Alternating current

The Foundation Course on Physics

Professor Vojtěch Mornstein

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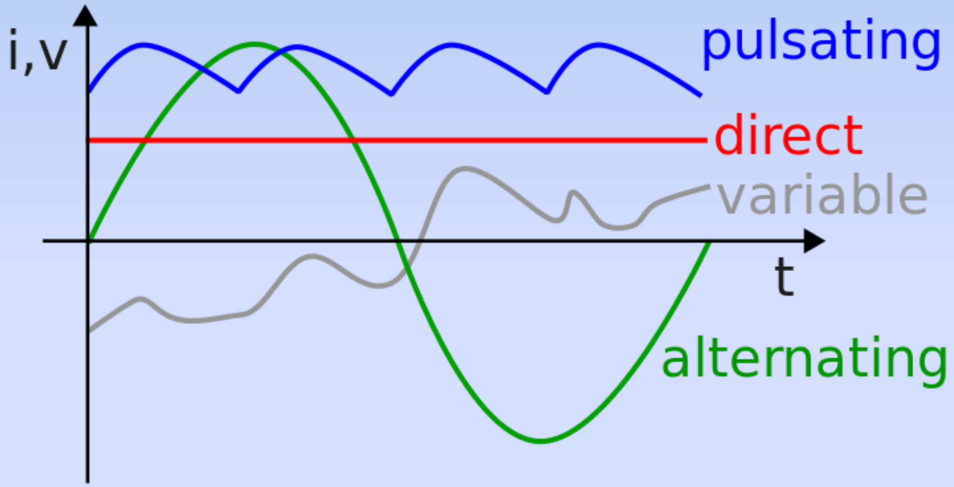
Alternating current

- What is electric current? What is direct and alternating current?



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Alternating current

Alternating current (AC) is used for powering various electrical devices. It is also efficient to be used for long-distance delivery of electrical energy (when using high voltage lines). To describe alternating currents or voltages, we can use similar quantities as used in the description of a simple harmonic motion:

The **cycle** is one complete waveform.

Period T [s] is the time duration of one cycle.

Frequency [Hz = s^{-1}] is the number of cycles per second.

Alternating current

Amplitude is the maximum value of positive or negative current (or voltage). Instantaneous values of alternating current and voltage are:

$$I_t = I_p \sin(2\pi f t + \phi) \qquad [A] \qquad \text{and}$$

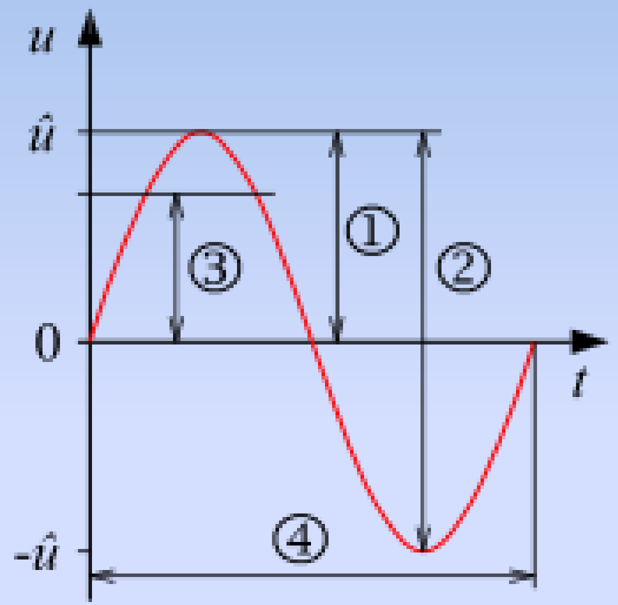
$$U_t = U_p \sin(2\pi f t + \phi) \qquad [V],$$

where I_t and U_t are the instantaneous values of current or voltage, I_p and U_p are the amplitudes of current or voltage (their peak values). ϕ (phi) is the initial phase angle which defines the values of I or U in time $t = 0$

Voltage is also denoted by the symbol of „V“ instead of „U“. There are some advantages and disadvantages.

