# Electrical Engineering
# HSLU, Semester 2

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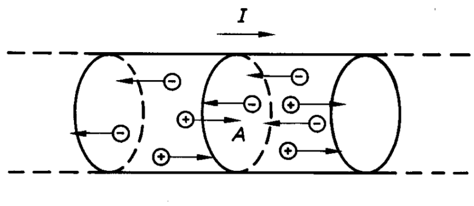
## Contents

# Part I

# Lectures

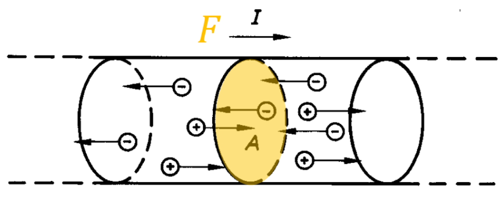
## 1 Current and voltage

### 1.1 Current strength or current $I$




$$I\ [A] = \frac{\text{el. charge}}{t}$$

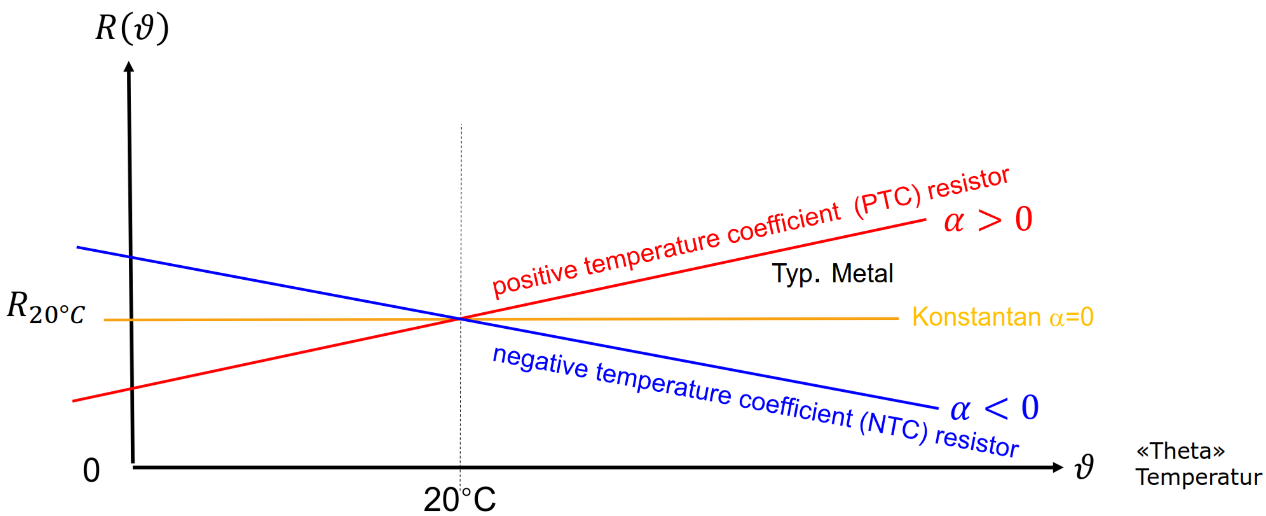
### 1.2 Current density $J$




The current density indicates how large the current per cross-sectional area (F) is:

$$J\ [\frac{A}{mm^2}] = \frac{I}{F}$$

### 1.3 Temperature dependence of the resistance




Depending on the material, the resistance can increase, remain the same or decrease with temperature. In ET+L we calculate using the linear approach.

$$\boxed{R(\vartheta) = R_{20}(1 + \alpha(\vartheta - 20°\mathrm{C})) = R_{20}(1 + \alpha\Delta T)}$$

## 1.4 Object properties

The resistance indicates the voltage required for a current. In addition to the material, the cross-sectional area and also the length are decisive factors.

$$R = \frac{U}{I}$$

## 1.5 Reciprocal quantities

### 1.5.1 Specific resistance

To describe material properties, the resistance per length and cross-sectional area is specified (precondition: homogeneous conductor, direct current):

$$\rho \, [\frac{\Omega \cdot mm^2}{m}] = R \cdot \frac{A}{l}$$

### 1.5.2 Conductance

### 1.5.3 Specific conductivity

# 2 Gravitational fields

## 2.1 Between bodies

$$\boxed{F_1 = F_2 = G\frac{m_1 m_2}{d^2}}$$

## 2.2 Between particles

### 2.2.1 Coulomb's law

It calculates the amount of force between two electrically charged particles at rest:

$$\boxed{F = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1 q_2}{r^2}}$$

where:

- $F$: Force [N];
- $q$: Charge [As];
- $\varepsilon_0$: absolute permittivity $= 8.8542 \cdot 10^{-12}$ [As/Vm].

## 2.3 Electric field and force on a charge $Q$

### 2.3.1 Homogeneous electric fields

$$\boxed{E = \frac{U}{d}}$$

where:

- $E$: electric field strength [V/m];
- $U$: voltage [V];
- $d$: distance of the electrodes [m].

### 2.3.2 Force on a point charge

$$\boxed{F = Q \cdot E}$$

where:

- $E$: electric field strength [V/m];
- $Q$: charge [As];
- $F$: force [N].

# 3 Capacitance and Capacitor

## 3.1 Capacitor

A capacitor is a device in which the capacitance is used.

## 3.2 Capacitance

Capacitance $C$ is the **capability** to store electric charge. It is measured by the charge divided by the applied voltage:

$$\boxed{C = \frac{Q}{U}}$$

where:

- $Q$: charge [As];
- $U$: voltage [V];
- $C$: capacitance [As/V = F (Farad)].

### 3.2.1 Capacitance of a plate capacitor

$$\boxed{C = \varepsilon \cdot \frac{A}{d}}$$

where:

- $A$: plate area (one side) [$m^2$];
- $d$: distance between plates [m];
- $C$: capacitance [F].

#### Permittivity

$$\boxed{\varepsilon = \varepsilon_r \cdot \varepsilon_0}$$

- $\varepsilon_r$: relative permittivity of the dielectric, relative to the air;
- $\varepsilon_0$: absolute permittivity [As/Vm].

### 3.2.2 Energy in a capacitor

If a capacitor is discharged with a constant current, the voltage decreases linearly:

$$\boxed{\int_0^{t_{\text{empty}}} U(t) \cdot I \, dt = I \cdot U_0 = \frac{I \cdot U_0 \cdot t_{\text{empty}}}{2}}$$

Or, simplified:

$$\boxed{W = \frac{1}{2} C \cdot U_0^2}$$

where:

- $W$: energy [J or Ws];
- $U_0$: initial voltage [V];
- $C$: capacitance [F].

