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## 6.3 GENERATION OF IMPULSE VOLTAGES

### 6.3.1 Standard Impulse Waveshapes

Transient overvoltages 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 a rise time of 0.5 to 10 $\mu$ s and decay time to 50% of the peak value of the order of 30 to 200 $\mu$ s. The waveshapes are arbitrary, but mostly unidirectional. It is shown that lightning overvoltage wave can be represented as double exponential waves defined by the equation

$$V = V_0 [\exp(-\alpha t) - \exp(-\beta t)] \tag{6.15}$$

where $\alpha$ and $\beta$ 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 to zero value. The general waveshape is given in Fig. 6.14. Impulse waves 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 $\mu$s, 1000 kV wave represents an impulse voltage wave with a front time of 1.2 $\mu$s, fall time to 50% peak value of 50 $\mu$s, and a peak value of 1000 kV. When impulse waveshapes 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 waveshape 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 $D$). 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)

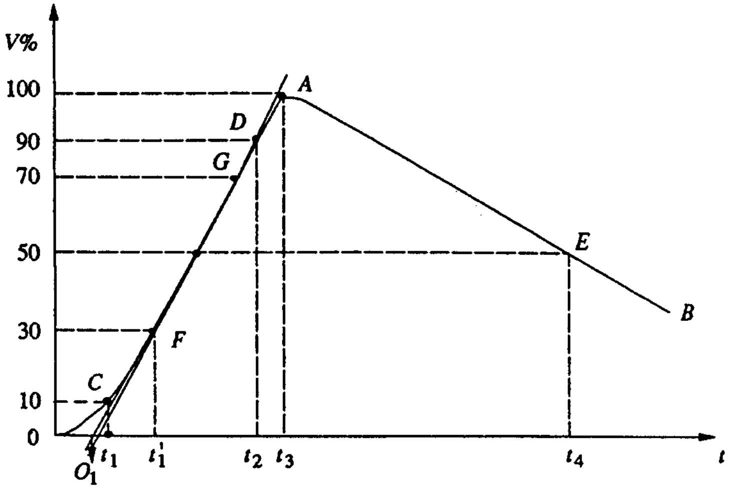


Fig. 6.14 Impulse waveform and its definitions

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 is $t_4$. $Ot_4$ is defined as the fall or tail time. In case the point $C$ is not clear or missing from the waveshape record, the point corresponding to 30% peak value $F$ is taken and its projection $t'_1$ is located on time axis. The wavefront 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 ± 30% and ± 20%. Indian standard specifications define 1.2/50 μs wave to be the standard impulse. The tolerance allowed in the peak value is ± 3%.

### 6.3.2 Theoretical Representation of Impulse Waves

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 μs, $\alpha = -0.0146$, $\beta = -2.467$, and $V_0 = 1.04$ when time $t$ is expressed in microseconds, $\alpha$ and $\beta$ control the front and tail times of the wave respectively.

### 6.3.3 Circuits for Producing Impulse Waves

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 over damped conditions or by the combination of two $R$-$C$ circuits. Different equivalent circuits that produce impulse waves are given in Figs. 6.15a to d. Out of these circuits, the ones shown in Figs. 6.15a to d are commonly used. Circuit shown in Fig. 6.15a is limited tomodel generators only, and commercial generators employ circuits shown in Figs. 6.15b to 6.15d.

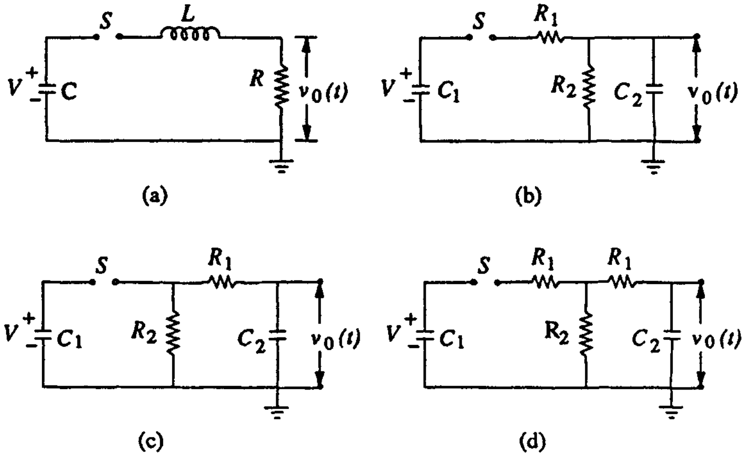


**Fig. 6.15** Circuits for producing impulse waves

A capacitor ($C_1$ or $C$) previously charged to a particular d.c. voltage is suddenly discharged into the waveshaping network ($LR$, $R_1R_2C_2$ or other combination) by closing the switch $S$. The discharge voltage $V_0\,(t)$ shown in Fig. 6.15 gives rise to the desired double exponential waveshape.

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

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

$$V = \frac{1}{C}\int_0^t i\,dt + Ri + L\frac{di}{dt} \tag{6.16}$$

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 transform equation,

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

or,

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

The voltage across the resistor $R$ (which is the output voltage) is, $v_0(s) = I(s)\,R$; hence,

$$v_0(s) = V\frac{R}{L}\,\frac{1}{s^2 + \frac{Rs}{L} + \frac{1}{LC}}$$

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

Hence, the roots of the equation $s^2 + \frac{Rs}{L} + \frac{1}{LC}$ 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 $v_0(t)$ is

$$v_0(t) = \frac{V\left(\frac{R}{2L}\right)}{\left[\frac{R^2}{4L^2} - \frac{1}{LC}\right]^{\frac{1}{2}}}\left[\exp(-\alpha t) - \exp(-\beta t)\right] \tag{6.17}$$

$$= V_0\left[\exp(-\alpha\, t) - \exp(-\beta\, t)\right] \tag{6.17a}$$

where,

$$V_0 = \frac{V\left(\frac{R}{2L}\right)}{\left[\frac{R^2}{4L^2} - \frac{1}{LC}\right]^{\frac{1}{2}}} = \frac{V}{\left[1 - \frac{4L}{CR^2}\right]^{\frac{1}{2}}} \tag{6.17b}$$

The sum of the roots $(\alpha + \beta) = -\frac{R}{2L}$

and, the product of the roots $\alpha\beta = \frac{1}{LC}$ (6.17c)

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 $L$. $\beta$ or the wave front time is determined and $\alpha$ 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 Generator Circuits*

The most commonly used configurations for impulse generators are the circuits shown in Figs. 6.15b 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 objects which are mainly capacitive in nature form part of $C_2$.

For the configuration shown in Fig. 6.15b, the output voltage across $C_2$ is given by, $v_0(t) = \frac{1}{C_2}\int_0^t i_2\,dt$.

Performing Laplace transformation, $\frac{1}{C_2 s} I_2(s) = v_0(s)$

where $i_2$ is the current through $C_2$.
Taking the current through $C_1$ as $i_1$ and its transformed value as $I_1(s)$,

$$I_2(s) = \left[\frac{R_2}{R_2 + \frac{1}{C_2 s}}\right] I_1(s)$$

$$I_1(s) = \frac{V}{s}\,\frac{1}{\frac{1}{C_1 s} + R_1 + \frac{R_2 \cdot \frac{1}{C_2 s}}{R_2 + \frac{1}{C_2 s}}}$$

where, $\frac{R_2 \cdot \frac{1}{C_2 s}}{R_2 + \frac{1}{C_2 s}}$ represents the impedance of the parallel combination of $R_2$ and $C_2$.