Alternating current

A sinusoidal alternating voltage.
1 = peak voltage, also amplitude,
2 = peak-to-peak voltage,
3 = effective value of voltage (root mean square, rms)
– see next slide
4 = Period, *T*



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Average value of alternating current or voltage is **zero**, because their variation with time is sinusoidal.

Country	Voltage V_{eff} [V]	Frequency [Hz]
Czechia	230	50
United Kingdom	230	50
United States	120	60
Japan	100	50, 60
Saudi Arabia	230	60
Tonga	240	50

Effective Voltage and Electrical Power

The **effective voltage (current)** is that value of direct voltage (current) which would produce the same expenditure of electrical energy in the circuit as the respective value of direct voltage (current). The following equations hold (under condition of sinusoidal time-course):

$$I_{eff} = \frac{I_p}{\sqrt{2}} \quad \text{and} \quad U_{eff} = \frac{U_p}{\sqrt{2}}$$

where I_p and U_p are the amplitudes of current or voltage (their peak values).

Effective Voltage and Electrical Power

Electrical power of alternating current:

$$P = U_{eff} I_{eff} = \quad R I_{eff}^{2} = \frac{U_{eff}^{2}}{R}$$

[W = VA = watt = volt-ampere]

The Ohm's law in its simple form is valid for AC only when using effective values of voltage and current.

Reactance and Impedance

Reactance can be described as “resistance to the flow of electric charge in AC circuits”. Impedance is the total reactance. In general, the reactance and impedance *Z* depend on the frequency of the alternating current.

Reactance of a **capacitor** in an AC circuit:

$$X_C = \frac{1}{2\pi f C} = \frac{1}{\varpi C} \quad [\Omega],$$

where X_C is the **reactance** of a capacitor of **capacity** *C* [F], *f* is the frequency [Hz] of the alternating current, and ω is angular frequency. The higher the frequency of an alternating current, the smaller is the reactance of a capacitor. In biological systems, **membranes behave like capacitors**!

- *When uncharged, i.e. when the voltage across its plates equals zero, the capacitor is charged by the greatest current.*
- This means that the **voltage is delayed with respect to the current** with a phase difference of $+\pi/2$, i.e. the amplitude of the current occurs by *T/4* earlier than the amplitude of the voltage.

Reactance and Impedance

Reactance of an **inductor (**or **solenoid, coil)** that is a part of an AC circuit:

$$X_L = \omega L = 2\pi f L \qquad [\Omega]$$

where X_L is the reactance of an inductor, and L is the **self-inductance** [H] of the inductor. The higher the frequency of an alternating current, the greater is the reactance of an inductor.

The alternating current passing through the winding of the solenoid produces a magnetic field. This field induces a voltage in the solenoid which has an opposite polarity to the voltage of the source (see Lenz's law).

This means that the **current is delayed with respect to voltage** with a phase difference of $-\pi/2$, i.e. the amplitude of the current occurs by $T/4$ later than the amplitude of voltage.

Impedance of a Circuit

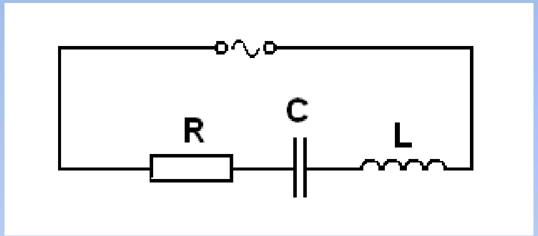


Fig. A resistor (R), capacitor (C) and inductor (L) connected in series.

It is often necessary to calculate the impedance of complex parts of electric circuits. For example, the following formula can be used for a resistor, capacitor and inductor (RCL) connected **in series** (Fig.):

$$Z = \sqrt{R^2 + \left(X_L - X_C\right)^2} \quad [\Omega]$$

where *R* is the resistance. The current in such an electric circuit is able to oscillate, which is very important for **production and transmission of electromagnetic waves (radiofrequencies)**. The strongest oscillation (resonance) occurs when the impedance of the circuit is minimal.

