HIGH VOLTAGE ENGINEERING

High voltage and current measurement

High Voltage Measurement

- The high voltage measurement requires special methods, which demands increase with the amplitude of measured voltages (from kV up to MV)
- High voltage measurement of:
  - AC voltages
  - DC voltages
  - Impulses and transients
- The high voltage measurements in HV laboratories or in practice requires different approaches

Sphere gaps

- The classic method for the voltage peak measurement of ac, dc and impulse voltages
- Simple and reliable devices, which are used mainly as reference instruments with a limited accuracy
- Sphere gaps consists from two identical sphere electrodes spaced by gap with air insulation
- The measured value is determined on the basis of the electrode distance, when the flashover occures, with regards to an atmospheric conditions

Sphere gaps

Peak value of flashover volatge of sphere gap at atmopheric pressure 1013 hPa and temperature 20°C

Distance [cm]	⌀ 2 cm		⌀ 10 cm	
	≅ (−)	(+)	≅ (−)	(+)
0,05	2,8			
0,10	4,7			
0,15	6,4			
0,20	8,0			
0,25	9,6			
0,30	11,2			
0,40	14,4			
0,50	17,4		16,8	
0,60	20,4		19,9	
0,70	23,2		23,0	
0,80	25,8		26,0	
0,90	28,3		28,9	
1,0	30,7		31,7	
1,2	(35,1)		37,4	
1,4	(38,5)		42,9	
1,5	(40,0)		45,5	
1,6			48,1	
1,8			53,5	
2,0			59,0	
2,2			64,5	
2,4			69,5	70,0
2,6			74,5	75,5
2,8			79,5	80,5
3,0			84,0	85,5
3,5			95,0	97,5
4,0			105	109
4,5			115	120
5,0			123	130
5,5			(131)	(139)
6,0			(138)	(148)
6,5			(144)	(156)
7,0			(150)	(163)
7,5			(155)	(170)

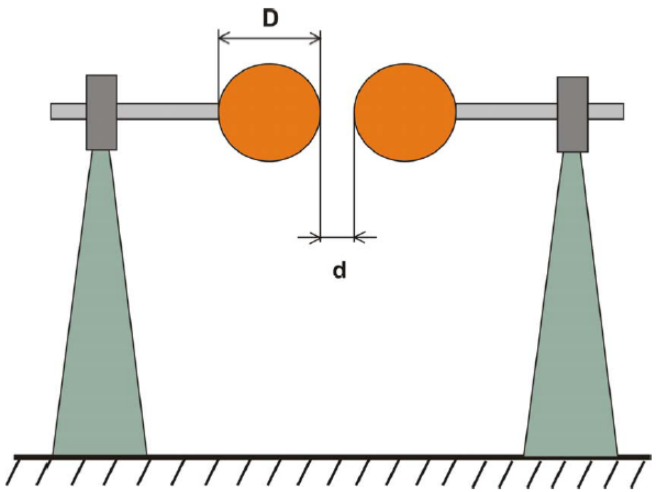
Distance [cm]	⌀ 50 cm		⌀ 150 cm	
	≅ (−)	(+)	≅ (−)	(+)
2,0	59,0			
2,2	64,5			
2,4	70,0			
2,6	75,5			
2,8	81,0			
3,0	86,0			
3,5	99,0			
4,0	112			
4,5	125			
5,0	138		138	
5,5	151		151	
6,0	164		164	
6,5	177		177	
7,0	189		190	
7,5	202		203	
8,0	214		215	
9,0	239		241	
10,0	263		266	
11	286	287	292	
12	309	311	318	
13	331	334	342	
14	353	357	366	
15	373	380	390	
16	392	402	414	
17	411	422	438	
18	429	442	462	
19	445	461	486	
20	460	480	510	
22	489	510	560	
24	515	540	610	
26	(540)	570	655	
28	(565)	(595)	700	
30	(585)	(620)	745	
32	(605)	(640)	790	
34	(625)	(660)	835	
36	(640)	(680)	875	880
38	(665)	(700)	915	925
40	(670)	(715)	955	965
45			1030	1060
50			1130	1150
55			1210	1240
60			1280	1310
65			1340	1380
70			1390	1430
75			1440	1480
80			(1490)	(1530)
85			(1540)	(1580)
90			(1580)	(1630)
100			(1660)	(1720)
110			(1730)	(1790)
120			(1800)	(1860)

