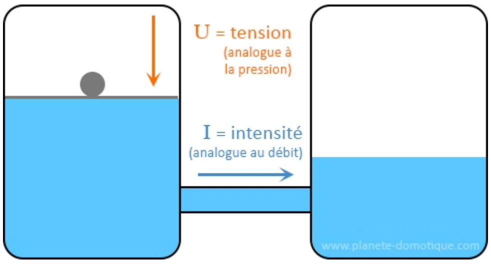
Chapter 1: Electrical Circuits

1. Current and voltage in electrical circuits

In this first part, we'll look at electricity measurement units and the different types of electricity available.

It's easy to see that water flowing down by gravity forms a circuit comparable to the electrical circuit:

- Water tank A corresponds to the generator,
- the water pipe corresponds to the electrical conductors,
- Reservoir B is assimilated to the receiver.



Tank A Tank B

Fig.1.1. Analogy electricity and a hydraulic system

The voltage corresponds to the water pressure in the pipe, while the current corresponds to the flow rate.

Water circulation depends on two factors:

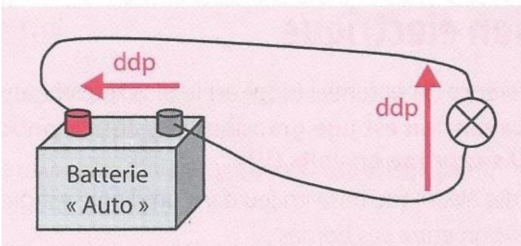
- the difference altitude without which water cannot circulate (by gravity) from the water supply to the bathtub,
- water flow rate, i.e. the volume water flowing through the pipe per second.

1.1. Potential difference

As with water, an electric current can only flow if there is a so-called potential difference (pd) between the two terminals of the generator. Without a potential difference, an electric current cannot flow.

Similarly, no current can flow through a receiving dipole there is a potential difference between its terminals.

The battery's potential difference is applied to the lamp.
A current through the lamp and illuminates it.



1.2. Electrical current

Electric current is an organized flow of electrons.

It corresponds to the number of electrons flowing during each second (electron flow rate). The intensity of the electric current can be compared to the flow of water in a hydraulic circuit.

As with a hydraulic circuit, it's important to match the conductor cross-section to the current to be passed.

To facilitate the movement of electrons and avoid overheating of the conductors, the conductor cross-section must be sufficient to ensure the free flow of electrical charges.

Closely related to the notion of current is the notion of resistance. Resistance, noted R, is expressed in Ohms (symbol:) and determines the ability of a circuit or other component to slow the passage of current. Thus, in a highly conductive circuit, the resistance is close to 0. Two elements that are not in contact will have a resistance approaching infinity. The formula indicating the relationship between power and resistance is Ohm's Law: $U = R \times I$ (voltage equal to the product of resistance and current).

When a current flows through the human body (made up around 75% water), it acts like a resistor.

The resistance of the human body varies according to :

- people,
- skin moisture,
- and also the circuit followed by the current in the body.

On average, the human body has a resistance of around 3 to 5 kΩ.

From the above formula, we can see that with a voltage of 12V, a current of 2.5mA (non-dangerous) will pass through the body. On the other hand, with a voltage of 230V, an intensity of 45mA is reached, which could be dangerous.

The current flowing through the human body is dangerous according to its intensity:
– 0.5 mA: this is the perception threshold
– at 10 mA: muscle contractions, threshold: maximum 3-4 minutes.
– at 30 mA: respiratory paralysis threshold: maximum 20-30 seconds.
– at 75 mA: irreversible cardiac fibrillation threshold: maximum 2 to 5 seconds.
– at 1000 mA: cardiac arrest: maximum 30 to 100 ms.

It should be noted that in all cases, whatever the capacity of a power supply, it will only deliver the current required by the load connected to it.

For example, a 50A 12V car battery won't be fatal to person touching the + and - terminals, since the human body will only consume 2 or 3mA.

2. Quantity electricity

The energy involved depends on the number electrons circulating.

The quantity of electricity Q transported by an electric current corresponds to the number n of electrons that have circulated.

$$Q = n \times e$$

Q: quantity electricity in coulombs (C) n:
number of electrons
e: quantity elementary electricity in coulombs (C)

The elementary quantity of electricity that of electron, and is denoted e :

$$e = 1.6 \times 10-19 \text{ C}$$

Another unit of electricity quantity: on batteries and accumulators, the quantity of electricity is often indicated in ampere-hours (Ah).

$$1 \text{ Ah} = 3600 \text{ C}$$

3. Electrical voltage

Potential difference (pd) is most often referred to as "voltage". Voltage is symbolized by the letter U and expressed in volts (V).

