SOLUTIONS FOR POWER SYSTEM STABILITY UNDER RENEWABLES DOMINATED OPERATING CONDITIONS

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The transition from fossil-based to renewable-based power generation is a challenge for the power system operators in adapting the control system design to ensure the system stability. There are two main changes that occur in power systems by the energy transition, i.e. the unpredictability of the renewable energy sources and the reduced mechanical inertia available in the rotational masses caused by the increased number of generation sources interfaced by power electronics. The problems that may occur spans from very fast phenomena, in the range of milliseconds, e.g. angle and frequency stability, to slow phenomena, in the range of tens of minutes or hours, e.g. load balancing. This keynote speech addresses some solutions that are designed to deal with the mentioned problems, among which the use of battery energy storage systems, the integration of the microgrids and virtual power plants into the frequency control loops, the use of syncrophasors for wide area monitoring and control. Additionally, asynchronously interconnected microgrids are promoted as resilience solutions in local energy communities.

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Solutions for power system stability under renewables dominated operating conditions

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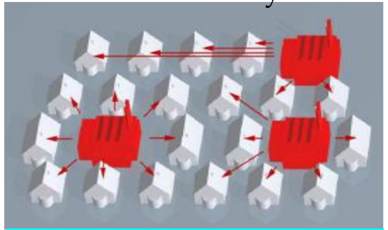
THE ENERGY TRANSITION

THE ENERGY TRANSITION

19th Century

Electrification society
“the coal age”

Unsustainable system



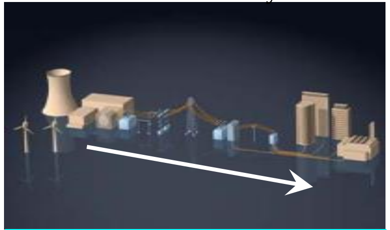
Generation and load ate islanded
Islanded supply and stochastic load

Fossil fuel based sources, hydro

20th Century

Development and diversification of generation
“fossil fuels age”

Unsustainable system

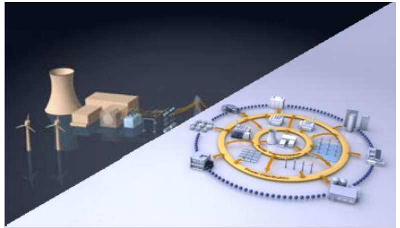


Generation follows the load
Integrated network, central generation, predictible stochastic load, unidirectional load flow

Fossil fuel based sources, hydro, nuclear

21st Century

Transition to the age of electrification
Challenges for a new approach
1) Demographics; 2) Resources availability; 3) Climatic changes



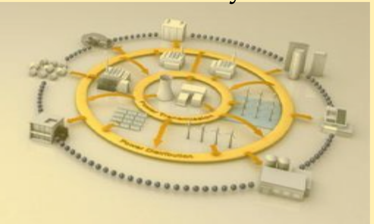
Choice to use various generation sources
Decentralization, Intermittent generation, the consumer becomes prosumer

Fossil fuel based sources, hydro, nuclear, biomass, wind, solar

21st Century

New electricity age
The electricity will be the energy source for most of the daily applications

Sustainable system



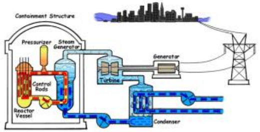
Load follows generation
Centralized + decentralized generation, intelligence with ICT, bidirectional load flows

Renewable energy sources (wind, solar, hydro, biomass) clean coal, gas, nuclear

THE ENERGY TRANSITION

NATURAL GAS

COAL

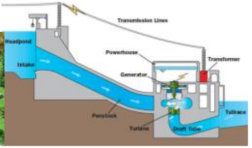


NUCLEAR

- Predictable
- Available

- Operate as base load power plants

HYDRO



- Predictable
- Less available

- Very flexible
- Appropriate for fast control

- Less predictable
- Randomly available

- Very volatile
- Unsuitable to ensure stability

On the frequency stability in power systems

FREQUENCY DEFINITION

ENTSO-E, Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators, 2016.

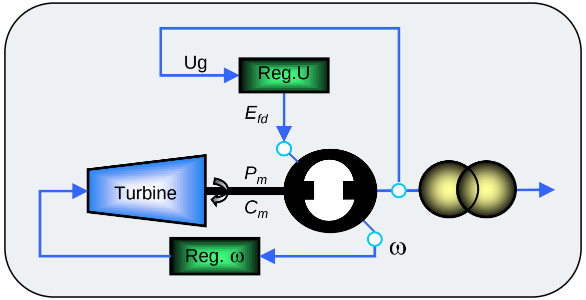
- **frequency** means the electric frequency of the system expressed in hertz that can be measured in all parts of the synchronous area under the assumption of a consistent value for the system in the time frame of seconds, with only minor differences between different measurement locations. Its nominal value is 50 Hz.

!

- the frequency slightly fluctuates from bus to bus due first to local load variations;
- the machines are all the time in transient state and hence small differences in the frequency value exist because of multiple factors;
- short-circuits and contingencies are the most dangerous conditions that can lead to large frequency fluctuations and, in some cases to the loss of synchronism of some generator and, even, to the collapse of the whole system;

WHERE TO MEASURE THE FREQUENCY?