Resonance in an RCL circuit

According to the last formula, the smallest *Z* can be reached when

$$(X_L - X_C)^2 = 0,$$

It means that

$$X_L = X_C.$$

(*R* does not depend on frequency, remains constant.)

This condition allows to find the **resonance frequency**:

$$2\pi f L = \frac{1}{2\pi f C} \quad \Rightarrow \quad (2\pi f)^2 = \frac{1}{LC} \quad \Rightarrow \quad f = \frac{1}{2\pi\sqrt{LC}}$$

AC Transformer

This device is used for transformation of electric alternating voltages from high to low values and vice versa. A transformer consists of two solenoids with common core, i.e. primary (p, input) winding, the secondary (s, output) winding, and the soft iron core – see Fig. "Soft" means here that the iron is not permanently magnetised due to the magnetic field produced by the primary winding.

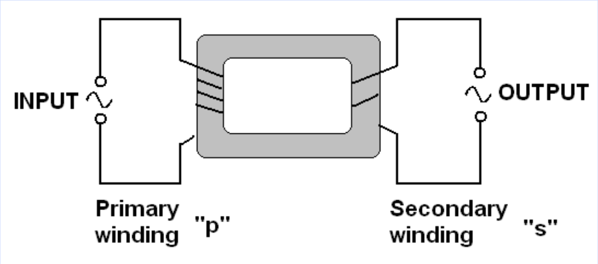
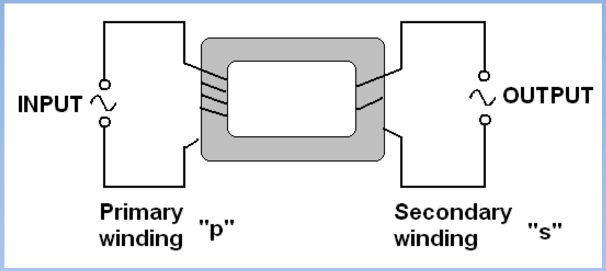


Fig. The AC transformer. The iron core is grey-coloured.

During transformation, a part of the electric energy is lost, mainly by conversion into heat. Therefore, ideal (efficiency = 100%) and practical transformers can be distinguished.

AC transformer



The following formulas are used for some practical calculations on transformers:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P} \qquad ,$$

where *V* is the voltage across the primary (*P*) or secondary (*S*) winding [V], *I* is the current through the winding [A], and N is the number of turns in the winding. Thus, in the transformer shown in the Fig., the voltage is reduced to one half and current increased twice (n_p = 4, n_s = 2).

