .

The solution for V_2 from the above equations will be

$$V_2 = \frac{MV_1}{\sigma L_1 L_2 C_1} \frac{1}{\gamma_2^2 - \gamma_1^2} [\cos \gamma_1 t - \cos \gamma_2 t] \quad (6.12)$$

where,

$$\sigma^2 = \frac{M^2}{L_1 L_2} = 1 - K^2$$

K = coefficient of coupling between the windings L_1 and L_2

$$\gamma_{1,2} = \frac{\omega_1^2 + \omega_2^2}{2} \mp \sqrt{\left(\frac{\omega_1^2 + \omega_2^2}{2}\right)^2 - \omega_1^2 \omega_2^2 (1 - K^2)}$$

$$\omega_1 = \frac{1}{\sqrt{L_1 C_1}} \text{ and } \omega_2 = \frac{1}{\sqrt{L_2 C_2}}$$

The output waveform is shown in Fig. 6.13b.

The peak amplitude of the secondary voltage V_2 can be expressed as,

$$V_{2max} = V_1 \sqrt{\frac{L_2}{L_1}} \quad (6.13)$$

$$e^{-\frac{2\sqrt{1-\sigma}}{\sqrt{(1+a)^2 + 4\sigma a}}}$$

where,

$$a = \frac{L_2 C_2}{L_1 C_1} = \frac{\omega_1^4}{\omega_2^4}$$

A more simplified analysis for the Tesla coil may be presented by considering that the energy stored in the primary circuit in the capacitance C_1 is transferred to C_2 via the magnetic coupling. If W_1 is the energy stored in C_1 and W_2 is the energy transferred to C_2 and if efficiency of the transformer is η , then

$$W_2 = \frac{1}{2} C_2 V_2^2 = \eta \left(\frac{1}{2} C_1 V_1^2 \right) \quad (6.14)$$

$$\text{from which } V_2 = \eta \sqrt{\frac{C_1}{C_2}} \quad (6.14a)$$

It can be shown that if the coefficient of coupling K is large oscillation frequency is less, and for large values of the winding resistance and K , the waveform may become a

unidirectional impulse. This is shown in the next sections while dealing with the generation of switching surges.

6.GENERATION OF IMPULSE VOLTAGES

6.0 Standard Impulse Wave-shapes

Transient over voltages due to lightning and switching surges cause steep build-up of voltage on transmission lines and other electrical apparatus. Experimental investigations showed that these waves have rise time of 0.5 to 10 μ s and decay time to 50% of peak value of the order of 30 to 200 μ s. The wave-shapes are arbitrary, but mostly unidirectional. It is shown that lightning over-voltage wave can be represented as double exponential waves defined by the equation

$$V=V_0 [\exp(-\alpha t)-\exp(-\beta t)] \quad (6.15)$$

where α and β are constants of microsecond values.

The above equation represents a unidirectional wave which usually has a rapid rise to the peak value and slowly falls zero value.

The general wave-shape is given in Fig. 6.14. Impulse wave are specified by defining their rise or front time, fall or tail time to 50% peak value, and the value of the peak voltage. Thus 1.2/50 μ s, 1000 kV wave represents an impulse voltage wave with a front time of 1.2 μ s, fall time to 50% peak value of 50 μ s, and a peak value of 1000 kV. When impulse wave-shapes are recorded, the initial portion of the wave will not be clearly defined or sometimes will be missing. Moreover, due to disturbances it may contain superimposed oscillations in the rising portion. Hence, the front and tail times have to be defined.

Referring to the wave-shape in Fig. 6.14, the peak value A is fixed and referred to as 100% value. The points corresponding to 10% and 90% of the peak values are located in the front portion (points C and D).

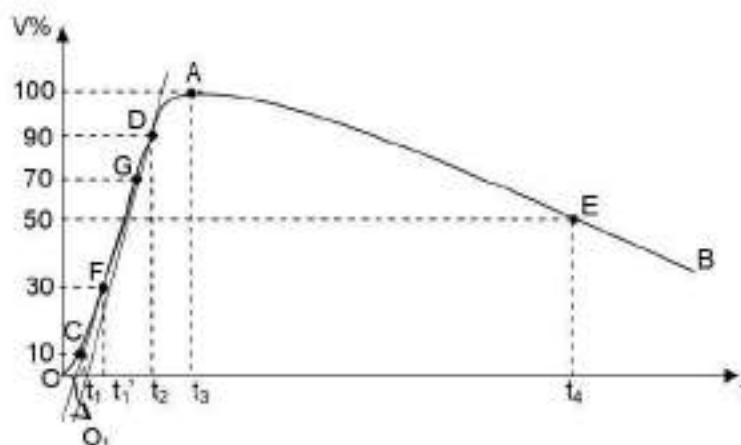


Fig.6.1 Impulse waveform and its definitions

The line joining these points is extended to cut the time axis at O_1 . O_1 is taken as the virtual origin. 1.25 times the interval between times t_1 and t_2 corresponding to points C and D (projections on the time axis) is defined as the front time, i.e. 1.25

$(O_1t_2 - O_1t_1)$. The point E is located on the wave tail corresponding to 50% of the peak value, and its projection on the time axis t_4 . O_1t_4 is defined as the fall or tail time. In case the point C is not clear or missing from the wave-shape record, the point corresponding to 30% peak value F is taken and its projection t_1 is located on time axis. The wave front time in that case will be defined as $1.67 (O_1t_3 - O_1t_1)$. The tolerances that can be allowed in the front and tail times are respectively $\pm 30\%$ and $\pm 20\%$. Indian standard specifications define $1.2/50 \mu s$ wave as standard impulses. Considering the tolerances allowed, all the above wave-shapes overlap and give rise to a wave-shape which lies within the specified limits. The tolerance allowed in the peak value is $\pm 3\%$.

The impulse waves are generally represented by the Eq. (6.15) given earlier. V_0 in the equation represents a factor that depends on the peak value. For impulse wave of $1.2/50 \mu s$, $a=0.0146$, $\beta = -2.467$, and $V_0 = 1.04$ when time t is expressed in microseconds.

α and β control the front and tail time of the wave respectively.

A double exponential waveform of the type mentioned in Eq. (6.15) may be produced in the laboratory with a combination of a series R-L-C circuit under overdamped condition or by the combination of two R-C circuits. Different equivalent circuits that produce impulse waves are given in Figs. 6.15 a to e. Out of these circuits, the ones shown in Figs. 6.2a to d are commonly used. Circuit shown in Fig. 6.15a is limited to model generators only, and commercial generators employ circuits shown in Figs. 6.2b to 6.2d.

