HIGH VOLTAGE ENGINEERING

High Voltage Generation

High Voltage Laboratory

- The needed voltage level increases with increasing of transmitted power
- Currently the majoroty of power is transmitted by ac systems with rated voltage of 400 kV
- At the same time there is an increasing portion of HVDC (high-voltage direct current) technology with the most common rated voltage of ±800 kV (became more economically atractive)

Voltage stresses

- The operating voltage does not seriously stress the insulation systém, however determines its dimensions
- The voltage stress arise from various overvoltages, when the peak value can be dependent (schwitching overvoltages) or independent on rated voltage (lightning overvoltages)
- For designing of insulation system is important to determine:
  - which voltage stresses must withstand
  - the reponse of the insulation system when subjected to these voltage stresses

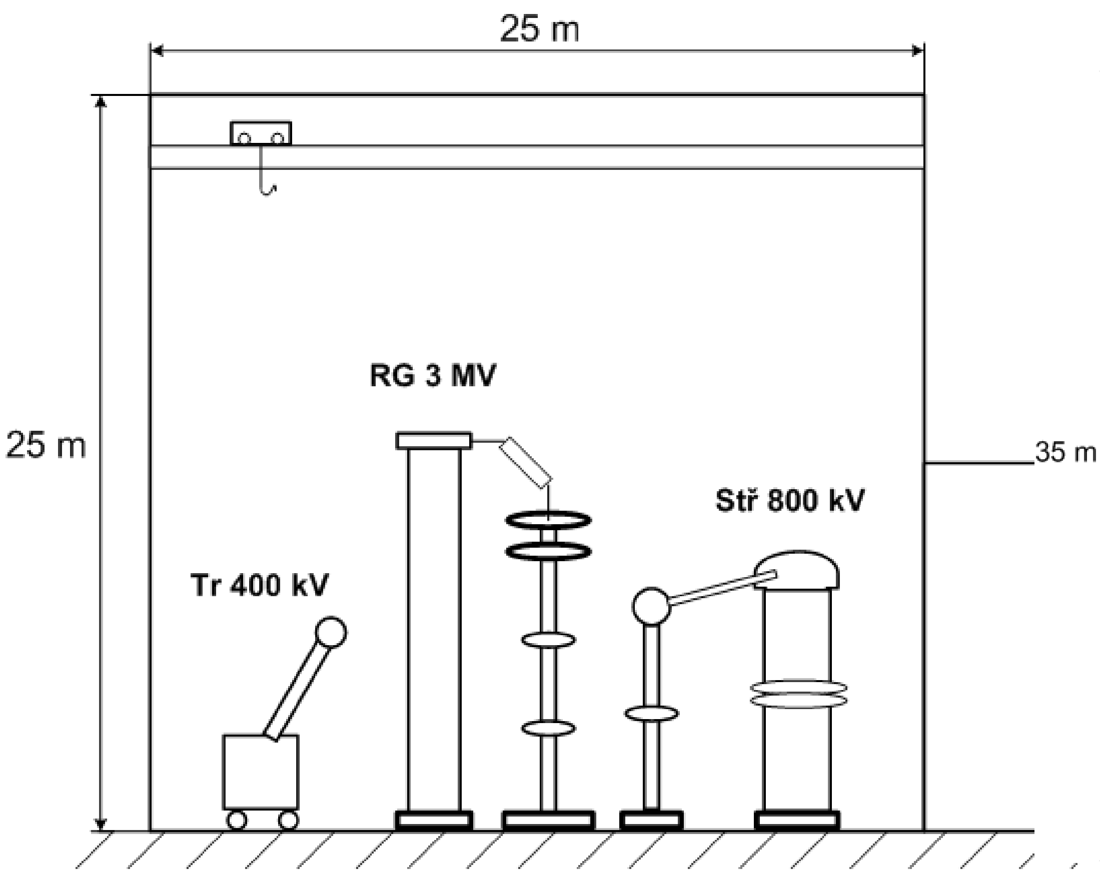
Testing Voltages

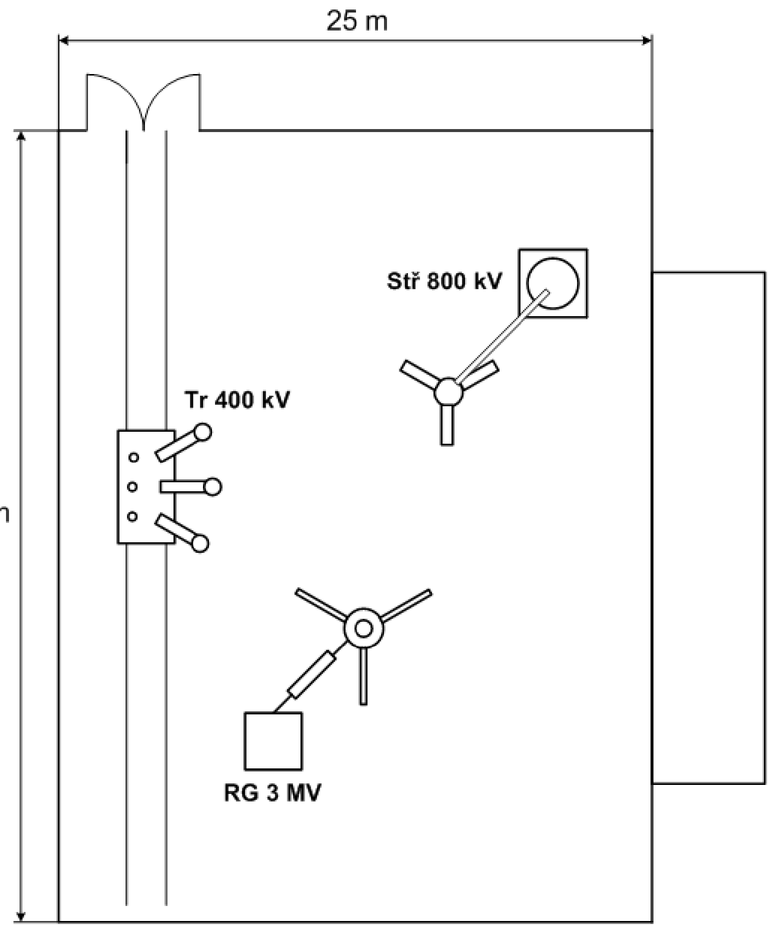
- An insulation system must be tested during its development and before commissioning
- Voltage tests
  - Testing with power frequency voltages
  - Testing with lightning impulse voltages
  - Testing with schwitching impulses
  - Testing with dc voltages
- Selection of the test and the value of testing voltage depends on type of devices and its rated voltage

Testing laboratories

Max. voltage	ac voltage	Lightning impulse	Schwitch-ing impulse	Minimal distance
(kV)				(m)
36	70	170	-	0,4
123	230	550	-	1,2
245	460	1050	-	2,5
420	510	1425	1050	5
525	630	1550	1175	8
765	850	2100	1550	12
1200	1400	2550	2100	20
1600	1900	3150	2550	30

