High Voltage Surge Generators

8.0 High Voltage Impulse Generators

In order that equipment designed to be used on high voltage lines, and others, be able to withstand surges caused in them during operation, it is necessary to test these equipment with voltages of the form likely to be met in service.

The apparatus which produces the required voltages is the impulse generator. In high voltage engineering, an impulse voltage is normally a unidirectional voltage which rises quickly without appreciable oscillations, to a peak value and then falls less rapidly to zero. A full impulse wave is one which develops its complete waveshape without flashover or puncture, whereas a chopped wave is one in which flash-over occurs causing the voltage to fall extremely rapidly. The rapid fall may have a very severe effect on power system equipment.

The lightning waveform, is a unidirectional impulse of nearly double exponential in shape. That is, it can be represented by the difference of two equal magnitude exponentially decaying waveforms. In generating such waveforms experimentally, small oscillations are tolerated. Figure 8.1 shows the graphical construction of the double exponential waveform

$$v(t) = V\,(e^{-\alpha t} - e^{-\beta t})$$

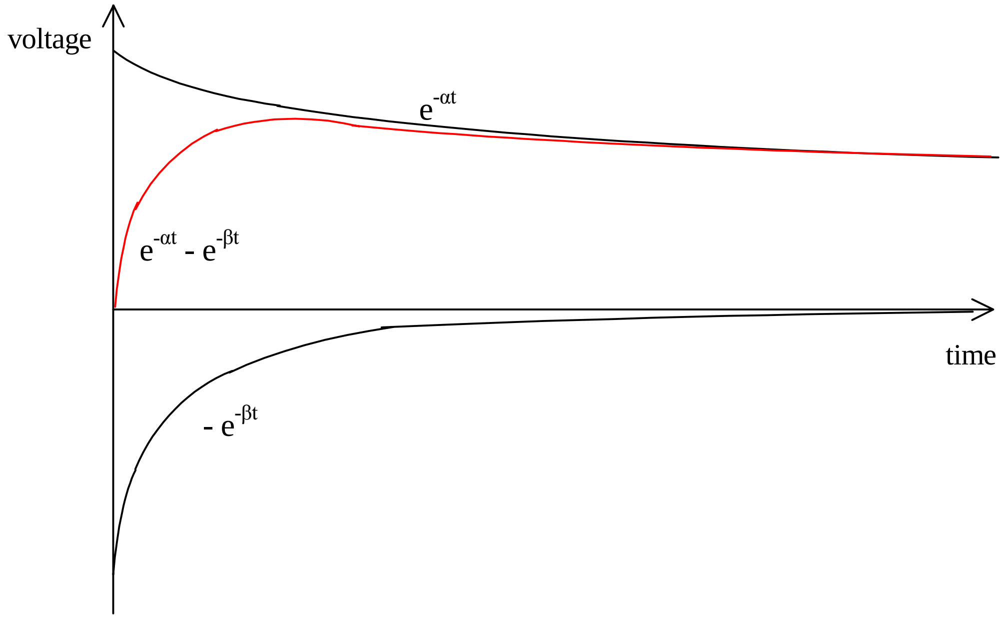


Figure 8.1 - Double exponential waveform

In most impulse generators, certain capacitors are charged in parallel through high series resistances, and then discharged through a combination of resistors and capacitors, giving rise to the required surge waveform across the test device.

8.1 Impulse Waveform

8.1.1 Single exponential waveform

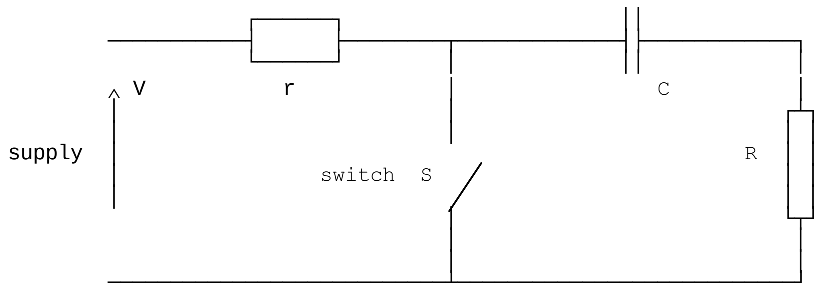


Figure 8.2 - Circuit to produce single exponential waveform

Consider the circuit shown in figure 8.1, The capacitor C is charged through the high series resistor r so that the capacitor gradually charges up to the supply voltage V. During the charging process there will be a small voltage across the load R, which falls to zero as the capacitor charges up. If the switch S is now closed, the charge on the capacitor discharges through the resistance R so that instantaneously the voltage across R rises to V and will then decay exponentially according to the equation $v = V\ e^{-t/CR}$, where CR is the time constant of the discharging circuit.

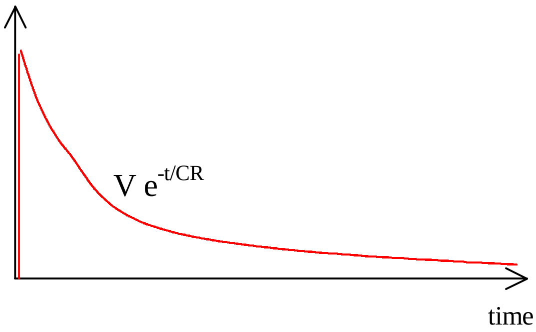


Figure 8.3 - Single exponential waveform

For this waveform, the rise time (wavefront time) is zero, and the time to fall to half maximum (wavetail time) corresponds to CR $\log_e 2$.

8.1.2 Double exponential waveform

The simple RC circuit to obtain the single exponential voltage waveform can be modified to generate a double exponential waveform by the addition of another capacitor to the circuit. Figure 8.4 shows the circuit used, with the capacitor C_1 being initially charged from an outside circuit.

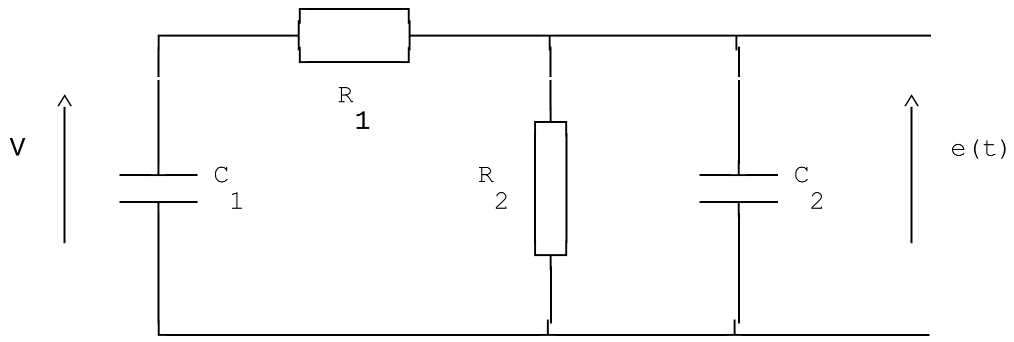


Figure 8.4 - Circuit to produce double exponential waveform

This circuit can be analysed using the Laplace transform equivalent circuit shown in figure 8.5.