~ a.c. voltage

= d.c. voltage

(−) Impulse voltage (U_{50}, - polarity)

(+) Impulse voltage (U_{50}, + polarity)



Correction on atmospheric condition

- Reference condition t_0=20°C, p_0=101,3 kPa, v_a=8,5 g/m^3
- Air density

$$\delta = \frac{p}{p_0} \cdot \frac{273 + t_0}{273 + t}$$

- The peak value of measured voltage

$$U = U_N \delta \quad \text{v rozsahu} \quad 0{,}95 < \delta < 1{,}05$$

- Humidity correction

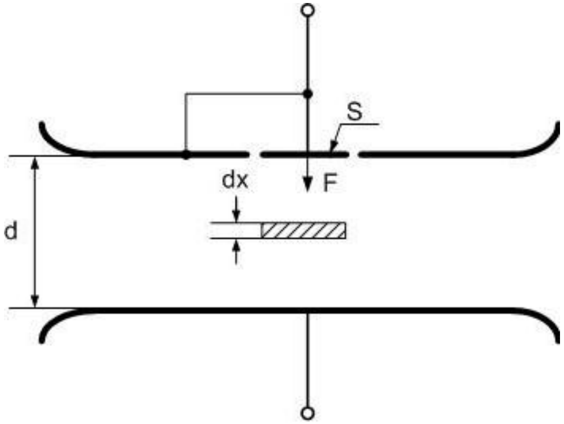
$$k_v = 1 + 0{,}002 \left(\frac{v}{\delta} - 8{,}5 \right)$$

Electrostatic voltmeter

- For direct measurement of high potential typically from hundreds of volts up to hundreds of kilovolts
- a.c. and d.c. voltage measurements
- High internal resistance
- High frequency bandwidth of measured voltage, few MHz (limited by serial resonance of measured circuit – parasitic inductance and capacity)
- Insulation gas is usually air or SF_6 gas for higher voltages (up to 1MV, accuracy 0.1%).
- The accuracy for special construction can reach 1 % and 2 % for common using

Electrostatic voltmeter

- Forse acting on free electrode



Energy density

$$w_e = \frac{1}{2}\varepsilon E^2$$

Energy in element dx

$$dw = w_e S dx = \frac{1}{2}\varepsilon S E^2 dx$$

Acting force on free electrode

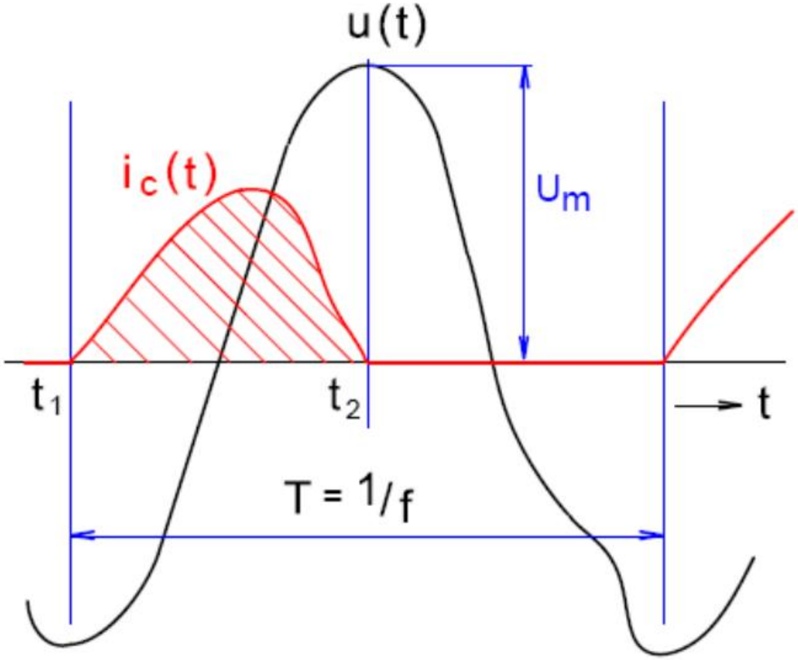
$$F = \frac{dw}{dx} = \frac{1}{2}\varepsilon S E^2 = \frac{1}{2}\varepsilon S \frac{U^2}{d^2}$$