## 3.3 Capacitors in parallel connection

Capacitances connected in parallel add up:

$$\boxed{C_{\text{tot}} = \frac{\sum_n Q_n}{U} = \sum_n C_n}$$

or

$$\boxed{C = \frac{\varepsilon \cdot (\sum_n A_n)}{d} = \sum_n C_n}$$

## 3.4 Capacitors in series connection

In a series connection, the reciprocal of the total capacitance is the sum of the reciprocals of the individual capacitances:

$$\boxed{\frac{1}{C_{\text{tot}}} = \sum_n \frac{1}{C_n}}$$

where:

- $C_{\text{tot}}$: total capacitance [F];
- $C_n$: capacitance of the $n$-th capacitor [F].

# 4 Transient Analysis in RC Circuits

## 4.1 Charging of a Capacitor

When a capacitor is charged through a resistor, the voltage across it increases exponentially:

$$\boxed{U_C(t) = U_0 \cdot \left(1 - e^{-t/(R \cdot C)}\right)}$$

with the time constant defined as:

$$\boxed{\tau = R \cdot C}$$

where:

- $U_C(t)$: voltage across the capacitor at time $t$ [V];
- $U_0$: applied voltage [V];
- $R$: resistance [Ω];
- $C$: capacitance [F];
- $\tau$: time constant [s].

## 4.2 Discharging of a Capacitor

When a charged capacitor discharges through a resistor, the voltage decays exponentially:

$$\boxed{U_C(t) = U_0 \cdot e^{-t/(R \cdot C)}}$$

and the discharging current is:

$$\boxed{I(t) = \frac{U_0}{R} \cdot e^{-t/(R \cdot C)}}$$

### 4.3 Transitional phase

$$\boxed{f(t) = A + \Delta \cdot \left(1 - e^{t/\tau}\right) = A + (B - A) \cdot (1 - e^{1/\tau})}$$

## 5 Additional Topics

### 5.1 Energy Stored in a Capacitor

The energy stored in a capacitor is given by:

$$\boxed{W = \frac{1}{2} C \cdot U_0^2}$$

where:

- $W$: energy [J];
- $C$: capacitance [F];
- $U_0$: voltage [V].

### 5.2 Charge–Voltage Relationship

For an ideal capacitor, the relationship between charge and voltage is:

$$\boxed{Q = C \cdot U}$$

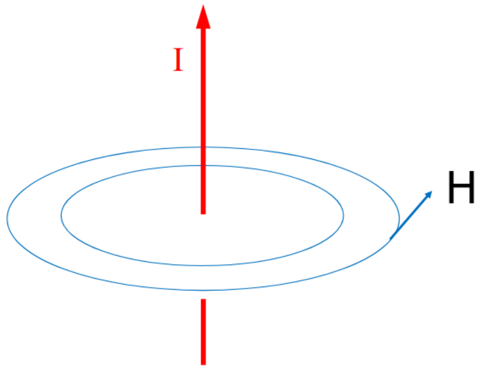
Moreover, the current is the time derivative of the charge:

$$\boxed{I = \frac{dQ}{dt} = C \cdot \frac{dU}{dt}}$$

Note that the voltage across an ideal capacitor cannot change instantaneously.

# 6 Electromagnetic fields

## 6.1 Hans Christian Ørsted Observation




1. The magnetic field lines encircle the current-carrying conductor;
2. The magnetic field lines lie in a plane perpendicular to the current-carrying wire;
3. If the direction of the current is reversed, the direction of the magnetic field lines is also reversed;
4. The strength of the field is directly proportional to the magnitude of the current;
5. The strength of the field at any point is inversely proportional to the distance of the point from the wire.

## 6.2 Definitions and formuals

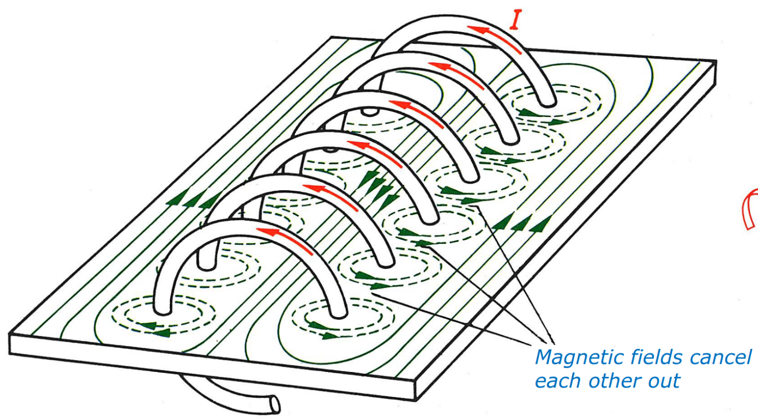
### 6.2.1 Magnetomotive force

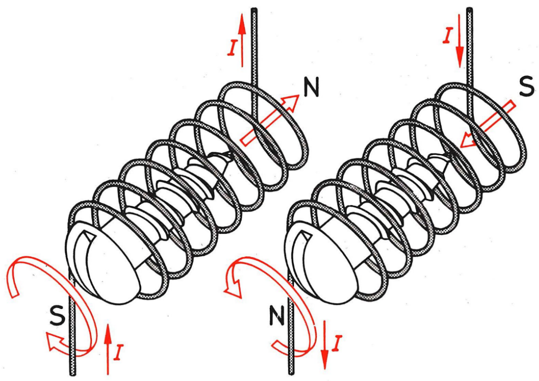
$$\boxed{\theta = N \cdot I}$$

### 6.2.2 Ampère's circuital law

$$\boxed{\theta = \oint \overrightarrow{H(s)} \cdot \mathrm{d}\vec{s}}$$

### 6.2.3 Magnetic field in a coil



### 6.2.4 Magnetic flux density

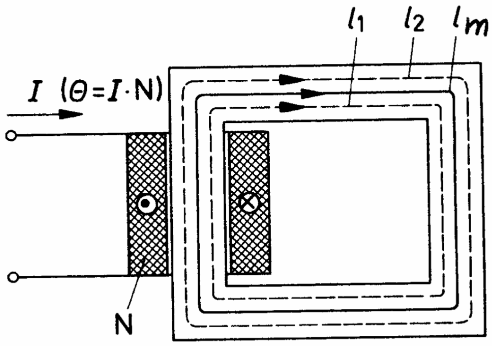
$$\boxed{B = \frac{\Phi}{A} = \mu \cdot H = \mu_0 \mu_r \cdot H}$$

where:

- $B$: magnetic flux density [T = Vs/m$^2$];
- $\Phi$: magnetic flux [Wb];
- $A$: area [m$^2$];
- $\mu$: magnetic permeability [H/m = Vs/Am];
- $H$: magnetic field strength [A/m];
- $\mu_0$: magnetic constant [$4\pi \cdot 10^{-7}$ Vs/Am];
- $\mu_r$: relative permeability.