- Synchronously connected

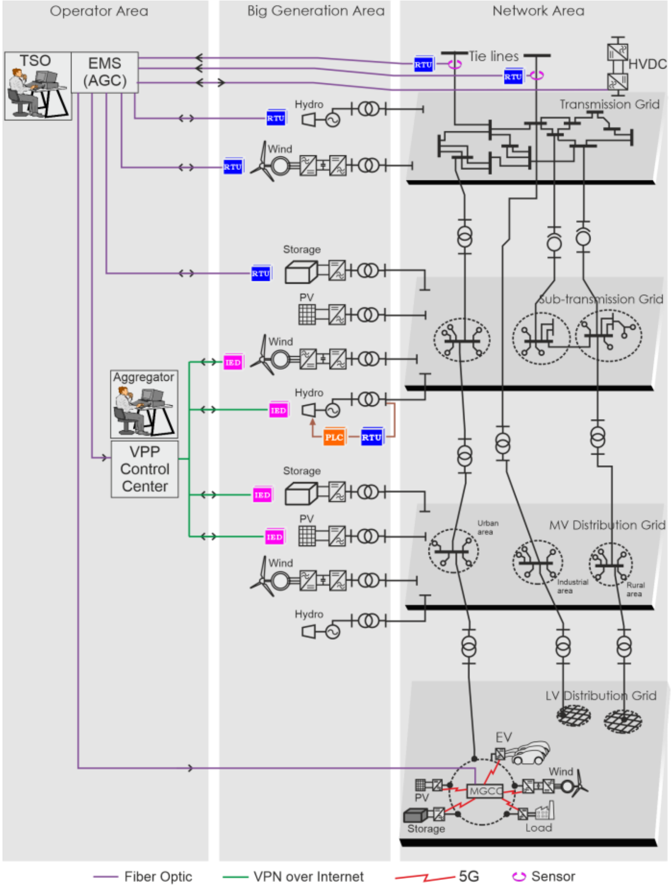


- rotor speed

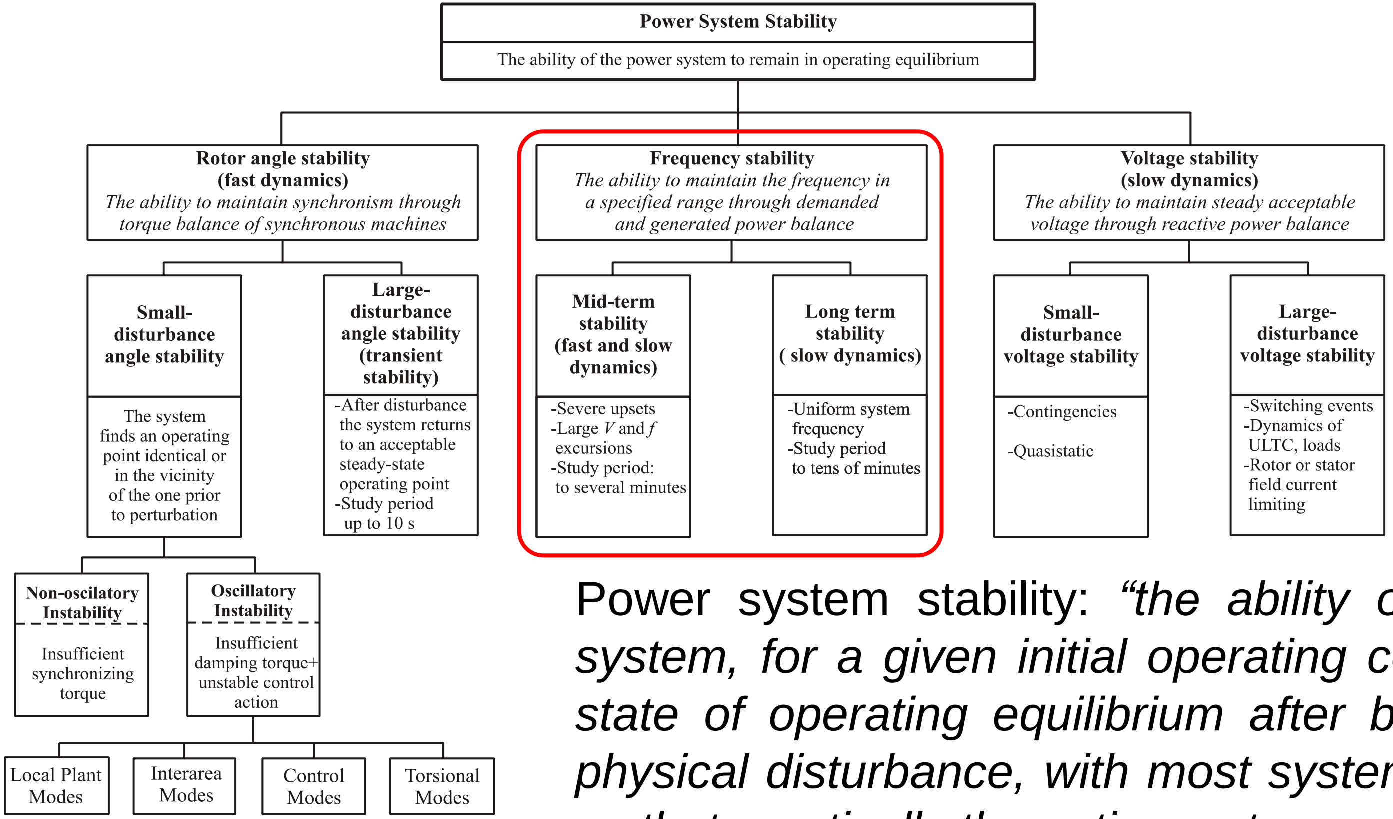
- Asynchronously connected

- PLL output

Power converter



POWER SYSTEM STABILITY



Power System Stability

The ability of the power system to remain in operating equilibrium

Rotor angle stability (fast dynamics)

