● Generation and measurement of impulse voltages

Impulse voltages are used to simulate internal surge voltages (switching surge) and external surge voltages (lightning surge) and their consequences for different dielectrics (insulators !) of gaseous, liquid or solid origin.

Impulse voltages are normally generated by discharging HV capacitors via spark gaps into “shaping” circuits of resistors and capacitors.

Measurement is accomplished by means of capacitive and/or resistive voltage division and a fast digital oscilloscope with storage facilities.

- **Rated values for impulse voltages**

6 MV

HV engineering defines an impulse voltage as a single, unipolar voltage impulse.

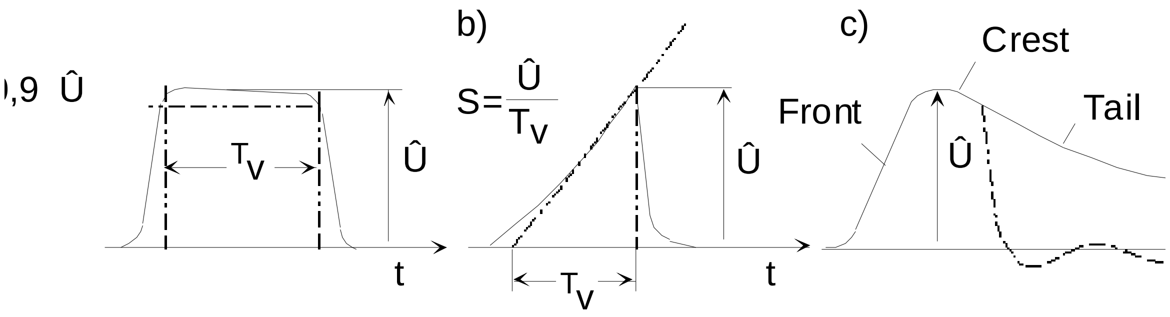
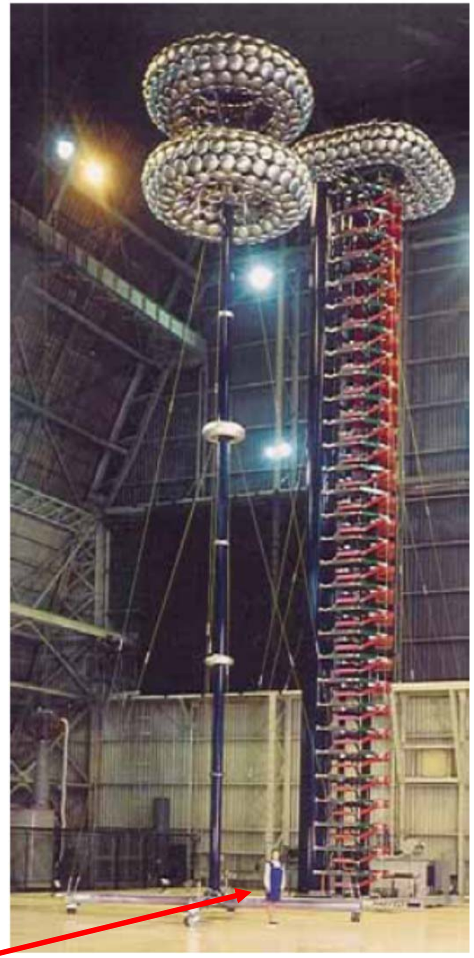


Fig. 7.1 Impulse voltages
a) Square impulse voltage, b) wedge impulse voltage, c) double exponential impulse voltage

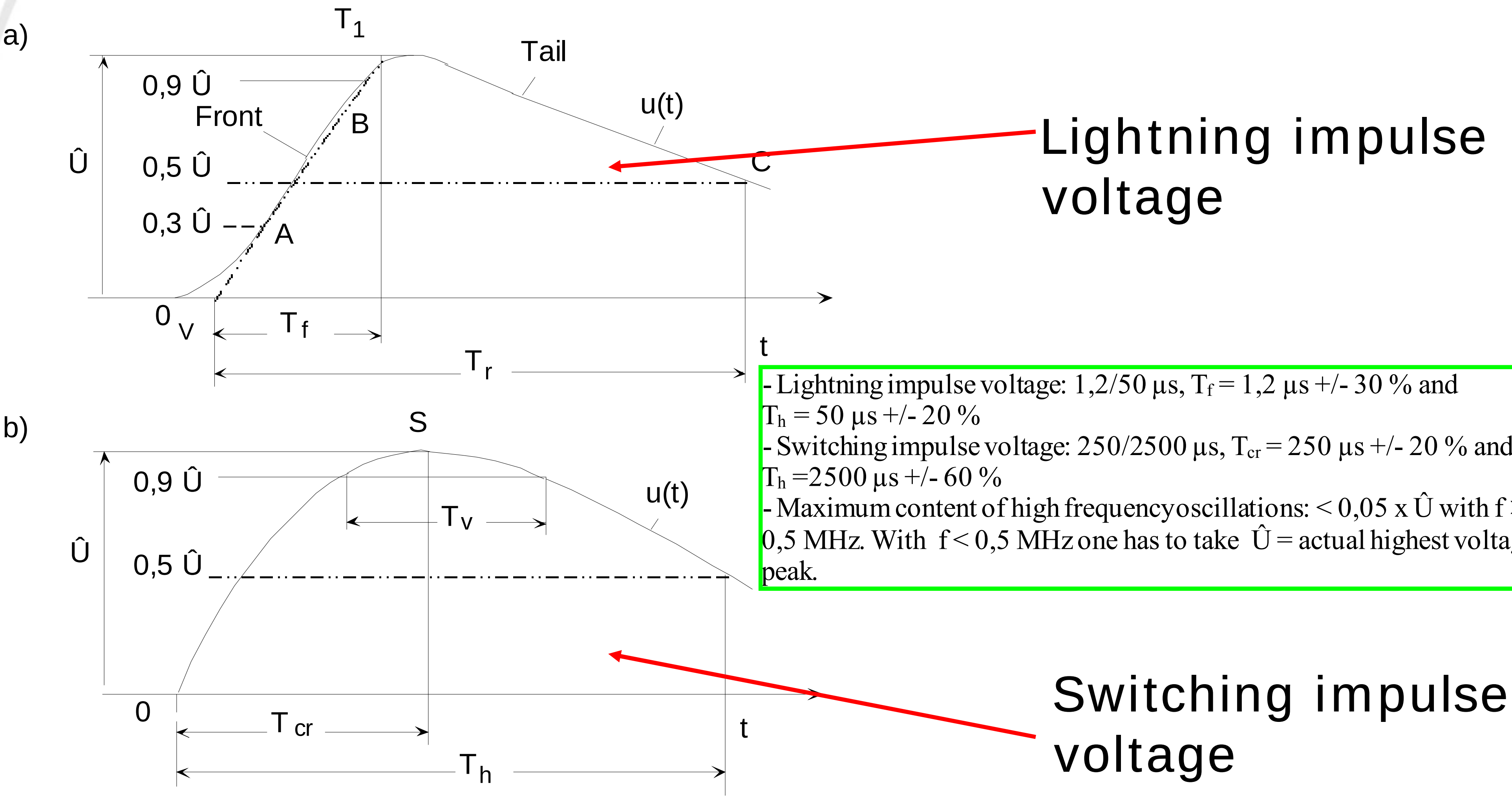


- Lightning impulse voltage: 0 ➜ Û in approximately 1 µs
- Switching impulse voltage: 0 ➜ Û after at least app. 100 µs

Impulse voltages for HV testing are standardized by means of IEC 60-2.