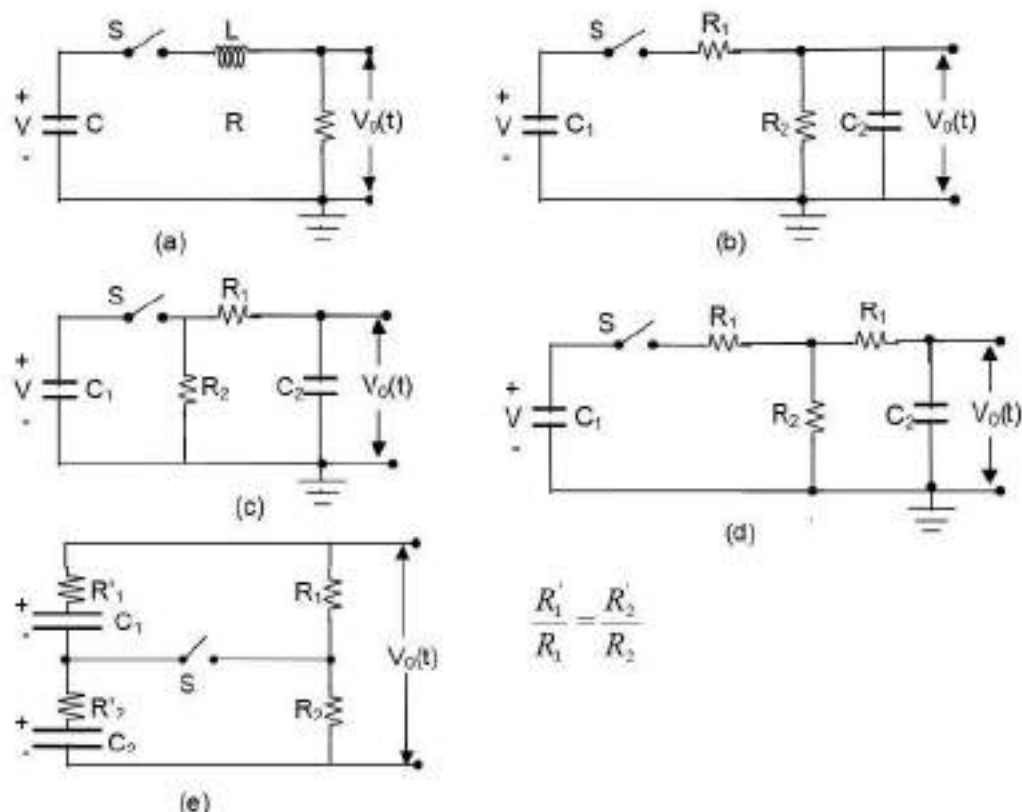


Fig.6.2 Circuits for producing impulse waves

A capacitor C_1 or C previously charged to a particular d.c. voltage is suddenly discharged into the wave-shaping network (L, R, R_1, R_2, C_2 or other combination) by closing the switch S . The discharge voltage $V_o(t)$ shown in Fig. 6.2 gives rise to the desired double exponential wave-shape.

Analysis of Impulse Generator Circuit Series R-L-C Type

Referring to Fig. 6.15 the current through the load resistance R is given by

$$V = \frac{1}{C} \int i dt + Ri + L \frac{di}{dt} \quad (6.16)$$

with initial condition at $t=0$ being $i(0)=0$ and the net charge in the circuit $i=dq/dt=0$. Writing the above equation as a Laplace transformer equation,

$$V/s = \left(\frac{1}{C_s} + R + L_s \right) I(s)$$

$$\text{or, } I(s) = \frac{V}{L} \left[\frac{1}{s^2 + \frac{R_s}{L} + \frac{1}{LC}} \right]$$

The voltage across the resistor R (Which is the output) is, $v_o(s) = I(s)R$, hence,

$$v_o(s) = V \frac{R}{L} \frac{1}{s^2 + \frac{R_s}{L} + \frac{1}{LC}}$$

For an overdamped condition, $R/2L \geq 1/\sqrt{LC}$

Hence, the roots of the equation $s^2 + \frac{R_s}{L} + \frac{1}{LC}$ are $\alpha = s_1 = -\frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$,

$$\beta = s_2 = -\frac{R}{2L} - \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

The solution of the equation for $v_o(t)$ is, $v_o(t) = \frac{V \left(\frac{R}{2L}\right)}{\left[\frac{R^2}{4L^2} - \frac{1}{LC}\right]^{\frac{1}{2}}} [e^{-\alpha t} - e^{-\beta t}] =$

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

The sum of the roots $\left(\alpha + \beta = -\frac{R}{2L}\right)$ and the product of the roots are $\alpha\beta = -\frac{1}{LC}$

The wave front and the wave tail times are controlled by changing the values of R and L simultaneously with a given generator capacitance C; choosing a suitable value for L. β or the wave front time is determined and α or the wave tail time is controlled by the value of R in the circuit. The advantage of this circuit is its simplicity. But the waveshape control is not flexible and independent. Another disadvantage is that the basic circuit is altered when a test object which will be mainly capacitive in nature, is connected across the output. Hence, the waveshape gets changed with the change of test object.

Analysis of the Other Impulse Circuits

The most commonly used configurations for impulse generators are the circuits shown in Fig. 6.2b and c. The advantages of these circuits are that the wave front and wave tail times are independently controlled by changing either R_1 or R_2 separately. Secondly, the test object which are mainly capacitive in nature from part of C_2 .

For the configuration shown in Fig. 6.2 b, the output voltage across C_2 is given by,

$v_o(t) = \frac{1}{C_2} \int_0^t i_2 dt$. Performing Laplace transformation, $\frac{1}{C_2 s} I_2(s) = v_o(s)$ where I_2 is the current through C_2 . Taking the current through C_1 as I_1 and its transformed value as $I_1(s)$,

$$I_2(s) = \left(\frac{R_2}{R_2 + \frac{1}{C_2 s}} \right) I_1(s) \text{ and } I_1(s) = \frac{V}{s} \frac{1}{\frac{R_1 + \frac{1}{C_1 s}}{R_2 + \frac{1}{C_2 s}}}$$

Substitution of $I_1(s)$ gives $v_o(s)$ and simplifying and taking inverse transform of

$$v_o(t) = \frac{V}{R_1 C_2 (\alpha - \beta)} [\exp(-\alpha t) - \exp(-\beta t)] \quad (6.20)$$

Usually, $\frac{1}{C_1 R_1}$ will be much smaller compared to $\frac{1}{R_1 C_2}$.

