International Solar Alliance Expert Training Course

Grid Code Development for PV System Integration

In partnership with the Clean Energy Solutions Center (CESC)

Professor Oriol Gomis-Bellmunt

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Supporters of this Expert Training Series

INTERNATIONAL SOLAR ALLIANCE

CLEAN ENERGY SOLUTIONS CENTER
ASSISTING COUNTRIES WITH CLEAN ENERGY POLICY
An Initiative of the Clean Energy Ministerial

CARBON TRUST

Expert Trainer: Prof Oriol Gomis-Bellmunt

- Professor in the Electrical Power Department of Technical University of Catalonia (UPC)
- Directive board member of the research group CITCEA-UPC, where he leads the group of power systems dominated by power electronics, including renewable energy (PV and wind), HVDC transmission systems and other power converter based systems (energy storage, EV chargers)
- 20+ years of experience in the fields of renewable energy, power electronics and power systems. Involved in a number of research projects and contracts of technology transfer to industry.
- Coauthor of 3 books, 7 patents and > 100 journal publications, mainly in the field of power electronics in power systems and grid integration of renewables.
- Supervision of 18 doctoral theses and >60 Bachelor and Master theses.

Overview of Training Course Modules

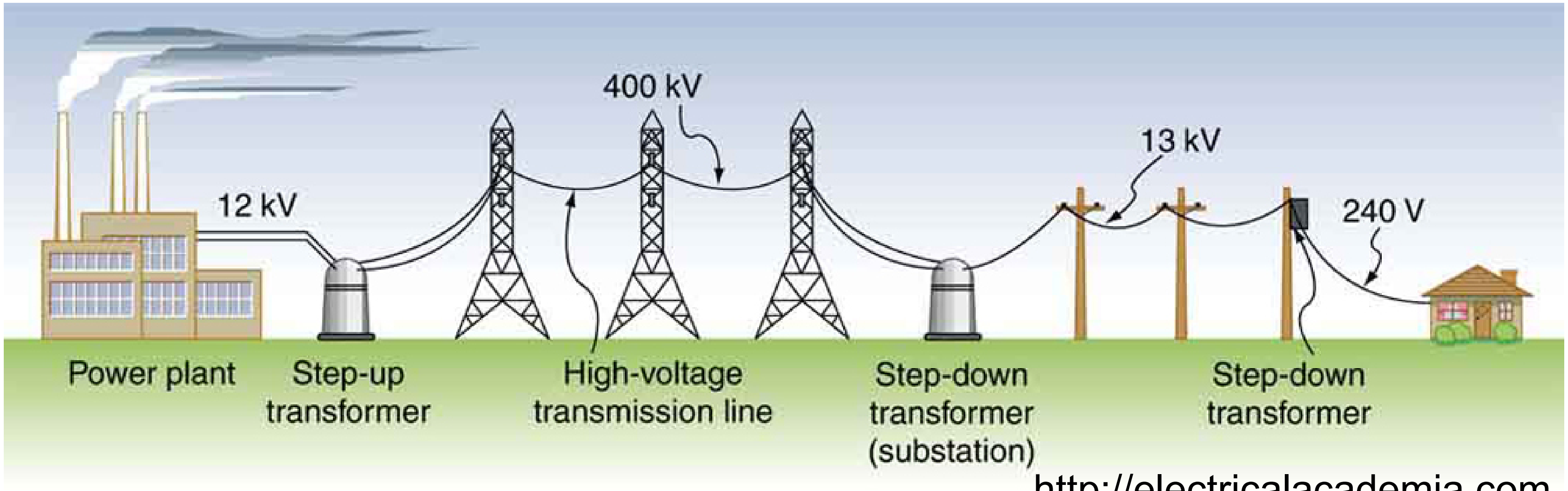
This Training is part of Module 4, and focuses on the issue of grid codes for PV integration

Outline

- Context: the electrical power system
- From PV farms to PV power plants
- Grid codes
- Voltage support
- Frequency support
- Inertia emulation
- Black-start
- Ramp control
- Other requirements

Electric power system

- Simple conversion, transport and control.
- Mainly AC generation, transmission and distribution
- Equilibrium between demand and generation required

