ELEC0080-1 - Energy Networks
Partim1: Electrical Energy Systems

Lecture 3: Electrical grid core components

Professor: Damien Ernst

Speaker: Maurizio Vassallo

Lecture plan

- The electrical grid and its role
- Cables, transmission and distribution lines
- Transformers and converters
- Consumption of electricity
- Production of electricity
- Electrical grid stability

Electrical grid – Introduction

An *electrical grid*, also called *power grid*, is an interconnected network built for the safe transmission of electricity from producers to consumers.

Core components:

- Transmission and distribution lines.
- Transformers and converters.
- Electricity producers.
- Electricity consumers.

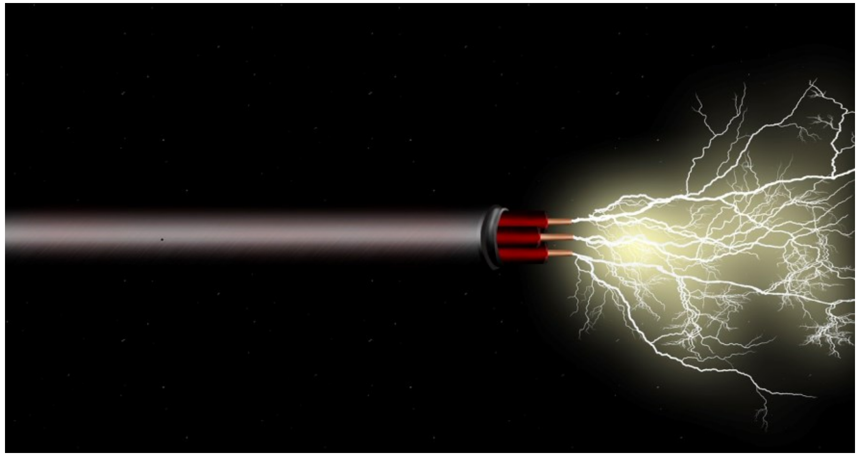
The proper management and control of the electrical grid to assure its stability is a significant challenge.

Power lines – Power cables

A *power cable* is an electrical cable which is composed of an assembly of electrical conductors, generally made of copper, held together within an insulator sheath.

Electrical conductivity:

- Copper: 5.96×10^7 S/m.
- Iron: 10^7 S/m.
- Sea water: 4.8 S/m.



Power lines – Transmission

Transmission power lines are concerned with the transport of electricity at high voltage on large distances (overhead, underground or submarine power lines).

Typical orders of magnitude (Belgium):

- Distance: > a few kilometers.
- Voltage: > a few dozen kV (400kV, 225kV, 150kV, 70kV).
- Current: AC three phases.

Transmission System Operator (TSO) in Belgium: Elia.

Power lines – Distribution

Distribution power lines are concerned with the transport of electricity at lower voltage on shorter distances (overhead and underground lines).

Typical orders of magnitude (Belgium):

- Distance: < a few kilometers.
- Voltage: < a few dozen kV (400V - 36kV).
- Current: AC three phases or AC single phase.

Management in Belgium: ORES, RESA, Sibelga, etc.

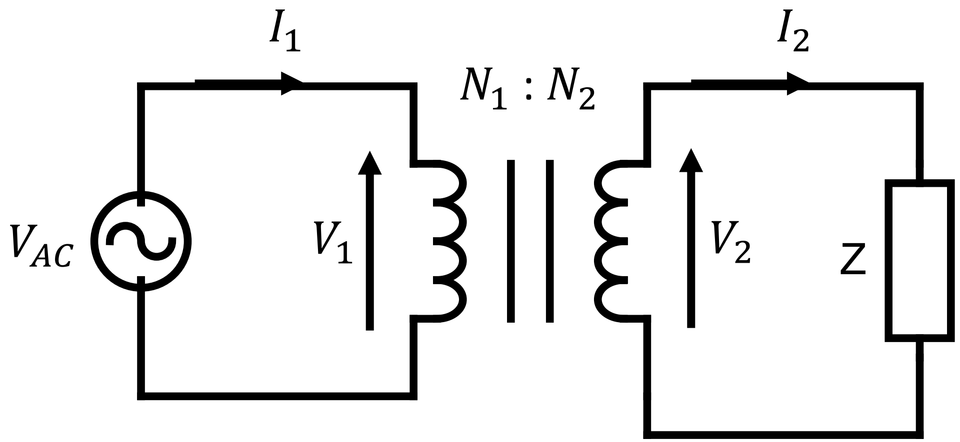
Transformers and converters

A *transformer* is a passive electrical device for transferring electrical energy between different circuits. In the power grid, its role is to step voltage up for transmission or down for distribution.