Testing laboratories



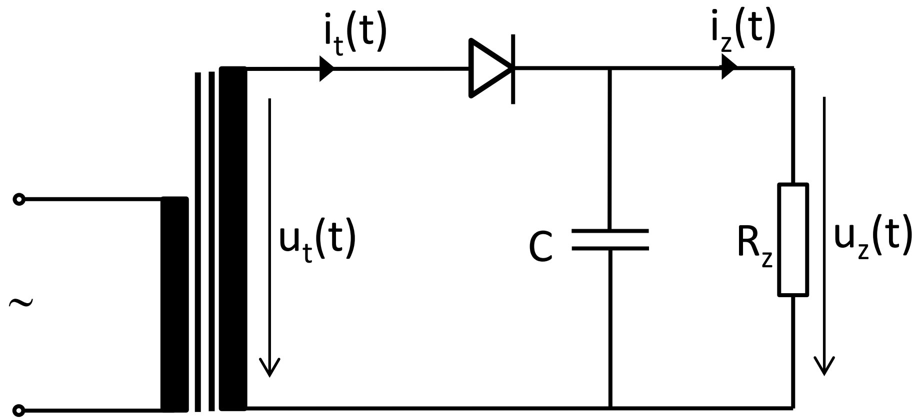


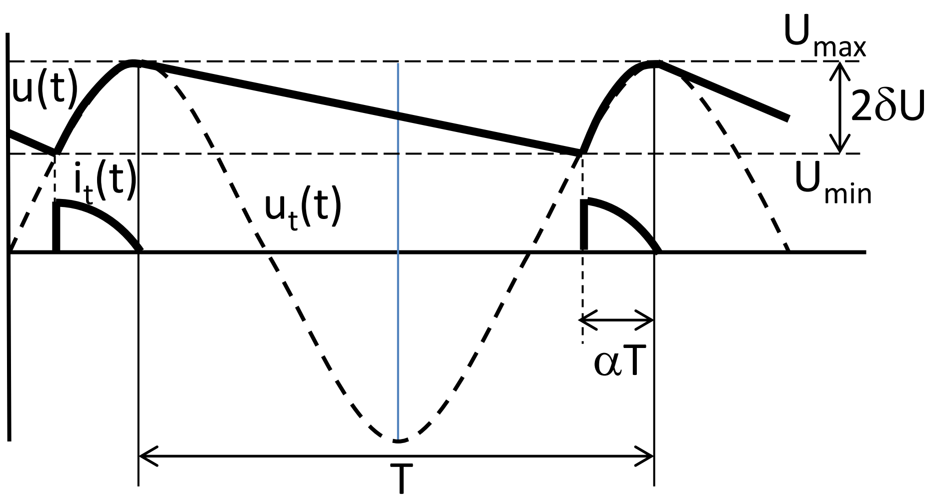
Generation of high voltages

- The high voltage generators are used both in high voltage laboratories and in numerous other applications
- Classes of generators
  - DC voltage sources
  - AC voltage sources
  - Impulse (transient) sources

Direct Voltages

- By transformation from ac voltages (rectifiers)





Charge Q transferred to load R_z during one period T

$$Q = \int_T i_z(t)dt = \frac{1}{R_z}\int_T u_z(t)dt =$$

$$= I_z T = \frac{I_z}{f}$$

where I_z is the mean value of current. Charge Q is also equal to:

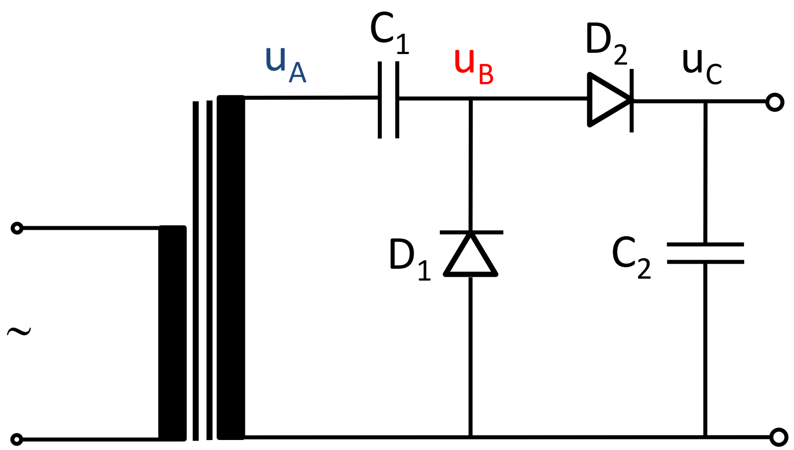
$$Q = \int_{\alpha T} i_t(t)dt = \int_T i_z(t)dt$$

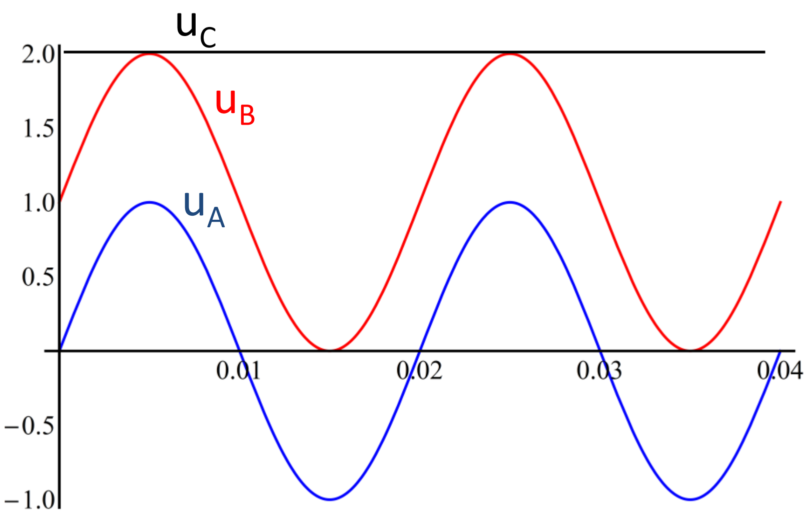
The exact solution is complicated, so α=0 is assumed and then the the voltage ripple can be expressed as:

$$Q = 2\delta UC \rightarrow \delta U = \frac{Q}{2C} = \frac{I_z}{2Cf}$$

Direct Voltages

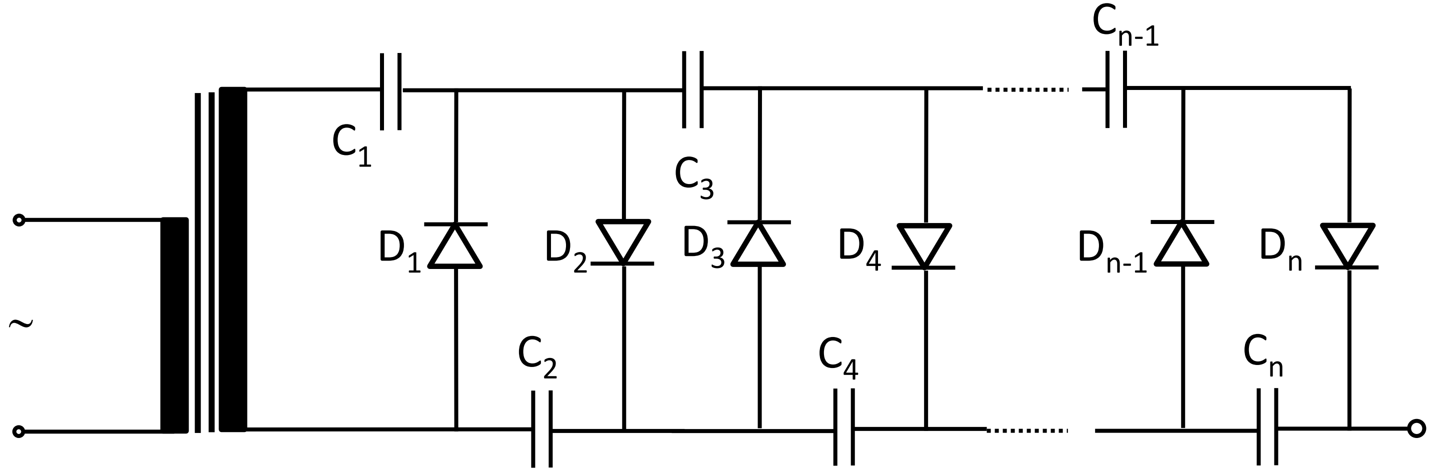
- Voltage doublers (Greinacher doubler)





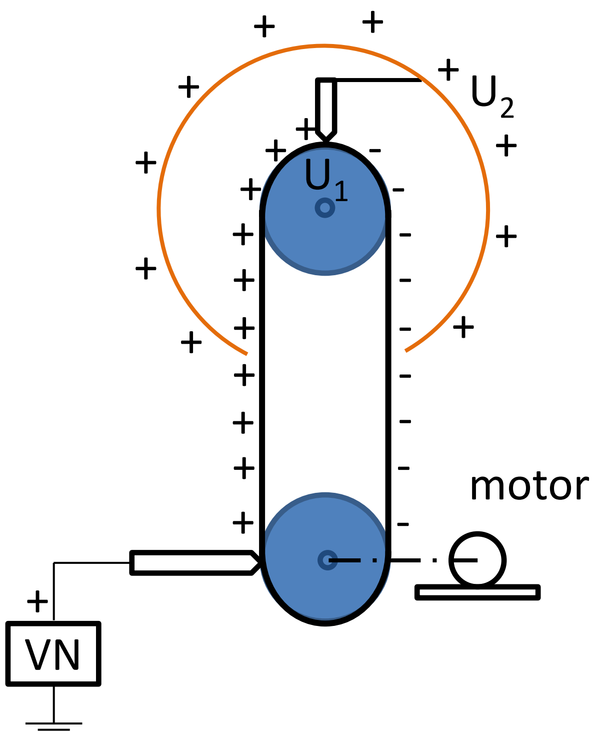
Direct Voltages

- Voltage multipliers (Cockcroft-Walton)



Direct Voltages

- Van de Graaff generator



- It is possible to reach extreme values of dc voltages (8MV)
- The large charge is reached by continuous charge acummulation on sphere electrode from belt by using collector
- The charge comes from higher potential U_1 to lower potential U_2.

AC voltages

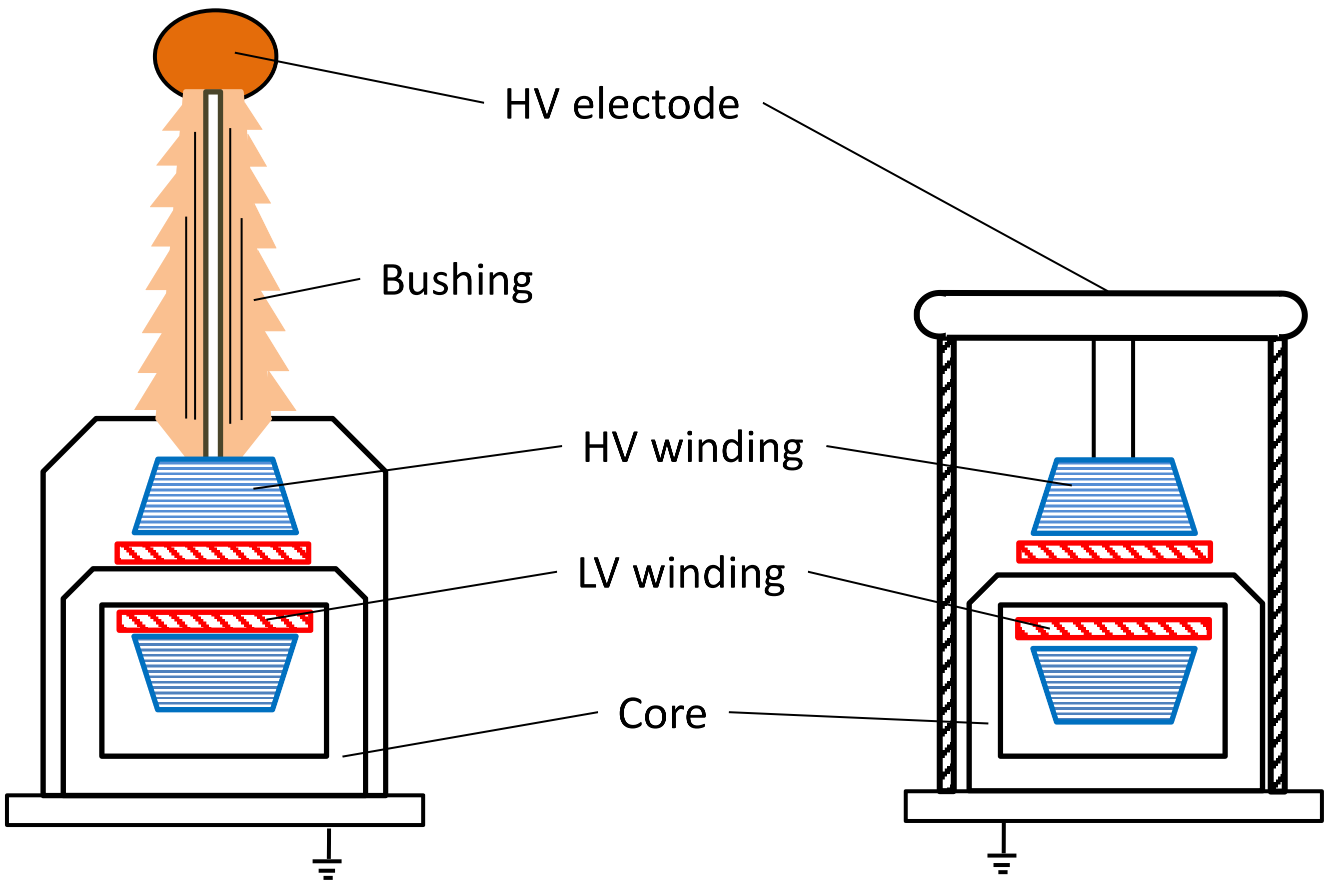
- AC testing suplies are usually single-phase
- The voltage shape must be pure sinusoidal as possible
- The ration between peak value and rms value must be $\sqrt{2} \pm 5\%$
- At high voltage testing of insulation system the load has always capacitive character. The source power is then

$$P = kU_n^2 \omega C_t$$

where $k \geq 1$ is constant which respect other capacitances of test circuit and C_t is capacity of tested object