The ability to maintain synchronism through torque balance of synchronous machines

Small-disturbance angle stability

The system finds an operating point identical or in the vicinity of the one prior to perturbation

Non-oscilatory Instability

Insufficient synchronizing torque

Oscillatory Instability

Insufficient damping torque+ unstable control action

Local Plant Modes

Interarea Modes

Control Modes

Torsional Modes

Large-disturbance angle stability (transient stability)

-After disturbance the system returns to an acceptable steady-state operating point

-Study period up to 10 s

Frequency stability

The ability to maintain the frequency in a specified range through demanded and generated power balance

Mid-term stability (fast and slow dynamics)

-Severe upsets

-Large V and f excursions

-Study period: to several minutes

Long term stability (slow dynamics)

-Uniform system frequency

-Study period to tens of minutes

Voltage stability (slow dynamics)

The ability to maintain steady acceptable voltage through reactive power balance

Small-disturbance voltage stability

-Contingencies

-Quasistatic

Large-disturbance voltage stability

-Switching events

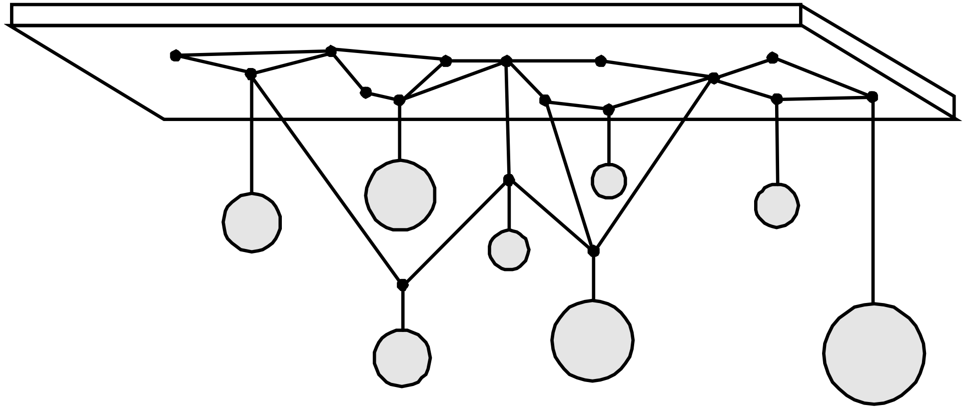
-Dynamics of ULTC, loads

-Rotor or stator field current limiting

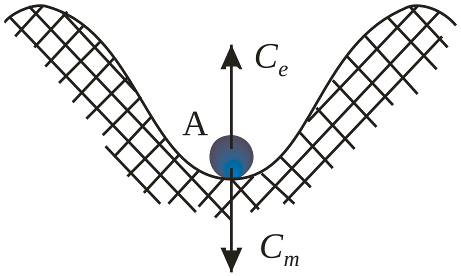
Power system stability: *“the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact”*

POWER SYSTEM STABILITY

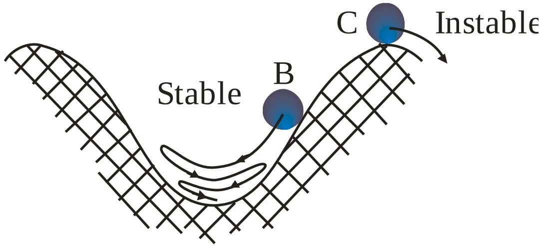
An analogy of the electromechanical oscillations phenomena with a mechanical system



