HIGH VOLTAGE SURGE GENERATORS

Fourth Year – Power Engineering

Instructor : Ahmed Kh. Ahmed

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.

HIGH VOLTAGE IMPULSE GENERATORS

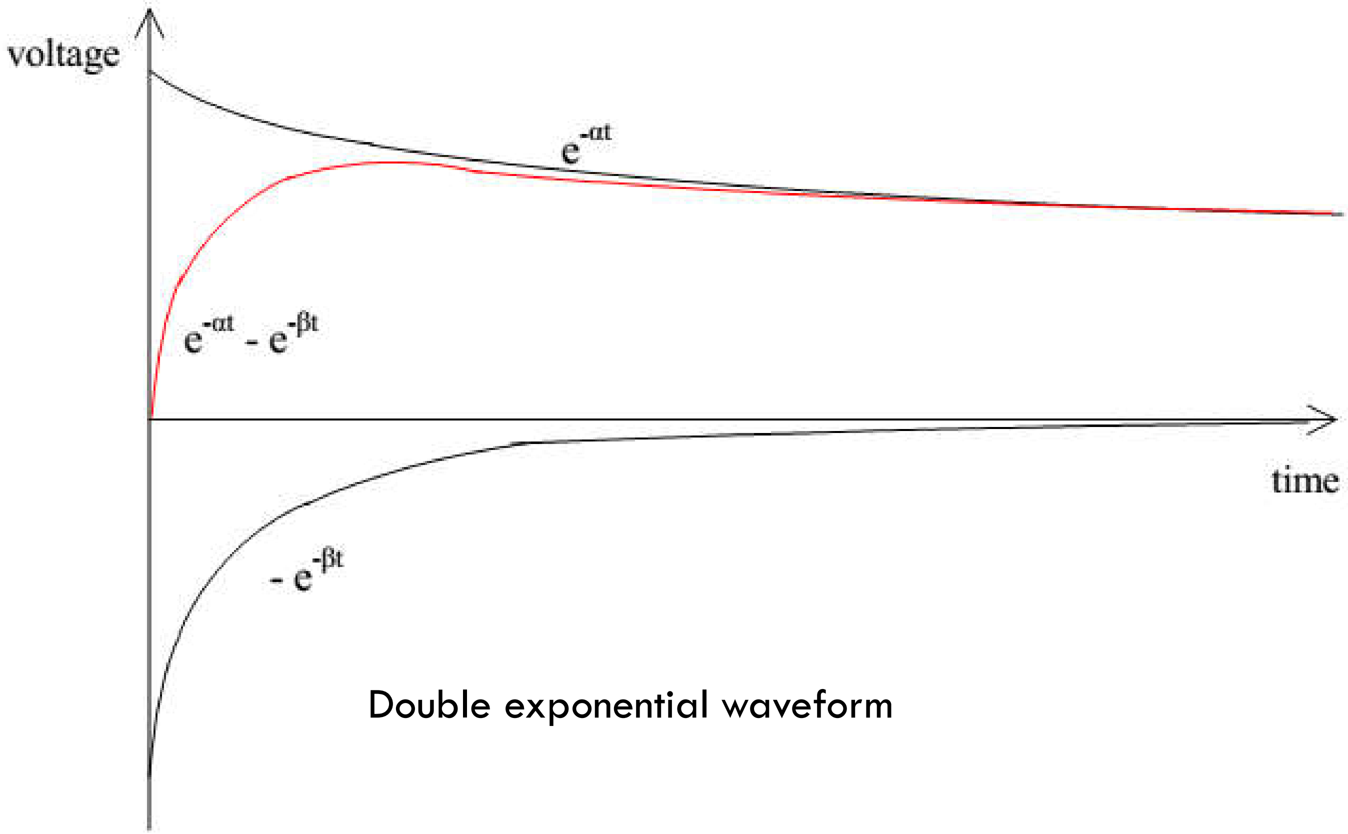
- The apparatus which produces the required voltages is the impulse generator.
- In high voltage engineering, an impulse voltage is normally a unidirectional voltage which rises quickly without appreciable oscillations, to a peak value and then falls less rapidly to zero.
- A full impulse wave is one which develops its complete wave shape 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.

