ELEC0080-1 - Energy Networks
Partim1: Electrical Energy Systems

Lecture 2: Introduction to electrical energy and electrical circuits

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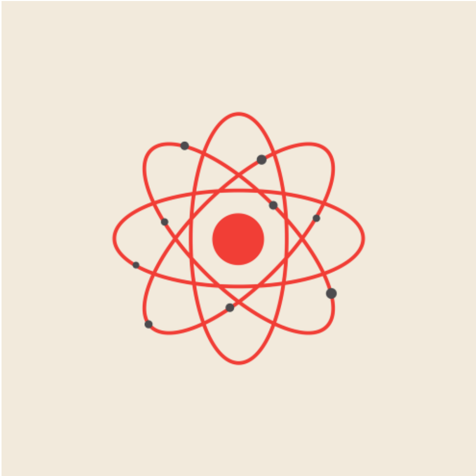
Lecture plan

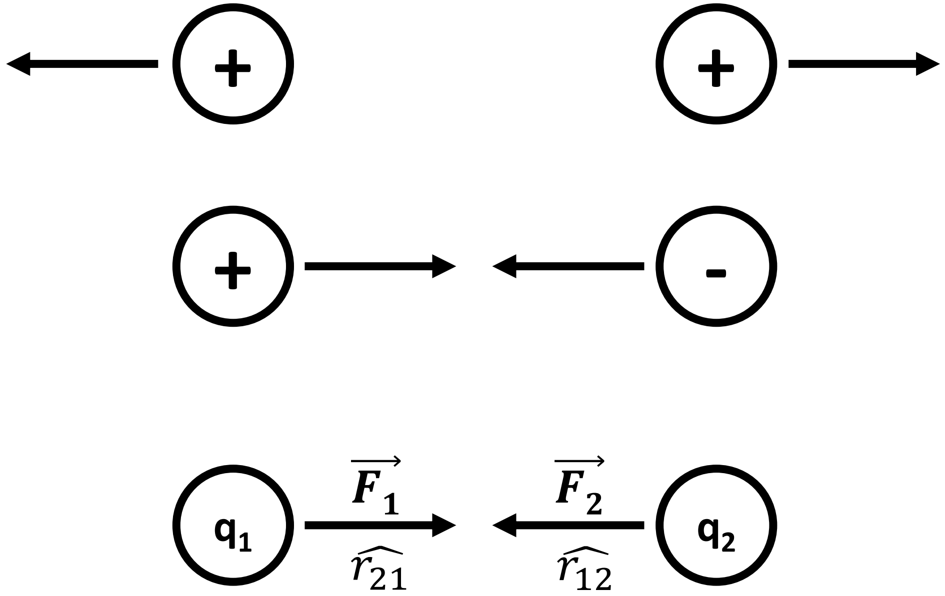
- What is electricity, especially electrical energy?
- Important units related to electrical energy
- Electric circuits main physics laws
- Direct Current (DC) VS Alternating Current (AC)
- Three phases AC circuits

What is electricity?

What is electricity?

Electricity is a physical phenomenon associated with the presence or motion of electrical charges, such as electrons or protons.





Same sign => Repulsion

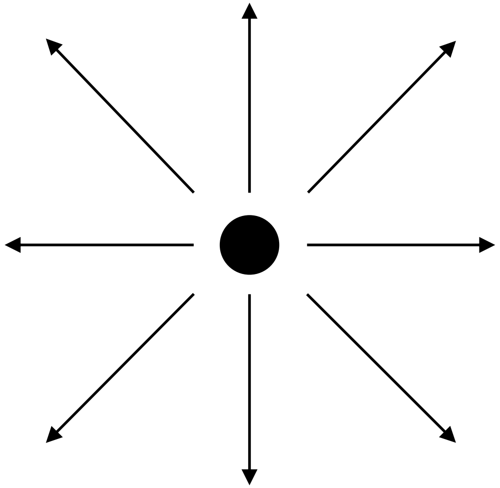
Opposite sign => Attraction

General case => Coulomb's law: $\overrightarrow{F_1} = -\overrightarrow{F_2} = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r_{12}^2} \widehat{r_{12}}$

with the permittivity of free space $\epsilon_0 = 8.854\ 10^{-12}\ C^2\ N^{-1}\ m^{-2}$

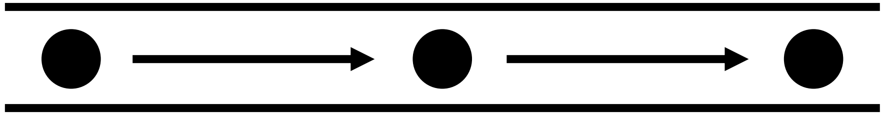
Electrical energy origin

Potential energy



Electric field

Kinetic energy



Electric current

Important units for electrical energy (1)

Joule (J): *Derived unit of energy in the International System of Units.*

Order of magnitude:

1 J = Heat to raise the temperature of 1g of water by 0.24°C.

1 J = Kinetic energy of tennis ball moving at 22 km/h.

1 J = Typical energy released as heat by a person at rest every 1/60 s.

⚠ 1 J is a very small amount of energy.

Important units for electrical energy (2)

Watt (W): *Derived unit of power in the International System of Units, quantifying the rate of energy transfer. 1 Watt corresponds to the transfer or 1 Joule of energy per second (1 W = 1 J/s).*

Order of magnitude:

5 W = Power of a typical LED.

500 W = Power consumption of an average desktop.

7.5 MW = Power generation of the Enercon E-126 (large wind turbine).

Important units for electrical energy (3)

Watt-hour (Wh): *Alternative unit of energy widely used in the field of electrical energy production/consumption. 1 Watt-hour corresponds to the total amount of energy produced during an hour by a constant power source of 1 W.*

<u>Order of magnitude:</u>

1 Wh = 3600 J.

10 kWh = Energy daily consumption of an average Belgian.

50 MWh = Energy daily consumption of a supercomputer

Important units for electrical energy (4)

Calorie (C): Alternative unit of energy widely used in the food industry, corresponding to 1000 calories (with a small "c"). A calorie is the amount of energy required to warm 1g of air-free water from 14.5 to 15.5 C at standard atmospheric pressure (4.184 J).

British thermal unit (Btu): Alternative unit of energy used in the gas business, with 1 Btu corresponding to 2.97×10^{-7} MWh.

Tonne of oil equivalent (toe): Alternative unit of energy, which is defined as the amount of energy released by burning one tonne of crude oil (1 toe = 11.63 MWh).

Barrel of oil equivalent (BOE): Alternative unit of energy, which is defined as the amount of energy released by burning one barrel of crude oil (1 BOE = 1.6282 MWh).

Exercises

Exercise 1: The world energy consumption was equal to 155,055 TWh in 2012. How many 1000 MW nuclear power plants would be required to generate over one year this amount of energy?

Exercise 2: There are 7 billion humans on Earth. Knowing that a human needs 2500 Calories of food per day in average, compare the total amount of energy consumed every day by human with the daily amount of oil energy consumed on the planet. The world consumes 90 million barrels of oil per day.