Types of conversions:

- Transformer: **AC** ⟶ **AC.**
- Inverter: **DC** ⟶ **AC.**
- Rectifier: **AC** ⟶ **DC.**
- Converter: **DC** ⟶ **DC.**

Transformers in circuits

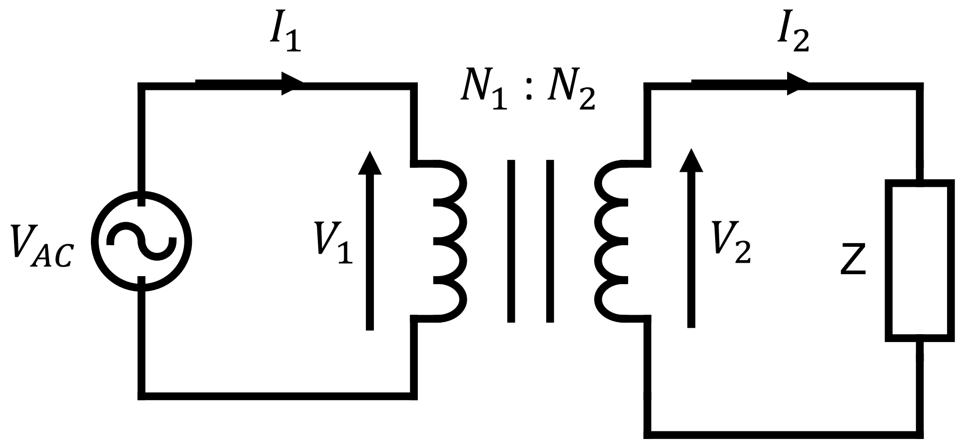


The transformer behavior (voltage stepping up/down) is characterized by the transformation ratio, which is dependent on the number of loops on each side (N_1 and N_2). The electrical transformer key formula is expressed as the following:

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1}$$

Exercises

Exercise 1: Let's consider the following transformer which is a bridge between the electrical transmission and distribution networks. If the transmission voltage V_1 is equal to 400kV and the distribution voltage V_2 is equal to 4kV, design an appropriate transformer (N_1 and N_2). Additionally, compute both currents (I_1 and I_2) if the impedance Z is purely resistive and equal to 10kΩ.



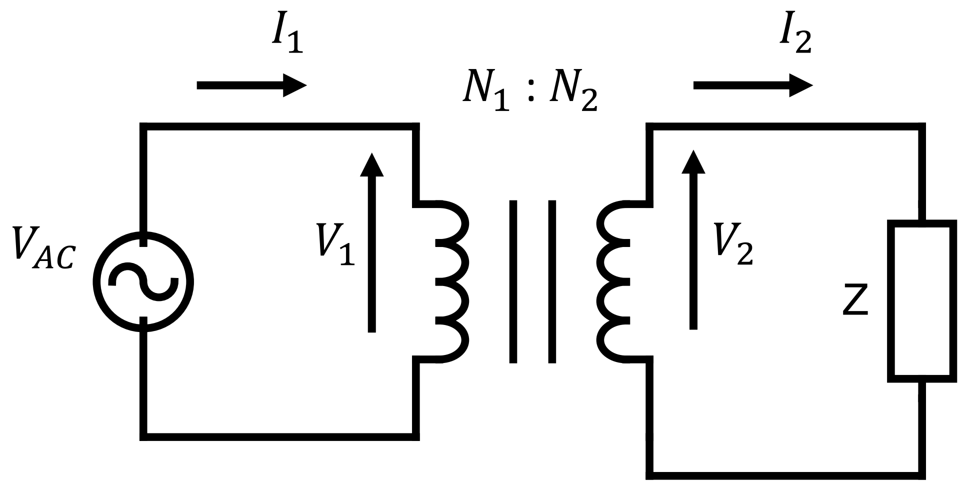
Exercises

<u>Answer 1:</u>

1. Transformer design:

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{4}{400} = 0.01$$

$\Longrightarrow N_2 = 5$ and $N_1 = 500$ (for instance)