Hence, the roots may be approximated as

$$\alpha \approx \frac{1}{R_1 C_2} \text{ and } \beta = \frac{1}{R_2 C_1} \quad (6.21)$$

Following a similar analysis, it may be shown that the output waveform for the circuit

$$v_o(t) = \frac{V C R_1 \alpha \beta}{(\beta - \alpha)} [\exp(-\alpha t) - \exp(-\beta t)]$$

configuration of Fig. 6.2c will be

where α and β are the roots of the Eq. (6.19). The approximate values of α and β given by Eq. (6.21) are valid for this circuit also. The equivalent circuit given in Fig. 6.2d is a

combination of the configurations of Fig. 6.15b and 6.15c. The resistance R_1 is made into two parts and kept on either side R_2 to give greater flexibility for the circuits. The configuration of Fig. 6.15e is not commonly used. It is useful only for testing high inductance test objects such as transformers.

Restrictions on the Ratio of the Generator and Load Capacitance, C_1/C_2 on the Circuit Performance

For a given waveshape, the choice of R_1 and R_2 to control the wave front and wave tail times is not entirely independent but depends on the ratio of C_1/C_2 . It can be shown mathematically that $R_2 = P(y)/C_1$ and $R_1 = Q(y)/C_1$ where $y = C_1 C_2$ and P and Q are

functions of y . In order to get real values for R_1 and R_2 for a given waveshape, a maximum and minimum value of y exists in practice. This is true whether the configuration of Fig. 6.2b or 6.2c is used. For example, with the circuit of Fig. 6.15b, the ratio of C_1/C_2 cannot exceed 3.35 for a $1/5 \mu s$ waveshape. Similarly, for a $1/50 \mu s$ waveshape the ratio C_1/C_2 lies between 106.5. If the configuration chosen is 6.15c, the minimum value of C_1/C_2 for $1/5 \mu s$ waveshape is about 0.01. The reader is referred to High Voltage Laboratory Techniques by Craggs and Meek for further discussion on the restrictions imposed on the ratio C_1/C_2 .

Effect of Circuit Inductances and Series Resistance on the Impulse Generator Circuits

The equivalent circuits shown in Fig. 6.2 a to e, in practice several stray series inductances. Further, the circuits occupy considerable space and will be spread over several meters in testing laboratory. Each component has some residual inductances and the circuit loop itself contributes for further inductance. The actual value of the inductance may vary from $10 \mu H$ to several hundreds of microhenries. The effect of the inductance is to cause oscillations in the wave front and in the wave tail portions. Sometimes, in order to control the front time a small inductance is added.

Waveshape Control

Generally, for a given impulse generator of Fig. 6.2b or c the generator capacitance C_1 and load capacitance C_2 will be fixed depending on the design of the generator and the test object. Hence, the desired waveshape is obtained by controlling R_1 and R_2 . The following approximate analysis is used to calculate the wave front and wave tail times. The resistance R_2 will be large. Taking the circuit inductance to be negligible during charging, C_1 charges the load capacitance C_2 through R_1 . Then the time taken for charging is approximately three times the time constant of the circuit and is given by

$$t_1 = 3.0 R_1 \frac{C_1 C_2}{C_1 + C_2} = 3R_1 C_e \quad (6.22) \quad \text{where } C_e = \frac{C_1 C_2}{C_1 + C_2}. \quad \text{If } R_1 \text{ is}$$

given in ohms and C_e in microfarads, t_1 is obtained in microseconds.

For discharging or tail time, the capacitance C_1 and C_2 may be considered to be in parallel and discharging occurs R_1 and R_2 . Hence, the time for 50% discharge is approximately given by $t_2 = 0.7(R_1 + R_2)(C_1 + C_2)$ (6.23)

These formulae for t_1 and t_2 hold good for the equivalent circuits are shown in Fig. 6.2b and c. For the circuit given in Fig. 6.2d, R is to be taken as $2 R_1$. With the approximate formulae, the wave front and wave tail times can be estimated to within $\pm 20\%$ for the standard impulse waves.

6.4 GENERATION OF IMPULSE CURRENTS

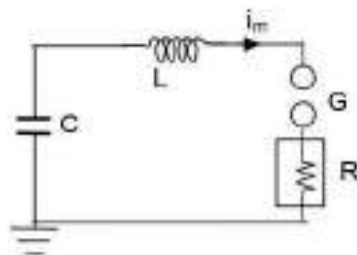
Lightning discharges involve both high voltage impulses and high current impulses on transmission lines. Protective gear like surge diverters have to discharge the lightning currents without damage. Therefore, generation of impulse current waveforms of high magnitude ($\approx 100\text{kA}$ peak) find application in testing work as well as in basic research on non-linear resistors, electric arc studies, and studies relating to electric plasmas in high current discharges.

6.4.1 Definition of Impulse Current Waveforms

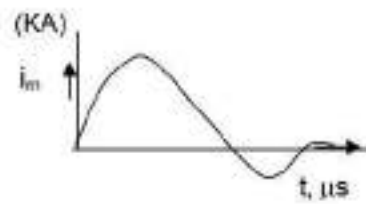
The waveshape used in testing surge diverters are 4/10 and 8/20 μs , the figures respectively representing the nominal wave front and wave tail times (see Fig. 6.14). the tolerances allowed on these times are $\pm 10\%$ only. Apart from the standard impulse current, waves, rectangular waves of long duration are also used for testing. The waveshape should be nominally rectangular in shape. The rectangular waves generally have durations of the order of 5.0 ms, with rise and fall times of the order of 0.5 to 5.0 ms, with rise and fall times of the waves being less than $\pm 10\%$ of their total duration. The tolerance allowed on the peak value is $+20\%$ and -0% (the peak value may be more than the specified value but not less). The duration of the wave is at least defined as the total time of the wave during which the current is least 10% of its peak value.

6.4.2 Circuits for Producing Impulse Current Waves

For producing impulse currents of large value, a bank of capacitors connected in parallel are charged to a specified value and are discharged through a series R-L circuit as shown in Fig. 6.20.



(a) Basic circuit of an impulse current generator



(b) Impulse current waveform

Fig. 6.3 Impulse current generator circuit and its waveform

C represents a bank of capacitors connected in parallel which are charged from a d.c. source to a voltage up to 200 kV. R represents the dynamic resistance of the test object and the resistance of the circuit and the shunt. L is an air cored high current inductor, usually a spiral tube of a few turns.

If the capacitor is charged to a voltage V and discharged when the spark gap is triggered, the current i_m will be given by the equation

$$V = Ri_m + L \frac{di_m}{dt} + \frac{1}{C} \int_0^t i_m dt \quad (6.24)$$

The circuit is usually under damped, so that $\frac{R}{2} < \sqrt{\frac{L}{C}}$. Hence i_m is given by,

$$i_m = \frac{V}{\omega L} e^{-\alpha t} \sin(\omega t) \text{ where } \alpha = \frac{R}{2L} \text{ and } \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

The time taken for the current i_m to rise from zero to the first peak value is

$$t_1 = t_f = \frac{1}{\omega} \sin^{-1} \frac{\omega}{\sqrt{LC}} \quad (6.26)$$

The duration for one half cycle of the damped oscillatory wave t_2 is,

$$t_2 = \frac{\pi}{\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}} \quad (6.27)$$

It can be shown that the maximum value of i_m normally independent of the value of V C

for a given energy $W = \frac{1}{2} CV^2$, and the effective inductance L. It is also clear from Eq.

