High voltage Engineering

High Voltage Generation

Lecture contents

- Impulse voltage generation

Transient/Impulse voltage

- Studies *of* transient disturbances on a transmission system have shown that lightning strokes and switching operations are followed by a traveling wave of a steep wave front
- When a voltage wave of this type reaches a power transformer it causes an unequal stress distribution along its windings and may lead to breakdown of the insulation system
- It has, therefore, become necessary to study the insulation behavior under impulse voltages

- An impulse voltage is a unidirectional voltage which rises rapidly to a maximum value and then decays slowly to zero
- The wave shape is generally defined in terms of the times t_1 and t_2 in microseconds, where t_1 is the time taken by the voltage wave to reach its peak value and t_2 is the total time from the start of wave to the instant when it has declined to one-half of the peak value
- The wave is then referred to as a t_1/t_2 wave

- The exact method of defining an impulse voltage, however, is specified by various International Standards
- The British Standard specification defines the impulse voltage in terms of nominal wave front and wave tail durations
- **Fig 4.5** shows the Shape of an impulse wave where the nominal wave front duration t_1 is specified as

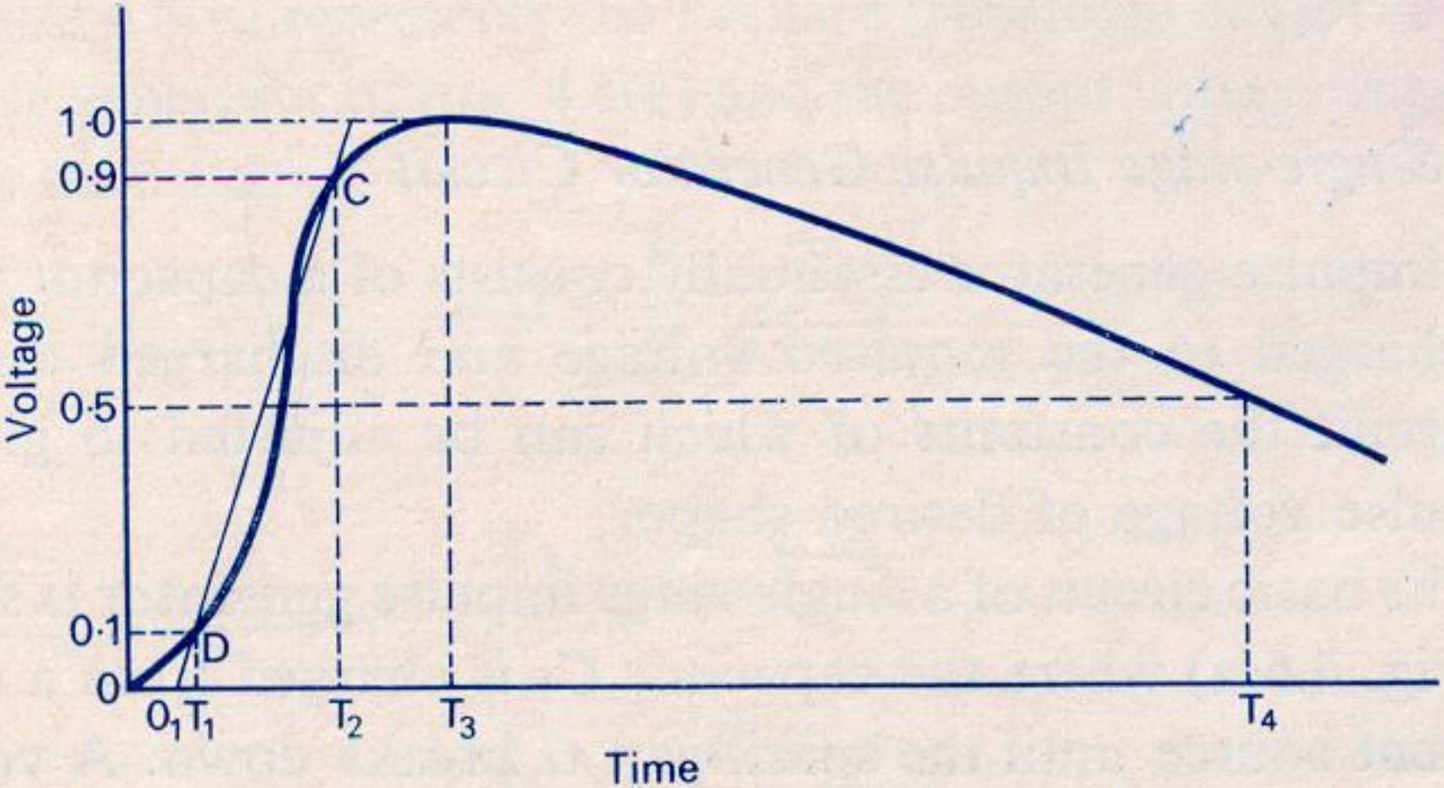


FIG. 4.5. General shape of an impulse voltage.