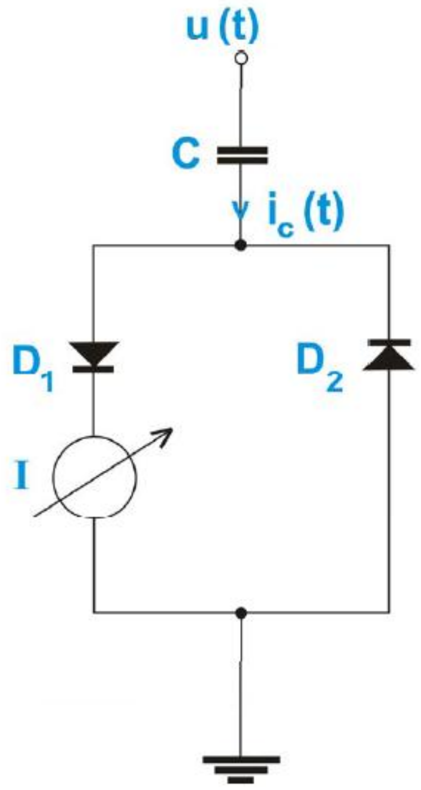
The force mean value for time variable voltage

$$\frac{1}{T}\int_0^T F(t)dt = \frac{\varepsilon S}{2d^2 T}\int_0^T U^2(t) = \frac{\varepsilon S}{2d^2} U_{RMS}^2$$

Peak voltmeter (Chubb-Fortescue method)

- Simple and accurate method for the peak measurement of a.c. voltages





Peak voltmeter (Chubb-Fortescue method)

Current through capacitor C:

$$i_C = C\frac{du}{dt}$$

Mean value of measured current:

$$I = \frac{1}{T}\int_{t_1}^{t_2} i_C dt = \frac{C}{T}[u(t_2) - u(t_1)] = \frac{C}{T}U_{pp}$$

Peak value of measured voltage:

$$U_m = \frac{I}{2Cf}$$

Voltage dividers

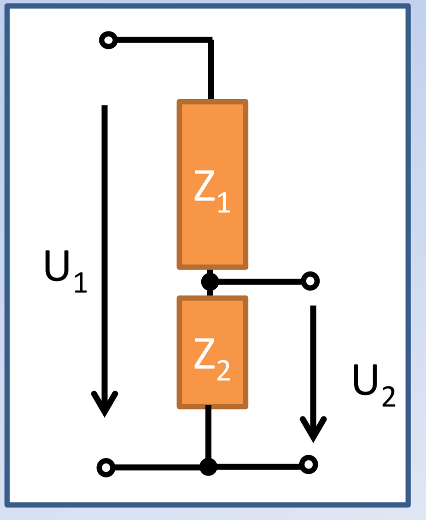
- Voltage divider can consists from the combination of passive elements (resitors, capacitors, inductors)
- The divider dimensions are related to maximal applied voltage

Divider ratio:

$$\frac{U_2}{U_1} = \frac{Z_2}{Z_1 + Z_2}$$

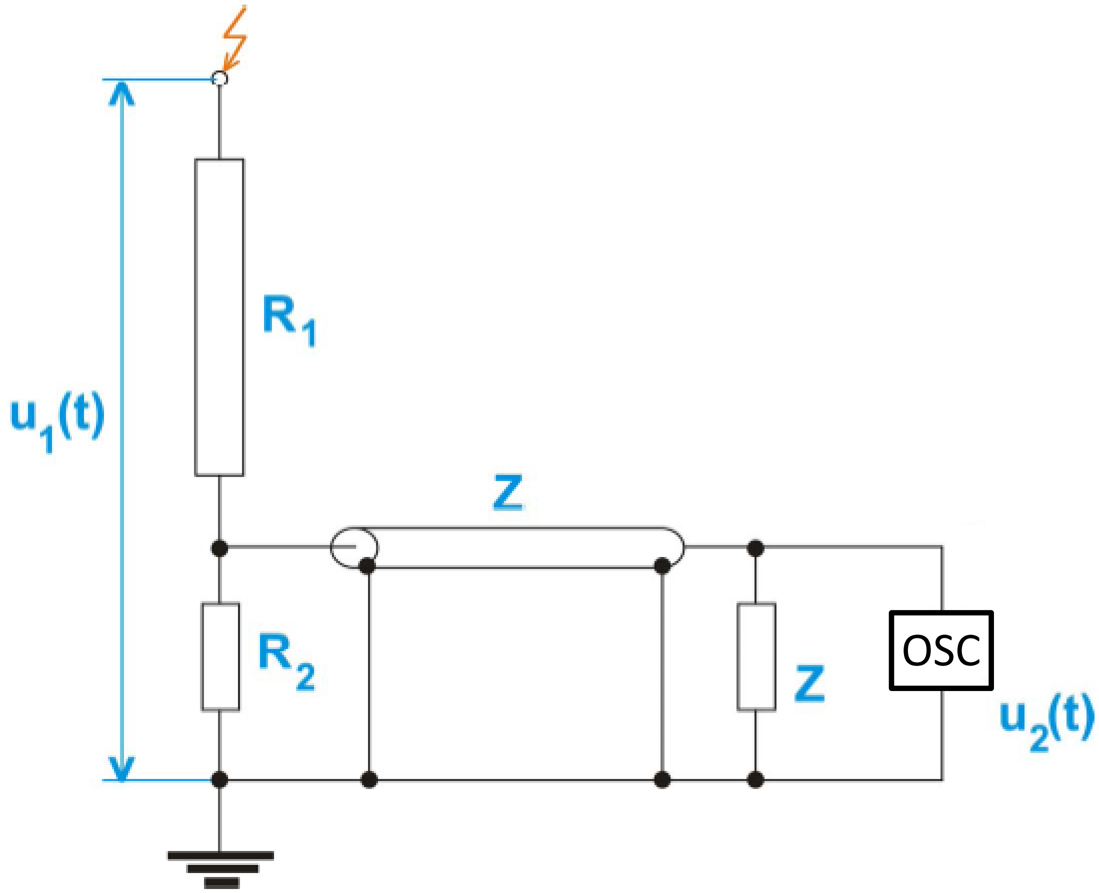
Resistive divider $\frac{U_2}{U_1} = \frac{R_2}{R_1+R_2}$