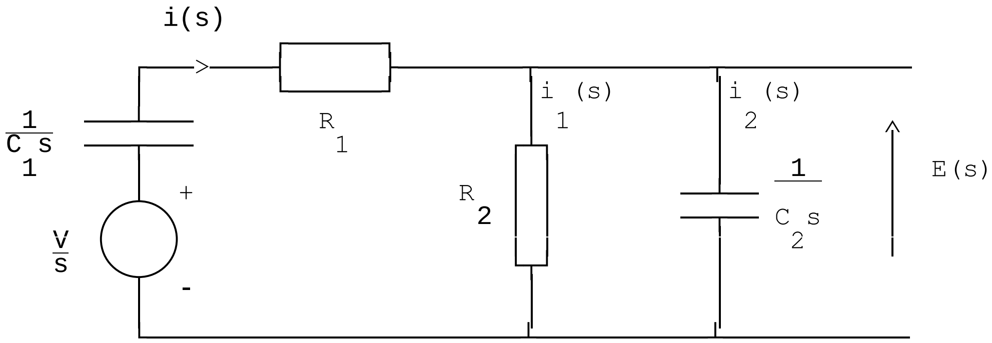


Figure 8.5 - Laplace equivalent circuit for double exponential

This circuit can be analysed in the following manner.

$$\frac{V}{s} = i(s)\,.\,\frac{1}{C_1\, s} + i(s)\,.\,R_1 + i_1(s)\,.\,R_2$$

$$E(s) = i_1(s)\,.\,R_2 = i_2(s)\,.\,\frac{1}{C_2\, s}, \quad \text{also} \quad \mathrm{i(s)} = \mathrm{i_1(s)} + \mathrm{i_2(s)}$$

$$\therefore\ \mathrm{i_1(s)\,.\,(\,R_2 + R_1 + \frac{1}{C_1 s}) + i_2(s)\,.\,(\,R_1 + \frac{1}{C_1 s}) = \frac{V}{s}}$$

$$\text{Also} \quad \mathrm{i_2(s) = C_2\, R_2\, s\,.\,i_1(s)}$$

$$\therefore\ \mathrm{i_1(s)\,.\,(\,R_2 + R_1 + \frac{1}{C_1 s} + R_1\, C_2\, R_2\, s + \frac{R_2\, C_2}{C}) = \frac{V}{s}}$$

$$\text{substitution gives} \quad \mathrm{E(s) = i_1(s)\,.\,R_2 = \frac{V\, C_1\, R_2}{R_1\, R_2\, C_1\, C_2\, s^2 + (C_1\, R_2 + C_1\, R_1 + C_2\, R_2)\, s + 1}}$$

If α and β are the solutions of the equation

$$\mathrm{R_1\, R_2\, C_1\, C_2\, s^2 + (C_1\, R_1 + C_1\, R_2 + C_2\, R_2)\, s + 1 = 0}$$

then the Laplace transform expression can be simplified as follows.

$$E(s) = \frac{V}{R_1\, C_2}\,.\,\frac{1}{(s+\alpha)(s+\beta)} = \frac{V}{R_1\, C_2}\,.\,\frac{1}{\beta - \alpha}\,.\left[\frac{1}{s+\alpha} - \frac{1}{s+\beta}\right]$$

$$\text{This gives} \quad \mathrm{e(t)} = \frac{\mathrm{V}}{\mathrm{C_2\, R_1}}\,.\,\frac{1}{\beta - \alpha}\,(e^{-\alpha t} - e^{-\beta t})$$

It is seen that the output waveform is of the double exponential form required.

For a 1/50 μs waveform, it can be shown that $\alpha \approx 0.0139$, and $\beta \approx 6.1$ when t is in μs. Also for the standard 1.2/50 μs IEC waveform, $\alpha \approx 0.0143$ and $\beta \approx 4.87$.

The alternate form of the circuit shown in figure 8.6 can also be used to obtain the double exponential waveform. The analysis of this circuit is also very similar.

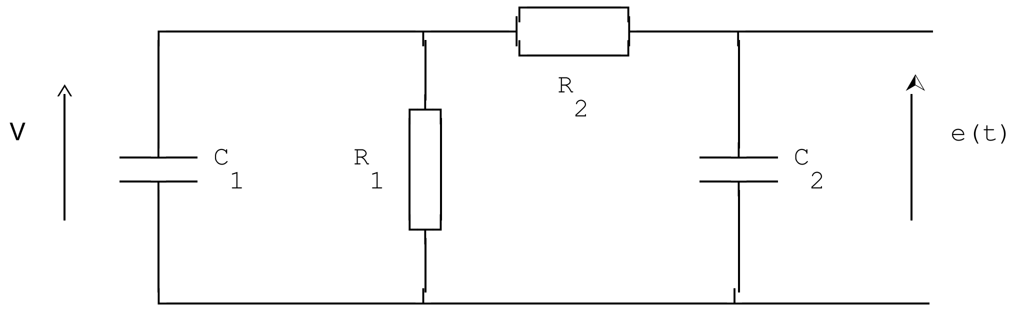


Figure 8.6 - Alternate Circuit to produce double exponential waveform

In practice, in addition to the main capacitors and inductors shown in the impulse generator circuit considered, stray capacitances will also be present. These will cause the order of the Laplace transform equation to become much higher and more complicated. Thus the actual waveform generated would be different and would contain superimposed fluctuations on the impulse waveform as shown in figure 8.7.

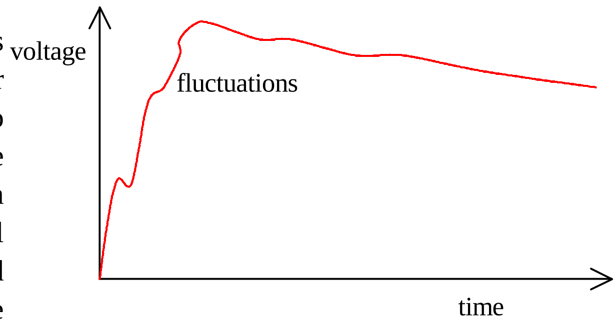


Figure 8.7 - Waveform with fluctuations

8.1.3 Calculation of α and β from resistance and capacitance values

Consider again the expression for the surge voltage

$$e(t) = \frac{V}{C_2 R_1} \cdot \frac{1}{\beta - \alpha} \cdot (e^{-\alpha t} - e^{-\beta t})$$

The peak value of this voltage occurs when its derivative becomes zero.

$$\frac{d\, e(t)}{d\, t} = 0, \quad \text{giving} \quad \alpha\, e^{-\alpha t} = \beta\, e^{-\beta t}$$

$$\because \ \beta >> \alpha, \qquad e^{(\beta - \alpha) t_1} = \frac{\beta}{\alpha} \approx e^{\beta t} \quad \text{------(1)}$$

$$\text{maximum value of voltage is} \quad E_{max} = \frac{V}{C_2 R_1} \cdot \frac{1}{\beta - \alpha} (1 - \alpha - \frac{\alpha}{\beta}) \approx \frac{V}{\beta\, C_2 R_1}$$

After reaching the peak, the voltage falls to half maximum in time t_2 given by

$$\frac{V}{2\,\beta\, R_1 C_2} \approx \frac{V}{\beta\, C_2 R_1} \cdot e^{-\alpha t_2}, \quad \because \ e^{-\beta t_2} << e^{-\alpha t_2}$$

$$\therefore \quad e^{-\alpha t_2} \approx \tfrac{1}{2} \quad \text{------(2)}$$

From equations (1) and (2) it is seen that the wavefront time t_1 is determined predominantly by β, and the wavetail time predominantly by α.

α and β are the solutions of the following quadratic equation in s.

$$R_1 R_2 C_1 C_2 s^2 + [\,(C_1 + C_2) R_2 + R_1 C_1\,] . s + 1 = 0$$

$$\text{so that} \quad \alpha . \beta = \frac{1}{R_1 R_2 C_1 C_2},$$

$$\text{also} \quad \alpha + \beta = \frac{(C_1 + C_2) R_2 + R_1 C_1}{R_1 R_2 C_1 C_2} \approx \beta \quad \because \beta \ll \alpha$$

$$\therefore \; \alpha \approx \frac{1}{(c_1 + C_2) R_2 + C_1 R_1}$$

$$\text{generally} \quad R_1 << R_2, \quad \text{so that}$$

$$\beta \approx \frac{C_1 + C_2}{R_1 C_1 C_2} \qquad \text{-----}(3)$$

$$\alpha \approx \frac{1}{(C_1 + C_2) R_2} \qquad \text{-----}(4)$$

Since β is a function of R_1, and α is a function of R_2, the effect of R_1 will be to determine the rate of rise of voltage across the load, and thus the wavefront time. It is thus known as the wavefront control resistance.