There's the man ☺

● **Rated values for lightning- and switching impulse voltages**



- Lightning impulse voltage: 1,2/50 µs, T_f = 1,2 µs +/- 30 % and T_h = 50 µs +/- 20 %
- Switching impulse voltage: 250/2500 µs, T_{cr} = 250 µs +/- 20 % and T_h =2500 µs +/- 60 %
- Maximum content of high frequencyoscillations: < 0,05 x Û with f > 0,5 MHz. With f < 0,5 MHz one has to take Û = actual highest voltage peak.

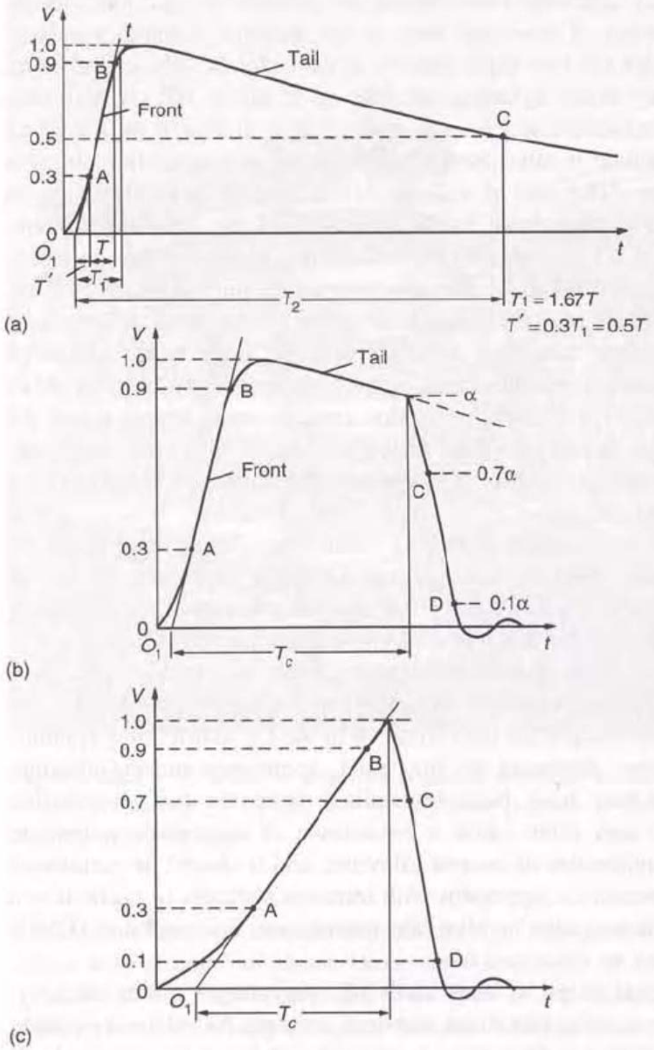


Figure 2.23 *General shape and definitions of lightning impulse (LI) voltages. (a) Full LI. (b) LI chopped on the tail. (c) LI chopped on the front. T_1: front time. T_2: time to half-value. T_c: time to chopping. O_1: virtual origin*

disruptive discharge. Although the definitions are clearly indicated, it should be emphasized that 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 per cent and 90 per cent of the peak value for full or chopped lightning impulses.

QUESTION ??? ☺
How does front chopping arise
Why is it relevant

● Capacitive circuits for impulse voltage supply

The most important basic circuits are pronounced type a and type b, respectively.

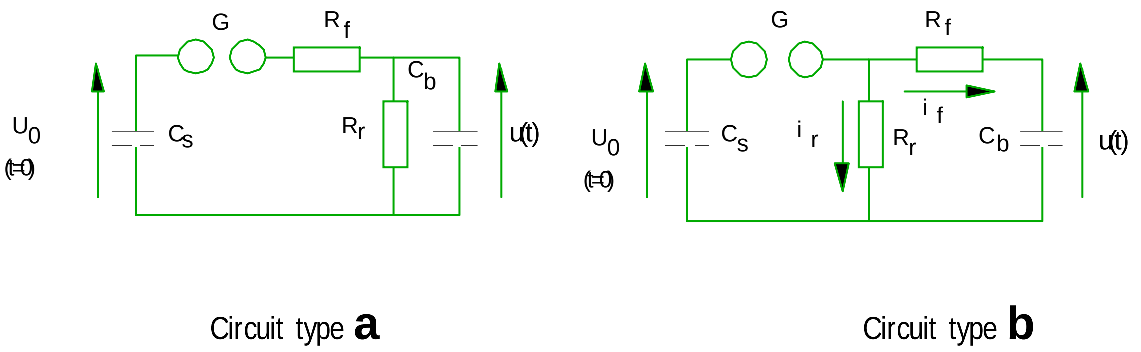


Fig. 7.3 Basic circuits used to generate impulse voltages.

We must discuss how this works !