HIGH VOLTAGE IMPULSE GENERATORS

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

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

HIGH VOLTAGE IMPULSE GENERATORS

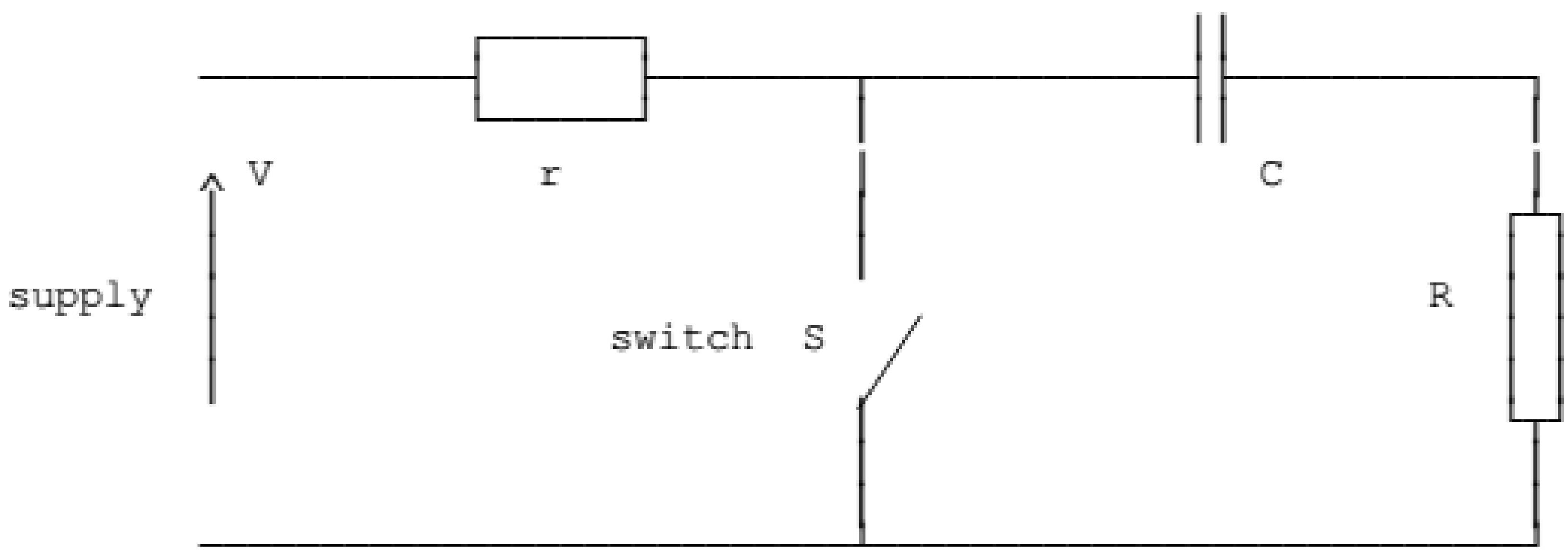


Double exponential waveform

HIGH VOLTAGE IMPULSE GENERATORS

- 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.

SINGLE EXPONENTIAL WAVEFORM



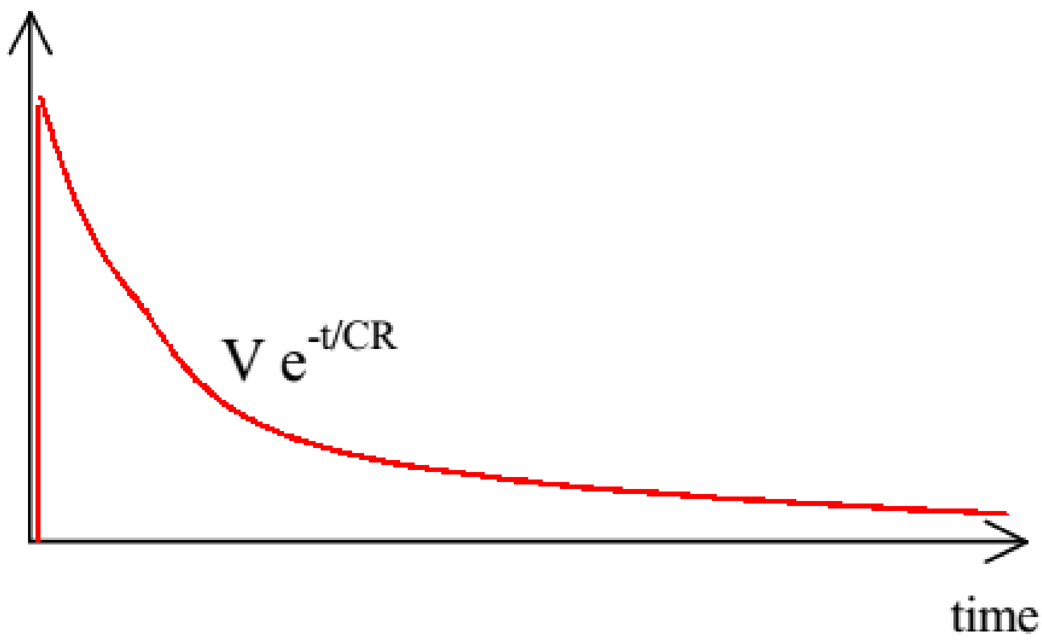
Circuit to produce single exponential waveform