Note: $\Phi$ is the sum of all B-field lines through the cross section A

### 6.2.5 Magnetic field strength in coil with iron core




$$\boxed{H = \frac{N \cdot I}{l_m} = \frac{\Theta}{l_m}}$$

where:

- $H$: magnetic field strength [A/m];
- $N$: number of turns;
- $I$: current [A];
- $l_m$: median field line length [m];
- $\Theta$: magnetomotive force [A].

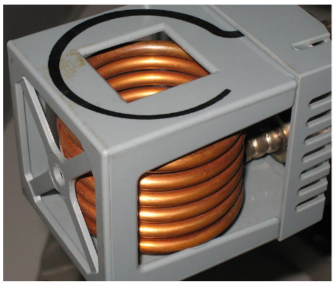
### 6.2.6 Magnetic relative permeability $\mu$

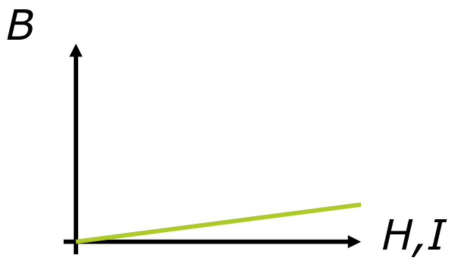
Permeability is a measure for the ability to conduct magnetic field lines:

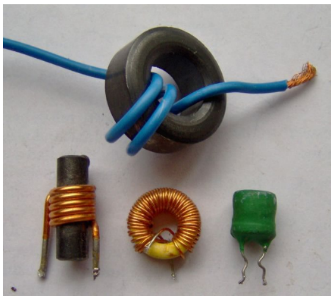
| **Material** | $\mu_\mathbf{r}$ |
|---|---|
| Air | 1 |
| Pure iron | up to 250'000 |
| Electrical steel | 500 . . . 7000 |
| Steel | 40 . . . 7000 |
| Water | 0.99991 |

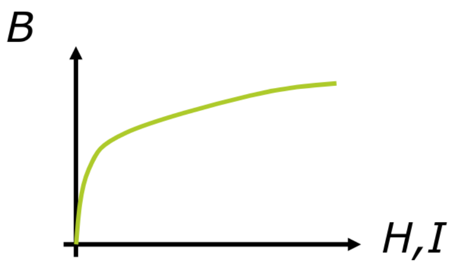
### 6.2.7 Coils with and without iron core

The magnetization curve of a coil without a core is linear, but there is significantly less flux density B than with an iron core.



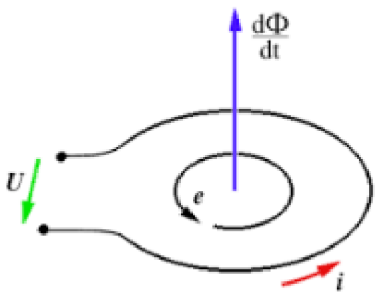


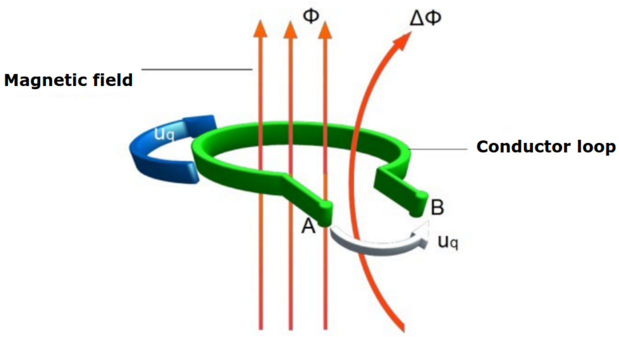






### 6.2.8 Law of induction and inductance

**Changing magnetic flux generates a voltage**




Phenomenon: a changing magnetic flux $\Phi$ induces a voltage in a conductor loop around it:

$$\boxed{U = -N \cdot \frac{\mathrm{d}\Phi}{\mathrm{d}t}}$$

### 6.2.9 Inductance and induction

Inductance L is the capability to generate a magnetic field. It is measured by the voltage divided by the rate of change of current over time. It is a measure of the magnetic "capacity" of an arrangement of conductors (e.g. coil) and can be compared to the capacity C of a capacitor. It indicates how much magnetic flux per ampere is generated.

$$\boxed{L = \frac{N \cdot \Phi}{I} = \frac{U}{\frac{\Delta I}{\Delta t}}}$$

where:

- $L$: inductance [H = Vs/A];
- $N$: number of turns;
- $\Phi$: magnetic flux [Wb];
- $I$: current [A];
- $U$: voltage [V].

### 6.2.10 Inductivity of a very long coil

The inductance of a very long coil can be calculated approximately with:

$$\boxed{L = \frac{\mu \cdot N^2 \cdot A}{l}}$$

where:

- $L$: inductance [H = Vs/A];
- $\mu$: magnetic permeability [Vs/Am];
- $N$: number of turns;
- $A$: cross-section of the coil [m$^2$];
- $l$: length [m].

### 6.2.11 Energy stored in an inductor

Since a variable magnetic field induces a voltage in which a current can also flow, the magnetic field must contain energy:

$$\boxed{W = \frac{1}{2} L \cdot I^2}$$

where:

- $W$: work, energy [J = Ws];
- $L$: inductance [H = Vs/A];
- $I$: current [A].

