Generation of high voltages
'Impulse Voltage'

- Disturbances of electric power transmission and distribution systems are frequently caused by two kinds of transient voltages whose amplitudes may greatly exceed the peak values of the normal a.c. operating voltage.
  - ➢ lightning overvoltages
  - ➢ switching phenomena

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Generation of high voltages 'Impulse Voltage'

Lightning overvoltages

- The lightning overvoltages, originated by lightning strokes hitting the phase wires of overhead lines or the busbars of outdoor substations.

- The amplitudes are very high, usually in the order of 1000 kV or more, as every stroke may inject lightning currents up to about 100 kA and even more into the transmission line.

- Too high voltage levels are immediately chopped by the breakdown of the insulation and therefore travelling waves with steep wave fronts and even steeper wave tails may stress the insulation of power transformers or other h.v. equipment severely.

Generation of high voltages
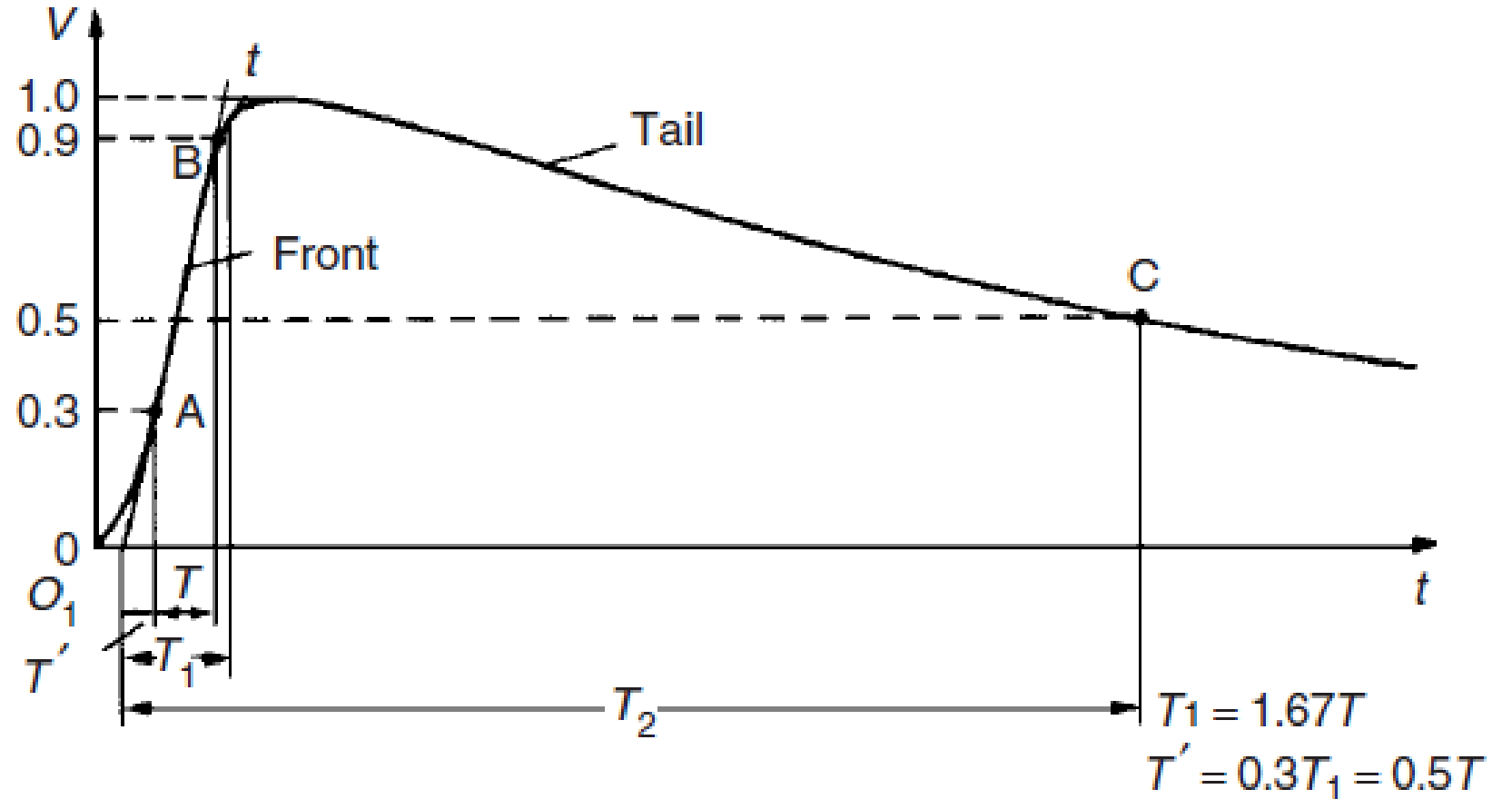## 'Impulse Voltage'

- Lightning protection systems, surge arresters and the different kinds of losses will damp and distort the travelling waves, and therefore lightning overvoltages with very different waveshapes are present within the transmission system.

- Although the actual shape of both kinds of overvoltages varies strongly, it became necessary to simulate these transient voltages by relatively simple means for testing purposes.

- The various national and international standards define the impulse voltages as a unidirectional voltage which rises more or less rapidly to a peak value and then decays relatively slowly to zero.