Capacitive divider $\frac{U_2}{U_1} = \frac{C_1}{C_1+C_2}$



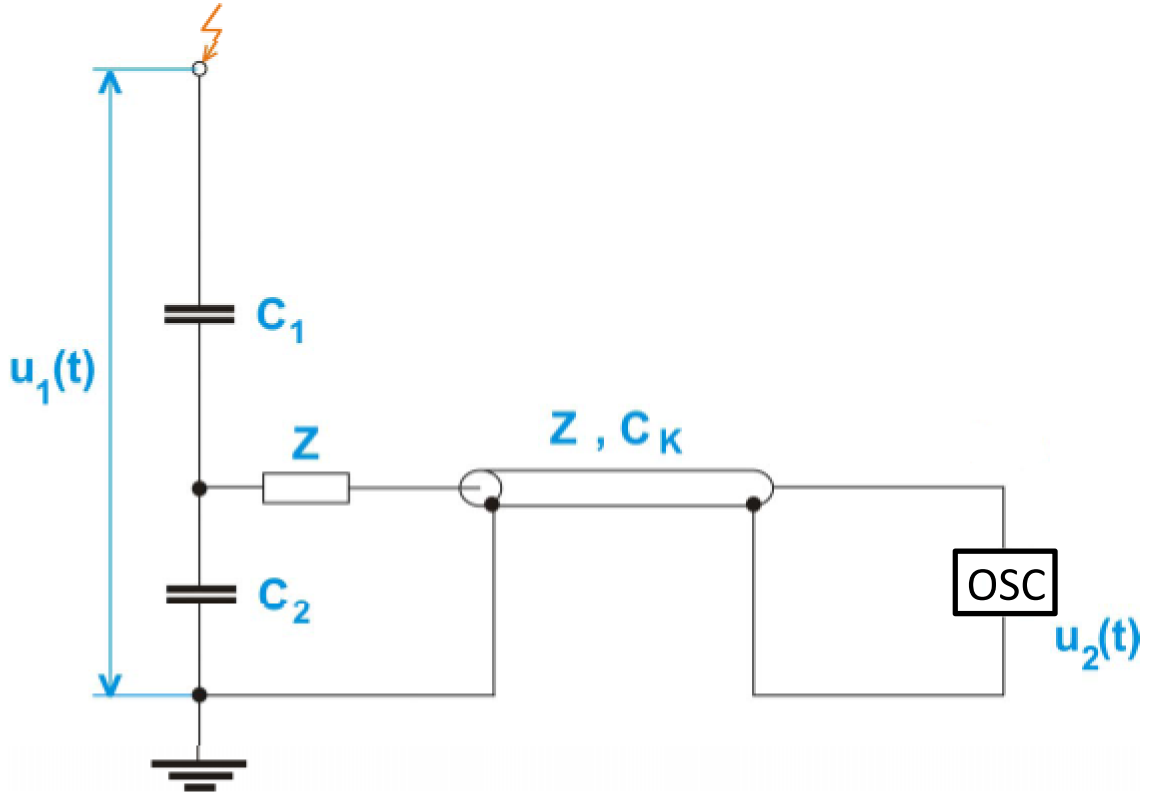
Resistive divider

- Měření stejnosměrných, střídavých a impulzních napětí
- Velikost chyby je funkcí součinu kapacity vn a odporu děliče

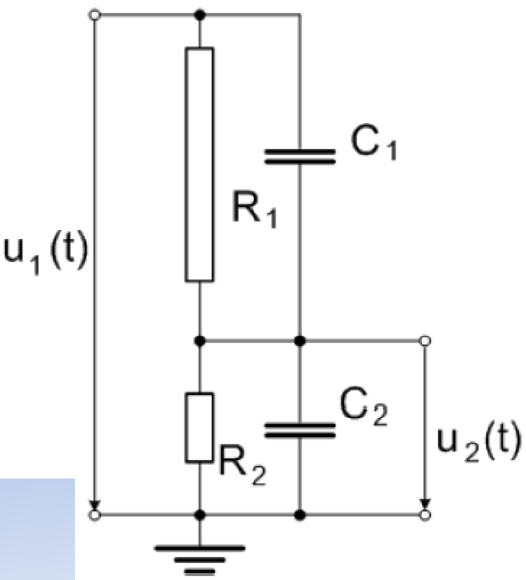


Capacitive divider

- Měření střídavých a impulzních napětí
- Jednodušší a reprodukuje věrněji než odporový dělič



RC voltage divider



- Capacitive divider is dominant for the fast transients and resistive divider for the slow transients
- Frequency independency can be reach by compensation

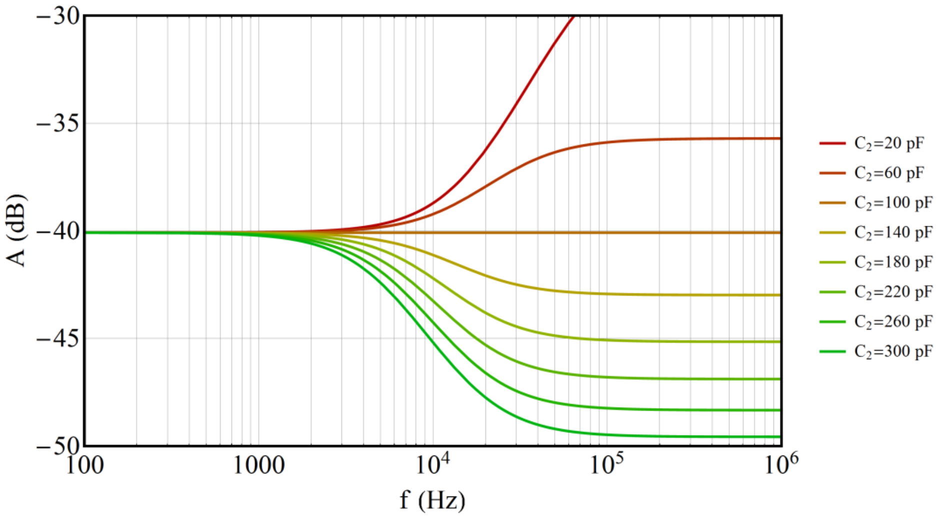
$$Z_1 = \frac{R_1}{1 + j\omega C_1 R_1} \qquad Z_2 = \frac{R_2}{1 + j\omega C_2 R_2}$$

$$\frac{U_2}{U_1} = \frac{\omega C_1 R_1 - jR_2}{\omega R_1 R_2 (C_1 + C_2) - j(R_1 + R_2)}$$