### 6.2.12 Current-voltage relationship of an inductor

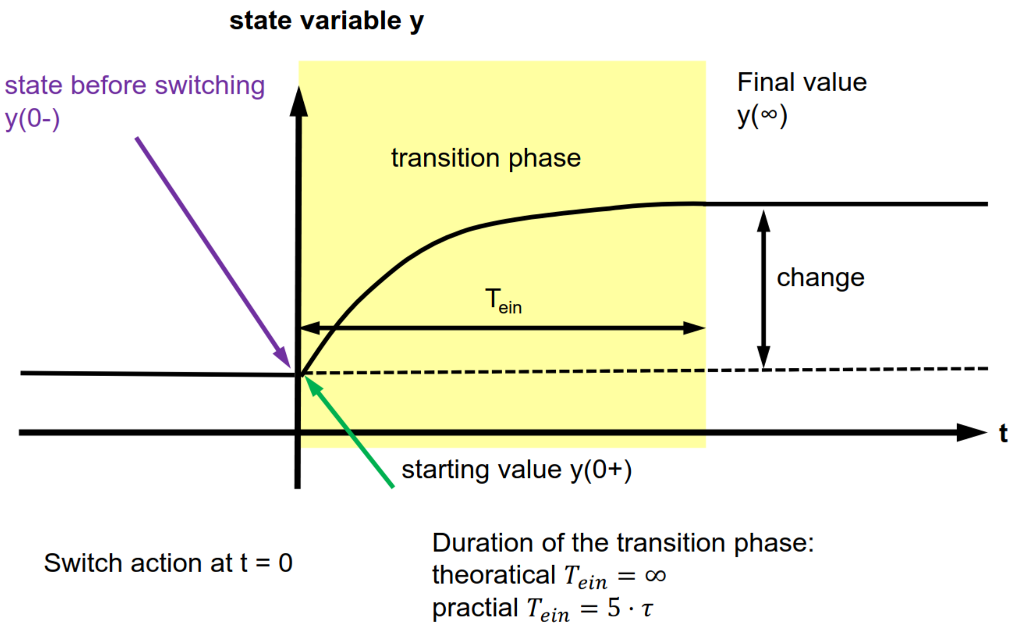
The current-voltage relationship of an inductor is:

$$\boxed{U = L \cdot \frac{\mathrm{d}I}{\mathrm{d}t}}$$

Special case:

$$\boxed{0 = L \cdot \frac{\mathrm{d}I}{\mathrm{d}t} \rightarrow u_c = 0}$$

### 6.2.13 Transient analysis




1. The state variable $y(t)$ is the variable that cannot change instantaneously. For the inductor, this is $i_L(t)$. The state just before the switch action:
$$y(0^-) = i_L(0^-).$$
2. The starting value is the state immediately before the switch action:
$$y(0^+) = i_L(0) = i_L(0^-).$$
That is, the state variable $i_L$ keeps the value from $t = 0^-$.
3. The final value is the value long after the switch action:
$$y(\infty) = i_L(\infty),$$
which is practically reached after $5\tau$.
4. The transient is described by the function of time:
$$y(t) = \text{final value} + \big(\text{starting value} - \text{final value}\big)\ \exp\left(-\frac{t}{\tau}\right).$$
Hence,
$$i_L(t) = i_L(\infty) + \Big(i_L(0+) - i_L(\infty)\Big)\ \exp\left(-\frac{t}{\tau}\right).$$

**Time constant $\tau$ for an inductor**

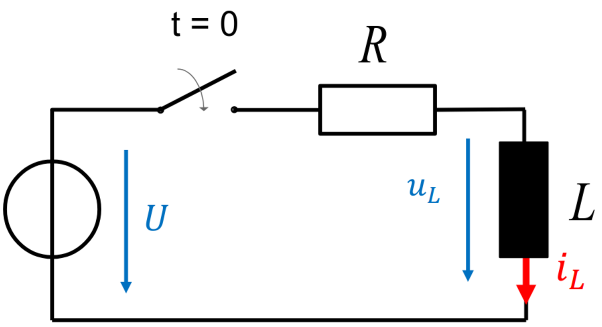
$$\boxed{\tau = \frac{L}{R}}$$

where:

- $\tau$: time constant [s];
- $L$: inductance [H];
- $R$: resistance [Ω].

## 6.3 Examples

### 6.3.1 Charging an inductor in a RL-network

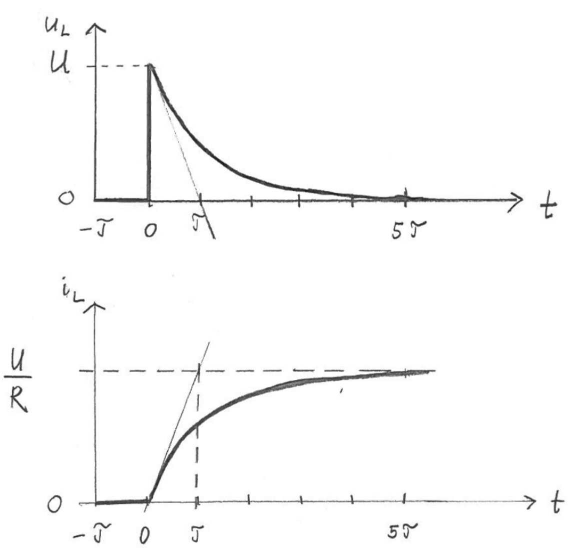



For t<0 stationary state, L discharged

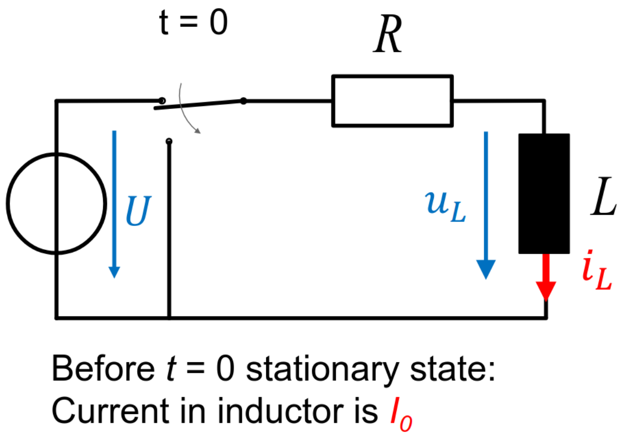
**Calculations**

$$\boxed{\begin{aligned} i_L &= \frac{U}{R} \cdot \left(1 - \exp\left(-\frac{t}{\tau}\right)\right) \\ u_L &= U \cdot \exp\left(-\frac{t}{\tau}\right) \end{aligned}}$$

**Graphical representation**



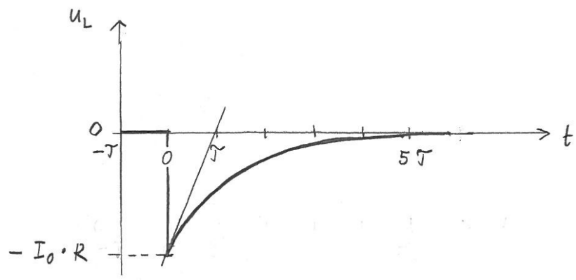
#### 6.3.2 Discharging an inductor in a RL-network