- steady-state



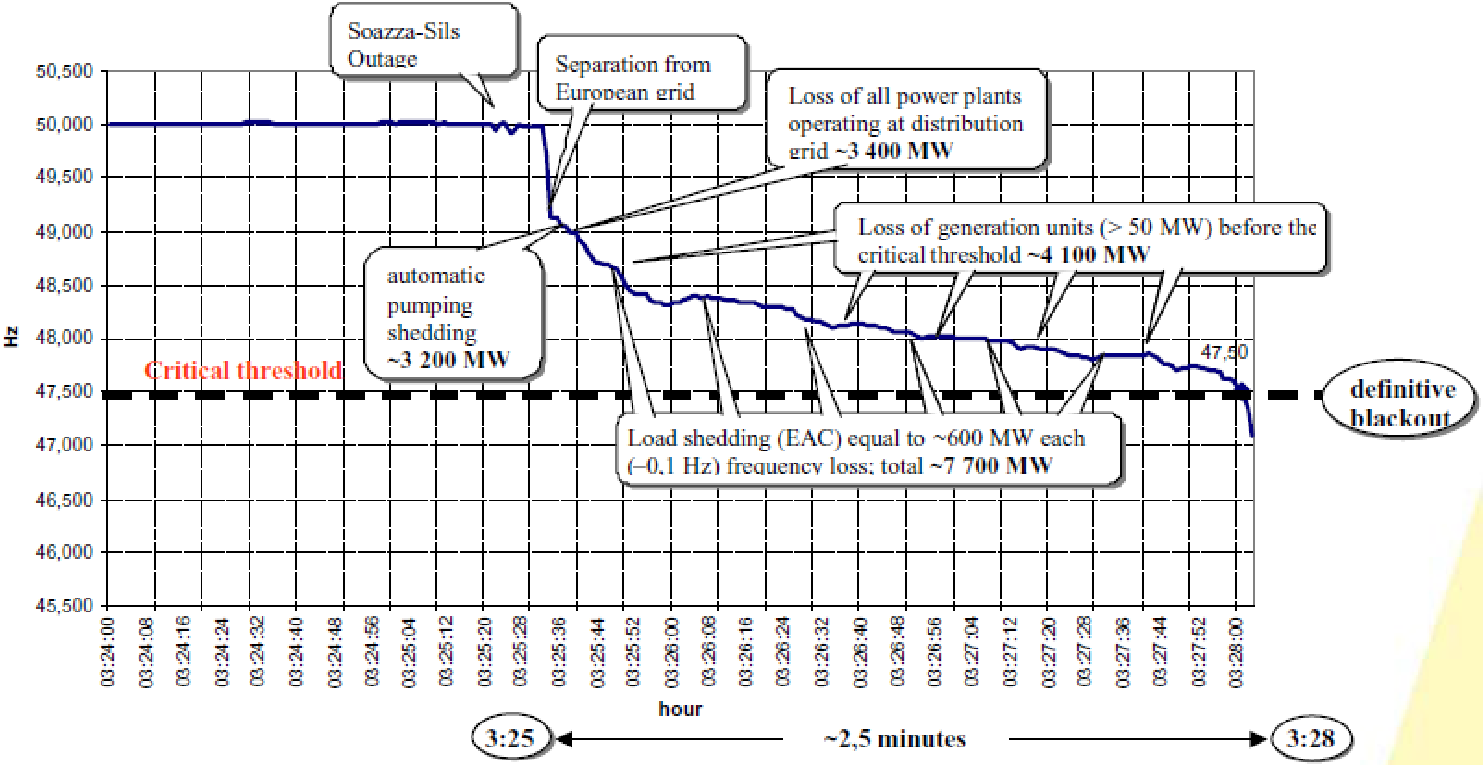
- perturbed operation



! Any change in the position of one ball (= operating point) will affect, more or less, all the balls from the system

MAJOR GRID PERTURBATION IN EUROPE

The Major grid blackout of the Italian power system, on 28 September 2003



Soazza-Sils Outage

Separation from European grid

Loss of all power plants operating at distribution grid ~3 400 MW

Loss of generation units (> 50 MW) before the critical threshold ~4 100 MW

automatic pumping shedding ~3 200 MW

Critical threshold

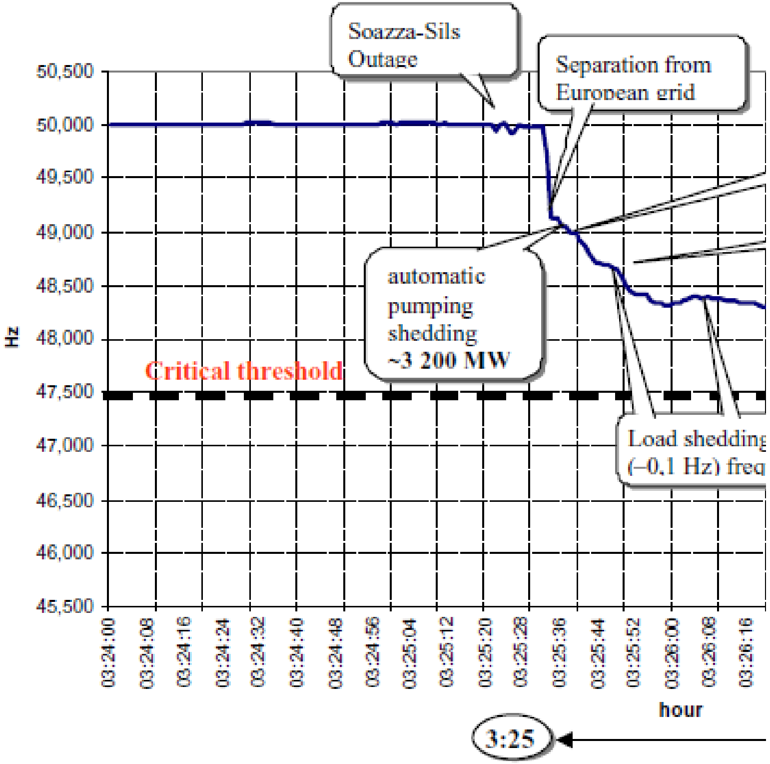
definitive blackout

Load shedding (EAC) equal to ~600 MW each (–0,1 Hz) frequency loss; total ~7 700 MW