- **$t_1 = 1.25\ T_1T_2$**
- Where
- ***OT_1* = time for the voltage wave to reach 10% of the peak voltage.**
- ***OT_2* = time for the voltage wave to reach 90% of the peak voltage.**
- The point O_1 where the line *CD* cuts the time axis is defined as the nominal starting-point of the wave
- The nominal wave tail t_2 is the time between O_1 and the point on the wave tail where the voltage is one-half the peak value, i.e. $t_2 = O_l T_4$.

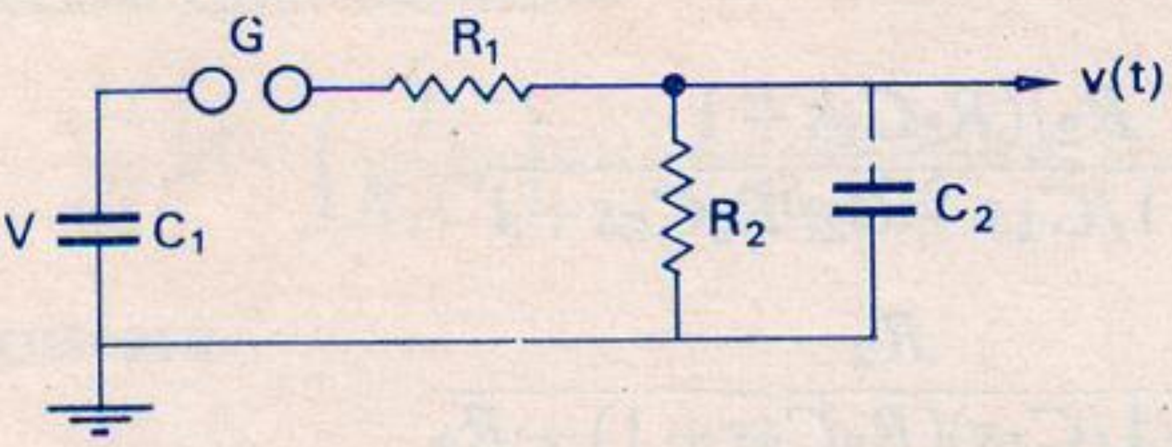
- The wave is then referred to as a $t_1/\ t_2$ wave and according to the standard specified in B.S. 923 a 1/50 μsec wave is the standard wave
- The specification permits a tolerance of up to ±50% on the duration of the wave front and ±20 % on the duration of the wave tail
- In the corresponding American specification, the nominal wave front duration is defined as given by $1.5T_1T_2$ and the standard wave is a 1.5/40 μsec
- The tolerances allowed on the wave front and the wave tail are ±0.5 μsec and ±10 μsec respectively

Single Stage Impulse Generator

- An impulse generator essentially consists of a capacitor which is charged to the required voltage and discharged through a circuit the constants of which can be adjusted to give an impulse voltage of desired shape.

- The basic circuit of a single-stage impulse generator is shown in **Fig. 5(a)** where the capacitor C_1 is charged from a direct current *source* until the spark-gap G breaks down
- A voltage is then impressed upon the object under test of capacitance C_2.

