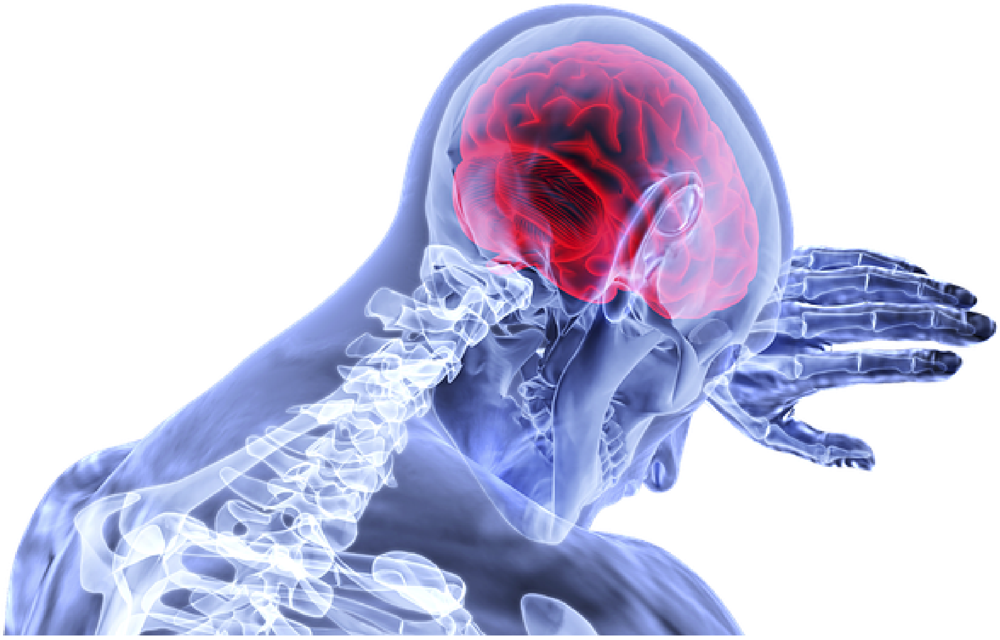
Lecturio Medical Education

Electricity II

See online here

Electric current is dangerous for people and animals for various reasons. Fluids of the human body conduct electricity; almost all organs function with the help of electrical impulses coming from the brain. These impulses control our movements and organs with a power of about 50 mV.



Different medical devices can measure electrical currents. For example, electrocardiography (**ECG**) provides information about the electrical activity of the heart, because the heart functions with self-generated electrical impulses.

However, if, for instance, an alternating current flows through the heart, this natural pump will try to follow the stronger and faster external impulses. This can eventually cause cardiac arrhythmia and ventricular fibrillation. The definition of alternating current and the quantities that are used to describe it will be clarified later in this article.

To understand different terminology used in electrical engineering, please read the article ‘Electricity I.’

Electric Field

An electric field is a **space around a charged particle in which another charged particle experiences a force**. An electric field can be represented by field lines along which an isolated positive charge would move if it were free to do so. These lines run from the positive pole to the negative pole and send each point of the electric field toward the force produced by a positive charge.

Electric field lines always emit vertically from the surface area of the conductive body. They point from positive charges toward negative charges. Depending on the course of the field lines, **radial, homogeneous, and inhomogeneous fields** are defined. Lines of the homogeneous field run parallel to each other and are of equal weight and density. If the lines are not parallel, then the field would be defined as inhomogeneous.