Substitution of $I_1(s)$ gives

$$v_0(s) = \frac{1}{C_2 s}\,\frac{R_2}{R_2 + \frac{1}{C_2 s}}\,\frac{V}{s}\,\frac{1}{\frac{1}{C_1 s} + R_1 + \frac{R_2(1/C_2 s)}{R_2 + (1/C_2 s)}}$$

After simplification and rearrangement,

$$v_0(s)=\frac{V}{R_1C_2}\left[\frac{1}{s^2+\left(\frac{1}{C_1R_1}+\frac{1}{C_2R_2}+\frac{1}{C_2R_1}\right)s+\frac{1}{C_1C_2R_1R_2}}\right] \tag{6.18}$$

Hence, the roots of the equation

$$s^2+\left[\frac{1}{C_1R_1}+\frac{1}{C_2R_2}+\frac{1}{C_2R_1}\right]s+\frac{1}{C_1C_2R_1R_2}$$

are found from the relations,

$$\alpha+\beta=-\left[\frac{1}{C_1R_1}+\frac{1}{C_2R_2}+\frac{1}{C_2R_1}\right] \tag{6.19}$$

$$\alpha\beta=\frac{1}{C_1C_2R_1R_2}$$

Taking inverse transform of $v_0(s)$ gives

$$v_0(t)=\frac{V}{R_1C_2\,(\alpha-\beta)}\left[\exp\,(-\alpha t)-\exp\,(-\beta t)\right] \tag{6.20}$$

Usually, $\frac{1}{C_1R_1}$ and $\frac{1}{C_2R_2}$ will be much smaller compared to $\frac{1}{R_1C_2}$.
Hence, the roots may be approximated as

$$\alpha\approx\frac{1}{R_1C_2}\text{ and, }\beta=\frac{1}{R_2C_1} \tag{6.21}$$

Following a similar analysis, it may be shown that the output waveform for the circuit configuration of Fig. 6.15c will be

$$v_0(t)=\frac{VC_1R_2\alpha\,\beta}{(\beta-\alpha)}\left[\exp\,(-\alpha t)-\exp\,(-\beta t)\right]$$

where $\alpha$ and $\beta$ are the roots of the Eq. (6.19). The approximate values of $\alpha$ and $\beta$ given by Eq. (6.21) are valid for this circuit also.

The equivalent circuit given in Fig. 6.15d is a combination of the configurations of Fig. 6.15b and Fig. 6.15c. The resistance $R_1$ is made into two parts and kept on either side of $R_2$ to give greater flexibility for the circuits.

### Restrictions on the Ratio of the Generator and Load Capacitances, $C_1/C_2$ 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

$$R_2=P(y)/C_1\quad\text{and}\quad R_1=Q(y)/C_1$$

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. 6.15b or 6.15c 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 μ s waveshape. Similarly, for a 1/50 μ s waveshape the ratio $C_1/C_2$ lies between 6 and 106.5. If the configuration chosen is 6.15c, the minimum value of $C_1/C_2$ for 1/5 μ s waveshape is about 0.3 and that for the 1/50 μ 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 Figs. 6.15a to d, in practice comprise several stray series inductances. Further, the circuits occupy considerable space and will be spread over several metres in a testing laboratory. Each component has some residual inductance and the circuit loop itself contributes for further inductance. The actual value of the inductance may vary from 10 μ 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. Inductances of several components and the loop inductance are shown in Fig. 6.16a. Figure 6.16b gives a simplified circuit for considering the effect of inductance. The effect of the variation of inductance on the waveshape is shown in Fig. 6.16c. If the series resistance $R_1$ is increased, the wave front oscillations are damped, but the peak value of the voltage is also reduced. Sometimes, in order to control the front time a small inductance is added.

### *Impulse Generators for Testing Objects having Large Capacitance*

When test objects with large capacitances are to be tested ($C > 5$ nF), it is difficult to generate standard impulses with front time within the specified tolerance of ± 30% and the specified less than 5% tolerance in the overshoot. This is mainly because of the effect of the inductance of the impulse generator and the front resistors. Normally the inductance of the impulse generator will be about 3 to 5 μH per stage and that of the leads about 1 μH/m. Also the front resistor which is usually of bifilar type, has inductance of about 2 μH/unit. An overshoot in the voltage wave of more than 5% will occur if $R/(\sqrt{L/c}) \leq 1.38$, where $R$ is the front resistance, $L$ is the generator inductance and $C$ is the equivalent capacitance of the generator given by $C = C_1 \cdot C_2/(C_1 + C_2)$.

### *Impulse Generators for Test Objects with Inductance*

Often impulse generators are required to test equipment with large inductance, such as power transformers and reactors. Usually, generating the impulse voltage wave of proper time-to-front and obtaining a good voltage efficiency are easy, but obtaining the required time-to-tail as per the standards will be very difficult. The equivalent circuit for medium and low inductive loads will be as shown in Fig. 6.16(d). For the calculation of time-to-tail the circuit can still be approximated as a series $C$-$R$-$L$ circuit. As the value $R/(\sqrt{L/C})$ decreases, the overshoot and the swing of the wave to the opposite polarity increases thereby deviating from the standard wave shape. Therefore, it is necessary to keep the value of the effective resistance $R$ in the circuit large. One method of doing this is to connect a large resistance, $R_2$ in parallel with the test object or to connect the untested winding of the transformer (load) with a suitable resistance. Another method that can be used is to increase the generator capacitance with which the time-to-tail also increases, but without alterating the time-to-front and the overshoot. Figure 6.16(d) gives the circuit arrangement for inductive loads and 6.16(e) gives the requirement of energy and capacitance of the impulse voltage generator. Figure B of 6.16(e) gives the generator capacitance required to give the time-to-tail values in the range of 40 to 60 μ s at different inductive loads.

## Waveshape Control

Generally, for a given impulse generator of Fig. 6.15b 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. Hence, the simplified circuit shown in Fig. 6.16b is used for wave front time calculation. 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

$$t_1 = 3.0 R_1 \frac{C_1 C_2}{C_1 + C_2} = 3 R_1 C_e \tag{6.22}$$

where $C_e = \frac{C_1 C_2}{C_1 + C_2}$. If $R_1$ is given in ohms and $C_e$ in microfarads, $t_1$ is obtained in microseconds.

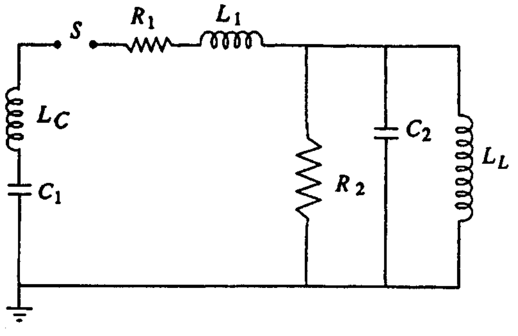


**Fig. 6.16** (a) Series inductances in impulse generator circuit

$L_C$ — Inductance of the generator capacitance $C_1$ and lead capacitances
$L_1$ — Inductance of the series resistance and the circuit loop inductance
$L_L$ — Test object inductance

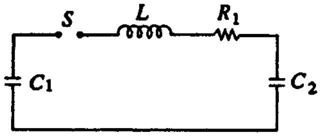


**Fig. 6.16** (b) Simplified circuit for calculation of wave front time
$L = L_C + L_1$ + any other added inductance

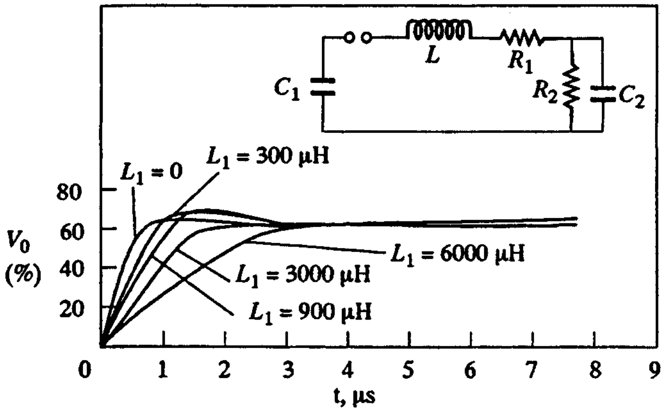
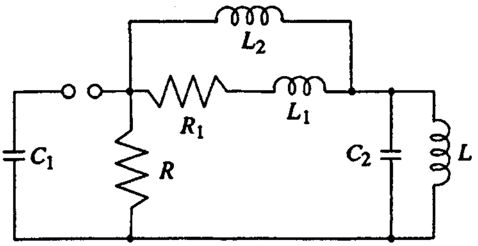
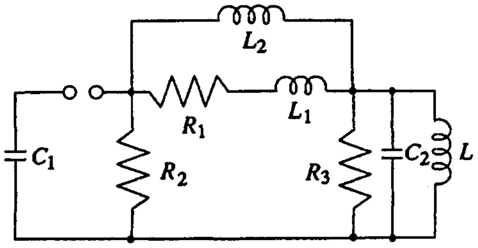