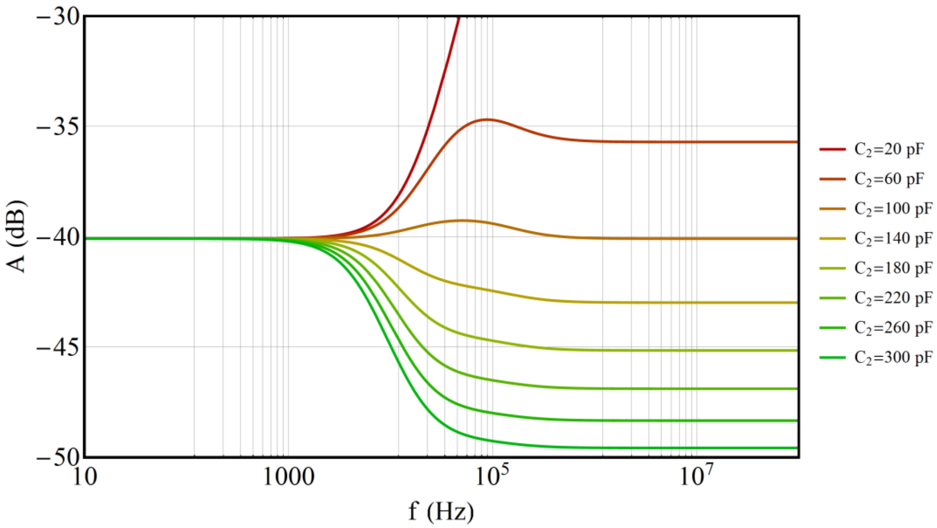
$$Im\left(\frac{U_2}{U_1}\right) = \frac{\omega R_1 R_2 (C_1 R_1 - C_2 R_2)}{(R_1 + R_2)^2 + \omega^2 R_1^2 R_2^2 \, (C_1 + C_2)^2} = 0$$

$$\Rightarrow C_1 R_1 = C_2 R_2$$

Compensation of RC divider



Attenuation of RC divider for various capacitors C_2, the divider is fully compensated when C_2=100 pF

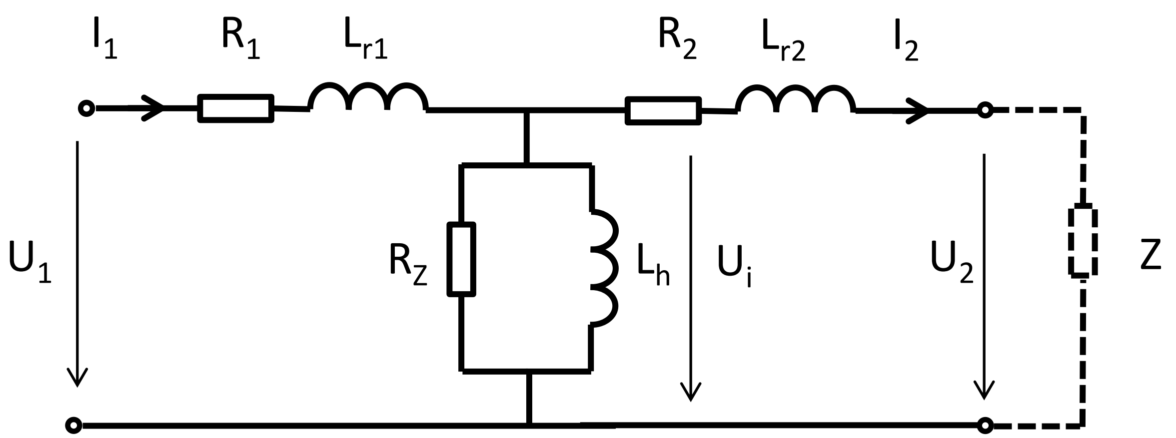


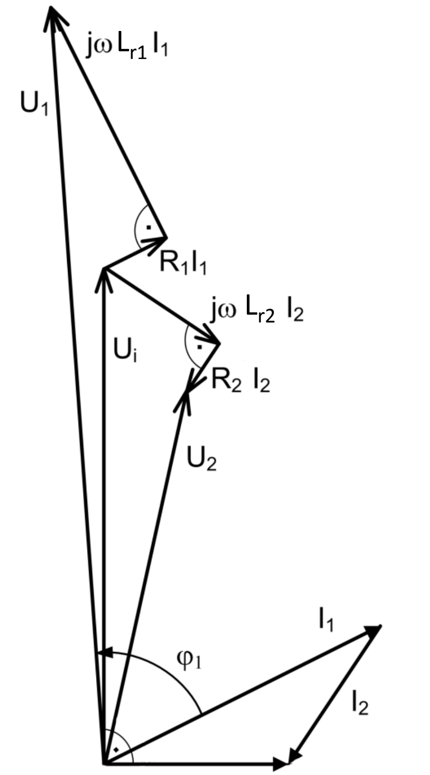
Attenuation of RC divider with parasitic inductance of 1 mH

