2024-2025
Fall Semester

Course of Power System Analysis

Course introduction

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Outline

Course objectives and practicalities

Traditional structure of power systems

Classification as a function of voltage

Power balance

Course objectives and practicalities

The course provides the fundamental concepts to **model power systems, understand their operation and design/coordinate some of its main components**.
The course is conceived for **EE** (**bachelor**)and **non-EE** (**master**) students.

The course is structured in **seven** main parts:

- **Introduction to power systems**
- **Recall of fundamental principles for the analysis of AC circuits and systems**
- **Elements of transmission lines for the transportation of electricity**
- **Fundamentals of electrical machines**
- **The power flow problem**
- **Short circuit analysis and protections**
- **Frequency regulation in power systems**

Course objectives and practicalities

Learning outcomes

By the end of the course, the student must be able to:

- **Understand the operational mechanisms of a power system**
- **Model and study a power system in steady state**
- **Model and study a power system in (some)transient conditions**
- **Design power systems components**

Course objectives and practicalities

Students' activities

- Attend lectures and labs
- Do lab homework
- Take the online quizzes

Course objectives and practicalities

Teaching approach and exam

Each week is normally structured with **lectures** and **labs** using different software tools.

Grading:

- Two intermediate evaluations during the semester (in person during classes).

Course objectives and practicalities

Course material

All the slides, notes, exercises, lectures videos, will be made progressively available on Moodle at this URL:

https://moodle.epfl.ch/course/view.php?id=18512

It is highly recommended to use the **moodle forum announcement Q&A** to ask questions to your teacher and TAs.

TA team

Francesco Gerini

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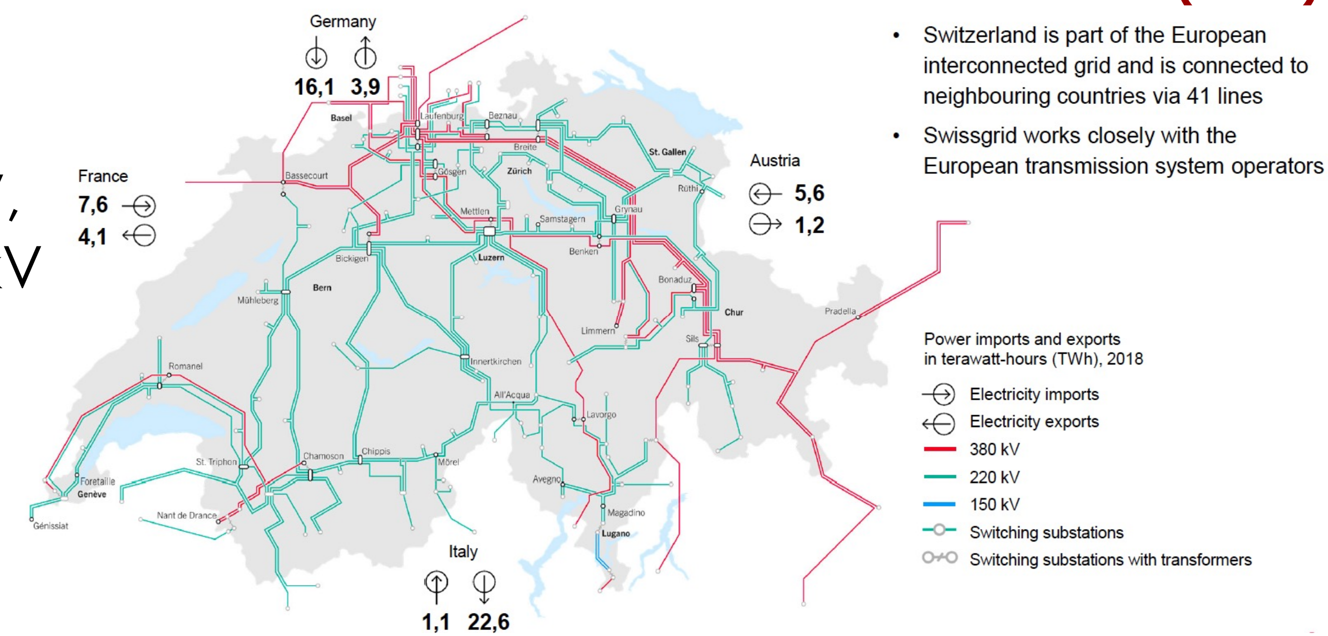
Traditional structure of power systems

The traditional structure of an interconnected electrical power systems is characterized by the following main hierarchical layers:

- **Production systems** (power plants);
- **Transmission networks** (rated voltages of 380 kV, 220 kV and 132 kV);
- **Distribution systems** (rated voltages of 50 kV, 20 kV, 15 kV, 11 kV and, for the low voltage, 0.4 kV).

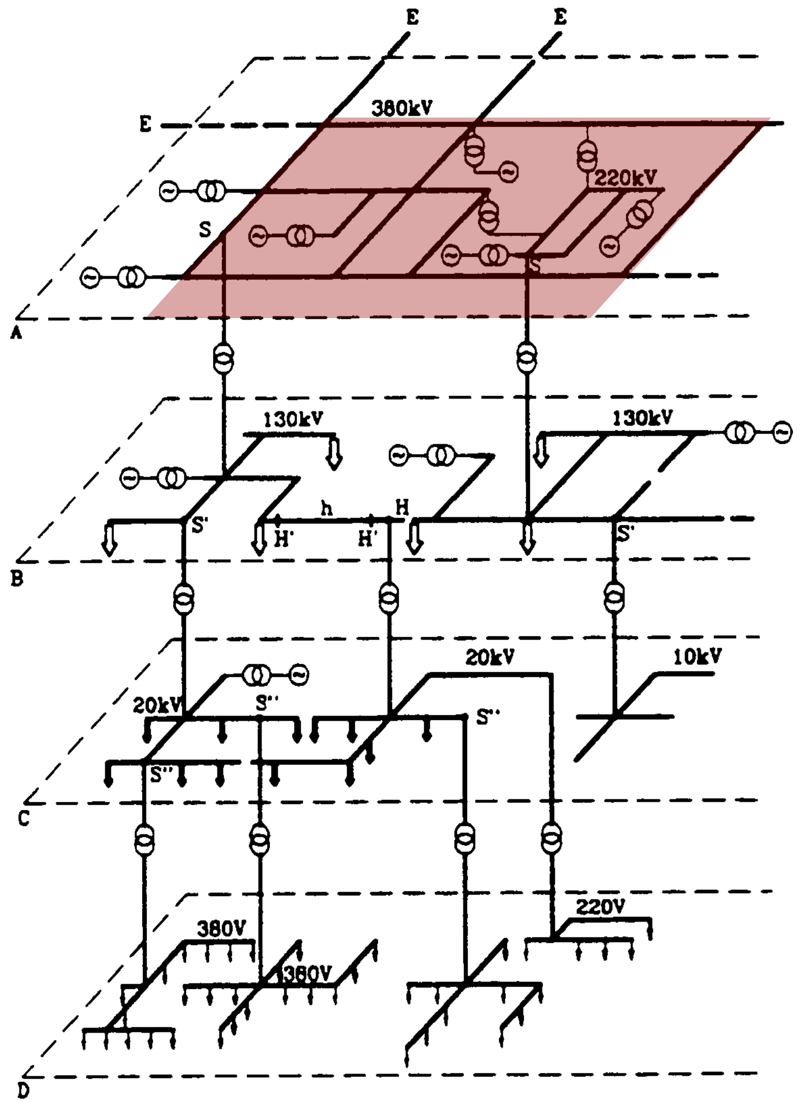
Swiss transmission network (2019)