**Fig. 6.16** (c) Effect of series inductance on wave front time. $v_0$ is the percentage of charging voltage V, to which $C_1$ is charged

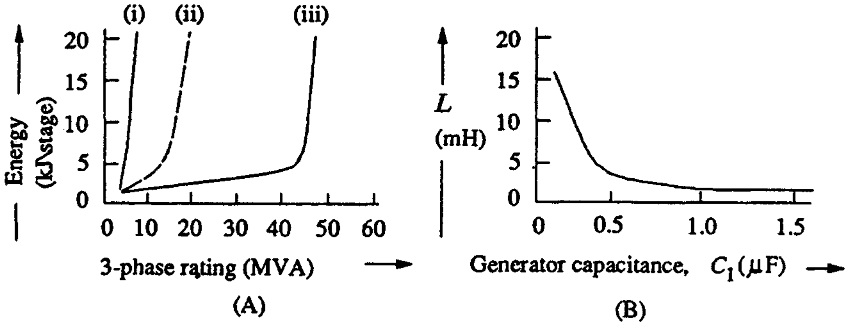


Medium inductance load (L = 0.4 to 15 mH)



Low inductance load (L = 0.4 to 4mH)

**Fig. 6.16** (d) Effect of inductive loads on impulse voltage generator circuits



Energy requirement per 200 kV stage of an impulse voltage generator as a function of the MVA rating of 3-phase reactor transformer. Curves (i) for 11 kV, (ii) for 22 kV and (iii) for 33 kV winding ratings.

Generator capacitance ($C_1$) required for different inductive loads ($L$) to give the standard tail time of an impulse voltage wave.

**Fig. 6.16** (e) Requirements of an impulse voltage generator energy and capacitance for the testing of the transformer (reactor) winding using standard impulse voltages

**Fig. 6.16** Series inductance in impulse generator circuits and its effect on waveshape

For discharging or tail time, the capacitances $C_1$ and $C_2$ may be considered to be in parallel and discharging occurs through $R_1$ and $R_2$. Hence, the time for 50% discharge is approximately given by

$$t_2 = 0.7\,(R_1 + R_2)\,(C_1 + C_2) \qquad (6.23)$$

These formulae for $t_1$ and $t_2$ hold good for the equivalent circuits shown in Fig. 6.15b and c. For the circuit given in Fig. 6.15d, $R$ is to be taken as $2R_1$. With the approximate formulae, the wave front and wave tail times can be estimated to within ± 20% for the standard impulse waves.

### 6.3.4 Multistage Impulse Generators—Marx Circuit

In the above discussion, the generator capacitance $C_1$ is to be first charged and then discharged into the wave shaping circuits. A single capacitor $C_1$ may be used for voltages up to 200 kV. Beyond this voltage, a single capacitor and its charging unit may be too costly, and the size becomes very large. The cost and size of the impulse generator increases at a rate of the square or cube of the voltage rating. Hence, for producing very high voltages, a bank of capacitors are charged in parallel and then discharged in series. The arrangement for charging the capacitors in parallel and then connecting them in series for discharging was originally proposed by Marx. Now-a-days modified Marx circuits are used for the multistage impulse generators.

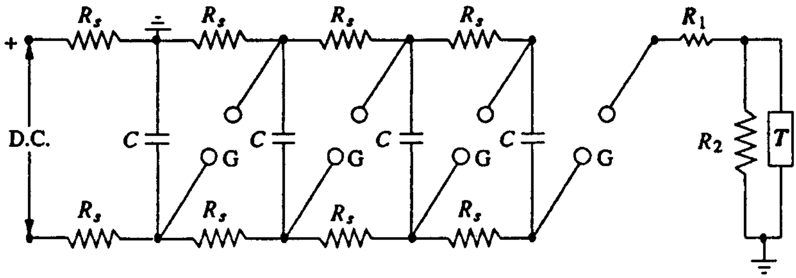


**Fig. 6.17a** Schematic diagram of Marx circuit arrangement for multistage impulse generator

$C$ — Capacitance of the generator
$R_s$ — Charging resistors
G — Spark gap
$R_1$, $R_2$ — Wave shaping resistors
$T$ — Test object

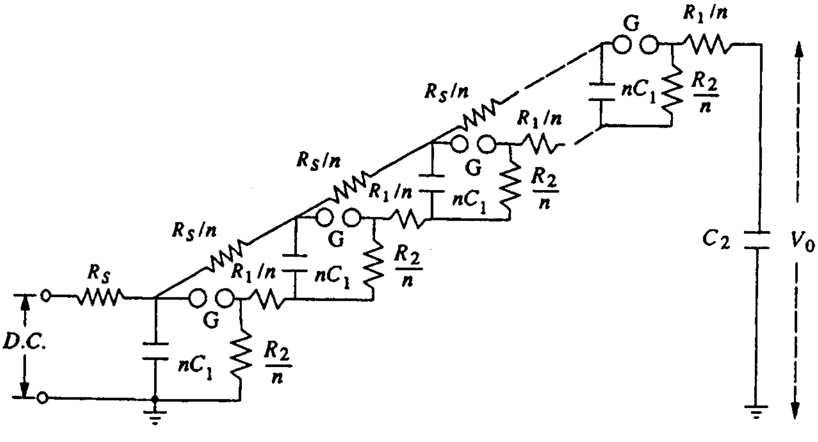


**Fig. 6.17b** Multistage impulse generator incorporating the series and wave tail resistances within the generator

The schematic diagram of Marx circuit and its modification are shown in Figs. 6.17a and 6.17b, respectively. Usually the charging resistance $R_s$ is chosen to limit the charging current to about 50 to 100 mA, and the generator capacitance $C$ is chosen such that the product $CR_s$ is about 10 s to 1 min. The gap spacing is chosen such that the breakdown voltage of the gap G is greater than the charging voltage $V$. Thus, all the capacitances are charged to the voltage $V$ in about 1 minute. When the impulse generator is to be discharged, the gaps G are made to spark over simultaneously by some external means. Thus, all the capacitors $C$ get connected in series and discharge into the load capacitance or the test object. The discharge time constant $CR_1/n$ (for $n$ stages) will be very very small (microseconds), compared to the charging time constant $CR_s$ which will be few seconds. Hence, no discharge takes place through the charging resistors $R_s$. In the Marx circuit is of Fig. 6.17a the impulse wave shaping circuit is connected externally to the capacitor unit. In Fig. 6.17b, the modified Marx circuit is shown, wherein the resistances $R_1$ and $R_2$ are incorporated inside the unit. $R_1$ is divided into $n$ parts equal to $R_1/n$ and put in series with the gap G. $R_2$ is also divided into $n$ parts and arranged across each capacitor unit after the gap G. This arrangement saves space, and also the cost is reduced. But, in case the waveshape is to be varied widely, the variation becomes difficult. The additional advantages gained by distributing $R_1$ and $R_2$ inside the unit are that the control resistors are smaller in size and the efficiency ($V_0/nV$) is high.