SINGLE EXPONENTIAL WAVEFORM

- 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

$$v = V\, e^{-t/CR}$$

SINGLE EXPONENTIAL WAVEFORM



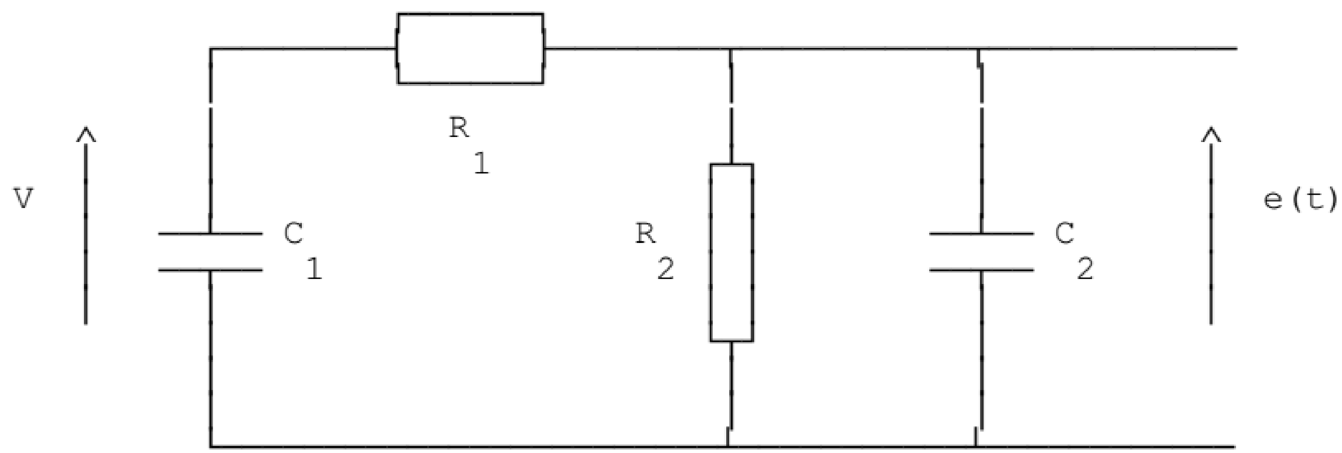
where CR is the time constant of the discharging circuit.

SINGLE EXPONENTIAL WAVEFORM

For this waveform, the rise time (wave front time) is zero, and the time to fall to half maximum (wave tail time) corresponds to CR log 2.

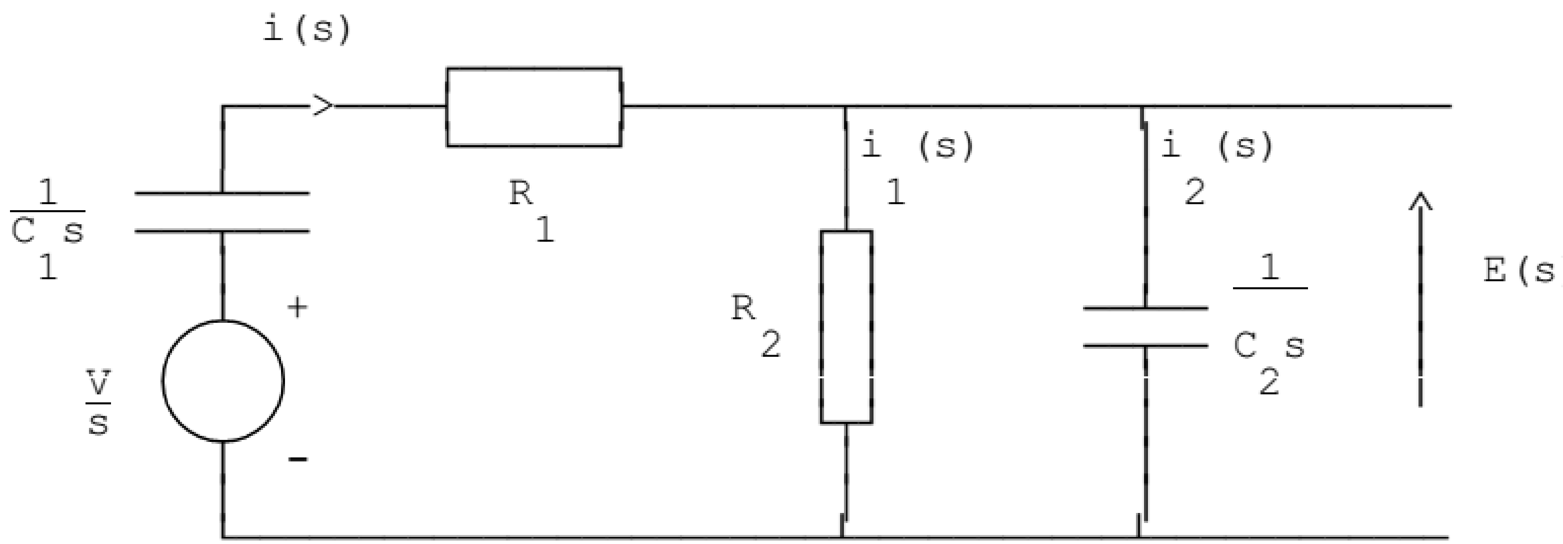
DOUBLE EXPONENTIAL WAVEFORM

- 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.
- The Figure shows the circuit used, with the capacitor C1 being initially charged from an outside circuit.