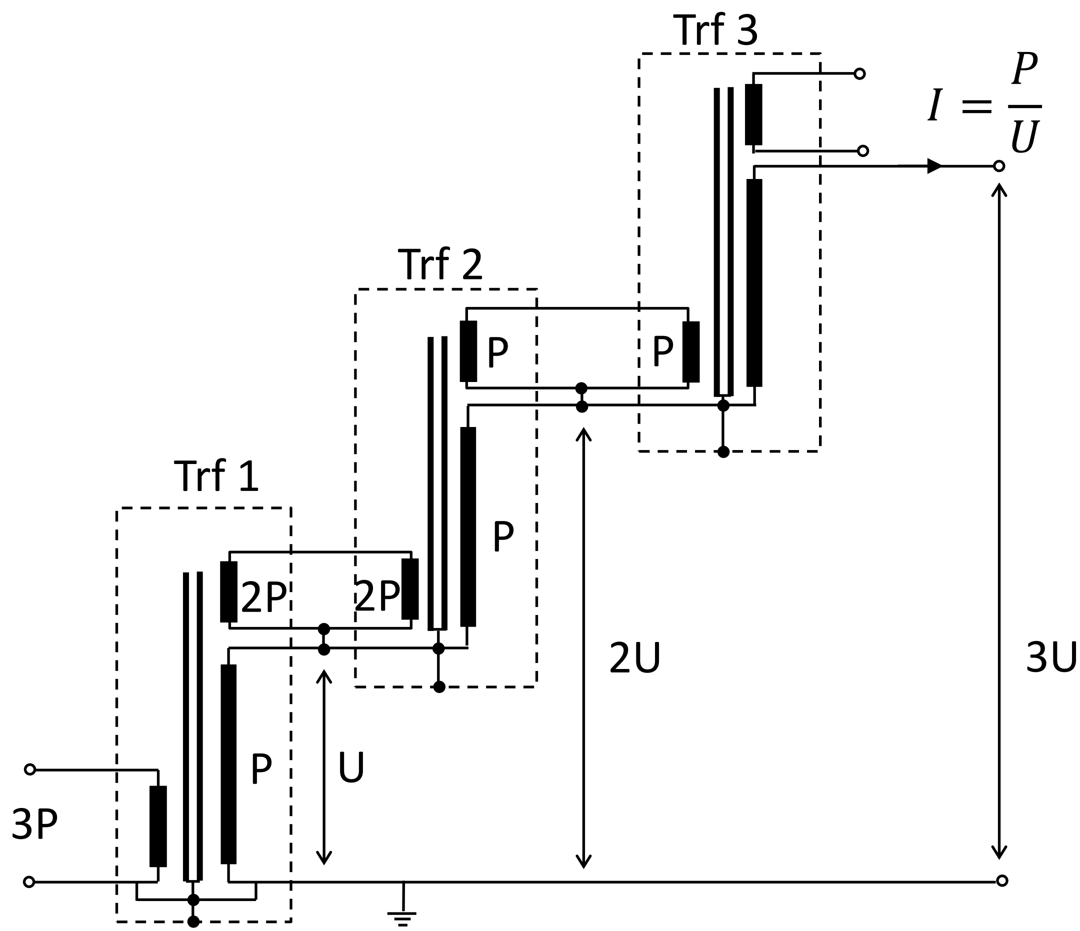
AC voltages

- Testing transformers



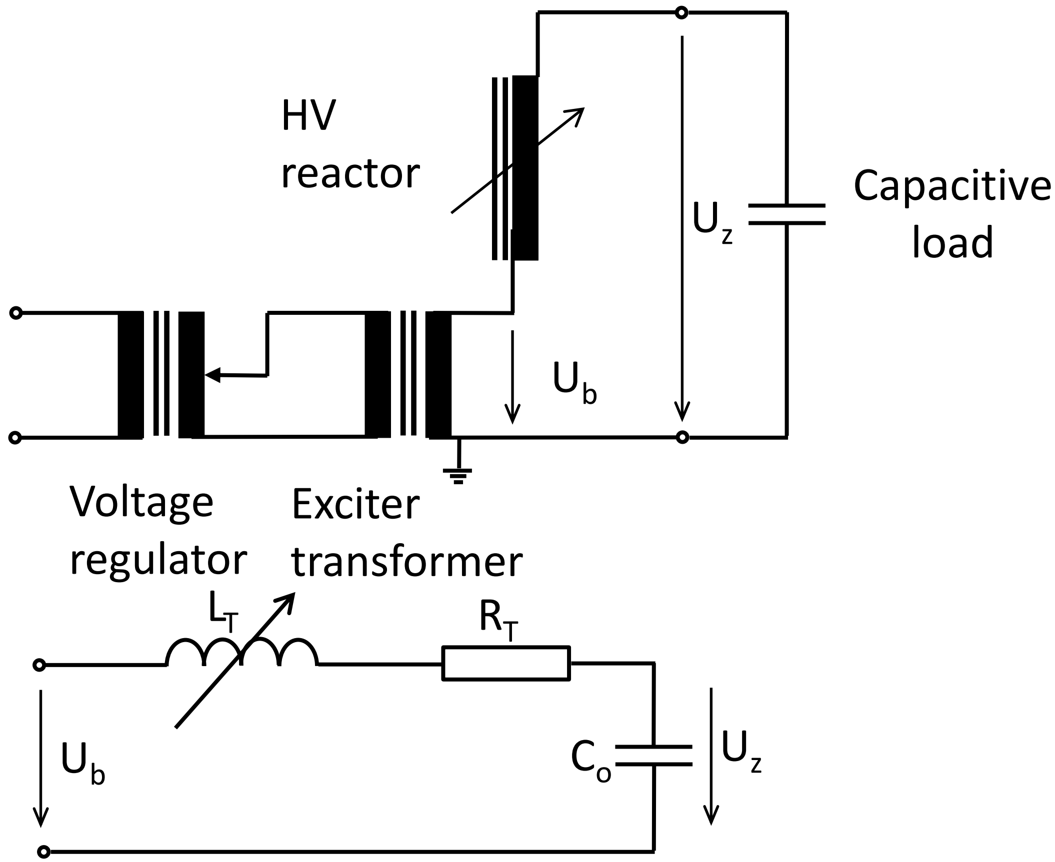
AC voltages

- Cascaded transformers



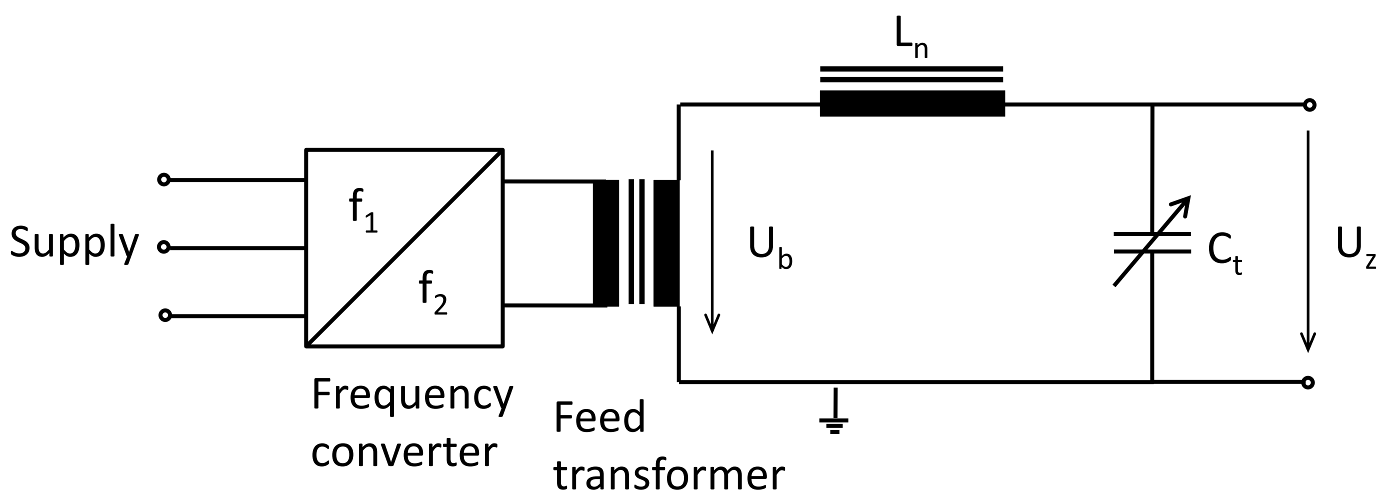
AC voltages

- Series resonant circuits



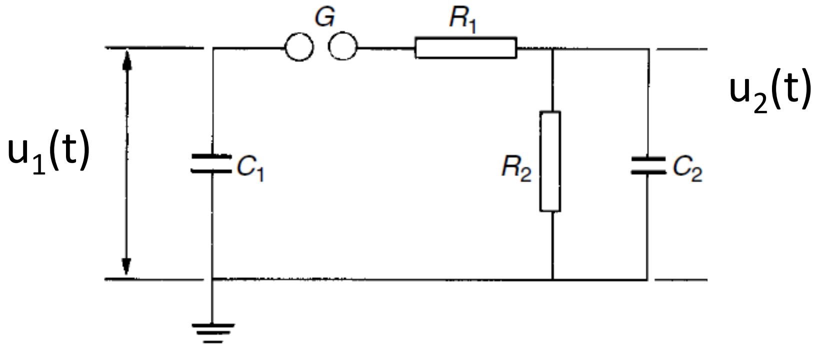
AC voltages