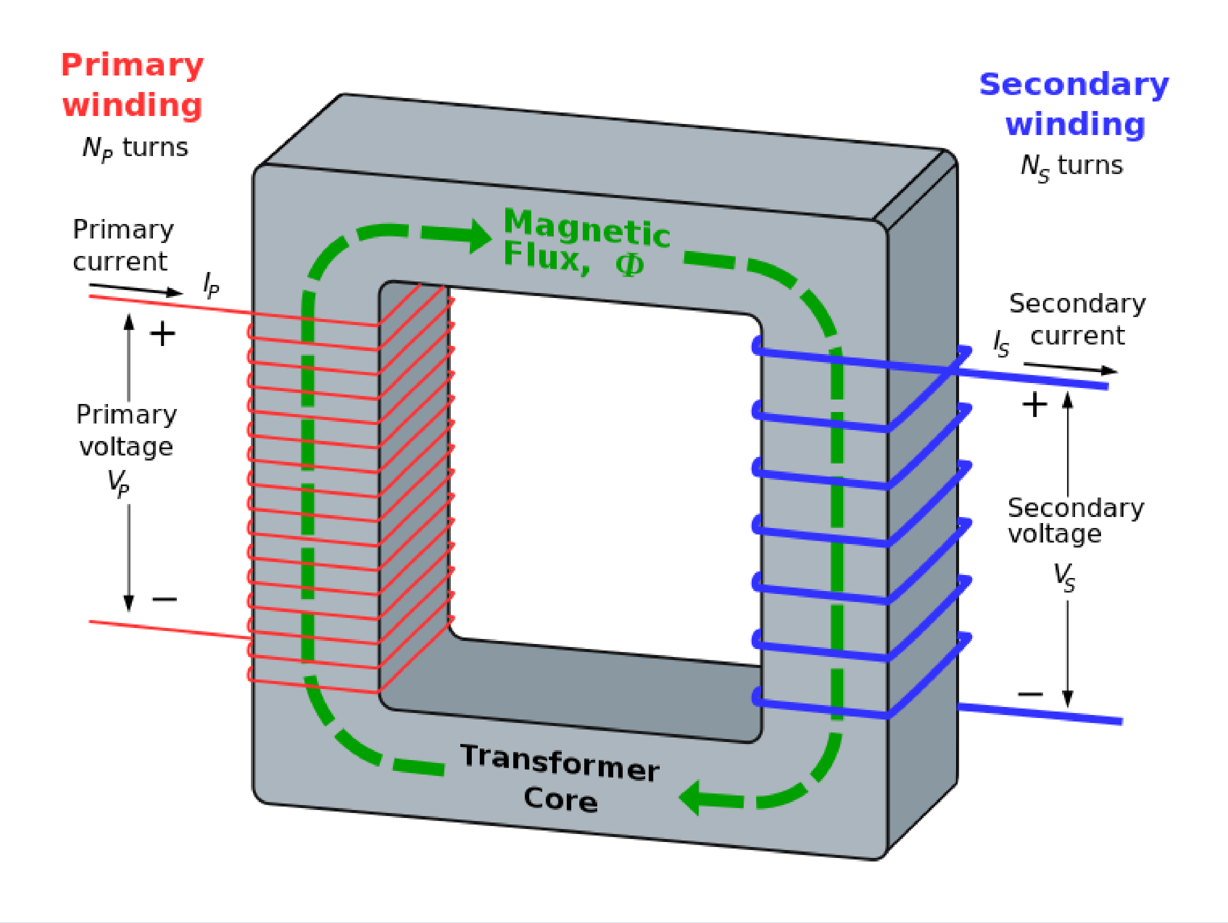
AC transformer

The transformer efficiency is given by relationship between the output and input power:

$$\eta = \frac{V_S I_S}{V_P I_P} \times 100 \qquad [\%]$$

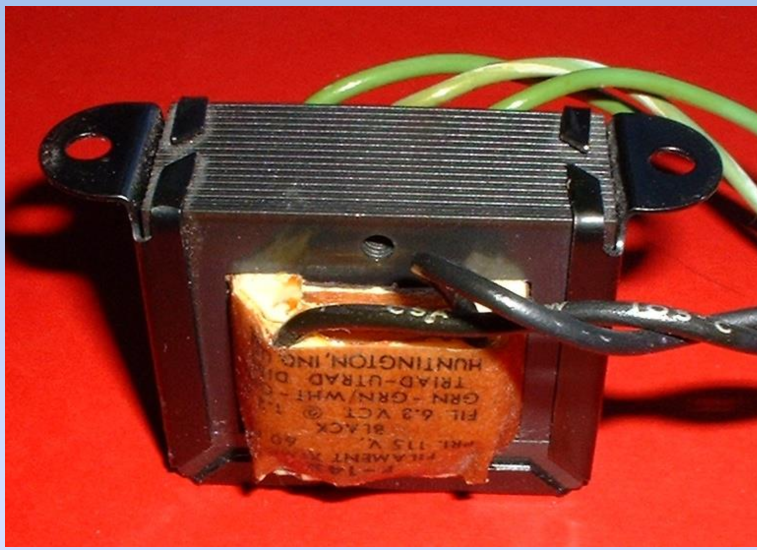
There are **"copper" and "iron" energy losses** in the transformer. The first ones are due to Joule's heat in copper winding wires, the second are due to some magnetization and demagnetization processes in the iron core.