Exercises

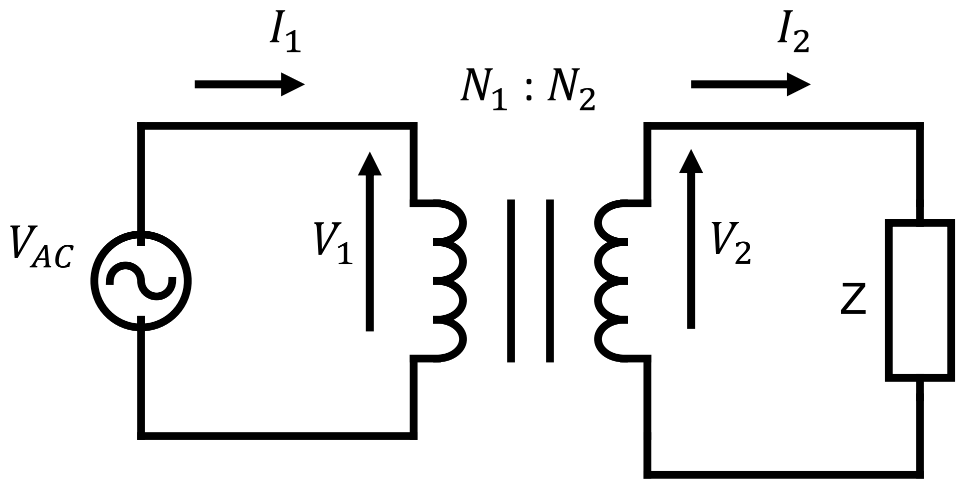
Answer 1:

2. Currents computation:

$$I_2 = \frac{V_2}{Z} = \frac{4}{10} = 0.4\text{A}$$

$$\frac{N_2}{N_1} = 0.01 = \frac{I_1}{I_2}$$

$$\Leftrightarrow I_1 = 0.01\, I_2 = 0.004\text{A}$$



Consumption of electricity

The electrical grid is connected to *loads*, which represent the consumption of electricity.

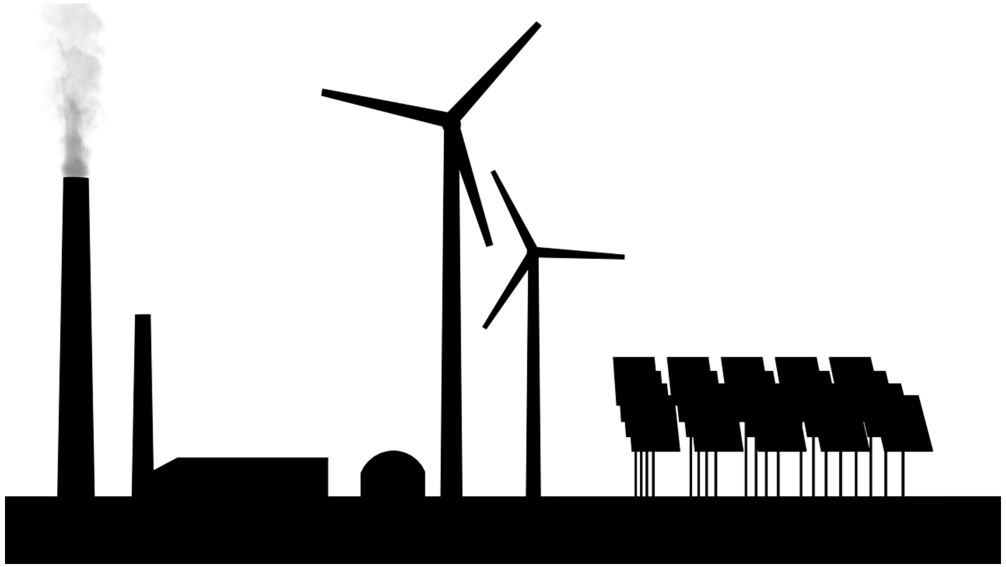
Electricity consumption:

- Transportation
- Heating/Cooling
- Lighting
- Stuff and objects
- Food
- Etc.

Production = Consumption

Production of electricity – Introduction

The electrical grid is connected to numerous *generating stations*, which represent the production of electricity.



Various electrical energy sources:

- Fossil fuel power stations (coal, gas, oil).
- Nuclear power plants.
- Renewable energy sources (hydroelectricity, Photovoltaic solar panels, wind, etc.).

Production = Consumption

Production of electricity – Capacity factor

The *capacity factor* provides information about the actual electrical energy output over a period of time (generally a year), compared to the maximum theoretical electrical energy output over that period. It is expressed as the following:

$$C_f = \frac{E(T)}{P\,.\,T}$$

with:

- $E(T)$ being the energy produced (MWh) over the period of time T.
- P being the theoretical installed power (MW).