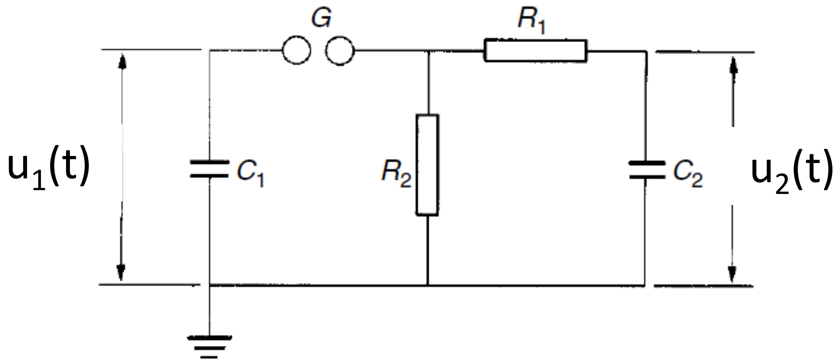
- Resonant circuits with variable test frequency



Impulse Voltages

- Single-stage impulse generator





The equations for the first circuit are:

$$u_1 = u_2 - R_1 C_1 u_1'$$
$$-C_1 u_1' = \frac{u_2}{R_2} + C_2 u_2'$$

Initial conditions

$$u_1(0) = U_c$$
$$u_2(0) = 0$$

Solution:

$$u_2 = kU_c[e^{\alpha_1 t} - e^{\alpha_2 t}]$$

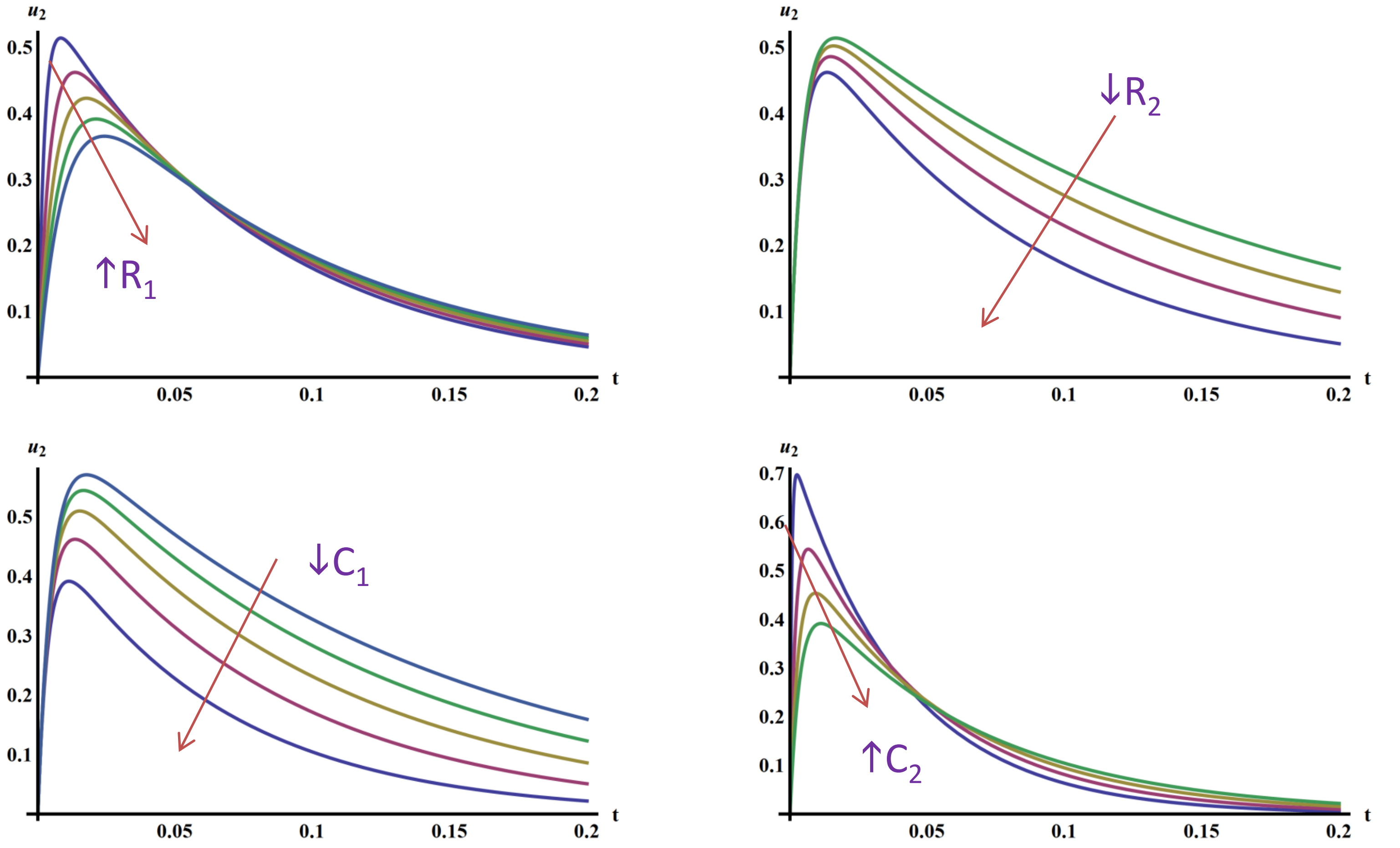
where

$$k = \frac{C_1 R_2}{\sqrt{(C_1R_1 + C_1R_2 + C_2R_2)^2 - 4R_1R_2C_1C_2}}$$

$$\alpha_1, \alpha_2 = \frac{C_1R_1 - C_1R_2 - C_2R_2 \pm \sqrt{(C_1R_1 + C_1R_2 + C_2R_2)^2 - 4R_1R_2C_1C_2}}{2R_1R_2C_1C_2}$$

Impulse Voltages

- The influence of generator parameters on the shape of output voltage



Impulse Voltages

- Voltage efficiency

The voltage efficiency of impulse generator can be determined from formula:

$$\eta = \frac{U_p}{U_c} < 1$$

where U_p is peak value of impuls and U_c is charging voltage.

The peak value U_p is:

$$U_p = u_2(t_{max})$$

where t_{max} can be find from condition

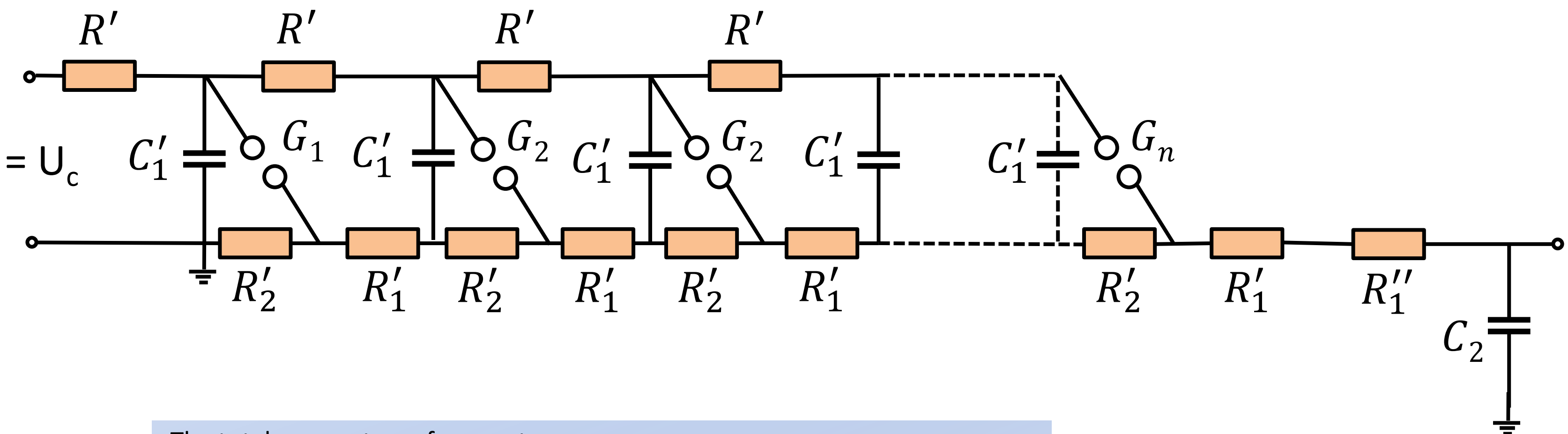
$$\frac{du_2}{dt} = 0$$

then $t_{max} = \frac{Ln\left(\frac{\alpha_1}{\alpha_2}\right)}{\alpha_2 - \alpha_1}$ and by substitution to formula for u_2 and formula for efficiency the final form is:

$$\eta = k\left(\left(\frac{\alpha_1}{\alpha_2}\right)^{\frac{\alpha_1}{\alpha_2 - \alpha_1}} - \left(\frac{\alpha_1}{\alpha_2}\right)^{\frac{\alpha_2}{\alpha_2 - \alpha_1}}\right)$$

Impulse Voltages

- Multi-stage impulse generator – Marx generator



The total parameters of generator are:

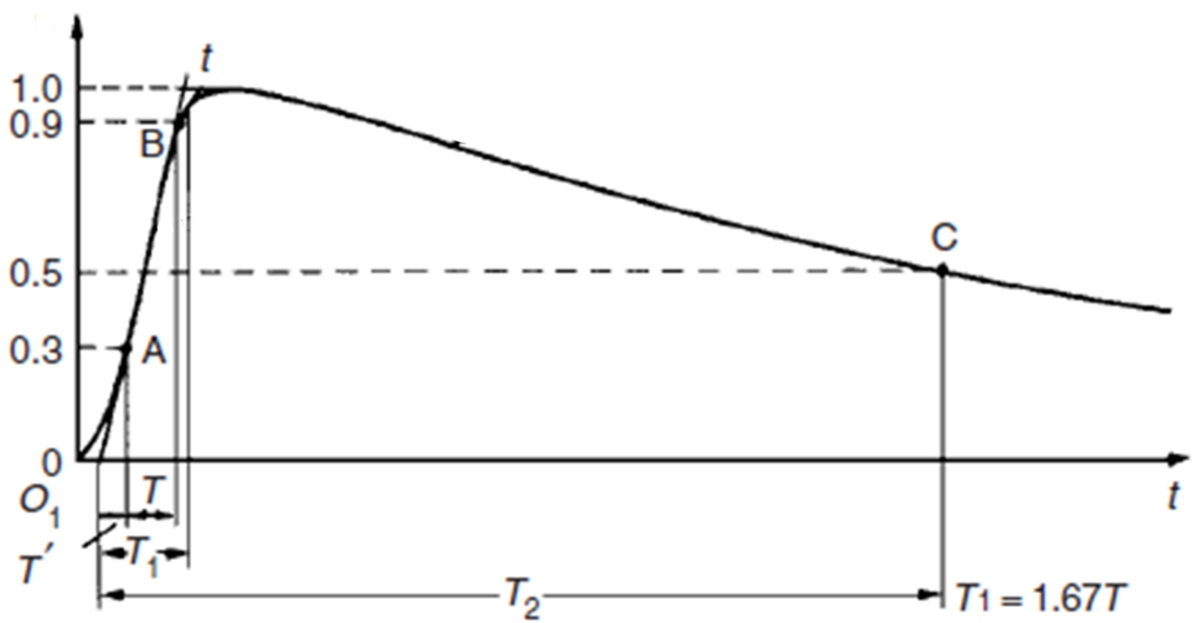
$$\frac{1}{C_1} = \sum_n \frac{1}{C_1'}$$