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Generation of high voltages 'Impulse Voltage'

- In the relevant IEC Standard 60, widely accepted today through national committees, a distinction is made between lightning and switching impulses, i.e. according to the origin of the transients.

- Impulse voltages with front durations varying from less than one up to a few tens of microseconds are, in general, considered as lightning impulses (LIs).

- Shapes of LI divided into:
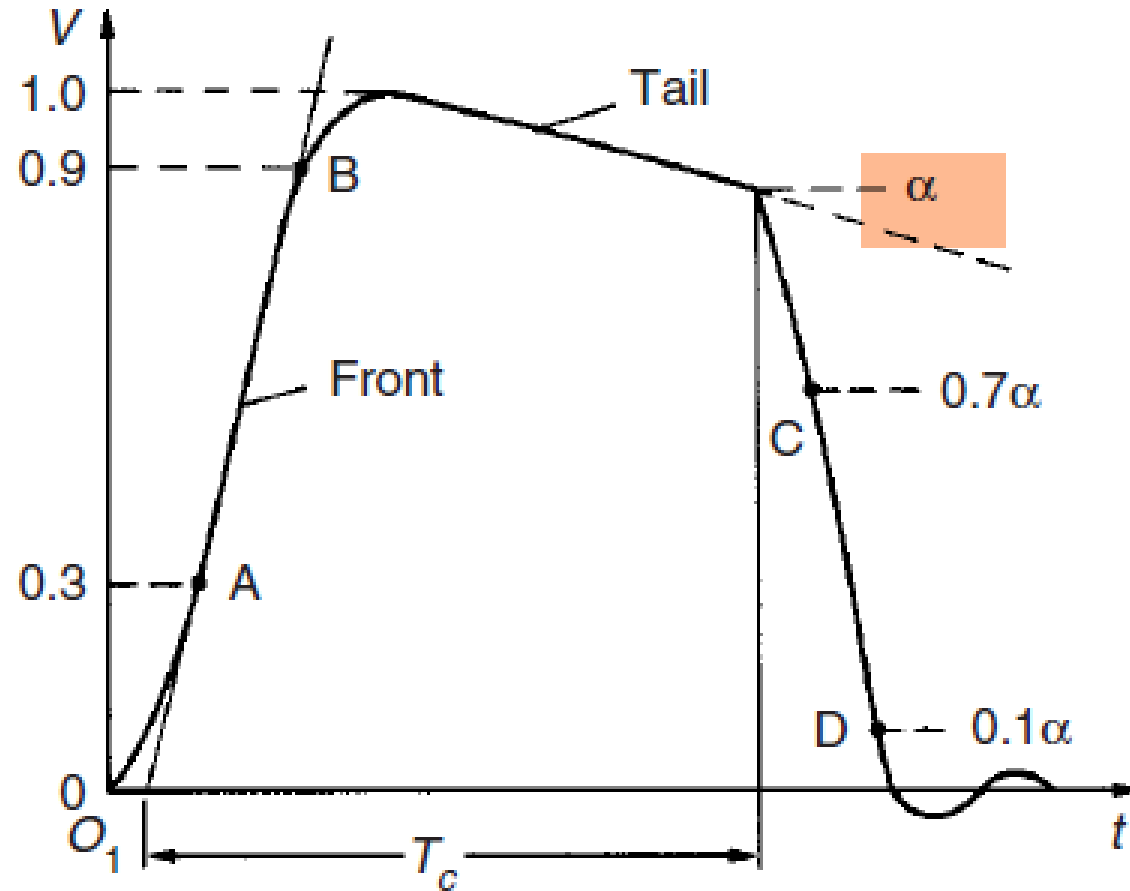   ➢ Full LI
    ➢ LI chopped on front
    ➢ LI chopped in tail

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Generation of high voltages 'Impulse Voltage'