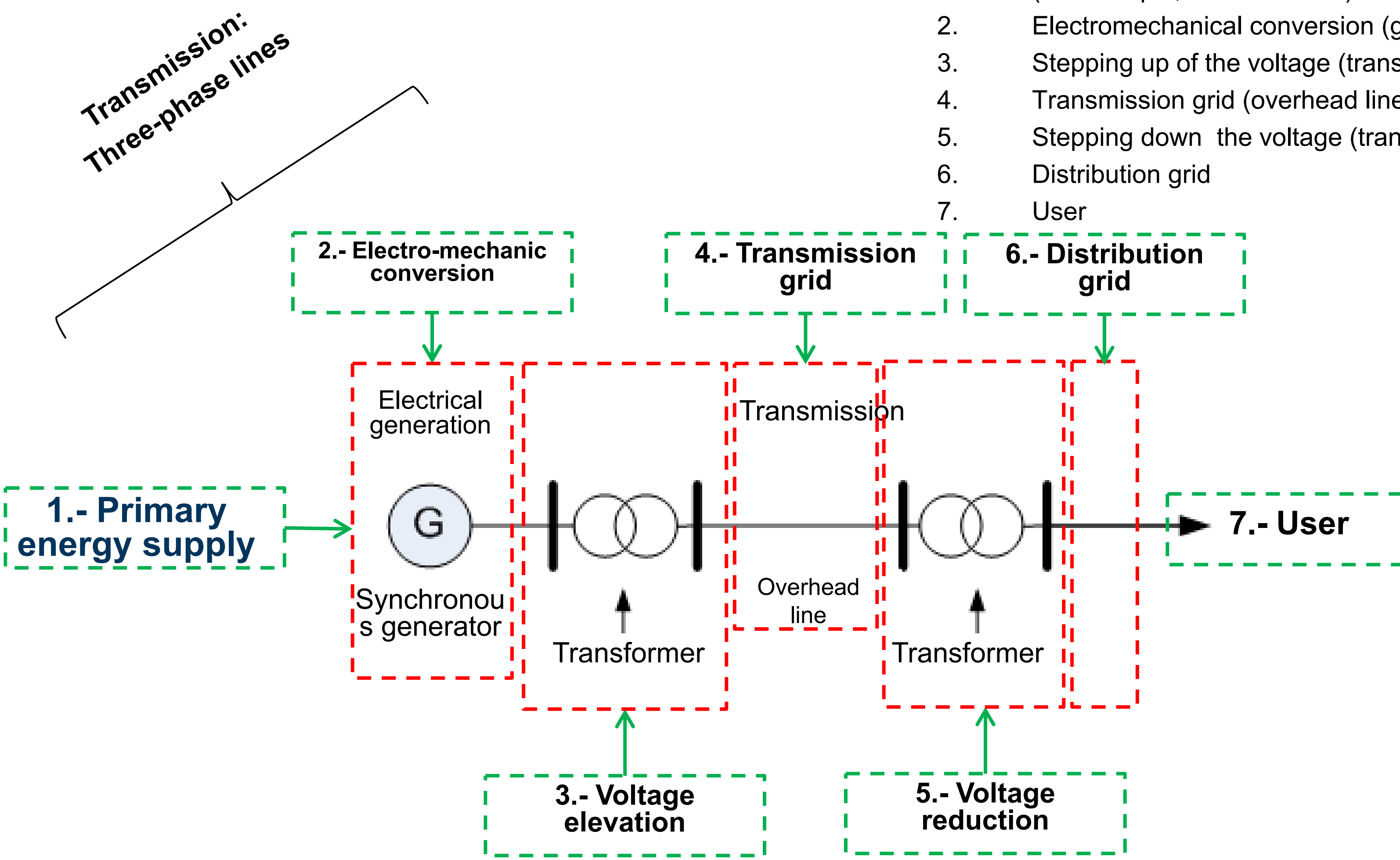


http://electricalacademia.com

Electric power system

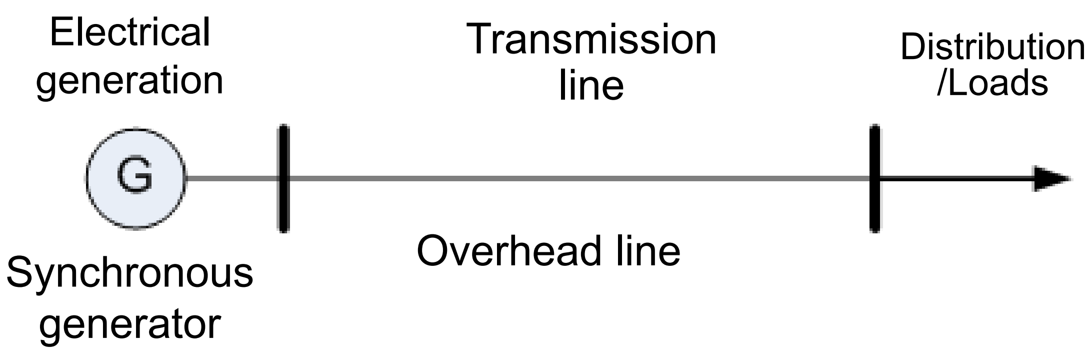
Classic system

1. Primary energy source to mechanical energy (for example, steam turbine)
2. Electromechanical conversion (generator)
3. Stepping up of the voltage (transformer)
4. Transmission grid (overhead line)
5. Stepping down the voltage (transformer)
6. Distribution grid
7. User



Electrical generation, transmission and distribution technologies

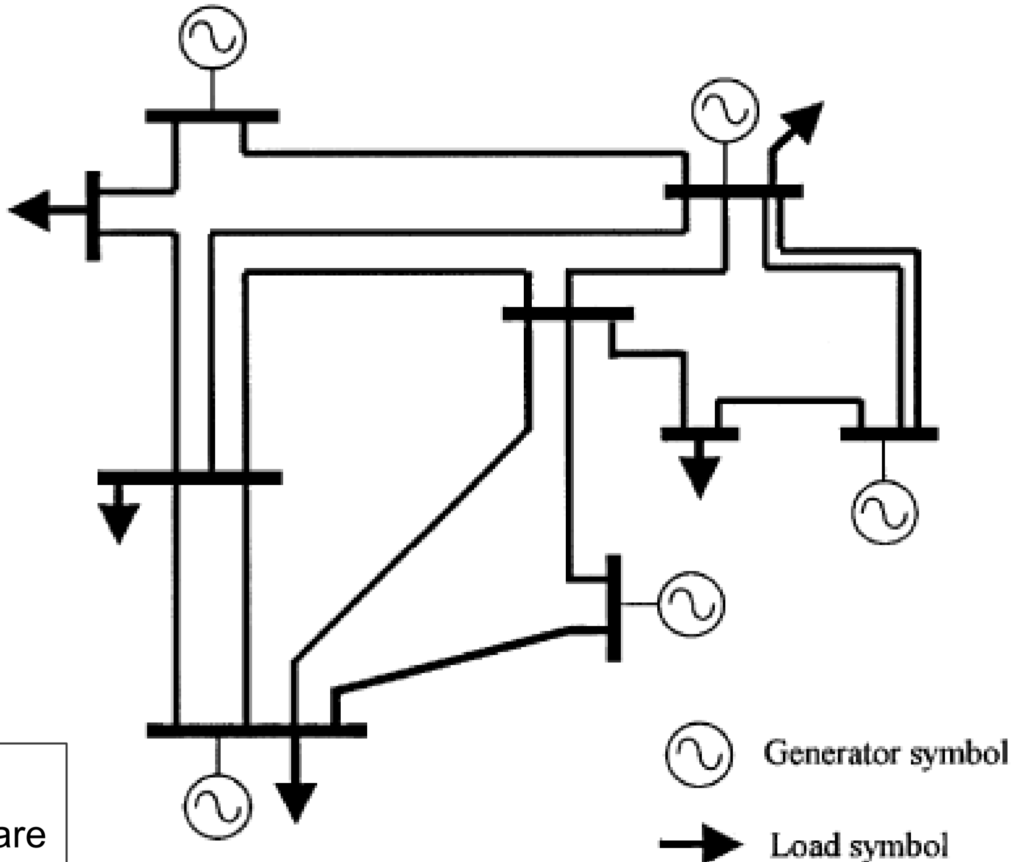
- Generation
  - Three-phase generators (synchronous)
- Transmission
  - DC (Direct current, high voltage)
  - AC (Alternating current)
- 3 phase AC system (predominant)
  - Transmission (high voltages): overhead lines or cables
  - Distribution (lower voltages): overhead lines or cables



Voltage and frequency as key quantities

- In a power system dominated by large synchronous generators, frequency is a **global** variable linked to the equilibrium between load and generation.
  - Generation > Load → Frequency increase
  - Generation < Load → Frequency decrease
  - Rate of change of frequency (generator speeds) depends on overall system **inertia** → faster change for low inertia systems.
- In modern and future power systems dominated by power electronics, the "meaning" of frequency can be defined and programmed in the converters. (It has not a physical meaning)
- Voltage is a **local** variable dependent on the power flows and power plants controls.

Electric power system: classical grid layout



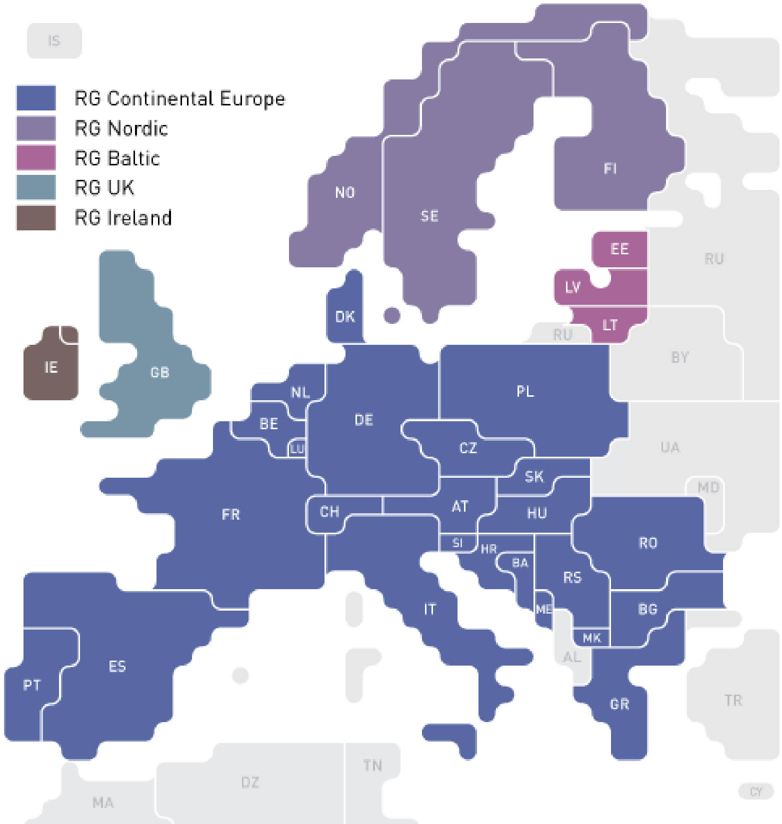
Note: all the connections are three-phase lines represented using single line diagram