The maximum voltage available at the output is given by

$$E_{\max} = \frac{V}{\beta\, C_2 R_1} = \frac{V\, R_1 C_1 C_2}{(C_1 + C_2) C_2 R_1} \approx V . \frac{C_1}{C_1 + C_2}$$

Thus the maximum (peak) voltage available at the output will depend on the ratio of C_2 to C_1, and on the charging voltage. If C_2 is low compared to C_1, then we can have a higher voltage peak. The voltage efficiency of the impulse generator can be approximately be estimated as $C_1/(C_1 + C_2)$ multiplied by a factor of about 0.95 (to account for approximations made in the analysis).

The wavefront control resistance can be connected either outside or within the impulse generator, or partly within and partly outside.

8.1.4 Definition of Wavefront and Wavetail times of practical waveforms

In practical impulse waveforms, the initial region and near the peak in the voltage are not very well defined. Also, near zero and near the peak, the rate of change is quite often much less than in the rest of the wavefront. Hence the wavefront time is not well defined. It is thus usual to define the wavefront by extrapolation based on a rise time for a specific change (say 10% to 90% or in even from 30% to 90% when the initial region is not clear). Figure 8.8 shows how the measurement of this rise time is made.

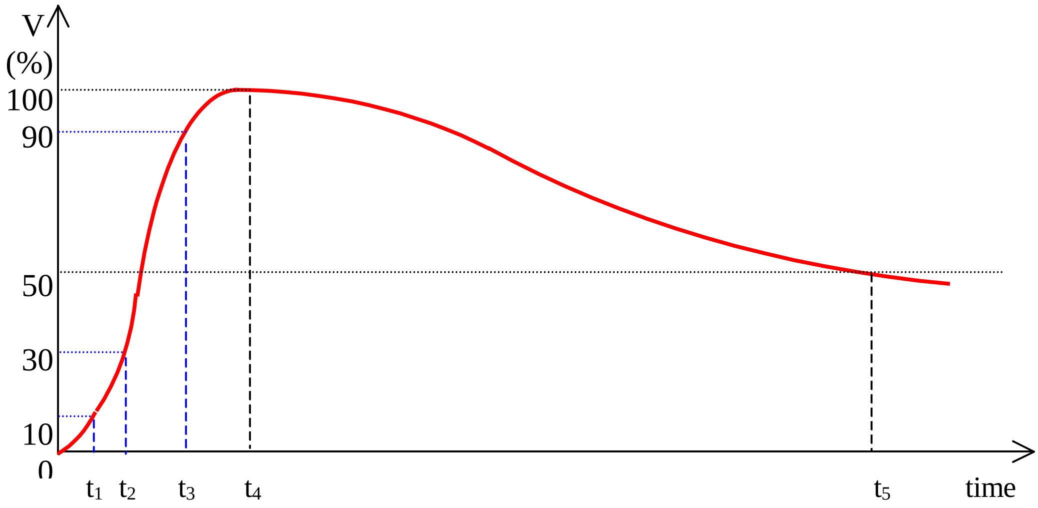


Figure 8.8 - Definition of wavefront

The wavefront time is given as $(t_3 - t_1)/(0.9 - 0.1)$ or $1.25\ (t_3 - t_1)$ for the 10% to 90% measurement and as $(t_3 - t_2)/(0.9 - 0.3)$ or $1.67\ (t_3 - t_2)$ for the 30% to 90% measurement.

The wavetail time is defined as the time from the initial point of the waveform to falling to 50 % of peak. In the case where the initial point is not well defined, the initial point may be extrapolated from the wavefront.

8.1.5 A valid approximate analysis of double exponential impulse generator circuit

The properties that in practical impulse waveforms the wavefront time is usually very much smaller than the wavetail time ($t_f << t_t$ and $\alpha << \beta$), and that impulse generators are designed for a high voltage efficiency may be made use of in making approximations to the solution.

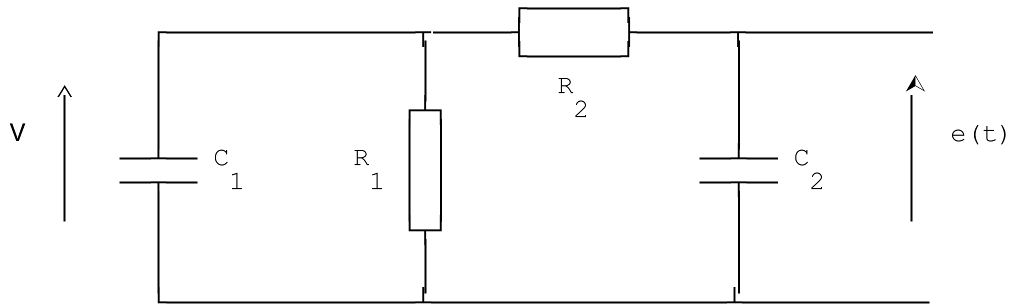


Figure 8.9 - Circuit to produce double exponential waveform

Consider the circuit shown in figure 8.9. Also, to obtain a small wavefront time and a long wavetail time, the series resistance R_2 must be small and the shunt resistance R_1 must be comparatively much larger.

Thus to analyse the wavefront, it is permissible to open circuit the resistor R_1 and redraw the approximate circuit as shown in figure 8.10.

During the wavefront, the charging rate was seen from figure 8.1 to be dependant mainly on the inverse time constant β. This should thus correspond to the inverse of the time constant of the approximate circuit.

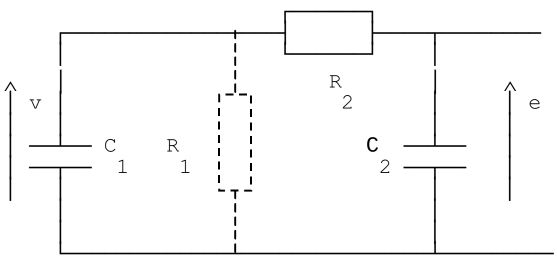


Figure 8.10 - Circuit to analyse wavefront

Thus

$$\beta \approx \frac{1}{R_2 C_{eq}} = \frac{C_1 + C_2}{R_2 C_1 C_2}$$

$$\text{where} \quad C_{eq} = \frac{C_1 C_2}{C_1 + C_2}, \quad \because C_1, C_2 \text{ are series}$$

which is the same expression obtained using the normal method of analysis. The approximate voltage efficiency of the impulse generator can also be determined from this circuit. The maximum possible value of the output voltage **e** that can be obtained can be determined by potential divider action. Thus

$$e = \frac{C_1}{C_1 + C_2} . v \quad \text{neglecting resistance } R_2$$

$$\therefore \text{ efficiency } \eta = \frac{e}{v} = \frac{C_1}{C_1 + C_2}$$

which also corresponds to the simple expression obtained earlier.

To obtain a high voltage efficiency, a large proportion of the energy from the initially charged capacitor C_1 must be retained in the capacitor C_1, so that $C_1 > C_2$.

Similarly, since both capacitors discharge through the resistor R_1, and since $R_1 >> R_2$, to analyse the wavetail, it is permissible to short circuit the resistor R_2 and redraw the approximate circuit as shown in figure 8.11.

During the wavetail, the discharging rate was seen from figure 8.1 to be dependant mainly on the inverse time constant α. This should thus correspond to the inverse of the time constant of the approximate circuit. Thus

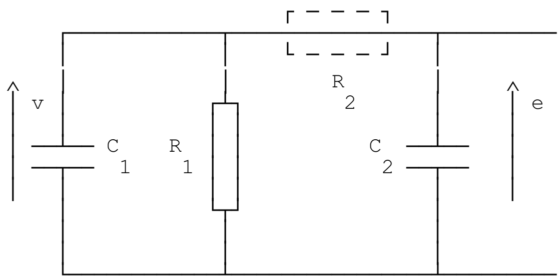


Figure 8.11 - Circuit to analyse wavetail

$$\alpha \approx \frac{1}{R_1 C_{eq}} = \frac{1}{R_1 (C_1 + C_2)}$$

$$\text{where} \quad C_{eq} = C_1 + C_2, \quad \because C_1, C_2 \text{ are paralleled}$$

which is the same expression obtained using the normal method of analysis.