Shape of 'full' lightning impulse voltage

$T_1 = 1.67T$

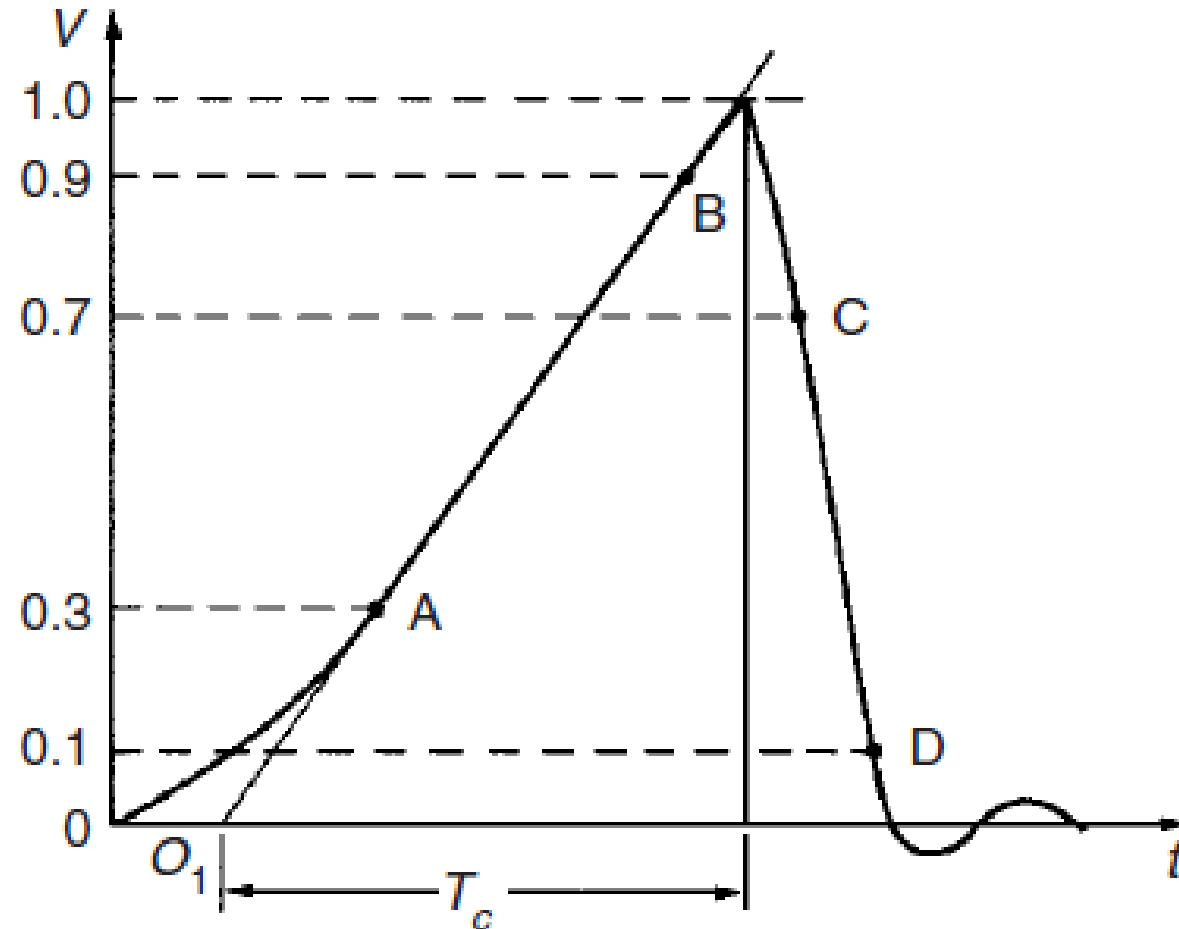$T' = 0.3T_1 = 0.5T$

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Shape of LI chopped on tail

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Shape of LI chopped on front

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Generation of high voltages
'Impulse Voltage'

T_1 : front time.

T_2 : time to half-value.

T_c: time to chopping.

O_1 : virtual origin

- The 'virtual origin' O_1 is defined where the line AB cuts the time axis.

- The 'front time' T_1, again a virtual parameter, is defined as 1.67 times the interval T between the instants when the impulse is 30 % and 90 % of the peak value.

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- For front-chopped impulses the 'time to chopping' T_c is about equal to T_1.

- The reason for defining the point A at 30 % voltage level can be found in most records of measured impulse voltages. It is quite difficult to obtain a smooth slope within the first voltage rise, as the measuring systems as well as stray capacitances and inductances may cause oscillations.

- For most applications, the (virtual) front time T_1 is 1.2 μs, and the (virtual) time to half-value T_2 is 50 μs.

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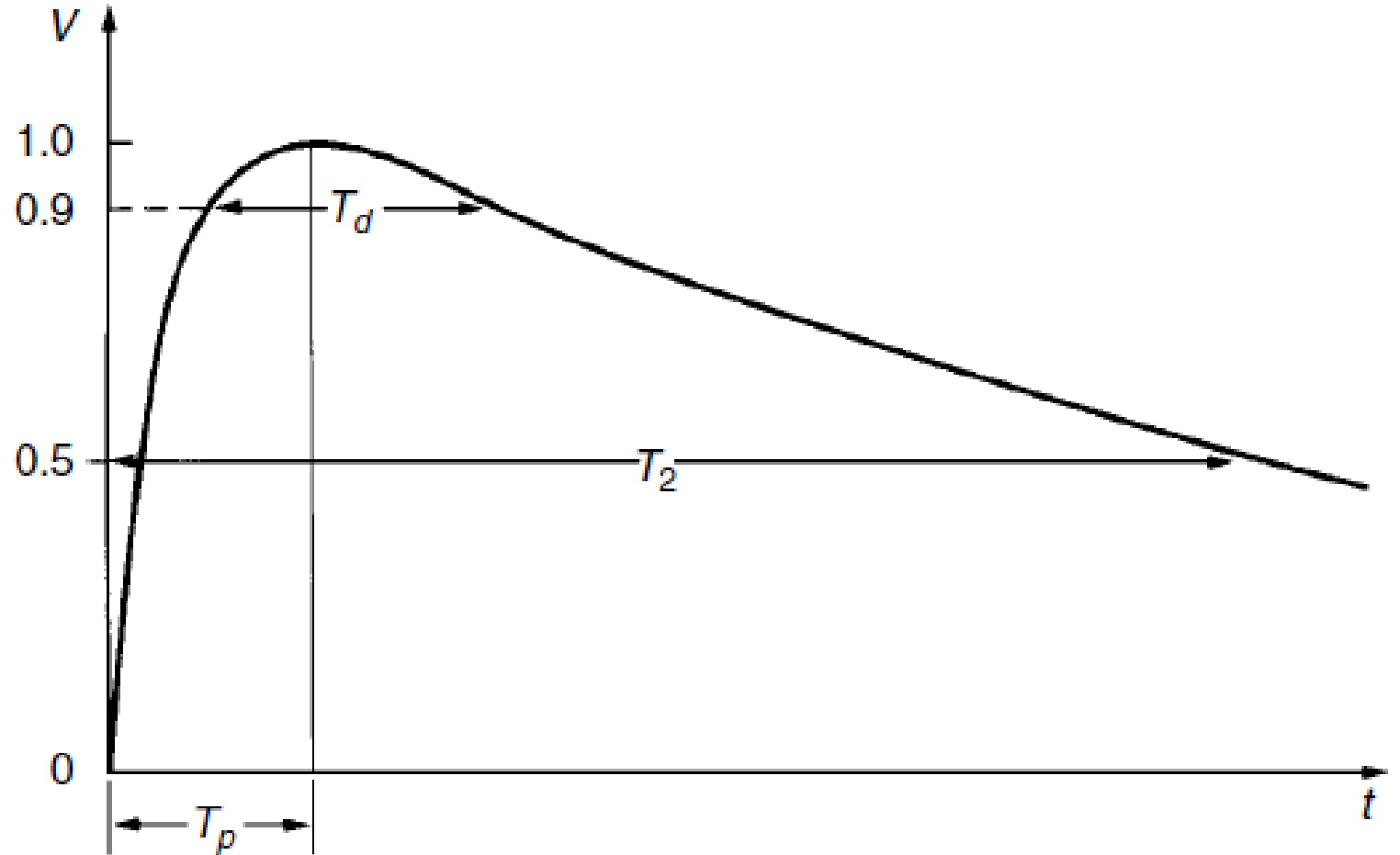
Generation of high voltages 'Impulse Voltage'