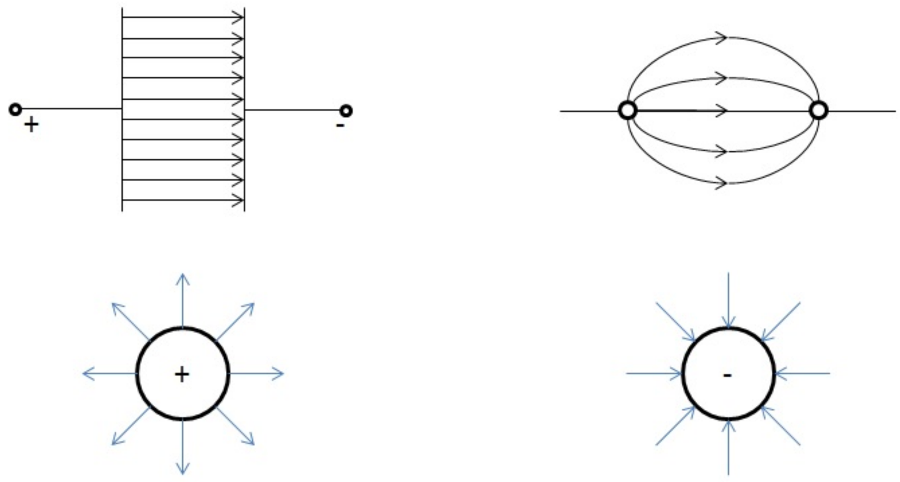


Image: Electric field lines. By Lecturio.

Electric Field Intensity

Electric field intensity (E) at a point of an electric field is the ratio of the force experienced by a charge at that point and the quantity of that charge. It is a vector quantity with the direction of a force (F). The movements of the charge in a homogeneous field require work (W):

$$\mathbf{W = F * s}$$

The charge runs along the electric field lines. Based on the following equations,

$$\mathbf{E = F / Q}$$
$$\mathbf{U = E * s}$$

where Q denotes ‘electric charge.’ Then we have the following equations:

$$\mathbf{W = F * s}$$
$$\mathbf{W = E * Q * s}$$
$$\mathbf{W = U * Q}$$

The electronvolt (eV) is a common unit for these types of work. The charge is thereby defined by a multiple of the elementary charge, and voltage is defined by the volts. The force that is exerted on the electric charge in the electric field results from E and Q:

$$\mathbf{F = E * Q}$$

Electrostatic Induction

Charges act on other charges in their environment. As they experience the force of the electric field, evenly distributed electrons of the uncharged conductor of the two oppositely charged plates collect on one side of the conductor, whereas the other side is deficient in electrons. The charges of the conductor are separated by the influence of the nearby charge.

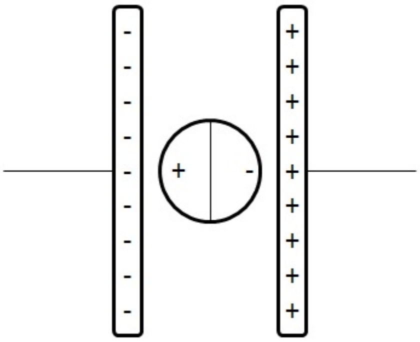


Image: Electrostatic induction. By Lecturio.

Because of the separation of charges, the uncharged body can be attracted by a charged body. Repulsion of likely charges thus proves the existence of the electric charge.

Now let’s imagine an electrostatic field in a medium (air) and take an uncharged metal sphere that consists of two parts, as demonstrated in the image below.

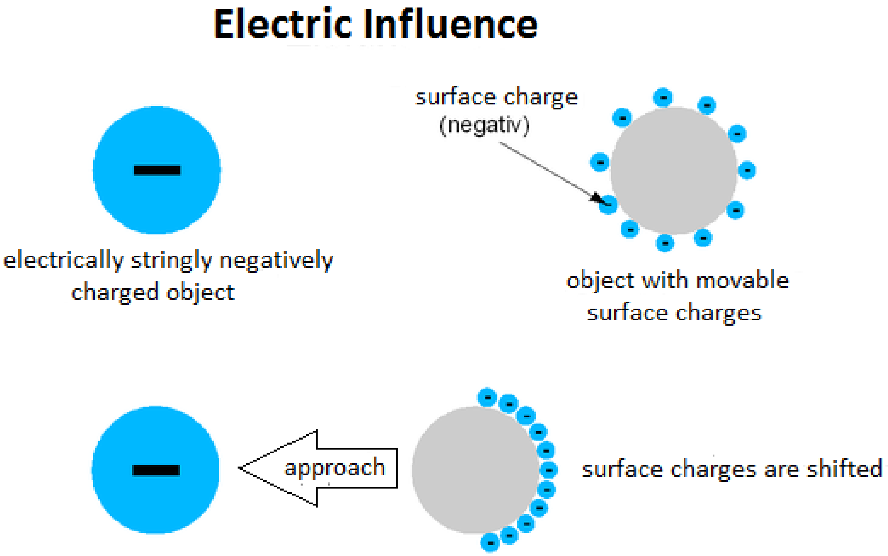


Image: Diagram of electric influence. By Lecturio.