Components for the basic circuits:

- C_S is the discharge capacitor
- G is the spark gap
- R_f is the damping resistor (for shaping the front)
- R_r is the discharge resistor (for shaping the tail)
- C_b is the load capacitor (the capacitance of the EUT)

Utilization factor (efficiency) and discharge energy

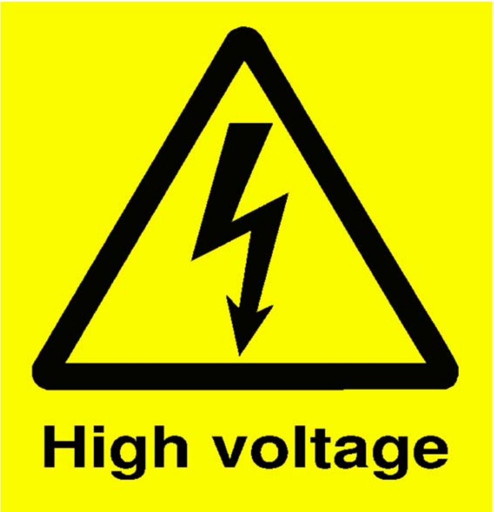
- Utilization factor

$$\eta = \frac{\hat{U}}{U_o} \leq \frac{C_s}{C_s + C_b}$$

For circuit b, simplified

- Maximum discharge energy

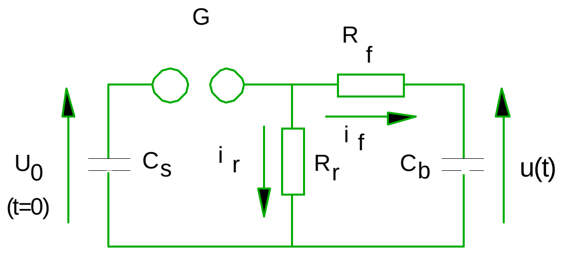
$$W = ½\, C_s \cdot U_o^2 \qquad [J]$$



● Calculation of single stage impulse voltage circuits

The components of the impulse voltage circuit must be designed well to create the desired impulse voltage waveform, ie. a 1,2/50 µs lightning impulse voltage.

Basic circuit b is normally used, because of a higher possible utilization factor.



Kirchhoffs 2. law (KVL) gives:

$$U_o - \frac{1}{C_s}\int_o^t (i_r + i_f)\, dt = i_r R_r = i_f R_f + u(t) \qquad V$$

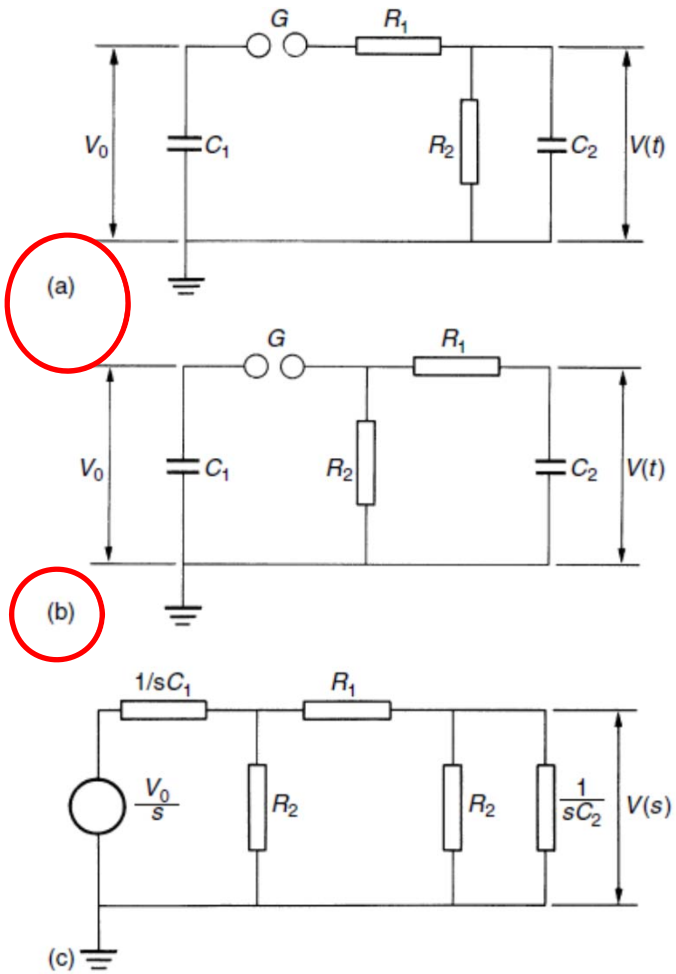


Figure 2.25 *Single-stage impulse generator circuits (a) and (b). C_1: discharge capacitance. C_2: load capacitance. R_1: front or damping resistance. R_2: discharge resistance. (c) Transform circuit*

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

where

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

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

Laplace domain ☺

By substitution we find

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

where

$$a = \left(\frac{1}{R_1C_1} + \frac{1}{R_1C_2} + \frac{1}{R_2C_2}\right);$$

$$b = \left(\frac{1}{R_1R_2C_1C_2}\right);$$

$$k = R_1C_2.$$

Output voltage a)

Depends on chosen components in the impulse generator and the ”load”.

For circuit Fig. 2.25(b) one finds the same general expression (eqn (2.23)), with the following constants; however,

$$\left.\begin{aligned} a &= \left(\frac{1}{R_1C_1}+\frac{1}{R_1C_2}+\frac{1}{R_2C_1}\right);\\ b &= \left(\frac{1}{R_1R_2C_1C_2}\right);\\ k &= R_1C_2. \end{aligned}\right\} \text{ as above} \tag{2.25}$$

For both circuits, therefore, we obtain from the transform tables the same expression in the time domain:

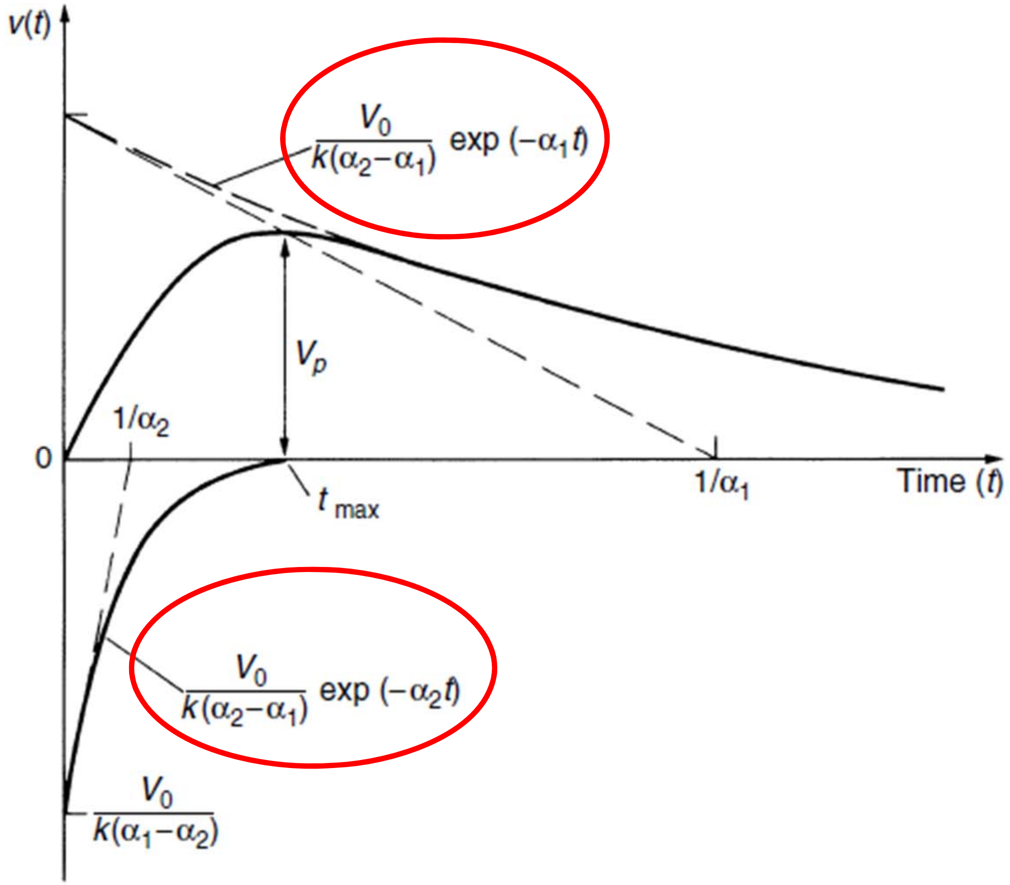
$$\boxed{V(t) = \frac{V_0}{k}\frac{1}{(\alpha_2 - \alpha_1)}[\exp(-\alpha_1 t) - \exp(-\alpha_2 t)]} \qquad (2.26)$$