Acha et al. “Power electronic control in electrical systems”

Power system characteristics

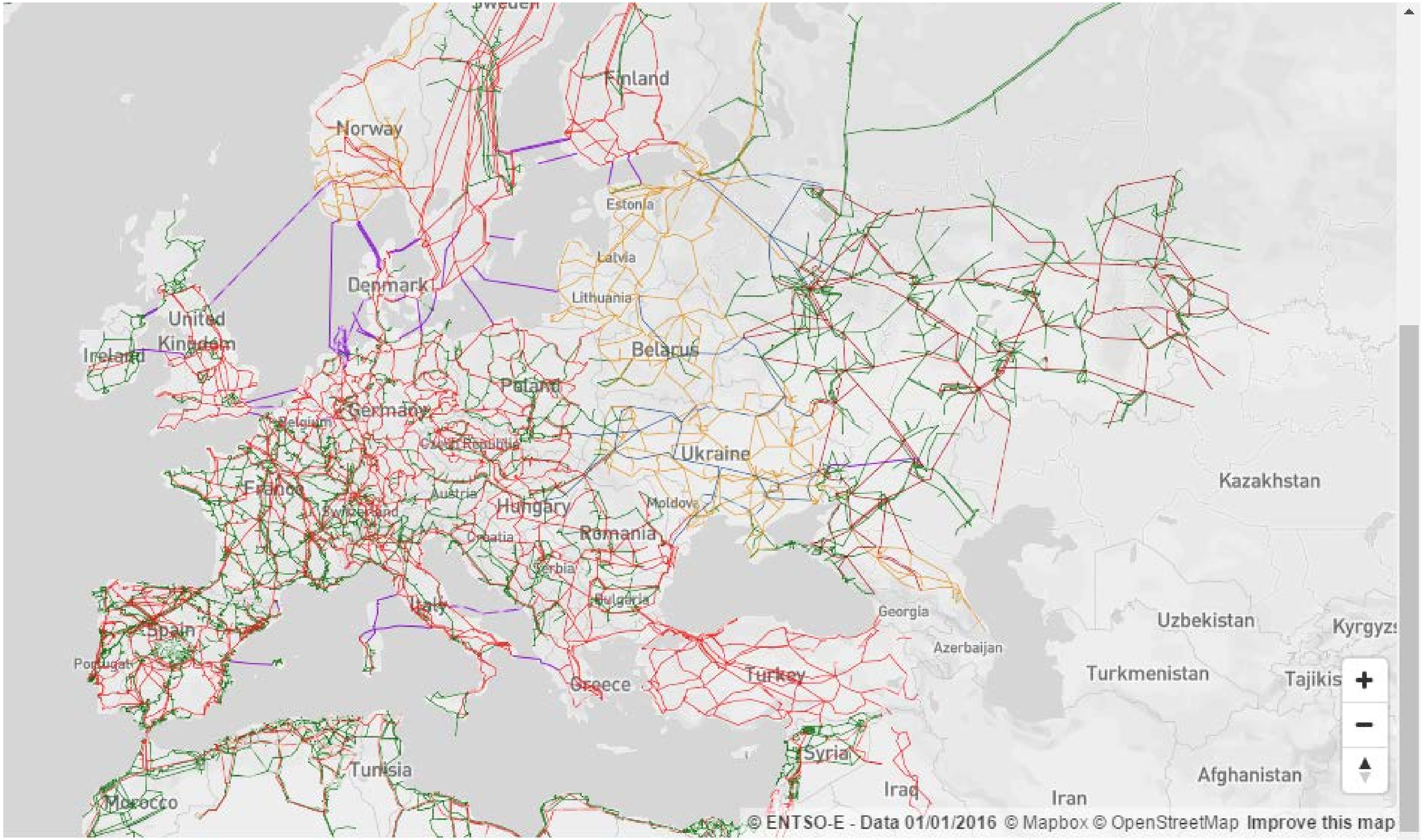
- Frequency
  - 50 Hz/ 60 Hz / other
  - DC?
- Normalized voltages
  - 3, 6, 10, 15, 20, 30, 45, 66, 132, 220, 400 kV
- Other used voltages
  - 11, 25, 110 kV
- Transport - Meshed
- Distribution - Meshed, radial operation

Voltage Levels	Magnitudes
Low Voltage (LV)	<1 kV
Medium Voltage (MV)	1 kV a 60 kV
High Voltage (HV)	60 kV a 275 kV
Ultra High Voltage (UHV)	>275 kV



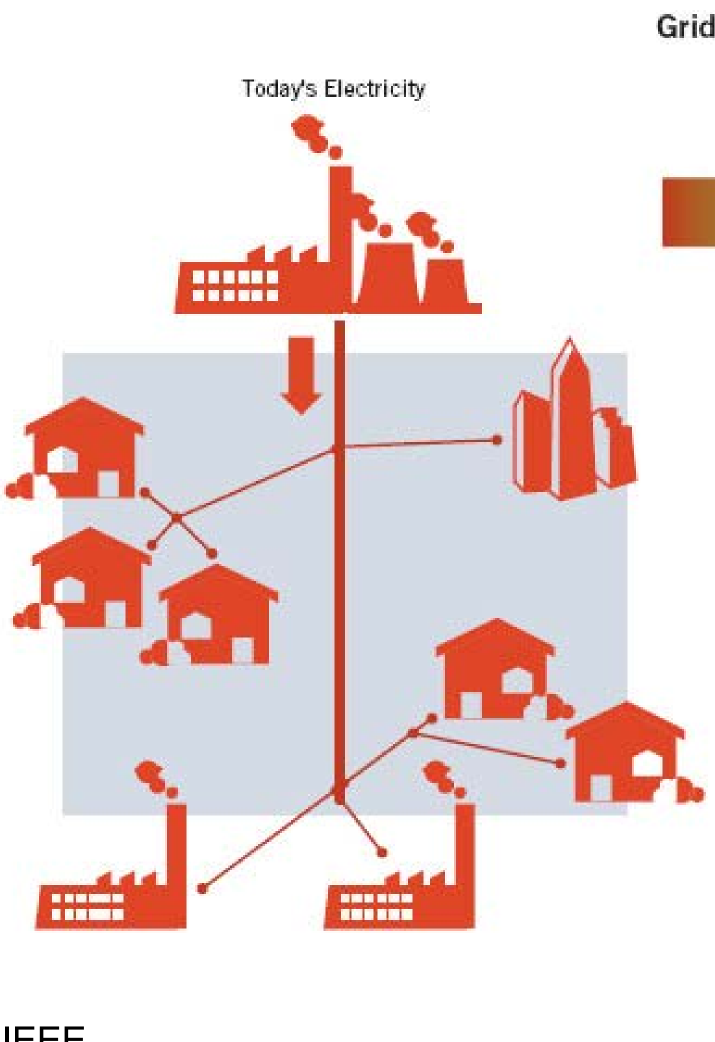
Synchronous zones in European power system. Source: ENTSO-E

