3.2 MULTISTAGE IMPULSE VOLTAGE GENERATOR

The difficulties encountered with spark gaps for the switching of very high voltages, the increase of the physical size of the circuit elements, the efforts Generation of high voltages 61necessary in obtaining high dace. voltages to charge C1 and, last but not least, the difficulties of suppressing corona discharges from the structure and leads during the charging period make the one-stage circuit inconvenient for higher voltages. In order to overcome these difficulties, in 1923 Marx35 suggested an arrangement where a number of condensers are charged in parallel through high ohmic resistances and then discharged in series through spark gaps. There are many different, although always similar, multistage circuits in use. To demonstrate the principle of operation, a typical circuit is presented in Figure 3.2.1 which shows the connections of a six-stage generator. The dace. Voltage charges the equal stage capacitors C01 in parallel through the high value charging resistors R0 as well as through the discharge (and also charging).

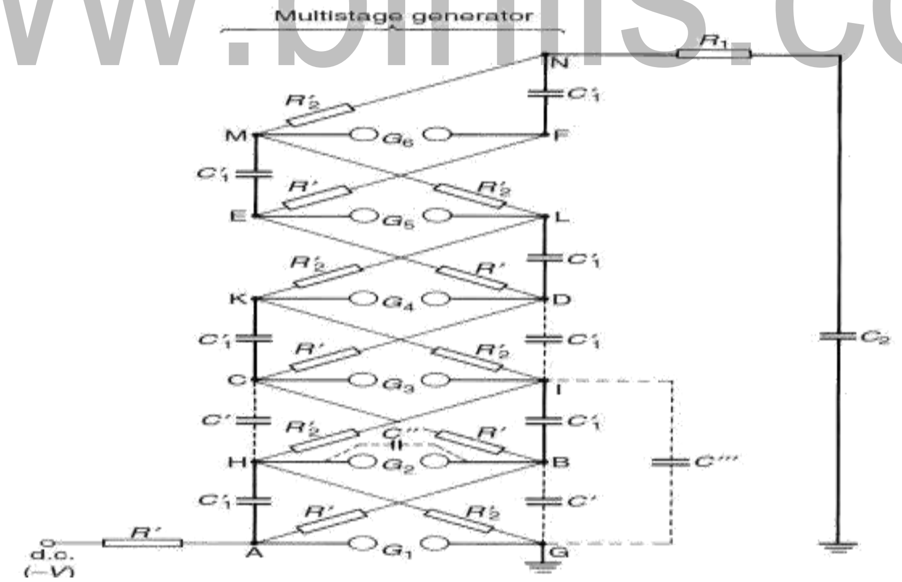


Figure 3.2.1 Basic circuit of a six-stage impulse generator (Marx generator) resistances

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 354]

As the point B still would remain at the charging potential, _V, thus a voltage of 2V would appear across G2. This high overvoltage would therefore cause this gap to break down and the potential at point I would rise to C2V, creating a potential difference of 3V across gapG3, if again the potential at point C would remain at the charging potential.This traditional interpretation, however, is wrong, since the potentials B and C can – neglecting stray capacitances – also follow the adjacent potentials of the points A and B, as the resistors R0 are between. We may only see up to now that this circuit will give an output voltage with a polarity opposite to that of the charging voltage. In practice, it has been noted that the gap G2 must be set to a gap distance only slightly greater than that at which G1 breaks down; otherwise it does not operate.

According to Edwards and Perry for an adequate explanation one may assume the stray capacitances C0, C00 and C000 within the circuit. The capacitances C0 are formed by the electrical field between adjacent stages; C000 has a similar meaning across two stages. C00 is the capacitance of the spark gaps. If we assume now the resistors as open circuits, we may easily see that the potential at point B is more or less fixed by the relative magnitudes of the stray capacitances. Neglecting C0 between the points Hand C and taking into account that the discharge capacitors C01 are large in comparison to the stray capacitances, point B can be assumed as mid-point of a capacitor voltage divider formed by C00 and C0/C000. Thus the voltage rise of point A from _V to zero will cause the potential B to rise from V to a voltage of

$$V_B = -V + V\left(\frac{C''}{C' + C'' + C'''}\right) = -V\left(\frac{C' + C'''}{C' + C'' + C'''}\right)$$

Hence the potential difference across G_2 becomes

$$V_{G2} = +V - (-V_B) = V\left(1 + \frac{C' + C'''}{C' + C'' + C'''}\right).$$

If C00 equals zero, the voltage across G2 will reach its maximum value 2V.This gap capacitance, however, cannot be avoided. If the stage capacitancesC0 and C000 are both zero, VG2 will equal V, and a sparking of G2 would not be possible. It is apparent, therefore, that these stray capacitances enhance favorable conditions for the operation of the generator. In reality, the conditions set by the above equations are approximate only and are, of course, transient, as the stray capacitances start to discharge via the resistors. As the values of C0 to C000 are normally in the order of some 10 pF only, the time constants for this discharge may be as low as 10_7 to 10_8 sec. Thus the voltage across G2 appears for a short time and leads to breakdown within several tens of nanoseconds. Transient over voltages appear across the further gaps, enhanced also by the fact that the output terminal N remains at zero potential mainly, and therefore additional voltages are built up across the resistor R02. So the breakdown continues and finally the terminal N attains a voltage of C6V, or nV, if n stages are present.