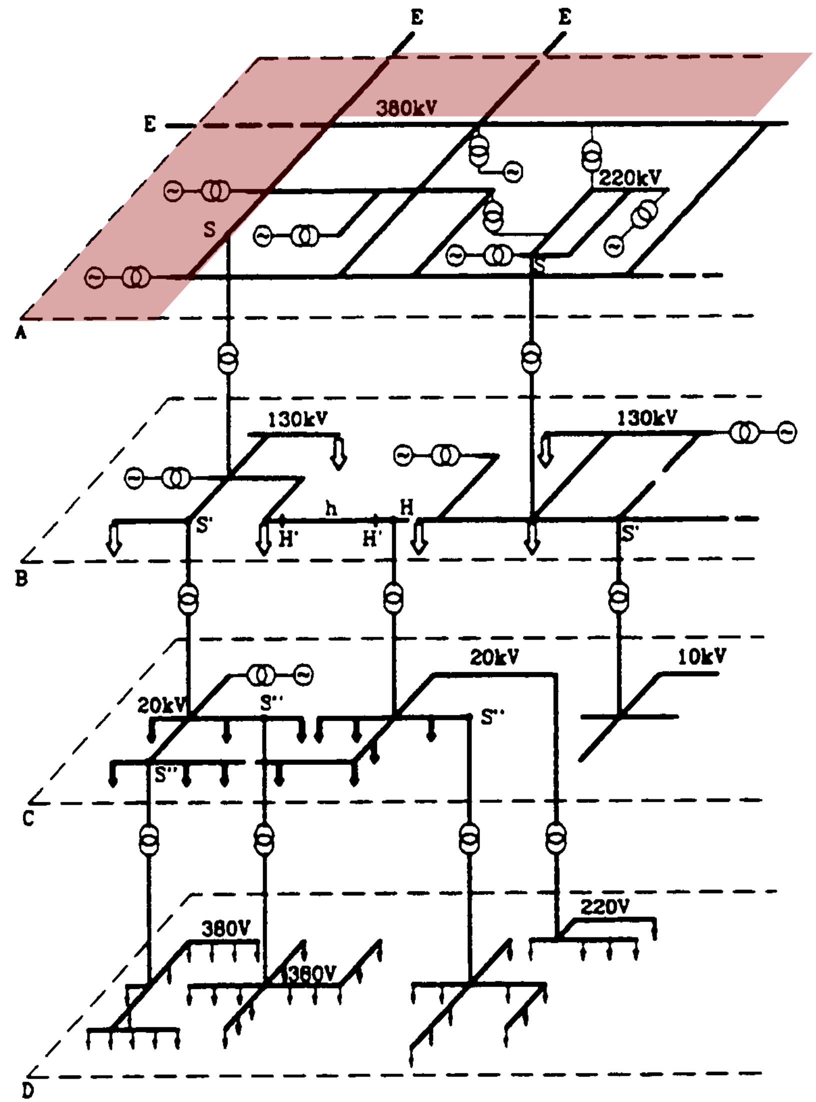
Traditional structure of power systems

Large power plants are feeding transmission networks towards **synchronous generators.** These machines are generally characterised by **rated voltages of 8, 15 or 20 kV** as a function of their power. Their physical connection to the transmission grid is realised by means of **step-up transformers** responsible to increase the voltage to the rated value of the transmission network (i.e. 380 kV, …).

The **network "A" allows the transport** the electrical energy towards **large distances as a function of the voltage level**. The main characteristic of the network is that it is **meshed** with typical distances between nodes in the range of **50 - 200 km**. The main aim of the this network is to transport the electricity with **high reliability levels** and **relatively low losses**.