DOUBLE EXPONENTIAL WAVEFORM

This circuit can be analysed using the Laplace transform equivalent circuit shown in figure below:



DOUBLE EXPONENTIAL WAVEFORM

This circuit can be analyzed in the following manner.

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

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

$$\therefore \; i_1(s) \cdot \left(R_2 + R_1 + \frac{1}{C_1 s} \right) + i_2(s) \cdot \left(R_1 + \frac{1}{C_1 s} \right) = \frac{V}{s}$$

$$\text{Also} \quad i_2(s) = C_2 R_2 s \cdot i_1(s)$$

DOUBLE EXPONENTIAL WAVEFORM

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

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

If α and β are the solutions of the equation

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

then the Laplace transform expression can be simplified as follows.

DOUBLE EXPONENTIAL WAVEFORM

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

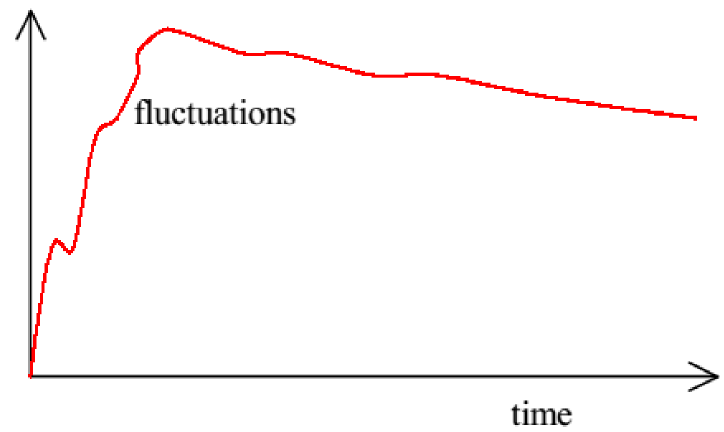
$$\text{This gives} \quad e(t) = \frac{V}{C_2 R_1} \cdot \frac{1}{\beta - \alpha} (e^{-\alpha t} - e^{-\beta t})$$

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 $\beta \approx 4.87$.

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 on the right of the slide.



CALCULATION OF ALFA AND BETA FROM THE C AND R.

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.

CALCULATION OF ALFA AND BETA FROM THE C AND R.

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

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

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

CALCULATION OF ALFA AND BETA FROM THE C AND R.

After reaching the peak, the voltage falls to half maximum in time t2 given by

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

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

CALCULATION OF ALFA AND BETA FROM THE C AND R.

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.

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

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

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

CALCULATION OF ALFA AND BETA FROM THE C AND R.

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

generally $R_1 << R_2$, so that

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

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

CALCULATION OF ALFA AND BETA FROM THE C AND R.

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

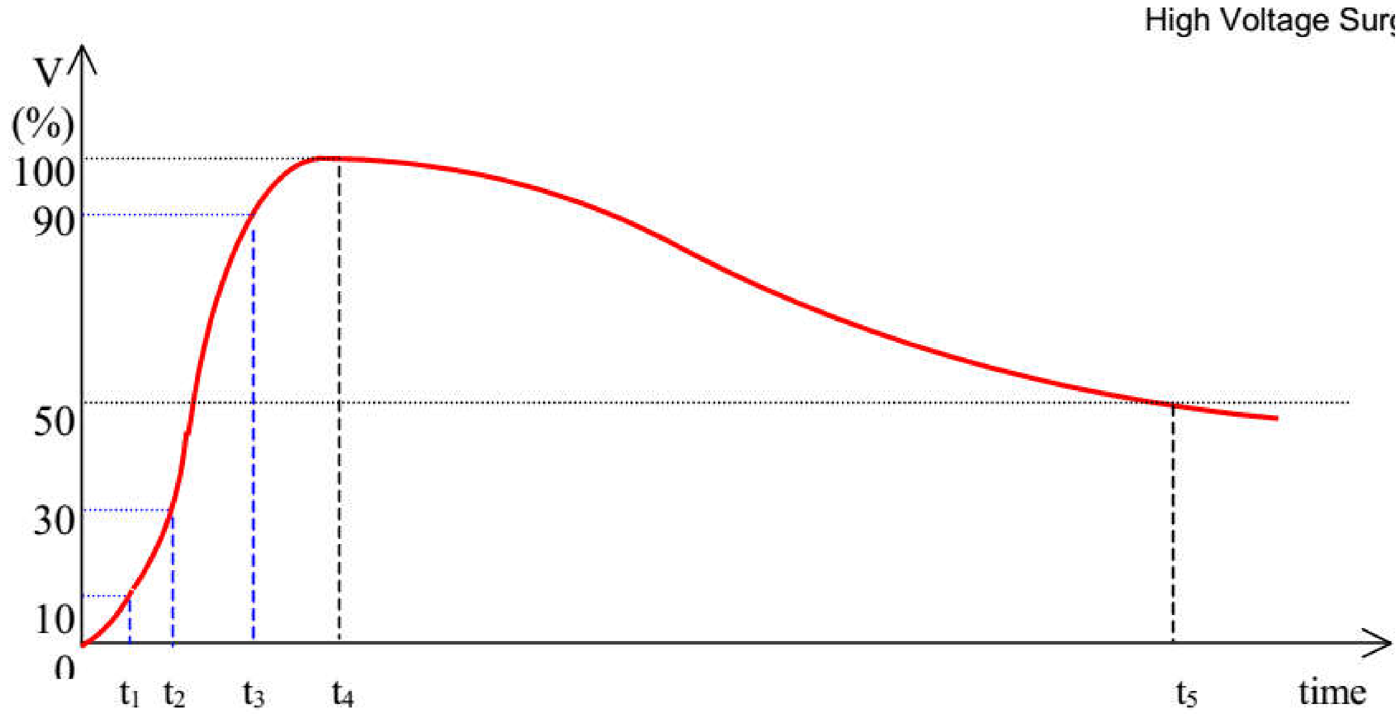
$$E_{\max} = \frac{V}{\beta\, C_2\, R_1} = \frac{V\, R_1 C_1 C_2}{(C_1 + C_2)\, C_2\, R_1} \approx V \cdot \frac{C_1}{C_1 + C_2}$$