The processes associated with the firing of such generators are even more sophisticated. They have been thoroughly analyzed and investigated experimentally.31,36,37_In practice for a consistent operation it is necessary to set the distance for the first gap G1 only slightly below the second and further gaps for earliest breakdown. It is also necessary to have the axes of the gaps in one vertical plane so that the ultraviolet illumination from the spark in the first gap irradiates the other gaps. This ensures a supply of electrons released from the gap to initiate breakdown during the short period when the gaps are subjected to the overvoltage.

If the first gap is not electronically triggered, the consistency of its firing and stability of breakdown and therefore output voltage is improved by providing ultraviolet illumination for the first gap. These remarks indicate only a small part of the problems involved with the construction of spark gaps and the layout of the generator.

The wave front control resistor R1 is placed between the generator and the load only. Such a single 'external' front resistor, however, has to withstand for a short time the full rated voltage and therefore is inconveniently long or may occupy much space. This disadvantage can be avoided if either a part of this resistance is distributed or if it is completely distributed within the generator. Such an arrangement is illustrated in Fig. 2.30, in which in addition the series connection of the capacitors C01 and gaps (as proposed originally byGoodlet_38_) is changed to an equivalent arrangement for which the polarity of the output voltage is the same as the charging voltage. The charging resistorsR0 are always large compared with the distributed resistors R01and R02, andR02is made as small as is necessary to give the required time to halve-valueT2.

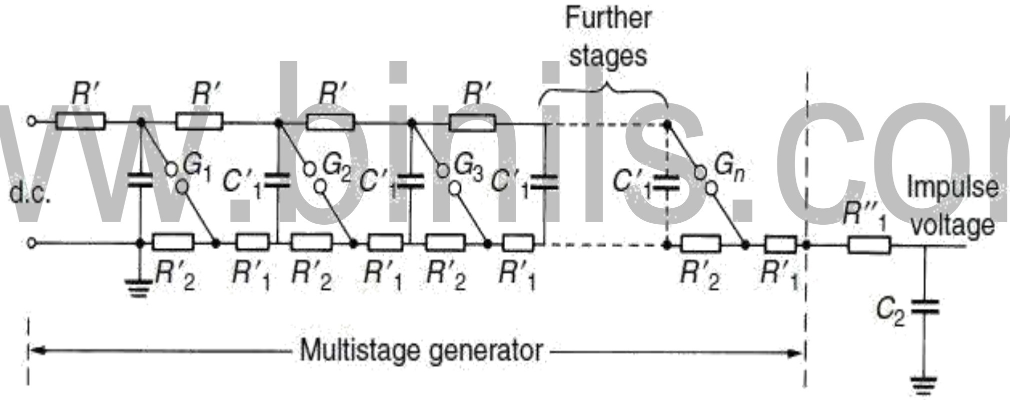


Figure 3.2.2 Multistage impulse generator with distributed discharge and front Resistors

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 381]

R02: discharge resistors. R01: internal front resistors. R001: external front resistorexcited by the inductance and capacitance of the external leads between the generator and the load, if these leads are long. If the generator has fired, the total is charge capacitance C1 maybe calculated as where n is the number of stages. The consistent firing of such circuits could be explained as for the generator.

3.4 CASCADED TRANSFORMERS

For voltages higher than 400 KV, it is desired to cascade two or more transformers depending upon the voltage requirements. With this, the weight of the whole unit is subdivided into single units and, therefore, transport and erection becomes easier. Also, with this, the transformer cost for a given voltage may be reduced, since cascaded units need not individually possess the expensive and heavy insulation required in single stage transformers for high voltages exceeding 345 kV. It is found that the cost of insulation for such voltages for a single unit becomes proportional to square of operating voltage. Fig. 3.9 shows a basic scheme for cascading three transformers. The primary of the first stage transformer is connected to a low voltage supply. A voltage is available across the secondary of this transformer. The tertiary winding (excitation winding) of first stage has the same number of turns as the primary winding, and feeds the primary of the second stage transformer.

The secondary winding of the second stage transformer is connected in series with the secondary winding of the first stage transformer, so that a voltage of 2V is available between the ground and the terminal of secondary of the second stage transformer. Similarly, the stage-III transformer is connected in series with the second stage transformer. With this the output voltage between ground and the third stage transformer, secondary is 3V. it is to be noted that the individual stages except the upper most must have three-winding transformers. The upper most, however, will be a two winding transformer. Figure shows metal tank construction of transformers and the secondary winding is not divided. Here the low voltage terminal of the secondary winding is connected to the tank. The tank of stage-I transformer is earthed.

The tanks of stage-II and stage-III transformers have potentials of V and 2V, respectively above earth and, therefore, these must be insulated from the earth with suitable solid insulation. Through h.t. bushings, the leads from the tertiary winding and the h.v. winding are brought out to be connected to the next stage transformer. However, if the high voltage windings are of mid-point potential type, the tanks are held at 0.5 V, 1.5 V and 2.5 V, respectively. This connection results in a cheaper construction and the high voltage insulation now needs to be designed for V/2 from its tank potential. The main disadvantage of cascading the transformers is that the lower stages of the primaries of the transformers are loaded more as compared with the upper stages. The loading of various windings is indicated by P in Figure 3.4.1 For the three-stage.