(6.25) that a low inductance is needed in order to get high current magnitudes for a given charging voltage V.

For an 8/20 μs standard impulse current wave $a = 0.0535 \times 10^6$ and $\omega = 0.113 \times 10^6$ when R, L and C are expressed in ohms, microhenries, and microfarads respectively. The product of LC=65. Hence, knowing the value of the generator capacitance, L can be

calculated as $L=65/C$, and R can be obtained from Eq. (6.25a) as $R=2 L\alpha$. The peak value of $i_n = I_p$ is given by $(VC)/14$ when V is kV, I_p in kilo-amperes, and C in microfarads.

6.4.3 Generation of High Impulse Currents

For producing large values of impulse currents, a number of capacitors are charged in parallel and discharge in parallel into the circuit. In order to minimize the effective inductance, the capacitors are subdivided into smaller units.

If there are n_1 groups of capacitors, each consisting of n_2 units and if L_0 is the inductance of the common discharge path, L_1 is that of each group and L_2 is that of each unit, then

the effective inductance L is given by
$$L = L_0 + \frac{L_1}{n} + \frac{L_2}{n_1 n_2}$$

Also, the arrangement of capacitors into a horse-shoe layout minimizes the effective load inductance.

The essential parts of an impulse current generator are:

- (i) a.d.c charging unit giving a variable voltage to the capacitor bank,
- (ii) capacitors of high value (0.5 to 5 μF) each with very low self inductance,

7.Measurement of High Voltages and Currents

The devices and instruments for measurement of high voltages and currents differ vastly from the low voltage and low current devices.

7.1 MEASUREMENT OF HIGH DIRECT CURRENT VOLTAGES

High voltages can be measured in a variety of ways. Direct measurement of high voltages is possible up to about 200 kV, and several forms of voltmeters have been devised which can be connected directly across the test circuit. High Voltages are also measured by stepping down the voltage by using transformers and potential dividers. The sparkover of sphere gaps and other gaps are also used, especially in the calibration of meters in high voltage measurements. Transient voltages may be recorded through potential dividers and oscilloscopes.

Lightning surges may be recorded using the Klydonograph.

Direct Measurement of High Voltages

7.1.1 Electrostatic Voltmeters

Principle is used in electrostatic voltmeter?

If the electric field is produced by the voltage V between a pair of parallel plate disc electrodes, the force F on an area A of the electrode, for which the field gradient E is the same across the area and perpendicular to the surface.

One of the direct methods of measuring high voltages is by means of electro-static voltmeters. For voltages above 10 kV, generally the attracted disc type of electrostatic voltmeter is used.

When two parallel conducting plates (cross section area A and spacing x) are charged q and have a potential difference V , then the energy stored in the is given by

Energy stored $W = \frac{1}{2} C V^2$ so that change $dW = \frac{1}{2} V^2 dC = F dx$

Force $F = \frac{1}{2} V^2 (dC/dx)$ Newton = $\frac{1}{2} A \epsilon (V^2/x^2)$.

It is thus seen that the force of attraction is proportional to the square of the potential difference applied, so that the meter reads the square value (or can be marked to read the rms value).

Electrostatic voltmeters of the attracted disc type may be connected across the high voltage circuit directly to measure up to about 200 kV, without the use of any potential divider or other reduction method. [The force in these electrostatic instruments can be used to measure both a.c. and d.c. voltages].

7.1.2 Sphere gaps

The sphere gap method of measuring high voltage is the most reliable and is used as the standard for calibration purposes. The breakdown strength of a gas depends on the ionisation of the gas molecules, and on the density of the gas. As such, the breakdown voltage varies with the gap spacing; and for a uniform field gap, a high consistency could be obtained, so that the sphere gap is very useful as a measuring device. By precise experiments, the breakdown voltage variation with gap spacing, for different diameters and distances, have been calculated and represented in charts. In the measuring device, two metal spheres are used, separated by a gas-gap. The potential difference between the spheres is raised until a spark passes between them. The breakdown strength of a gas depends on the size of the spheres, their distance apart and a number of other factors. A spark gap may be used for the determination of the peak value of a voltage wave, and

for the checking and calibrating of voltmeters and other voltage measuring devices. The density of the gas (generally air) affects the spark-over voltage for a given gap setting. Thus the correction for any air density change must be made. The air density correction factor $\delta = 0.386P/(273+t)$

The spark over voltage for a given gap setting under the standard conditions (760 torr pressure and at 20°C) must be multiplied by the correction factor to obtain the actual spark-over voltage.

The breakdown voltage of the sphere gap (figure 6.2) is almost independent of humidity of the atmosphere, but the presence of dew on the surface lowers the breakdown voltage and hence invalidates the calibrations.

The breakdown voltage characteristic (figure 6.3) has been determined for similar pairs of spheres (diameters 62.5 mm, 125 mm, 250 mm, 500 mm, 1 m and 2 m)

When the gap distance is increased, the uniform field between the spheres becomes distorted, and accuracy falls.

The limits of accuracy are dependant on the ratio of the spacing d to the sphere diameter D , as follows. $d < 0.5 D$, accuracy = $\pm 3\%$; $0.75 D > d > 0.5 D$, accuracy = $\pm 5\%$

For accurate measurement purposes, gap distances in excess of $0.75D$ are not used.

The breakdown voltage characteristic is also dependant on the polarity of the high voltage sphere in the case of asymmetrical gaps (i.e. gaps where one electrode is at high voltage and the other at a low voltage or earth potential). If both electrodes are at equal high voltage of opposite polarity (i.e. $+\frac{1}{2} V$ and $-\frac{1}{2} V$), as in a symmetrical gap, then the polarity has no effect. Figure 6.4 shows these breakdown voltage variations. In the case of the asymmetrical gap, there are two breakdown characteristics; one for the positive high voltage and the other for the negative high voltage. Since the breakdown is caused by the flow of electrons, when the high voltage electrode is positive, a higher voltage is generally necessary for breakdown than when the high voltage electrode is negative. However, when the gaps are very far apart, then the positive and the negative characteristics cross over due to various space charge effects. But this occurs well beyond the useful operating region. Under alternating voltage conditions, breakdown will occur corresponding to the lower curve (i.e. in the negative half cycle under normal gap spacings). Thus under normal conditions, the a.c. characteristic is the same as the negative characteristic.