Exercises

Exercise 3: Compare the money spent on gas and coal to produce one MWh of electricity. The efficiency of a Combined Cycle Gas Turbine (CCGT) power plant is 60%. The one of a last generation coal-fired power plant is 43%. The price of gas is currently 3 $/MMBtu (1 MMBtu is equal to 10^6 Btu). There are 8.14 MWh of energy in one ton of coal, which costs 40$.

Exercises

Answer exercise 1:

Yearly energy produced by a single 1000 MW power plant:

=> $1000 \times 10^6 \times 24 \times 365 = 8.76$ TWh.

Number of nuclear power plants required:

=> $\frac{155055}{8.76} = 17700$.

Exercises

Answer exercise 2:

Daily energy consumed by humans through food:

=> $\frac{7 \times 10^9 \times 2500 \times 4184}{3600}$ = 20.34 TWh.

Daily energy consumed by humans through oil:

=> $90 \times 10^6 \times 1.6282 \times 10^6$ = 146.5 TWh.

Humans consume 7.21 times more energy through oil than food.

Exercises

<u>Answer exercise 3:</u>

Money spent on gas:

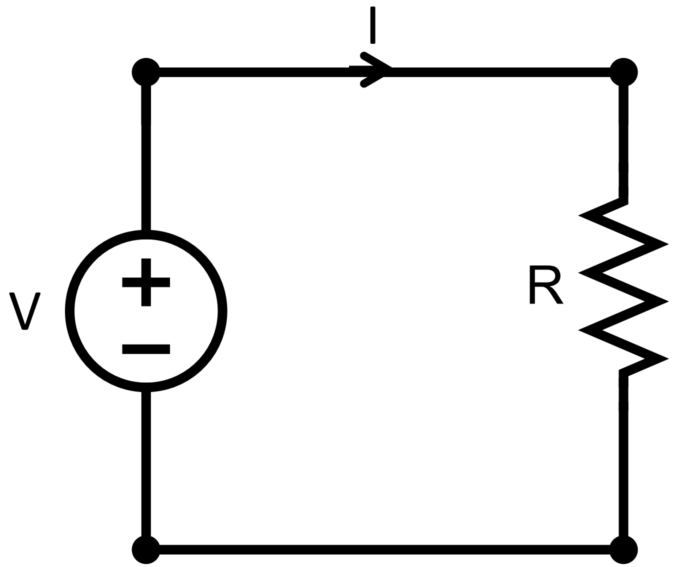
=> $\frac{3}{2.97 \times 10^{-7} \times 10^{6} \times 0.6}$ = 16.84 \$/MWh.

Money spent on coal:

=> $\frac{40}{8.14 \times 0.43}$ = 11.43 \$/MWh.

Producing electricity from coal is really cheaper than gas.

Introduction to electric circuits (1)



Voltage V: Expressed in Volt (V), it corresponds to a potential difference between two circuit nodes.

Current I: Expressed in Ampere (A), it corresponds to a motion of electrical charges.

Resistance R: Expressed in Ohm (Ω), it corresponds to an opposition to the flow of electric current.

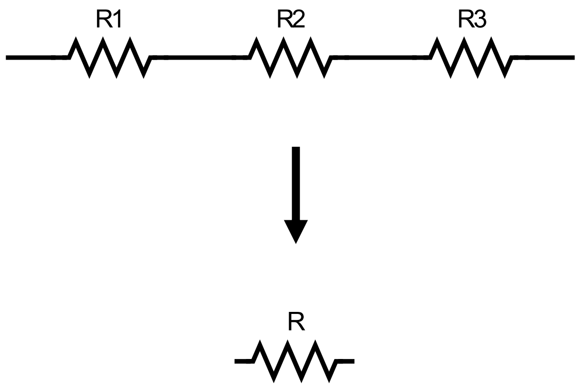
Conductance G: Expressed in Siemens (S), it is the exact opposite of the resistance (G = 1/R).

Ohm's law: $$V = R\,I$$

Electric power: $$P = V\,I = R\,I^2$$

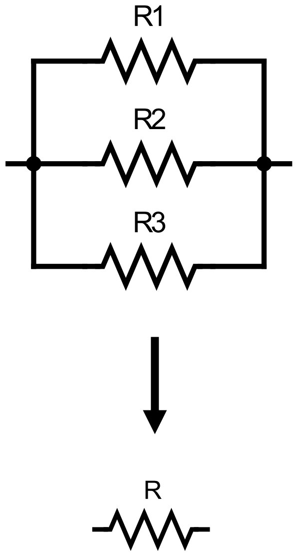
Introduction to electric circuits (2)

Resistances in series



$$R = \sum_i R_i = R_1 + R_2 + R_3$$

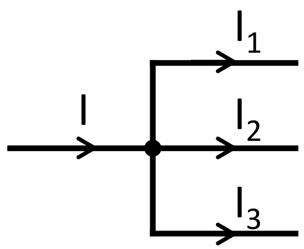
Resistances in parallel



$$\frac{1}{R} = \sum_i \frac{1}{R_i} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Introduction to electric circuits (3)

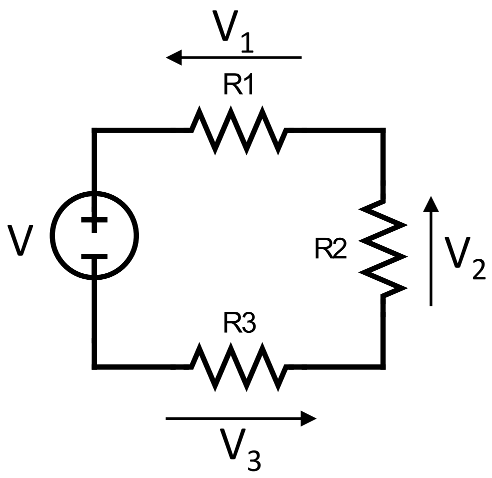
Kirchhoff's current law



$$I = \sum_i I_i = I_1 + I_2 + I_3$$

Conservation of charge

Kirchhoff's voltage law



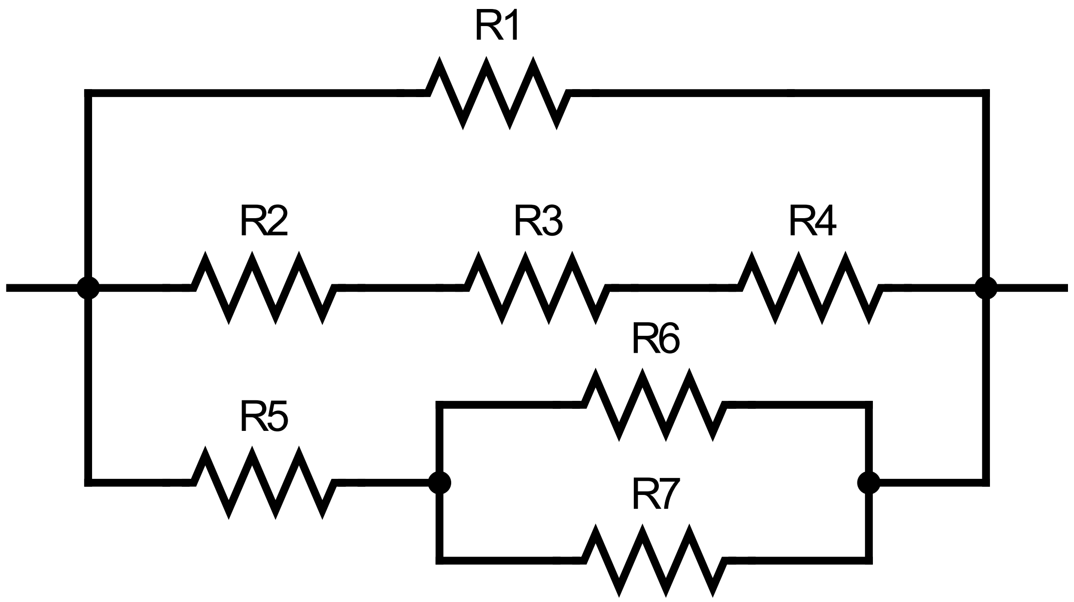
$$0 = \sum_i V_i = V - V_1 - V_2 - V_3$$