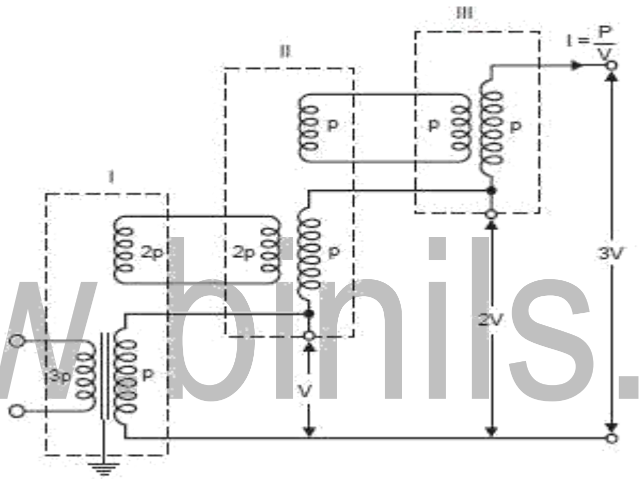


Figure 3.4.1 Basic 3 stage cascaded transform

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 302]

The primary winding of stage-III transformer is loaded with P and so also the tertiary winding of second stage transformer. Therefore, the primary of the second stage transformer would be loaded with 2P.Extending the same logic; it is found that the first stage primary would be loaded with P. Therefore, while designing the primaries and tertiary's of these transformers, this factor must be taken into consideration. The total short circuit impedance of a cascaded transformer from data for individual stages can be obtained.

The equivalent circuit of an individual stage is shown in Figure 3.4.1.Here Zp, Zs, and Zt, are the impedances associated with each winding. The impedances are shown in series with an ideal 3-winding transformer with corresponding number of turns Np, Ns and Nt. The impedances are obtained either from calculated or experimentally-derived results of the three short circuit tests between any two windings taken at a time.

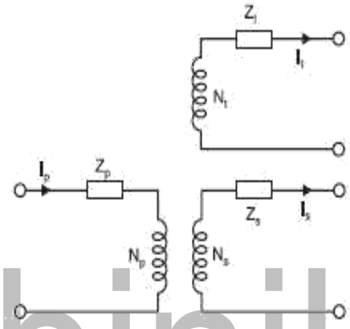


Figure 3.4.2 Equivalent circuit of one stage

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 315]

- Let *Zps* = leakage impedance measured on primary side with secondary short circuited and tertiary open.
- *Zpt* = leakage impedance measured on primary side with tertiary short circuited and secondary open.
- *Zst* = leakage impedance on secondary side with tertiary short circuited and primary open.

3.5 RESONANT TRANSFORMER

The equivalent circuit of a single-stage-test transformer along with its capacitive load is shown in Figure 3.5.1 Here $L1$ represents the inductance of the voltage regulator and the transformer primary, L the exciting inductance of the transformer, $L2$ the inductance of the transformer secondary and C the capacitance of the load. Normally inductance L is very large as compared to $L1$ and $L2$ and hence its shunting effect can be neglected. Usually the load capacitance is variable and it is possible that for certain loading, resonance may occur in the circuit suddenly and the Current will then only be limited by the resistance of the circuit and the voltage across the test specimen may go up as high as 20 to 40 times the desired value. Similarly, presence of harmonics due to saturation of iron core of transformer may also result in resonance. Third harmonic frequencies have been found to be quite disastrous. With series resonance, the resonance is controlled at fundamental frequency and hence no unwanted resonance occurs.

The development of series resonance circuit for testing purpose has been very widely welcome by the cable industry as they faced resonance problem with test transformer while testing short lengths of cables. In the initial stages, it was difficult to manufacture continuously variable high voltage and high value reactors to be used in the series circuit and therefore, indirect methods to achieve this objective were employed. Fig. 3.15 shows a continuously variable reactor connected in the low voltage winding of the step up transformer whose secondary is rated for the full test voltage. $C2$ represents the load capacitance. If N is the transformation ratio and L is the inductance on the low voltage side of the transformer, then it is reflected with $N2\ L$ value on the secondary side (load side) of the transformer. For certain setting of the reactor, the inductive reactance may equal the capacitive reactance of the circuit, hence resonance will take place.