The European electric power system



www.entsoe.eu

Power system transformation



Source: IEEE

New concepts in the power system

Classic system

• **Primary energy source to mechanical energy (steam turbine)**	G
• **Electromechanical conversion (electrical generator)**	G
• ***Stepping up of the voltage (transformer)***	GT
• *Transmission grid (overhead line)*	T
• *Stepping down the voltage (transformer)*	TD
• Distribution grid	D
• User	D

GENERATION
TRANSMISSION
DISTRIBUTION

New concepts

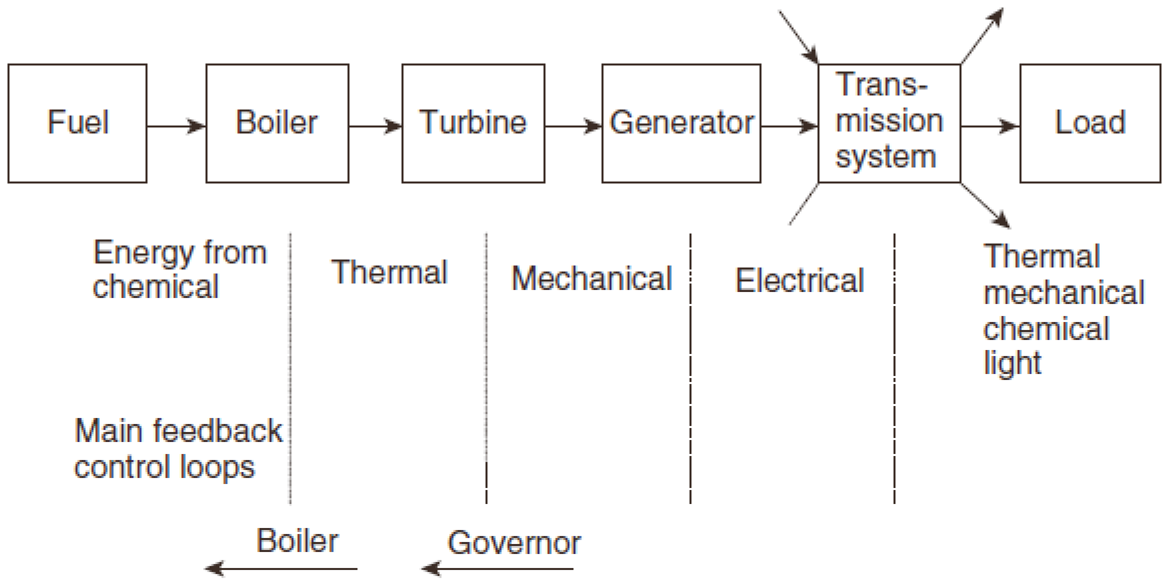
• **Distributed generation**	DG
• **Microgrids**	DG
• **Non-conventional renewable generation**	G
• *FACTS (Flexible AC Transmission systems)*	T
• *HVDC*	T
• ***Energy storage***	GTD
• Prosumers	D

Power system operator

- The system operator conducts the needed actions to ensure the security and continuity of supply, as well as the proper coordination between production and transmission, ensuring that the energy produced by the generators is transported to distribution networks under the quality conditions required by the regulations.