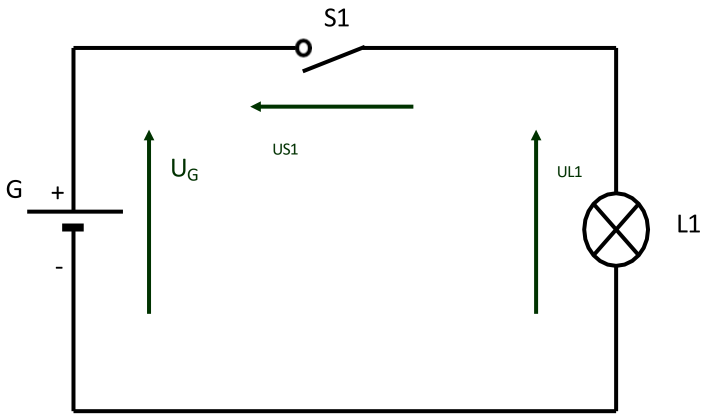
The electrical energy involved in a dipole is :

$$W = Q \times U$$

W: energy in joules (J)
Q: quantity electricity in coulombs (C) U:
voltage in volts (V)

Voltage is represented by an arrow pointing

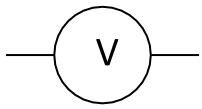
Example:



The device that measures voltage is the voltmeter.

Analog voltmeter

Digital voltmeter



Symbol

Voltmeter connection: the voltmeter is connected in parallel between the two points of the circuit whose potential difference is to be determined.

4. Electrical current

Intensity is the number of coulombs carried per second by the electric current.

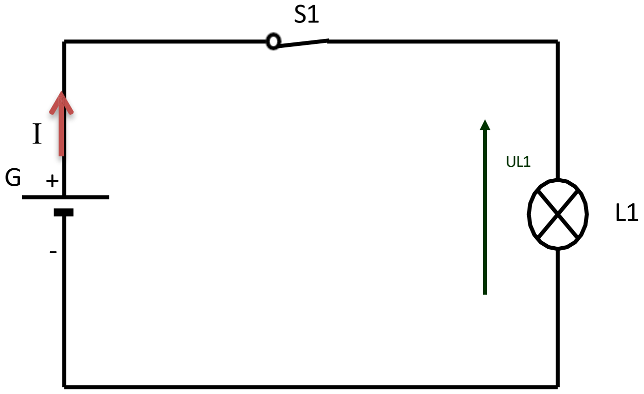
The intensity of electric current is symbolized by the letter I and expressed in amperes (A). Intensity is equal to the quantity of electricity flowing during a unit of time.

$$I = Q / t$$

I: current intensity in amperes (A)
Q: quantity electricity in coulombs (C) t:
time in seconds (s)

Current intensity is symbolized by an arrow on the electrical diagram, pointing from plus to minus.

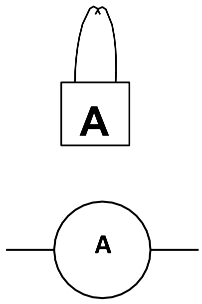
Example:



The device that measures the intensity of an electric current is the ammeter.

Analog ammeter

Current clamp



Symbol

Connecting the ammeter: the current to be measured must flow through the ammeter. The ammeter is connected in series with the electrical circuit.

5. Alternating current and direct current

AC or DC is usually indicated just after voltage, to indicate what a power supply delivers, or the type of power supply a device requires: for example, 230 VAC alternating current is the mains current coming out of an electrical socket, and 12 VDC direct current is the power supply for a small appliance.

In a direct current, electrical charges move in only one direction, from [-] to [+], whereas in an alternating current, the direction of the charges changes very regularly. An alternating current is therefore defined not only by its voltage, but also by its frequency, i.e. the number of times the charges change direction. This frequency is 50 Hz in most countries, including Algeria, and 60 Hz in the USA. Most power supplies are marked 50/60 Hz, indicating that they accept both frequencies.

Current types

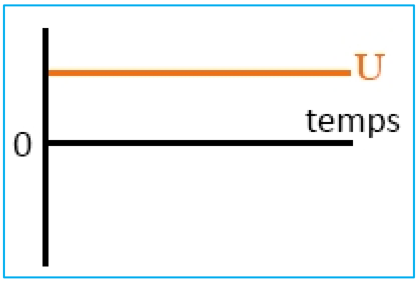
Direct current

Symbol =

DC in English

Graphical representation

Direct current is the current delivered by batteries.



