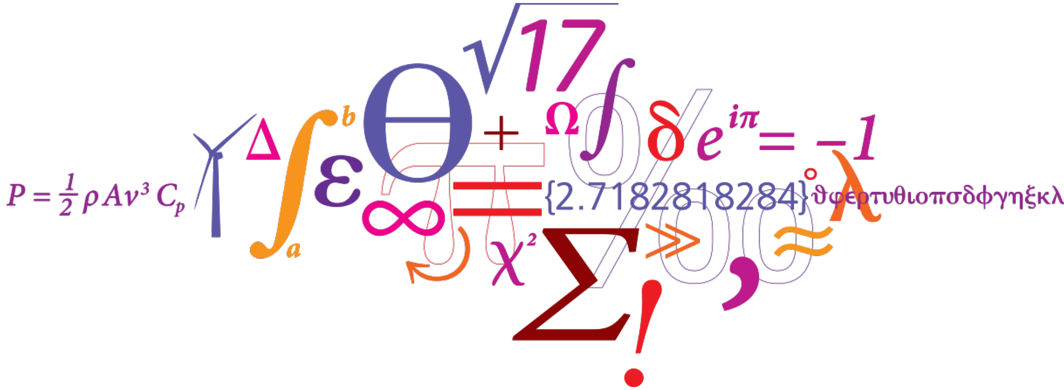
Power System Fundamentals – part II

a module of the

Grid Connection and Integration of Wind Power

part of the

DTU Online Master's Progamme



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Learning objectives

After this module you should be able to:

- Understand the **main characteristics** of **control of voltage and frequency** in power systems

- List the main **ancillary services**

- Describe the **basic principles** of power system **stability**

Definition of ancillary services

- CIGRÉ report - overview of International Practices
  - ***definitions*** for ancillary services can ***differ significantly*** based on who is using the terms. While some definitions emphasize the importance of ancillary services for ***system security and reliability***, others mention the use of ancillary services to ***support electricity transfers from generation to load*** and to ***maintain power quality***
- Some TSOs are including ***more specific types*** of ancillary services than others ***because***
  - ***differences in*** the ***definitions*** (above)
  - some of the required properties of the generation plants are ***embedded in conventional power plants*** using directly grid connected synchronous generators.
  - ***new ancillary service products*** seem to pop up in power systems ***with large scale penetration of renewables***.

Requirements for – and types of – ancillary services

- Active power ***reserves*** (using ENTSO-E glossary)
  - Frequency containment reserves (FCR)
  - Frequency restoration reserves (FRR)
  - Replacement reserves (RR)
- Properties required to ***maintain*** power system ***stability*** today (Energinet.dk terminology)
  - Short-circuit power
  - Continuous voltage control
  - Voltage support during faults
  - Inertia
- ***Possible new*** ancillary service ***products*** (research references)
  - Fast frequency response (includes “inertia”-like support)
  - Synchronising power
  - Power oscillation damping
  - Black-start capability

Control of frequency

- **The frequency of a system is dependent on the active power balance.**

- As frequency is a **common factor** throughout the system, a change in active power demand at one point is reflected throughout the system

- Because there are many generators supplying power into the system, some means must be provided to allocate change in demand to the generators:
  - **speed governor** on each generating unit provides primary speed control function
  - supplementary control originating at a central control center **allocates generation**

- The control of generation and frequency is commonly known as **load frequency control** (LFC) or **automatic generation control** (AGC).

Control of frequency

- Based on ENTSO-E definition (Network Code and Operation Handbook), Load Frequency Control (LFC) includes:
  - **Primary** frequency control.
  - **Secondary** power-frequency control.
  - **Tertiary** control.

- ENTSO-E refers to the reserves for frequency control as Operating Reserves (OR), and specifically indicates the abovementioned controls as:
  - Frequency Containment Reserves (**FCR**).
  - Frequency Restoration Reserves (**FRR**).
    - Automatic FRR (aFRR)
    - Manual FRR (mFRR)
  - Replacement Reserves (**RR**).