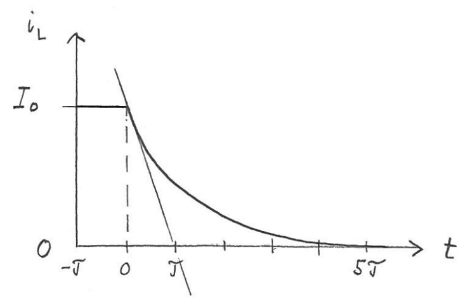



**Calculations**

$$\boxed{\begin{aligned} i_L &= I_0 \cdot \exp\left(-\frac{t}{\tau}\right) \\ u_L &= -I_0 \cdot R \cdot \exp\left(-\frac{t}{\tau}\right) \end{aligned}}$$

**Graphical representation**



# 7 Alternating current (AC)

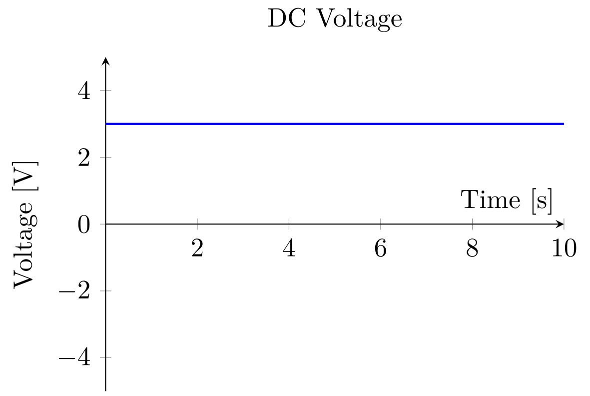
## 7.1 Generation of alternating current / voltage

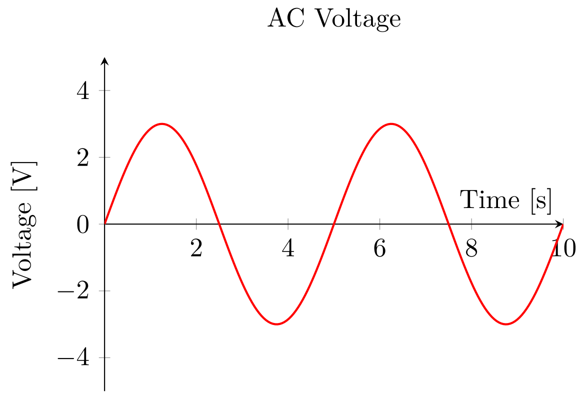
$$\boxed{U = -N \cdot \frac{\Delta\Phi}{\Delta t}}$$

where:

- $U$: voltage [V];
- $N$: number of turns;
- $\Phi$: magnetic flux [Wb].

## 7.2 Comparison of AC and DC



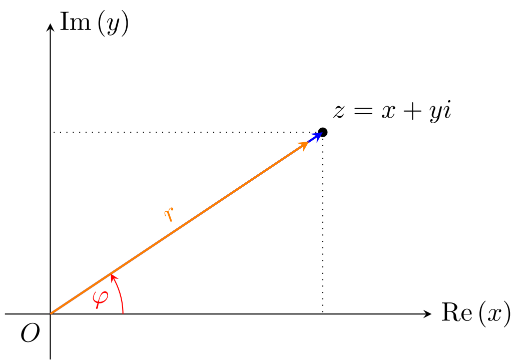

### 7.2.1 Advantages of AC

- Simple voltage transformation;
- Efficient trransmission;
- Easier generation;
- Compatibility with electric motors.

### 7.2.2 Disadvantages of AC

- Complexity in storage;
- Higher risk of shock;
- Complex circuits;
- Higher rectification costs.

## 7.3 Phasors




$$\boxed{z = x + yi = r\angle\varphi}$$

## 7.4 Oscillation as a function of the angle

Sinusoidal voltage has an instantaneous value $u(t)$ or $u$ for every time $t$.

After a period of time $T$, the curve repeats itself.

$$\boxed{u(t) = \widehat{U}\sin(\omega \cdot t)}$$

## 7.5 Zero phase angle $\varphi$

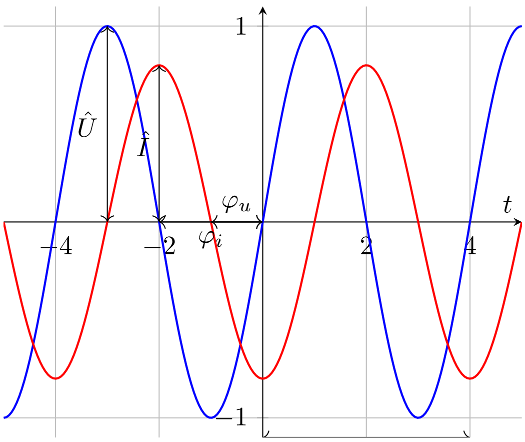
$$\boxed{u(t) = \widehat{U}\sin(\omega \cdot t + \varphi_u)}$$

### 7.5.1 Phase shift $\Delta\varphi$ between two signals

$$\boxed{\begin{aligned} u(t) &= \widehat{U}\sin(\omega \cdot t + \varphi_u) \\ i(t) &= \widehat{I}\sin(\omega \cdot t + \varphi_i) \end{aligned}}$$

The phase shift between two signals is the difference between the their zero phase signals:

$$\boxed{\Delta\varphi = \varphi_u - \varphi_i}$$




## 7.6 Power in a sinusoidal signal and effective value

### 7.6.1 Instantaneous power

The instantaneous power $p(t)$ is the actual power at a specific time $t$ and is the product of the voltage $u(t)$ and the current $i(t)$ at that moment:

$$\boxed{p(t) = u(t) \cdot i(t) = \frac{u(t)^2}{R} = i(t)^2 \cdot R}$$

The active power $P$ corresponds to the mean value of the instantaneous powerr $p(t)$ averaged over a period $T$:

$$\boxed{P = \frac{1}{T}\int_0^T p(t)\,dt}$$

### 7.6.2 Effective value

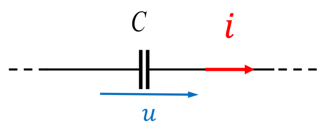
The effective value $U_{\text{eff}}$ of a sinusoidal signal is the voltage that would generate the same power in a resistor as the sinusoidal signal:

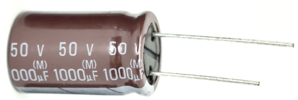
$$\boxed{U_{\text{eff}} = \sqrt{\frac{1}{T}\int\limits_0^T u(t)^2\,dt} = \frac{\widehat{U}}{\sqrt{2}}}$$