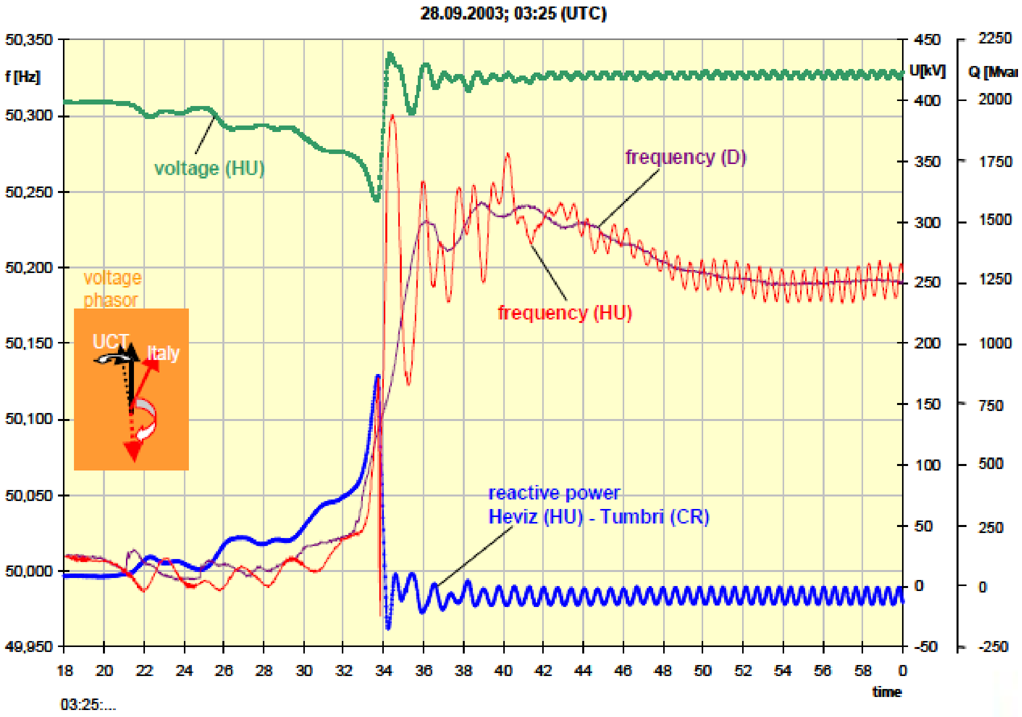
3:25 ~2,5 minutes 3:28

MAJOR GRID PERTURBATION IN EUROPE

The Major grid blackout of the Italian power system, on 28 September 2003

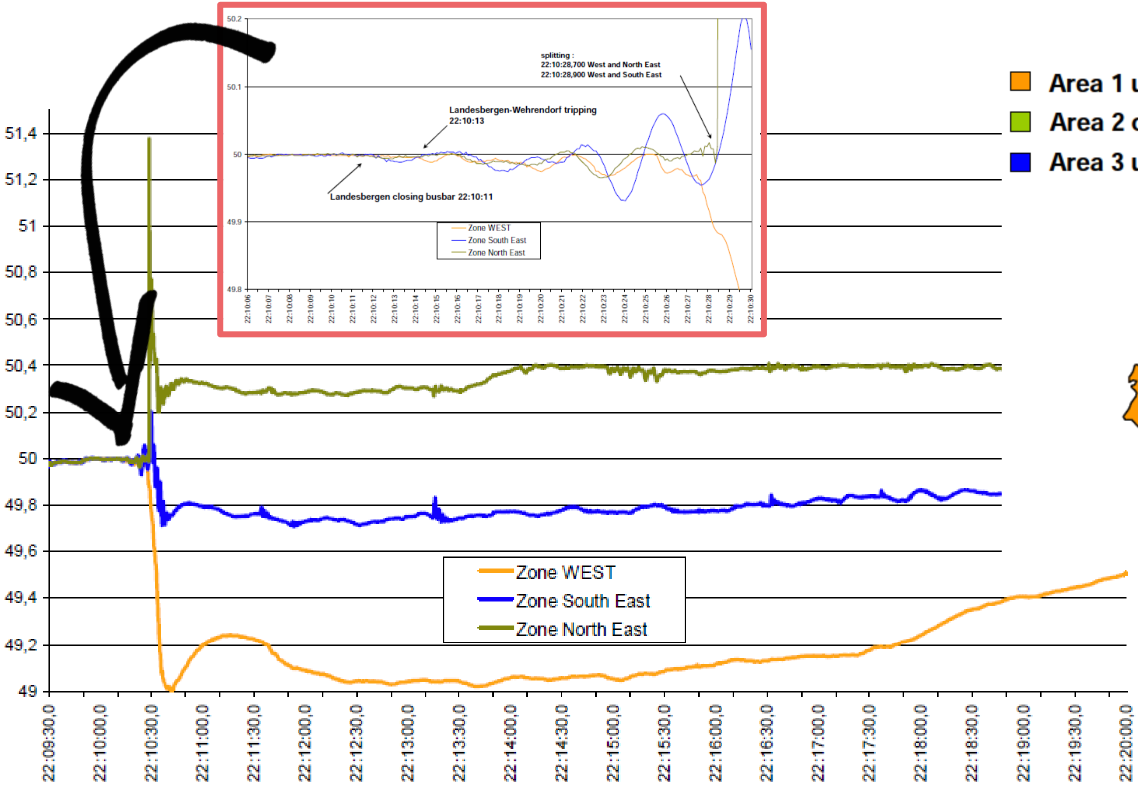


f,U – Uchtelfangen (D) –Vigy(F) / Heviz (HU)