- In general the specifications permit a tolerance of up to 30% for T_1 and 20% for T_2.

- Such impulse voltages are referred to as a T_1/T_2 impulse, and therefore the 1.2/50 impulse is the accepted standard lightning impulse voltage today.

- Lightning impulses are therefore of very short duration, mainly if they are chopped on front.

- Due to inherent measurement errors and uncertainties in the evaluation the 'time parameters' T_1, T_2 and T_c or especially the time difference between the points C and D can hardly be quantified with high accuracy.

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- **Switching phenomena**

- The amplitudes of switching impulses are always related to the operating voltage and the shape is influenced by the impedances of the system as well as by the switching conditions.

- The rate of voltage rise is usually slower, but it is well known that the waveshape can also be very dangerous to different insulation systems, especially to atmospheric air insulation in transmission systems with voltage levels higher than 245 kV.

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Generation of high voltages
'Impulse Voltage'

General shape of switching impulse voltages

Generation of high voltages
'Impulse Voltage'

- The time to half-value T_2 is defined similarly as before,

- The time to peak T_p is the time interval between the *actual* origin and the instant when the voltage has reached its maximum value.

- An additional parameter is therefore the time T_d, the time at 90% of crest value.

- The standard switching impulse has time parameters (including tolerances) of $T_p = 250\,\mu s \pm 20\%$, $T_2 = 2500\,\mu s \pm 60\%$ and is therefore described as a 250/2500 impulse.

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Generation of high voltages 'Impulse Voltage'

Impulse generating circuits

- Types of impulse generating circuits:
  - Single stage impulse generator circuit
  - Multistage impulse generator circuit (Marx Generator)

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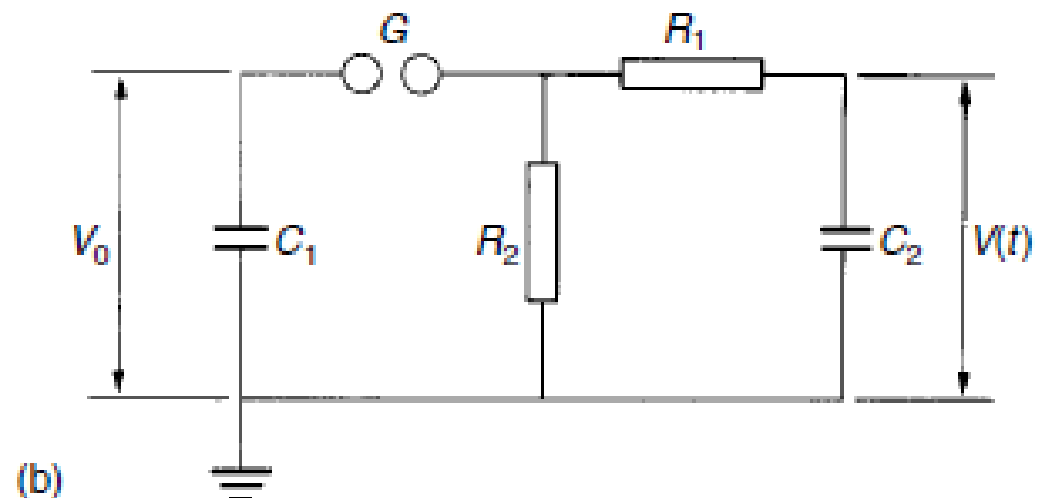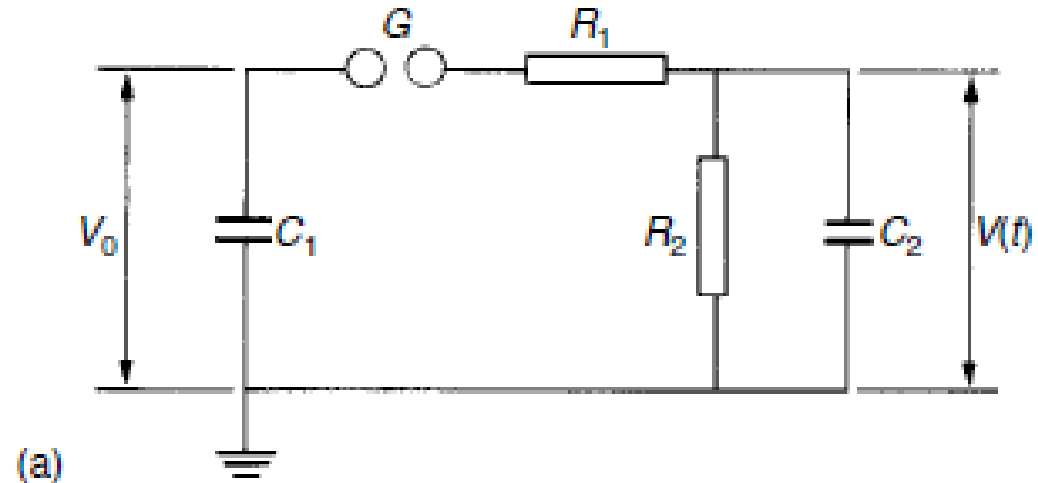## 'Impulse Voltage, single stage'