Conservation of energy

Exercises

Exercise 1: Compute the equivalent resistance of this sub-circuit:

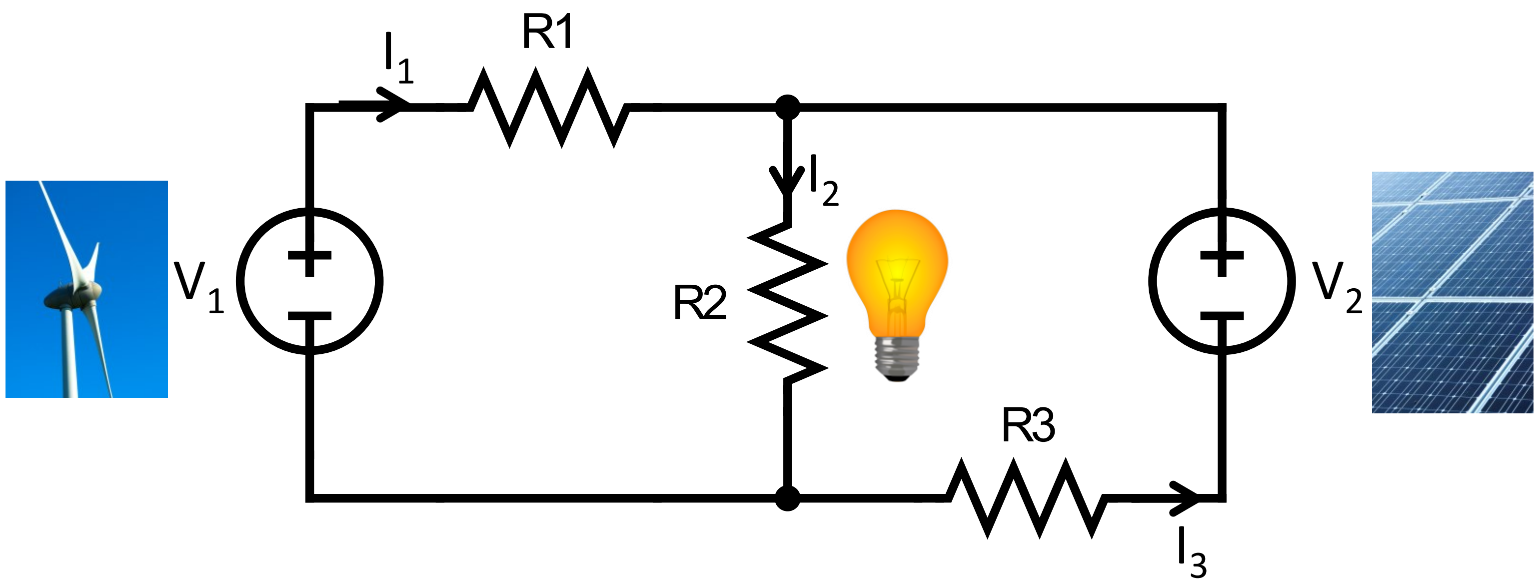
R_1 = 10 kΩ
R_2 = 1 kΩ
R_3 = 500 Ω
R_4 = 5 kΩ
R_5 = 10 kΩ
R_6 = 500 Ω
R_7 = 5 kΩ



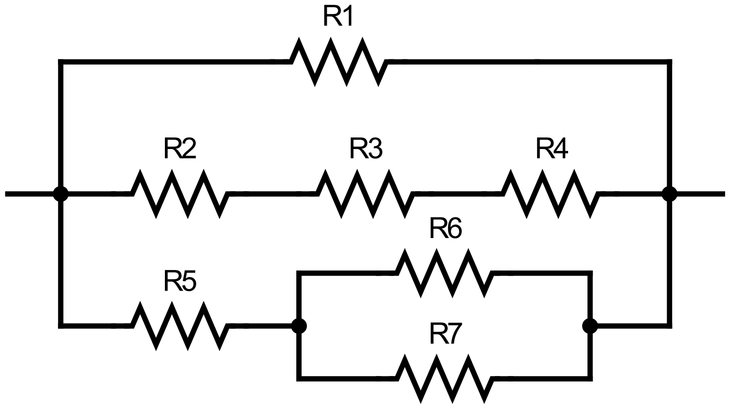
Exercises

<u>Exercise 2:</u> Compute the power dissipated in resistor R_2 in the following electric circuit, knowing the voltage power sources and the resistances. In fact, this electric circuit can be seen as the modelling of the delivery of power generated by two generators (V_1 and V_2) to a load (R_2), taking into account the losses in the network (R_1 and R_3).

$V_1 = 500$ V
$V_2 = 300$ V
$R_1 = 200\ \Omega$
$R_2 = 1\ \mathrm{k}\Omega$
$R_3 = 100\ \Omega$



Exercises



R_1 = 10 kΩ
R_2 = 1 kΩ
R_3 = 500 Ω
R_4 = 5 kΩ
R_5 = 10 kΩ
R_6 = 500 Ω
R_7 = 5 kΩ

Answer 1:

Upper branch: R_{upper} = R_1 = 10 kΩ

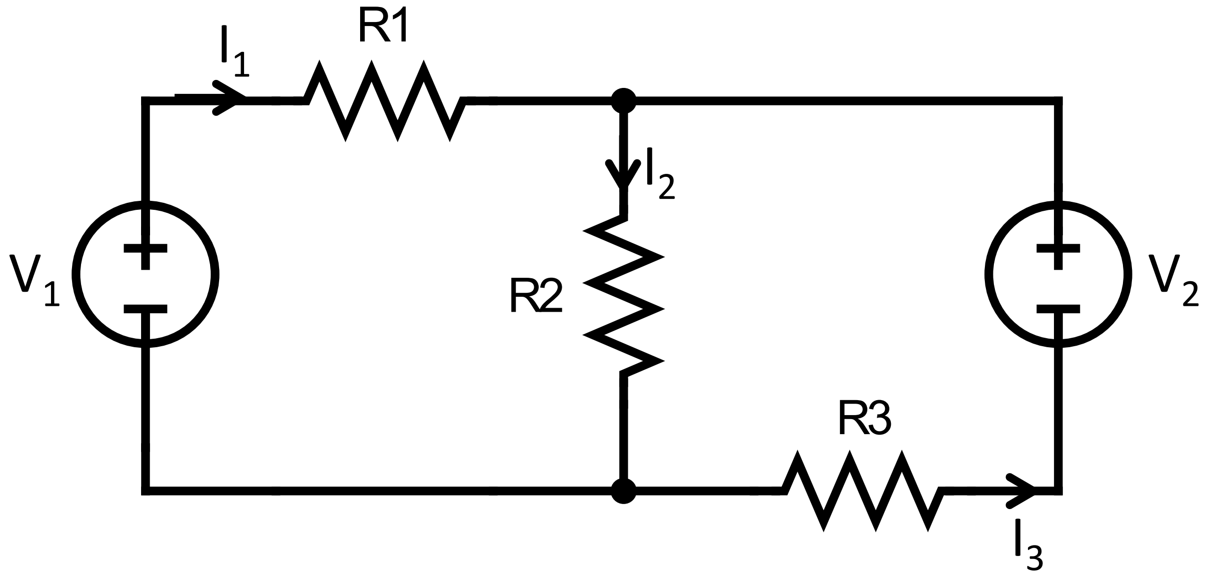
Middle branch: R_{mid} = $R_2 + R_3 + R_4$ = 6.5 kΩ

Bottom branch: $R_{bottom} = R_5 + \frac{R_6 R_7}{R_6 + R_7}$ = 5.4 kΩ

Resitance equivalente: $R = \frac{R_{upper}\, R_{mid}\, R_{bottom}}{R_{mid}\, R_{bottom} + R_{upper}\, R_{bottom} + R_{upper}\, R_{mid}}$

= 2.27 kΩ

Exercises



Answer 2:

Application of Kirchhoff's laws:

(1) $I_2 = I_1 + I_3$

(2) $V_1 - R_1 I_1 - R_2 I_2 = 0$

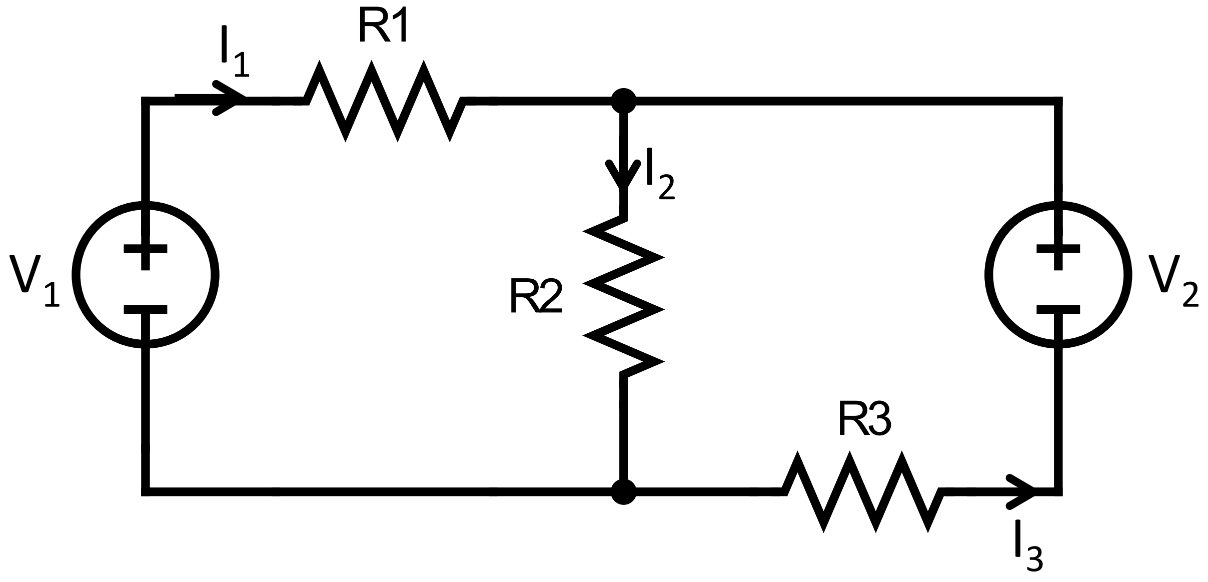
(3) $V_2 - R_3 I_3 - R_2 I_2 = 0$

(4) $V_1 - R_1 I_1 - V_2 + R_3 I_3 = 0$

(1) → (2) $V_1 - R_1 I_1 - R_2 I_1 - R_2 I_3 = 0$

(4) → (2) $V_1 - R_1 I_1 - R_2 I_1 + R_2 (\frac{V_1 - R_1 I_1 - V_2}{R_3}) = 0$

Exercises



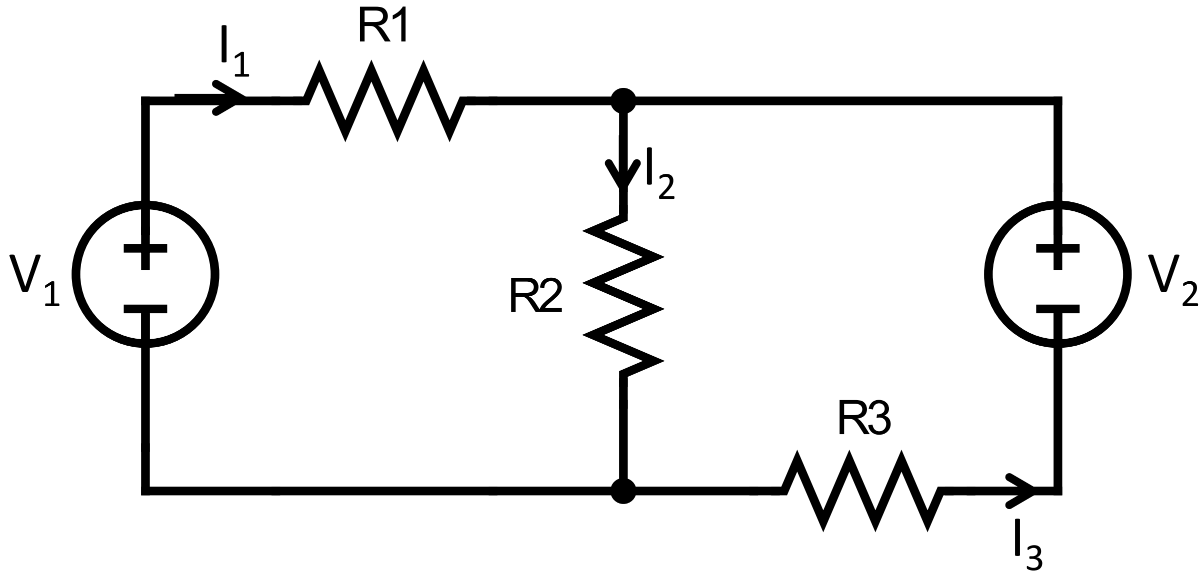
Answer 2:

Determination of current I_1:

$$V_1 - R_1 I_1 - R_2 I_1 + R_2 \left(\frac{V_1 - R_1 I_1 - V_2}{R_3}\right) = 0$$

$$\Leftrightarrow I_1 = \frac{V_1 + (V_1 - V_2)\frac{R_2}{R_3}}{R_1 + R_2 + \frac{R_1 R_2}{R_3}} = 0.78125 \text{ A}$$