8.1.6 Wavefront and Wavetail Control

In a practical impulse generator circuit, the nominal voltage is defined by the peak theoretical voltage and the nominal energy is defined by the maximum stored energy. The capacitance values in the impulse generator circuit are not variable except for the capacitance contribution of the test object. Thus waveshape control is achieved by varying the resistance values.

As has already been derived

$$\alpha = \frac{1}{R_1 (C_1 + C_2)}, \quad \beta = \frac{C_1 + C_2}{R_2 C_1 C_2}, \quad \eta = \frac{C_1}{C_1 + C_2}$$

$$\text{giving} \quad \frac{1}{\alpha} = \frac{R_1 C_1}{\eta}, \quad \frac{1}{\beta} = \eta R_2 C_2$$

The wavefront time $\mathbf{t_f}$ and the wavetail time $\mathbf{t_t}$ may be evaluated as follows.

Defining the wavefront from 10 % to 90 % and considering only that β determines the wavefront,

$$t_f = \frac{(t_b - t_a)}{0.9 - 0.1} = 1.25\,(t_b - t_a)$$

$$1 - 0.1 = e^{-\beta t_a}, \quad 1 - 0.9 = e^{-\beta t_b}$$

$$\text{so that} \quad t_a = -\frac{1}{\beta}\log_e(0.9) = \frac{0.1054}{\beta}, \quad t_b = -\frac{1}{\beta}\log_e(0.1) = \frac{2.3026}{\beta}$$

$$\text{i.e.} \quad t_f = 1.25\,(t_b - t_a) = \frac{1.25 \times 2.197}{\beta} = \frac{2.75}{\beta}$$

$$\text{i.e.} \quad t_f = 2.75\,\eta\, R_2 C_2$$

It can also be shown that if the wavefront is considered from 30 % to 90 %, the corresponding expression becomes

$$t_f = 3.243\,\eta\, R_2 C_2$$

Similarly, defining the wavetail time as the time to decay to 50 % of peak, and considering only that α determines the wavetail,

$$0.5 = e^{-\alpha t_t}, \quad \text{so that} \quad \alpha = -\frac{\log_e 0.5}{t_t}, \quad \text{giving} \quad t_t = \frac{0.693}{\alpha}$$

$$\text{Thus} \quad t_t = \frac{0.693\, R_1 C_1}{\eta}$$

8.2 Operation of Impulse Generator

8.2.1 Uncontrolled operation

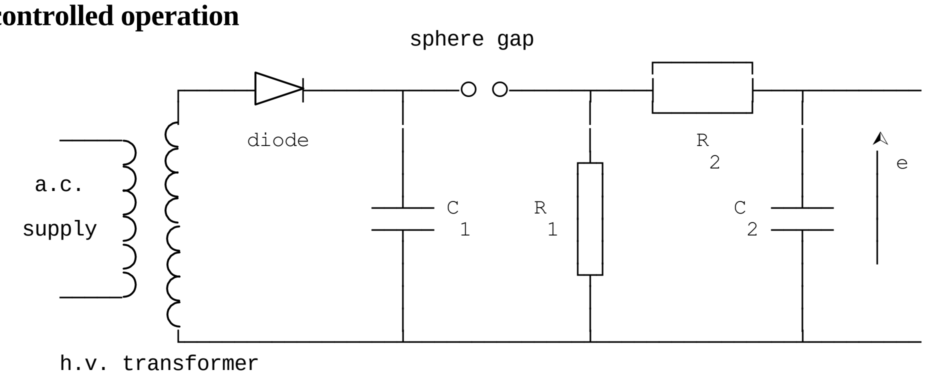


Figure 8.12 - Circuit for uncontrolled operation

In the simplest form of the single stage impulse generator, shown in figure 8.12, the high direct voltage required is obtained from a high voltage transformer through a high voltage rectifier. The direct voltage need not be smooth as it only has to charge the first capacitor to peak value. A sphere gap is used as the switch, and as the charge on the capacitor builds up, so does the voltage across the sphere gap.

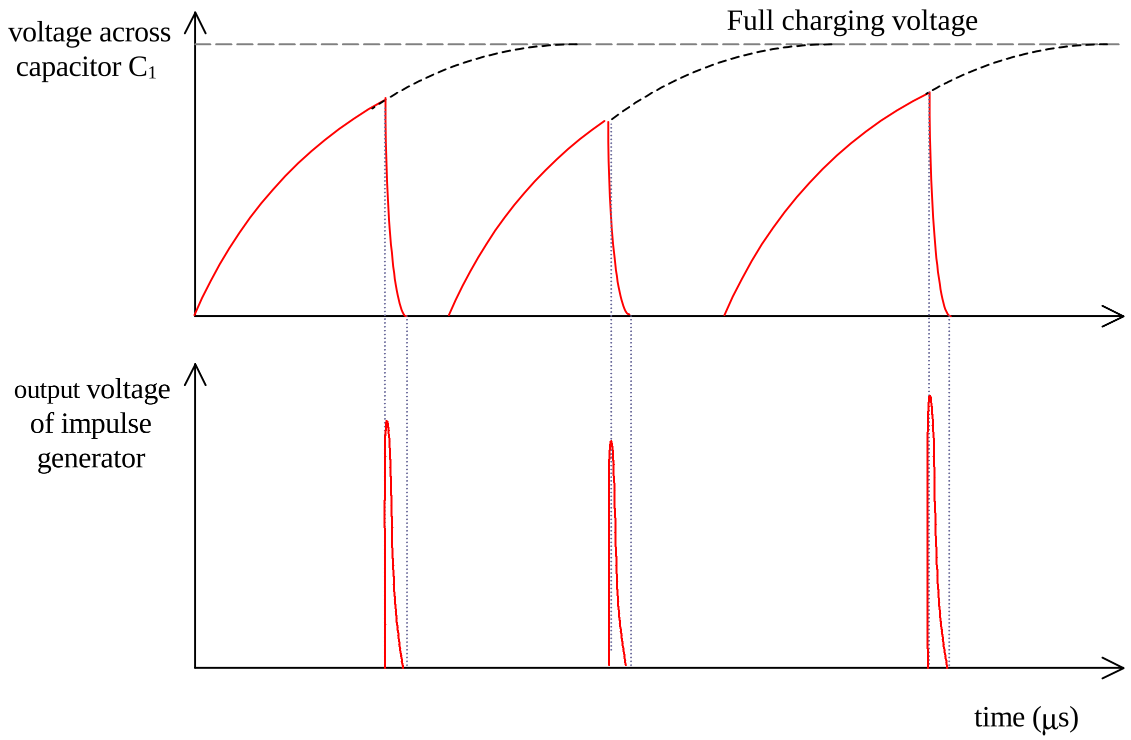


Figure 8.13 - Impulse generator waveforms for uncontrolled operation

In the uncontrolled operation, the break down voltage of the sphere gap is less than the peak value of the supply, so that it effectively closes when the voltage across the gap builds up above its breakdown value. The capacitor would then discharge through the impulse generator circuit producing an impulse waveform. The impedance of the impulse generator charging circuit is much higher than that of the impulse generator circuit so that during the impulse the rectifier and other related components can be disregarded. Subsequently, the capacitor would charge up again and the process would be repetitive. However, as the breakdown of a sphere gap is not exactly a constant but statistical, the time of occurrence of the impulse nor the exact magnitude are controllable. The waveforms of the voltage of the charging capacitor and of the impulse generator output are shown in figure 8.13.

8.2.2 Controlled operation

In the controlled mode of operation, the same basic circuit is used, but the capacitor is allowed to reach the full charging voltage without the sphere gap breaking down. The spark over voltage is set at slightly higher than the charging voltage. In this case, at the sphere gap we need a special arrangement, such as a third sphere between the other two, to be able to initiate breakdown of the gap. The modified circuit is shown in figure 8.14.