The same can be applied to the effective value $I_{\text{eff}}$:

$$\boxed{I_{\text{eff}} = \frac{\widehat{I}}{\sqrt{2}}}$$

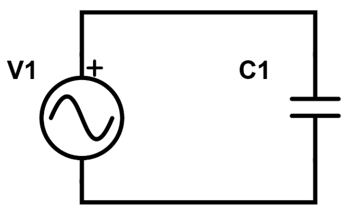
## 7.7 Relationship between current and voltage on a capacitor

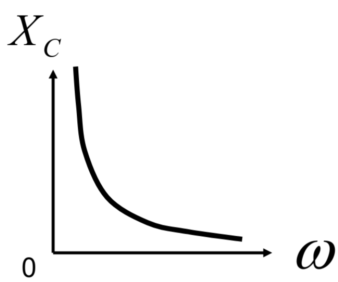



$$\boxed{i = C \cdot \frac{\Delta u}{\Delta t}}$$

## 7.8 Capacitive reactance $X_c$



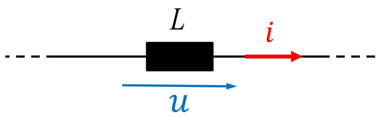




$$\boxed{X_c = \frac{1}{\omega \cdot C}}$$

where:

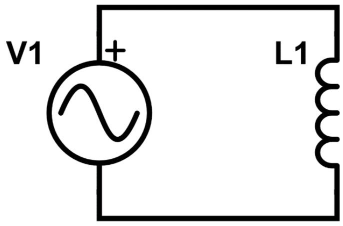
- $X_c$: capacitive reactance [Ohm];
- $\omega$: angular frequency [rad/s];
- $C$: capacitance [F = As/V].

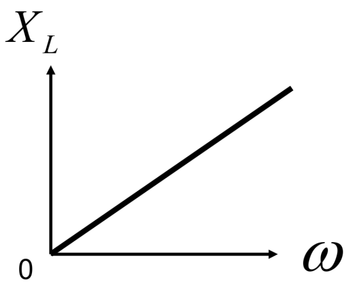
### 7.9 Relationship between current and voltage on an ideal inductor




$$\boxed{u = L \cdot \frac{\Delta i}{\Delta t}}$$

### 7.10 Inductive reactance $X_L$




$$\boxed{X_L = \omega \cdot L}$$

where:

- $X_L$: inductive reactance [Ohm];
- $L$: inductance [H];
- $\omega$: angular frequency [rad/s];

## 7.11 Vectors properties

### 7.11.1 Multiply

The magnitude (es. the radius $r$ in polar representation) is multiplied and the angle is added:

$$\boxed{\begin{aligned} r_c &= r_a \cdot r_b \\ \varphi_c &= \varphi_a + \varphi_b \end{aligned}}$$

### 7.11.2 Divide

The magnitude is devided and the angle is subtracted:

$$\boxed{\begin{aligned} r_c &= \frac{r_a}{r_b} \\ \varphi_c &= \varphi_a - \varphi_b \end{aligned}}$$

## 7.12 Impedance $Z$

The impedance is the ratio of voltage and current phasor. It's a complex number.

$$\boxed{\begin{aligned} Z &= \frac{u(t)}{i(t)} \\ |Z| &= \frac{|u(t)|}{|i(t)|} \\ \angle Z &= \angle u(t) - \angle i(t) = \Delta\varphi \end{aligned}}$$

Therefore, the impedance corresponds to the AC resistance with phase shift:

$$\boxed{\underline{Z} = \frac{\underline{U}}{\underline{I}} = \frac{U\angle\varphi_u}{I\angle\varphi_i} = Z\angle(\varphi_u - \varphi_i) = Z\angle\varphi_Z}$$

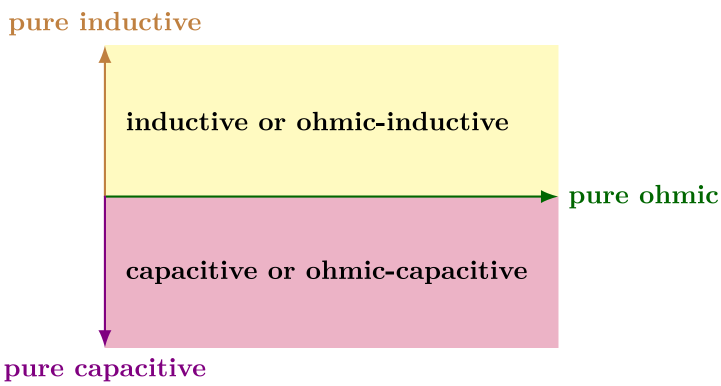
where:

- $Z$: impedance [Ohm];
- $\underline{U}$: voltage phasor [V];
- $\underline{I}$: current phasor [A];
- $\varphi_u$: phase angle of the voltage [rad];
- $\varphi_i$: phase angle of the current [rad];
- $\varphi_Z$: phase angle of the impedance [rad].

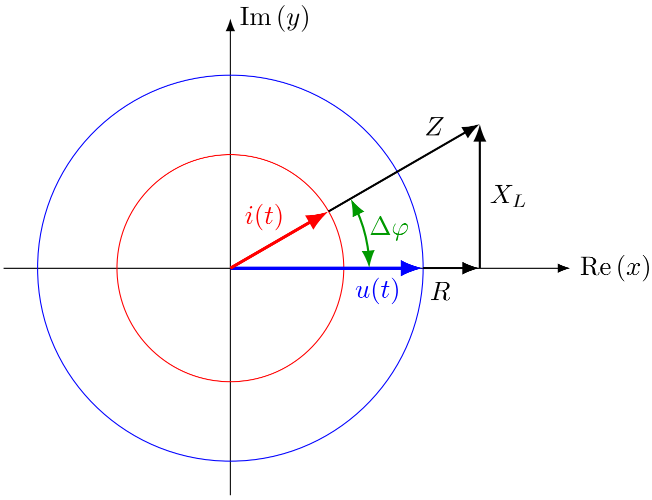
### 7.12.1 Types of impendance

The angle of the impedance $\varphi_Z$ indicates the type of impedance:

- $\varphi_Z > 0° \to$ voltage is ahead of current;
- $\varphi_Z = 0° \to$ voltage and current are in phase;
- $\varphi_Z < 0° \to$ current is ahead of voltage.