As a result of electrostatic forces, the electrons inside the sphere start to separate in such a way that negative charges will accumulate opposite to the negatively charged plate because unlike charges attract each other. If we separate the two hemispheres from each other and then remove them from the field, we will get two oppositely charged bodies. This **influence of the electrostatic force on the charges** is called ‘electrostatic induction.’

Capacitance

Capacitance [F]

ε = the electric constant
ε_{R} = the relative static permittivity of the material between the plates

A capacitor consists of two closely adjacent conductors. The two conductors are oppositely charged. Because of the mutual attraction of the charges, the amount of the charge collected on both plates at the same voltage will be bigger than if the conductors were separated. A capacitor has a large capacity (capacitance). If both conductors have plates, they are called ‘parallel plate capacitors.’ The capacitance C is a quotient of the charge Q and the voltage U between the conductors.

$$\mathbf{C = Q / U}$$

A capacitance of 1 farad produces 1 V of voltage for an electric charge of 1 C. The capacitance of a parallel plate capacitor is directly proportional to the surface area of the conductor plates A and inversely proportional to the separation distance between the plates d.

In case there is air or a vacuum between the plates, the following equation applies:

$$\mathbf{C = \varepsilon * A / d}$$

If there is dielectric material between the plates, the following equation applies:

$$\mathbf{C = \varepsilon * \varepsilon_{R} * A / d}$$

The more charges are collected on the plates, the bigger the electrical voltage is between them, i.e. the relation **Q ~ U** applies.

Note: The larger the capacitance is, the more charges can be accumulated on the plates at a given voltage.

Series capacitors

For series capacitors apply the following equations:

$\mathbf{Q = Q1 = Q2 = Q3 = \ldots = Qn}$
$\mathbf{1/C = 1/C1 = 1/C2 = 1/C3 = \ldots = 1/Cn}$
$\mathbf{U = U1 + U2 + U3 + \ldots + Un}$
$\mathbf{U = Q / C}$

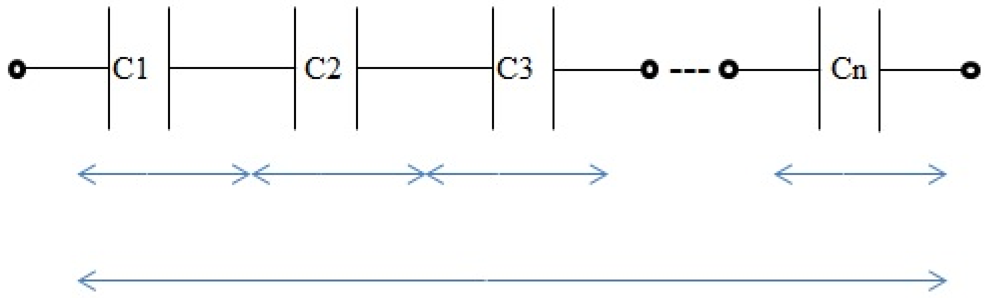


Image: Series capacitors. By Lecturio.