Impulse generators are nominally rated by the total voltage (nominal), the number of stages, and the gross energy stored. The nominal output voltage is the number of stages multiplied by the charging voltage. The nominal energy stored is given by $\frac{1}{2}C_1V^2$ where $C_1 = C/n$ (the discharge capacitance) and $V$ is the nominal maximum voltage ($n$ times charging voltage). A 16-stage impulse generator having a stage capacitance of 0.280 μ F and a maximum charging voltage of 300 kV will have an energy rating of 192 kW sec. The height of the generator will be about 15 m and will occupy a floor area of about 3.25 × 3.00 m. The waveform of either polarity can be obtained by suitably changing the charging unit polarity.

### 6.3.5 Components of a Multistage Impulse Generator

A multistage impulse generator requires several components parts for flexibility and for the production of the required waveshape. These may be grouped as follows:

#### *(i) d.c. Charging Set*

The charging unit should be capable of giving a variable d.c. voltage of either polarity to charge the generator capacitors to the required value.

#### *(ii) Charging Resistors*

These will be non-inductive high value resistors of about 10 to 100 kilo-ohms. Each resistor will be designed to have a maximum voltage between 50 and 100 kV.

#### *(iii) Generator Capacitors and Spark Gaps*

These are arranged vertically one over the other with all the spark gaps aligned. The capacitors are designed for several charging and discharging operations. On dead short circuit, the capacitors will be capable of giving 10 kA of current. The spark gaps will be usually spheres or hemispheres of 10 to 25 cm diameter. Sometimes spherical ended cylinders with a central support may also be used.

### *(iv) Wave-shaping Resistors and Capacitors*

Resistors will be non-inductive wound type and should be capable of discharging impulse currents of 1000 A or more. Each resistor will be designed for a maximum voltage of 50 to 100 kV. The resistances are bifilar wound or non-inductive thin flat insulating sheets. In some cases, they are wound on thin cylindrical formers and are completely enclosed. The load capacitor may be of compressed gas or oil filled with a capacitance of 1 to 10 μF.

Modern impulse generators have their wave-shaping resistors included internally with a flexibility to add additional resistors outside, when the generator capacitance is changed (with series parallel connection to get the desired energy rating at a given test voltage). Such generators optimize the set of resistors. A commercial impulse voltage generator uses six sets of resistors ranging from 1.0 ohm to about 160 ohms with different combinations (with a maximum of two resistors at a time) such that a resistance value varying from 0.7 ohm to 235 ohms per stage is obtained, covering a very large range of energy and test voltages. The resistors used are usually resin cast with voltage and energy ratings of 200 to 250 kV and 2.0 to 5.0 kWsec. The entire range of lightning and switching impulse voltages can be covered using these resistors either in series or in parallel combination.

### *(v) Triggering System*

This consists of trigger spark gaps to cause spark breakdown of the gaps (see Sec. 6.5).

### *(vi) Voltage Dividers*

Voltage dividers of either damped capacitor or resistor type and an oscilloscope with recording arrangement are provided for measurement of the voltages across the test object. Sometimes a sphere gap is also provided for calibration purposes (see Chapter 7 for details).

## 6.3.6 Generation of Switching Surges

Now-a-days in extra high voltage transmission lines and power systems, switching surge is an important factor that affects the design of insulation. All transmission lines rated for 220 kV and above, incorporate switching surge sparkover voltage for their insulation levels. A switching surge is a short duration transient voltage produced in the system due to a sudden opening or closing of a switch or circuit breaker or due to an arcing at a fault in the system. The waveform is not unique. The transient voltage may be an oscillatory wave or a damped oscillatory wave of frequency ranging from few hundred hertz to few kilo hertz. It may also be considered as a slow rising impulse having a wave front time of 0.1 to 10 ms, and a tail time of one to several ms. Thus, switching surges contain larger energy than the lightning impulse voltages.

Several circuits have been adopted for producing switching surges. They are grouped as (*i*) impulse generator circuit modified to give longer duration waveshapes, (*ii*) power transformers or testing transformers excited by d.c. voltages giving oscillatory waves and these include Tesla coils.

Standard switching impulse voltage is defined, both by the Indian Standards and the IEC, as 250/2500 μs wave, with the same tolerances for time-to-front and time-to-tail as those for the lightning impulse voltage wave i.e. time-to-front of (250 ± 50) μs and time-to-half value of (2500 ± 500) μs. Other switching impulse voltage waves commonly used for testing the lightning arresters are 250/1500 μs with a tolerance of ± 500 μs in time-to-half value.

Figure 6.18 shows the impulse generator circuits modified to give switching surges. The arrangement is the same as that of an impulse generator. The values of $R_1$ and $R_2$ for producing waveshapes of long duration, such as 100/1000 μs or 400/4000 μs, will range from 1 to 5 kilo-ohms and 5 to 20 kilo-ohms respectively. Thus, $R_1$ is about 20 to 30% of $R_2$. The efficiency of the generator gets considerably reduced to about 50% or even less. Moreover, the values of the charging resistors $R_1$ are to be increased to very high values as these will come in parallel with $R_2$ in the discharge circuit.

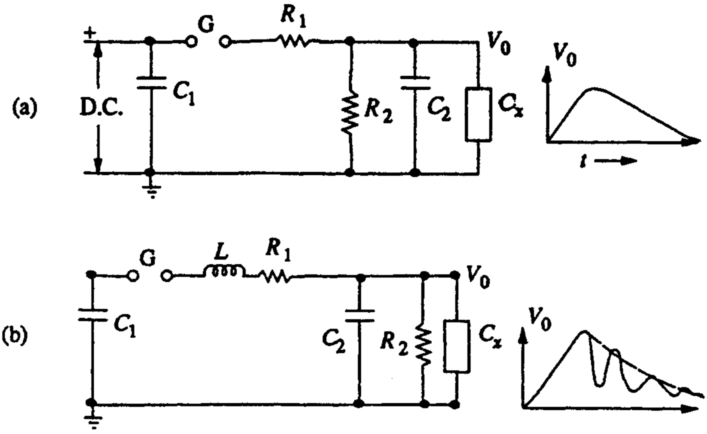


**Fig. 6.18** Circuits for producing switching surge voltages. Also shown are the output waveshapes across the load $C_x$

The circuit given in Fig. 6.18b produces unidirectional damped oscillations. With the use of an inductor $L$, the value of $R_1$ is considerably reduced, and the efficiency of the generator increases. The damped oscillations may have a frequency of 1 to 10 kHz depending on the circuit parameters. Usually, the maximum value of the switching surge obtained is 250 to 300 kV with an impulse generator having a nominal rating of 1000 kV and 25 kW sec. Bellaschi *et al.*[12] used only an inductor $L$ of low resistance to produce switching impulse up to 500 kV. A sphere gap was included in parallel with the test object for voltage measurement and also for producing chopped waves.

Switching surges of very high peaks and long duration can be obtained by using the circuit shown in Fig. 6.19. An impulse generator condenser $C_1$ charged to a low voltage d.c. (20 to 25 kV) is discharged into the low voltage winding of a power or testing transformer. The high voltage winding is connected in parallel to a load capacitance $C_2$, a potential divider $R_2$, a sphere gap S, and the test object. Through an autotransformer action, switching surge of proper waveshape can be generated across

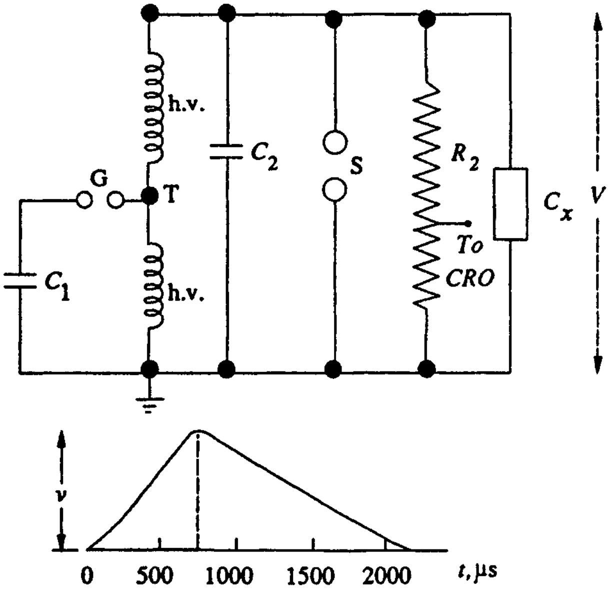


**Fig. 6.19** Circuit for producing switching surges using a transformer

$C_1$ — Surge generator
$T$ — Power transformer
$C_2$ — Load capacitance
$C_x$ — Test object

G — Triggering spark gap
$S$ — Sphere gap
$R_2$ — Potential divider
h.v.,l.v. — Transformer high and low voltage windings

the test object. The efficiency obtained by this method is high but the transformer should be capable of withstanding very high voltages.