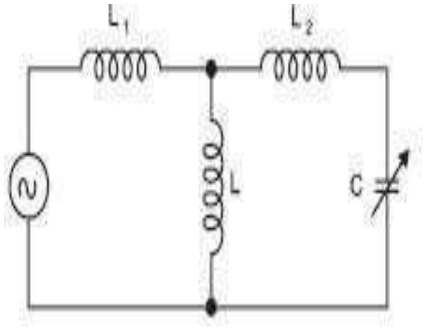


Figure 3.5.1 Equivalent circuit of a single stage loaded transformer

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 375]

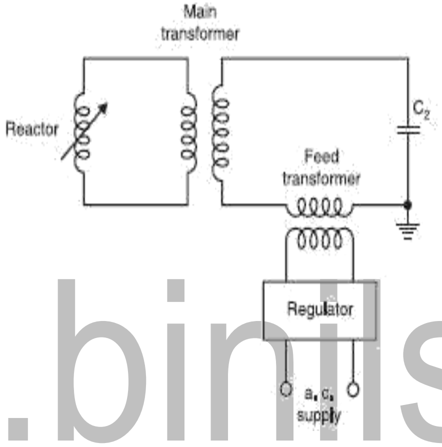


Figure 3.5.2 Single transformer/reactor series resonance circuit

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 395]

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 the high voltage side. This is a disadvantage of the method. The inductor are designed for high quality factors $Q = \omega L / R$. The feed transformer, therefore, injects the losses of the circuit only. It has now been possible to manufacture high voltage continuously variable reactors 300 kV per unit using a new technique with split iron core. With this, the testing step up transformer can be omitted as shown in Figure 3.5.2. The inductance of these inductors can be varied over a wide range depend upon the capacitance of the load to produce resonance. Here R is usually of low value. After the resonance condition is achieved, the output voltage can be increased by increasing the input voltage.

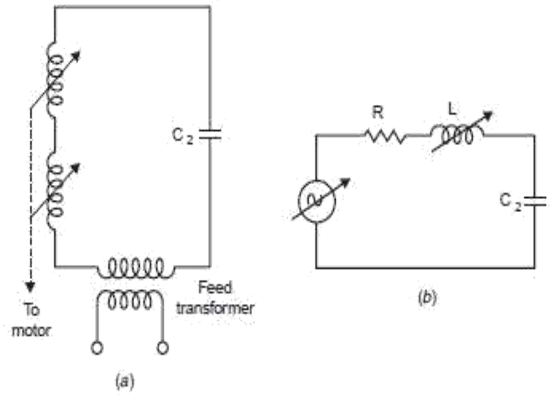


Figure 3.5.3 (a) Series resonance circuit with variable h.t. reactors (b) Equivalent circuit

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 405]

Figure 3.5.3 (b) represents an equivalent circuit for series resonance circuit. Here R is usually of low value. After the resonance condition is achieved, the output voltage can be increased by increasing the input voltage. The feed transformers are rated for nominal current ratings of the reactor. Under resonance, the output voltage will be Where Q is the quality factor of the inductor which usually varies between 40 and 80. This means that with Q = 40, the output voltage is 40 times the supply voltage.

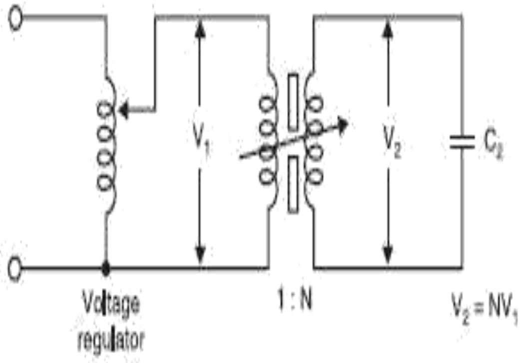


Figure 3.5.4 Parallel resonance system

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 415]

3.1 SINGLE-STAGE IMPULSIVE VOLTAGE GENERATOR CIRCUITS

The introduction to the full impulse voltages as defined in the previous section leads to simple circuits for the generation of the necessary wave shapes. The rapid increase and slow decay can obviously be generated by discharging circuits with two energy storages, as the wave shape may well be composed by the superposition of two exponential functions. Again the load of the generators will be primarily capacitive, as insulation systems are tested. This load will therefore contribute to the stored energy. A second source of energy could be provided by an inductance or additional capacitor. For lightning impulses mainly, a fast discharge of pure inductor is usually impossible, as h.v. chokes with high energy content can never be built without appreciable stray capacitances. Thus a suitable fast discharge circuit will always consist essentially of two capacitors. Single-stage generator circuits Two basic circuits for single-stage impulse generators are shown in Figure 3.1.1.The capacitor C_1 is slowly charged from a dace. source until the spark gap breaks down. This spark gap acts as a voltage-limiting and voltage-sensitive switch, whose ignition time (time to voltage breakdown) is very short in comparison to T_1. As such single-stage generators may be used for charging voltages from some kV up to about 1 MV, the sphere gaps) will offer proper operating conditions.

An economic limit of the charging voltage V0 is, however, a value of about 200 to 250 kV, as too large diameters of the spheres would otherwise be required to avoid excessive in homogeneous field distributions between the spheres. The resistors R_1, R_2 and the capacitance C_2 form the wave shaping network. R1 will primarily damp the circuit and control the front time T_1. R_2 will discharge the capacitors and therefore essentially control the wave tail.

The capacitance C_2 represents the full load, i.e. the object under test as well as all other capacitive elements which are in parallel to the test object (measuring devices; additional load capacitor to avoid large variations of T_1/T_2, if the test objects are changed). No inductances are assumed so far, and are neglected in the first fundamental analysis, which is also necessary to understand multistage generators. In general this approximation is permissible, as the inductance of all circuit elements has to be kept as low as possible. Within the ‘discharge’ capacitance C_1. As C1 is always much larger than C_2, this figure determines mainly the cost of a generator. For the analysis we may use the Laplace transform circuit sketched .which simulates the boundary condition, that for t 0 C1 is charged to V0 and for t > 0 this capacitor is directly connected to the wave shaping network. For the circuit Fig. 3.21(a) the output voltage is thus given by the expression.