Exercises



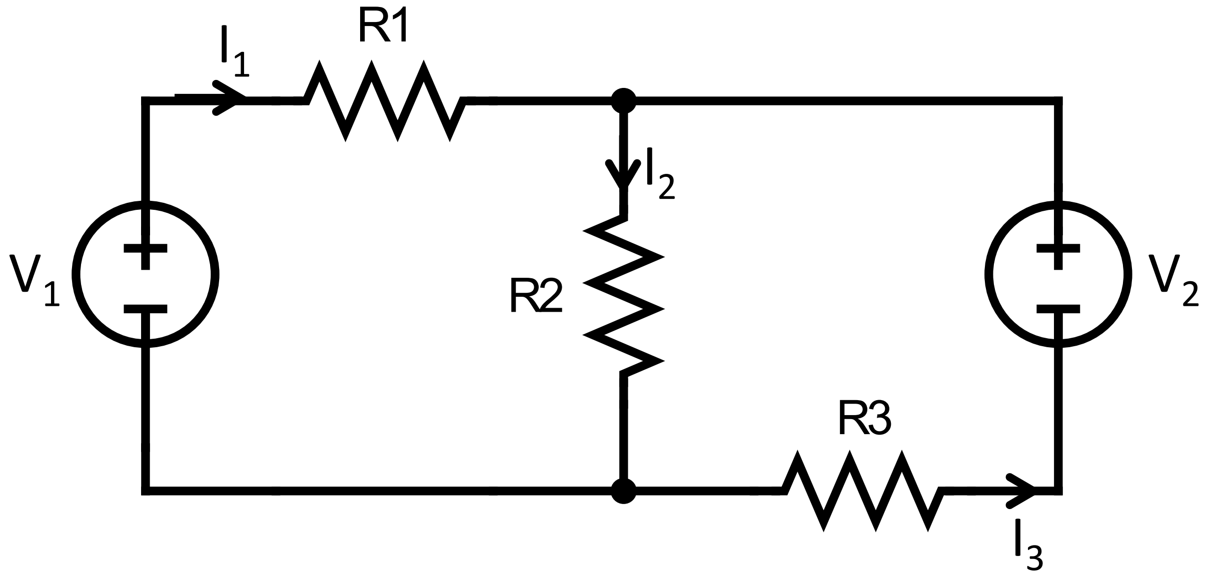
Answer 2:

Determination of current I_3:

$$(4) \quad V_1 - R_1 I_1 - V_2 + R_3 I_3 = 0$$

$$\Leftrightarrow I_3 = \frac{V_2 + R_1 I_1 - V_1}{R_3} = \text{-0.4375 A}$$

Exercises



Answer 2:

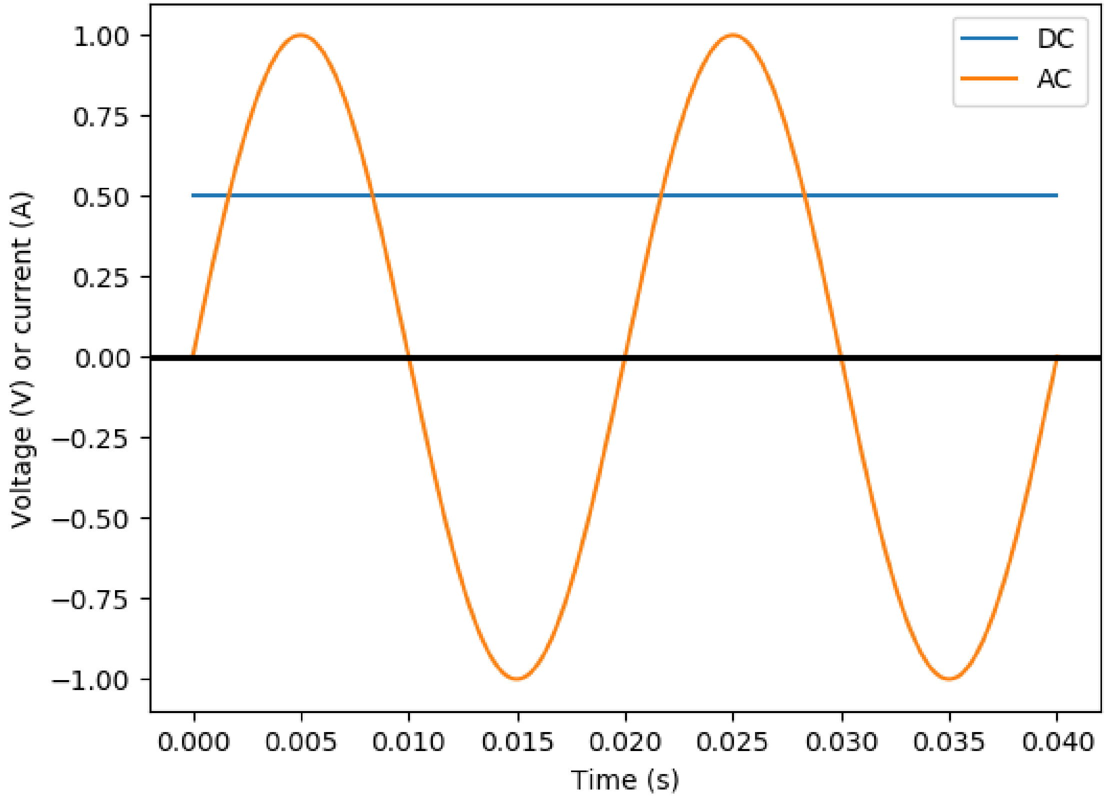
Determination of current I_2:

$$(1) \quad I_2 = I_1 + I_3 = 0.34375 \text{ A}$$

Determination of the power dissipated in resistor R_2 :

$$P = R_2 I_2^2 = 118.16 \text{ W}$$

Direct Current (DC) VS Alternating Current (AC)



Direct Current (DC): Electric current which flows in one unique direction. Such currents are typically produced by batteries in many devices, or in HVDC power lines.

Alternating Current (AC): Electric current which periodically reverses direction, many waveforms being possible (sine, triangular, square waves, etc.). Such currents are typically encountered in the electrical grid as sinusoidal waves of 50 Hz or 60 Hz depending on the country (a few exceptions exist).