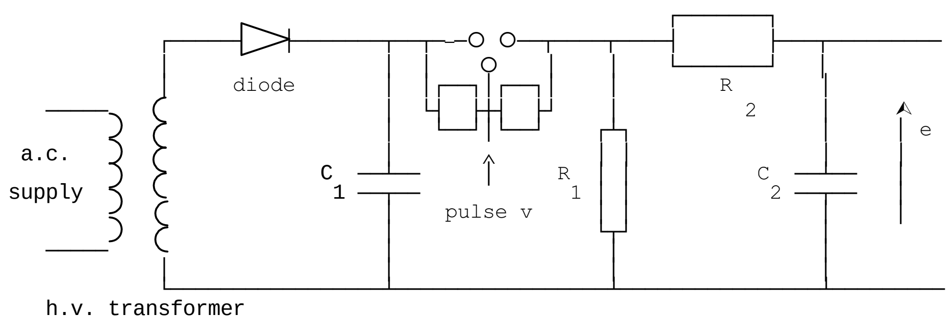


Figure 8.14 - Circuit for controlled operation

The potential across the main gap is divided into two by means of 2 equal resistors R, each of about 100 MΩ. By this means, half the applied voltage V appears across each of the two auxiliary gaps.

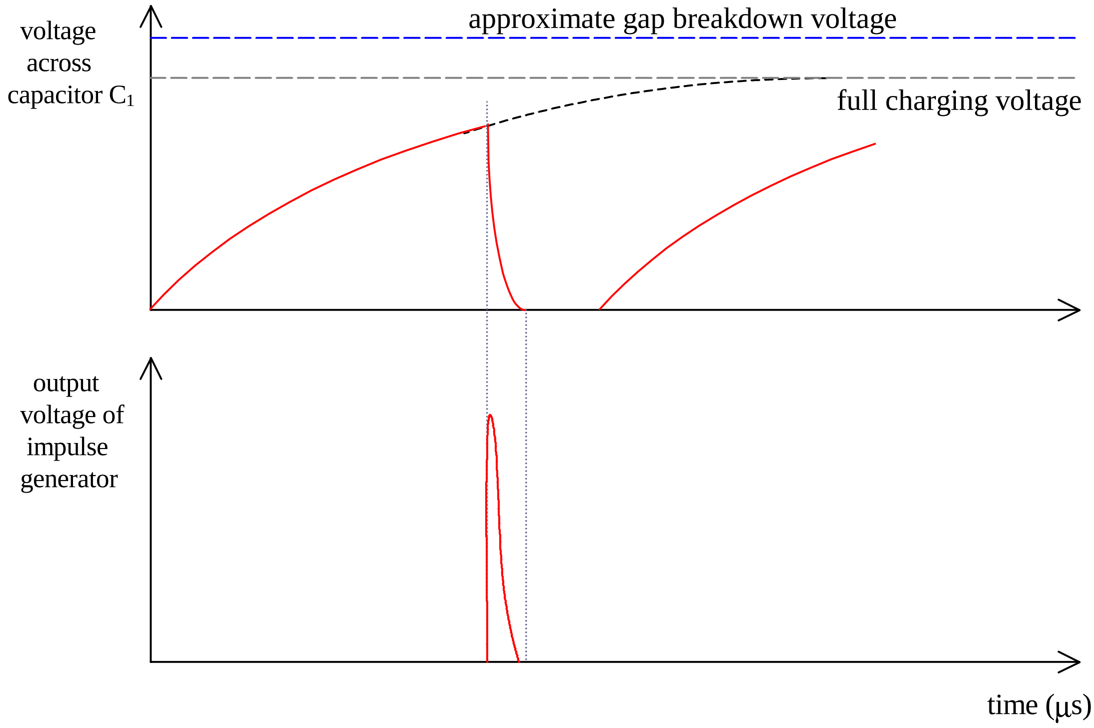


Figure 8.15 - Impulse generator waveforms for controlled operation

Once the capacitor C_1 has charged up to the full value, a small pulse voltage **v** is applied (about 20 %) at the third electrode (also known as the trigger electrode). This pulse raises the voltage across one of the auxiliary gaps to more than half the charging voltage (½ V + v) so that it would be just sufficient to breakdown the gap. As this auxiliary gap breaks down, the full voltage would be applied across the remaining auxiliary gap causing it also to breakdown.

Once both auxiliary gaps have broken down, the ionisation present in the region would cause the main gap also to breakdown almost simultaneously and thus the impulse voltage would be applied. The waveforms for the controlled operation are shown in figure 8.15.

8.2.3 Trigatron gap

The third sphere arrangement described for the trigger arrangement is not very sensitive. A better arrangement is to have an asymmetrical gap arrangement. The trigatron gap is such an arrangement which is in general use.

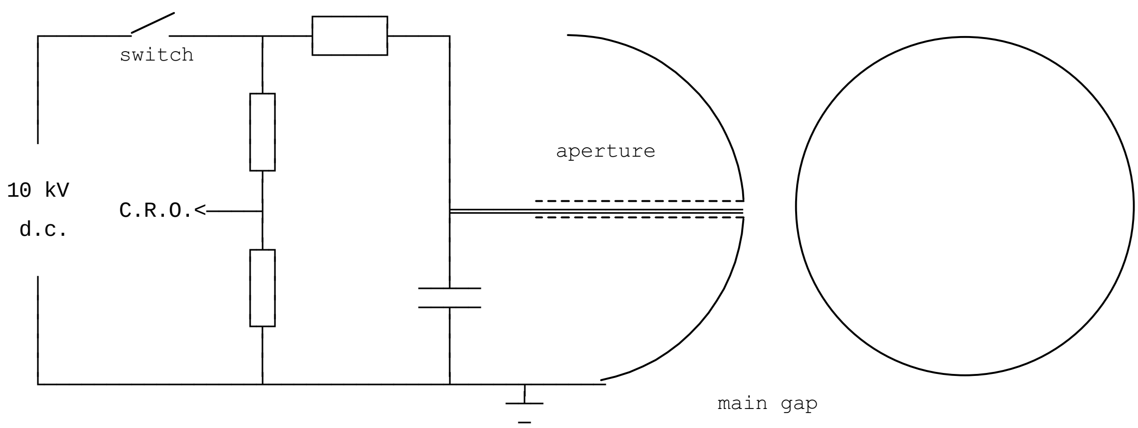


Figure 8.16 - Trigatron gap arrangement

The main gap has one of its spherical electrodes earthed, and as a cup with a hole at the centre. A pin protrudes through it, and is insulated from the electrode with solid insulation. The pin has an auxiliary circuit which can supply high voltage of about 10 kV to it. Since the pin is sharp, corona is produced at a relatively low voltage causing it to spark over to the earthed electrode.

Thus when the generator needs to be energised, a pulse is applied to the pin. Breakdown of the pin gap simultaneously causes the main gap and hence the impulse generator to operate. A delay is usually provided between the auxiliary d.c. source and the pin so that the oscilloscope time base can be started just prior to the impulse being initiated. When the polarity of the generator is changed, it is necessary to change the polarity of the auxiliary supply as well. Since the pilot gap is much smaller than the main gap, we need to apply only a proportionately lower pulse for initiation. Also the performance with the trigatron gap is much more consistent than with the third sphere arrangement.

8.3 Multi-stage Impulse Generators

To obtain large impulse voltages, a multistage impulse generator is used so that the relative size of the high voltage transformer can be kept small, and the costs small. The basic idea is to charge a number of capacitors in parallel through a rectifier from a high voltage transformer and then to discharge them in series, giving the nominal output voltage equal to the charging voltage multiplied by the number of stages in the impulse generator.

In the practical circuit, the capacitors are not all charged to the same voltage, due to the resistances that come in series during charging being not negligible compared to the leakage resistances of the capacitors (especially when the number of stages are large). In theory, the number of gaps and the capacitors may be increased to give almost any desired multiple of the charging voltage and it has been found feasible in practice to operate a 50 stage impulse generator. The number which can be used successfully is limited to some extent, however, by the fact that the high resistance between the supply and the distant capacitors reduce the impulse voltage obtainable.