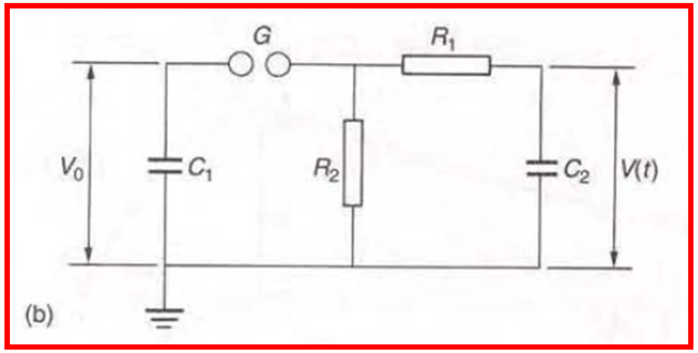
We recognize the output voltage to be the difference between two exponentials

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

$$\alpha_1, \alpha_2 = \frac{a}{2} \mp \sqrt{\left(\frac{a}{2}\right)^2 - b}.$$

Output impulse voltage – doubly exponential





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

$$\boxed{\eta = \frac{V_p}{V_0};} \tag{2.28}$$

V_p being the peak value of the output voltage as indicated in Fig. 2.26. Obviously this value is always smaller than 1 or 100 per cent. It can be calculated

WHY – obviously? ☺

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

$$t_{max} = \frac{\ln(\alpha_2/\alpha_1)}{(\alpha_2 - \alpha_1)}. \tag{2.29}$$

Substituting this equation into eqn (2.26), one may find

$$\eta = \frac{(\alpha_2/\alpha_1)^{-[(\alpha_2/\alpha_1 - \alpha_1)]} - (\alpha_2/\alpha_1)^{-[(\alpha_2/\alpha_2 - \alpha_1)]}}{k(\alpha_2 - \alpha_1)}. \tag{2.30}$$

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. The differences in efficiency η can only be due, therefore, to differences in the value of $\boxed{k = R_1 C_2}$ for both circuits. We may first calculate this term for the circuit Fig. 2.25(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. The product $R_1 C_2$ is found by eqn (2.27) by forming

$$\alpha_1 \cdot \alpha_2 = b$$

$$\alpha_1 + \alpha_2 = a \tag{2.31}$$

and by the substitution of a and b from eqn (2.25). Then we obtain

$$k = R_1 C_2 = \frac{1}{2}\left(\frac{\alpha_2 + \alpha_1}{\alpha_2 \cdot \alpha_1}\right)\left[1 - \sqrt{1 - 4\frac{\alpha_2 \cdot \alpha_1}{(\alpha_2 + \alpha_1)^2}\left(1 + \frac{C_2}{C_1}\right)}\right]. \tag{2.32}$$

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

$$\boxed{k \cong \frac{1 + C_2/C_1}{(\alpha_2 + \alpha_1)}.} \tag{2.33}$$

For circuit b)

The substitution of this expression in eqn (2.30) finally results in

$$\eta = \frac{C_1}{(C_1 + C_2)} = \frac{1}{1 + (C_2/C_1)}$$

For circuit a)

$$\eta \cong \frac{C_1}{(C_1 + C_2)} \frac{R_2}{(R_1 + R_2)} = \frac{1}{(1 + C_2/C_1)} \frac{1}{(1 + R_1/R_2)}.$$