AC circuits – Motivations for power grid

The use of Direct Current (DC) to transmit significant power was not efficient originally. Let’s remind that the power is expressed as the following:

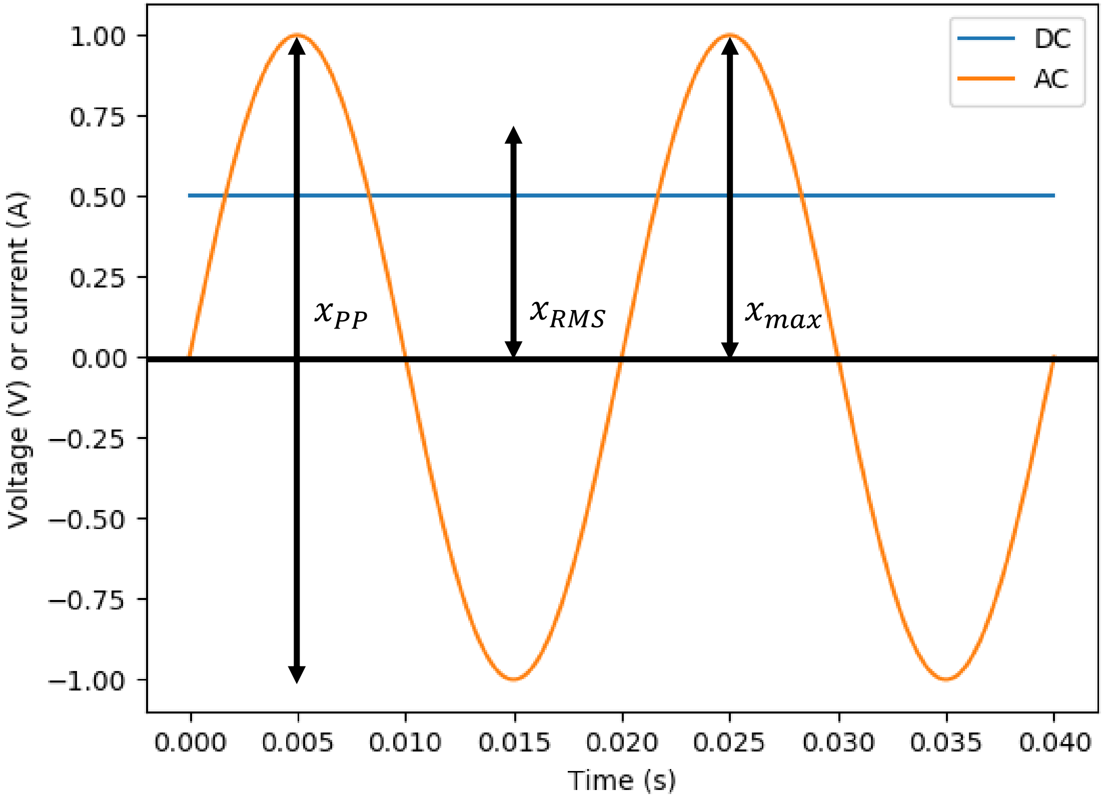
$$P = V\ I$$

Because it was difficult to increase the voltage at that time, the current was increased instead. However, the power lost explodes with such practice:

$$P_L = R\ I^2$$

Presenting better properties, the Alternating Current (AC) was adopted together with the transformer which enable to step up or down the voltage.

AC circuits – Root Mean Squared values

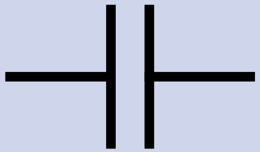


When discussing about alternating current (AC), RMS values are generally employed. They represent an indication of the amount of AC power that produces the same heating effect as an equivalent DC power.

$$x_{RMS} = \lim_{T\to\infty} \sqrt{\frac{1}{2T}\int_{-T}^{T} x^2(t)dt}$$

For sinusoidal waveforms: $x_{max} = \sqrt{2}\, x_{RMS}$

AC circuits – New electrical components

Electrical Component	Resistor	Inductor	Capacitor
Schematic			
Formula	$V = R\ I$	$v = L\ \frac{di}{dt}$	$i = C\ \frac{dv}{dt}$
Impedance	$Z = R$	$Z = j\omega L = j2\pi f L$	$Z = \frac{1}{j\omega C} = \frac{1}{j2\pi f C}$
DC behavior	Resistor	Wire	Open circuit

AC circuits – Power

In AC circuits, due to the presence of both resistive (resistors) and reactive components (inductors and capacitors), the power is decomposed into both the active or real power and the reactive power. The so-called complex power is expressed as the following:

$$S = P + jQ$$

with:

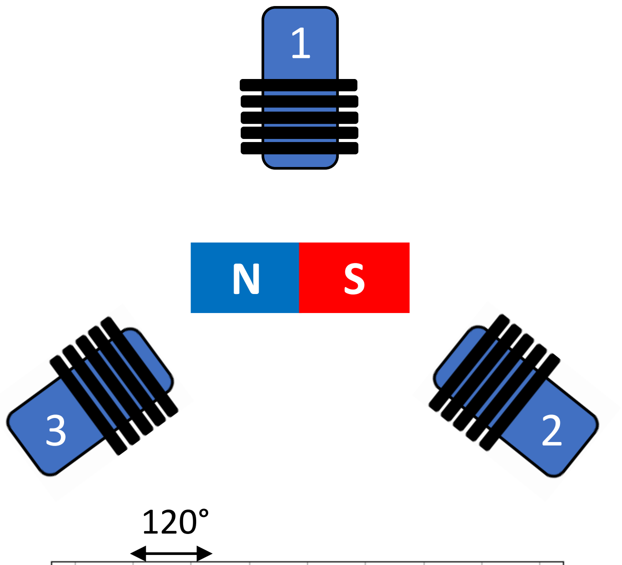
- S being the complex power (VA).
- P being the active or real power (W).
- Q being the reactive power (var).

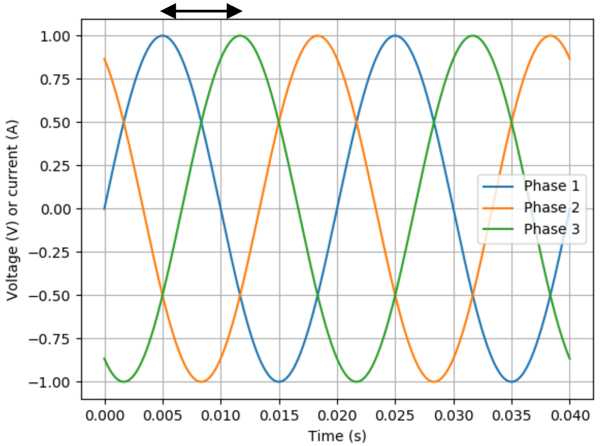
Three phases AC circuits – Introduction

Question: Have you ever wondered why are there generally 6 main cables (2 x 3 in fact) on high voltage power lines ?

In most European countries including Belgium, the transport and distribution of electricity is performed using three phases AC circuits.

Three phases AC circuits – Origin

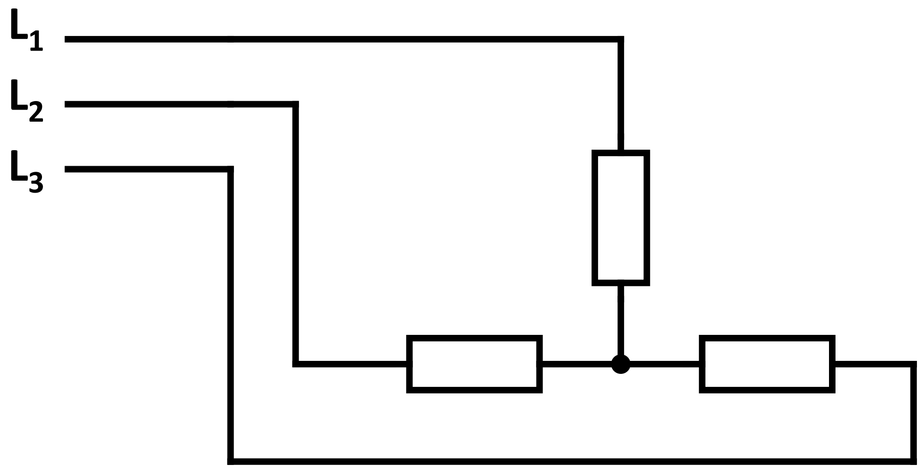




1. The magnetized rotor is continuously rotating due to an external force.
2. This rotational movement causes a rotating magnetic field.
3. According to Maxwell laws about electromagnetism, an electromotive force is induced into the solenoid wires.