Single stage impulse generator

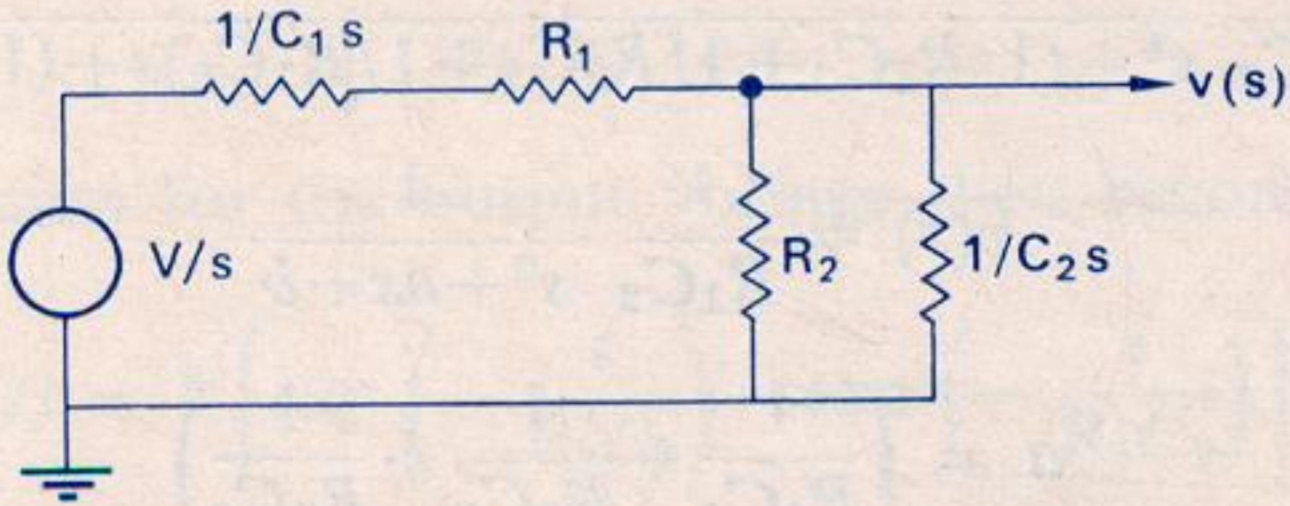


(a) Circuit arrangement

- ***a) Single-stage Impulse Generator Circuit***

- The wave-shaping resistors R_1 and R_2 control respectively the front and the tail of the impulse voltage available across C_2. An analysis of the simple circuit is given as follows.

- **Figure 4.6 (b)** represents the Laplace transform circuit of the impulse generator of **Fig. 4.6 (a)** and the output voltage is given by the expression:



(b) Transform circuit

FIG. 4.6. Single-stage impulse generator.

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

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

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

2. Transient / Impulse Voltage

a) Single-stage Impulse Generator Circuit

By Substitution:

$$v(s) = \frac{V}{s}\,\frac{R_2/(R_2C_2s+1)}{R_1+1/C_1s+R_2/R_2C_2s+1}$$

$$= \frac{V}{s}\,\frac{R_2}{(R_1+1/C_1s)(R_2C_2s+1)+R_2}$$

$$= \frac{V}{s}\,\frac{R_2}{R_1R_2C_2s+1/C_1s+R_2C_2/C_1+R_1+R_2}$$

$$= \frac{V}{R_1C_2}\,\frac{1}{s^2+(1/R_1C_1+1/R_2C_2+1/R_1C_2)s+(1/R_1R_2C_1C_2)}$$

Transient Voltage

a) Single-stage Impulse Generator Circuit

or

$$v(s) = \frac{V}{R_1 C_2} \frac{1}{s^2 + as + b},$$

where

$$a = \left(\frac{1}{R_1 C_1} + \frac{1}{R_2 C_2} + \frac{1}{R_1 C_2} \right)$$

and

$$b = \left(\frac{1}{R_1 R_2 C_1 C_2} \right)$$

$$v(s) = \frac{V}{R_1 C_2} \frac{1}{s_1 - s_2} \left[\frac{1}{s - s_1} - \frac{1}{s - s_2} \right].$$

2. Transient / Impulse Voltage

a) Single-stage Impulse Generator Circuit

Where S_1 and S_2 are the roots of the equation $s_2+as+b = 0$ and both will be negative. From the transform tables

$$v(t) = \frac{V}{R_1C_2(s_1-s_2)}[\exp(s_1t)-\exp(s_2t)].$$

In a practical case R_2 is much greater than R_1 and C_1 much greater than C_2 and an approximate solution is obtained by examining the auxiliary equation:

2. Transient / Impulse Voltage

$$s^2 + \left(\frac{1}{R_1C_1} + \frac{1}{R_2C_2} + \frac{1}{R_1C_2}\right)s + \left(\frac{1}{R_1R_2C_1C_2}\right) = 0,$$

Where the value of $(1/R_1C_1 + 1/R_2C_2)$ is much smaller than $1/R_1C_2$.