MAJOR GRID PERTURBATION IN EUROPE

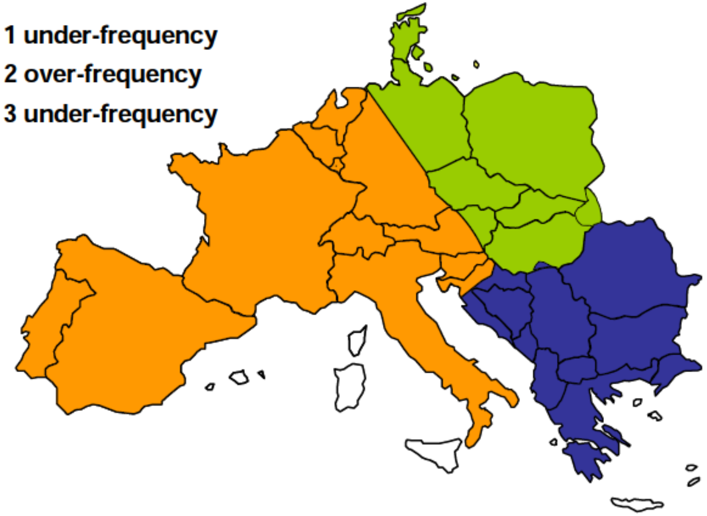
The de-synchronization of the ENTSO-E Continental Europe, on 4 November 2006