Voltage dividing because of resistor R2 location

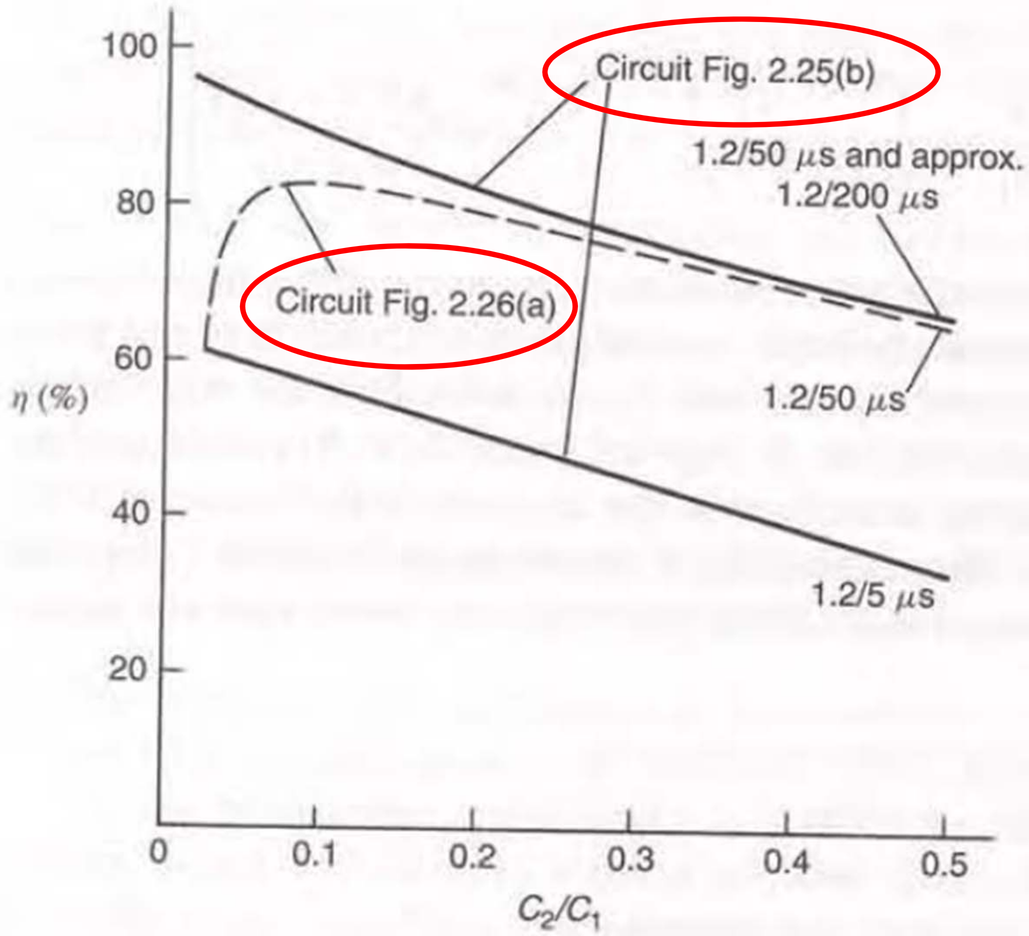


Figure 2.27 *Voltage efficiency factors η in dependency of the capacitance ratio C_2/C_1 for lightning impulses T_1/T_2*

Circuit Fig. 2.25(a):

$$R_1 = \frac{1}{2C_1}\left[\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right) - \sqrt{\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)^2 - \frac{4(C_1+C_2)}{\alpha_1\alpha_2\cdot C_2}}\,\right]. \qquad (2.36)$$

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

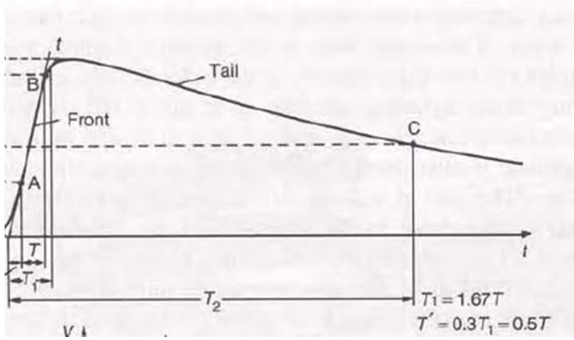
Circuit Fig. 2.25(b):

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

$$R_2 = \frac{1}{2(C_1+C_2)}\left[\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right) + \sqrt{\left(\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\right)^2 - \frac{4(C_1+C_2)}{\alpha_1\alpha_2 C_1}}\,\right]. \qquad (2.39)$$

All these equations contain the time constants $1/\alpha_1$ and $1/\alpha_2$, which depend upon the waveshape. 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, i.e. in Figs 2.23 and 2.24. This relationship can be found by applying the definitions to the analytical expression for $V(t)$, this means to eqn (2.26). 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



The standardized nominal values of T_1 and T_2 are difficult to achieve in practice, as even for fixed values of C_1 the load C_2 will vary and the exact values for R_1 and R_2 according to eqns (2.38) and (2.39) are in general not available. These resistors have to be dimensioned for the rated high voltage of the generator and are accordingly expensive. The permissible tolerances for T_1 and T_2 are therefore necessary and used to graduate the resistor values. A recording of the real output voltage $V(t)$ will in addition be necessary if the admissible impulse shape has to be testified.

Another reason for such a measurement is related to the value of the test voltage as defined in the recommendations.[2,3] This magnitude corresponds to the crest value, if the shape of the lightning impulse is smooth. However, oscillations or an overshoot may occur at the crest of the impulse. If the frequency of such oscillations is not less than 0.5 MHz or the duration of overshoot not over 1 μsec, a 'mean curve' (see Note below) should be drawn through the curve. The maximum amplitude of this 'mean curve' defines the value of the test voltage. Such a correction is only tolerated, provided their single peak amplitude is not larger than 5 per cent of the crest value. Oscillations on the front of the impulse (below 50 per cent of the crest value) are tolerated, provided their single peak amplitude does not exceed 25 per cent of the crest value. It should be emphasized that these tolerances constitute the permitted differences between specified values and those actually recorded by measurements. Due to measuring errors the true values and the recorded ones may be somewhat different.

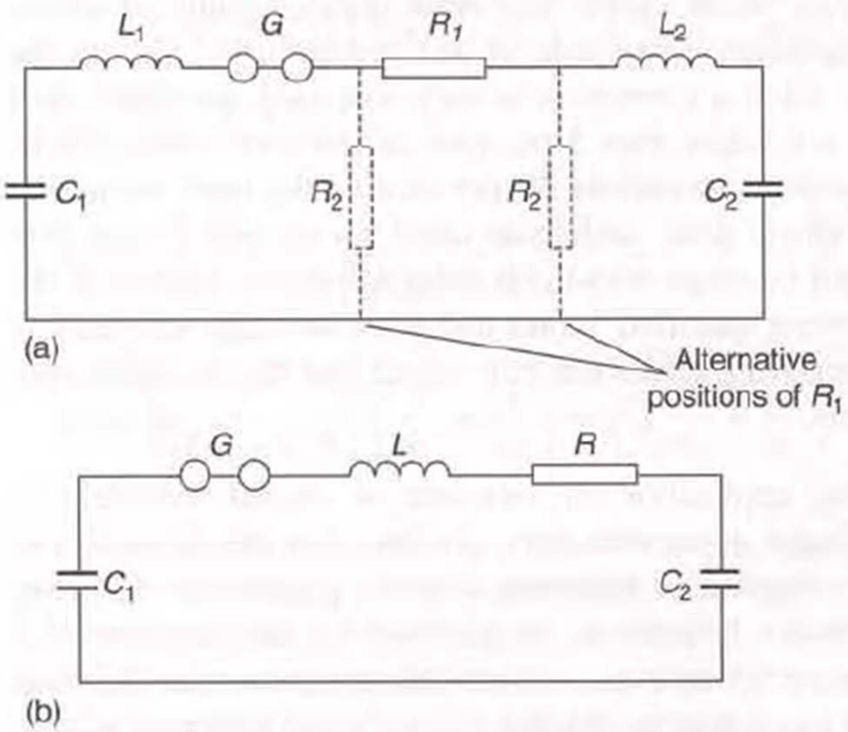


Figure 2.28 *Simplified circuit of impulse generator and load. Circuit showing alternative positions of the wave tail control resistance. (b) Circuit for calculation of wave front oscillations*