Traditional structure of power systems

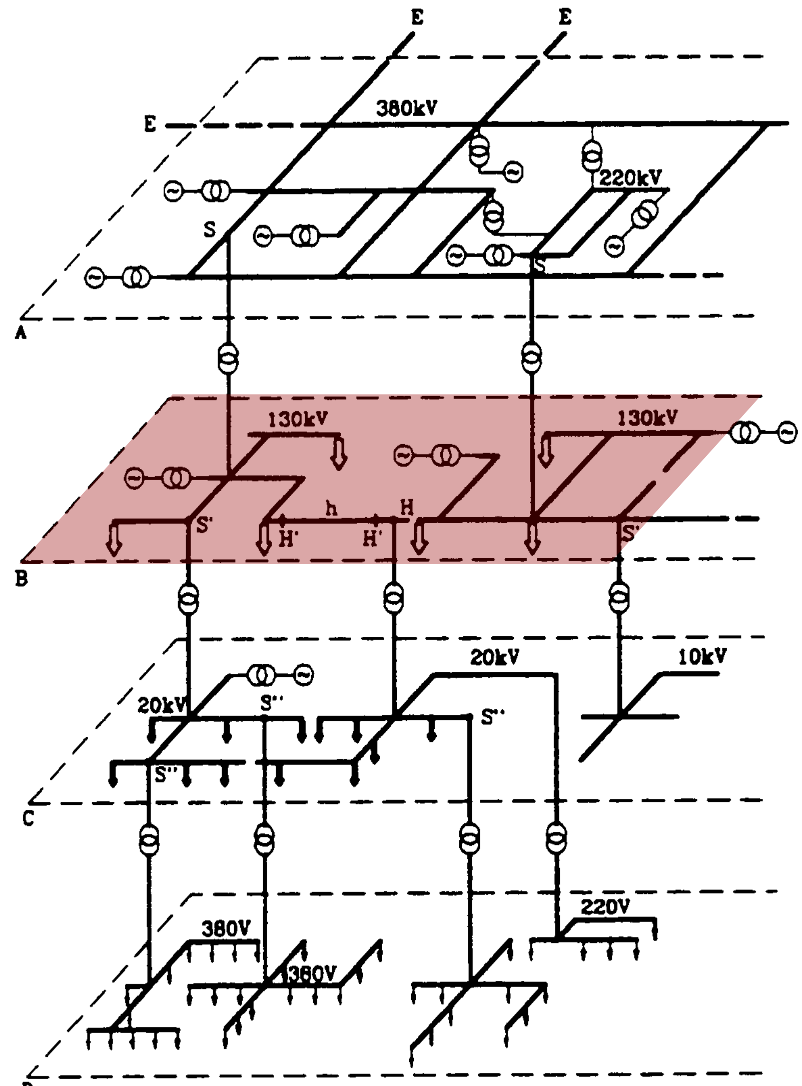


Lines **"E"** are interconnecting country transmission networks.
They allow the exchanges in normal and emergency conditions (i.e., market trading towards tie-lines or emergency recovery after a blackout).
These lines allows to increase the reliability and the economy of the operation of the entire electrical infrastructure.

Traditional structure of power systems

Nodes **"S"** are connected, towards dedicated stations, to networks **"B"** called **sub-transmission networks**. These are characterised by rated voltages in the order of **110-130 kV**.
Typical distances between nodes of sub-transmission networks are in the order of **30-40 km**. They are operated with a light-meshed structure generally changeable as a function of the operational requirements.

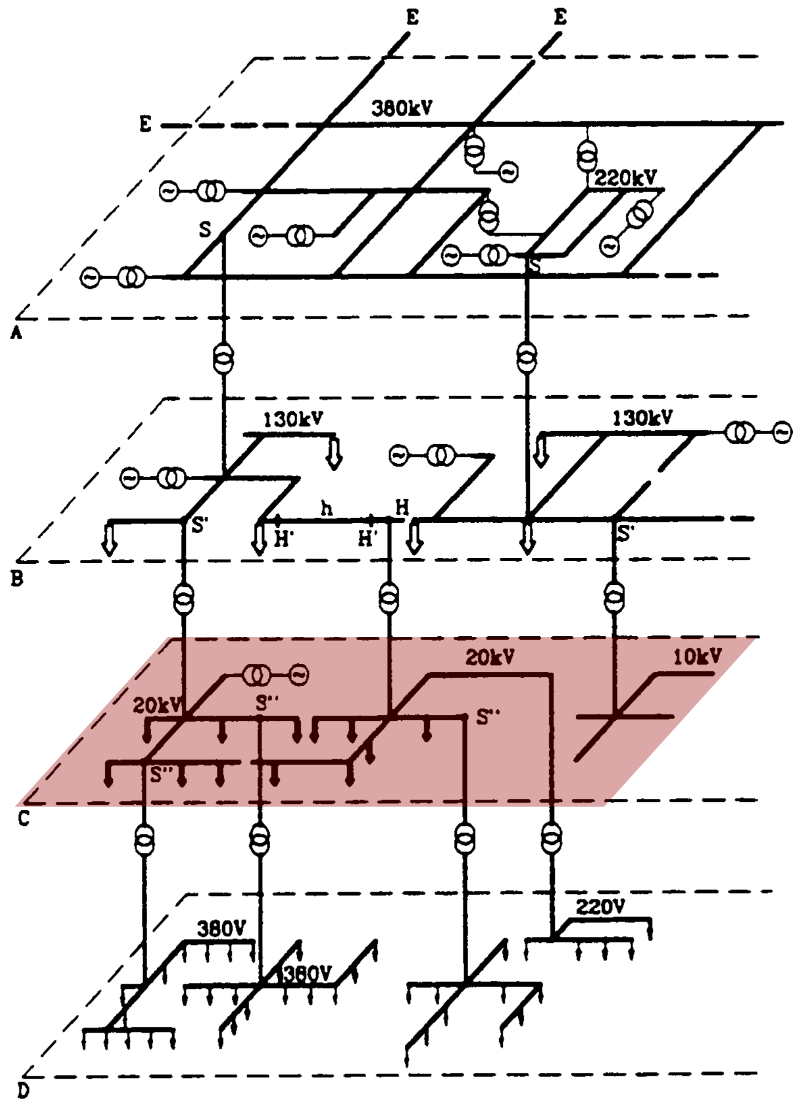
Sub-transmission networks supply both large industrial customers or distribution networks towards dedicated stations called **primary-substations** (nodes **S'**).
In sub-transmission networks there is the possibility to have power injection from plants with rated power typically in the range between **1 to 50 MW**.