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

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).

DEFINITION OF WAVEFRONT AND WAVETAIL TIMES OF PRACTICAL WAVEFORMS



DEFINITION OF WAVEFRONT AND WAVETAIL TIMES OF PRACTICAL WAVEFORMS

The wavefront time is given as

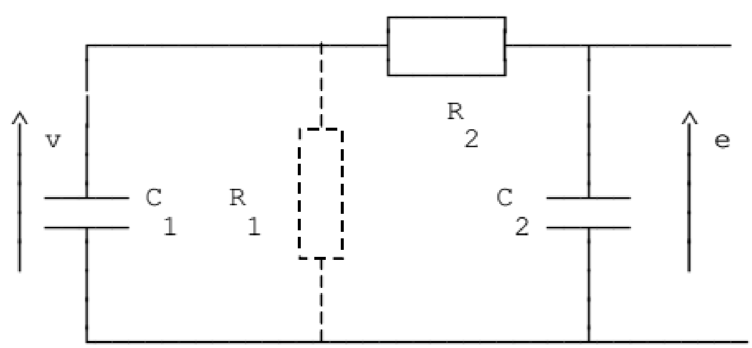
- (t3 - t1)/(0.9 - 0.1)
- or 1.25 (t3 - t1) for the 10% to 90% measurement and as
- (t3 - t2)/(0.9 - 0.3) or 1.67 (t3 - t2) for the 30% to 90% measurement.

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 $(t_f << t_t \text{ and } \alpha << \beta)$

to obtain a small wavefront time and a long wavetail time, the series resistance R2 must be small and the shunt resistance R1 must be comparatively much larger.

Thus to analyse the wavefront, it is permissible to open circuit the resistor R1 and redraw the approximate circuit as shown in figure



A VALID APPROXIMATE ANALYSIS OF DOUBLE EXPONENTIAL IMPULSE GENERATOR CIRCUIT

During the wavefront, the charging rate is dependent mainly on the inverse time constant β.

Thus

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

where $C_{eq} = \dfrac{C_1 C_2}{C_1 + C_2}$, $\because C_1, C_2$ are series

A VALID APPROXIMATE ANALYSIS OF DOUBLE EXPONENTIAL IMPULSE GENERATOR CIRCUIT

- 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.

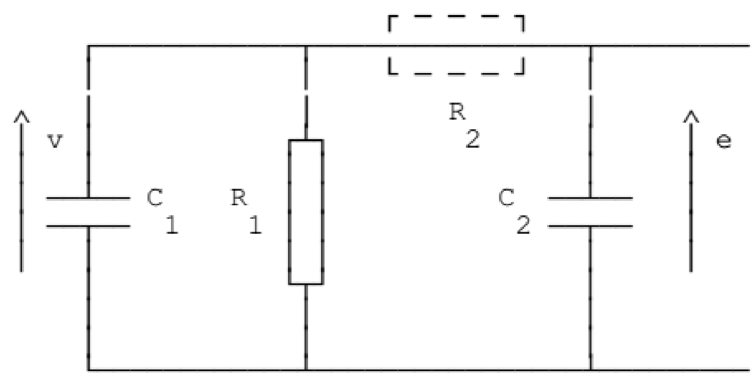
$$e = \frac{C_1}{C_1 + C_2} . v \quad \text{neglecting resistance } R_2$$

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

A VALID APPROXIMATE ANALYSIS OF DOUBLE EXPONENTIAL IMPULSE GENERATOR CIRCUIT

To obtain a high voltage efficiency, a large proportion of the energy from the initially charged capacitor C1 must be retained in the capacitor C1, so that C1 > C2.