Control of frequency

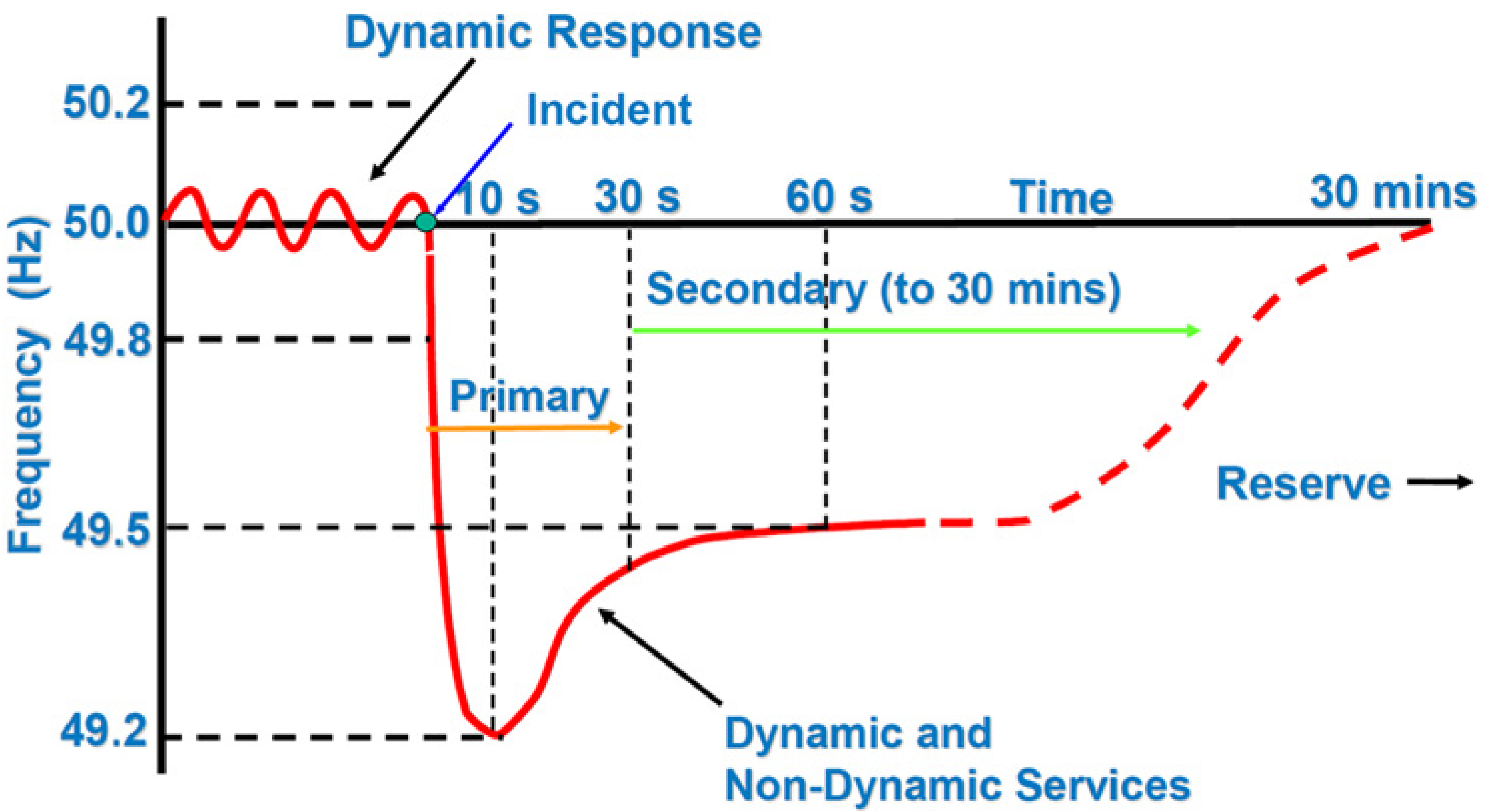
- The **primary frequency control** (automatic) aims at achieving the operational reliability of the synchronous area, by stabilizing the system frequency in the time-frame of seconds (within 30s) at an acceptable stationary value after a disturbance or incident.