Orders of magnitude (UK):

- Nuclear: ± 80%.
- Solar energy: ± 10%.
- Off-shore wind: ± 40%.

Production of electricity – Fossil fuel

Fossil fuel power plants produce electricity through the burning of coal, oil or gas. Thermal energy is converted into mechanical energy which is finally converted into electrical energy through the use of synchronous generators.

Key figures:

- Percentage of world power generation in 2016: ± 65%.
- Typical fossil fuel plant output power: 500 MW.
- Typical capacity factor: ± 50% (coal) and ± 40% (gas).

Production of electricity – Fossil fuel

Advantages:

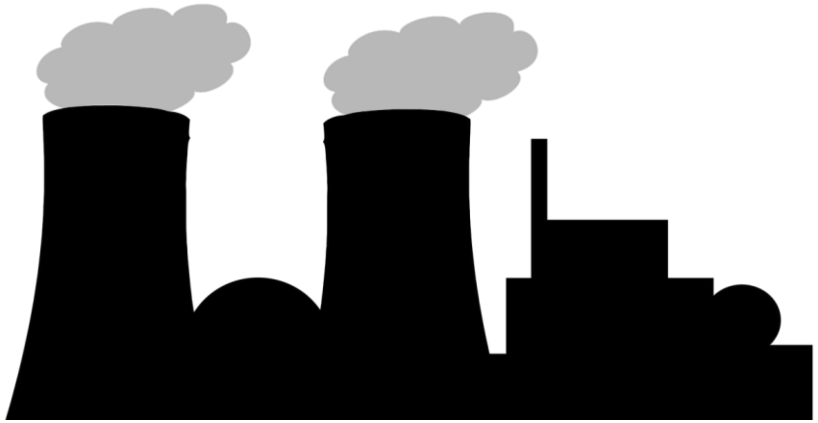
- Reliable, efficient and mature technology.
- Relatively low cost compared to alternatives.
- Predictable electrical energy output.

Disadvantages:

- Emission of several pollutants such as NO_x and SO_x.
- Emission of greenhouse gas (CO_2).
- Limited amount of fossil fuels on Earth.

Production of electricity – Nuclear

Nuclear power plants produce electricity through the nuclear fission reaction. Thermal energy is converted into mechanical energy which is finally converted into electrical energy through the use of synchronous generators.



Key figures:

- Percentage of world power generation in 2016: ± 10%.
- Typical nuclear reactor output power: 1000 MW.
- Typical capacity factor: ± 80%.

Production of electricity – Nuclear

Advantages:

- No emission of pollutants nor greenhouse gas (CO_2).
- Reliable, efficient and mature technology.
- Very low cost compared to alternatives.
- Predictable electrical energy output.

Disadvantages:

- Disastrous consequences in case of failure.
- Complex management of nuclear wastes.
- Significant initial investment required.
- Extremely low flexibility.

Production of electricity – Hydroelectricity

Hydroelectric power plants produce electricity by transforming the gravitational power of rainfall. There are multiple types of hydroelectricity: conventional (dams), pumped-storage (e.g. Coo), run-of-the-river, tides (oceans).

Key figures:

- Percentage of world power generation in 2016: ± 16%.
- Power range for hydroelectricity: 1 kW - 22.5 GW.
- Typical capacity factor: ± 40%.

Production of electricity – Hydroelectric

Advantages:

- Renewable, no dependence upon limited reserve of fuels.
- No pollution nor greenhouse gas (CO_2).
- High flexibility (fast ramped up/down).
- Very cost-effective solution.

Disadvantages:

- Ecosystem damage and loss of lands.
- Terrible consequences in case of failure.
- Significant initial investment required.

Production of electricity – Wind turbine

Wind turbines produce electricity by exploiting the natural energy of the wind. Mechanical energy is directly converted into electrical energy through the use of an asynchronous generator.

Key figures:

- Percentage of world power generation in 2016: ± 4%.
- Typical power of a single wind turbine: 3 MW.
- Typical capacity factor: ± 40% (off-shore),
  ± 30% (on-shore).