Two of the commonly used impulse generator circuits are shown. However, as the principles involved are similar only one will be described.

8.3.1 Marx Impulse Generator Circuit

Marx was the first to propose that multistage impulse generators can be obtained by charging the capacitors in parallel and then connecting them in series for discharging.

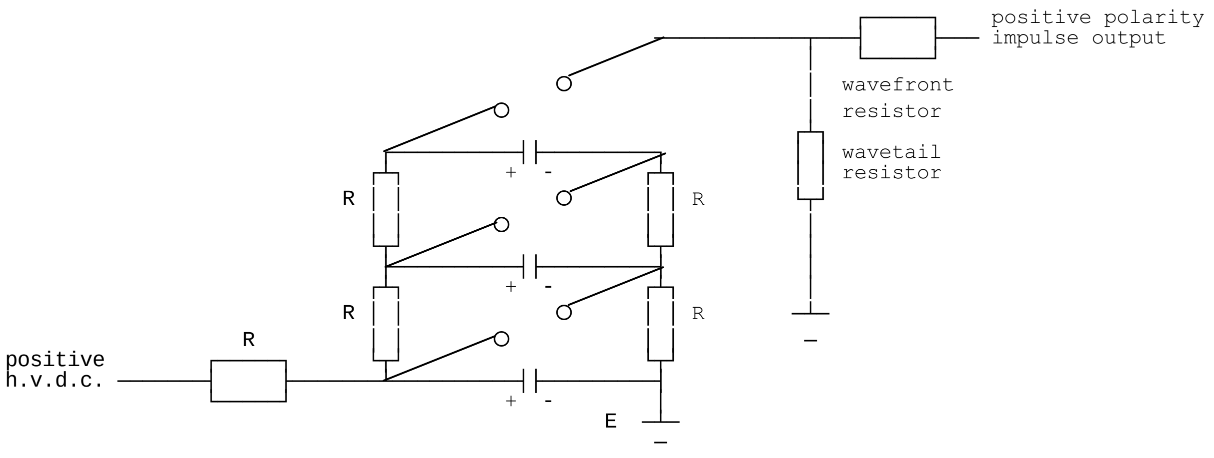


Figure 8.17 - Marx Impulse generator circuit

In the circuit shown in figure 8.17, the resistances R are the charging resistors which are very high in value, and selected such that charging of all capacitors occurs in about 1 minute. The waveshaping circuit is external to the capacitor stages shown. The waveform of the surge generated depends on the resistance, inductance and capacitance of the testing circuit connected. In the modified Marx circuit is more common use, the part of the charging resistors are made use of for waveshape control.

8.3.2 Goodlet Impulse Generator Circuit

The Goodlet impulse generator circuit is very similar to the Marx impulse generator circuit except that the Goodlet circuit gives a negative polarity output for a positive polarity input while the Marx circuit gives the same polarity output.

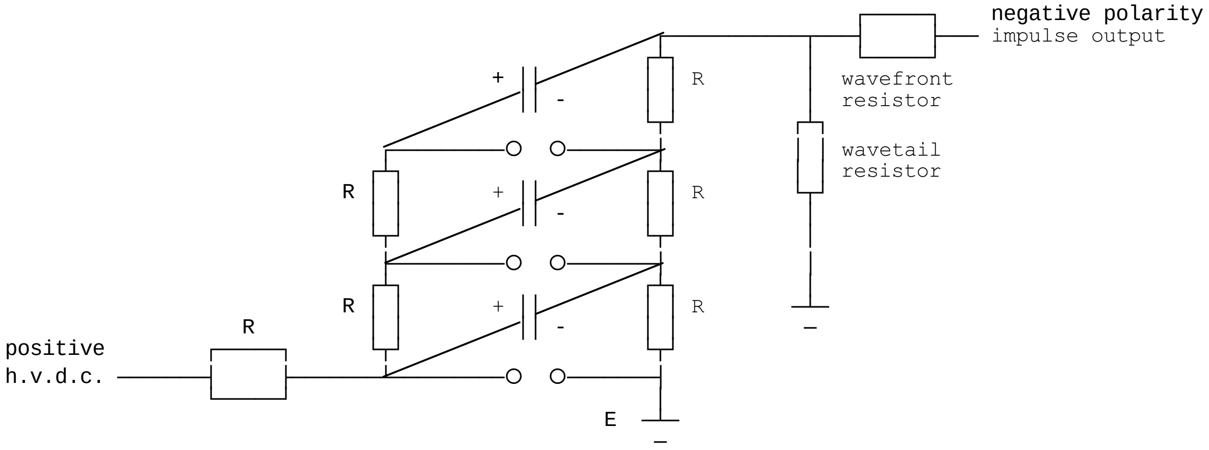


Figure 8.18 - Goodlet Impulse generator circuit

Since all the gaps in the impulse generator should be of almost the same spacing, if they are to breakdown in succession, the spheres of the gaps are fixed along an insulating rod which can be rotated so that the gaps simultaneously increase or decrease as required.

In the case of a controlled impulse generator, the magnitude of the impulse voltage is not directly dependant on the gap spacing as in the case of uncontrolled generators. In this case, a certain range of impulse voltages are available for the same gap spacing. This range is determined by the conditions that (a) uncontrolled operation should not occur, (i.e. the spark over voltage of the gaps must be greater than the applied direct voltage), and (b) the spark over voltage must not be very much larger than the applied voltage (in which case breakdown cannot be initiated even with the pulse).

8.3.3 Simultaneous breakdown of successive sphere gaps

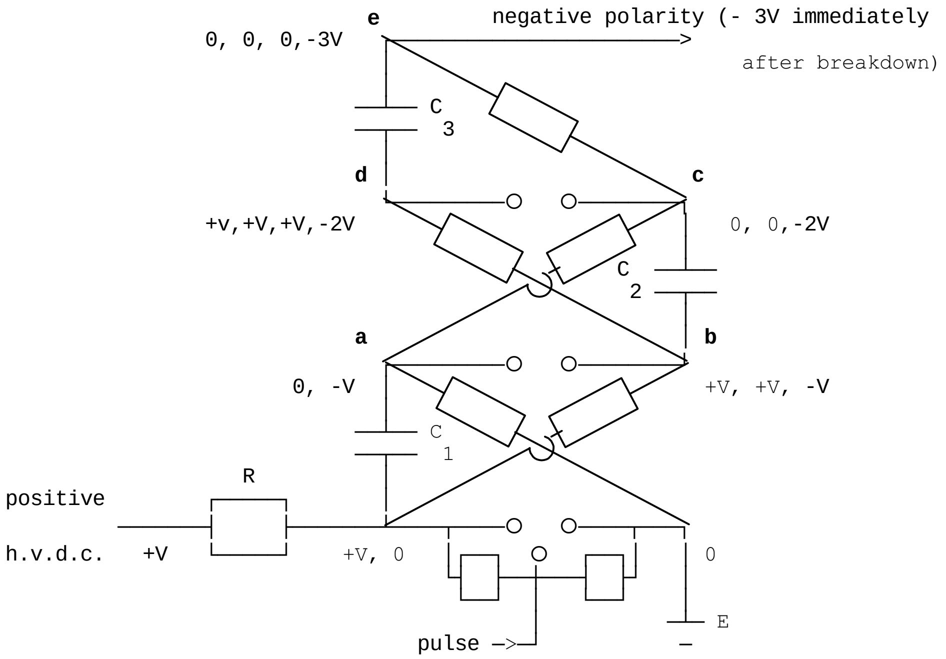


Figure 8.19 - Physical arrangement of the Goodlet Impulse generator circuit

The resistance and capacitance units are arranged so that the sphere gaps are placed one above the other. The capacitors are placed in either two or 4 parallel columns, and the resistances are arranged in a diagonal manner, as shown. The capacitors are mounted vertically above each other with layers of insulation separating them. This arrangement is shown in figure 8.19, without the waveshape control elements.