$$s^2 + \left(\frac{1}{R_1C_2}\right)s + \left(\frac{1}{R_2C_1}\right)s + \frac{1}{R_1R_2C_1C_2}$$

$$\left(\frac{1}{R_2C_1}\right)s \;(Was\ addded\ as\ approximately\ zero.)$$

2. Transient / Impulse Voltage

a) Single-stage Impulse Generator Circuit

and the graph of the expression is shown in **Fig. 6.**

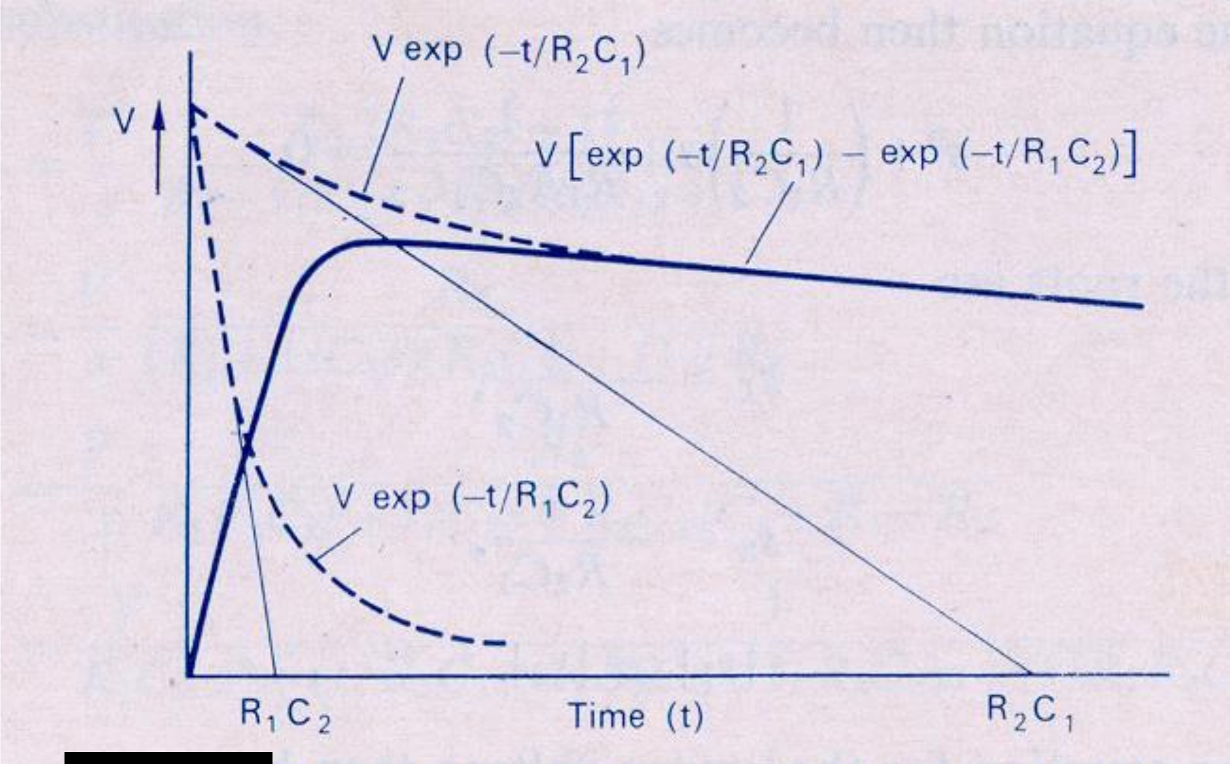


Fig: 6 The impulse voltage wave and its components.

2. Transient / Impulse Voltage

a) Single-stage Impulse Generator Circuit

and the roots are

$$s_1 \simeq -\frac{1}{R_1C_2},$$

$$s_2 \simeq -\frac{1}{R_2C_1},$$

and $$|s_1| \gg |s_2|.$$

The equation for the output voltage then becomes

$$v(t) = V\left[\exp\left(-\frac{t}{R_2C_1}\right) - \exp\left(-\frac{t}{R_1C_2}\right)\right]$$

2. Transient / Impulse Voltage

a) Single-stage Impulse Generator Circuit

The above analysis shows that the wave shape depends upon the values of the generator and the load capacitances and the wave-control resistances

The exact wave shape will be affected by the inductance in the circuit and the stray capacitances

The inductance depends upon the physical dimensions of the circuit and is kept as small as possible.

2. *Transient / Impulse Voltage*

a) Single-stage Impulse Generator Circuit

The simplified circuit is shown in **Fig. 7(a)** where C_1 = discharge capacitance of generator C_2 = capacitance of the load, L_1 = internal inductance of generator, L_2 = external inductance of load and connections, R_1 = resistance controlling the wave front, R_2 or R = resistance controlling the wave tail

2. *Transient / Impulse Voltage*

a) Single-stage Impulse Generator Circuit

The wave-tail resistance can be either on the load side or on the generator side

Tail of the impulse wave is generally long compared with its front-as is in the case of a standard wave voltage of 1/50 or 1.5/40 μsec very little error results from ignoring the wave-tail resistance in the calculation of the wave front duration

The circuit, therefore, can be further simplified to the form shown in **Fig. 7(b).**