Production of electricity – Wind turbine

Advantages:

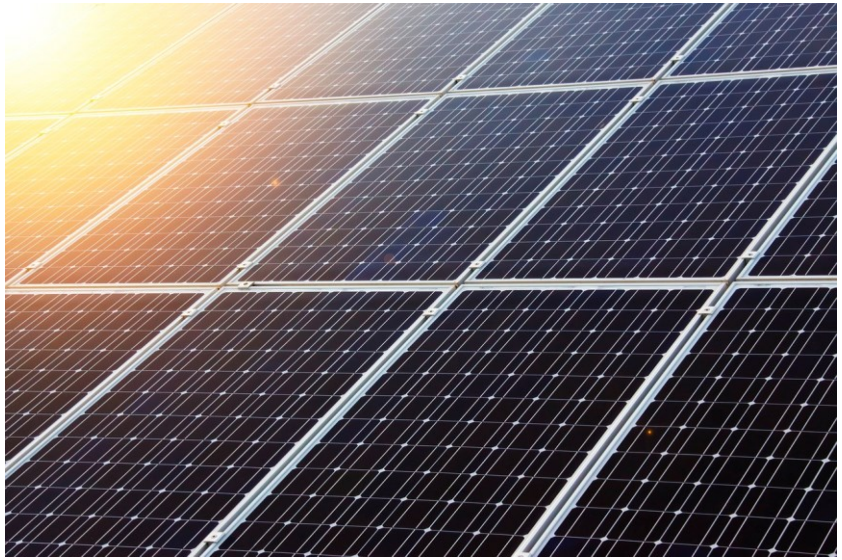
- Renewable, no dependence upon limited reserve of fuels.
- No pollution nor greenhouse gas (CO_2).
- Cost-effective, with continuously decreasing prices.

Disadvantages:

- Extremely high production volatility (intermittent).
- Difficulty to find locations (winds, remoteness, neighbors).
- Negative impact on birds.

Production of electricity – Solar PV panel

Solar Photovoltaic panels produce electricity by exploiting the natural energy of the sun. They are composed of PV cells which capture sunlight photons and generate electricity through the photovoltaic effect.



Key figures:

- Percentage of world power generation in 2016: ± 2%.
- Typical power of a 1 m^2 solar PV panel: 200W.
- Typical capacity factor: ± 10% (Belgium).

Production of electricity – Solar PV panel

Advantages:

- Renewable, no dependence upon limited reserve of fuels.
- No pollution nor greenhouse gas (CO_2).
- Cost-effective, with continuously decreasing prices.

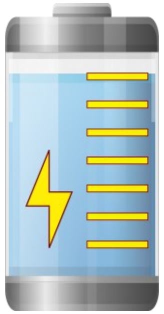
Disadvantages:

- Extremely high production volatility (intermittent).
- May cause overvoltages on distribution networks.
- Recycling of solar PV panels.

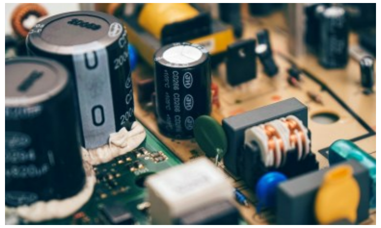
Exercises

<u>Exercise 1:</u> Complete the simplified connection scheme of a classical PV panel, briefly describing each component as well as indicating the nature of the current (DC or AC). Non-exhaustive list of components:

Solar PV panel

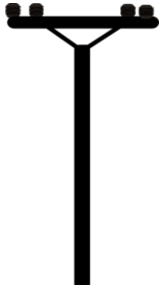


Batteries



DC/AC inverter

Home

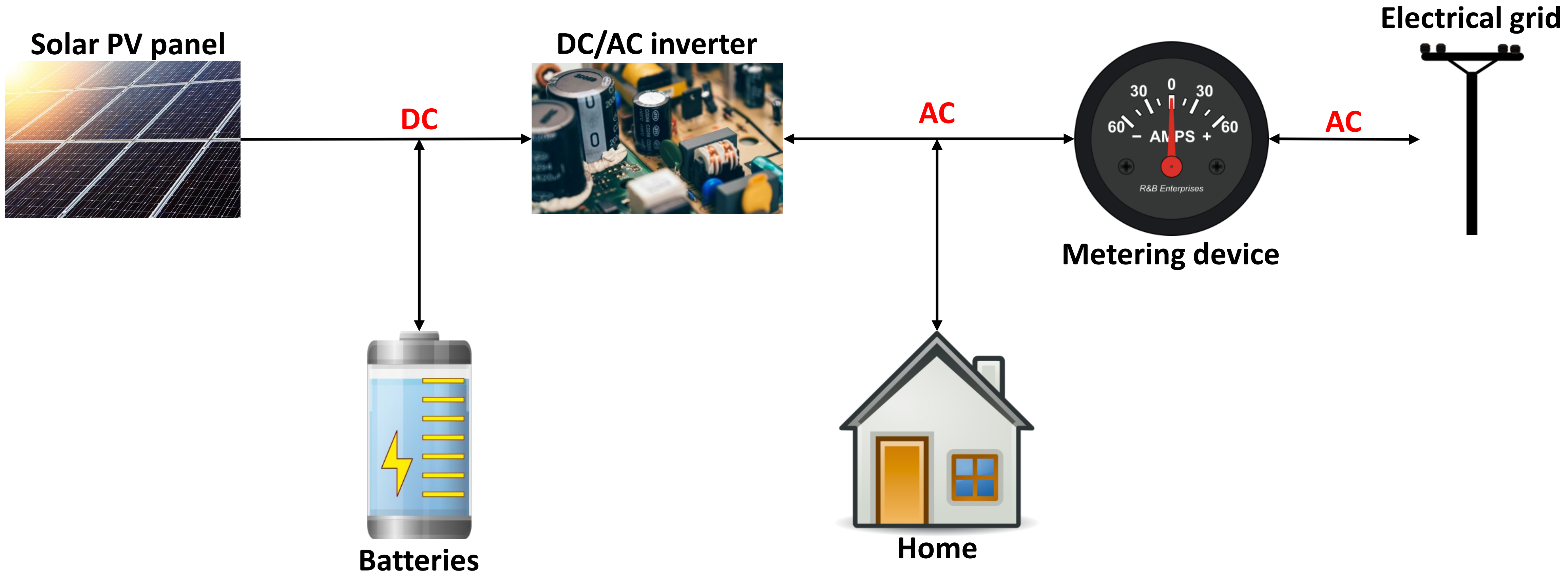


Electrical grid

Metering device

Exercises

Answer 1:



Production of electricity – Biomass

Biomass power plants produce electricity through the burning of biomass products. These can either be by-products or specifically-chosen plants which are grown and directly burned or transformed into biofuels.

Key figures:

- Percentage of world power generation in 2016: ± 2%.
- Typical biomass plant output power: 100 MW.
- Typical capacity factor: ± 60%.

Production of electricity – Biomass

Advantages:

- Renewable source of energy (with conditions).
- Carbon neutrality (no net emission of CO_2).

Disadvantages:

- Can be exploited in an unsustainable way (deforestation).
- Emission of some pollutants (e.g. methane).

Production of electricity – Geothermal

Geothermal power plants exploit the natural heat of the earth to produce electricity. A fluid is sent through pipes in the depths of the earth to absorb thermal calories.

Key figures:

- Percentage of world power generation in 2016: < 1%.
- Typical geothermal plant output power: 100 MW.
- Typical capacity factor: ± 70%.

Production of electricity – Geothermal

Advantages:

- Renewable, no dependence upon limited reserve of fuels.
- No pollution nor greenhouse gas (CO_2).
- Excellent reliability.

Disadvantages:

- Limited amount of eligible locations.
- Potentially give rise to earthquakes.
- Significant initial investment required.

Energy Management System (EMS)

An *Energy Management System (EMS)* is a computer-based tool developed to better manage electrical energy flows. These systems have already proven to greatly improve the energy efficiency of electrical power grids, which is capital in the scope of the current energy transition.

Energy Management Systems are mainly used by operators of electric utility grids in order to better monitor, control and optimize the performance of electrical energy generation, consumption and transmission. More recently, EMS are getting more and more popular at a smaller scale as well, typically in microgrids. The increasing penetration of renewable energy sources coupled with the multiplication of electrical energy storage devices are really making EMS essential at every scales.

Electrical energy storage

The efficient *storage of energy*, especially electrical energy, is a core challenge of the energy transition. It is considered a key solution to handle the volatility of renewable energy sources.

To be stored, electrical energy has to be converted into another form of energy:

- Chemical energy => Batteries, hydrogen.
- Potential energy => Hydro-pumped station.
- Kinetic energy => Flywheels.

Electrical grid stability – Introduction (1)

Keeping the electrical grid in a *stable* state is a very complicated task. Besides other complex mechanisms, the following rule has to be respected at all time:

$$P(t) = C(t)$$

with:

- $P(t)$ being the production of electricity at time t.
- $C(t)$ being the consumption of electricity at time t.