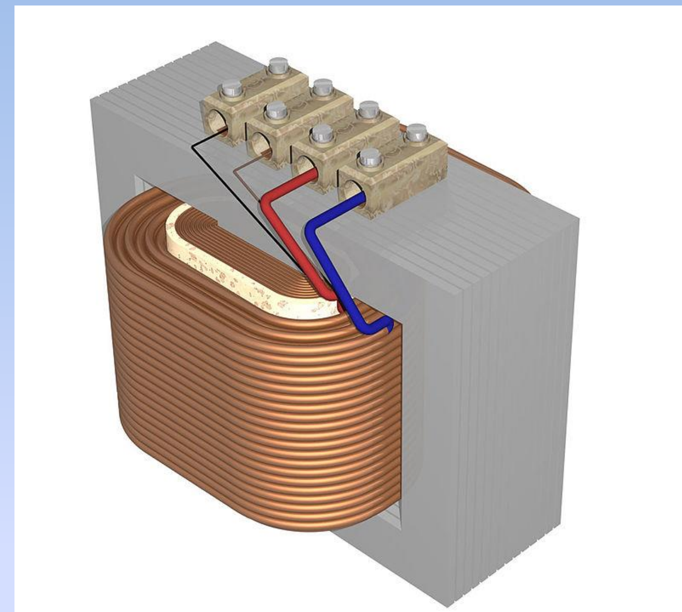
Transformer



$$\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P}$$

Transformer – real look





Windings are usually arranged concentrically to minimize flux leakage
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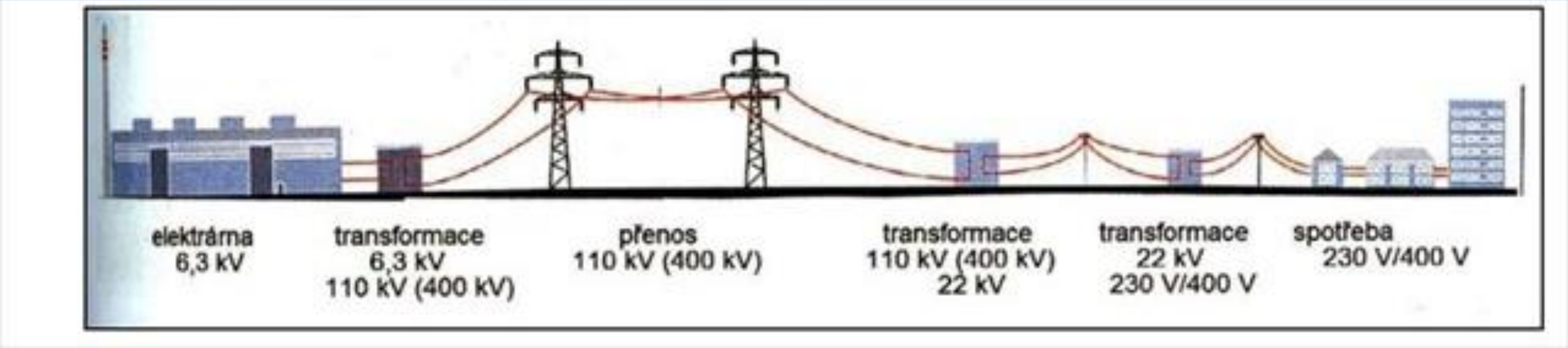
Transmission System

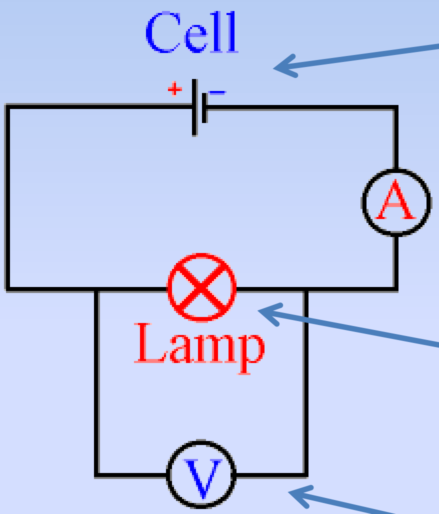


Power plant **transformation** **transmission** **transformation** **consumption**