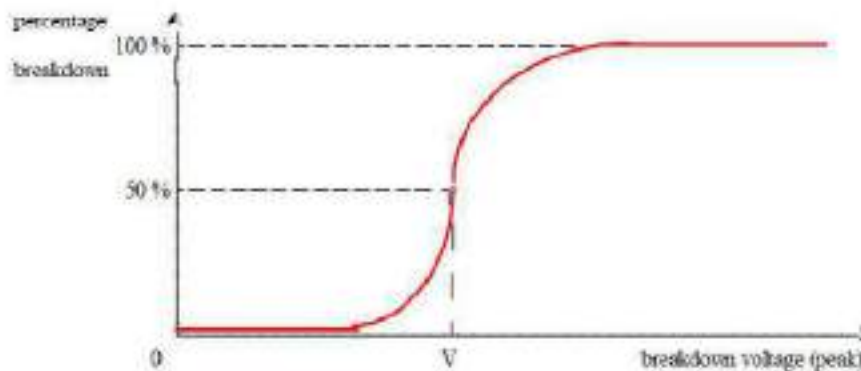
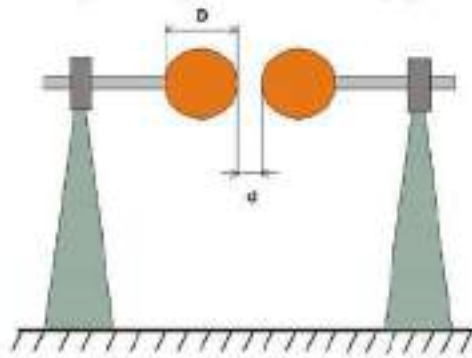
In sphere gaps used in measurement, to obtain high accuracy, the minimum clearance to be maintained between the spheres and the neighbouring bodies and the diameter of shafts are also specified, since these also affect the accuracy (figure 6.5). There is also a tolerance specified for the radius of curvature of the spheres. "The length of any diameter shall not differ from the correct value by more than 1% for spheres of diameter up to 100 cm or more than 2% for larger spheres". Peak values of voltages may be measured from 2 kV up to about 2500 kV by means of spheres. One sphere may be earthed with the other being the high voltage electrode, or both may be supplied with equal positive and negative voltages with respect to earth (symmetrical gap).

When spark gaps are to be calibrated using a standard sphere gap, the two gaps should not be connected in parallel. Equivalent spacing should be determined by comparing each gap in turn with a suitable indicating instrument.

Needle gaps may also be used in the measurement of voltages up to about 50 kV, but errors are caused by the variation of the sharpness of the needle gaps, and by the corona forming at the points before the gap actually sparks over. Also the effect of the variation of the humidity of the atmosphere on such gaps is much greater.

Usually, a resistance is used in series with the sphere gap, of about 1ohm/V sparkover conditions to about a maximum of 1 A.

However for impulse measurements, a series resistance must not be used since this causes a large drop across the resistance. In measuring impulse voltages, since the breakdown does not occur at exactly the same value of voltage each time, what is generally specified is the 50 % breakdown value. A number of impulses of the same value is applied and a record is kept of the number of times breakdown occurs, and a histogram is plotted with the peak value of the impulse voltage and the percentage of breakdown (figure 6.6).



The factors that are influencing the peak voltage measurement using sphere gap are (i)Nearby earthed objects (ii)Atmosphere conditions (iii)Influence of humidity (iii)Irradiation (iv)Polarity and rise time of voltage waveform (v)Switching surge

7.1.3 GENERATING VOLTMETER(GVM)

A generating voltmeter is a variable capacitor voltage generator which generates current proportional to the voltage to be measured. It provides loss free measurement of D.C and A.C voltages. It is driven by a synchronous motor and does not absorb power or energy from the voltage measuring source.

Whenever the source loading is not permitted or when direct connection to the high voltage source is to be avoided, the generating principle is employed for the measurement of high voltages, A generating voltmeter is a variable capacitor electrostatic voltage generator which generates current proportional to the voltage to be measured. Similar to electrostatic voltmeter the generating voltmeter provides loss free measurement of d.c. and a.c. voltages. The device is driven by an external constant speed motor and does not absorb power or energy from the voltage measuring source. The principle of operation is explained with the help of Fig. 4.8. *H* is a high voltage electrode and the earthed electrode is subdivided into a sensing or pick up electrode *P*, a guard electrode *G* and a movable electrode *M*, all of which are at the same potential. The high voltage electrode *H*

develops an electric field between itself and the electrodes P , G and M . The field lines are shown in Fig. 7.1. The electric field density ϵ is also shown. If electrode M is fixed and the voltage V is changed, the field density ϵ would change and thus a current $i(t)$ would flow between P and the ground.

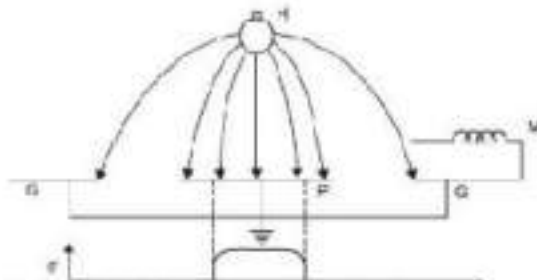


Fig.7.1 Principle of generating voltmeter

The high voltage electrode and the grounded electrode in fact constitute a capacitance system. The capacitance is, however, a function of time as the area A varies with time and, therefore, the charge $q(t)$ is given as $q(t)=C(t)V(t)$

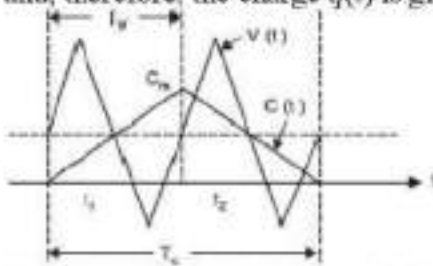


Fig. 7.2 Capacitance and voltage variation

Differentiating with respect to t gives $i(t)=dq/dt= V(dC/dt)$ for DC voltage application.