Similarly, since both capacitors discharge through the resistor R1, and since R1 >> R2, to analyse the wavetail, it is permissible to short circuit the resistor R2 and redraw the approximate circuit as shown



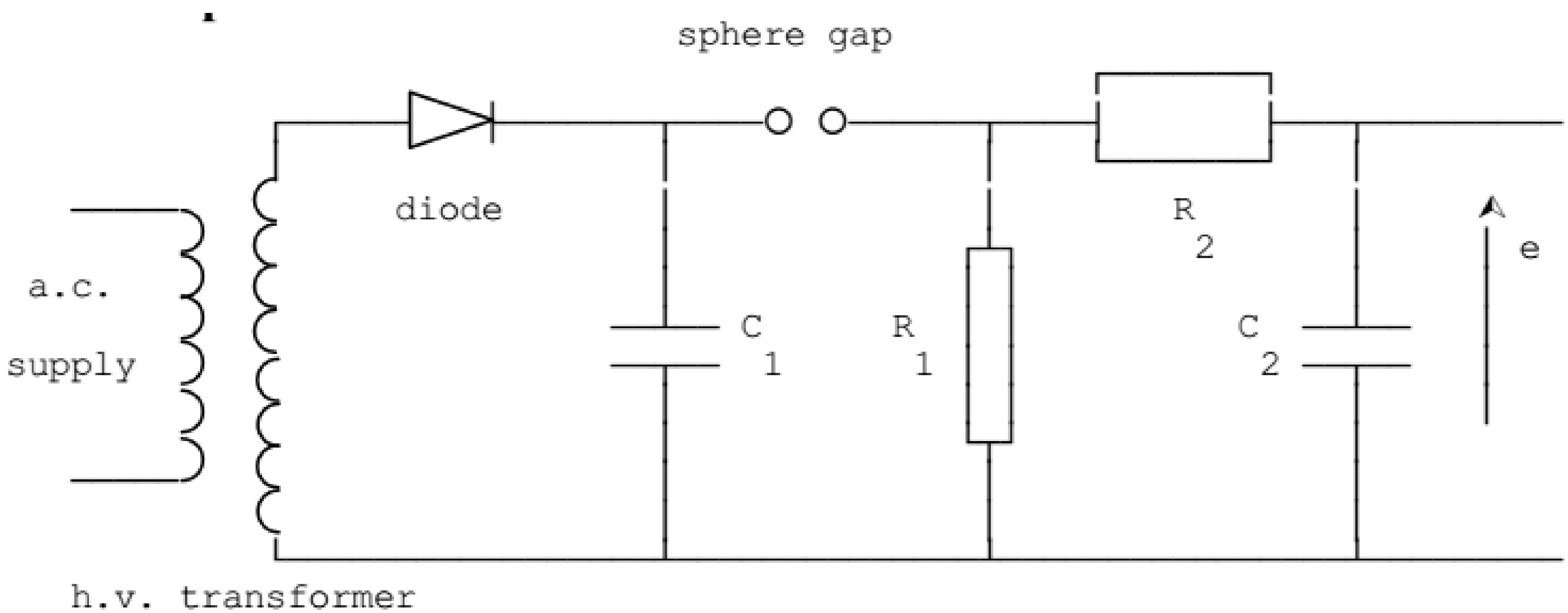
A VALID APPROXIMATE ANALYSIS OF DOUBLE EXPONENTIAL IMPULSE GENERATOR CIRCUIT

During the wavetail, the discharging rate was seen to be dependant mainly on the inverse time constant α.

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

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

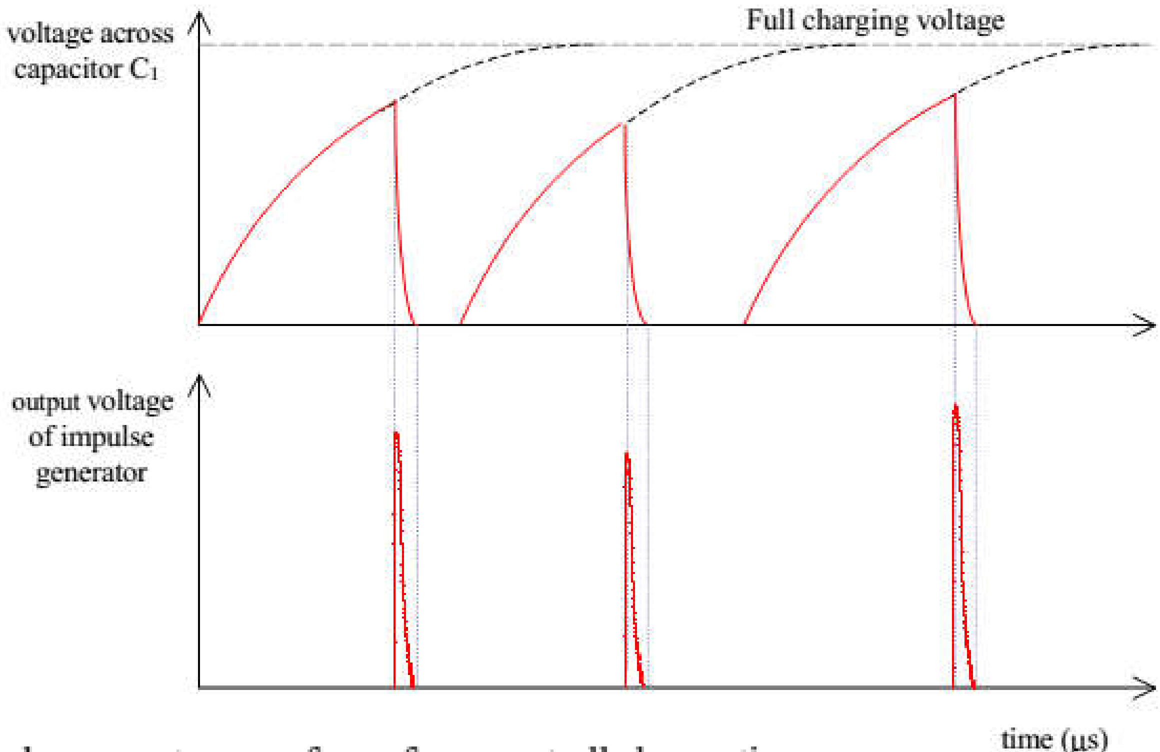
- OPERATION OF IMPULSE GENERATOR
- UNCONTROLLED OPERATION