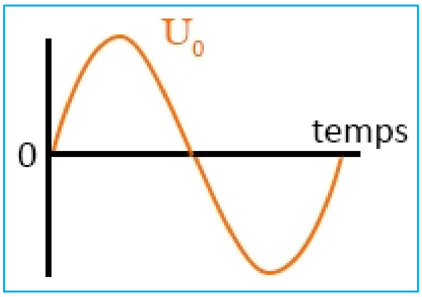
Alternating current

Symbol ≈

AC in English

Graphical representation

Alternating current is the current distributed to your installation.



6. Real power and apparent power

Another essential concept is electrical power. Power is expressed in watts (symbol: W) and is denoted P. It is the product of voltage and current ($P = U \times I$), and as it takes into account the quantity and movement of electricity, it indicates the energy supplied in one second by the electrical circuit.

$$P = U \times I$$

Power	voltage	Current
in watts (W)	in volts (V)	in amperes (A)

N.B.: This is the formula for the simplest case, direct current, where the voltage does not vary. In the case of alternating current, more complex formulas come into play, and this formula is used to calculate apparent power.

This notion of apparent power explains why, in alternating current, to have an accurate measurement of the power consumed, you need an accurate measurement of the voltage.

Depending on the type of load, there may be an offset between voltage and current (inductive load). Power is then totally dependent on voltage measurement.

You won't have this problem on a resistive load (such as a radiator), but you may have it on a motor (washing machine, etc.).

Here is an order of magnitude of powers present in everyday objects:

- Phone charger: 5 W
- Electrical appliance (TV, printer, etc.) on standby: 5 to 10 W
- Refrigerator: 200 W
- Air conditioning: 400 W
- Computer in operation with LCD monitor: 80 W
- Lamp with energy-saving bulb: 10 W
- Dishwasher: 1200 W
- Washing machine: 2500 W
- Classic oven: 2000 to 2500 W
- Electric heating: 1000 W to 2000 W

You'll sometimes find power expressed in volt-amperes (VA): this is apparent power. Where the watt measures real power (active power) and therefore depends on various factors, the voltampere expresses apparent power, i.e. the maximum value of power that can be taken.

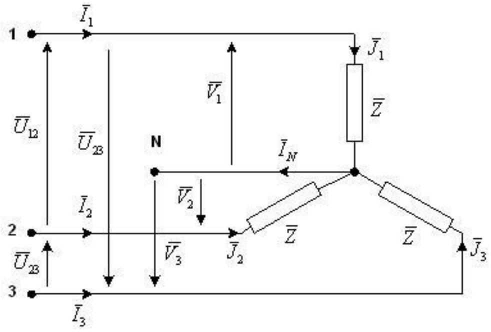
The formula for power [$P = U \times I$] given below is always valid for calculating apparent power, whatever the particularities of the circuit being measured.

For a direct current (DC) circuit, real power is equal to apparent power. The volt-ampere is therefore only relevant for alternating current (AC) circuits.

7. Three-phase circuit

7.1. Tensions

It's a system made up of 3 single-phase sinusoidal AC voltages of the same RMS value V, phase-shifted by 2π/3 with respect to each other, and having a common point N called the Neutral point. It is therefore a balanced system.



- $V_1 = V\sqrt{2}\,\omega t$
- $V_2 = V\sqrt{2}\sin\left(\omega t - \frac{2\pi}{3}\right)$
- $V_3 = V\sqrt{2}\sin\left(\omega t - \frac{4\pi}{3}\right)$

$$\vec{V}_1 + \vec{V}_2 + \vec{V}_3 = \vec{0}$$

V: rms value

These voltages are called single-phase or phase-to-neutral voltages. You can also measure the voltage between 2 phases, to obtain compound voltages.

$$\begin{cases} U_{12} = V_1 - V_2 \\ U_{23} = V_2 - V_3 \\ U_{31} = V_3 - V_1 \end{cases}$$