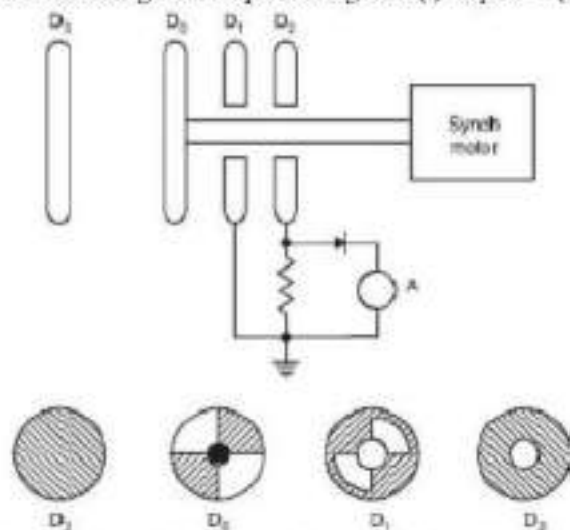


Fig.7.3 schematic diagram of a generating voltmeter

GVM shown in Fig.7.3 which employs rotating vanes for variation of capacitance. The high voltage electrode is connected to a disc electrode D_1 which is kept at a fixed distance on the axis of the other

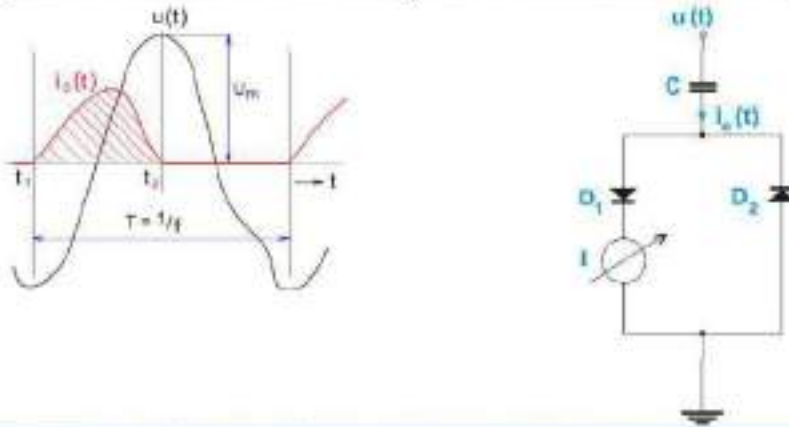
low voltage electrodes D_2 , D_1 , and D_0 . The rotor D_6 is driven at a constant speed by a synchronous motor at a suitable speed. The rotor vanes of D_3 cause periodic change in capacitance between the insulated disc D_2 and the high voltage electrode D_5 . The number and shape of vanes are so designed that a suitable variation of capacitance (sinusoidal or linear) is achieved. The a.c. current is rectified and is measured using moving coil meters. If the current is small an amplifier may be used before the current is measured.

Advantages of generating Voltmeter: (i) Scale is linear and extension of voltage range is easy (ii) Source loading is zero (iii) It can measure wide range of voltages (iv) There is no connection to H.V. electrode.

Disadvantage: (i) need calibration (ii) Careful construction is needed (iii) Disturbance in position and mounting of the electrodes make the calibration invalid.

7.2 THE CHUBB-FORTESCUE METHOD (for peak Ac HV measurement)

Simple and accurate method for the peak measurement of a.c. voltages.



Current through capacitor C:

$$i_C = C \frac{du}{dt}$$

Mean value of measured current:

$$I = \frac{1}{T} \int_{t_1}^{t_2} i_C dt = \frac{C}{T} [u(t_2) - u(t_1)] = \frac{C}{T} U_{pp}$$

Peak value of measured voltage:

$$U_m = \frac{I}{2Cf}$$

7.3 Voltage dividers

Voltage dividers for a.c., d.c. or impulse voltages may consist of resistors or capacitors or a convenient combination of these elements. Inductors are normally not used as voltage dividing elements as pure inductances of proper magnitudes without stray capacitance cannot be built and also these inductances would otherwise form oscillatory circuit with the inherent capacitance of the test object and this may lead to inaccuracy in measurement and high voltages in the measuring circuit. The height of a voltage divider depends upon the flash over voltage and this follows from the rated maximum voltage applied.

Now, the potential distribution may not be uniform and hence the height also depends upon the design of the high voltage electrode, the top electrode. For voltages in the megavolt range, the height of the divider becomes large. As a thumb rule following clearances between top electrode and ground may be assumed.

2.5 to 3 metres/MV for d.c. voltages.

2 to 2.5 m/MV for lightning impulse voltages.

More than 5 m/MV rms for a.c. voltages.

More than 4 m/MV for switching impulse voltage.

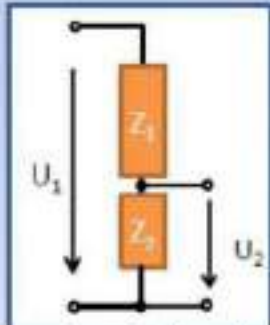
The divider dimensions are related to maximal applied voltage. The potential divider is most simply represented by two impedances Z_1 and Z_2 connected in series and the sample voltage required for measurement is taken from across Z_2 .

Divider ratio:

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

Resistive divider $\frac{U_2}{U_1} = \frac{R_2}{R_1 + R_2}$

Capacitive divider $\frac{U_2}{U_1} = \frac{C_1}{C_1 + C_2}$



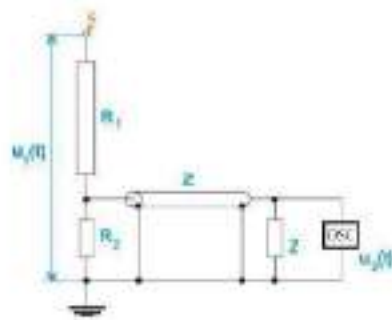
The voltage V_2 is normally only a few hundred volts and hence the value of Z_2 is so chosen that V_2 across it gives sufficient deflection on a CRO. Therefore, most of the voltage drop is available across the impedance Z_1 and since the voltage to be measured is in megavolt the length of Z_1 is large which result in inaccurate measurements because of the stray capacitances associated with long length voltage dividers (especially with impulse voltage measurements) unless special precautions are taken. On the low voltage side of the potential dividers where a screened cable of finite length has to be employed for connection to the oscillograph other errors and distortion of wave shape can also occur.

7.4 Resistive Dividers

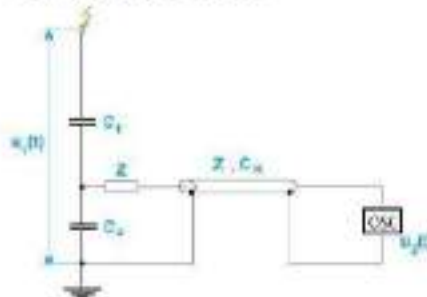
The resistance potential dividers are the first to appear because of their simplicity of construction, less space requirements, less weight and easy portability. These can be placed near the test object which might not always be confined to one location.

The length of the divider depends upon two or three factors. The maximum voltage to be measured is the first and if height is a limitation, the length can be based on a surface flash over gradient in the order of 3–4 kV/cm irrespective of whether the resistance R_1 is of liquid or wirewound construction. The length also depends upon the resistance value but this is implicitly bound up with the stray capacitance of the resistance column, the product of the two (RC) giving a time constant the value of which must not exceed the duration of the wave front it is required to record.

It is to be noted with caution that the resistance of the potential divider should be matched to the equivalent resistance of a given generator to obtain a given wave shape.