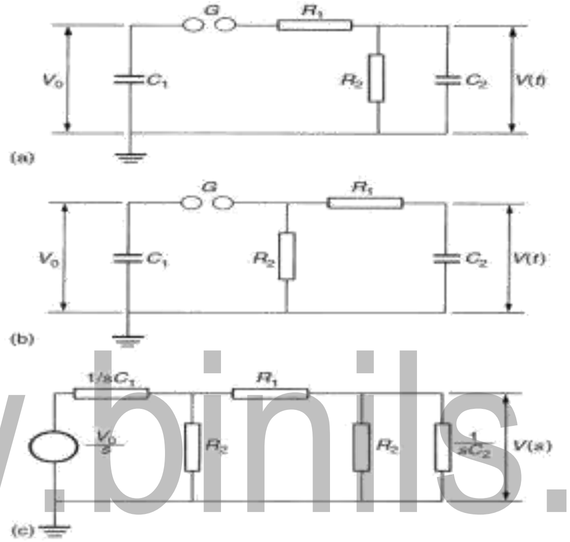
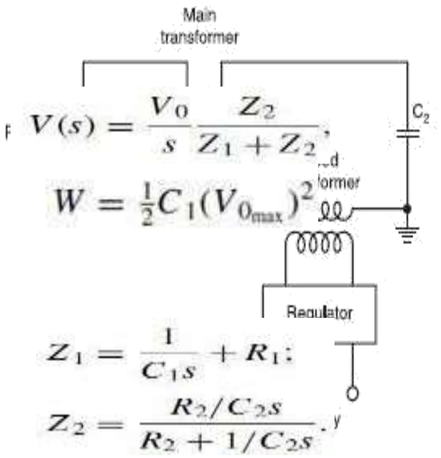


Figure 3.1.1 Single-stage impulse generator circuits (a) and (b). C1: discharge capacitance. C2 : load capacitance. R1 : front or damping resistance. R2 : discharge resistance. (c) Transform circuit Before starting the analysis, we should mention the most significant parameter of impulse

[Source: “High Voltage Engineering” by C.L. Wadhwa , Page – 425]



$$V(s) = \frac{V_0}{s}\frac{Z_2}{Z_1 + Z_2},$$

$$W = \tfrac{1}{2}C_1(V_{0_{\max}})^2$$

Where

$$Z_1 = \frac{1}{C_1 s} + R_1;$$

$$Z_2 = \frac{R_2/C_2 s}{R_2 + 1/C_2 s}.$$

Where,

$$a = \left(\frac{1}{R_1C_1} + \frac{1}{R_1C_2} + \frac{1}{R_2C_2}\right);$$
$$b = \left(\frac{1}{R_1R_2C_1C_2}\right);$$
$$k = R_1C_2.$$

For circuit Fig. (b) one finds the same general expression eqn , with the following constants; however,

$$a = \left(\frac{1}{R_1C_1} + \frac{1}{R_1C_2} + \frac{1}{R_2C_1}\right);$$
$$\left.\begin{aligned} b &= \left(\frac{1}{R_1R_2C_1C_2}\right); \\ k &= R_1C_2. \end{aligned}\right\} \text{ as above}$$
$$\alpha_1, \alpha_2 = \frac{a}{2} \mp \sqrt{\left(\frac{a}{2}\right)^2 - b}.$$

For both circuits, therefore, we obtain from the transform tables the same expression in the time domain:

$$V(t) = \frac{V_0}{k}\frac{1}{(\alpha_2 - \alpha_1)}[\exp(-\alpha_1 t) - \exp(-\alpha_2 t)]$$

Although one might assume that both circuits are equivalent, a larger difference may occur if the voltage efficiency, 5, is calculated. This efficiency is defined as

$$\eta = \frac{V_p}{V_0};$$

$$\eta = \frac{(\alpha_2/\alpha_1)^{-[(\alpha_2/\alpha_1-\alpha_1)]} - (\alpha_2/\alpha_1)^{-[(\alpha_2/\alpha_2-\alpha_1)]}}{k(\alpha_2-\alpha_1)}.$$

$$R_1 = \frac{1}{2C_1}\left[\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right) - \sqrt{\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)^2 - \frac{4(C_1+C_2)}{\alpha_1\alpha_2 \cdot C_2}}\right].$$

$$R_2 = \frac{1}{2(C_1+C_2)}\left[\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right) + \sqrt{\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)^2 - \frac{4(C_1+C_2)}{\alpha_1\alpha_2 C_2}}\right].$$

Circuit Fig. 2.25(b):

$$R_1 = \frac{1}{2C_2}\left[\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right) - \sqrt{\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)^2 - \frac{4(C_1+C_2)}{\alpha_1\alpha_2 C_1}}\right].$$

$$R_2 = \frac{1}{2(C_1+C_2)}\left[\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right) + \sqrt{\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)^2 - \frac{4(C_1+C_2)}{\alpha_1\alpha_2 C_1}}\right].$$