Parallel capacitors

For parallel capacitors, apply the following equations:

U = U1 = U2 = U3 = … = Un
C = C1 + C2 + C3 + … + Cn
Q = Q1 + Q2 + Q3 + … + Qn
Q = C * U

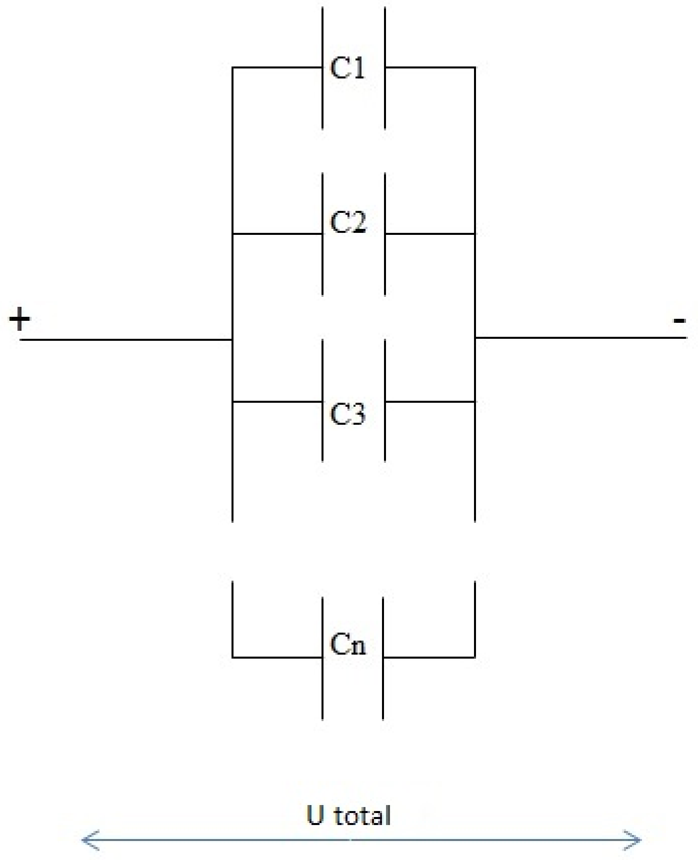


Image: Parallel capacitors. By Lecturio.

Parallel Plate Capacitors

Capacitance [F]

$\varepsilon_{0\,=}$ the electric constant
$\varepsilon_{R\,=}$ the relative static permittivity of the material between the plates

A capacitor consists of two closely adjacent conductors. The two conductors are oppositely charged. Because of the mutual attraction of the charges, the amount of the charge collected on both plates at the same voltage will be bigger than if the conductors were separated. A capacitor has a large capacity (capacitance). If both conductors have plates, they are called ‘parallel plate capacitors.’ The capacitance C is a quotient of the charge Q and the voltage U between the conductors.

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If there is the dielectric material between the plates, the following equation applies:

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The more charges are collected on the plates, the bigger the electrical voltage is between them, i.e. the relation **Q ~ U** applies.

Note: The larger the capacitance is, the more charges can be accumulated on the plates at a given voltage.

Series capacitors

For series capacitors, apply the following equations:

Q = Q1 = Q2 = Q3 = … = Qn
1/C = 1/C1 = 1/C2 = 1/C3 = … = 1/Cn
U = U1 + U2 + U3 + … + Un
U = Q / C

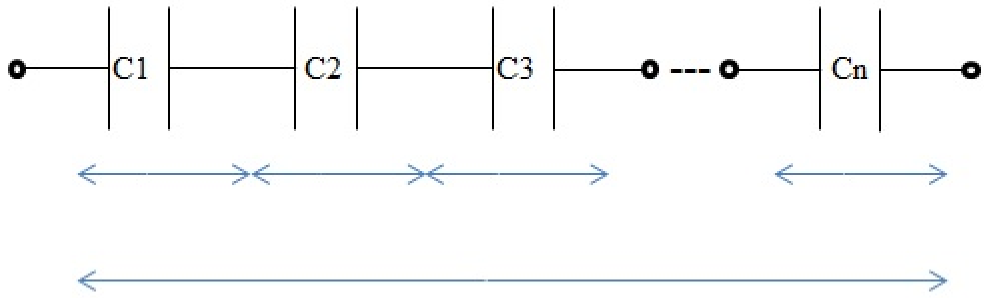

Image: Series capacitors. By Lecturio.