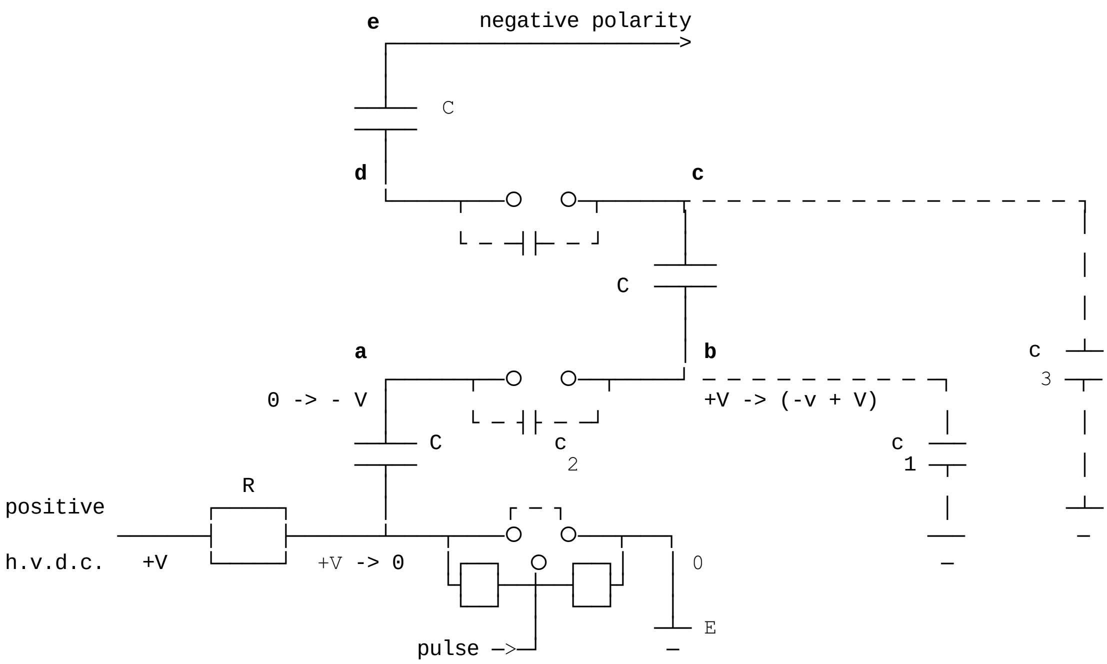
Once the initial pulse breaks down the first gap, the breakdown of the successive gaps occurs in the following manner.

If the supply voltage is **+V**, under steady charged condition and before the breakdown of the gaps, the voltage across each capacitor will be **V**, assuming the leakage across the capacitors is negligible.

When the trigger pulse is applied, the breakdown of the trigger electrode and hence of the first gap occurs, and the voltage across it falls to zero (disregarding the arc voltage drop). As the voltage across the capacitor C_1 cannot change instantly, the voltage at **a** must fall to **-V** from **0**. Due to the initial voltage **+V** at **b**, which also occurs across the stray capacitance to earth at **b**, and since this stray capacitance too cannot discharge suddenly, the voltage at **b** must remain at **+V**. Thus a voltage of **+2V** must appear across the second gap **ab**. This voltage is sufficient to breakdown the gap (as the settings of the gaps are so arranged), and thus the gap breaks down. This breakdown causes the voltage at **b** to change to that at **a** (i.e. to **-V**). Since C_2 does not discharge suddenly, the voltage at **c** falls to **-2V.** The voltage at **d** would remain at **+V** which value it would have reached when **b** became **+V**. Thus the voltage of **3V** across the third gap breaks it down. Similarly, any other gaps present would breakdown in succession.

Effect of sphere gap capacitances on the successive breakdown

In the above analysis, the sphere gaps are assumed to be large and the stray capacitances across the gaps have been neglected. However, when the voltage of the impulse generator is increased, the gaps further. In this case we must also take the gap capacitance into account. Figure 8.20 shows the impulse generator circuit with the stray capacitances also indicated, and with $C_1 = C_2 = C_3 = C$.



c_1, c_2 and c_3 are stray capacitances

[Some of the resistors have been left out of the figure for clarity of presentation]

Figure 8.20 - Stray Capacitances of the Goodlet Impulse generator circuit

When the first gap breaks down due to the trigger pulse, since one end of the gap is at each potential, the other end will also come to earth potential. Since the voltage across the first capacitor cannot change suddenly, the voltage at **a** falls to **- V**. This change of **-V** would cause, by potential divider action, a change of

$$\frac{v}{V} = \frac{c_2}{c_2 + c_1 + \dfrac{c_3\,C}{c_3 + C}}$$

voltage of **- v** at **b**, so that the voltage at **b** just after the breakdown of the first gap is (**- v + V**). From figure 8.21

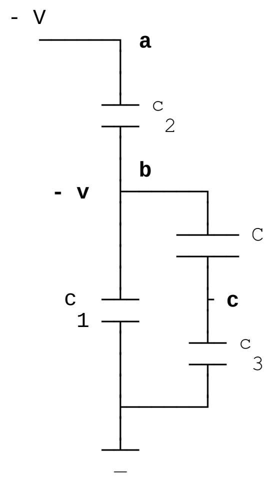


Figure 8.21

Being stray capacitance, $c_3 << C$, so that $\dfrac{c_3\,C}{c_3 + C} \approx c_3$

$$\therefore \frac{v}{V} = \frac{c_2}{c_1 + c_2 + c_3}$$

Therefore the potential at **b** after the breakdown of the first gap is given by

$$v_b = -v + V = V\left[1 - \frac{c_2}{c_1 + c_2 + c_3}\right]$$

At this instant, the potential at **a** has fallen from **0** to **- V**. Therefore the potential difference across **ab** after breakdown of the gap is given by

$$v_{ab} = -v - V\left[1 - \frac{c_2}{c_1 + c_2 + c_3}\right]$$

$$= V\left[2 - \frac{c_2}{c_1 + c_2 + c_3}\right] = V\left[1 + \frac{c_1 + c_3}{c_1 + c_2 + c_3}\right]$$

If the gap is large, $c_2 = 0$, and the voltage across the second sphere gap is **2V**, which is the ideal case, since this ensures the breakdown of successive gaps.

On the other hand, if $c_1 + c_3$ is small compared to c_2, then the voltage across the second sphere gap is approximately equal to **V**, so that the breakdown of successive gaps would not occur. Therefore, for good operating conditions, $c_1 + c_3$ must be large, and c_2 small, so that the upper gaps would breakdown simultaneously.

Generally, for a small impulse generator, since the sphere gap is small, c_2 is high and $c_1 + c_3$ small, so that the conditions for the breakdown of successive gaps is poor. In this case, c_1 can be deliberately increased to improve breakdown conditions. In the case of large impulse generators, c_2 is small, so that the conditions are favourable for the breakdown of the upper gaps.

Effect of illumination on the breakdown of gaps

In general the voltage appearing across an upper gap, on the breakdown of the gap immediately below it, must be sufficient to initiate the breakdown of the gap. Since breakdown must be almost instantaneous, there should be some amount of initial electrons present in the gap. The presence of ultra-violet illumination aids breakdown due to photo-ionisation. To make use of this phenomena, the sphere gaps in the impulse generator are arranged one above the other so that the illumination caused by the breakdown of one gap illuminates the next.