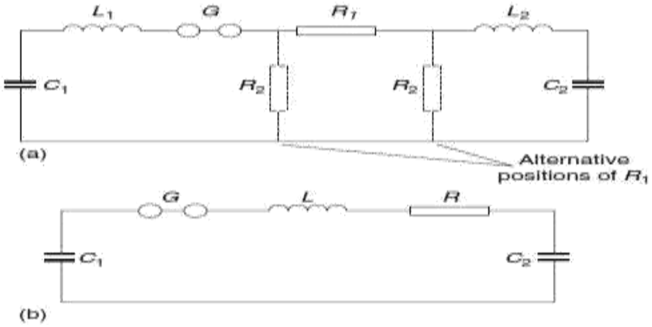
All these equations contain the time constants 1/¿1 and 1/¿2, which depend upon the wave shape. There is, however, no simple relationship between these time constants and the times T_1, T_2 and Tp as defined in the national or international recommendations.This relationship can be found by applying the definitions to the analytical expression for Vt,this means to equation. The relationship is irrational and must be computed numerically. The following table shows the result for some selected wave shapes: The standardized nominal values of T_1 and T_2 are difficult to achieve in practice, as even for fixed values of C_1 the load C_2 will vary and the exact values for R_1 and R_2 according to above equation in general not available.

These resistors have to be dimensioned for the rated high voltage of the generator and are accordingly expensive. The permissible tolerances forT_1 and T_2 are therefore necessary and used to graduate the resistor values. According of the real output voltage V(t) will in addition be necessary if the admissible impulse shape has to be testified.

Another reason for such a measurement is related to the value of the test voltage as defined in the recommendations. This magnitude corresponds to the crest value, if the shape of the lightning impulse is smooth. However, oscillations or an overshoot may occur at the crest of the impulse. If the frequency of such oscillations is not less than 0.5MHz or the duration of overshoot not over 1 sec, a ‘mean curve’ (see Note below) should be drawn through the curve. The maximum amplitude of this ‘mean curve’ defines the value of the test voltage. Such a correction is only tolerated, provided their single peak amplitude is not larger than 5 per cent of the crest value.

Oscillation son the front of the impulse (below 50 per cent of the crest value) are tolerated, provided their single peak amplitude does not exceed 25 percent of the crest value. It should be emphasized that these tolerances constitute the permitted differences between specified values and those actually recorded by measurements. Due to measuring errors the true values and the recorded ones may be somewhat different. Note. With the increasing application of transient or digital recorders in recording of impulse voltages it became very obvious that the definition of a ‘mean curve’ for the evaluation of lightning impulse parameters of waveforms with oscillations and/or overshoot, as provided by the standards, is insufficient. Any software, written to evaluate the parameters, needs clear instructions which are not yet available. As this matter is still under consideration (by CIGRE Working Group 33.03) and a revision of the current standards may provide solutions, no further comments to this problem are given. The origin of such oscillations or the overshoot can be found in measuring errors as well as by the inductances within every branch of the circuit or the stray capacitances, which will increase with the physical dimensions of the circuit.

If individual inductances L1, L2 are considered within the discharge circuit as indicated in Figure a second order differential equation determines the output voltage across the load capacitance C2. However, such an equivalent circuit cannot be exact, as additional circuits related to stray capacitances are not taken into account. Thus we may only combine the total inductance within the C1 –C2 circuit to single inductance L, as shown in Figure 3.1.2 and neglect the positions of the tail resistors, which have no big influence.



[Source: "High Voltage Engineering" by C.L. Wadhwa , Page - 432]

Figure 3.1.2 Simplified circuit of impulse generator and load. Circuit showing alternative positions of the wave tail control resistance. (b) Circuit for calculation of wave front oscillations

3.6 TRIPPING AND CONTROL OF IMPULSE GENERATORS

In large impulse generators, the spark gaps are generally sphere gaps or gaps formed by hemispherical electrodes. The gaps are arranged such that sparking of one gap results in automatic sparking of other gaps as overvoltage is impressed on the other. In order to have consistency in sparking, irradiation from an ultra-violet lamp is provided from the bottom to all the gaps. To trip the generator at a predetermined time, the spark gaps may be mounted one movable frame, and the gap distance is reduced by moving the movable electrodes closer.

This method is difficult and does not assure consistent and controlled tripping. A simple method of controlled tripping consists of making the first gap a three electrode gap and firing it from a controlled source. Figure gives the schematic arrangement of a three electrode gap The first stage of the impulse generator is fitted with a three electrode gap, and the central electrode is maintained at a potential in-between that of the top and the bottom electrodes with the resistors R\ and RL. The tripping is initiated by applying a pulse to the thyratron G by closing the switch S. The capacitor C produces an exponentially decaying pulse of positive polarity the pulse goes and initiates the oscillograph time base. The thyratron conducts on receiving thepulse from the switch S and produces a negative pulse through the capacitance Ci at the central electrode of the three electrode gap. Hence, the voltage between the central electrode and the top electrode of the three electrode gap goes above its sparking potential and thus the gap conducts. The time lag required for the thyratron firing and breakdown of the three electrode gap ensures that the sweep circuit of the oscillograph begins before the start of the impulse generator voltage.