- The **secondary frequency control** (automatic or manual) aims to restore within few minutes (15 minutes after incident) the system frequency in the time frame defined within the synchronous area by releasing system-wide activated frequency containment reserves. For large interconnected systems, where a de-centralised frequency restoration control is implemented, frequency restoration also aims at restoring the balance between generation and load for each TSO, and consequently restore power exchanges between TSOs to their set point.

- The **tertiary control**, activated manually and centrally at the TSO control center, aims to restore the operating reserve or to anticipate on expected imbalances. Typically the activation time is from 15 minutes up to hours.

Control of frequency

Mechanics of frequency control



Source: National Grid

Control of voltage

- The **objective of voltage control is to maintain an optimal operation of the electrical network**, while providing the consumers within a pre-defined voltage quality.

- In practical network operation the **voltage** needs to be continuously **monitored** to ensure that the power supply conforms to the regulation and does not produce any **damage** to the connected equipment.

- The control of the voltage can be performed at three different time scales that are called **primary** voltage control, **secondary** voltage control.

Control of voltage

- **Primary voltage control** is the automatic control performed by voltage controllers in the range of milliseconds since a deviation of the voltage respect to the set point is detected. An automatic voltage regulator acts on the excitation field of a generator to keep the required voltage at its terminals.

- **Secondary voltage control** is a slower control in the range of seconds to a minute that acts to bring the voltage in a region back to the normal profile. The objective of this control is to restore the voltage profiles to the required values within a region, but minimizing circulating reactive power flows and maximizing reactive reserves. The main actuators are the set-point voltages of the primary controllers of the generators within a region.

Control of voltage

- Control of voltage levels is accomplished by **controlling** the production, absorption, and flow of **reactive power** at all levels in the system

- Generating units provide the **basic means** of voltage control

- Additional means are usually required to control voltage throughout the system:
  - **sources or sinks of reactive power**, such as shunt capacitors, shunt reactors, synchronous condensers, and static VAr compensators (SVCs)
  - **line reactance compensators**, such as series capacitors
  - **regulating transformers**, such as tap-changing transformers and boosters

- **Voltage regulation bring benefits also to the active power transfer capability**