The compound voltage system is balanced

$$\vec{U}_{12} + \vec{U}_{23} + \vec{U}_{31} = \vec{0}$$

As the system is balanced, the 3 voltages have the same RMS value V

Relationship between U and V :

$$U_{12}^2 = V_1^2 + V_2^2 - 2V_1^2 V_2^2 \cos 120$$

$$U_{12}^2 = U = V\sqrt{3}$$

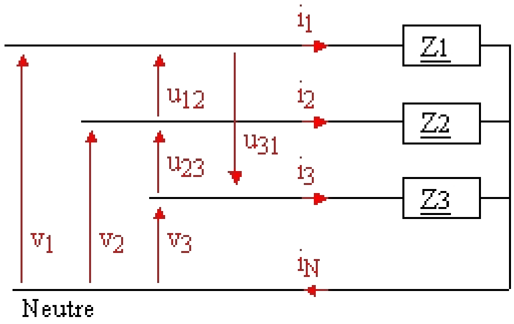
7.2. Intensities

The balanced three-phase source supplies the three-phase receivers, which can be balanced or unbalanced. On the other hand, there are 2 types of coupling possible for receivers

TriangleΔ and Etoile Y

The source can also Y and Δ

1. Balanced star connection :



The 3 dipoles must be completely identical

$$Z_1 = Z_2 = Z_3 = Z$$

$$\begin{cases} I_1 = V_1 / Z(1) \\ I_2 = V_2 / Z(2) \\ I_3 = V_3 / Z(3) \end{cases} \qquad I_1 = I_1 = I_1 = I$$

Depending on the nature of the dipoles, the phase shift between currents will be more or less important and is identical for all 3 phases (between +π/2 and -π/2).

Energy balance

Total active power consumption :

$$P_t = P_1 + P_2 + P_3$$

$$\begin{cases} P_1 = V_1 I_1 \cos \phi(1) \\ P_2 = V_2 I_2 \cos \phi(2) \\ P_3 = V_3 I_3 \cos \phi(3) \end{cases} = VI \cos \phi$$

$$P_t = 3VI \cos \phi$$

$$V = \frac{U}{\sqrt{3}} \quad \rightarrow P_t = 3 \frac{U}{\sqrt{3}} I \cos \phi = \sqrt{3} UI \cos \phi$$

Total reactive power consumption

$$\begin{cases} Q_1 = V_1 I_1 \sin \phi(1) \\ Q_2 = V_2 I_2 \sin \phi(2) \\ Q_3 = V_3 I_3 \sin \phi(3) \end{cases} = VI \sin \phi$$

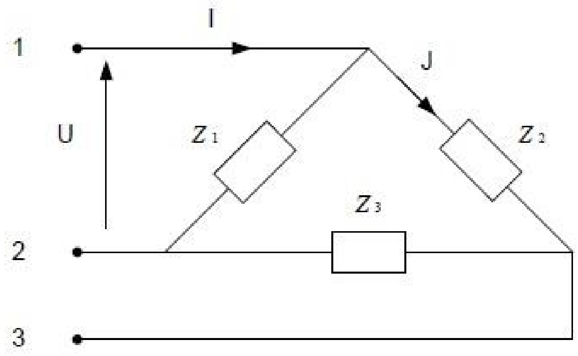
$$Q_t = \sqrt{3} UI \sin \phi$$

Total apparent power consumption

$$S_t = \sqrt{P_t^2 + Q_t^2} = UI\sqrt{3}$$

2. Balanced triangle coupling

❖ There is no neutral in a delta connection



Each impedance will be subjected to the phase-to-phase voltage U and will have the current through it.

$J = \frac{I}{\sqrt{3}}$ (I: line current, comes from the source; *J*: phase current, flows through the receiver)

If the system is balanced, the 3 impedances ($Z_1 = Z_2 = Z_3 = Z$) are totally identical.

Energy balance

Total active power consumption :

$$P_t = P_1 + P_2 + P_3$$

$$\begin{cases} P_1 = U_1 J_1 \cos \phi(1) \\ P_2 = U_2 J_2 \cos \phi(2) \\ P_3 = U_3 J_3 \cos \phi(3) \end{cases} = UJ \cos \phi$$

$$J = \frac{I}{\sqrt{3}} \rightarrow P_t = \sqrt{3}UI \cos \phi$$

Total reactive power consumption

$$\begin{cases} Q_1 = U_1 J_1 \sin \phi(1) \\ Q_2 = U_2 J_2 \sin \phi(2) \\ Q_3 = U_3 J_3 \sin \phi(3) \end{cases} = UJ \sin \phi$$

$$Q_t = \sqrt{3}UI \sin \phi$$

Reactive power is more abstract than active power, but the fact that it can be compensated for can offer a way of saving energy and therefore lowering electricity bills.