Numerous difficulties:

- Accurate forecast of a continuously varying consumption (human nature, weather, weekday or weekend, holidays, season, etc.).
- Accurate forecast of constantly changing production (multiple different sources, unexpected technical problems, predictability of renewable energy sources, etc.).

Electrical grid stability – Introduction (2)

In the unfortunate case of an imbalance between the production $P(t)$ and consumption $C(t)$ of electricity, the overall voltage V and frequency f in the electrical grid are affected. If such imbalance remains with no corrective action executed, a chain reaction could potentially degenerate into a blackout.

Possible imbalances and effects:

- $P(t) < C(t)$: Overall voltage V and frequency f decrease.
- $P(t) > C(t)$: Overall voltage V and frequency f increase.

Reliable regulation mechanisms are required to avoid the occurrence of blackouts!

Electrical grid stability – Regulation

In Belgium, the principal regulation mechanism is the existence of three so-called *reserves*, which can be promptly activated in order to compensate for a lack of electricity production.

- **Primary reserve:** Of very short response time (a few seconds), the primary reserve goal is to get the equilibrium back ($P(t) = C(t)$) and limit the damages.

- **Secondary reserve:** Slightly slower than the primary reserve, the objective of this second reserve is to get the power grid back to its target frequency and voltage.

- **Tertiary reserve:** Contrarily to the first two reserves which are automatic, this one is manually activated and shares the same goal as the secondary reserve.

Circuit Breaker

A *circuit breaker* is a safety device which interrupts the electric current whenever a fault is detected in the electrical circuit. More specifically, it consists of an electrical switch automatically triggered by excess currents, the origin being either an overload or a short circuit. Its role is to protect both the electrical circuit from damage and the living beings from potentially deadly situations.

Power grid congestion

A *power grid congestion* is a particular situation where a transmission or distribution line is unable to transfer the required electrical power, due to the fact that the maximum power supported by the power line is exceeded.

Diverse origins for this problem:

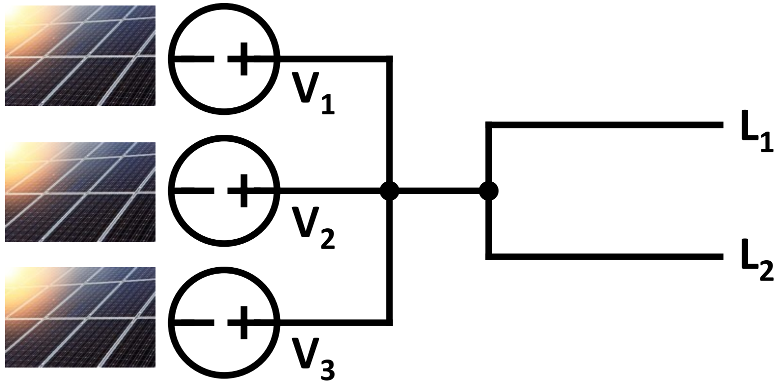
- Undersized power line for significant power generation.
- Undersized power line for significant power consumption.
- Adjacent power line damaged or out of service.

Exercises

<u>Exercise 1:</u> The following electrical circuit represent a small street with three houses equipped with PV solar panels, and connected to the main power grid through two identical power lines. Evaluate the risk of congestion if:

1. A power line is out of service.
2. A new house equipped with PV solar panels is built in the street.

$P_{1,max} = $ 1kW
$P_{2,max} = $ 2kW
$P_{3,max} = $ 1.5kW
$P_{L_1,max} = P_{L_2,max} = $ 3kW



Exercises

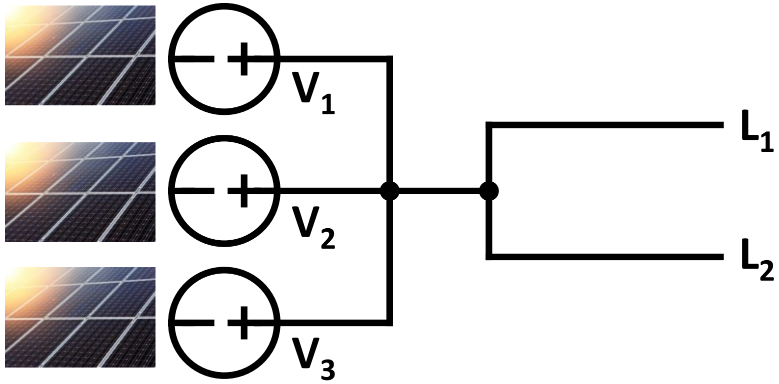
Answer 1:

0. Current situation:

$$\sum_{i}^{N} P_{i,max} \leq \sum_{i}^{N} P_{L_i,max}$$

$\Longrightarrow$ 4.5kW $\leq$ 6 kW

OK, no congestion!