### 7.12.2 Graphical representation




## 7.13 Admittance $Y$

The reciprocal of the impedance $Z$ is the admittance $Y$ and thus the ratio of the current and voltage phasor. The admittance therefore corresponds to the AC conductance with phase shift:

$$\boxed{\begin{array}{l} \underline{Y} = \dfrac{\underline{I}}{\underline{U}} = \dfrac{I\angle\varphi_i}{U\angle\varphi_u} = Z\angle(\varphi_i - \varphi_u) = Z\angle\varphi_Y \\ |\underline{Y}| = \dfrac{1}{|\underline{Z}|} \Longrightarrow \varphi_Y = -\varphi_Z \end{array}}$$

## 7.14 Current and voltage relations

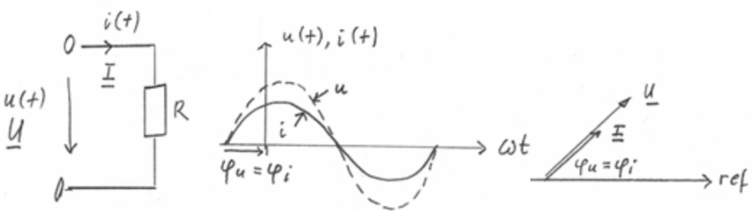
### 7.14.1 Resistor $R$

**Current-voltage relationship for instantaneous values**

$$\boxed{u_R(t) = R \cdot i_R(t)}$$

**Impedance = Ohmic resistance**

$$\boxed{R = \frac{U_R}{I_R}\angle 0°}$$



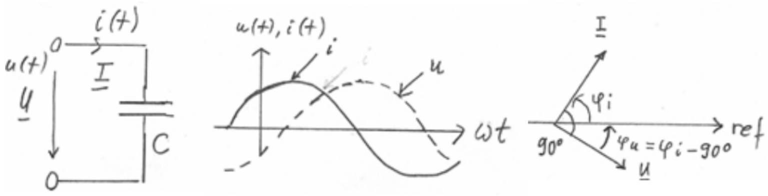

### 7.14.2 Capacitor $C$

**Current-voltage relationship for instantaneous values**

$$\boxed{i_C(t) = C \cdot \frac{du_C(t)}{dt}}$$

**Impendance = Capacitive reactance**

$$\boxed{X_C = \frac{U_C}{I_C} = \frac{1}{\omega \cdot C} \angle -90°}$$




Current leads the voltage by 90 degrees

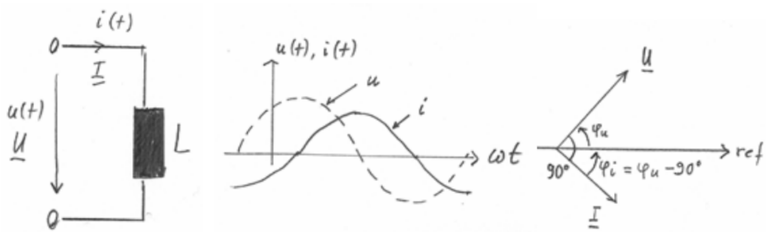
### 7.14.3 Inductor $L$

**Current-voltage relationship for instantaneous values**

$$\boxed{u(t) = L \cdot \frac{di(t)}{dt}}$$

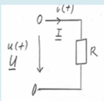
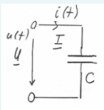
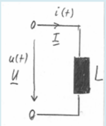
**Impendance = Inductive reactance**

$$\boxed{X_L = \frac{U_L}{I_L} = \omega \cdot L \angle +90°}$$



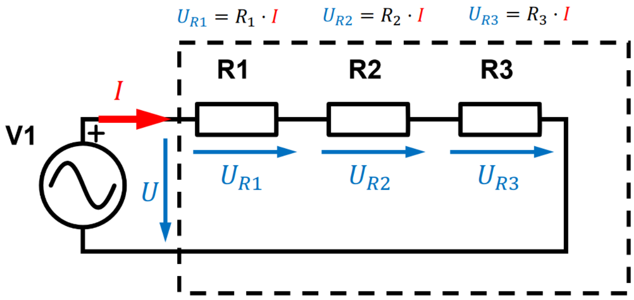

Current lags the voltage by 90 degrees

## 7.15 Impendance and admittance phasor with R, C and L

| | | **Phase shift** $\boldsymbol{\varphi_z = \varphi = \varphi_U - \varphi_I}$ | **Impedance $\underline{Z}$** $\underline{Z} = \frac{\underline{U}}{\underline{I}} \angle \varphi_Z$ | **Admittance $\underline{Y}$** $\underline{Y} = \frac{1}{\underline{Z}} = \frac{\underline{I}}{\underline{U}} \angle \varphi_Y$ |
|---|---|---|---|---|
|  | $\varphi_u = \varphi_i$ | $0°$ | $\underline{Z_R} = R\angle 0°$ | $\underline{Y_R} = \frac{1}{R}\angle 0°$ |
|  | $\varphi_u = \varphi_i - 90°$ | $-90°$ | $\underline{Z_C} = \frac{1}{\omega \cdot C}\angle - 90°$ | $\underline{Y_C} = \omega \cdot C\angle + 90°$ |
|  | $\varphi_i = \varphi_u - 90°$ | $90°$ | $\underline{Z_L} = \omega \cdot L\angle + 90°$ | $\underline{Y_L} = \frac{1}{\omega \cdot L}\angle - 90°$ |

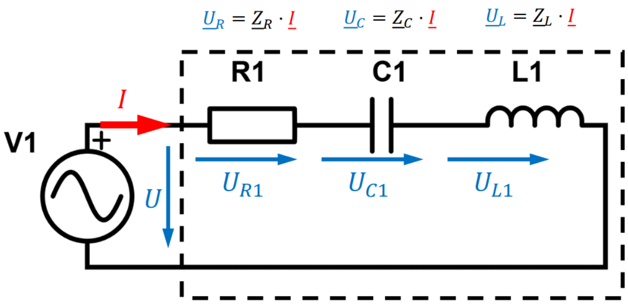
### 7.15.1 Series connection

**Resistances**




$$R_{\text{equi}} = \frac{U}{I} = \frac{U_{R1} + U_{R2} + U_{R3}}{I} = R_1 + R_2 + R_3$$