🟧 **Area 1 under-frequency**

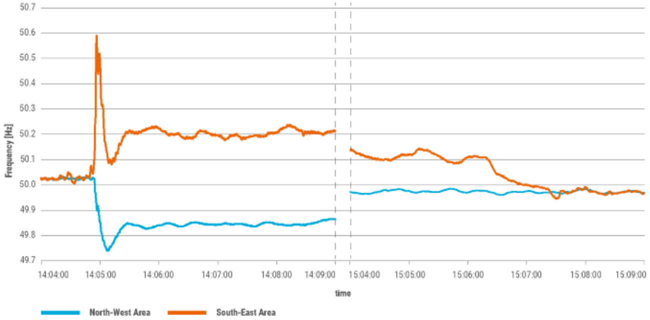
🟩 **Area 2 over-frequency**

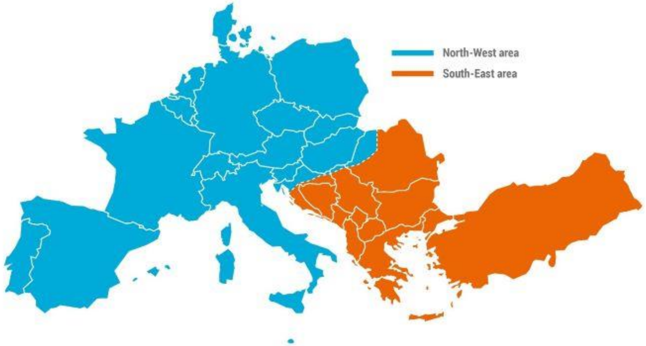
🟦 **Area 3 under-frequency**



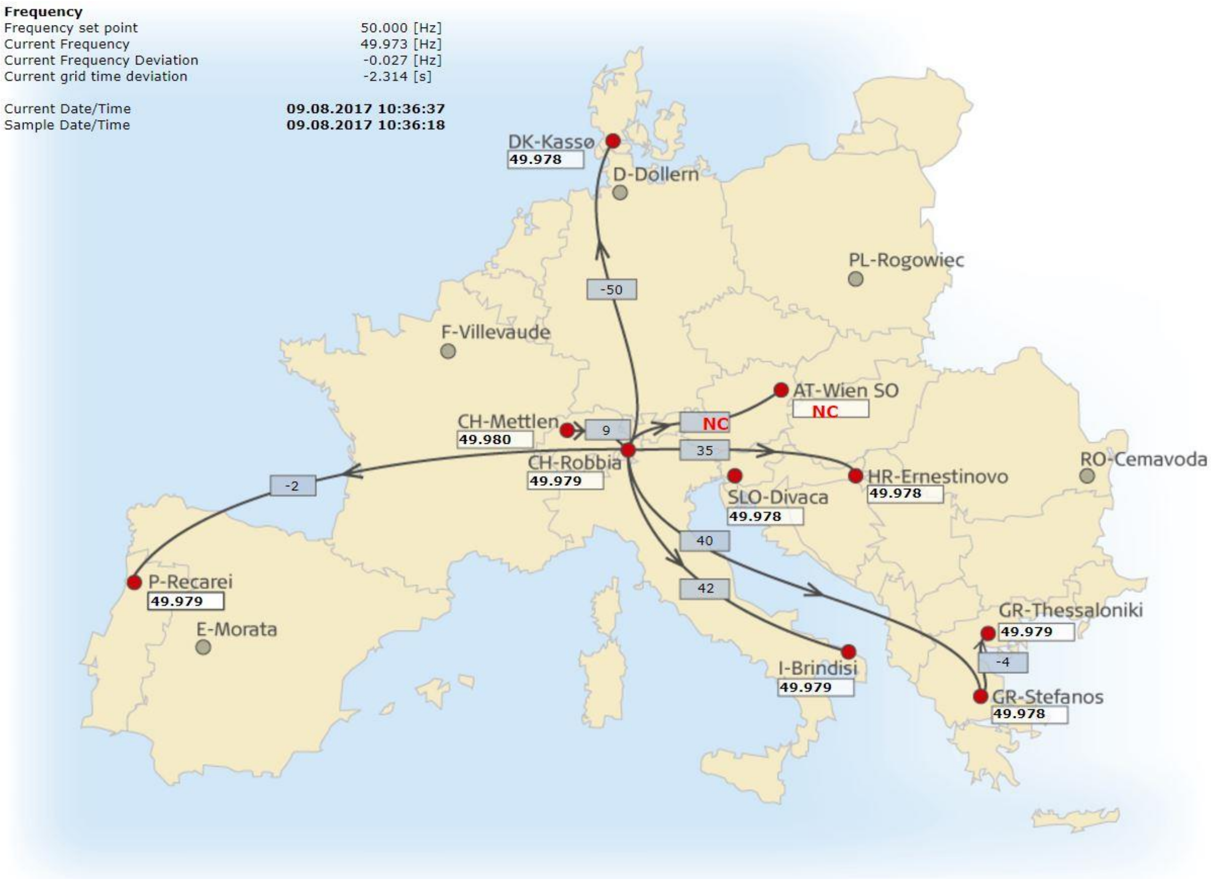
MAJOR GRID PERTURBATION IN EUROPE

The de-synchronization of the ENTSO-E Continental Europe, on 8 January 2021





WIDE AREA MEASUREMENT IN EUROPE



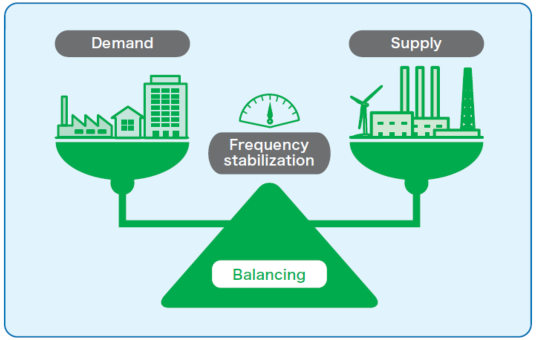
Frequency

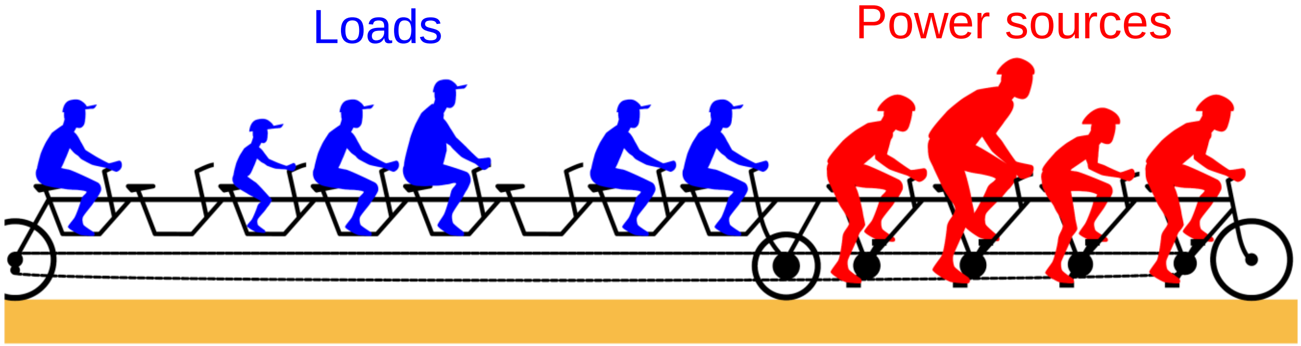
Frequency set point	50.000 [Hz]
Current Frequency	49.973 [Hz]
Current Frequency Deviation	-0.027 [Hz]
Current grid time deviation	-2.314 [s]
Current Date/Time	**09.08.2017 10:36:37**
Sample Date/Time	**09.08.2017 10:36:18**