Single stage impulse generators

C_1: discharge capacitance.

C_2 : load capacitance.

R_1: front or damping resistance.

R_2 : discharge resistance

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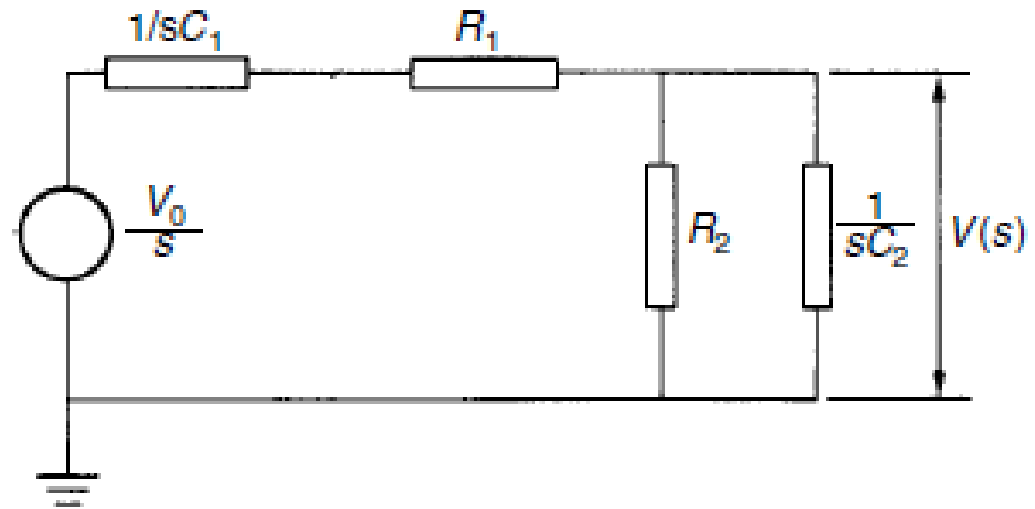# Generation of high voltages 'Impulse Voltage, single stage'

- The capacitor C_1 is slowly charged from a d.c. source until the spark gap G breaks down and instantaneously connects C_1 to the circuit

- The sphere or spark gap is two adjacent metal whose a limited separation distance. It acts as a voltage-limiting and voltage-sensitive switch, whose ignition time (time to voltage breakdown) is very short in comparison to T_1.

- The resistors R_1, R_2 and the capacitance C_2 form the wave-shaping network.

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Generation of high voltages
'Impulse Voltage, single stage'

- R_1 will primarily damp the circuit and control the front time T_1.

- R_2 will discharge the capacitors and therefore essentially control the wave tail.

- The capacitance C_2 represents the full load, i.e. the object under test as well as all other capacitive elements which are in parallel to the test object (measuring devices; additional load capacitor to avoid large variations of T_1/T_2, if the test objects are changed).

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Single stage impulse generators
s-domain
"circuit (a)"

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- The output voltage is thus given by the expression