$$R_1 \cong R = 2\sqrt{\frac{L}{C}}$$

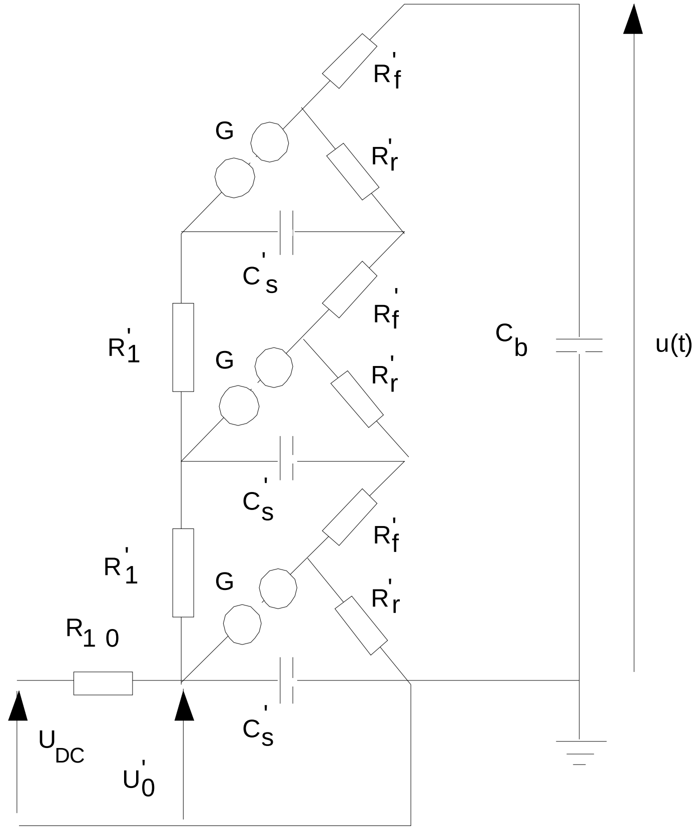
where

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

For a non-oscillatory behavior.

Critically damped!

Cascaded impulse generator (Marx generator)



R' charging resistor
C' stage capacitors
R_2 discharge resistors
R_1 external discharge resistor

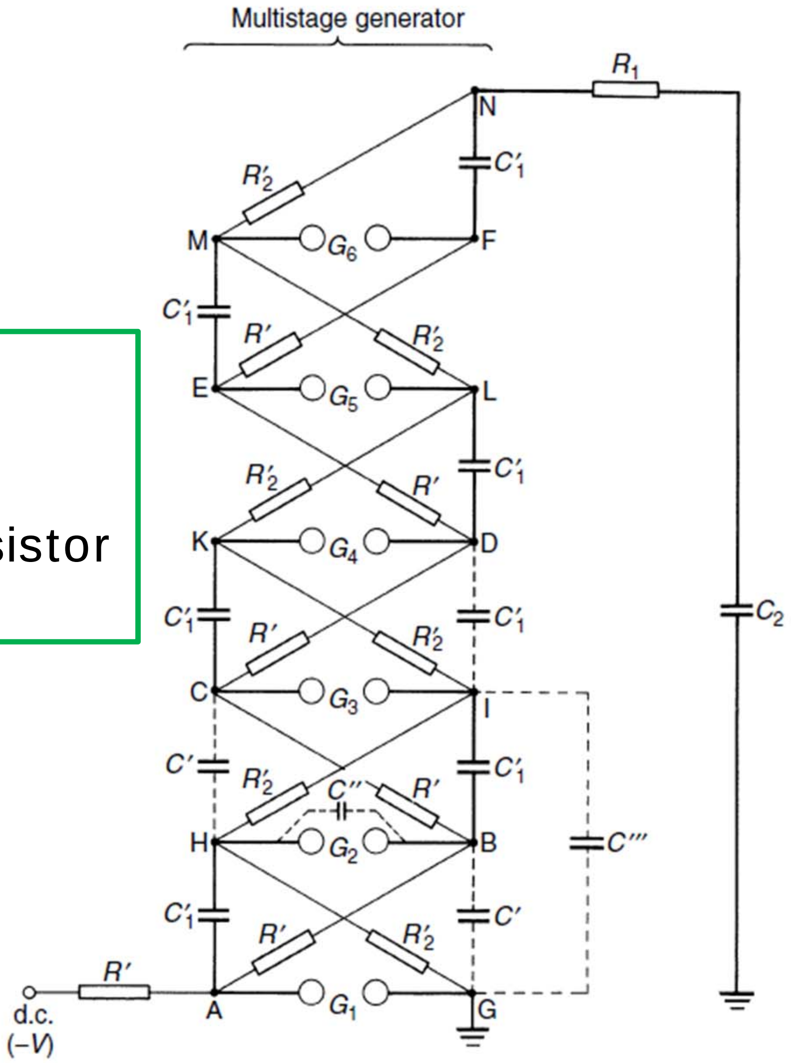


Figure 2.29 *Basic circuit of a six-stage impulse generator (Marx generator)*

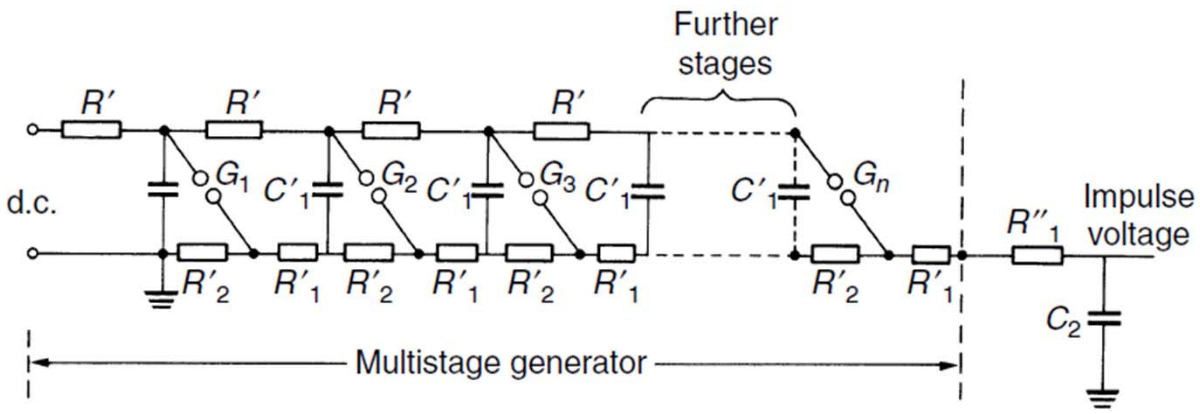


Figure 2.30 *Multistage impulse generator with distributed discharge and front resistors. R'_2: discharge resistors. R'_1: internal front resistors. R''_1: external front resistor*

$$\frac{1}{C_1} = \sum^{n} \frac{1}{C'_1};$$

the effective front resistance R_1 as

$$R_1 = R''_1 + \sum^{n} R'_1;$$

and the effective discharge resistance R_2 – neglecting the charging resistances R' – as

$$R_2 = nR'_2 = \sum^{n} R'_2;$$

where n is the number of stages.