2. *Transient / Impulse Voltage*

a) Single-stage Impulse Generator Circuit

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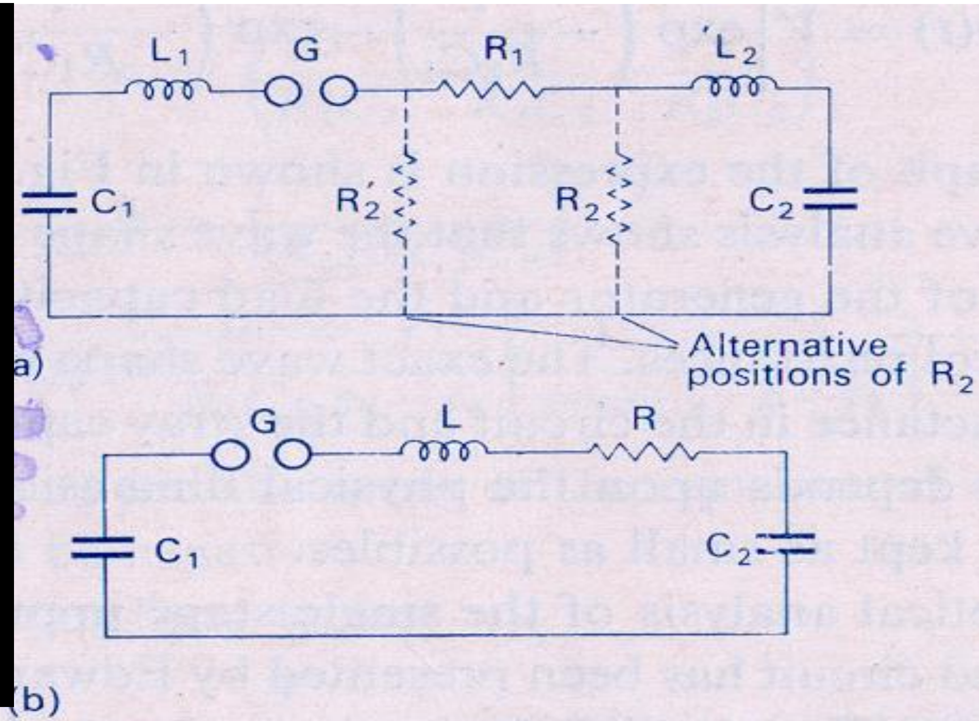

Fig: 7: Simplified circuit of impulse generator and load. (a) Circuit showing alternative positions of the wave-tail control resistance. (b) Circuit for calculation of wave front.

2. *Transient / Impulse Voltage*

b) Multistage Impulse Generator Circuit

The one-stage circuit is not suitable for higher voltages because of the difficulties in obtaining high direct current voltages

In order to overcome these difficulties, Marx suggested an arrangement where a number of condensers are charged in parallel through resistances and discharged in series through spark gaps

A typical circuit is presented in **Fig.8** which shows the connections for a five-stage generator

The stage capacitors C are charged in parallel through high-value charging resistors *R.* At the end of the charging period, the points *A, B,……E* will be at the potential of the d.c. source,