Traditional structure of power systems

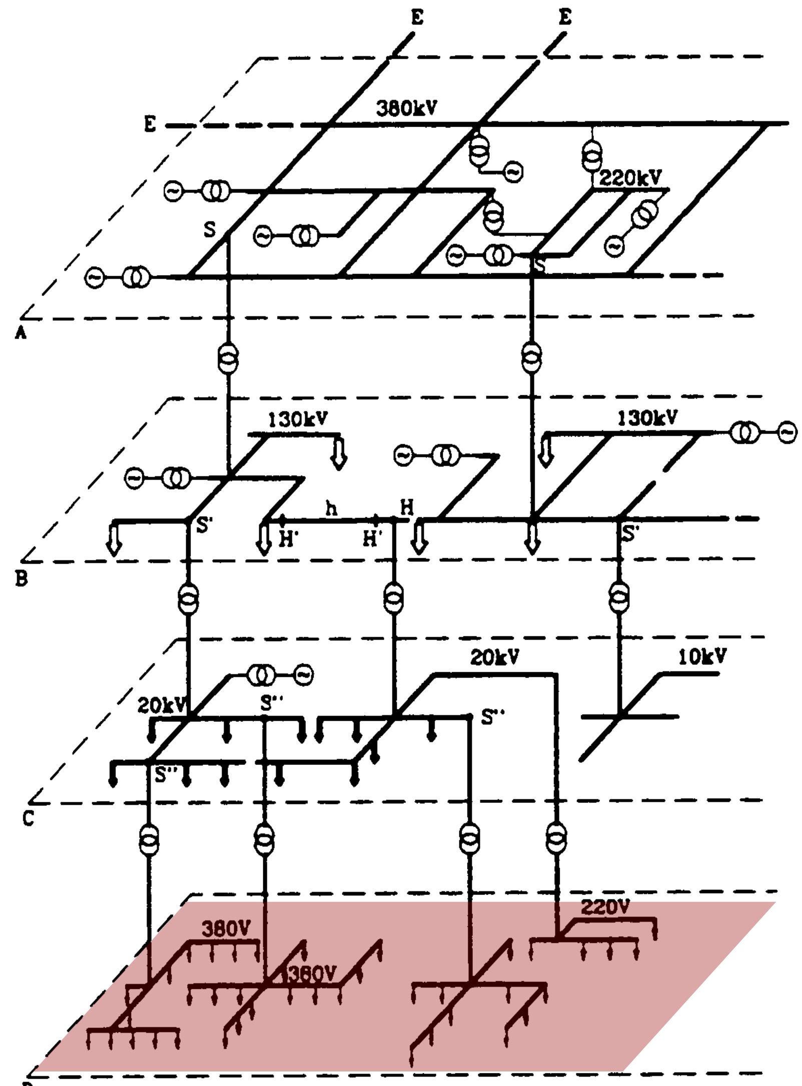
Power distribution networks C, have typical rated voltages between **11 to 66 kV** and a topology that is usually **radial**. The radial configuration is operated in '**open-loops**' that enable to change the topology of the system.
These networks provide electricity to public services and customers with maximum rated power between (typically) **1 - 5 MW**.

The extension of these networks does not exceeds **10-20 km** for the case of overhead lines (rural networks) and **few km** for the case of cable lines (urban networks).



Traditional structure of power systems

Networks **“D”** compose the low-voltage distribution with rated voltage (for instance in Europe) of **400 V**. These networks supply loads within **3 to 40 kW**.
The extension of these networks is of **few hundreds of meters** in urban contexts or max **1 km** in rural contexts.



Traditional structure of power systems

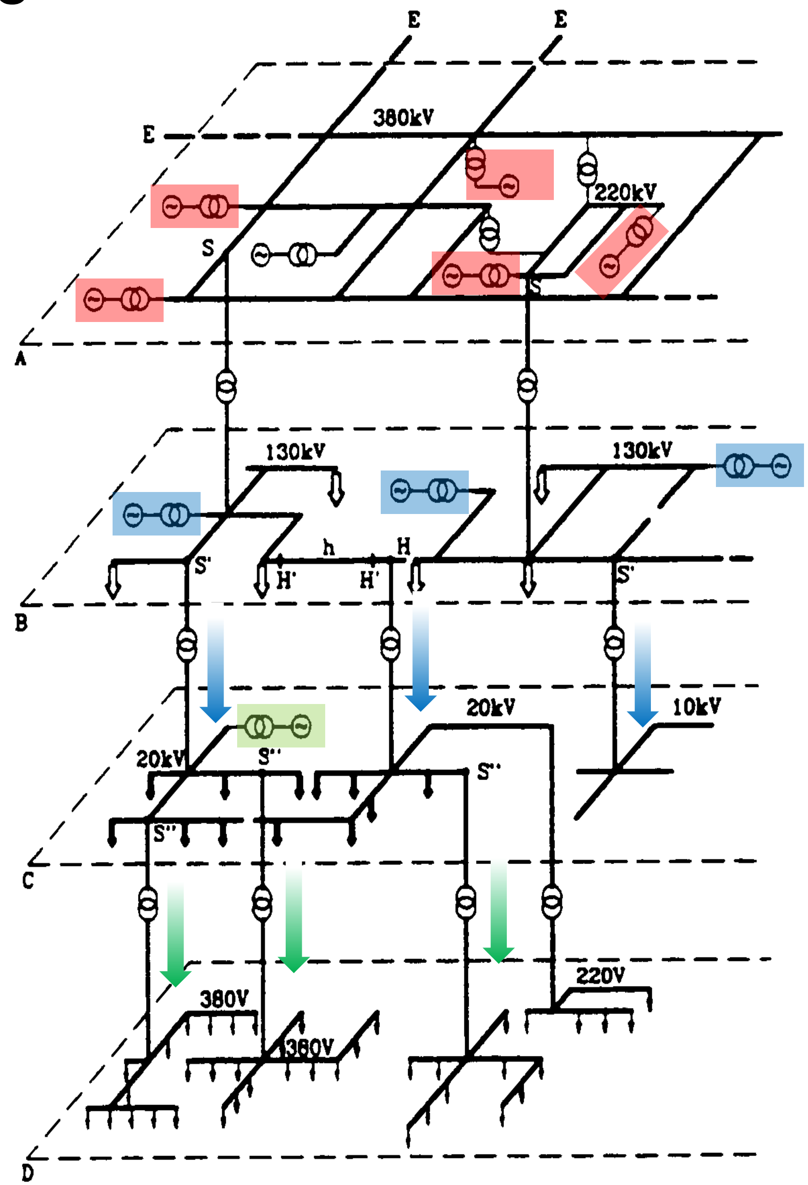
Impact of distributed generation

Transmission

Sub-transmission

Distribution (medium voltage)

Distribution (low voltage)