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

where

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

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

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- The output voltage is thus given by the expression "circuit (a)"

$$V(s) = \frac{V_0}{k} \frac{1}{s^2 + as + b};$$

where

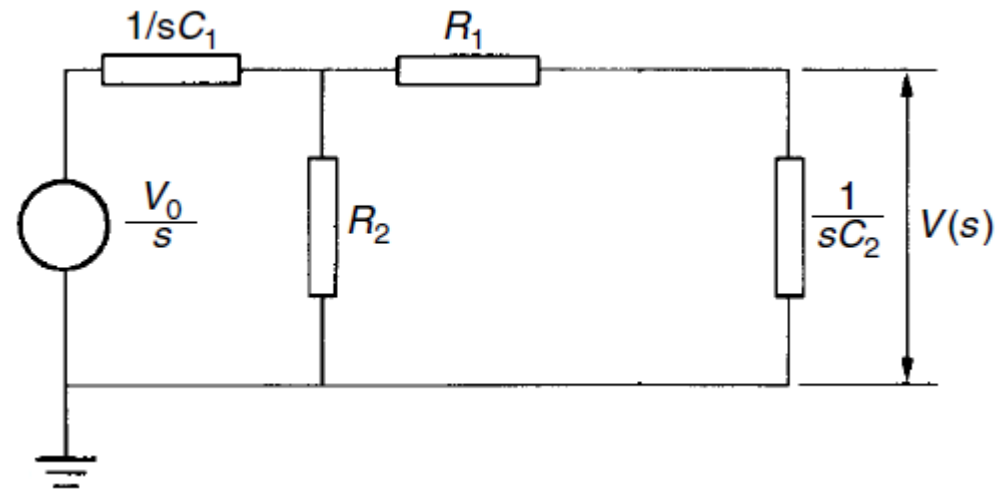$$a = \frac{1}{R_1 C_1} + \frac{1}{R_1 C_2} + \frac{1}{R_2 C_2}$$

$$b = \frac{1}{R_1 R_2 C_1 C_2}$$

$$k = R_1 C_2$$

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Generation of high voltages
'Impulse Voltage, single stage'

Single stage impulse generators
s-domain
"circuit (b)"

- The output voltage is thus given by the expression

$$V(s) = \frac{1/(C_2 s)}{1/(C_2 s) + Z_{Th}} V_{Th};$$

where

$$Z_{Th} = \frac{R_2 / (C_1 s)}{R_2 + 1/(C_1 s)} + R_1$$

$$V_{Th} = \frac{R_2}{R_2 + 1/(C_1 s)} \frac{V_0}{s}$$

- The output voltage is thus given by the expression "circuit (b)"

$$V(s) = \frac{V_0}{k} \frac{1}{s^2 + as + b};$$

where

$$a = \frac{1}{R_1 C_1} + \frac{1}{R_1 C_2} + \frac{1}{R_2 C_1}$$

$$b = \frac{1}{R_1 R_2 C_1 C_2}$$
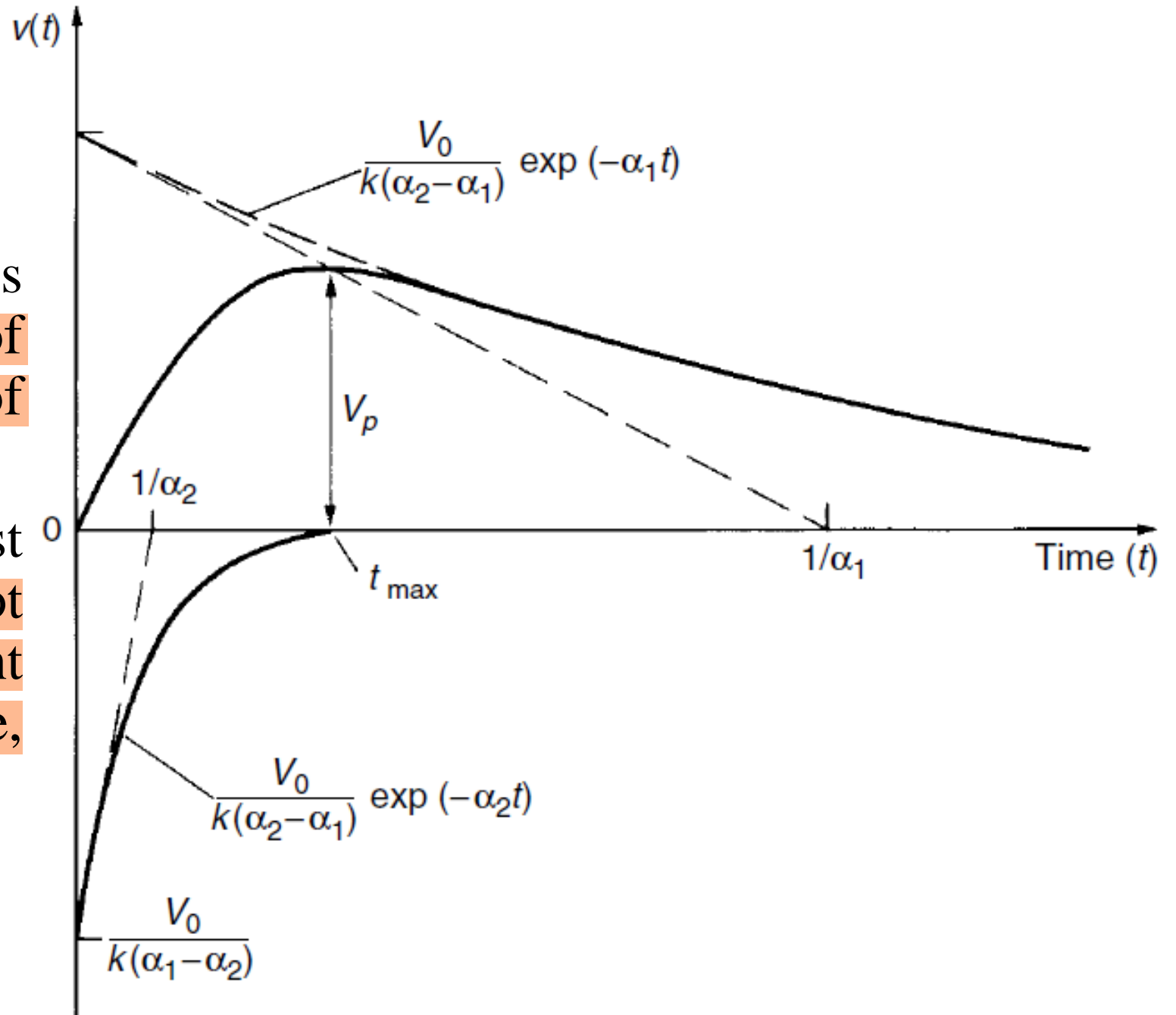
$$k = R_1 C_2$$