Power system stability

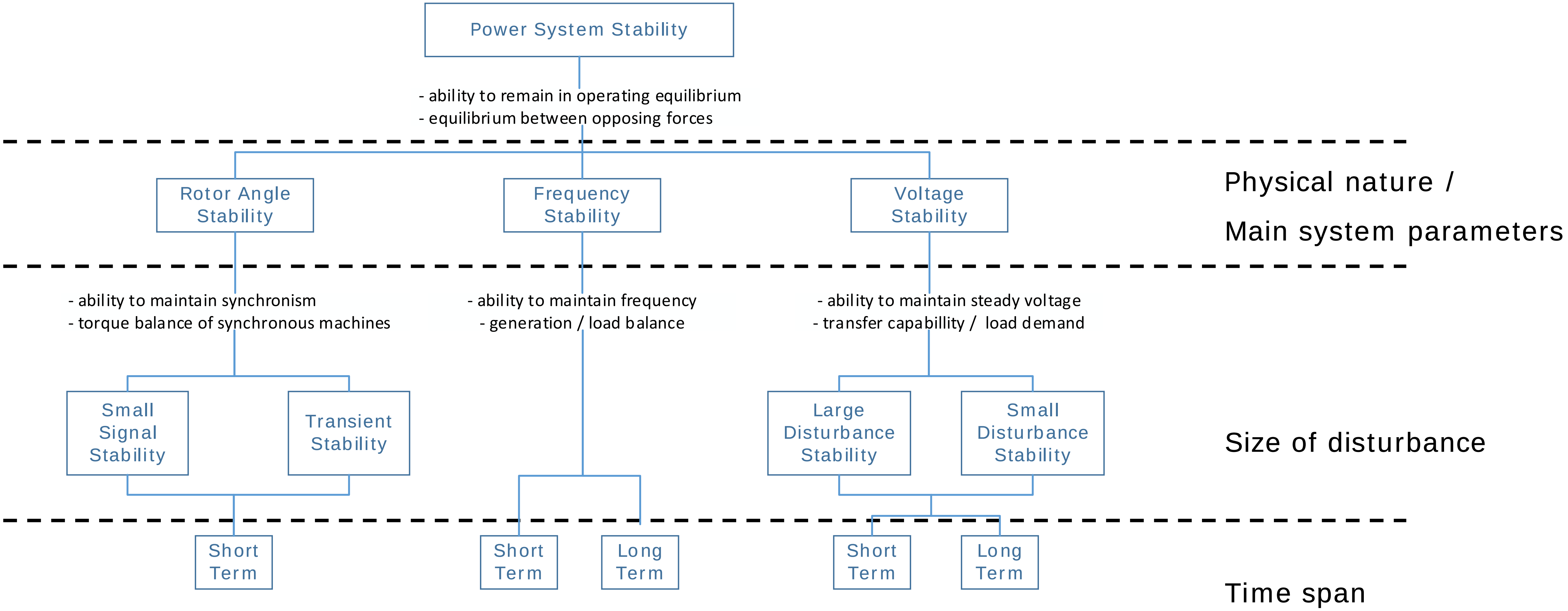
- A system is stable if it **regains a state of operating equilibrium after being subjected to a physical disturbance**, with all system variables bounded so that the system integrity is preserved.

- **The power system is a highly nonlinear system which operates in a constantly changing environment** (loads, generator outputs, topology and key operating parameters change continually).

- When subjected to a disturbance, the system stability depends on:
  - **nature** of the **disturbance**
  - **initial** operating **condition**

- The **disturbances** may be small or large:
  - **small** disturbances in the form of load changes occur continually
  - **large** disturbances of a severe nature, such as a short-circuit on a transmission line or loss of a large generator

Power system stability classification



P. Kundur, et al., "Definitions and Classifications of Power System Stability", IEEE Trans. on Power Systems, pp. 1387-1401, 2004

Rotor angle stability

- **Rotor angle stability** is the ability of interconnected synchronous machines to remain in **synchronism** under normal operating conditions and after being subjected to a disturbance.

- Rotor angle stability depends on the ability to **restore / maintain** equilibrium between **electromagnetic** torque and **mechanical** torque of each synchronous machine in the system.

- A fundamental factor involved in the stability problem is the manner in which the **power output** from the machines **varies** as their rotor oscillate.

Frequency stability

- **Ability to maintain steady frequency within a nominal range following a disturbance resulting in a significant imbalance between system generation and load**:
  - instability that may result occurs in the form of sustained frequency swings leading to tripping of generating units and/or loads
  - determined by the overall response of the system as evidenced by its mean frequency rather than relative motions of rotors of generators

- In a small “island” system, frequency stability could be of concern for any disturbance causing a significant loss of load and/or generation

- In a large interconnected system, frequency stability would be of concern only following a severe system upset resulting in the system splitting into one or more islands

Frequency stability – case study

- Disturbance on 4.10.2006
- Significant East-West power flows as a result of international power trade and the obligatory exchange of wind feed-in inside Germany
- Disconnection of double circuit 380 kV line Conneforde-Diele
- Overload on other lines, cascade tripping, loss of synchronims, system separated