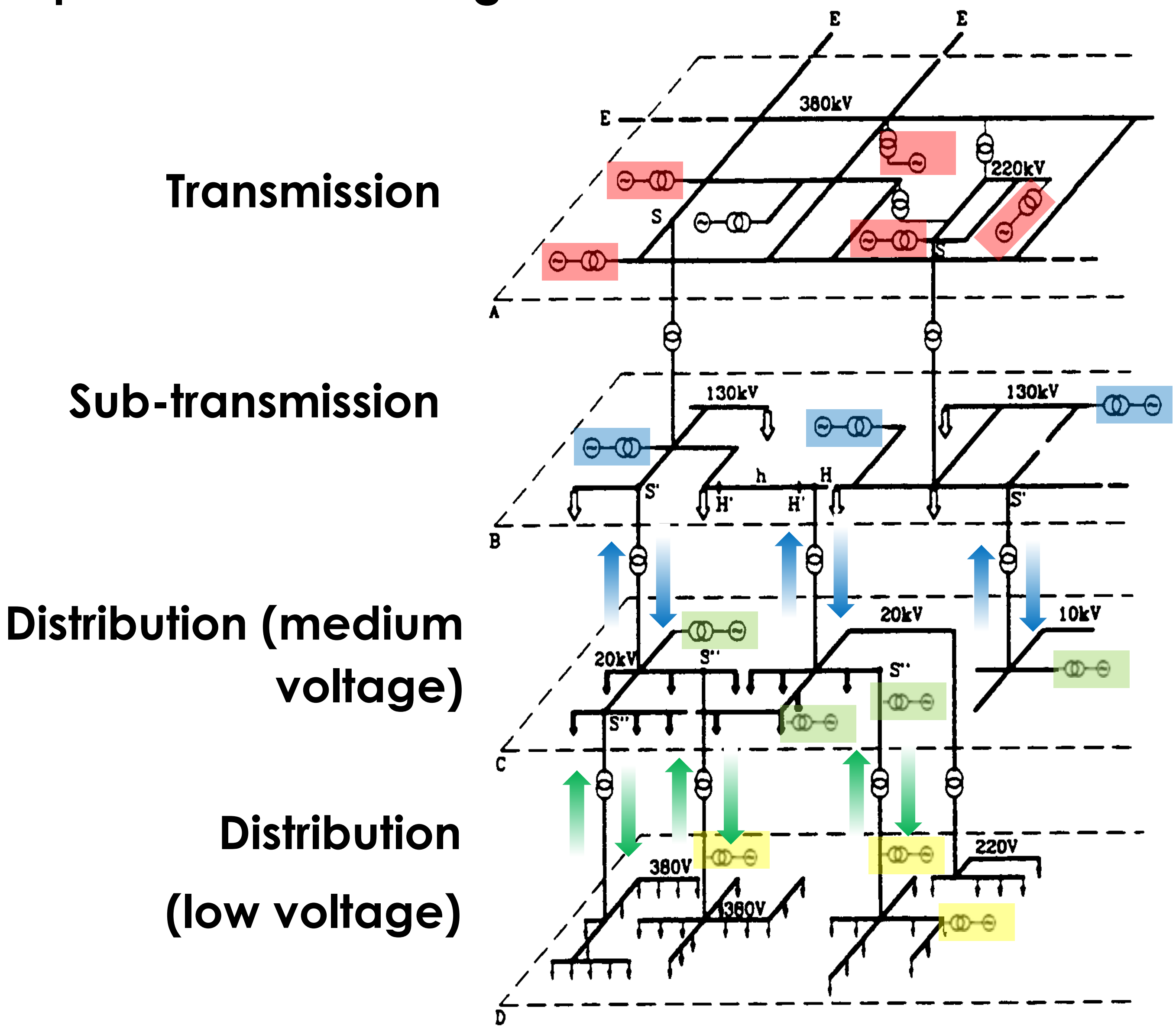
Without **distributed generation**

Unidirectional powerflows

from transmission to distribution networks.

Traditional structure of power systems

Impact of distributed generation



Without **distributed generation**

Bidirectional powerflows

from transmission to distribution networks.

Outline

Course objectives and practicalities

Traditional structure of power systems

Classification as a function of voltage

Power balance

Classification as a function of voltage

Traditionally, there has been the necessity of concentrating the production in power plants that are, in general, **far from loads →** necessity of a **transportation network over long distances**. The consequences of this choice are:

- Increase of the rated voltage of the lines to **limit, for the same transmitted power, the current flowing toward the lines** (↓ losses ↓ use of materials with low resistivity);
- utilisation of simple static electrical machines (transformers) **capable of changing the parameters of the power in a simple and reliable way**;
- simplification of the electro-mechanic conversion chain (motors – generators);
- **Adoption of AC systems that simplify the satisfaction of the above needs.**

However, it is worth noting that, as it will be clarified later, the use of an AC network has some drawbacks:

- **complex control of voltage and frequency**;
- **limit the transmission capability of the lines;**
- **stability issues for the network**.

Classification as a function of voltage

Rated voltage (kV)	Max short-circuit power (MVA)	Max short-circuit current (kA)	Typical power (MVA)	Max rated current (kA)
220	10000	26	600	1,6
130	5000	22	300	1,3
30	1000-2000	20-40	60-120	1,15-2,3
6-10	250-500	15-50	15-30	0,85-2,9
0,38	30	45	1,6	2,5

IMPORTANT: in any level of a power system (i.e., transmission, sub-transmission, or distribution networks) characterised by a given rated voltage V_n, all the equipments are **designed to withstand a specific value of voltage** (i.e. $V_n \pm \Delta V$) where, in general, ΔV, is a small fraction of V_n. Therefore, **one of the main control functions in any power system refers to keep the voltage as close as possible to the rated value for any layer of the grid** (i.e., transmission, sub-transmission, or distribution networks).

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Power balance

Fundamental observation #1: in a power system **the amount of energy that can be stored in the components of its electrical circuit, is negligible**. Therefore, the constraint imposed by the first principle of thermodynamics imposes that **the electricity produced by the generators must match the one of the loads (in practice) instantaneously.**

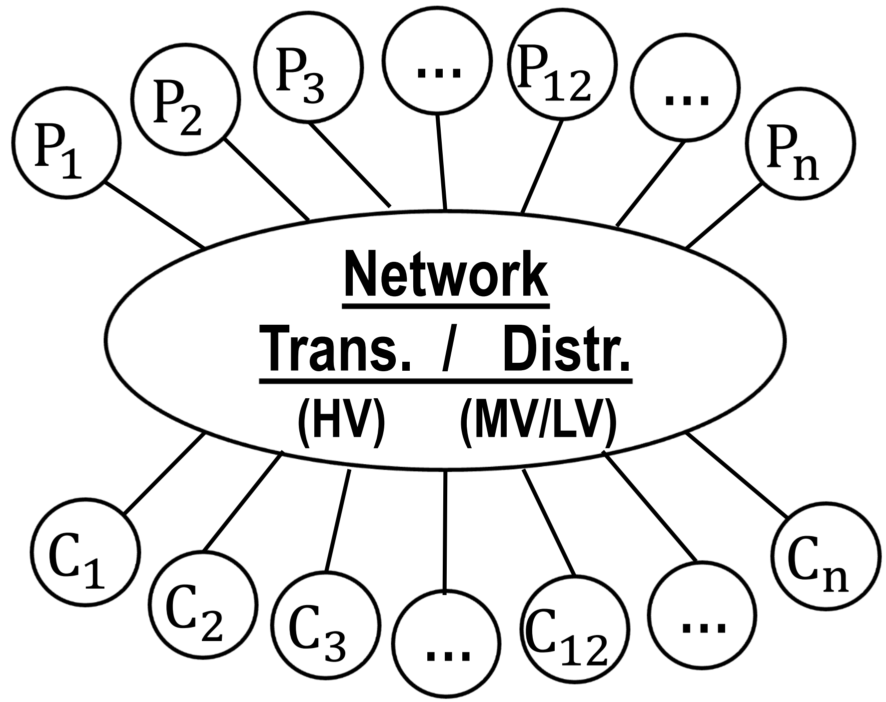
Fundamental observation #2: if the **power systems loads are inelastic**, namely **they do not change their value in response to changes in the electricity price or supply conditions** and are a **stochastic quantity, to supply them, we need a full control of the electricity generation.**