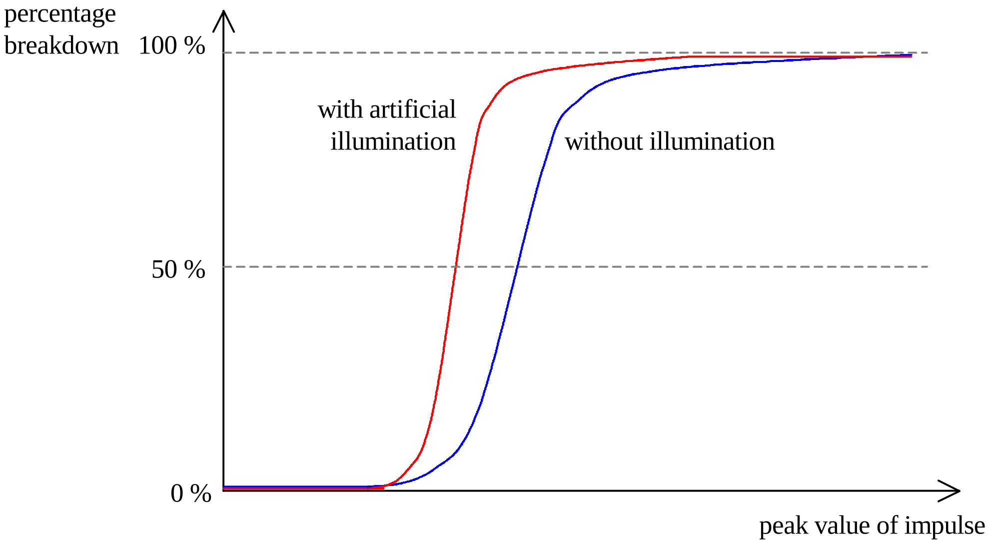


Figure 8.22 - Statistical breakdown characteristic

The breakdown of a sphere gap is subject to statistical variations. The peak value of the impulse necessary for the breakdown of a gap may vary over a small range, as shown in figure 8.22. If artificial illumination is provided at the gap (as with the ultra violet radiation from the breakdown of the previous gap), the uncertainty of the breakdown for a particular gap setting is reduced. This is due to the fact that a certain amount of electrons/second are created by phot-ionisation in the gap, and the breakdown is more constant.

Due to the presence of stray capacitances etc, the order of the differential equation governing the impulse waveform is increased, and the practical circuit will have exponential terms to the order of the number of storage elements.

Modified Goodlet impulse generator circuit

To obtain a good impulse voltage waveform, it is necessary to damp out the oscillations caused. This is done using waveshape control resistances distributed throughout the multi-stage impulse generator, as shown in figure 8.23.

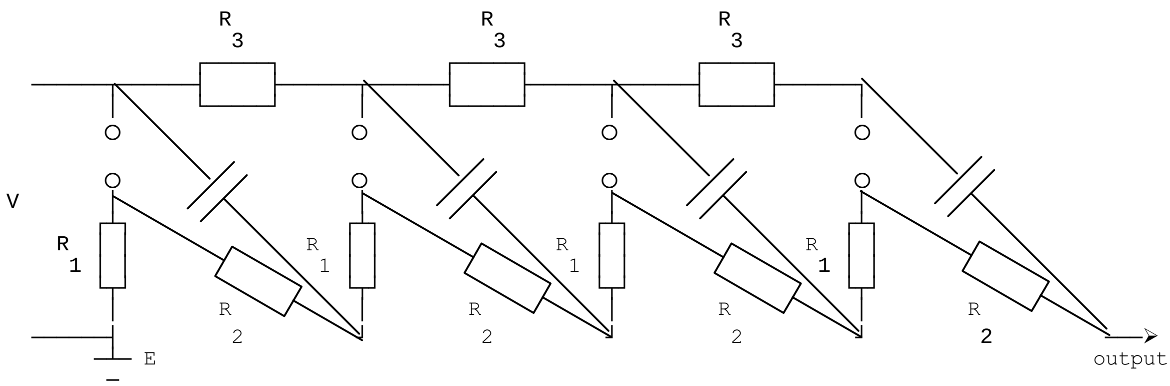


Figure 8.23 - Multi-stage impulse generator with distributed waveshape control elements

In the figure shown, the wavefront control resistances R_1 is distributed between the different stages. The wavetail control resistors R_2 are also distributed to the stages. The resistance R_3 is required only for the purpose of charging the capacitances in parallel, and is not part of the actual impulse generating circuit. Thus R_3 is selected large compared to R_1 and R_2. By proper selection of R_1 and R_2 the desired wavefront and wavetail can be obtained.

8.3.4 Generation of chopped impulse waveforms

The basic impulse generator circuit is for the generation of the full impulse waveform. Sometimes it is necessary to obtain a chopped wave (to represent the lightning waveform appearing when a gap flashes over). The chopping action can be accomplished by having a gap across the load at the last stage of the impulse generator as shown in figure 8.24.

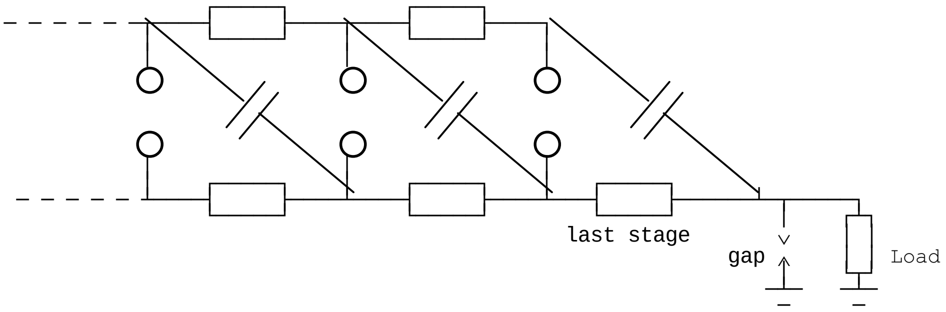


Figure 8.24 - Multi-stage impulse generator to obtain chopped waveform

The exact point of flashover on the surge waveform depends on the breakdown voltage against time characteristic of the gap. For an uncontrolled gap, this is rather uncertain, so that the instant of application of the collapse is not controllable. This is not satisfactory.

The problem can be overcome by having a triggered gap or a trigatron gap after the last stage. A pulse is applied to the pilot gap at the instant the waveform is required to be chopped, so that the point of chopping is well defined. [The instant of application of the pulse for this is in fact synchronised with the initiation of the impulse, but with an intended delay introduced.] Figure 8.25 show the chopped wave obtained, and the arrangement to obtain the chopped wave using a trigatron type gap.

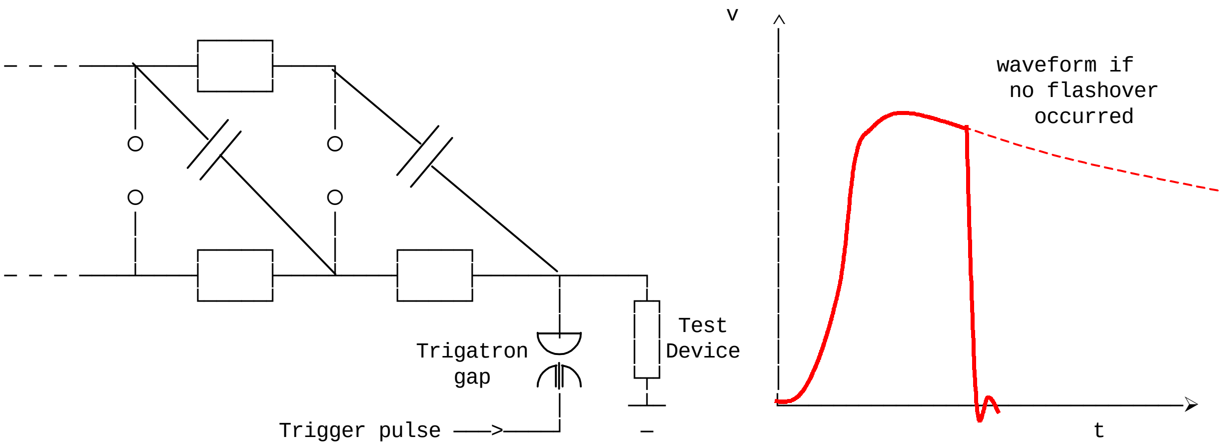


Figure 8.25 - Chopped waveform & Circuit to obtain chopped waveform