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- The output voltage in *t*-domain is thus given by the expression

$$V(t) = \frac{V_0}{k} \frac{1}{\alpha_2 - \alpha_1} \left(e^{-\alpha_1 t} - e^{-\alpha_2 t} \right);$$

where α_1 and α_2 are the roots of $s^2 + as + b = 0$, or

$$\alpha_{1,2} = \frac{a}{2} \mp \sqrt{\left(\frac{a}{2} \right)^2 - b}$$

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- The output voltage is therefore the superposition of two exponential functions of different signs.

- According to the last equation, the negative root leads to a larger time constant $1/\alpha_1$ than the positive one, which is $1/\alpha_2$.

$$v(t)$$

$$\frac{V_0}{k(\alpha_2-\alpha_1)} \exp(-\alpha_1 t)$$

$$V_p$$

$$1/\alpha_2$$

$$t_{max}$$

$$1/\alpha_1$$

$$\text{Time } (t)$$

$$\frac{V_0}{k(\alpha_2-\alpha_1)} \exp(-\alpha_2 t)$$

$$\frac{V_0}{k(\alpha_1-\alpha_2)}$$

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

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

V_p being the peak value of the output voltage. Obviously, this value is always smaller than 1 or 100 per cent.

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Generation of high voltages 'Impulse Voltage, single stage'

- It can be calculated as by finding t_{max} from $dV(t)/dt = 0$; this time for the voltage $V(t)$ to rise to its peak value is given by

$$t_{max} = \frac{\ln(\alpha_2 / \alpha_1)}{\alpha_2 - \alpha_1}$$

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

Generation of high voltages 'Impulse Voltage, single stage'

- For a given impulse shape T_1/T_2 or T_p/T_2 of the impulse voltages the values of α_1 and α_2 must be equal for both circuits

- The differences in efficiency can only be due, therefore, to differences in the value of $k = R_1 C_2$ for both circuits.

- We may first calculate this term for the circuit (b), which has always a higher efficiency for a given ratio of C_2/C_1, as during the discharge the resistors R_1 and R_2 do not form a voltage-dividing system.

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- The product R_1C_2 is found as:

$$\alpha_1.\alpha_2 = b; \quad \alpha_1 + \alpha_2 = a$$

$$a = \frac{1}{R_1C_1} + \frac{1}{R_1C_2} + \frac{1}{R_2C_1}; \quad b = \frac{1}{R_1R_2C_1C_2}$$

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

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- For $C_2 << C_1$, which is fulfilled in all practical circuits, and with $\alpha_2 >> \alpha_1$ for all normalized waveshapes, one may simplify this equation to:

$$k \cong \frac{1 + C_2/C_1}{\alpha_1 + \alpha_2}$$

$$\text{Note}: \sqrt{1 + \Delta} \approx 1 + \frac{1}{2}\Delta$$

- The substitution of this expression in efficiency equation finally results in

$$\eta \cong \frac{1}{1 + C_2/C_1}$$

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- The voltage efficiency for this circuit will therefore rise continuously, if (C_2/C_1) decreases to zero. The last equation indicates the reason why the discharge capacitance C_1 should be much larger than the load C_2.

- Less favourable is the circuit (a). The calculation of η may be based upon the substitution of α_1 and α_2 in the previous equations of circuit (a) and a treatment of the ratio $R_1/R_2 = f(C_2/C_1)$, which increases heavily with decreasing values of C_2/C_1.

- With minor approximations and the inequality $\alpha_2 \gg \alpha_1$ one may find the result η for the circuit (a).

$$\eta \cong \frac{1}{1 + C_2/C_1} \cdot \frac{1}{1 + R_1/R_2}$$

Generation of high voltages
'Impulse Voltage, single stage'

Voltage efficiency factors in dependency of the capacitance ratio C_2/C_1 for lightning impulses T_1/T_2