Magnetic field and electric current

F = force (in Newtons)
I = current intensity (in amperes)
l = length (in meters)
B = magnetic flux density

Every magnetic field exerts a force on a current-carrying conductor. This force is generated by the overlapping of the magnetic fields of the conductor and the magnet. In a magnetic field, a free-moving current-carrying conductor experiences a force perpendicular to the direction of the electric current and the magnetic field.

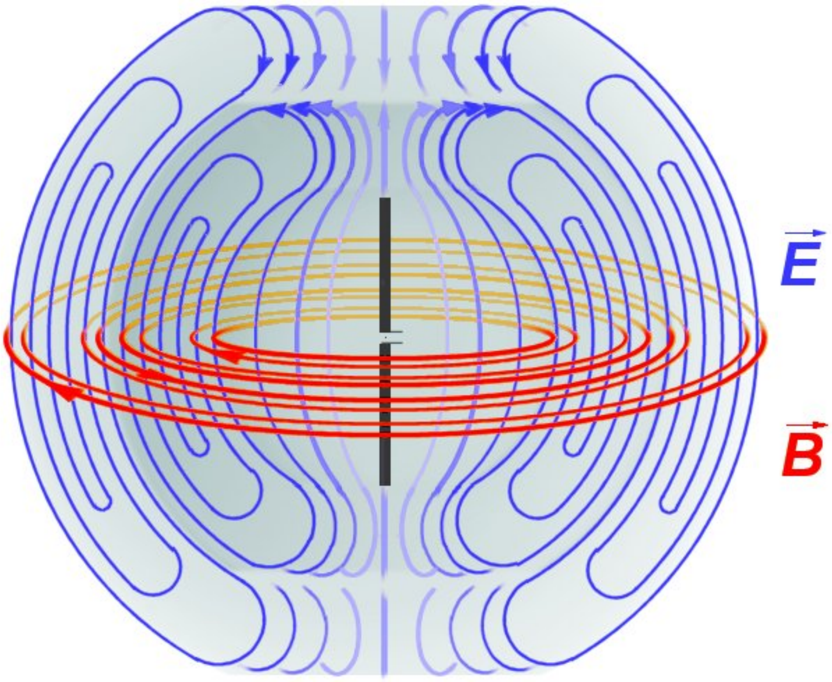

Image: Diagram of the electric (blue) and magnetic (red) fields surrounding a dipole antenna radiating a radio wave. By Averse. License: CC BY-SA 3.0.

The direction of the diversion of a conductor piece in a magnetic field can be determined by the **UVW-rule** (also called the **right-hand rule**). Spread your thumb, your index finger, and your middle finger so that your thumb points in the direction of the technical current, your index finger points in the direction of the magnetic field, and your middle finger points in the direction of the movement of the conductor.

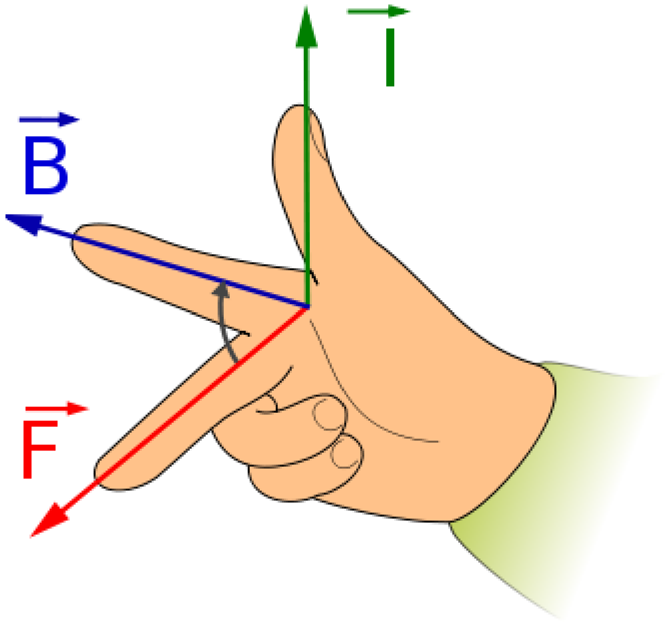

Image: Right-hand rule. By Canarris. License: CC BY-SA 3.0.