Generation of three alternating currents (AC) of same amplitude and frequency, but with a phase difference of 120° between each.

Three phases AC circuits – Advantages



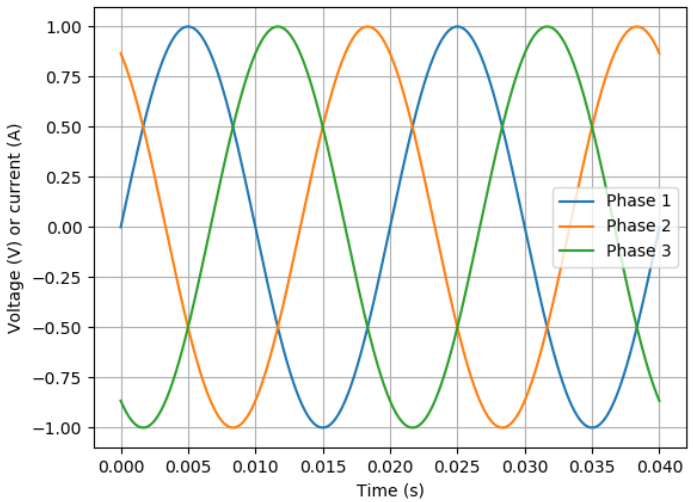
Single-phase AC:

- 1 cable for the phase.
- 1 cable for the neutral.

Three-phases AC:

- 3 cables for the phases.
- 0 or 1 cable for the neutral (not always required if balanced because easily obtained by summing the three phases).

=> 3 times as much power using 1.5 or 2 times as many wires.



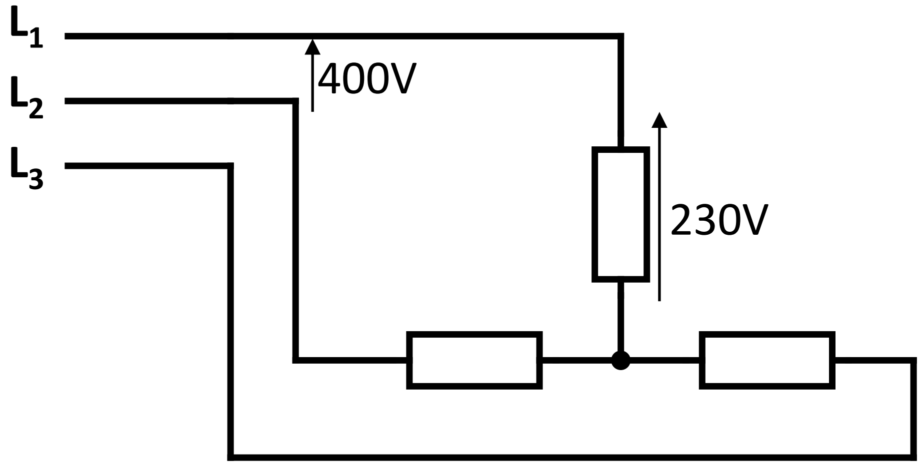
Three phases AC circuits – Mathematically

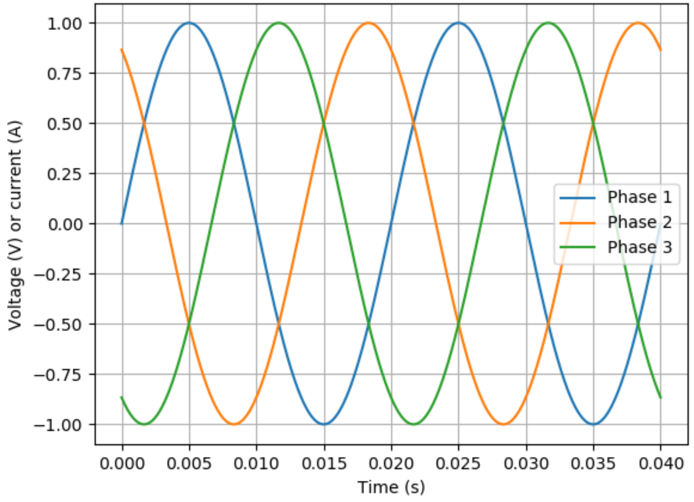
Mathematically:

$$v_1 = V_{max}\,\text{sin}(\omega t + \ \varphi) = \sqrt{2}\,V_{RMS}\,\text{sin}(\omega t + \ \varphi)$$

$$v_2 = V_{max}\,\text{sin}(\omega t + \ \varphi - \tfrac{2}{3}\pi) = \sqrt{2}\,V_{RMS}\,\text{sin}(\omega t + \ \varphi - \tfrac{2}{3}\pi)$$

$$v_3 = V_{max}\,\text{sin}(\omega t + \ \varphi \ - \tfrac{4}{3}\pi) = \sqrt{2}\,V_{RMS}\,\text{sin}(\omega t + \ \varphi \ - \tfrac{4}{3}\pi)$$



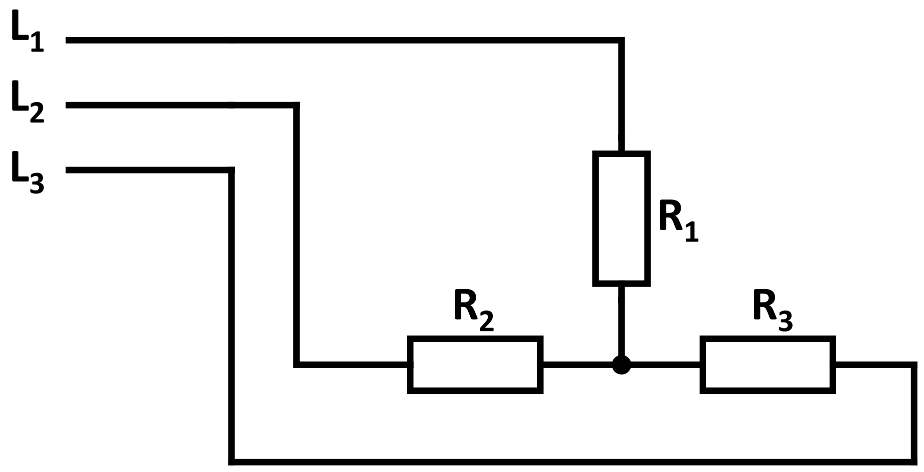


Important values:

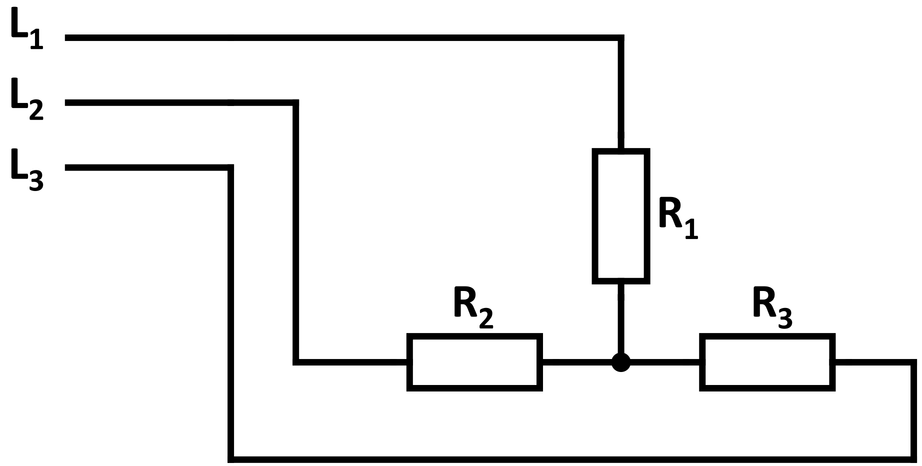
- RMS voltage between the phase and the neutral point: $V_{RMS}^{PN} = 230V$.
- RMS voltage between two phases: $V_{RMS}^{PP} = \sqrt{3}\,V_{RMS}^{PN} = \ 400V$.

Exercises

Exercise 1: Let's consider the following three phases AC circuit which represents the distribution of electricity to some consumers. Making the assumption that the loads are all purely resistive and equal to 100Ω, draw the voltage signals in each power line and compute the total power delivered by this distribution network.



Exercises

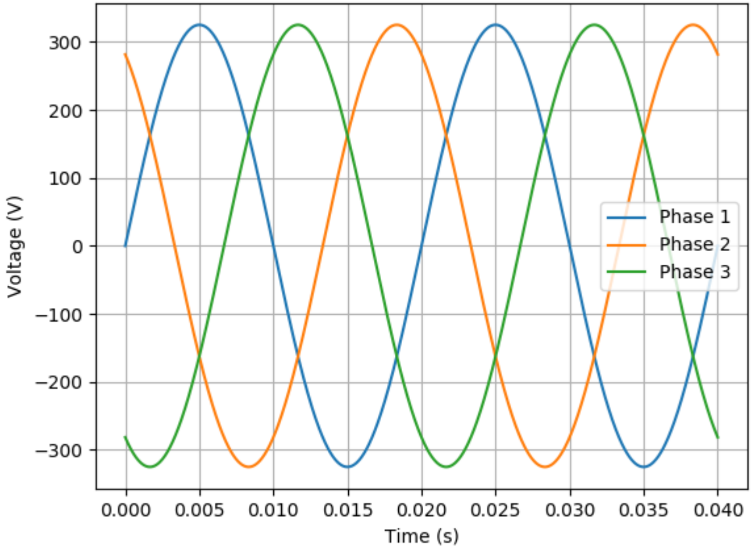


Answer 1:

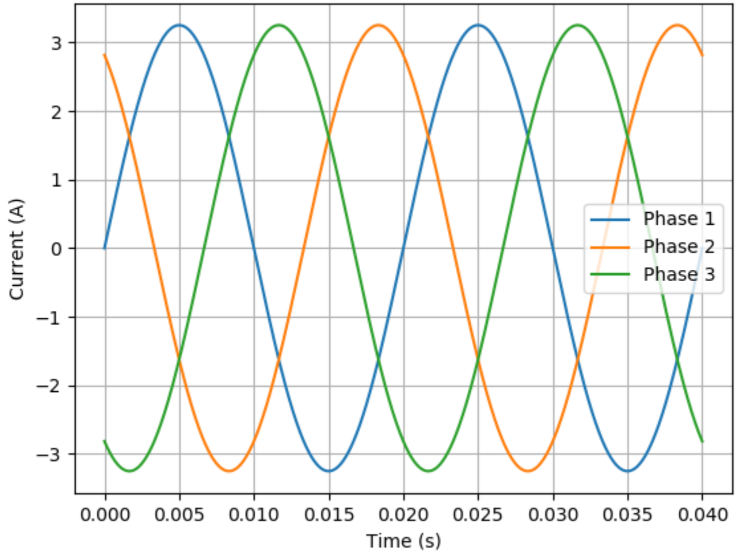
1. Signals drawing:

- $V_{RMS} = 230V$
- $V_{max} = \sqrt{2}\, V_{RMS} = 325V$
- $V_{PP} = 2\, V_{max} = 650V$
- $I_{RMS} = \frac{V_{RMS}}{R} = 2.3A$
- $I_{max} = \sqrt{2}\, I_{RMS} = 3.25A$
- $I_{PP} = 2\, I_{max} = 6.5A$

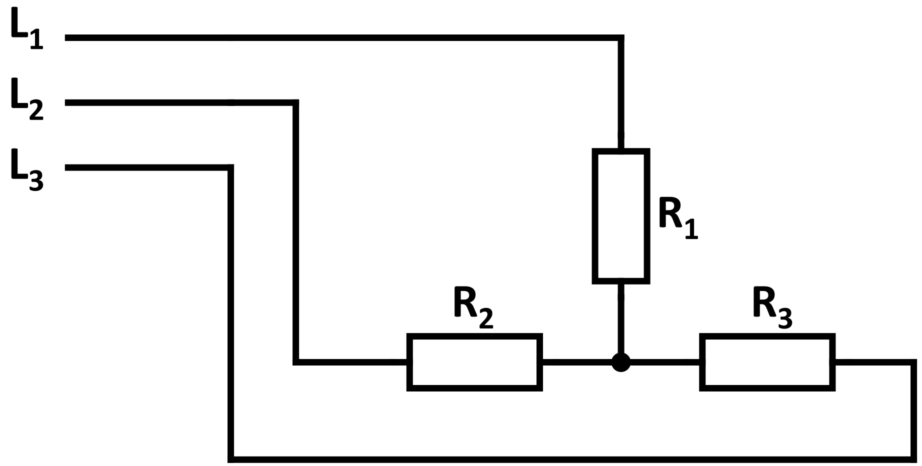
Voltage $v(t)$



Current $i(t)$



Exercises



Answer 1:

2. Power computation:

$$P_{1L} = V_{RMS}\, I_{RMS} = 529W$$

$$P_T = 3\, P_{1L} = 1587W$$

Documentation work – Hybrid AC/DC grid

Source: Wang, P., Goel, L., Liu, X., & Choo, F.H. (2013). Harmonizing AC and DC: A Hybrid AC/DC Future Grid Solution. *IEEE Power and Energy Magazine, 11*, 76-83.

Questions:

1. What is “the war of currents”? Explain both the context and the resolution.
2. What is behind the acronym “HVDC”? What are the motivations for preferring this technology rather than the present transmission AC network?
3. Explain the recent significant changes in distribution networks making electrical engineers reconsidering DC as a viable alternative to the present AC distribution network.
4. Which solution is proposed by the author? Explain the first grid structure proposed.

Note: Skip the section named *Hybrid DC/AC Grid Structure II* together with Figure 4 .

Any questions?