● Measurement of impulse peak voltage by means of measuring sphere gaps

The breakdown of gases in a quasihomogeneous electric field will develop within very few microseconds (1-2 µs), typically nanoseconds, measured from the time, where the voltage rises above the breakdown voltage U_d.

This quality makes it feasible to measure the peak voltage of an impulse voltage by means of a sphere gap, as long as the tail half-life time $T_r > 50$ µs.

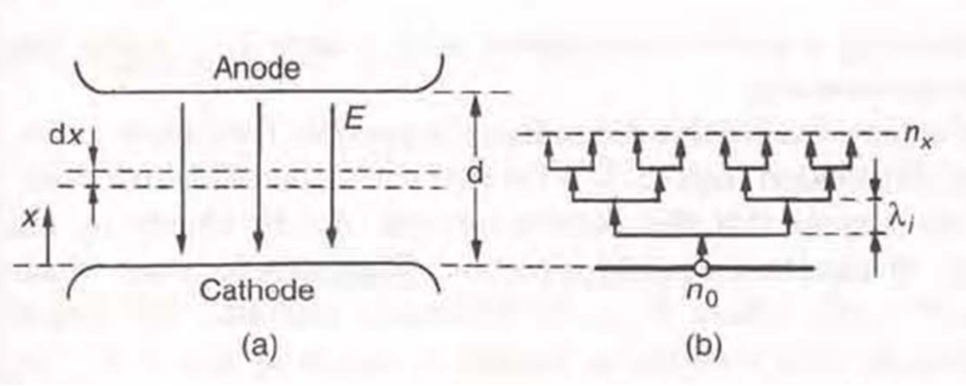
The measuring accuracy will be comparable to the measuring accuracy with AC-voltages, ie. below 3 %

The breakdown time delay will consist of a statistical and a formative time for the gas discharge to develop.

- The statistical time delay is determined by the time elapsed from the moment of the voltage impression and to the presence of an initial electron at the place in the field space comprising the maximum field strength.

The statistical time delay can practically be eliminated by means UV-illumination or radioactive radiation of the cathode.

- The formative time delay is determined by the physical development time for the electron avalanche to pass the electrode gap. It depends, among other things, of the gap length.

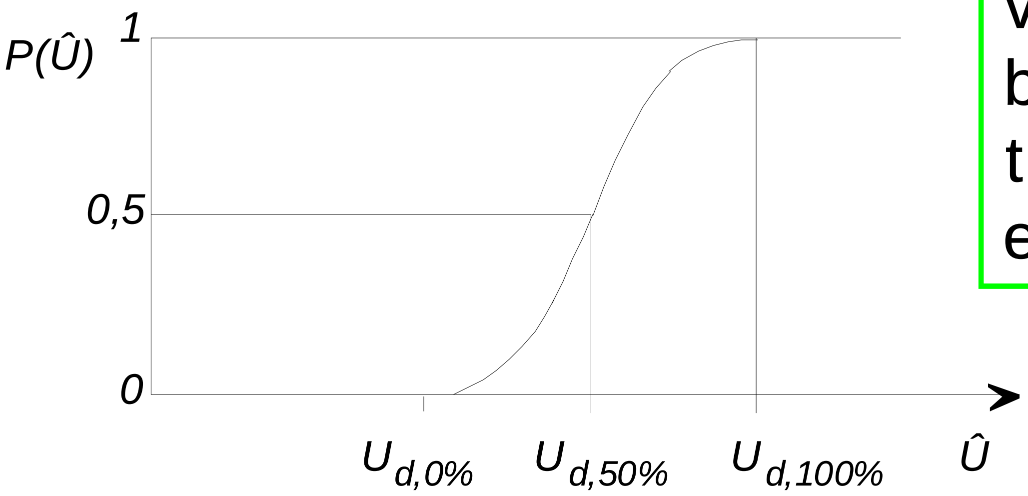


● **50 % breakdown voltage**

Spheregap breakdown voltage tables (ie. from IEC 60-2) gives the so called standard atmospherically (nominal air density) converted 50 % breakdown voltage $\hat{U}_{do}$.

The following relation apply for impulse voltages:

$$U_{d,50\%} \simeq \hat{U}_d \simeq d\,\hat{U}_{do}$$



So for impulse voltages we ALWAYS mean the 50% breakdown voltage when using breakdown voltage tables or when nothing else is stated !

Tell a story about the testing of large Power transformers ☺

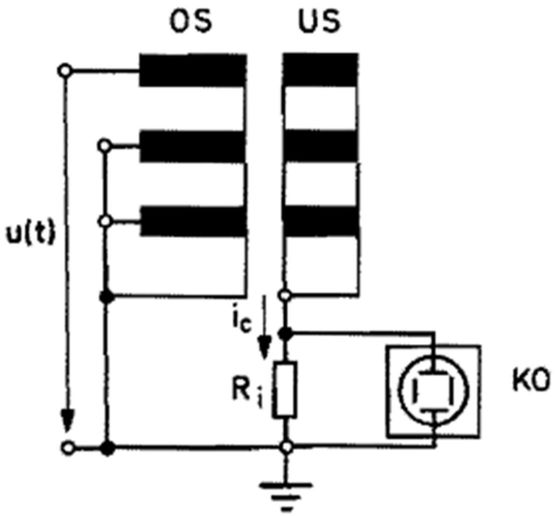


Bild 3.9-4
Schaltung zur Prüfung mit Blitzstoß-spannung nach Elsner
OS Oberspannungswicklung,
US Unterspannungswicklung

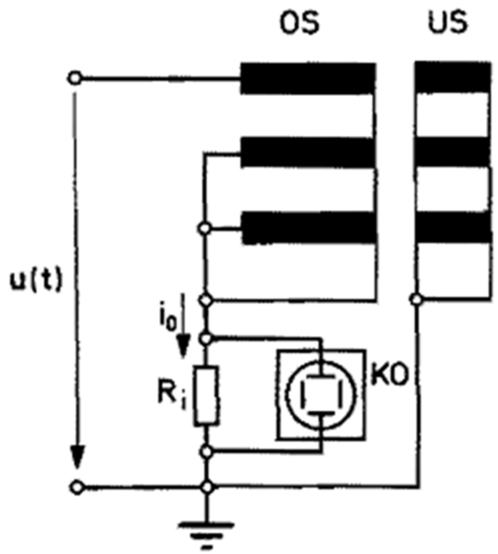
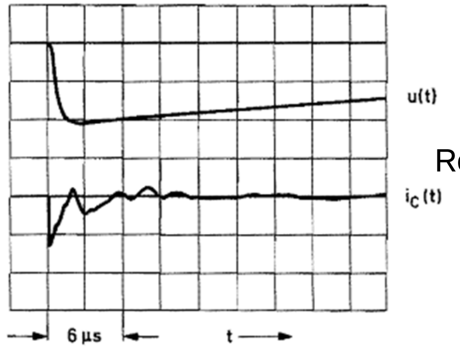
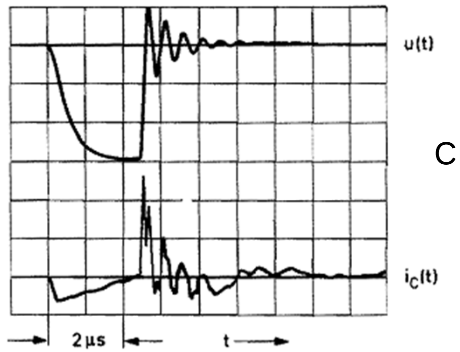