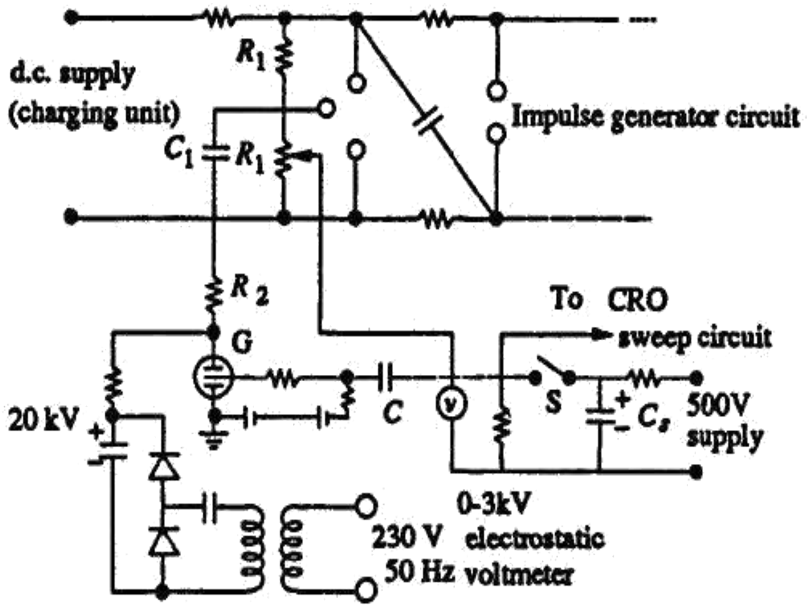


Figure 3.6.1 Tripping of an impulse generator with a three electrode gap

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 467]

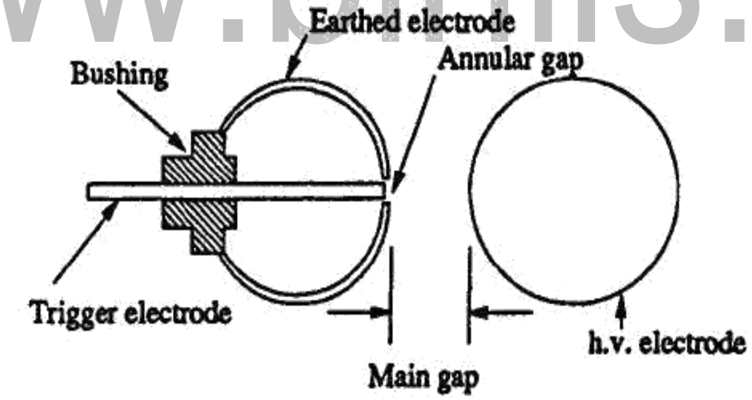


Figure 3.6.2Trigatron gap

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 476]

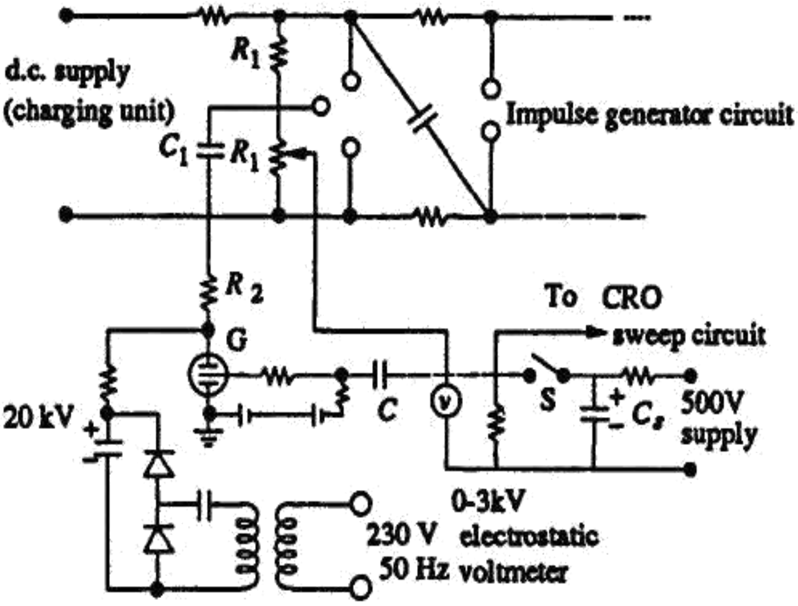


Figure 3.6.3 Trigatron gap and tripping circuit

[Source: "High Voltage Engineering" by C.L. Wadhwa , Page – 495]

A trigatron gap consists of high voltage spherical electrode of suitable size, an earthed main electrode of spherical shape, and a trigger electrode through the main electrode. The trigger electrode is a metal rod with an annular clearance of about 1 mm fitted into the main electrode through a bushing. The trigatron is connected to a pulse circuit as shown in fig. 3.26 b. Tripping of the impulse generator is effected by a trip pulse which produces a spark between the trigger electrode and the earthed sphere. Due to space charge effects and distortion of the field in the main gap, spark over of the main gap Fig. 3.27 applied for correct operation.