2. Transient / Impulse Voltage

b) Multistage Impulse Generator Circuit

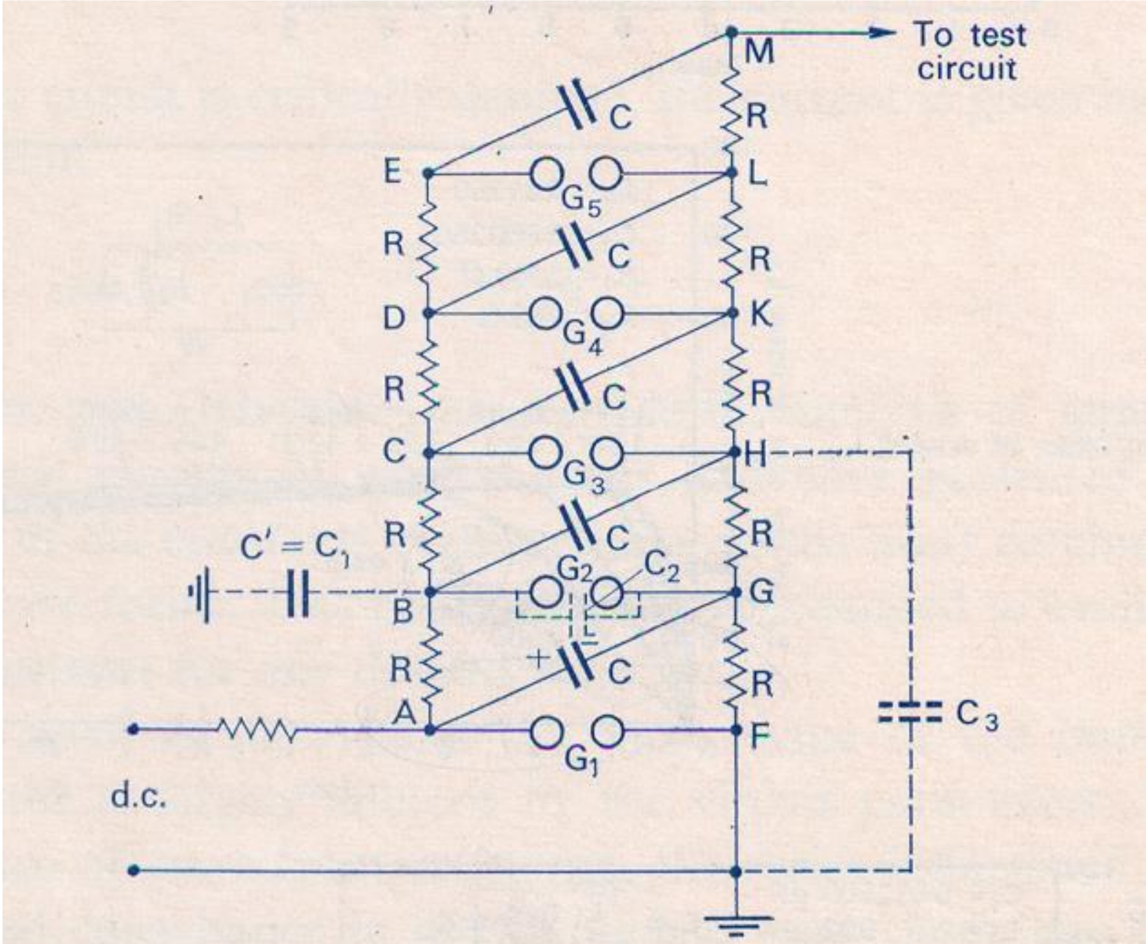

Fig: 8 Basic circuit of a five-stage impulse generator.

2. *Transient / Impulse Voltage*

b) Multistage Impulse Generator Circuit

e.g. + *V* with respect to earth, and the points *F, G,……*, *M* will remain at the earth potential

The discharge of the generator is initialized by the breakdown of the spark gap *AF* which is followed by simultaneous breakdown of all the remaining gaps

When the gap *AF* breaks down, the potential on the point *A* changes from + *V* to zero and that on point *G* swings from zero to -*V owing* to the charge on the condenser *A.G*

If for the time being the stray capacitance C is neglected, the potential on *B* remains + *V* during the interval the gap *AF* sparks over.

2. *Transient / Impulse Voltage*

b) Multistage Impulse Generator Circuit

A voltage *2V,* therefore, appears across the gap *BG* which immediately leads to its breakdown

This breakdown creates a potential difference of *3V* across *CH;* the breakdown process, therefore, continues and finally the potential on *M* attains a value of - *5V*

In effect, the low voltage plates of the stage capacitors are successively raised to - *V,* - *2V, …….* - *nV,* if there are *n* stages

This arrangement gives an output with polarity opposite to that of the charging voltage.

2. Transient / Impulse Voltage

b) Multistage Impulse Generator Circuit

The above considerations suggest that a multistage impulse generator should operate consistently irrespective of the number of stages

In practice for a consistent operation it is essential to set the first gap (G_1) for breakdown only slightly below the second gap *(G_2)*

A more complete analysis shows that the voltage distribution across the second and higher gaps immediately after the breakdown of the lowest gap (G_1) is governed by the stray capacitances and gap capacitances shown in dotted lines in **Fig.4.11.** The effect of stray capacitances on voltage across G_2 immediately after breakdown of G_1 may be estimated as follows:

2. Transient / Impulse Voltage

b) Multistage Impulse Generator Circuit

Assume the resistors as open circuits and the stray capacitances negligible in comparison with the stage capacitors. Let *(A)* in **Fig.8** be charged to + *V*