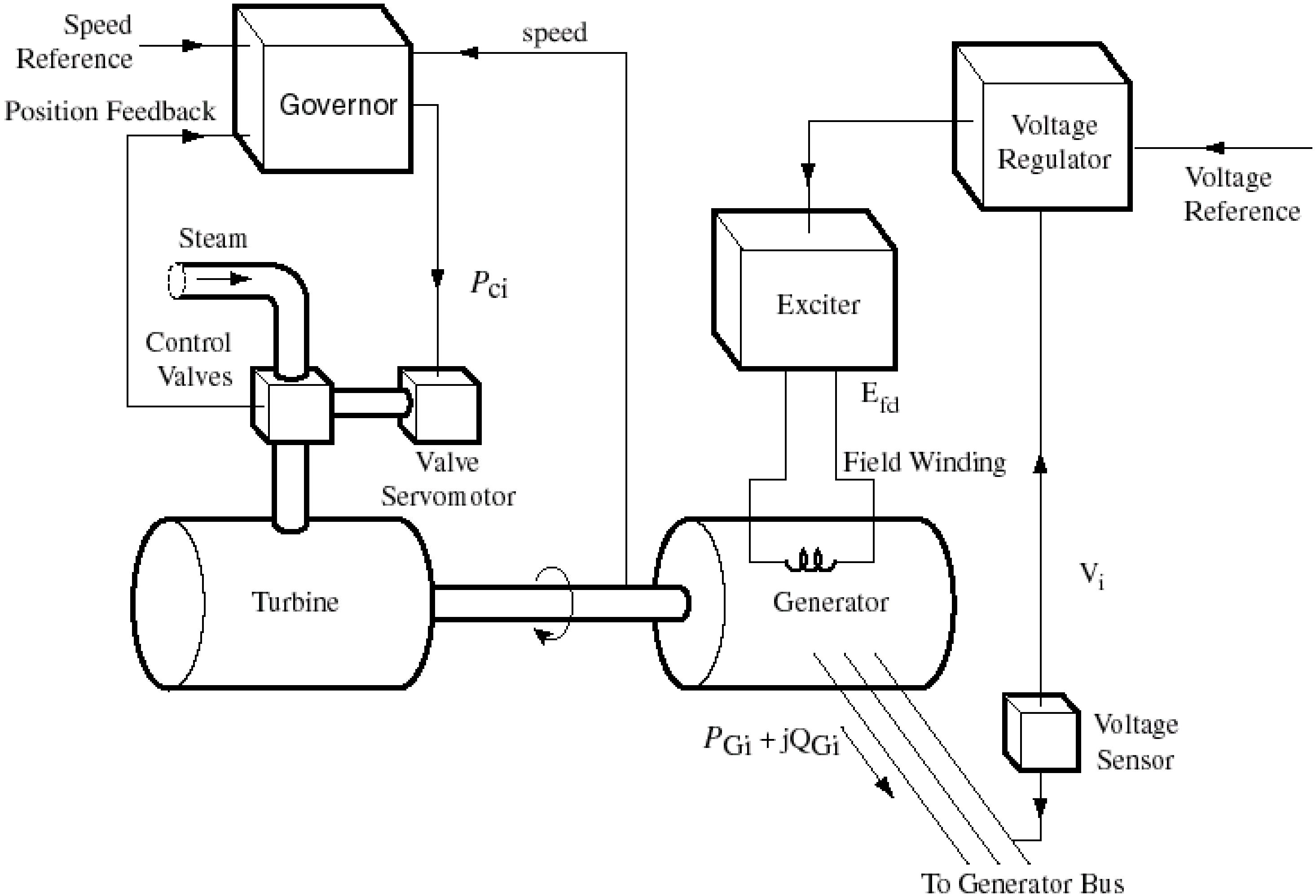
Conventional power plants regulation

FREQUENCY REGULATION <-> ACTIVE POWER
VOLTAGE REGULATION <-> REACTIVE POWER



Renewable Energy in Power Systems, Freires and Infield (2008) Wiley

Conceptual regulation of a conventional power plant



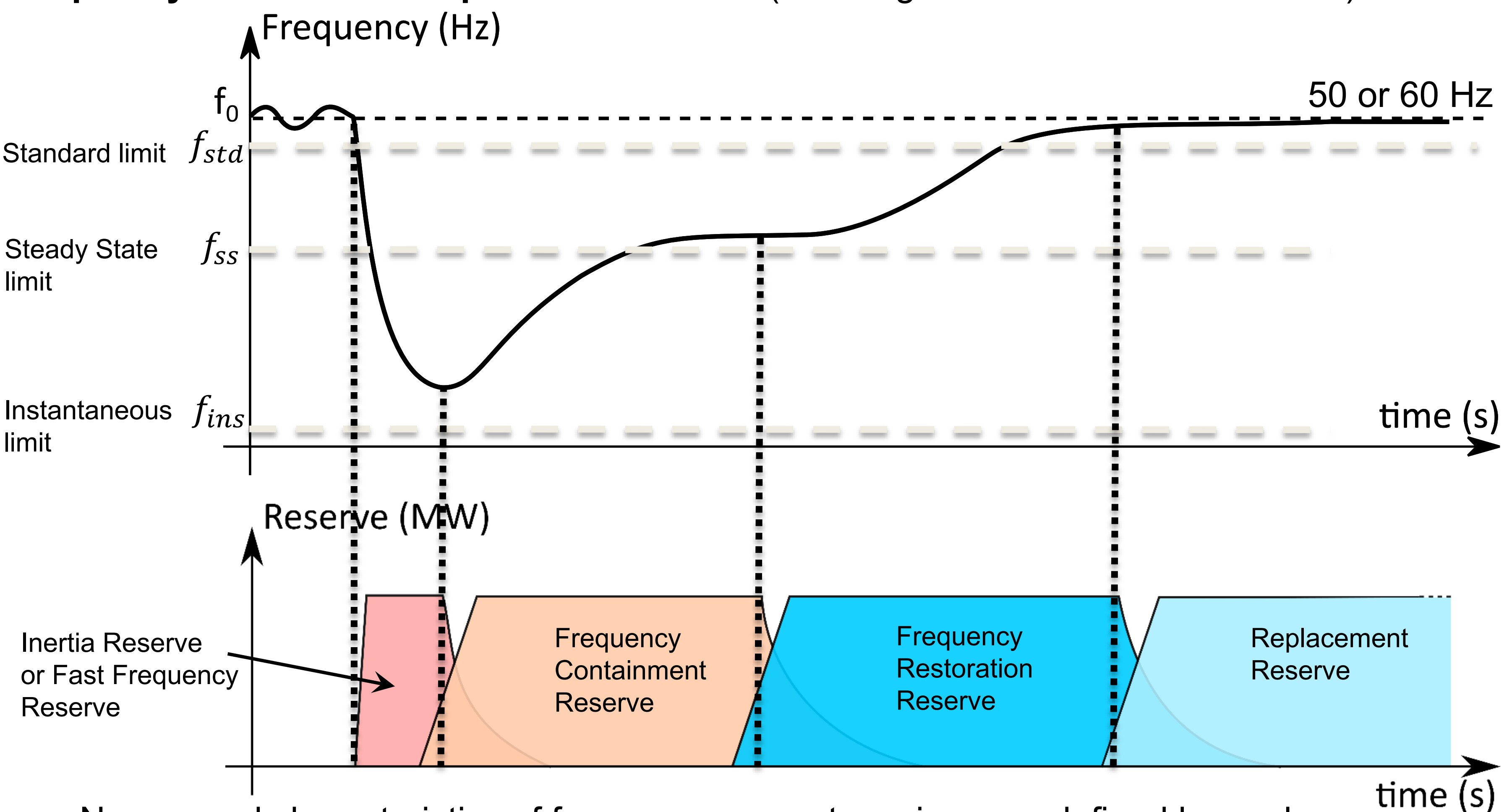
Les Hajagos, Kestrel Power Engineering, December 6-7, 2000, SERC

Frequency control

- Maintain **equilibrium generation-demand**
- Maintain the **frequency** of the system **constant**
- Accomplish the energy exchange agreements with neighboring areas
- Keep enough energy reserve

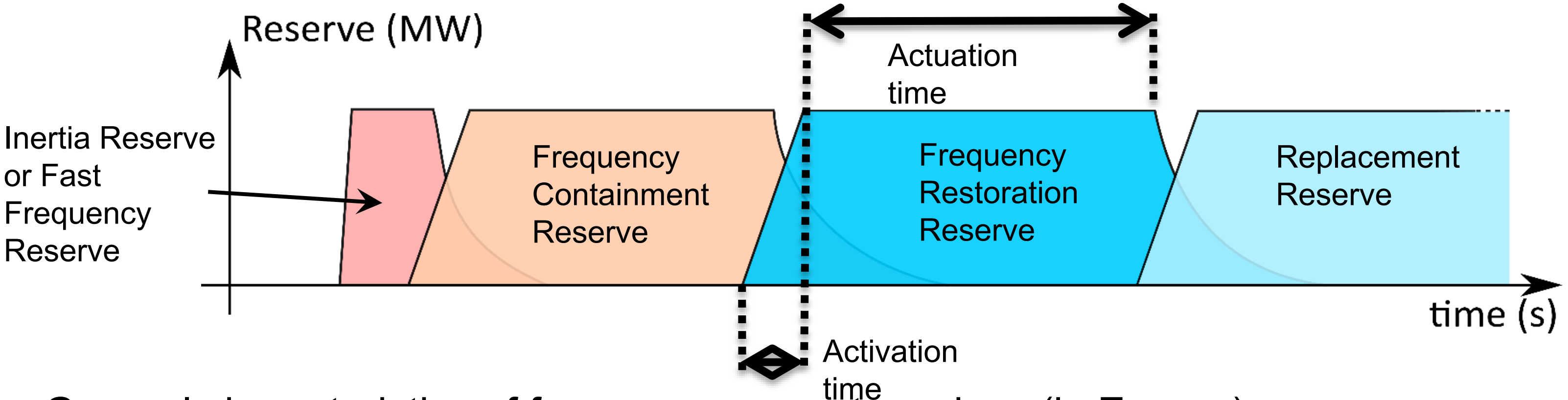
Frequency response

Frequency evolution after power imbalance (loss of generation/load connection)



- Names and characteristics of frequency support services are defined by each Transmission System Operator

Frequency response



General characteristics of frequency support services (in Europe)

Service	Activation	Activation Time	Actuation Time	Provision from Synchronous Generation
Inertia Reserve *(New service for non-Synchronous Generation)*	Automatic	< 1-2 s	~ seconds	Kinetic energy from rotation mass
Frequency Containment Reserve	Automatic	< 30 s	~ minutes	Governor (power-frequency droop control)
Frequency Restoration Reserve	Manual/ Automatic	~ minutes	As long as required	Manual power dispatch/ PI compensator
Replacement Reserve	Manual	~ minutes	As long as required	Manual power dispatch

From PV farms to PV power plants

- Renewables are increasingly required to be more grid friendly and provide regulation and flexibility to the power system where they are connected
- Grid integration of intermittent renewables is a challenge and the future of renewables is very related to it.
- The massive penetration of intermittent renewables (solar PV and wind farms) has raised the concern of system operators.
- Nowadays, renewable power plants do not only generate power when the resource is available (farms), they have to be operated as power plants supporting the power system.