If the current direction is perpendicular to the direction of the magnetic field, the force on the straight section of the conductor is equal to the product of the electric current, to the length of the conductor section in the magnetic field, and to the magnetic field density:

$$\mathbf{F = I * l * B}$$

The magnetic flux density is given by the magnetic field constant and the magnetic field strength:

$$\mathbf{B = \mu 0 * H}$$

Magnetic Induction and Faraday’s Experiment

Along with the laws of the magnetomotive force, the law of induction represents one of the fundamental laws of electrical engineering. It was discovered by Faraday, who tried to answer the question of whether the reversal of Ampere’s circuital law was possible. Because it describes the origin of magnetic fields from electric currents, the reversal law would mean that magnetic fields could produce electricity. The following figure shows Faraday’s experiment:

Image: Faraday’s experiment. By Lecturio.

Near the switchable coil there is a so-called conductor loop, i.e. a coil with a single turn (N = 1). Its ends are connected to a voltmeter, which penetrates a portion of the conductor with the magnetic flux produced by the closed switch S.

While working with this experimental arrangement, Faraday came to the following conclusions: if the S switch is closed, magnetic flux is formed in the coil with a flowing current, as demonstrated in the image. This current is constant because it is generated by a continuous current. If the switch is open, there is no current, and, as a result, there is no magnetic field. In both cases, the voltmeter does not display any deflections.

The voltage can be detected only while switching the current of the coil on or while switching it off.

Conclusion: When a conductor loop is penetrated by magnetic flux lines, the voltage is created only if the flow comprised of the conductor loop changes over time. If it remains constant, no voltage will be observed. The production of voltage by the time-varying magnetic field is called ‘magnetic induction’ or ‘induced voltage.’ It is an electromotive force, or compliance voltage, because it makes electricity flow around the circuit of a conductor loop, which supplies the electrical energy—here, e.g., to the voltmeter.

Note: The current powered by induced voltage is directed in such a way that its external magnetic field, in conjunction with the (external) magnetic field created by induction, can inhibit the induction process. The induced current counteracts the cause of induction.

Lorentz Force

When charge carriers move in a magnetic field, they experience a so-called Lorentz force, which can be described in the following vector equation:

$$\mathbf{F = Qv \times B}$$

A particle of charge Q moves in the presence of a magnetic field of density B with velocity v. If only one conductor moves through a magnetic field, its quasi-free electrons experience the Lorentz force.

The Lorentz force acts:

- perpendicular to the particle’s line of flight.
- perpendicular to the magnetic force vector.

Alternating Current

ω = magnetic field
Φ_0 = the largest magnetic flux
t = time

If a conductor loop rotates evenly in a magnetic field, an alternating current will be induced. This current is characterized by the fact that it periodically changes in size and polarity. **Alternating current** is represented on a graph by a **sinusoidal wave**. If the ends of a rotating coil are connected to an external circuit, an alternating current is created whose direction varies sinusoidally with time and changes once in each period. It is designated as an alternating current.

Suppose that the coil rotates with angular velocity ω in a magnetic field; the magnetic flux passing through the coil is time-dependent and is represented by the following equation:

$$\Phi = \Phi_0 * \cos \omega t$$

Options for describing angular velocity:

- By frequency f: $\omega = 2 * \pi * f$
- By periodic time T: $\omega = (2*\pi) / T$