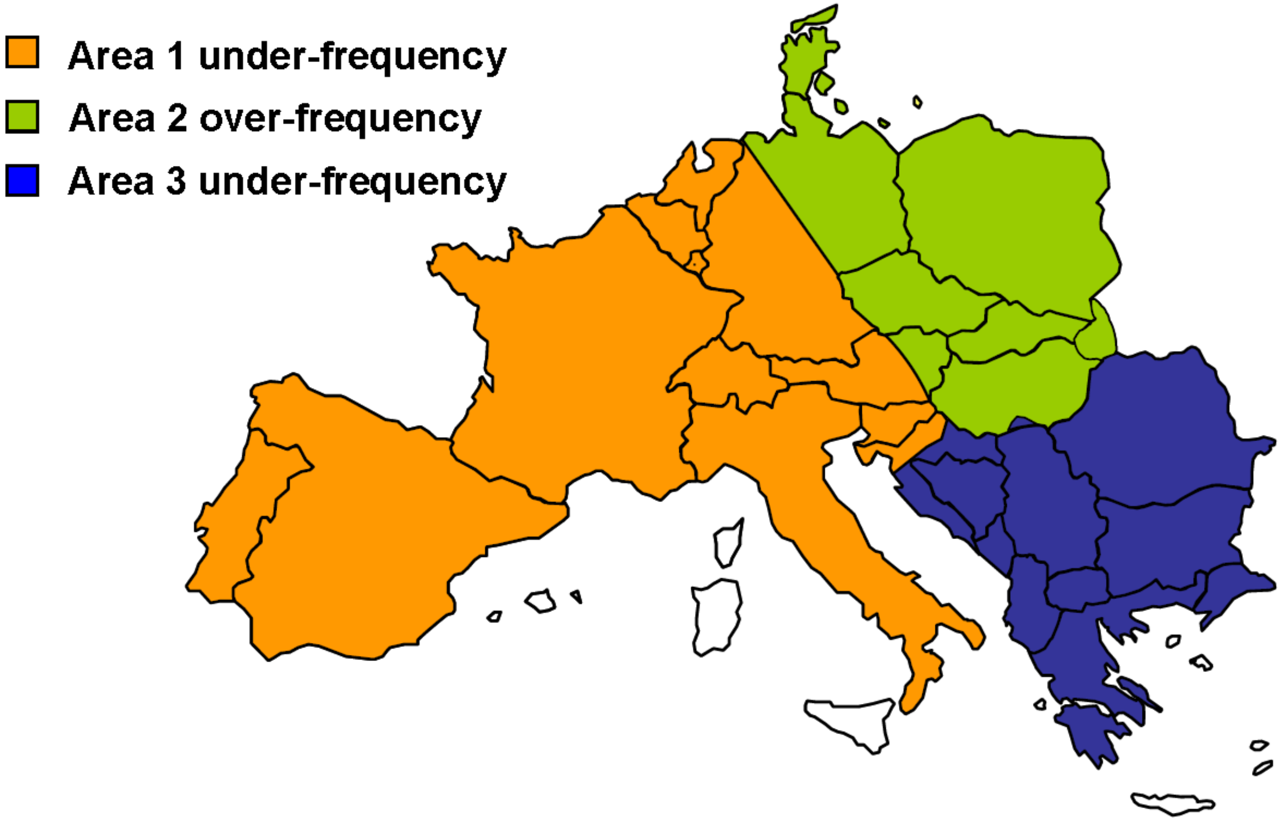