Grid code requirements

- **Grid codes** are the **requirements** imposed by the **power system operators** that a **power plant** must **accomplish** to be connected (and to sell energy) to the grid.
- These requirements are detailed in a document **(Grid code)** that details which is the behavior of the power plant both in steady state conditions and during transient operation.
- For instance, in Spain the connection of wind power is defined in the Operational Procedure (PO) documents PO 12.2 y el PO 12.3.

Grid-code requirements – What needs to be controlled?

- Voltage and frequency support: Power plants are required to contribute to the voltage support with reactive power and to the frequency with active power.
- Active power control: Power plants can be demanded to curtail or control the active power to a given set-point.
- Reactive power control: Power plants can be demanded to regulate the reactive power to a given set-point.

Grid-code requirements – What needs to be controlled?

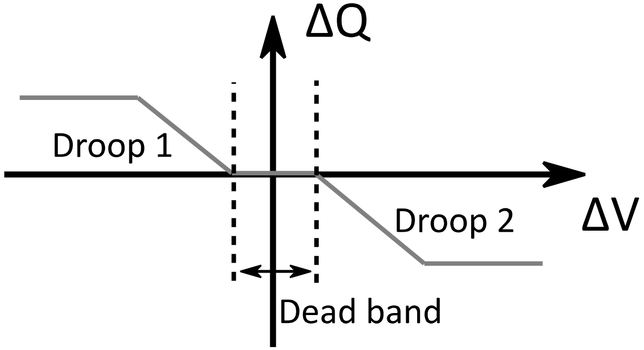
- Low and High Voltage Ride Through: Power plants are required to remain connected when there is large voltage deviation during a fault.
- Ramp control: Power plants need to limit the rate of change of the power injected to the network. Especially relevant for PV plants! Energy storage is needed.
- Inertia emulation: Power electronics based power plants can be demanded to emulate the inertia of synchronous generator.

Grid-code requirements – What needs to be controlled?

- Black-start: Power plants can be required to restore the system voltage and frequency and contribute to restart the system after a blackout.
- Grid forming: Power plants can be required to contribute to control the system synchronism, not synchronizing the converters with the existing grid, but imposing and creating (forming) a grid. This requirement is increasingly important for power systems dominated by converters.
- Power oscillation damping: Power plants can be required to damp oscillations of the system, adjusting active and/or reactive power injections.

Reactive Power & Voltage

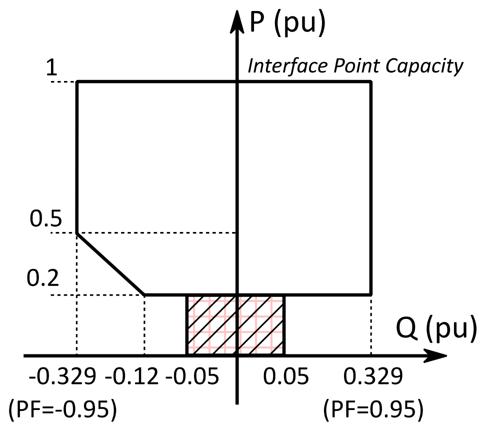
- Reactive power is provided by,
  - **PV inverters**
  - Other devices: **capacitors, synchronous condensers, FACTS or transformer regulation**.
- Possible control modes:
  - **Reactive power control**
  - **AC voltage control**
  - **Power factor control**
- Voltage control defined with a V-Q droop characteristic



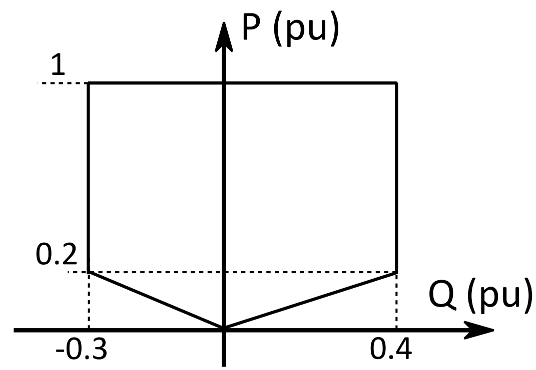
ΔV: voltage variation from nominal value
ΔQ: additional reactive power demand requested to WPP

Reactive Power & Voltage

- Grid codes define
  - Voltage operating range
  - **PQ curves**: reactive power limits depending on active power

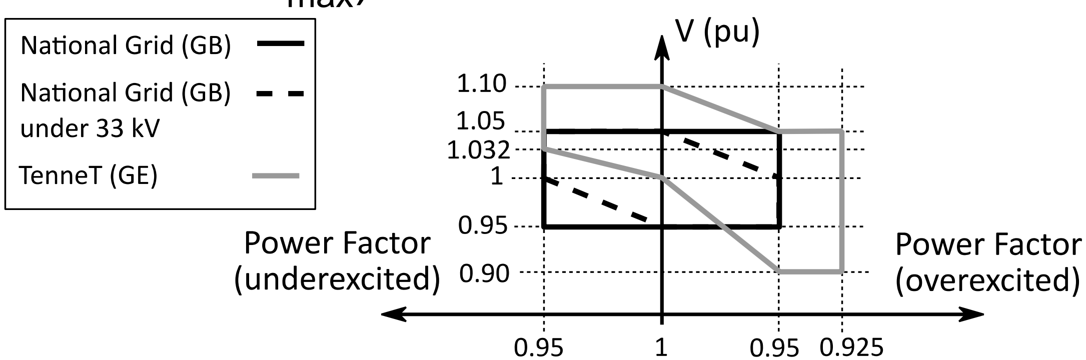


National Grid



TenneT

- **Voltage-power factor curves**: voltage limits depending on power factor (or similar, such as Q/P_{max})