Fundamental observation #3: in a **power system experiencing a progressive dismantling of centralized controlled generation in favor of stochastic renewables**, there is the **need to add systems in place capable to keep the power balance**.

Power balance

Vertically integrated power system

In a so-called **vertically-integrated power system** (i.e., a **monopoly**), there is only one company responsible to **produce, transport** and **deliver** the electrical energy to the final consumers.

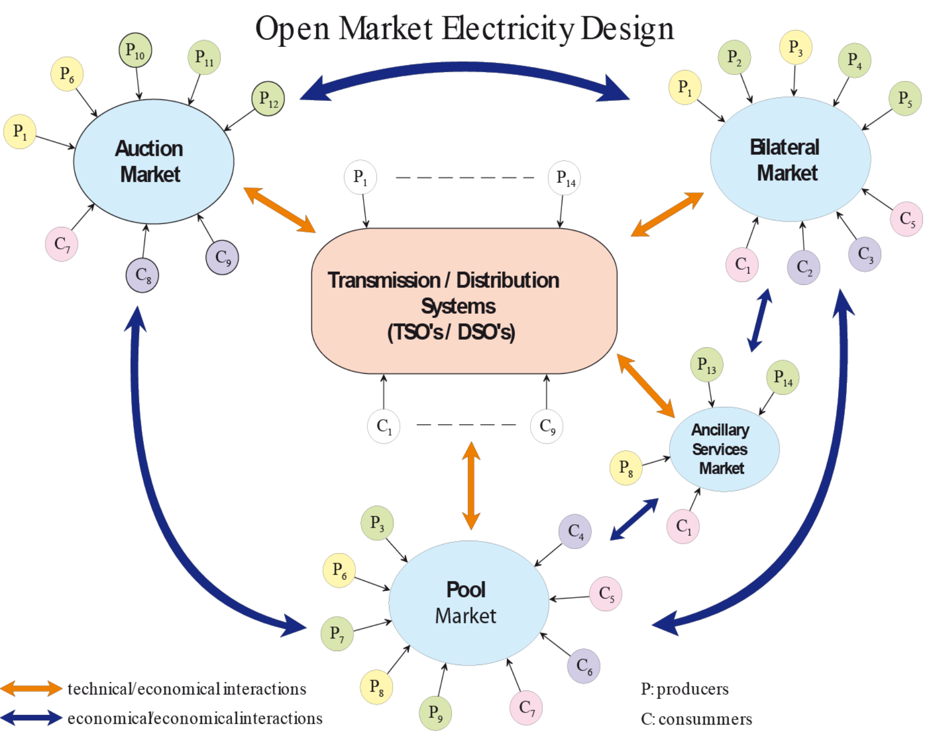


Main features:

- Consumers have no choice of providers.
- The electricity price is regulated (to be the least possible).
- The electrical system is optimally operated as a single entity.

Power balance

Markets – Deregulated/unbundled power systems

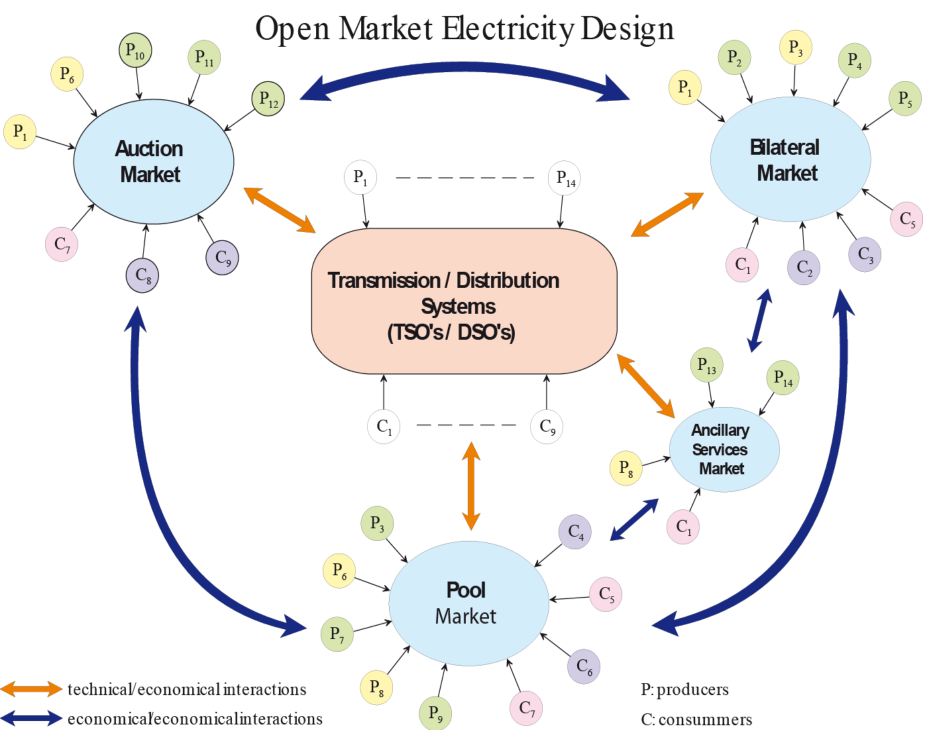


Key points:

1. Electricity supply: from **vertically integrated** to **unbundled.**
2. The Electrical energy is a **product** made available by different **independent providers** (or **producers**) and its delivery is a **service** managed by transmission and distribution systems operators (TSO/DSO)
3. The product is **traded** according to different auctioning mechanisms in appropriate market places (**pool**, **bilateral**)
4. TSO/DSO take care of the **physical feasibility** of the delivery of the market trading (i.e. power system operation).