*Af*ter breakdown of G_1 the point G initially at earth will assume a potential - *V,* but the potential of *B* is fixed by the relative magnitudes of C_1, C_2 and C_3 and is given by

$$V_{BH} = V\left(\frac{C_1+C_3}{C_1+C_2+C_3}\right).$$

Hence the voltage across the gap (G_2)

$$V_{G_2} = V\left(1+\frac{C_1+C_2}{C_1+C_2+C_3}\right).$$

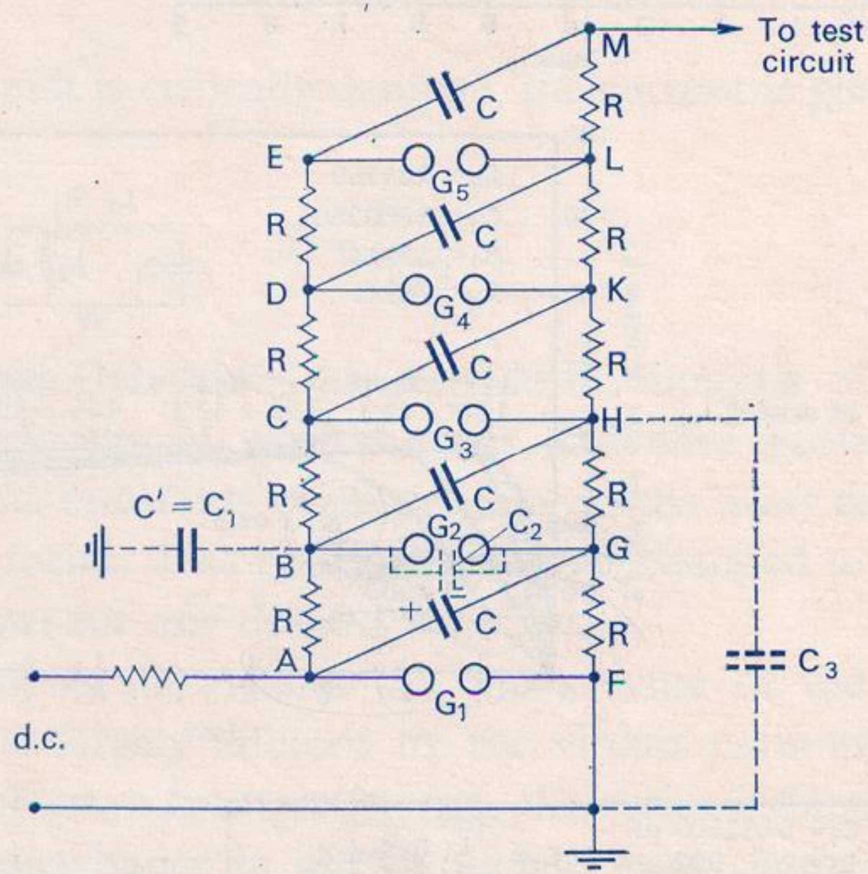

FIG. 4.11. Basic circuit of a five-stage impulse generator.

2. *Transient / Impulse Voltage*

b) Multistage Impulse Generator Circuit

If $C_2 = 0$, V_{G2} reaches its maximum value of *2V.* If both C_1 and Cs are zero, *V* G. will equal to *V,* i.e. its minimum value

It is apparent, therefore, that the most favorable conditions for the operation of the generator occur when the gap capacitance C_2 is small and the stray capacitances C_1 and C_3 are large

The conditions set by the above expression are transient, as the stray capacitors start discharging

The practical stray capacitors are of low values, consequently the time constants are relatively short 0.1 micro second or less

2. Transient / Impulse Voltage

b) Multistage Impulse Generator Circuit

For consistent breakdown of all gaps the axes of the gaps should be in one vertical plane so that the ultraviolet illumination from the spark in the first gap irradiates the other gaps

This ensures a supply of electrons in the gaps to initiate breakdown during the short period when the gaps are subjected to the over-voltage

The consistency in the firing of the first stage spark gap is improved by providing illumination from ultraviolet lamps placed below the first gap

2. Transient / Impulse Voltage

b) Multistage Impulse Generator Circuit

The wave-front control resistors, in a multistage generator, can be connected either externally to the generator or distributed within the generator, or partly in and partly outside it

In the best arrangement, about half of the resistance is outside the generator

An advantage of distributing the wave-front resistors within the generator is that it reduces the need for an external resistor capable of withstanding the full impulse voltage.