### *Multi Test Sets for High Voltage Testing*

In many small laboratories like in the teaching institutions, small industries and utility organizations, the requirements of high voltages may be less than about 200 kV, 50 Hz, a.c., 400 kV d.c. and 400 kV standard lightning and switching impulse voltages. The power requirements will be around 5 kW or kVA and the energy requirement will be less than 1.5 kJ. For such applications, flexible and universally interchangeable modular systems of the above voltage and energy ratings are available under different trade names. These systems mainly consist of

*(i) a.c. Testing Transformers :*
With continuous power ratings of 3 to 5 kVA with a short time rating about 150%. The unit can be one single transformer of up to 100 kV(rms), or 2 or 3 units connected in cascade with voltage ratings up to 300 kV(rms).

*(ii) d.c Units :*
A.C. transformer with the addition of a rectifier unit and a filter capacitor, with ripple factor at rated current less than 5% and a voltage drop or regulation less than 10%, for a single stage output of about 100 kV (half-wave rectifier) constitute a d.c. set. D.C. sets are available as multi-stage voltage doubler units with one pulse output, or as a quadampler unit of up to 400 kV rating with the same specifications. In either case, the power ratings will be about 3 to 5 kW continuous. The rectifier stacks used are the selenium diode type.

*(iii) Impulse Voltage Units :*
Marx circuit of 2 to 4 stages can be assumed using the transformer and d.c. rectifier unit described earlier for an output voltage of about 400 kV(peak) using a one stage rectifier unit. The necessary wave front and wave tail resistors and load capacitances are normally provided. The units are assembled with modular components mounted on suitable insulating columns. The units normally have voltage efficiency of about 90%.

All the basic units are clearly and compactly arranged. By having increased number of units the system can be expanded to obtain higher and desired type of voltage. Control cubicles/boxes are provided for the control and measurement of voltages. The units can be mounted on wheels or located permanently in a test hall of size 4m × 3m × 3m.

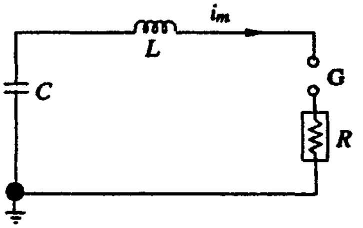
Multi-test sets are currently being manufactured and assembled in India by some leading manufacturers of high voltage test equipments.

## 6.4 GENERATION OF IMPULSE CURRENTS

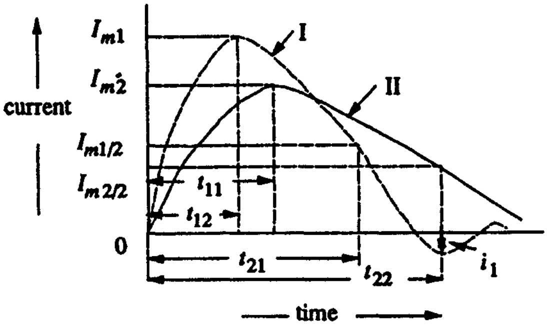
Lightening discharges involve both high voltage impulses and high current impulses on transmission lines. Protective gear like surge diverters have to discharge the lightning currents without damage. Therefore, generation of impulse current waveforms of high magnitude (≈ 100 kA peak) find application 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 waveshapes used in testing surge diverters are 4/10 and 8/20 μ s, the figures respectively representing the nominal wave front and wave tail times (see Fig. 6.14). The tolerances allowed on these times are ± 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 0.5 to 5 ms, with rise and fall times of the waves being less than ±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 defined as the total time of the wave during which the current is at least 10% of its peak value.



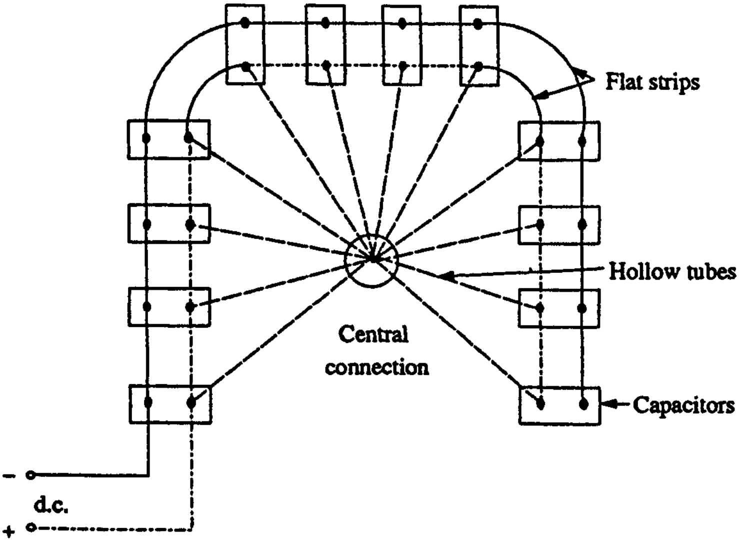
(a) Basic circuit of an impulse current generator



$t_1$ and $t_{12}$ = time-to-front of waves I and II
$t_{21}$ and $t_{22}$ = time-to-tail of waves I and II

I — damped oscillatory wave
II — overdamped wave
$i_1$ — overshoot

(b) Types of impulse current waveforms



(c) Arrangement of capacitors for high impulse current generation

**Fig. 6.20** Impulse current generator circuit and its waveform

### 6.4.2 Circuit 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. $C$ 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

$$V = R\,i_m + L\frac{di_m}{dt} + \frac{1}{C}\int_0^t i_m\,dt \tag{6.24}$$

The circuit is usually underdamped, so that

$$\frac{R}{2} < \sqrt{L/C}$$

Hence, $i_m$ is given by

$$i_m = \frac{V}{\omega L}\,[\exp(-\alpha t)]\,\sin(\omega t) \tag{6.25}$$

where $$\alpha = \frac{R}{2L} \text{ and } \omega = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \tag{6.25a}$$

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

$$t_1 = t_f = \frac{1}{\omega}\sin^{-1}\frac{\omega}{\sqrt{LC}} = \frac{1}{\omega}\tan^{-1}\frac{\omega}{\alpha} \tag{6.26}$$

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

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

It can be shown that the maximum value of $i_m$ is normally independent of the value of $V$ and $C$ 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 $V$.

The present practice as per IEC 60.2 is to express the characteristic time $t_2$ as the time for half value of the peak current, similar to the definition given for standard impulse voltage waves. With this definition, the values of $\alpha$ and $\omega$ for 8/20 μs impulse wave will be $\alpha = 0.0535 \times 10^6$ and $\omega = 0.113 \times 10^6$, when $R$, $L$, $C$ are expressed in ohms, henries and farads respectively. The product $LC$ will be equal to 65 and the peak value of $i_m$ is given by $(VC)/14$. Here, the charging voltage is in kV and $i_m$ is in kA.