Instrument voltage transformers

- Single phase transformers
- In the electrical power grid performs the measuring function (information, billing) and also as inputs for protection devices
- Galvanic isolation of high voltage circuits from measuring instruments

Instrument voltage transformers

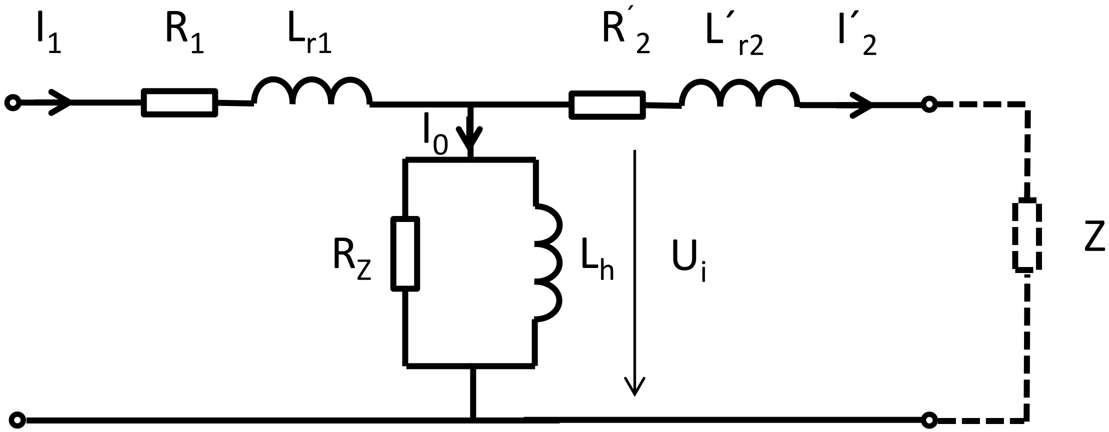




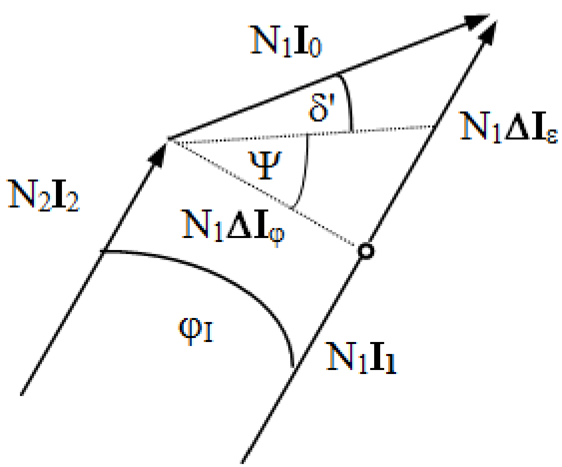
Voltage error definition

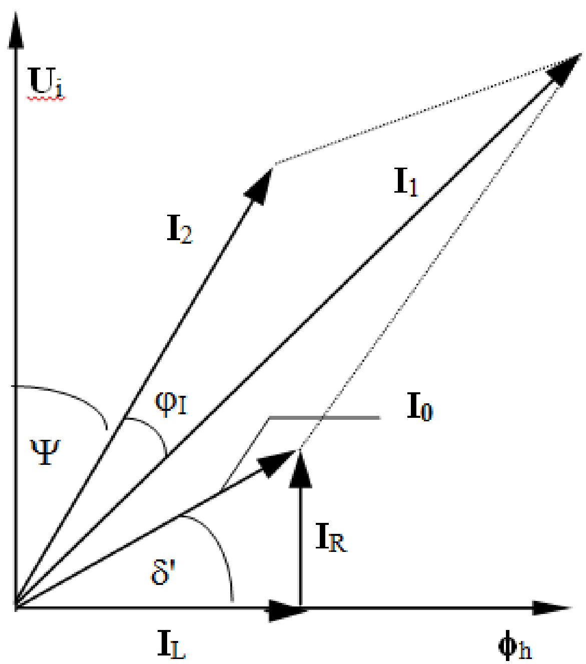
$$\varepsilon_U = \frac{p_U U_2 - U_1}{U_1} \cdot 100$$