$$R_1 = R_1' + \sum_n R_1'$$

$$R_2 = \sum_n R_2'$$

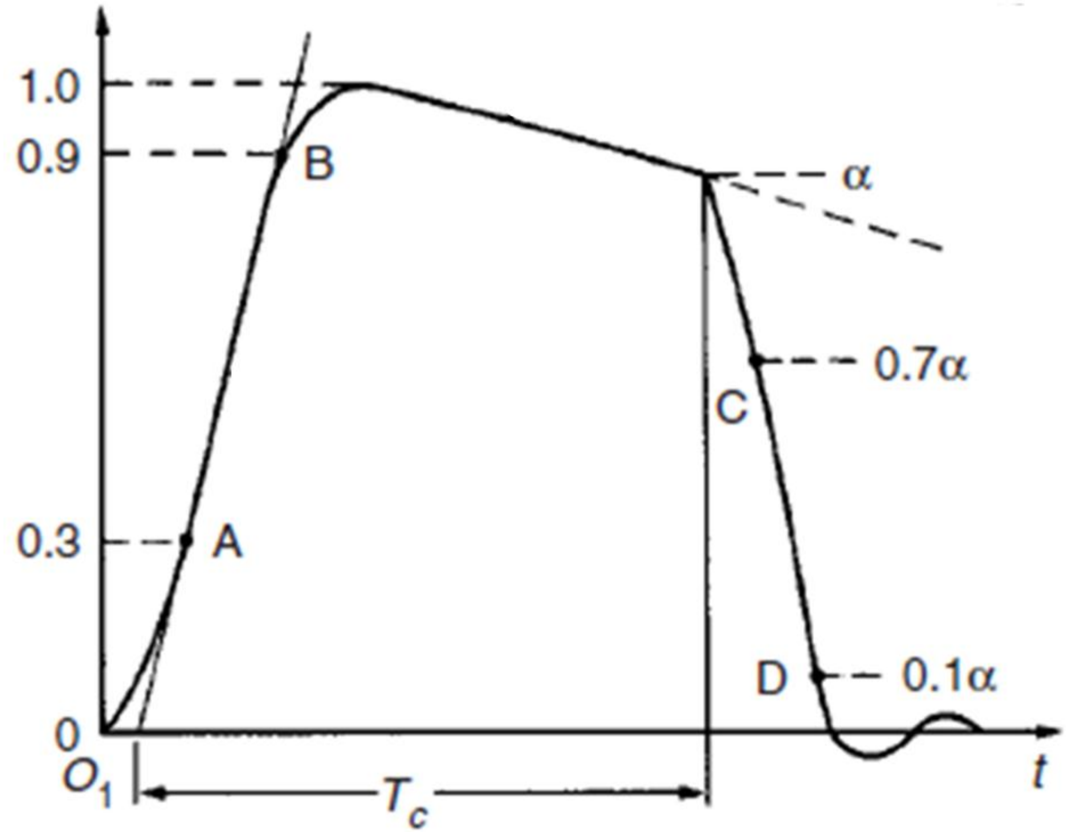
Impulse Voltages

- Full impulses
  - Lightning impulses
    - T_1 =1,2 μs ±30%, T_2 =50 μs ±20%,
  - Schwitching impulses
    - T_1 =250 μs±20%, T_2 =2500 μs±20%



Impulse Voltages

- Chopped impulses



Designing of impulse generator

- Detrmination of parameters (Angelini)
  - for all connection of impulse generator is possible to express the output voltage as

$$\eta u = \frac{\alpha U_c}{\sqrt{\alpha^2 - 1}} \left[e^{\frac{-(\alpha - \sqrt{\alpha^2 - 1})t}{\Theta}} - e^{\frac{-(\alpha + \sqrt{\alpha^2 - 1})t}{\Theta}} \right]$$