### 6.4.3 Generation of High Impulse Currents

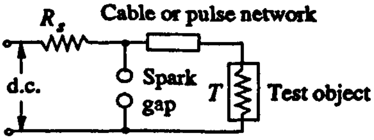
For producing large values of impulse currents, a number of capacitors are charged in parallel and discharged in parallel into the circuit. The arrangement of capacitors is shown in Fig. 6.20c. In order to minimize the effective inductance, the capacitors are subdivided into smaller units. If there are $n_1$ 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

$$L = L_0 + \frac{L_1}{n} + \frac{L_2}{n_1 n_2}$$

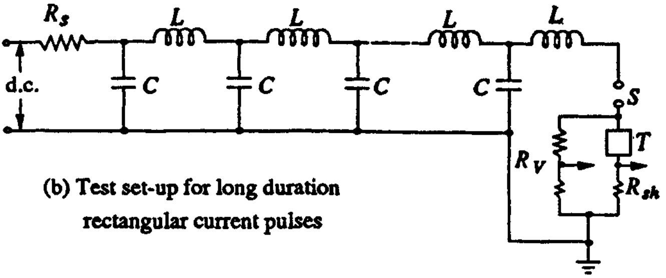
Also, the arrangement of capacitors into a horse-shoe shaped layout minimizes the effective load inductance.

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, capable of giving high short circuit currents,
(*iii*) an additional air cored inductor of high current value,
(*iv*) proper shunts and oscillograph for measurement purposes, and
(*v*) a triggering unit and spark gap for the initiation of the current generator.



(a) Basic circuit



(b) Test set-up for long duration rectangular current pulses

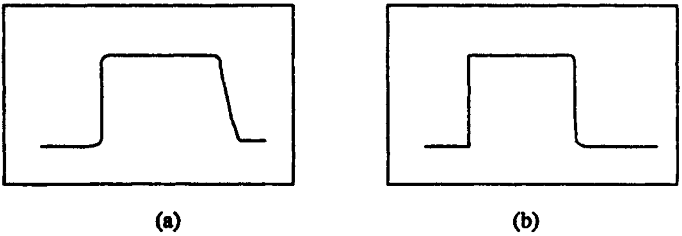
**Fig. 6.21** Basic circuit and schematic set-up for producing rectangular current pulses

$R_s$ — Charging resistor
$S$ — Trigger spark gap
$T$ — Test object
$L$-$C$ — Pulse forming network
$R_V$ — Potential divider for voltage measurement
$R_{sh}$ — Current shunt for current measurement

### 6.4.4 Generation of Rectangular Current Pulses

Generation of rectangular current pulses of high magnitudes (few hundred amperes and duration up to 5 ms) can be done by discharging a pulse network or cable previously charged. The basic circuit for producing rectangular pulses is given in Fig. 6.21. The length of a cable or an equivalent pulse forming network is charged to a specified d.c. voltage. When the spark gap is short-circuited, the cable or pulse network discharges through the test object.

To produce a rectangular pulse, a coaxial cable of surge impedance $Z_0 = \sqrt{L_0/C_0}$ (where $L_0$ is the inductance and $C_0$ is the capacitance per unit length) is used. If the cable is charged to a voltage $V$ and discharged through the test object of resistance $R$, the current pulse $I$ is given by $I = V/(Z_0 + R)$. A pulse voltage $RV/(R + Z_0)$ is developed across the test object $R$, and the pulse current is sustained by a voltage wave ($V$-$IR$). For $R = Z_0$, the reflected wave from the open end of the cable terminates the pulse current into the test object, and the pulse voltage becomes equal to $V/2$.



(a) Pulse waveform using pulse forming network (3.5 μ s)
(b) Pulse waveform using a coaxial cable (3.6 μ s)

**Fig. 6.22** Current waveforms produced by rectangular current generators

In practice, it is difficult to get a coaxial cable of sufficient capacitance and length. Often artificial transmission lines with lumped $L$ and $C$ as shown in Fig. 6.21b are used. Usually, 6 to 9 $L$-$C$ sections will be sufficient to give good rectangular waves. The duration of the pulse time is seconds ($t$) is given by $t = 2\,(n - 1)\sqrt{LC}$, where $n$ is the number of sections used, $C$ is the capacitance per stage or section, and $L$ is the inductance per stage or section.

The current waveforms produced by an artificial line or pulse network and a coaxial cable are shown in Figs. 6.22a and b.

## 6.5 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.

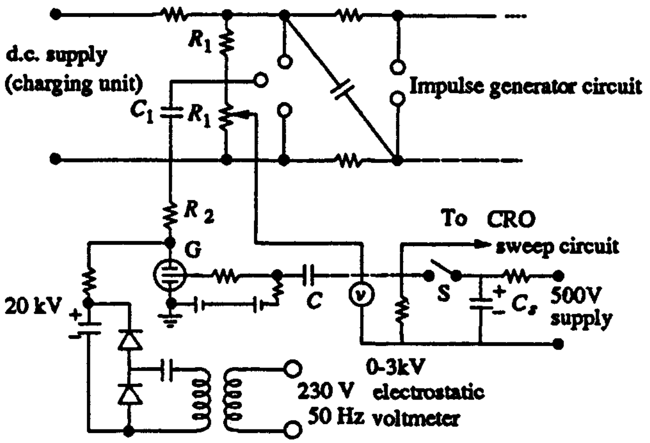


Fig. 6.23 Tripping of an impulse generator with a three electrode gap

To trip the generator at a predetermined time, the spark gaps may be mounted on a 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 6.23 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 $R_1$ and $R_L$. 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 the pulse from the switch S and produces a negative pulse through the capacitance $C_1$ 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

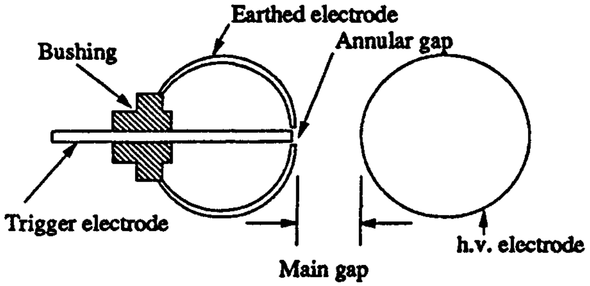
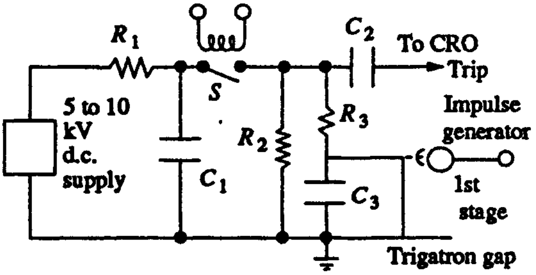


Fig. 6.24 (a) Trigatron gap



(b) Tripping circuit using a trigatron

**Fig. 6.24** Trigatron gap and tripping circuit

begins before the start of the impulse generator voltage. The resistance $R_2$ ensures decoupling of voltage oscillations produced at the spark gap entering the oscilloscope through the common trip circuit.

The three electrode gap requires larger space and an elaborate construction. Now-a-days a trigatron gap shown in Fig. 6.24 is used, and this requires much smaller voltage for operation compared to the three electrode gap. A trigatron gap consists of a 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. 6.24b. 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, sparkover of the main gap

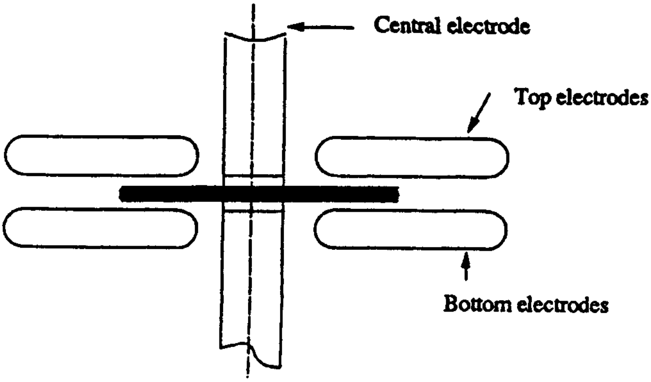


**Fig. 6.25** Three electrode gap for high current switching

occurs. The trigatron gap is polarity sensitive and a proper polarity pulse should be applied for correct operation.