- OPERATION OF IMPULSE GENERATOR
- UNCONTROLLED OPERATION

- In the simplest form of the single stage impulse generator, 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.

- OPERATION OF IMPULSE GENERATOR - UNCONTROLLED OPERATION



· Impulse generator waveforms for uncontrolled operation

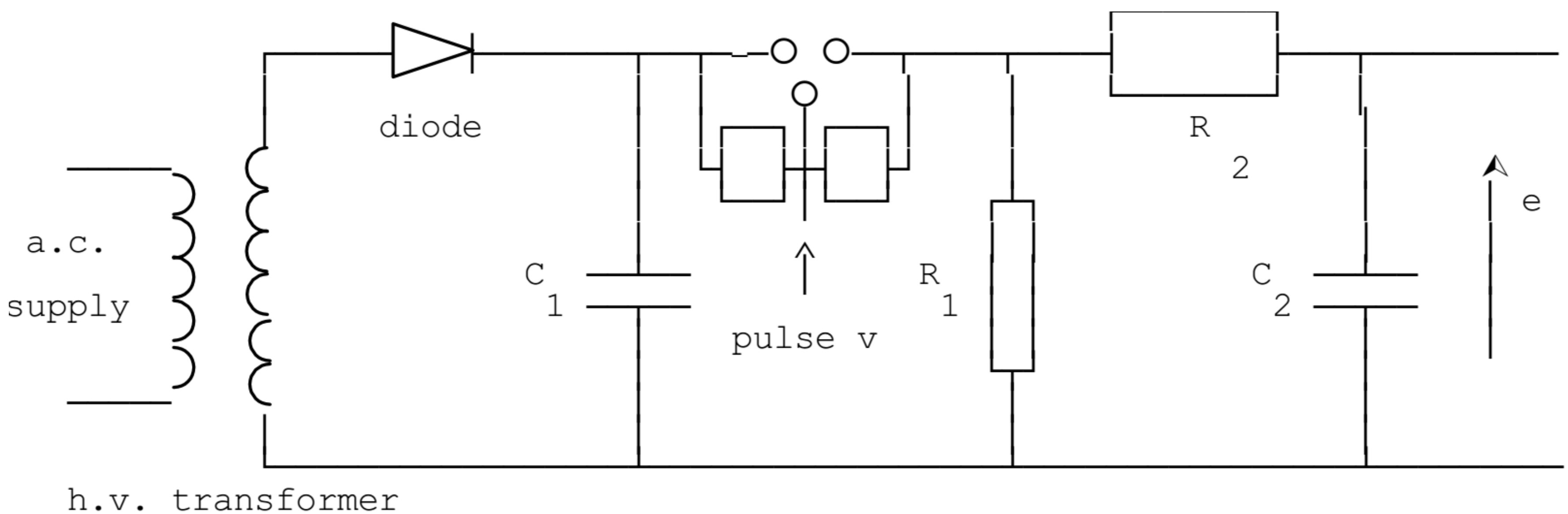
- OPERATION OF IMPULSE GENERATOR
- UNCONTROLLED OPERATION

- 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.