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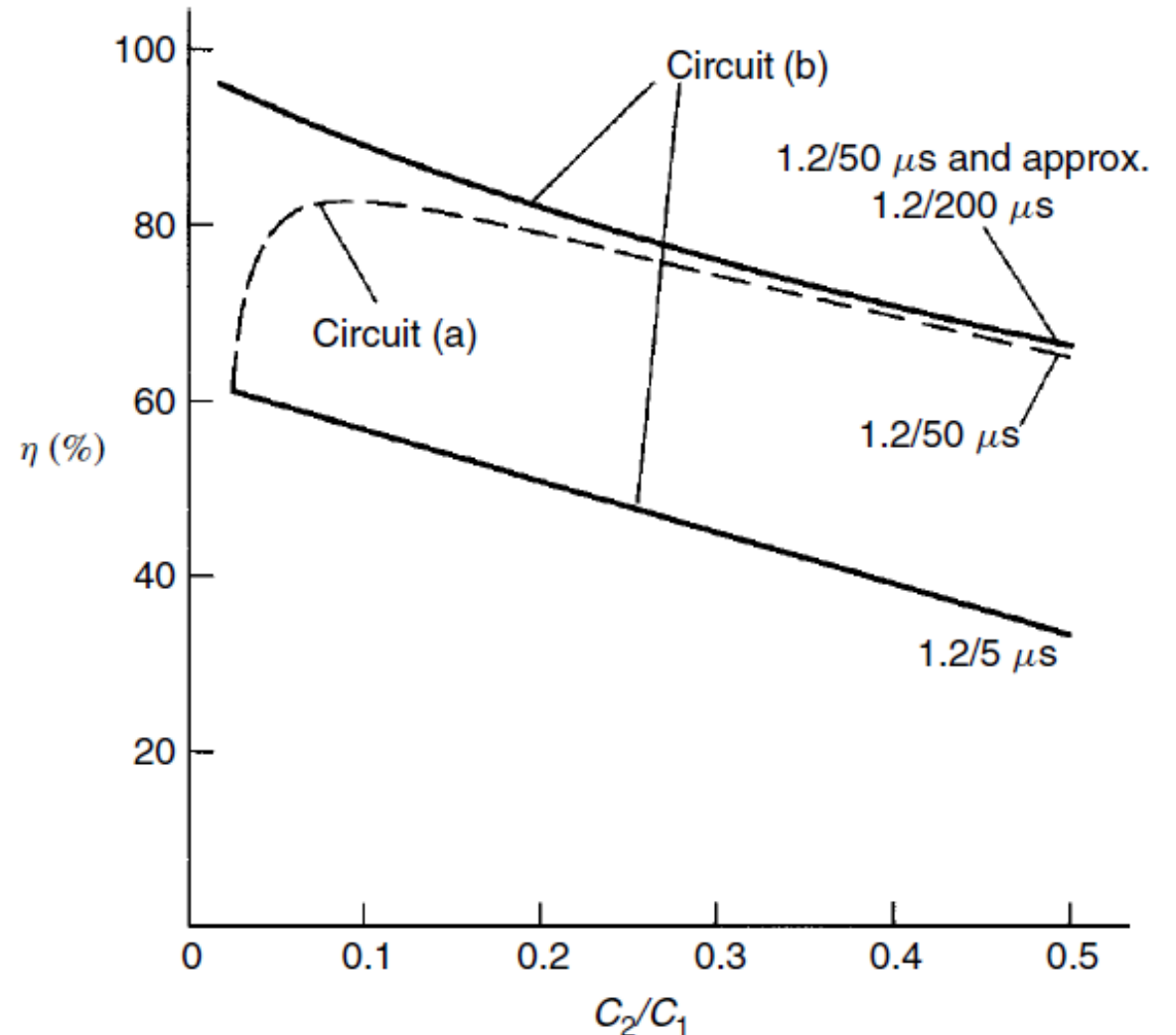
- The comparison with circuit (b) shows the decrease in due to an additional factor. As the ratio R_1/R_2 is dependent upon the waveshape, the simple dependency from (C_2/C_1) only is lost.

- For a 1.2/50 μs impulse and similar impulse voltages the rapid increase of R_1/R_2 leads to a decrease of $C_2/C_1 = 0.1$;

- therefore, the efficiency moves through an optimum value and decreases for high C_2/C_1 values as well as for small ones.

- One could even show that for very small C_2/C_1 ratios this circuit will fail to work.

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Generation of high voltages 'Impulse Voltage, single stage'

<u>Dimensioning of circuit elements:</u>

- The common task is to find the resistor values for R_1 and R_2, as C_2 and C_1 are known in general.

- For larger generators, the discharge capacitors are always given and dimensioned for a good efficiency within a certain range of C_2.

- This total load capacitance can easily be measured if it is not known in advance.

- The values a and b can be further represented as:

$$a = \alpha_1 + \alpha_2 \quad b = \alpha_1 \alpha_2$$

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- The unknown resistance values can then be calculated. The result will be for (circuit (a)):

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

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

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- The unknown resistance values can then be calculated. The result will be for (circuit (b)):

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

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

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- All these equations contain the time constants $1/\alpha_1$ and $1/\alpha_2$, which depend upon the wave-shape.

- There is, however, no simple relationship between these time constants and the times T_1, T_2 and T_p as defined in the national or international recommendations.

- This relationship can be found by applying the definitions to the analytical expression for $V(t)$.

- The relationship is irrational and must be computed numerically.

- The following table shows the result for some selected wave-shapes:

T_1/T_2 (µs)	T_p/T_2 (µs)	$1/\alpha_1$ (µs)	$1/\alpha_2$ (µs)
1.2/5	–	3.48	0.80
1.2/50	–	68.2	0.405
1.2/200	–	284	0.381
250/2500	–	2877	104
–	250/2500	3155	62.5

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