**Impedances**



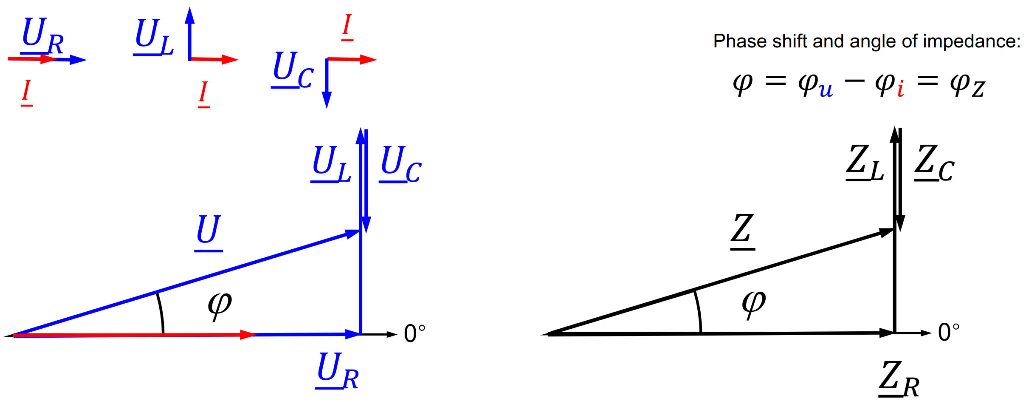

$$Z_{\text{equi}} = \frac{\underline{U}}{\underline{I}} = \frac{U_{R1}\angle 0° + U_{C1}\angle - 90° + U_{L1}\angle + 90°}{I\angle 0°} = \underline{Z_1} + \underline{Z_2} + \underline{Z_3}$$

Adding voltages in series connection means adding impedances:

$\underline{U_R} = \underline{Z_R} \cdot \underline{I} = R \cdot \angle\varphi_i$

$\underline{U_L} = \underline{Z_L} \cdot \underline{I} = X_L\angle 90° \cdot \angle\varphi_i$

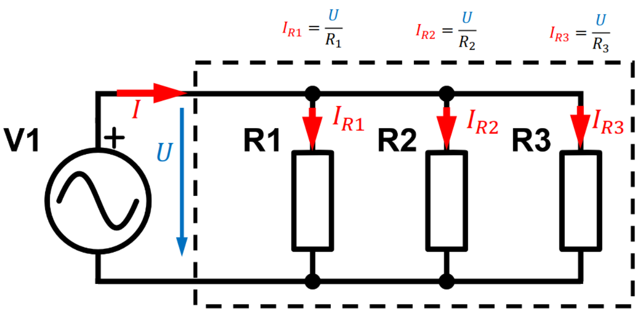
$\underline{U_C} = \underline{Z_C} \cdot \underline{I} = X_C\angle -90° \cdot \angle\varphi_i$




$$\boxed{Z_{\text{eq}} = Z_1 + Z_2 + Z_3}$$

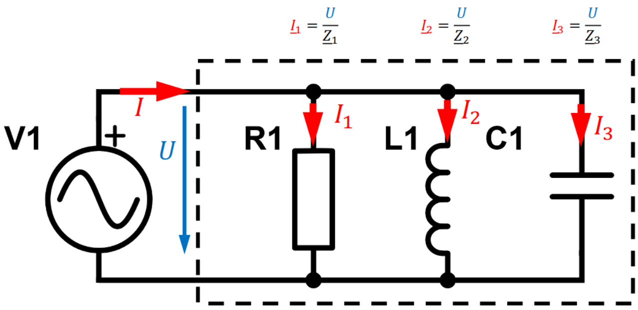
### 7.15.2 Parallel connection

**Resistances**




$$\boxed{R_{textequi} = \frac{U}{I} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{1}{G_1 + G_2 + G_3}}$$

**Impedances**



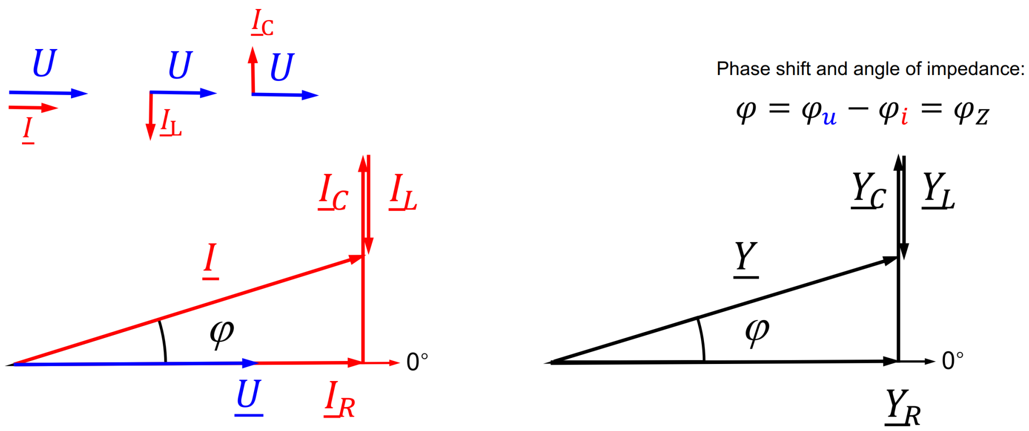

$$\boxed{Z_{\text{equi}} = \frac{\underline{U}}{\underline{I}} = \frac{U}{I\angle 0°} = \frac{1}{\dfrac{1}{\underline{Z_1}} + \dfrac{1}{\underline{Z_2}} + \dfrac{1}{\underline{Z_3}}} = \frac{1}{\underline{Y_1} + \underline{Y_2} + \underline{Y_3}}}$$

Adding currents in parallel connection means adding admittances:

$$\underline{I}_R = \frac{\underline{U}_R}{\underline{Z}_R} = \frac{U}{R} \cdot \angle\varphi_u$$

$$\underline{I}_L = \frac{\underline{U}_L}{\underline{Z}_L} = \frac{U}{X_L} \angle\varphi_u - 90°$$

$$\underline{I}_C = \frac{\underline{U}_C}{\underline{Z}_C} = \frac{U}{X_C} \angle\varphi_u + 90°$$




$$\boxed{\underline{Z}_{\text{eq}} = \frac{1}{\underline{Y}_1 + \underline{Y}_2 + \underline{Y}_3}}$$

## 7.16 AC newtwork analysis

AC network analysis is similar to DC network analysis but calculated with phasors.

### 7.16.1 Kirchhoff's current law (KCL)

$$\boxed{\underline{I}_1 + \underline{I}_2 + ... + \underline{I}_n = \sum_{k=1}^{n} \underline{I}_k = 0}$$

### 7.16.2 Kirchhoff's voltage law (KVL)

$$\boxed{\underline{U}_1 + \underline{U}_2 + ... + \underline{U}_n = \sum_{k=1}^{n} \underline{U}_k = 0}$$

### 7.16.3 Voltage and current phasor relationship for circuit elements

$$\boxed{\underline{U} = \underline{Z}_{\text{Element-type}} \cdot \underline{I}}$$