Alternating current circuit with ohmic resistance R

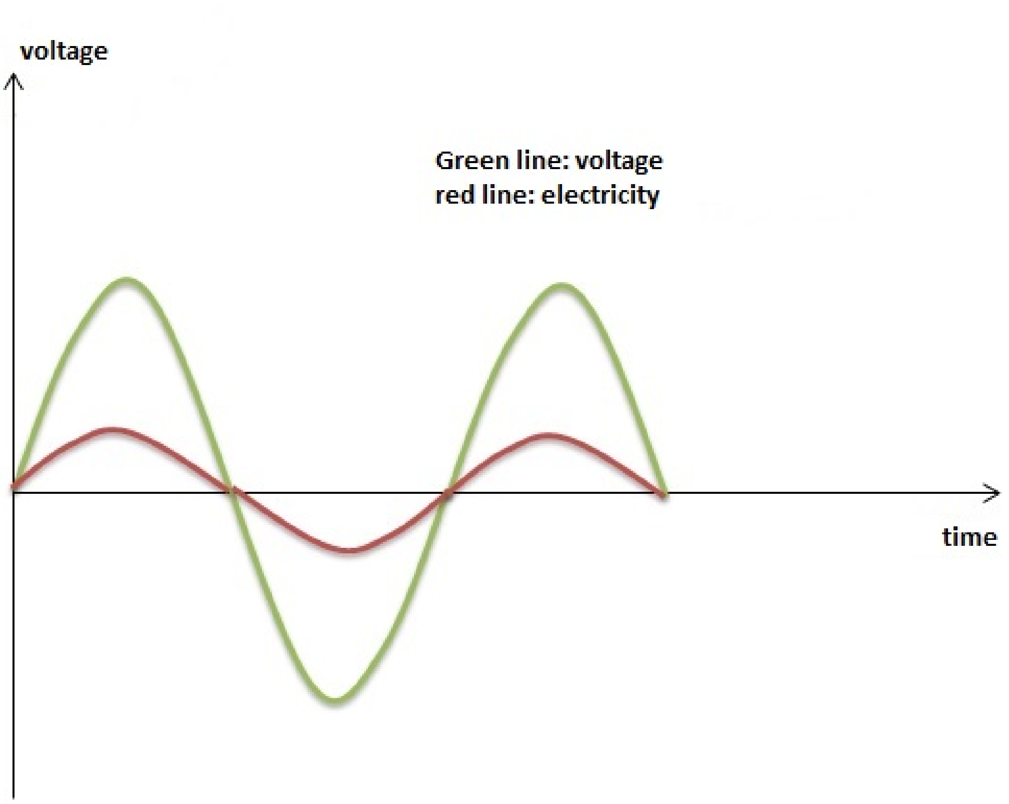

Image: Alternating current circuit with ohmic resistance R.

The graphic representation shows that the current is in phase with the voltage. The ‘effective current’ of the alternating current refers to the current that has to have a direct current to be able to produce the same capacity with the same resistance.

Alternating current circuit with inductive resistance L

The calculation of the inductive resistance is given by the equation:

$$X_L = U_{eff} / I_{eff} = \omega * L$$

The current can also run after the voltage. The phase shift is:

$\varphi = \pi / 2 = 90^\circ$

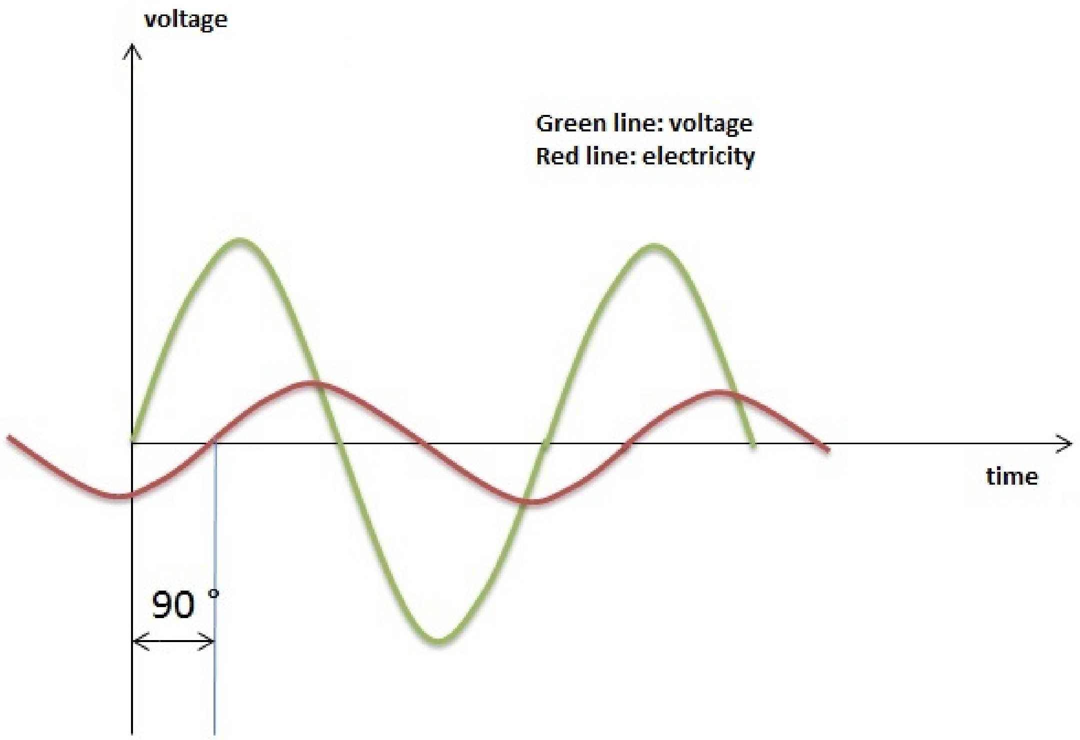

Image: Alternating current circuit with inductive resistance L.

Alternating current with capacitive resistance C

In addition, the current can run ahead of the voltage. The phase shift is:

$\varphi = \pi / 2 = 90°$

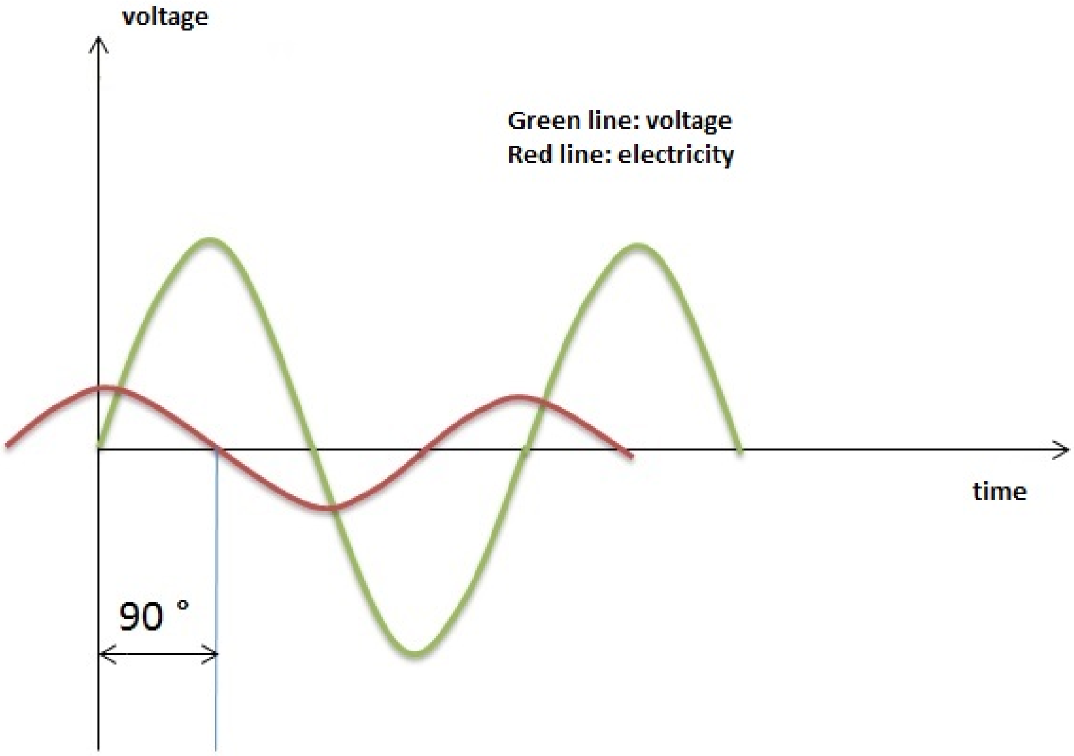

Image: Alternating current with capacitive resistance C.

References

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Notes