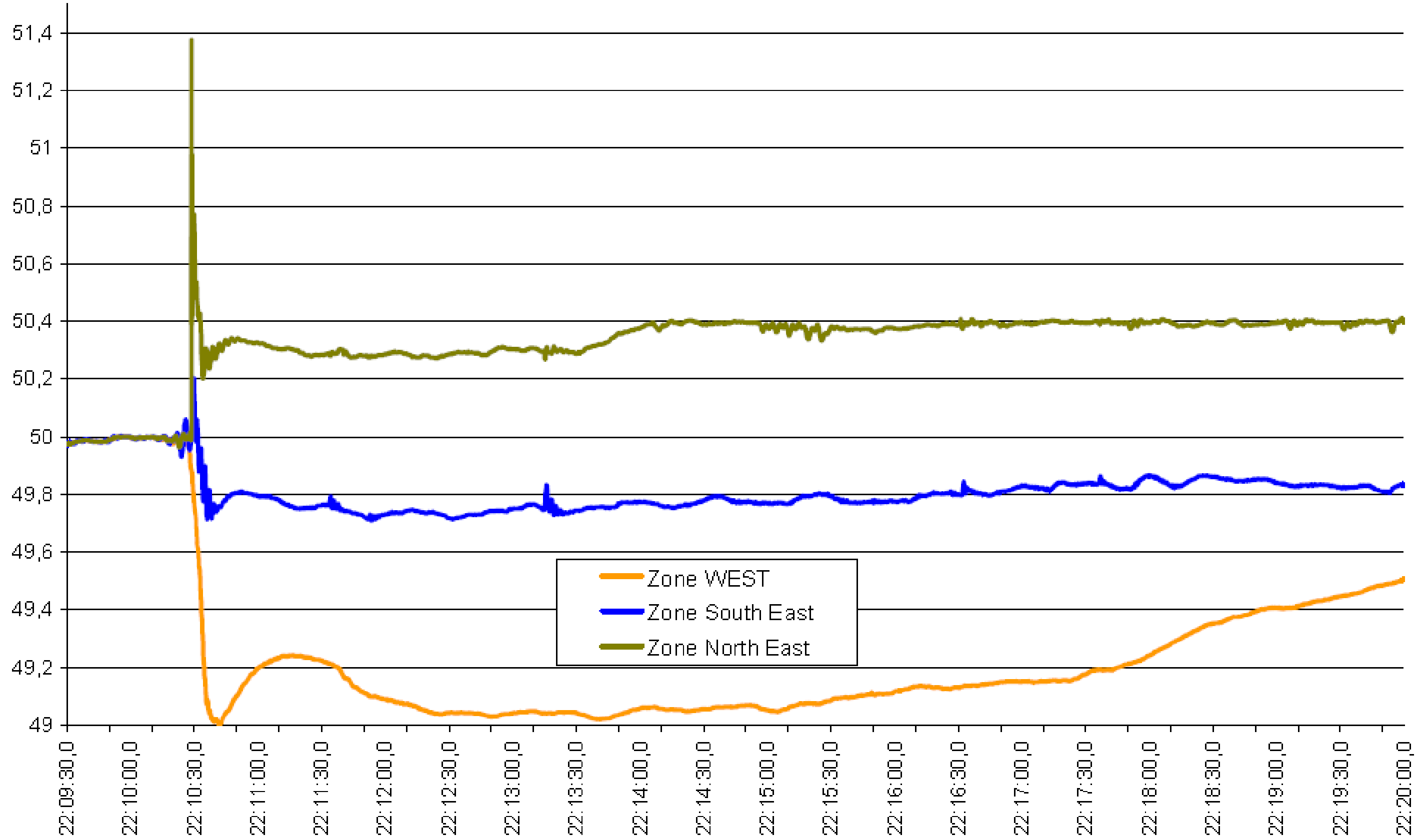