Measuring instruments

- The construction of instruments for measuring electric currents, voltages and other electric quantities are beyond this lecture’s scope. However, it is absolutely necessary to know that:
- **Voltmeters** are characterised by very high intrinsic resistance. They must be connected in parallel to a “resistor” or “appliance” of which the voltage difference is to be measured. The measuring range of a voltmeter can be inceased by “series resistors”.
- **Ampermeters (ammeters)** are characterised by very low intrinsic resistance. They must be connected in series into a circuit. The measuring range of an ammeter can be increased by “shunts” – small resistors added in parallel.

A circuit with a voltmeter and ammeter

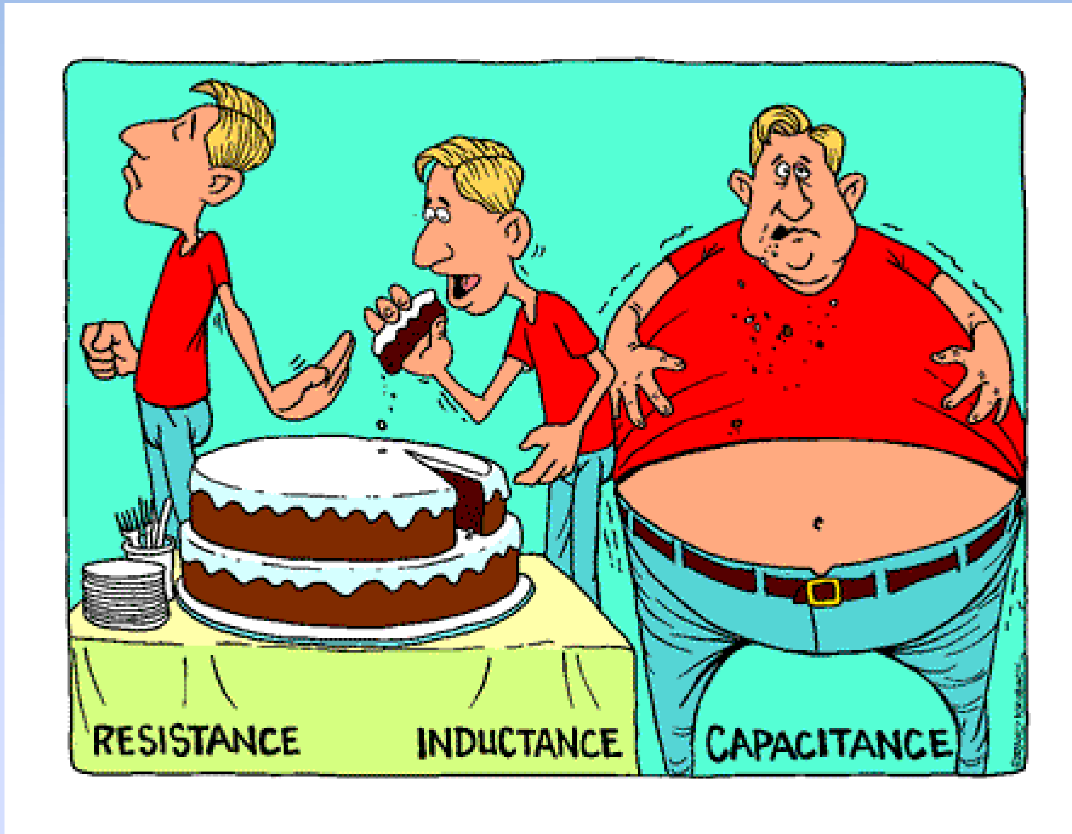


Cell – source of electric energy

A – ammeter, ampermeter – very low impedance

Lamp – appliance, resistor

V – voltmeter – very high impedance



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