OPERATION OF IMPULSE GENERATOR - CONTROLLED OPERATION

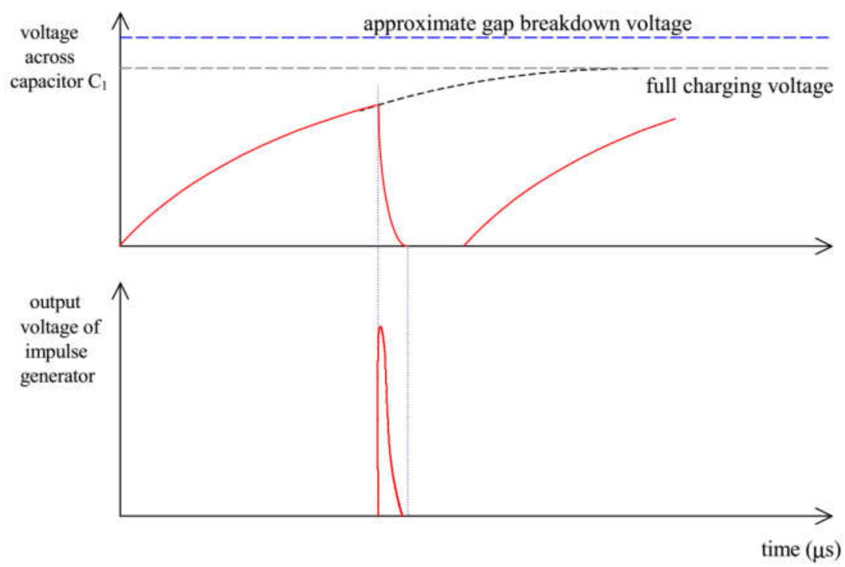
- In the controlled mode of operation, the same basic circuit is used, but the capacitor is allowed to reach the full charging voltage without the sphere gap breaking down.
- The spark over voltage is set at slightly higher than the charging voltage.
- In this case, at the sphere gap we need a special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

OPERATION OF IMPULSE GENERATOR - CONTROLLED OPERATION



OPERATION OF IMPULSE GENERATOR - CONTROLLED OPERATION

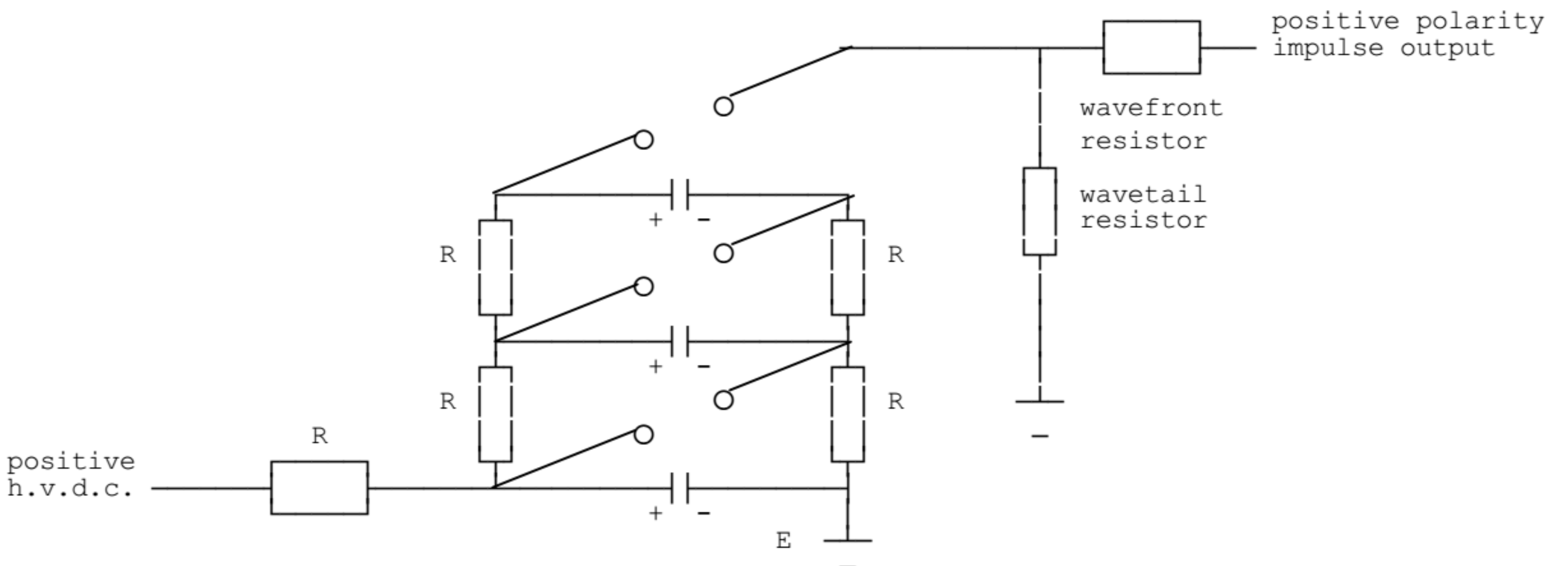
- The potential across the main gap is divided into two by means of 2 equal resistors R, each of about 100 MΩ.
- By this means, half the applied voltage V appears across each of the two auxiliary gaps .



Impulse generator waveforms for controlled operation

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.



MARX IMPULSE GENERATOR CIRCUIT

In the circuit shown in Prev. Slide, 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

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.

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 .

GOODLET IMPULSE GENERATOR CIRCUIT

- 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) .