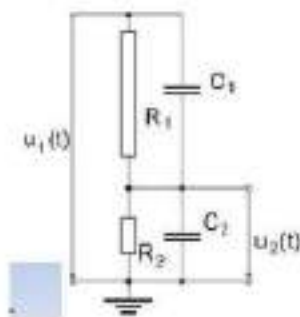


Capacitive Dividers



Capacitance potential dividers are more complex than the resistance type. For measurement of impulse voltages not exceeding 1 MV capacitance dividers can be both portable and transportable. In general, for measurement of 1 MV and over, the capacitance divider is a laboratory fixture. The capacitance dividers are usually made of capacitor units mounted one above the other and bolted together. It is this failure which makes the small dividers portable. A screening box similar to that described earlier can be used for housing both the low voltage capacitor unit C_2 and the matching resistor if required. The low voltage capacitor C_2 should be non-inductive. A form of capacitor which has given excellent results is of mica and tin foil plate, construction, each foil having connecting tags coming out at opposite corners. This ensures that the current cannot pass from the high voltage circuit to the delay cable without actually going through the foil electrodes. It is also important that the coupling between the high and low voltage arms of the divider be purely capacitive. Hence, the low voltage arm should contain one capacitor only; two or more capacitors in parallel must be avoided because of appreciable inductance that would thus be introduced. Further, the tapings to the delay cable must be taken off as close as possible to the terminals of C_2 .

7.5 RC Voltage Divider



$$Z_1 = \frac{R_1}{1 + j\omega C_1 R_1} \quad Z_2 = \frac{R_2}{1 + j\omega C_2 R_2}$$

$$\frac{U_2}{U_1} = \frac{\omega C_1 R_1 - jR_2}{\omega R_1 R_2 (C_1 + C_2) - j(R_1 + R_2)}$$

$$\operatorname{Im} \left(\frac{U_2}{U_1} \right) = \frac{\omega R_1 R_2 (C_1 R_1 - C_2 R_2)}{(R_1 + R_2)^2 + \omega^2 R_1^2 R_2^2 (C_1 + C_2)^2} = 0$$

$$\Rightarrow C_1 R_1 = C_2 R_2$$

7.6 MEASUREMENT OF HIGH D.C., AND IMPULSE CURRENTS

High currents are used in power system for testing circuit breakers, cables lightning arresters etc. and high currents are encountered during lightning discharges, switching transients and short faults. These currents require special techniques for their measurements.

7.6.1 High Direct Currents

Low resistance shunts are used for measurement of these currents. The voltage drop across the shunt resistance is measured with the help of a milli-voltmeter. The value of the resistance varies usually between 10 microhm and 13 milliohm. This depends upon the heating effect and the loading permitted in the circuit. The voltage drop is limited to a few millivolts usually less than 1 V. These resistances are oil immersed and are made as three or four terminal resistances to provide separate terminals for voltage measurement for better accuracy.

7.6.2 Hall Generators

Hall effect is used to measure very high direct current. Whenever electric current flows through a metal plate placed in a magnetic field perpendicular to it, Lorentz force will deflect the electrons in the metal structure in a direction perpendicular to the direction of both the magnetic field and the flow of current. The charge displacement results in an e.m.f. in the perpendicular direction called the Hall voltage. The Hall voltage is proportional to the current I , the magnetic flux density B and inversely proportional to the plate thickness d i.e., $V_H = RBI/d$

where R is the Hall coefficient which depends upon the material of the plate and temperature of the plate. For metals the Hall coefficient is very small and hence semiconductor materials are used for which the Hall coefficient is high.

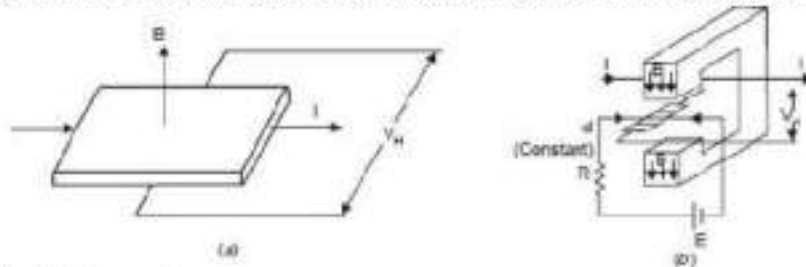


Fig. Hall generator
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When large d.c. currents are to be measured the current carrying conductor is passed through an iron cored magnetic circuit (Fig. (b)). The magnetic field intensity produced by the conductor in the air gap at a depth d is given by $H = I/(2\pi d)$

The Hall element is placed in the air gap and a small constant d.c. current is passed through the element. The voltage developed across the Hall element is measured and by using the expression for Hall voltage the flux density B is calculated and hence the value of current I is obtained.

7.6.3 High Power Frequency Currents

High Power frequency currents are normally measured using current transformers as use of low resistance shunts involves unnecessary power loss. Besides, the current transformers provide isolation from high voltage circuits and thus it is safer to work on HV circuits Fig. below shows a scheme for current measurements using current transformers and electro-optical technique.

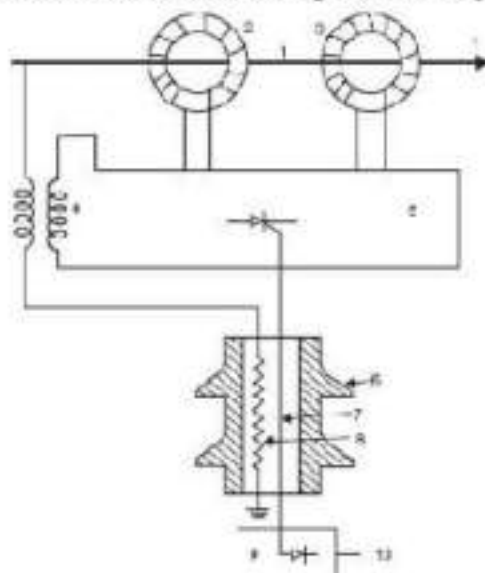


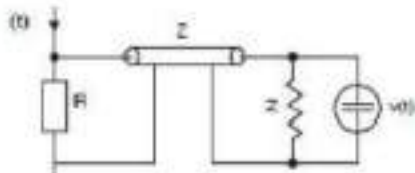
Fig. Current transformers and electro-optical system for high a.c. current measurements

A voltage signal proportional to the current to be measured is produced and is transmitted to the ground through the electro-optical device. Light pulses proportional to the voltage signal are transmitted by a glass optical fibre bundle to a photodetector and converted

back into an analog voltage signal. The required power for the signal convertor and optical device are obtained from suitable current and voltage transformers.