### *Three Electrode Gap for Impulse Current Generator*

In the case of impulse current generators using three electrode gaps for tripping and control, a certain special design is needed. The electrodes have to carry high current from the capacitor bank. Secondly, the electrode has to switch large currents in a small duration of time (in about a microsecond). Therefore, the switch should have very low inductance. The erosion rate of the electrodes should be low.

For high current capacitor banks, a number of spark gap switches connected in parallel as shown in Fig. 6.25 are often used to meet the requirement. Recently, trigatron gaps are being replaced by triggered vacuum gaps, the advantage of the latter being fast switching at high currents (> 100 kA) in a few nanoseconds. Triggering of the spark gaps by focused laser beams is also adopted since the performance is better than the conventional triggering methods.

## QUESTIONS

Q.6.1 Explain with diagrams, different types of rectifier circuits for producing high d.c. voltages.

Q.6.2 What are the special features of high voltages rectifier valves? How is proper voltage division between the valves ensured, if a number of tubes are used in series ?

Q.6.3 Why is a Cockcroft-Walton circuit preferred for voltage multiplier circuits ? Explain its working with a schematic diagram.

Q.6.4 Give the expression for ripple and regulation in voltage multiplier circuits. How are the ripple and regulation minimized ?

Q.6.5 Describe, with a neat sketch, the working of a Van de Graaff generator. What are the factors that limit the maximum voltage obtained ?

Q.6.6 Explain the different schemes for cascade connection of transformers for producing very high a.c. voltages.

Q.6.7 Why is it preferable to use isolating transformers for excitation with cascade transformer units, if the power requirement is large ?

Q.6.8 What is the principle of operation of a resonant transformer ? How is it advantageous over the cascade connected transformers ?

Q.6.9 What is a Tesla coil ? How are damped high frequency oscillations obtained from a Tesla coil ?

Q.6.10 Define the front and tail times of an impulse wave. What are the tolerances allowed as per the specifications ?

Q.6.11 Give different circuits that produce impulse waves explaining clearly their relative merits and demerits.

Q.6.12 Give the Marx circuit arrangement for multistage impulse generators. How is the basic arrangement modified to accommodate the wave time control resistances ?

Q.6.13 How are the wave front and wave tail times controlled in impulse generator circuits ?

Q.6.14 Explain the different methods of producing switching impulses in test laboratories.

Q.6.15 Explain the effect of series inductance on switching impulse waveshapes produced.

Q.6.16 Describe the circuit arrangement for producing lightning current waveforms in laboratories.

Q.6.17 How is the circuit inductance controlled and minimized in impulse current generators ?

Q.6.18 How are rectangular current pulses generated for testing purposes ? How is their time duration controlled ?

Q.6.19 Explain one method of controlled tripping of impulse generators. Why is controlled tripping necessary ?

Q.6.20 What is a trigatron gap ? Explain its functions and operation.

Q.6.21 An impulse generator has 12 capacitors of 0.12 μF, and 200 kV rating. The wave front and wave tail resistances are 1.25 kΩ and 4 kΩ respectively. If the load capacitance including that of the test object is 10 000 pF, find the wave front and wave tail times and the peak voltage of impulse wave produced.

Q.6.22 A 8-stage impulse generator has 0.12 μF capacitors rated for 167 kV. What is its maximum discharge energy ? If it has to produce a 1/50 μs waveform across a load capacitor of 15,000 pF, find the values of the wave front and wave tail resistances.

Q.6.23 Calculate the peak current and waveshape of the output current of the following generator. Total capacitance of the generator is 53 μF. The charging voltage is 200 kV. The circuit inductance is 1.47 mH, and the dynamic resistance of the test object is 0.051 ohms.

Q.6.24 A single phase testing transformer rated for 2 kV/350 kV, 3500 kVA, 50 Hz on testing yields the following data: (i) No-load voltage on H.V. side = 2% higher than the rated value when the input voltage is 2 kV on the L.V. side. (ii) Short circuit test with H.V. side shorted, rated current was obtained with 10% rated voltage on the input side. Calculate the self-capacitance on the H.V. side and the leakage reactance referred to the H.V. side. Neglect resistance.

Q.6.25 Determine the ripple voltage and regulation of a 10 stage Cockcroft-Walton type d.c. voltage multiplier circuit having a stage capacitance = 0.01 μF, supply voltage = 100 kV at a frequency of 400 Hz and a load current = 10mA.

Q.6.26 A voltage doubler circuit has $C_1 = C_2 = 0.01$ μF and is supplied from a voltage source of $V = 100 \sin 314t$ kV. If the d.c. output current is to be 4 mA, calculate the output voltage and the ripple.

Q.6.27 The primary and secondary winding inductances of a Tesla coil are 0.093 H and 0.011 H respectively with a mutual inductance between the windings equal to 0.026 H. The capacitance included in the primary and secondary circuits are respectively 1.5 μF and 18 ηF. If the Tesla coil is charged through a 10 kV DC supply, determine the output voltage and its waveform. Neglect the winding resistances.

Q.6.28 An impulse current generator is rated for 60 kW sec. The parameters of the circuit are $C = 53$ μF, $L = 1.47$ μH and the dynamic resistance = 0.0156 ohm. Determine the peak value of the current and the time-to-front and the time-to-tail of the current waveform.

## WORKED EXAMPLES

**Example 6.1:** A Cockcroft-Walton type voltage multiplier has eight stages with capacitances, all equal to 0.05 μF. The supply transformer secondary voltage is 125 kV at a frequency of 150 Hz. If the load current to be supplied is 5 mA, find (*a*) the percentage ripple, (*b*) the regulation, and (*c*) the optimum number of stages for minimum regulation or voltage drop.

*Solution*: (*a*) *Calculation of Percentage Ripple*

$$\text{The ripple voltage } \delta V = \frac{I}{fC}\,\frac{(n)\,(n+1)}{2}$$

$I = 5$ mA, $f = 150$ Hz, $C = 0.05$ μF, and $n = 8$,

$$\therefore \qquad \delta V = \frac{5\times 10^{-3}}{150\times 0.05\times 10^{-6}}\times\frac{8\times 9}{2}$$

$$= 24 \text{ kV}$$

$$\%\text{ ripple} = \frac{\delta V\times 100}{2nV_{\max}} = \frac{24\times 100}{2\times 125\times 8}$$

$$= 1.2\%$$

(*b*) *Calculation of Regulation*

$$\text{Voltage drop, } \Delta V = \frac{I}{fC}\left(\frac{2}{3}n^3+\frac{n^2}{2}-\frac{n}{6}\right)$$

$$= \frac{5\times 10^{-3}}{150\times 0.05\times 10^{-6}}\left[\left(\frac{2}{3}\times 8^3\right)+\left(\frac{1}{2}\times 8^2\right)-\frac{8}{6}\right]$$

$$= 248 \text{ kV}$$

$$\therefore \qquad \text{regulation}\left(\frac{V}{2nV_{\max}}\right) = \frac{248}{2\times 8\times 125} = \frac{124}{1000}$$

$$= 12.4\%$$

(*c*) *Calculation of Optimum Number of Stages* ($n_{\text{optimum}}$)

Since $n > 5$,

$$n_{\text{optimum}} = \sqrt{V_{\max} fC/I}$$

$$= \sqrt{\frac{125\times 150\times 0.05\times 10^{-6}\times 10^{+3}}{5\times 10^{-3}}}$$

$$= \sqrt{125\times 1.5}$$

$$= 13.69$$

$$= 14 \text{ stages}$$

**Example 6.2:** A 100 kVA, 400 V/250 kV testing transformer has 8% leakage reactance and 2% resistance on 100 kVA base. A cable has to be tested at 500 kV using the above transformer as a resonant transformer at 50 Hz. If the charging current of the cable at 500 kV is 0.4 A, find the series inductance required. Assume 2% resistance for the inductor to be used and the connecting leads. Neglect dielectric loss of the cable. What will be the input voltage to the transformer ?