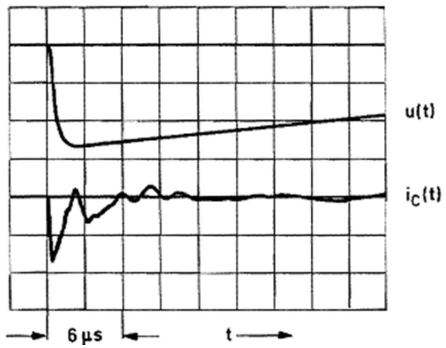
Bild 3.9-5
Schaltung zur Prüfung mit Blitzstoß-spannung nach Hagenguth
OS Oberspannungswicklung,
US Unterspannungswicklung



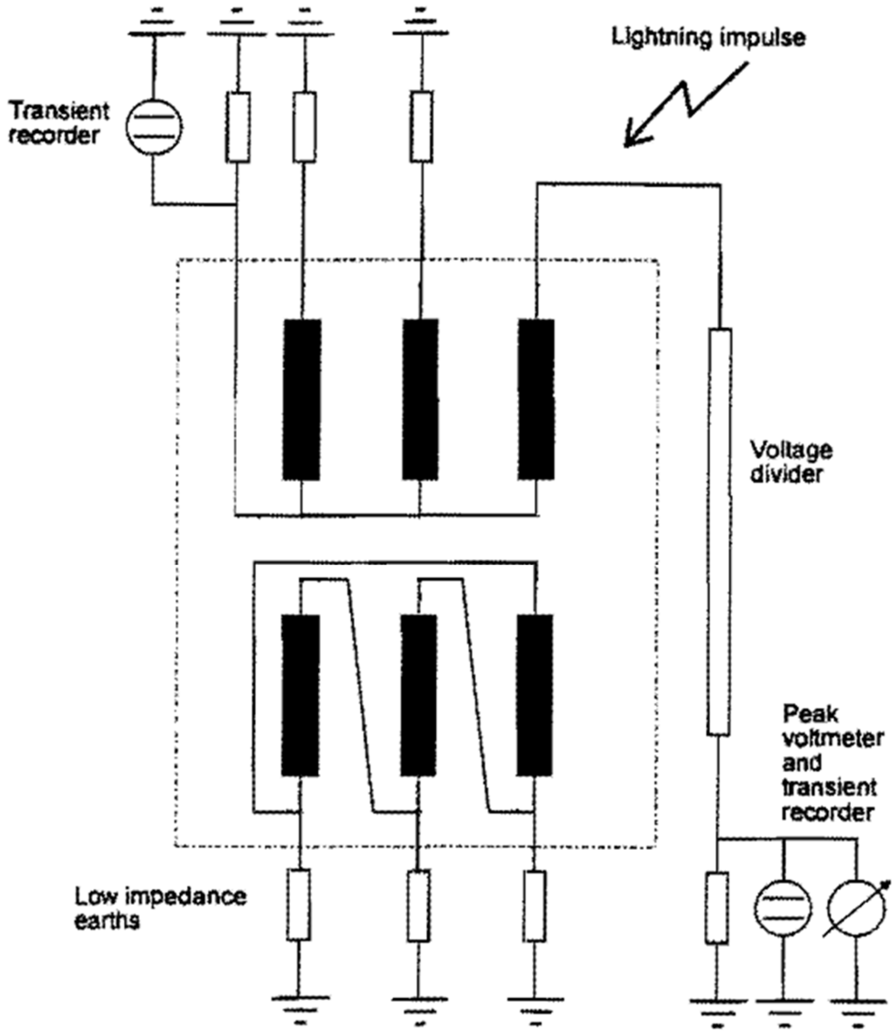
Reduced wave



Chopped wave



Control with full wave



Lightning impulse test arrangement

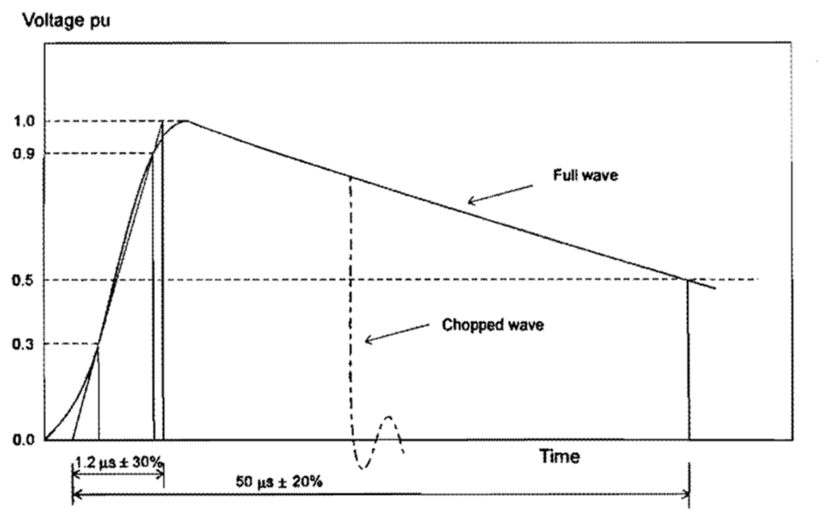


Fig. 10.6 Lightning impulse wave shape

The test sequence required by NGC for routine tests on every unit, at the voltage level specified in Table 10.2, is:

(i) 1 Reduced full wave (between 50 and 75%);
(ii) 1 Full wave (100%);
(iii) 2 Chopped waves (115%);
(iv) 2 Full waves (100%);
(v) 1 Reduced full wave (at same level as first impulse).

Transient recordings of the applied voltage and of the current at the neutral end of the winding under test are taken.

The transformer passes the test if there is no evidence of complete or incipient failure from audible indications or changes in the voltage or current records.