3.3 VANDIGRAFF GENERATOR

In electromagnetic generators, current carrying conductors are moved against the electromagnetic forces acting upon them. In contrast to the generator, electrostatic generators convert mechanical energy into electric energy directly. The electric charges are moved against the force of electric fields, thereby higher potential energy is gained at the cost of mechanical energy. The basic principle of operation is explained with the help of Figure 3.3.1An insulated belt is moving with uniform velocity ν in an electric field of strength E (x). Suppose the width of the belt is b and the charge density ζ consider a length dx of the belt, the charge dq = ζ bdx. The force experienced by this charge (or the force experienced by the belt). Figure 3.3.1 shows belt driven electrostatic generator developed by Van de Graaf in 1931. An insulating belt is run over pulleys. The belt, the width of which may vary from a few cms to meters is driven at a speed of about 15 to 30 m/sec, by means of a motor connected to the lower pulley. The belt near the lower pully is charged electro statically by an excitation arrangement. The lower charge spray unit consists of a number of needles connected to the controllable dace. source (10 kV–100 kV) so that the discharge between the points and the belt is maintained.

The charge is conveyed to the upper end where it is collected from the belt by discharging points connected to the inside of an insulated metal electrode through which the belt passes. The entire equipment is enclosed in an earthed metal tank filled with insulating gases of good dielectric strength viz. SF6 etc. So that the potential of the electrode could be raised to relatively higher voltage without corona discharges or for a certain voltage a smaller size ofthe equipment will result. Also, the shape of the h.t., electrode should be such that the surface gradient of electric field is made uniform to reduce again corona discharges, even though it is desirable to avoid corona entirely. An isolated sphere is the most favorable electrode shape and will maintain a uniform field *E* with a voltage of *Er* where *r* is the radius of the sphere.

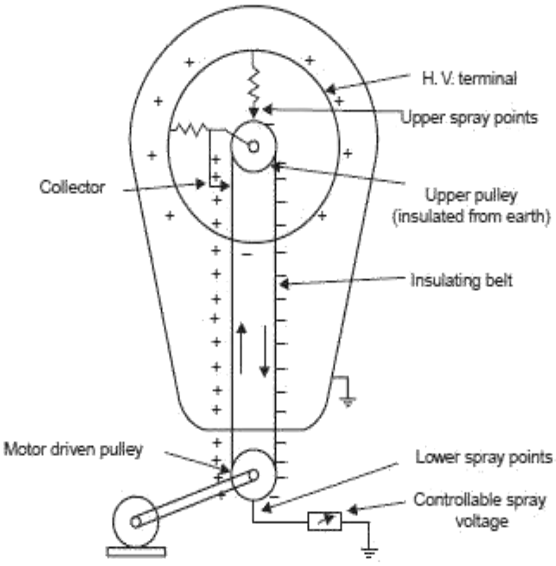


Figure 3.3.1 Van de Graft generator

As the h.t. electrode collects charges its potential rises. The potential at any instant is given as $V = q/C$ where q is the charge collected at that instant. It appears as though if the charge were collected for a long time any amount of voltage could be generated. However, as the potential of electrode rises, the field set up by the electrode increases and that may ionize the surrounding medium and, therefore, this would be the limiting value of the voltage. In practice, equilibrium is established at a terminal voltage which is such that the charging current equals the discharge current which will include the load current and the leakage and corona loss currents. The moving belt system also distorts the electric field and, therefore, it is placed within properly shaped field grading rings. The grading is provided by resistors and additional corona discharge elements. The collector needle system is placed near the point where the belt enters the h.t. terminal. A second point system excited by a self-inducing arrangement enables the down going belt to be charged to the polarity opposite to that of the terminal and thus the rate of charging of the latter, for a given speed, is doubled. The self inducing arrangement requires insulating the upper pulley and maintaining it at a potential higher than that of the h.t. terminal by connecting the pulley to the collector needle system. The arrangement also consists of a row of points connected to the inside of the h.t. terminal and directed towards the pulley above its points of entry into the terminal.

As the pulley is at a higher potential (positive), the negative charges due to corona discharge at the upper spray points are collected by the belt. This neutralizes any remaining positive charge on the belt and leaves an excess of negative charges on the down going belt to be neutralized by the lower spray points. Since these negative charges leave the h.t. terminal, the potential of the h.t. terminal is raised by the corresponding amount. In order to have a rough estimate of the current supplied by the generator, let us assume that the electric field E is normal to the belt and is homogeneous.

We know that $D = \varepsilon 0\ E$ where D is the flux density and since the medium surrounding the h.t. terminal is say air $\varepsilon r = 1$ and $\varepsilon 0 = 8.854 \times 10–12$ F/meter. According to Gauss law, $D = \zeta$ the surface charge density. From above equation it is clear that current I depend upon ζ, b and ν. The belt width (b) and velocity being limited by mechanical reasons, the current can be increased by having higher value of ζ. ζ can be increased by using gases of higher dielectric strength so that electric field intensity E could be increased without the inception of ionization of the medium surrounding the h.t. terminal. However, with all these arrangements, the actual short circuit currents are limited only to a few mA even for large generators.

The advantages of the generator are:

- Very high voltages can be easily
- generated Ripple free output
- Precision and flexibility of control

The disadvantages are:

- Low current output
- Limitations on belt velocity due to its tendency for vibration.