$P_{1,max} =$ 1kW
$P_{2,max} =$ 2kW
$P_{3,max} =$ 1.5kW
$P_{L_1,max} = P_{L_2,max} =$ 3kW

Exercises

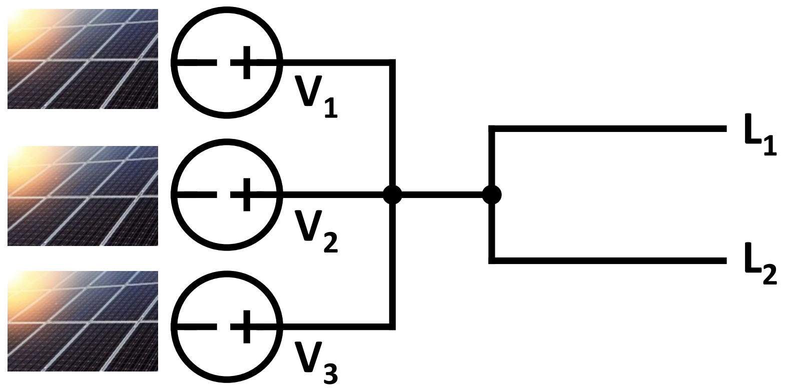
<u>Answer 1:</u>

1. Power line out of service:

$$\sum_{i}^{N} P_{i,max} \nleq \sum_{i}^{N} P_{L_i,max}$$

$\Longrightarrow$ 4.5kW $\nleq$ 3 kW

KO, congestion!



$P_{1,max} =$ 1kW
$P_{2,max} =$ 2kW
$P_{3,max} =$ 1.5kW
$P_{L_1,max} = P_{L_2,max} =$ 3kW

Exercises

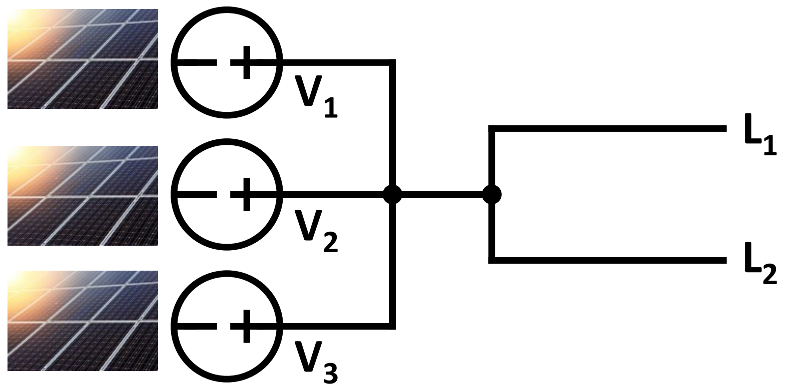
<u>Answer 1:</u>

2. New PV solar panels:

$$\sum_{i}^{N} P_{i,max} \leq \sum_{i}^{N} P_{L_i,max}$$

$\Longrightarrow$ 4.5kW + $P_{4,max} \leq$ 6 kW

$\Longrightarrow$ $P_{4,max} \leq$ 1.5 kW to avoid congestions!



$P_{1,max} =$ 1kW
$P_{2,max} =$ 2kW
$P_{3,max} =$ 1.5kW
$P_{L_1,max} = P_{L_2,max} =$ 3kW

Documentation work – Transformers

Source : Leonardo Energy (2009) - Energy-efficient-distribution-transformers.

Questions:

1. What is the definition of efficiency in a transformer? What are some typical efficiency values for transformers?
2. What are the different types of losses in a transformer? What are the possible solutions to each loss?
3. Why do transformers result inefficient over long period of times? What benefit would we have increasing their performances?
4. What are the different types of transformers? In your opinion, why is hydrogen gas (hydrogen gas has much higher thermal conductivity than other cooling systems) not used for cooling transformers?
5. What are the key advantages of investing in high-efficiency distribution transformers? Explain the Endesa project.

Any questions?

Extra material

- **How Electricity Gets to You –** Wendover Productions (*https://www.youtube.com/watch?v=xhxo2oXRiio*)