  - Constants α, η, Θ for the connection A and B are shown in the table

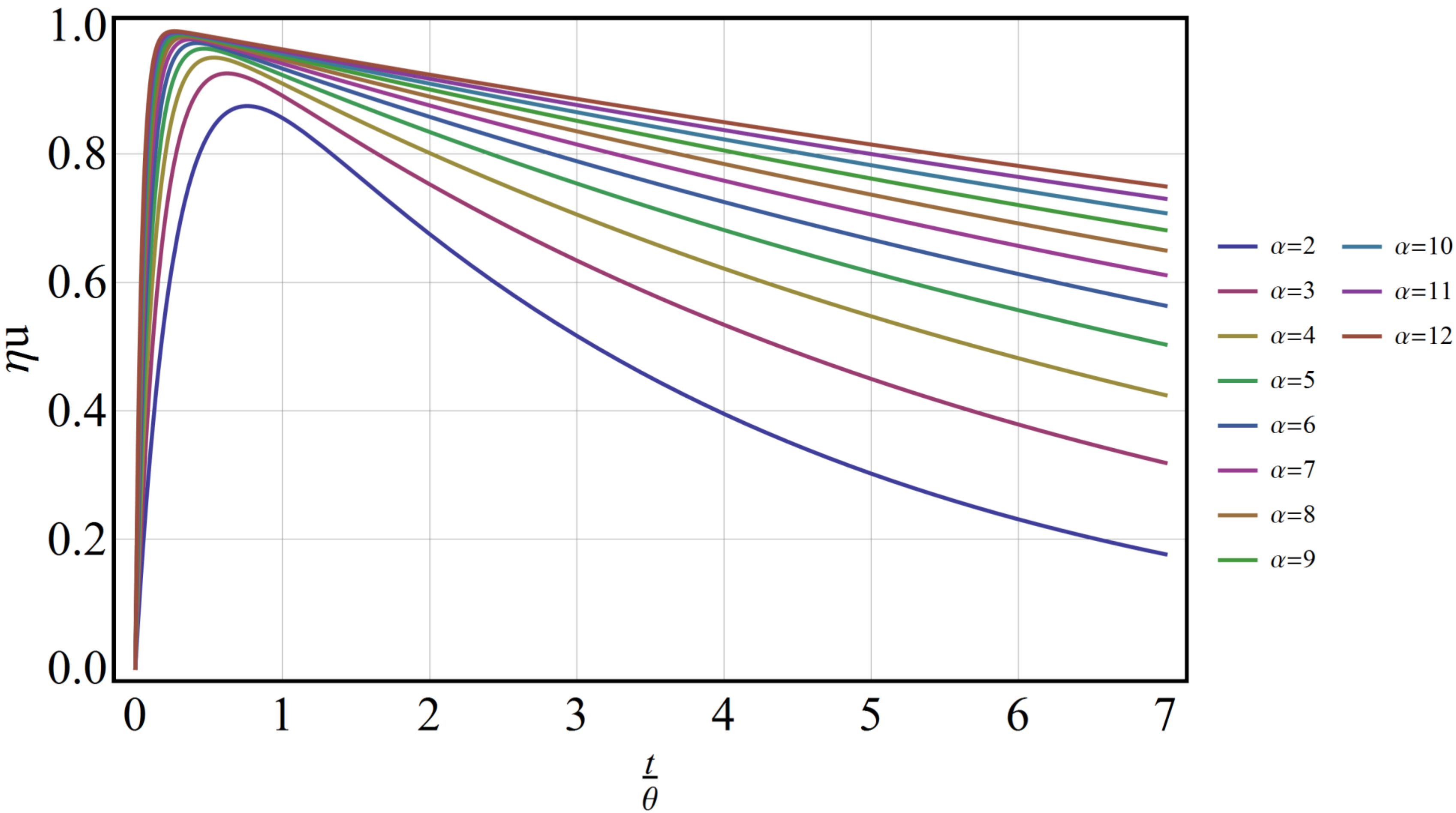
Connection	$\alpha=$	$\eta=$	$\Theta=$
A	$\frac{\eta}{2}\sqrt{\frac{R_2 C_1}{R_1 C_2}}$	$1 + \frac{C_2}{C_1} + \frac{R_1}{R_2}$	$\sqrt{C_1 C_2 R_1 R_2}$
B	$\frac{\eta}{2}\sqrt{\frac{R_2 C_1}{R_1 C_2}}$	$1 + \frac{C_2}{C_1}\left(1 + \frac{R_1}{R_2}\right)$	$\sqrt{C_1 C_2 R_1 R_2}$

Designing of impulse generator

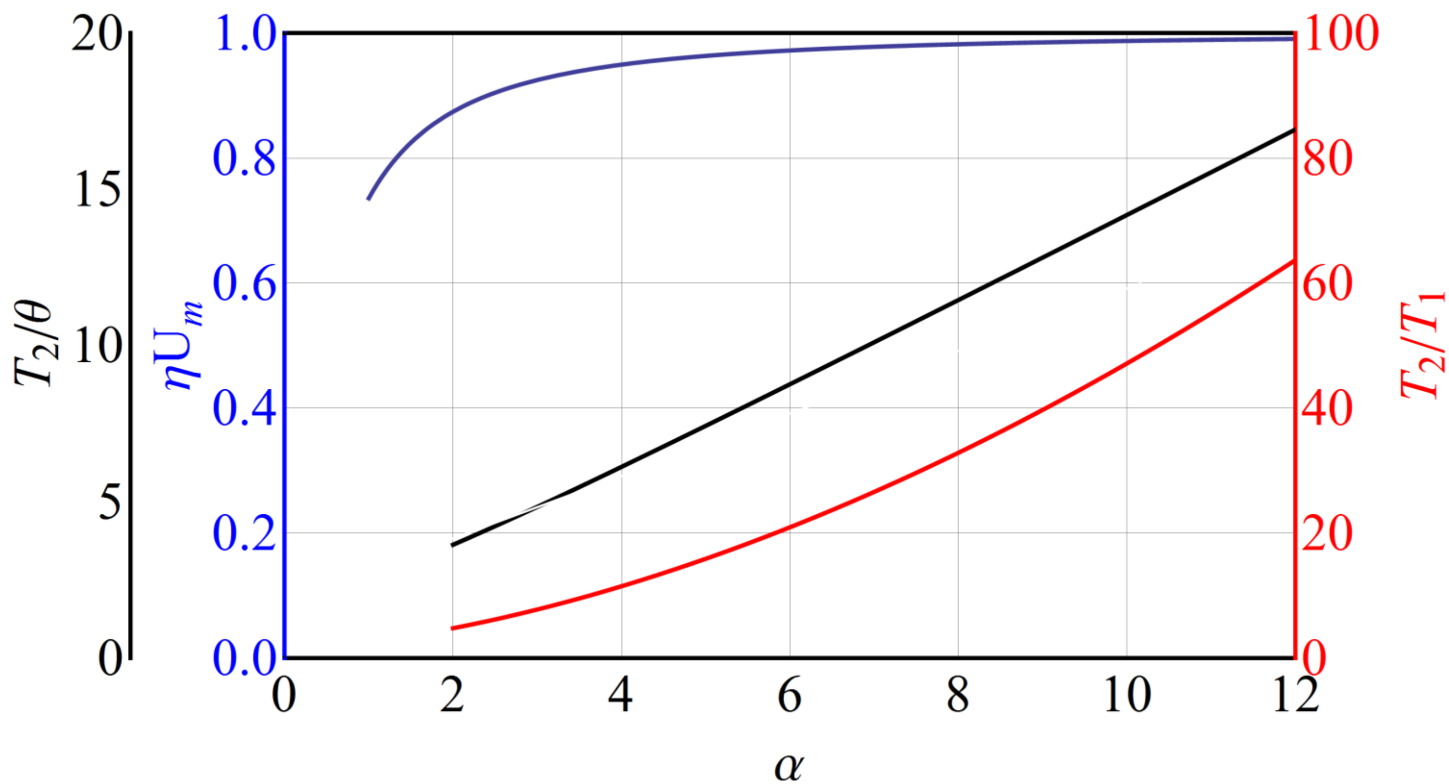
– The formulas for parameters determinantion

Zapojení	X=	R_1=	R_2=
A	$\frac{1}{\alpha^2}\left(1+\frac{C_1}{C_2}\right)$	$\frac{\alpha\Theta}{C_1}\left(1-\sqrt{1-X}\right)$	$\frac{\alpha\Theta}{C_1+C_2}\left(1+\sqrt{1-X}\right)$
B	$\frac{1}{\alpha^2}\left(1+\frac{C_2}{C_1}\right)$	$\frac{\alpha\Theta}{C_2}\left(1-\sqrt{1-X}\right)$	$\frac{\alpha\Theta}{C_1+C_2}\left(1+\sqrt{1-X}\right)$

Designing of impulse generator



Designing of impulse generator



Designing of impulse generator

- The required waveform of impulse voltage is usually known (T_1 and T_2) and parameters R_1, R_2, C_1 and C_2 are looked for
- One pair of parameters is choosed and second is consequently determined using previous graph

- Numerical calculation
  - The different numerical methods can be used for direct solving of equation system to find required parameters (see the Mathematica file)