*Solution* : The maximum current that can be supplied by the testing transformer is

$$\frac{100\times 10^3}{250\times 10^3} 0.4 \text{ A}$$

$X_C =$ Reactance of the cable is

$$\frac{V_C}{I} = \frac{500\times 10^3}{0.4} = 1250 \text{ k}\Omega$$

$X_L =$ Leakage reactance of the transformer is

$$\frac{\%X}{100}\times\frac{V}{I} = \frac{8}{100}\times\frac{250\times 10^3}{0.4} = 50 \text{ k}\Omega$$

At resonance, $X_C = X_L$.
Hence, additional reactance needed

$$= 1250 - 50 = 1200\ \text{k}\Omega$$

Inductance of additional reactance (at 50 Hz frequency)

$$\frac{1200 \times 10^3}{2\pi \times 50} = 3820\ \text{H}$$

$R$ = Total resistance in the circuit on 100 kVA base is 2% + 2% = 4%.
Hence, the ohmic value of the resistance

$$= \frac{4}{100} \times \frac{250 \times 10^3}{0.4} = 25\ \text{k}\Omega$$

Therefore, the excitation voltage $E_2$ on the secondary of the transformer

$$\begin{aligned} &= I \times R \\ &= 0.4 \times 25 \times 10^3 \\ &= 10 \times 10^3\ \text{V or } 10\ \text{kV} \end{aligned}$$

The primary voltage or the supply voltage, $E_1$

$$\begin{aligned} &= \frac{10 \times 10^3 \times 400}{250 \times 10^3} \\ &= 16\ \text{V} \end{aligned}$$

$$\text{Input kW} = \frac{16}{400} \times 100 = 4.0\ \text{kW}$$

(The magnetizing current and the core losses of the transformer are neglected.)

**Example 6.3**: An impulse generator has eight stages with each condenser rated for 0.16 μF and 125 kV. The load capacitor available is 1000 pF. Find the series resistance and the damping resistance needed to produce 1.2/50 μs impulse wave. What is the maximum output voltage of the generator, if the charging voltage is 120 kV ?

*Solution* : Assume the equivalent circuit of the impulse generator to be as shown in Fig. 6.15b.

$C_1$, the generator capacitance $= \dfrac{0.16}{8} = 0.02\ \mu\text{F}$

$C_2$, the load capacitance $= 0.001\ \mu\text{F}$

$t_1$, the time to front $= 1.2\ \mu\text{s}$

$$= 3.0 R_1 \frac{C_1 C_2}{C_1 + C_2}$$

$$\therefore \quad R_1 = 1.2 \times 10^{-6} \frac{C_1 + C_2}{C_1 C_2} \times \frac{1}{3}$$

$$= 1.2 \times 10^{-6} \frac{0.021 \times 10^{-6}}{0.02 \times 0.001 \times 10^{-12}} \times \frac{1}{3}$$

$$= 420\ \Omega$$

$$t_2\text{, time to tail} = 0.7(R_1 + R_2)(C_1 + C_2)$$
$$= 50 \times 10^{-6}\ \text{s}$$

or, $0.7(420 + R_2)(0.021 \times 10^{-6}) = 50 \times 10^{-6}$

or, $R_2 = 2981\ \Omega$

The d.c. charging voltage for eight stages is

$$V = 8 \times 120 = 960\ \text{kV}$$

The maximum output voltage is

$$\frac{V}{R_1 C_2 (\alpha - \beta)} (e^{-\alpha t_1} - e^{-\beta t_1})$$

where $\alpha \approx \frac{1}{R_1 C_2}$, $\beta = \frac{1}{R_2 C_1}$ and $V$ is the d.c. charging voltage.

Substituting for $R_1$, $C_1$ and $R_2$, $C_2$,

$$\alpha = 0.7936 \times 10^{+6}$$
$$\beta = 0.02335 \times 10^{+6}$$

∴ maximum output voltage = 932.6 kV.

**Example 6.4**: An impulse current generator has a total capacitance of 8 μF. The charging voltage is 25 kV. If the generator has to give an output current of 10kA with 8/20 μs waveform, calculate (*a*) the circuit inductance and (*b*) the dynamic resistance in the circuit.

*Solution*: For an 8/20 μs impulse wave,

$$\alpha = R/2L = 0.0535 \times 10^{+6}$$

and, the product to $LC = 65$. Given $C = 8\ \mu\text{F}$ ($L$ in μH, $C$ in μF, and R in ohms) Therefore, the circuit inductance is

$$\frac{65}{C} = 8.125\ \mu\text{H}$$

The dynamic resistance $2L\alpha = 2 \times \frac{65 \times 10^{-6}}{8} \times 0.0535 \times 10^{+6}$

$$= 0.8694\ \text{ohms}$$

Peak current is given by $\frac{VC}{14} = 10\ \text{kA}$

($V$ in kV, $C$ in μF, and $I$ in kA),

∴ charging voltage needed is,

$$V = \frac{14 \times 10}{8} = 15.5\ \text{kV}$$

**Example 6.5** (*Alternative Solution*) : Assuming the wave to have a time-to-half value of 20 μs and a time-to-front of 8 μs, the time-to-first half cycle of the damped oscillatory wave will be 20 μs. Then

$$t_1 = t_f = 1/\omega\ [\arctan(\omega/\alpha)] = 8\ \mu\text{s}$$

and $t_2 = \pi/\omega = 20\ \mu\text{s}$

Therefore, $\omega = \pi/t_2 = \pi \times 10^6/20 = 0.1571 \times 10^6$

$\arctan(\omega/\alpha) = \omega \cdot t_1 = 1.2566.$

i.e. $\omega/\alpha = 0.8986$ radians

and $\alpha = 0.1748 \times 10^6.$

Then, $\sqrt{1/(LC) - \alpha^2} = 0.1571 \times 10^6.$

Substituting the value of $\alpha$ and simplifying,

$LC = 32.47 \times 10^{12}$, hence $L = 4.06\ \mu H$

and $R = 2L.\alpha = 1.419$ ohm

$i_m = V/\omega L \,.\, \text{Exp}\,(-\alpha t) = 10$ kA

$V = \omega L \times 10 \times \text{Exp}\,(-\alpha t) = 25.8$ kV.

**Example 6.6**: A 12-stage impulse generator has 0.126 μF condensers. The wave front and the wave tail resistances connected are 800 ohms and 5000 ohms respectively. If the load condenser is 1000 pF, find the front and tail times of the impulse wave produced.

*Solution*: The generator capacitance $C_1 = \frac{0.126}{12} = 0.0105\ \mu F$

The load capacitance $C_2 = 0.001\ \mu F$

Resistances, $R_1 = 800$ ohms and $R_2 = 5000$ ohms

$$\therefore \quad \text{time to front, } t_1 = 3(R_1)\left(\frac{C_1 C_2}{C_1 + C_2}\right)$$

$$= 3 \times 800 \times \frac{(0.0105 \times 10^{-6} \times 0.001 \times 10^{-6})}{(0.0105 + 0.001) \times 10^{-6}}$$

$$= 2.19\ \mu s$$

$$\text{time to tail, } t_2 = 0.7(R_1 + R_2)(C_1 + C_2)$$

$$= 0.7(800 + 5000) \times (0.0105 + 0.001) \times 10^{-6}$$

$$= 46.7\ \mu s$$

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