Power balance

Markets – Deregulated/unbundled power systems



Key points:

5. Since the market is unable to guarantee the continuous (real-time) equilibrium in the system, the operators are mandated to schedule and deploy a number of **ancillary services** like: frequency/voltage controls, congestions management, reserve support, black start capabilities, etc.

6. Ancillary services are **provided by market actors**.

7. The **physical network** (Kirchhoff's laws) is interacting with the commercial networks (i.e. auctioning laws).

Power balance

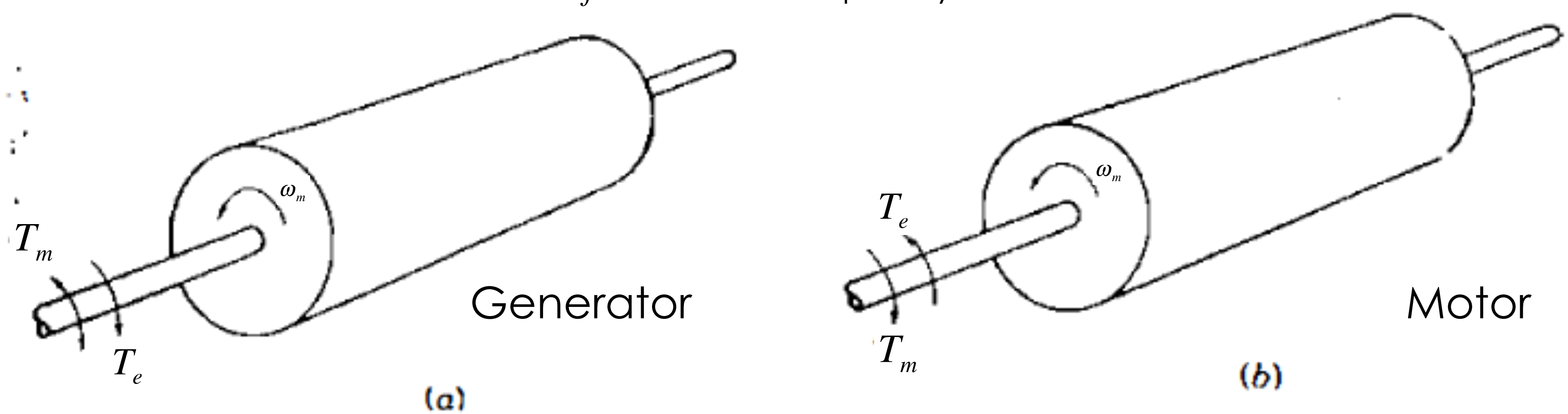
Link with network frequency

The equation governing the **rotor motion** of a synchronous **generator** is based on the **elementary principle of the dynamic of a rotating mass with one degree of freedom**: the accelerating torque is the product of the moment of inertia of the rotor times its angular acceleration.

$$J\frac{d^2\vartheta_m}{dt^2} = T_m - T_e$$

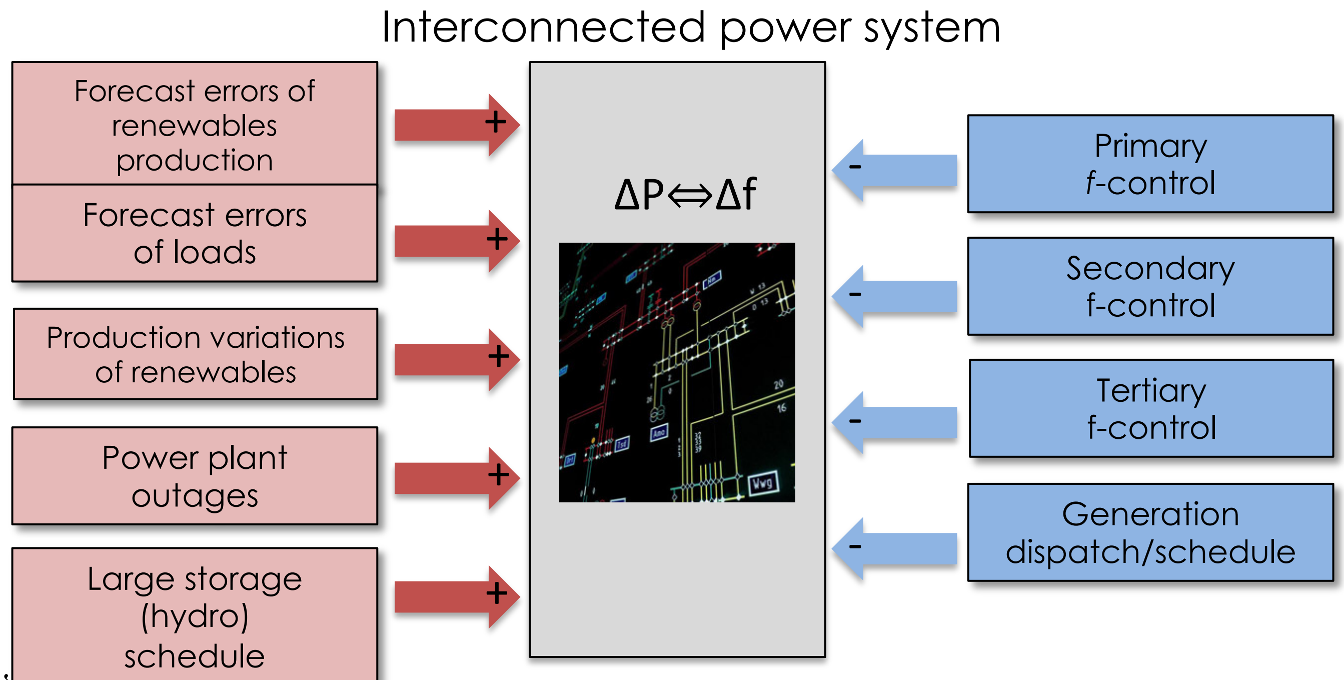
$$\frac{d\vartheta_m}{dt} = \omega_m = \frac{\omega_e}{p} = \frac{2\pi f}{p}$$