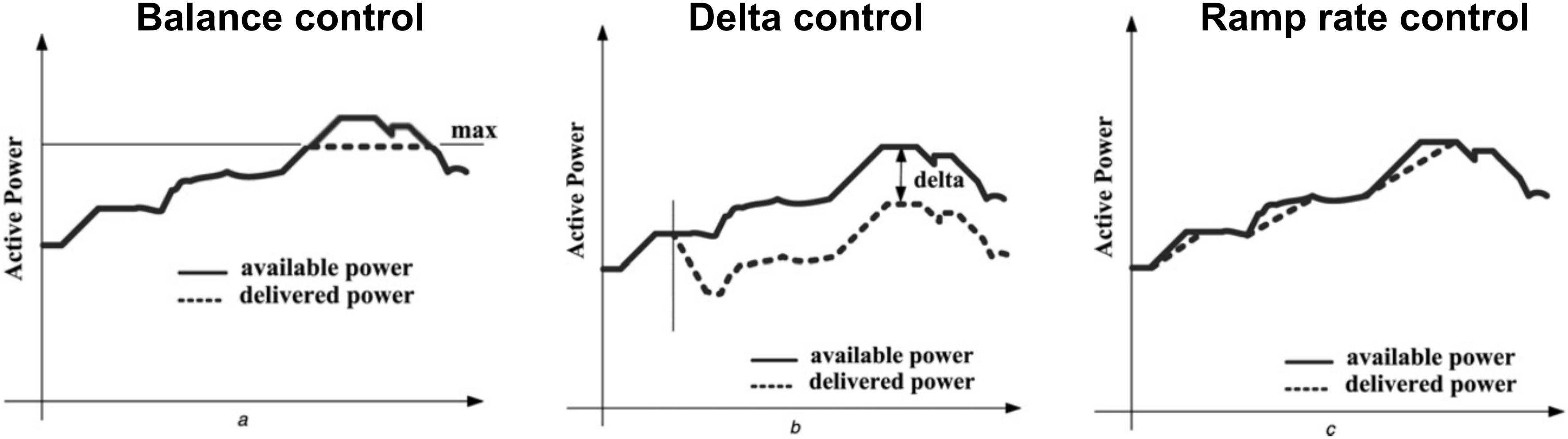


Active Power Management

- At renewable Plant level:

Normal operation	Maximum power extraction
Balance control	Limit to a constant value of active power
Delta control	Reduction of (constant amount) of generation
Power ramp rate control	Limitation of increase or decrease of active power

Balance control **Delta control** **Ramp rate control**



M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms, " *IET Renewable Power Generation*, 2009

Frequency response

- **No available inertia in solar PV power plants!**

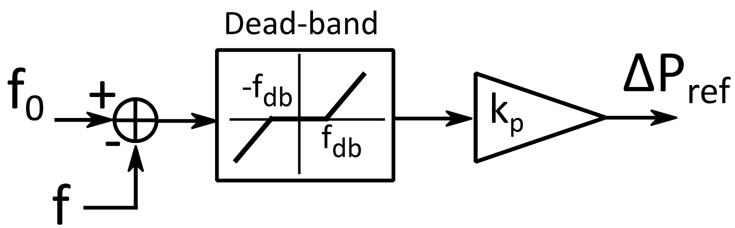
- **Over-frequency event.** The solar power plant can reduce power:
  - Adapting the operation point of the panels (related to MPPT)
  - Storing energy if energy storage is available.

- **Under-frequency event**. The solar power plant can increase power:
  - **Deloading operation** - the plant operates below the maximum possible power to ensure a power reserve.
  - Use energy storage systems.

Frequency response

Deloading operation:

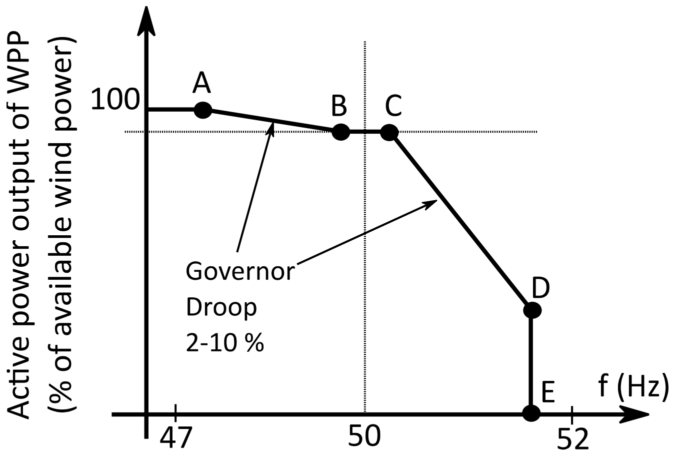
- It ensures power reserve for under-frequency events.
- Advantages:
    - It can be used to provide **any frequency support service**.
- Disadvantages:
    - Solar generation has to be permanently **curtailed**, which reduces the income from power generation.
- Implementation:
    - Droop control based on frequency deviation
    - Manual active power dispatch

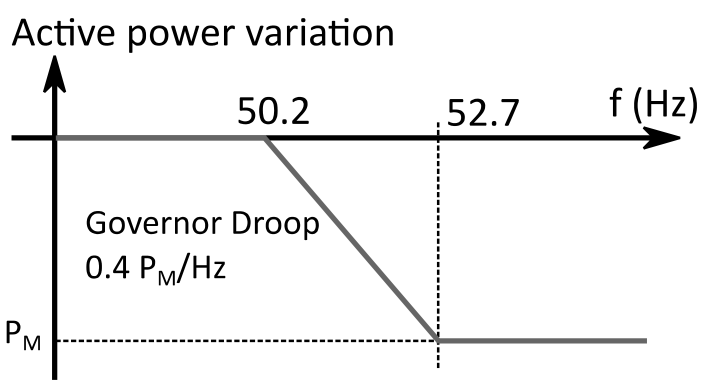


Frequency-power droop control with frequency dead-band

Frequency response

- Grid codes define
  - Frequency operating range
  - **Frequency-power droop characteristic:**



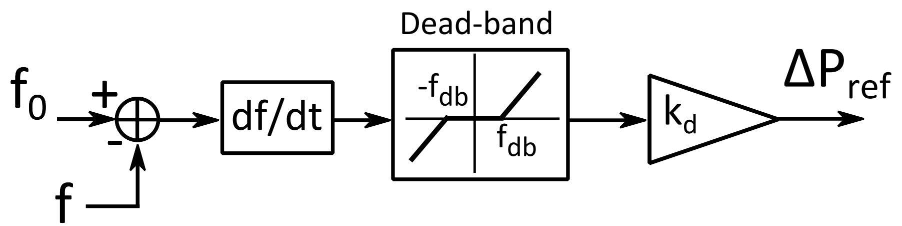


EirGrid
- Deadband between B-C
- Over and underfrequency events

TenneT
- Only overfrequency events

Inertia emulation

Inertia emulation or "synthetic inertia". Inertial response can be achieved proposing additional control schemes that affect the generated active power in the presence of frequency deviations, in order to allow them to behave similar to synchronized generating units in these situations.