Figure 4: Schematic map of UCTE area split into three areas

G. Maas, M. Bial, J. Fijalkowski, Final report-system disturbance on 4 November 2006, Tech. rep., Union for the Coordination of Transmission of Electricity in Europe (2007).

Frequency stability – case study



6200MW wind generation tripped due to over frequency

AGC reduced frequency to 50.3Hz

Wind power started to reconnect automatically

Initial generation deficit of 770MW

One additional unit of 120MW tripped

No load shedding

Initial power imbalance: 8940 MW deficit

Largest frequency gradient: 120 - 150 mHz/s

Hydro plant storage pumps shed: 1600MW

Load shed during first 8s: 17000 MW

G. Maas, M. Bial, J. Fijalkowski, Final report-system disturbance on 4 November 2006, Tech. rep., Union for the Coordination of Transmission of Electricity in Europe (2007).

Voltage stability

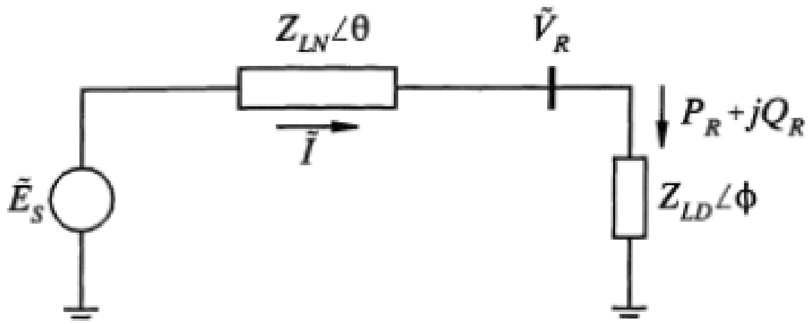
- **Ability of power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition**

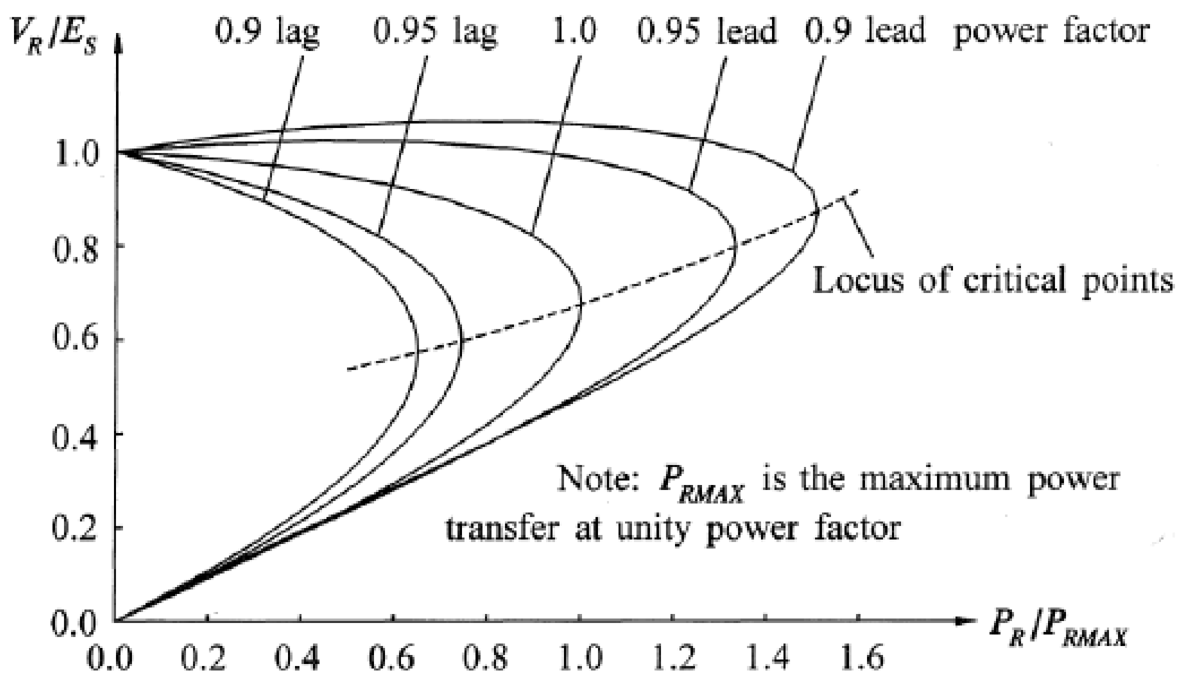
- A system experiences voltage instability when a disturbance, increase in load demand, or change in system condition causes

- Main factor causing voltage instability is the inability of power system to maintain a proper balance of reactive power and voltage control actions

- The driving force for voltage instability is usually the load, following a condition of reduced transmission system voltages

Voltage stability example – nose curve





Summary

- Analyzed the main **features** regarding control of voltage and frequency
- Defined their **connection** to the **ancillary services**
- Listed the main power system **stability issues** and how they are used for evaluating the **operating criteria** of a power system