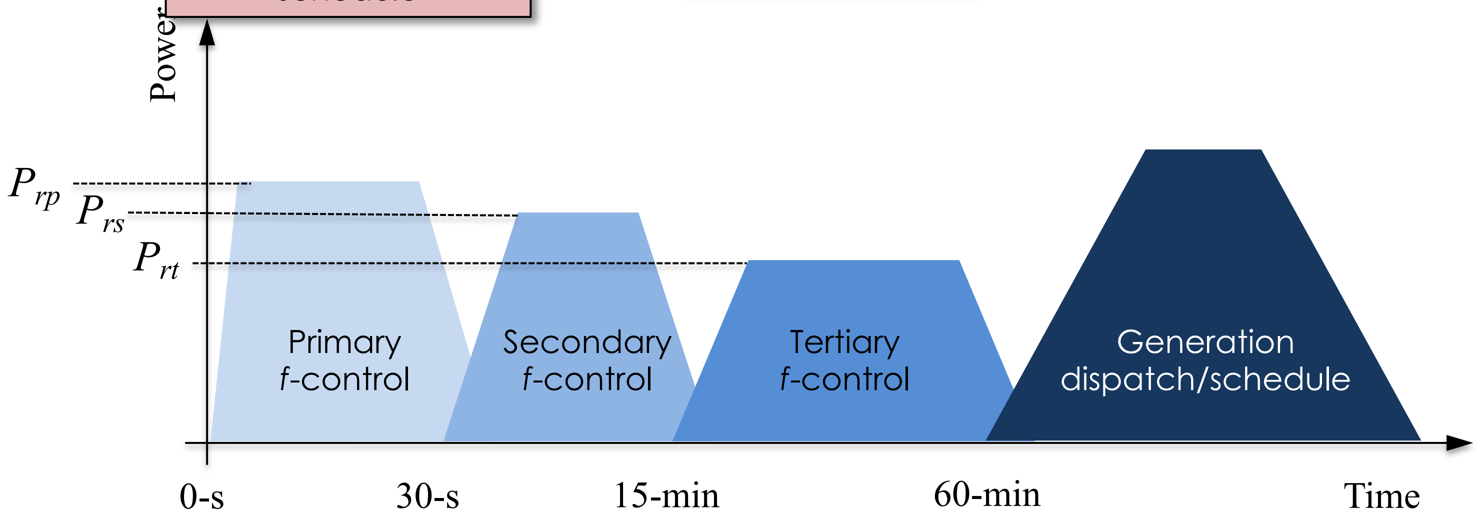
- J total moment of inertia of the rotor masses
- ϑ_m angular displacement of the rotor with respect to a stationary axis
- T_m mechanical torque supplied by the prime mover
- T_e net electrical or electromagnetic torque;
- ω_e mechanical angular speed
- ω_m electrical angular speed
- p number of magnetic pairs of poles
- f electrical frequency



Power balance

Link with network frequency





Power balance

Link with network frequency

As can be observed from the previous picture, the the **link between the power imbalance and the network frequency** (that constitutes the *control variable*) involves three time-frames of the frequency control scheme.

Primary-frequency controllers are locally installed in generation units and act immediately after a power imbalance resulting in a frequency deviation (locally measured). Droop regulators usually compose these controllers. The amount of the primary-control reserve is called **Frequency Containment Reserve** (P_{rp} in the previous figure) represents the **maximum amount of power available in the interconnected network after a frequency imbalance**. This concept can be applied to a single generation unit or to the whole system.

Power balance

Link with network frequency

As can be observed from the previous picture, the the **link between the power imbalance and the network frequency** (that constitutes the *control variable*) involves three time-frames of the frequency control scheme.

Secondary-frequency controllers are, in general, centralised for each area that composes the interconnected power system and are responsible for compensating the frequency deviation from the rated value after the primary control intervention. The time-frame of the secondary-frequency control ranges from a **few tens of second to a few minutes**. In an area of the interconnected network, the **secondary-control reserve, called Frequency Restoration Reserve** (P_{rs} in the previous figure) represents the **power responsible for bringing the frequency back to its rated value** (i.e. 50 Hz).

Power balance

Link with network frequency

As can be observed from the previous picture, the the **link between the power imbalance and the network frequency** (that constitutes the *control variable*) involves three time-frames of the frequency control scheme.

The power that can be connected, automatically or manually, in order to provide an **adequate secondary control reserve**, belongs to the **tertiary-frequency control** and is known as the **tertiary control reserve called also Frequency Replacement Reserve** (P_{rt} in the previous figure). This reserve must be used in such a way that it will contribute to the **restoration of the secondary control reserve.** In general, we have that $P_{rp} \geq P_{rs} \geq P_{rt}$.

Power balance

Link with network frequency

Activation of primary, secondary and tertiary frequency controls as a consequence of a power plant outage

Primary control / containment reserve
0.5 min. after outage

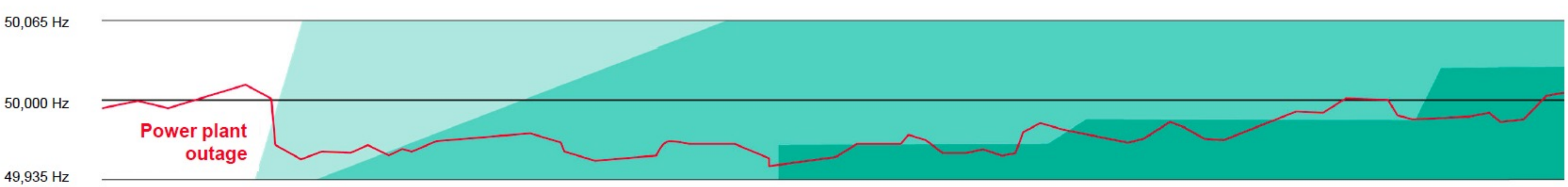
- Frequency measurement in the power plants
- Automatically activated in the generator of the power plant
- Across Europe

Secondary control / frequency restoration reserve
5 min. after outage

- Measurements at the Swiss cross-border lines
- Activated by the central load frequency controller at Swissgrid
- Across Switzerland

Tertiary control / frequency replacement reserve
15 min. after outage

- Easing of secondary control
- Activated by the operator
- Contracts with individual providers



Power balance

Electricity markets timeline

In view of the concepts seen before, this is the general timeframe of the electricity market, the various products and participants.