$$\Delta E_k = \frac{1}{2} J_{wt} \left(\omega_0^2 - \omega_f^2 \right)$$

J_{wt}: *WT inertia constant*

Fault-Ride Through

- Capability to remain connected to the main grid during temporarily faults

Typical FRT profile

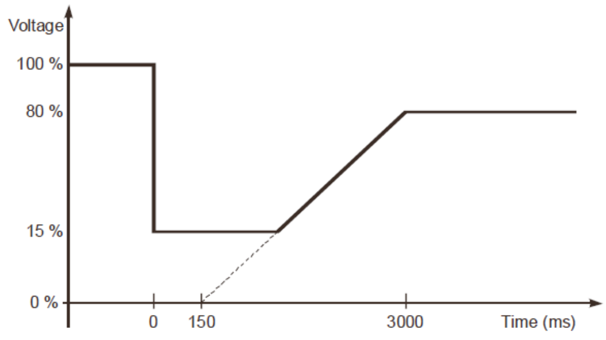
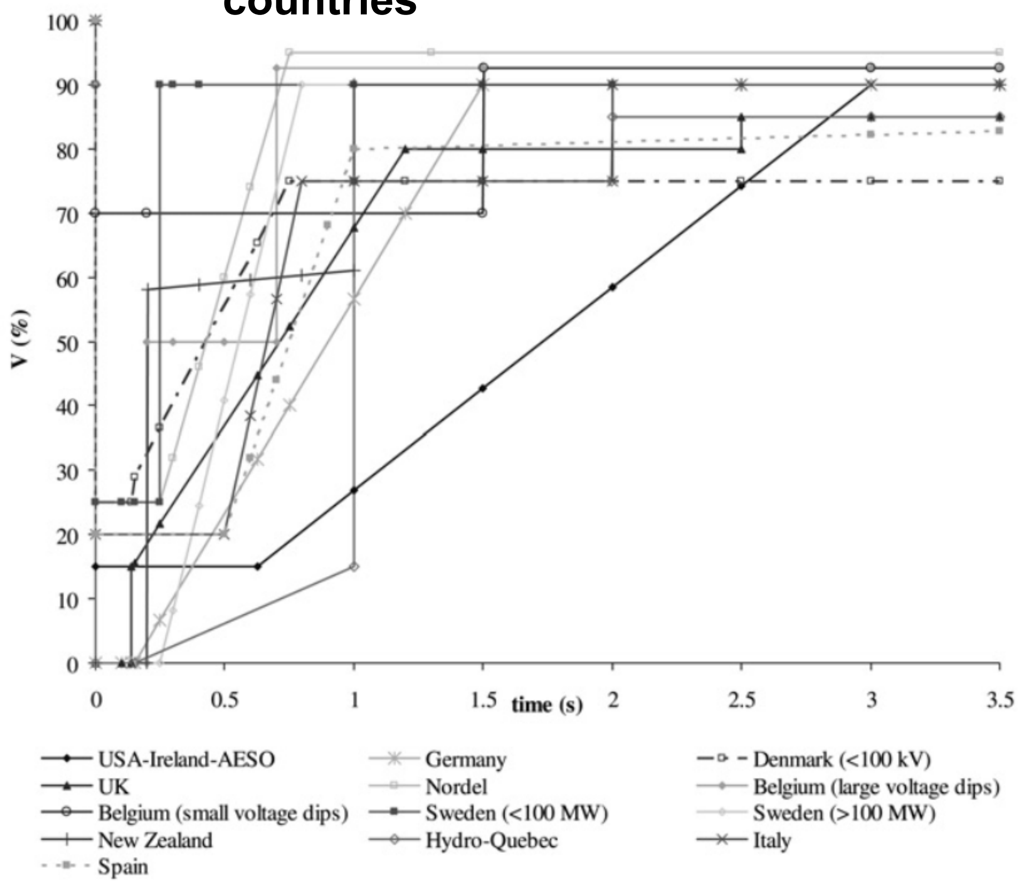


Figure 6.7 Fault ride-through voltage profile

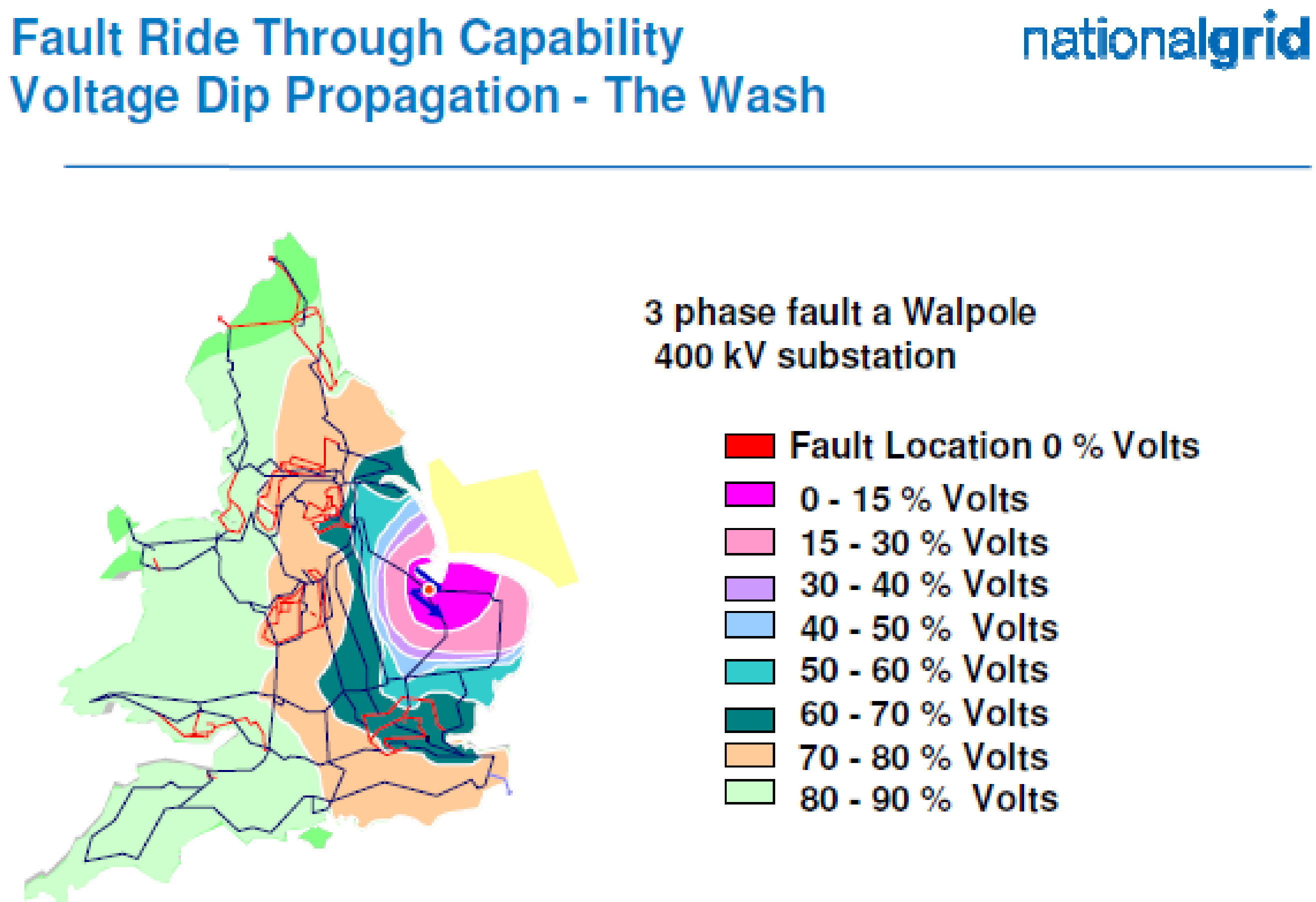
- The voltage must stay above the FRT profile during faults

FRT profile in different countries



M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms, " IET Renewable Power Generation, 2009

Example of a voltage sag propagation



http://www.nationalgrid.com/NR/rdonlyres/FA318C28-0CB2-4AA6-B7FE-F29AFA3FBBBC/56382/2FaultRideThroughBackground100912.pdf

Summary

- The power System is experiencing a deep transformation.
- Massive penetration of renewables (PV and wind) has raised the concern of system operators. PV power plants are not required only generate power when the resource is available (farms), they have to be operated as power plants supporting the power system.
- System support main requirements include voltage support, active and reactive power management, frequency support, inertia emulation, fault-ride through.

Thanks for your attention!

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