2. Transient / Impulse Voltage

b) Multistage Impulse Generator Circuit

If all the series resistances are distributed within the generator, the inductance and capacitance of the external leads and the load form an oscillatory circuit

An external resistance, therefore, becomes necessary to damp out these oscillations

The method of placing part of the wave-front control resistance in series with each gap serves to protect against disruptive discharge as well as to damp out any generator internal oscillation

Wave-tail control resistances are generally used as the charging resistors within the generator

2. Transient / Impulse Voltage

b) Multistage Impulse Generator Circuit

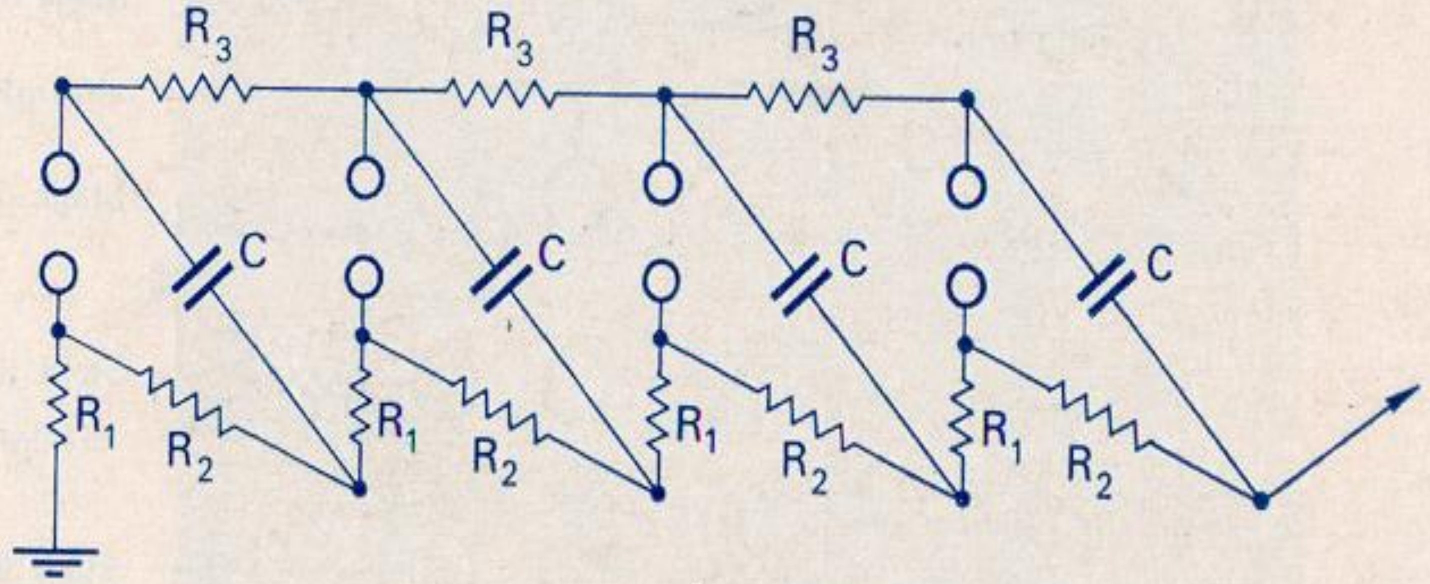

Fig: 9. Multi-stage generator with distributed series resistors.

2. Transient / Impulse Voltage
b) Multistage Impulse Generator Circuit

The circuit shown in **Fig.9** is commonly used to obtain high efficiency with distributed series resistors.

The value of R_3 is made large compared with R_1 and R_2 is made as small as is necessary to obtain the required length of the wave tail.

In a practical generator employing this circuit, the voltage drop in R_1 was made less than 1% of the output voltage by selecting suitable values of the parameters

The stage capacitance was 0.2 μF, R_1 was about 40Ω and the wave-tail resistance R_2 required for a 5 μ sec wave tail was about 25Ω. R_3 was made nearly 10kΩ

2. *Transient / Impulse Voltage*

b) Multistage Impulse Generator Circuit

Impulse generators are characterized by the total nominal voltage, the number of stages and the stored energy

The nominal output voltage is given by the product of the highest charging voltage and the number of stages

Because *of* the resistance and inductance in series with the generator and the test circuits, the voltage across the test object is lower than the nominal output of the generator

The nominal energy of the generator is defined as **$\frac{1}{2} C_g V^2$** , where C_g denotes the discharge capacitance of the generator and *V* the maximum nominal voltage.

2. Transient / Impulse Voltage

b) Multistage Impulse Generator Circuit

The energy required varies over a wide range depending upon the nature of the object under test.

For example, the energy of the generator can be low for testing insulator strings, isolators, etc., whereas when tests are carried out on objects of low impedance such as transformers, the energy must be higher

Conclusive Formulae for Wave Front and Tail for Impulse Generator Problems

The resistance R_2 will be large. Hence, the simplified circuit is used for wave front time calculation. Taking the circuit inductance to be negligiule 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

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

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.

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

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

Next Lecture

- Generation of High voltage
  - Problem discussion