Current transformers



Assuming conditions $\mathbf{I}_0 << \mathbf{I}_1$, resp. $\mathbf{I}_0 << \mathbf{I}_2$ ends of phasors $\mathbf{I}_1$ and $\mathbf{I}_2$ can be considered as parallel





Current error of CT

Current error

$$\varepsilon_I = \frac{p_I I_2 - I_1}{I_1} \cdot 100$$

From simplified phasor diagram can be expressed as

$$\varepsilon_I = \frac{N_2 I_2 - N_1 I_1}{N_1 I_1} = \frac{N_1 \Delta I_\varepsilon}{N_1 I_1} = -\frac{N_1 I_0}{N_1 I_1} \sin(\delta' + \psi)$$

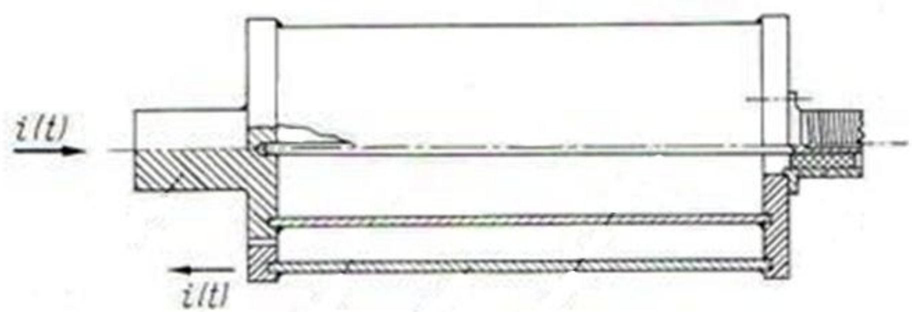
where $N_1 I_0 = Hl = \frac{Bl}{\mu_0 \mu_r}$*, then the amplitude and phase error can be expressed as:*

$$\varepsilon_I = \frac{Bl}{\mu_0 \mu_r N_1 I_1} \sin(\delta' + \psi)$$

$$\varphi_I \approx tg\,\varphi_I = \frac{Bl}{\mu_0 \mu_r N_1 I_1} \cos(\delta' + \psi)$$

Coaxial shunts

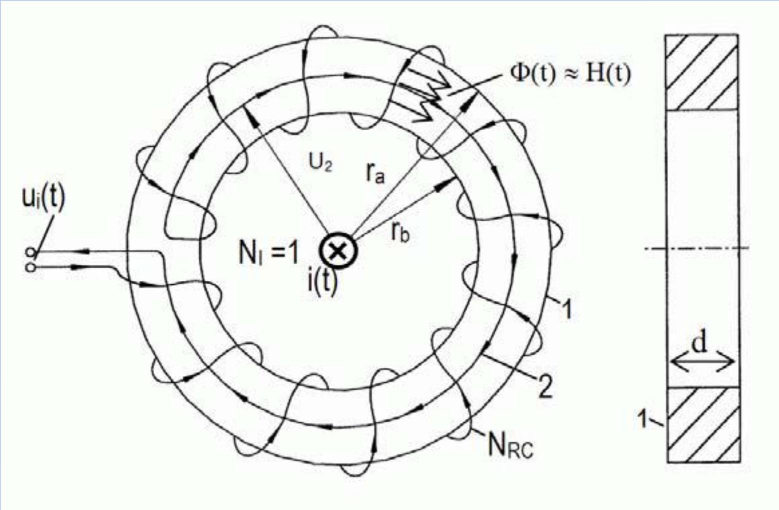
- The measured high current (a.c., d.c., impulses) flows throught accurate resistor
- The skin effect at higher frequencies is eliminated by coaxial construction – manganin strips arranged into cylindric area
- Disadvantages can be the galvanic connection of measuring system with measured circuit and thermal and mechanical stress in case of high current measurement



Rogowski coil

Measured current can be expressed as:

$$i(t) = \frac{1}{M}\int_0^T u(t)dt$$



where M is a mutual inductance between conductor N_1 and sensing winding N_{RC}

For harmonic current:

$$I(\omega) = \frac{U_i(\omega)}{j\omega M}$$

The RC constant (ratio) is then:

$$k_{RC} = \frac{U_i}{\omega I}$$