7.6.4 High Frequency and Impulse Currents

In power system the amplitude of currents may vary between a few amperes to a few hundred kiloamperes and the rate of rise of currents can be as high as $10^{10} A/sec$ and the rise time can vary between a few micro seconds to a few macro seconds. Therefore, the device to be used for measuring such currents should be capable of having a good frequency response over a very wide frequency band. The methods normally employed are—(i) resistive shunts; (ii) elements using induction effects; (iii) Faraday and Hall effect devices. With these methods the accuracy of measurement varies between 1 to 10%. Fig. shows the circuit diagram of the most commonly used method for high impulse current measurement. The voltage across the shunt resistance R due to impulse current $i(t)$ is fed to the oscilloscope through a delay cable D . The delay cable is terminated through an impedance Z equal to the surge impedance of the cable to avoid reflection of the voltage to be measured and thus true measurement of the voltage is obtained. Since the dimension of the resistive element is large, it will have residual inductance L and stray capacitance C . The inductance could be neglected at low frequencies but at higher frequencies the inductive reactance would be comparable with the resistance of the shunt. The effect of inductance and capacitance above 1 MHz usually should be considered. The resistance values range between 10 micro ohm to a few milliohms and the voltage drop is of the order of few volts. The resistive shunts used for measurements of impulse currents of large duration is achieved only at considerable expense for thermal reasons. The resistive shunts for impulse current of short duration can be built with rise time of a few nano seconds of magnitude. The resistance element can be made of parallel carbon film resistors or low inductance wire resistors of parallel resistance wires or resistance foils.



Assuming the stray capacitance to be negligibly small the voltage drop across the shunt in complex frequency domain may be written as $V(s) = I(s)[R + Ls]$

It is to be noted that in order to have flat frequency response of the resistive element the stray inductance and capacitance associated with the element must be made as small as possible. In order to minimise the stray field effects following designs of the resistive elements have been suggested and used

1. Bifilar flat strip shunt.
2. Co-axial tube or Park's shunt
3. Co-axial squirrel cage shunt.

The bifilar flat strip shunts suffer from stray inductance associated with the resistance element and its potential leads are linked to a small part of the magnetic flux generated by the current that is being measured. In order to eliminate the problems associated with the bifilar shunts, coaxial shunts were developed. Here the current enters the inner cylinder of the shunt element and returns through an outer cylinder. The space between the two

cylinders is occupied by air which acts like a perfect insulator. The voltage drop across the element is measured between the potential pick up point and the outer case. The frequency response of this element is almost a flat characteristic upto about 1000 MHz and the response time is a few nanoseconds. The upper frequency limit is governed by the skin effect in the sensitive element.

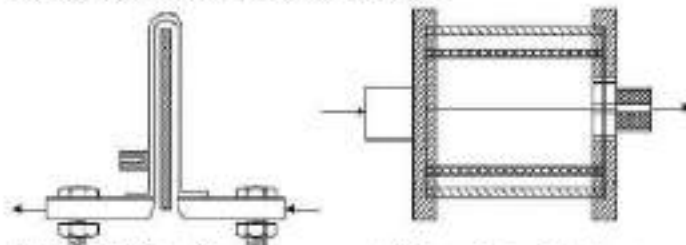


Fig. (i) Bifilar flat strip; (ii) Co-axial squirrel cage

Squirrel cage shunts are high ohmic shunts which can dissipate larger energies as compared to coaxial shunts which are unsuitable due to their limitation of heat dissipation, larger wall thickness and the skin effect. Squirrel cage shunt consists of thick metallic rods or strips placed around the periphery of a cylinder and the structure resembles the rotor construction of a double squirrel cage induction motor. The step response of the element is peaky and, therefore, a compensating network is used in conjunction with the element to improve its frequency response. Rise times less than 8 ns and band width of 400 MHz have been obtained with these shunts.

7.6.5 Elements using Induction Effects (Rogowski coil)

If the current to be measured is flowing through a conductor which is surrounded by a coil as shown in Fig., and M is the mutual inductance between the coil and the conductor, the voltage across the coil terminals will be: $v(t) = M(di/dt)$

Usually the coil is wound on a non-magnetic former in the form of a toroid and has a large number of turns, to have sufficient voltage induced which could be recorded. The coil is wound criss-cross to reduce the leakage inductance. If M is the number of turns of the coil, A the coil area and lm its mean length, the mutual inductance is given by

$$M = \mu_0 NA^2 / lm$$

Usually an integrating circuit RC is employed as shown in Fig. to obtain the output voltage proportional to the current to be measured. The output voltage is given by $v_o(t) = Mi(t)/(RC)$

Integration of $v(t)$ can be carried out more elegantly by using an appropriately wired operational amplifier. The frequency response of the Rogowski coil is flat upto 100 MHz but beyond that it is affected by the stray electric and magnetic fields and also by the skin effect.

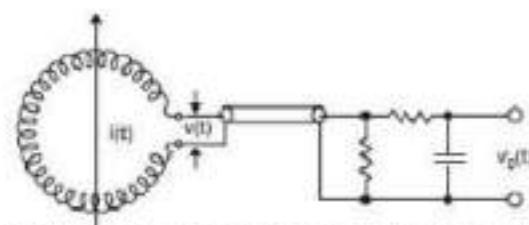


Fig. Rogowski coil for high impulse current measurements

7.6.6 Magnetic Links

These are used for the measurement of peak magnitude of the current flowing in a conductor. These links consist of a small number of short steel strips on high retentivity. The link is mounted at a known distance from the current carrying conductor. It has been found through experiments that the remanant magnetism of the link after impulse current of 0.5/5 micro sec shape passes through the conductor is same as that caused by a direct current of the same peak value. Measurement of the remanance possessed by the link after the impulse current has passed through the conductor enables to calculate the peak value of the current. For accurate measurements, it is usual to mount two or more links at different distances from the same conductor. Because of its relative simplicity, the method has been used for measurement of lightning current especially on transmission towers.

It is to be noted that the magnetic links help in recording the peak value of the impulse current but gives no information regarding the wave shape of the current. For this purpose, an instrument called Fulcronograph has been developed which consists of an aluminium wheel round the rim of which are slots containing magnetic links of sufficient length to project on both sides of the wheel. As the wheel is rotated, the links pass successively through a pair of narrow coils through which flows the current to be measured. The current at the instant during which a particular link traverses the coil, can be determined by a subsequent measurement of the residual flux in the link and, therefore, a curve relating the variation of current with time can be obtained. The time scale is governed by the speed of rotation of the wheel.

Hall Generators

The high amplitude a.c. and impulse currents can be measured by Hall Generator described earlier. For the Hall Generator, though a constant control current flows which is permeated by the magnetic field of the current to be measured, the Hall voltage is directly proportional to the measuring current. This method became popular with the development of semi-conductor with sufficient high value of Hall constant. The band width of such devices is found to be about 50 MHz with suitable compensating devices and feedback.