- Synchronized frequency measurements

Basics of frequency control

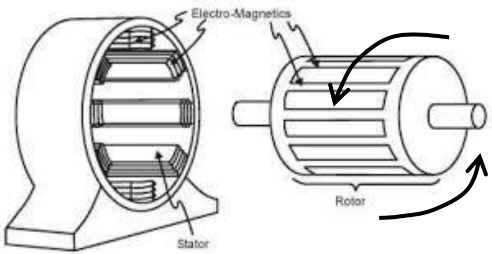
FUNDAMENTALS OF FREQUENCY CONTROL

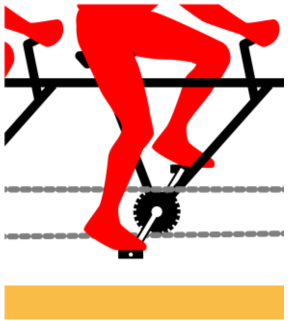




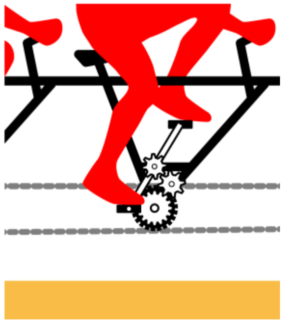
Stationary

Rotating

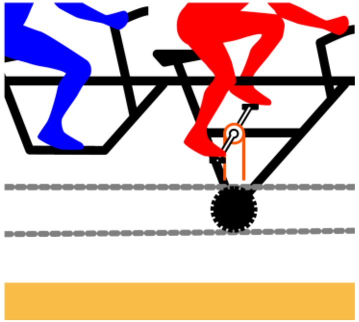




Steam/gas turbine
High speed
Strong

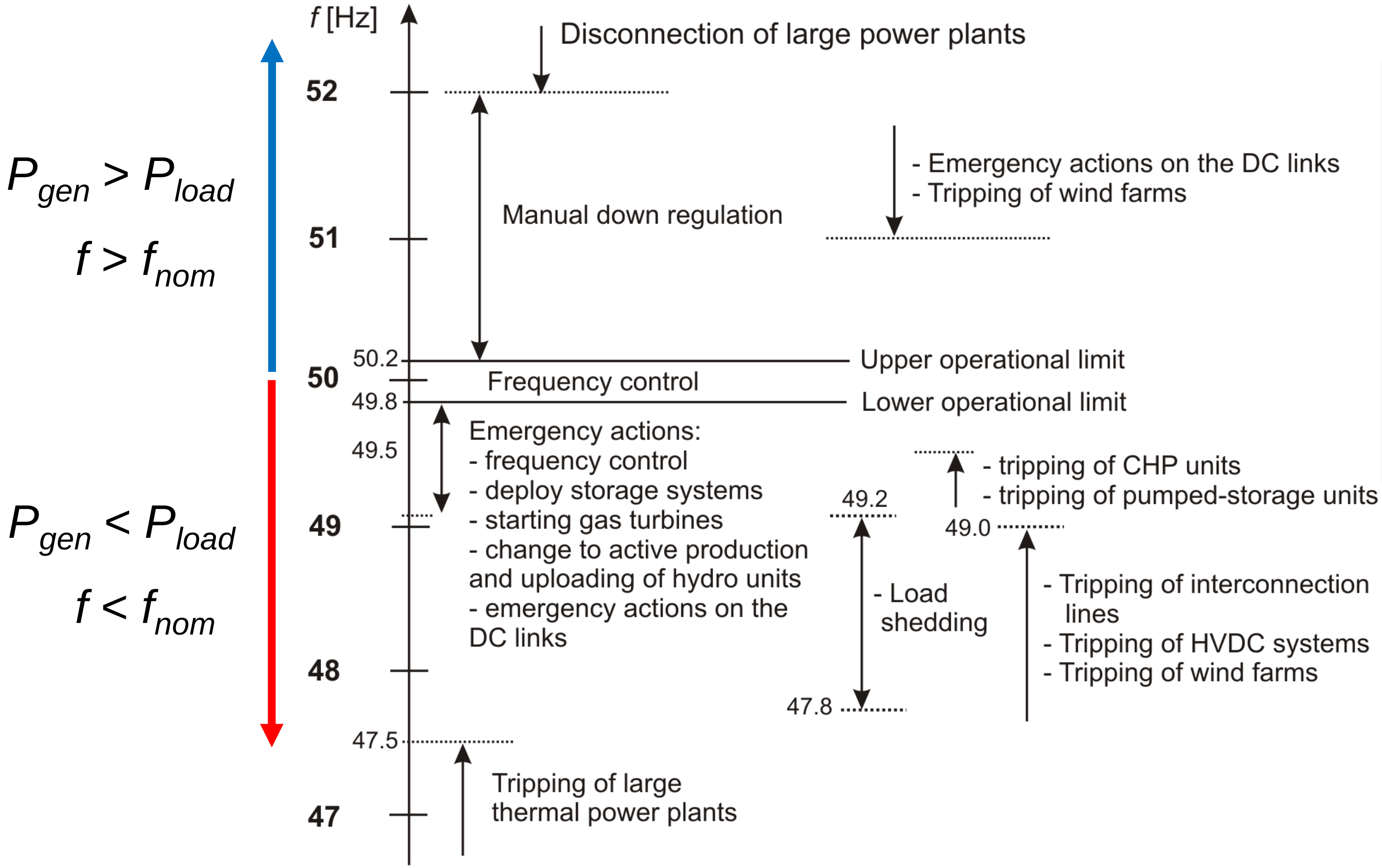


Hydro turbine
Small speed
Medium



Wind turbine
Low/No speed
Weak

FREQUENCY OPERATIONAL THRESHOLDS



$P_{gen} > P_{load}$

$f > f_{nom}$

$P_{gen} < P_{load}$

$f < f_{nom}$

Disconnection of large power plants

Manual down regulation

- Emergency actions on the DC links
- Tripping of wind farms

Upper operational limit

Frequency control

Lower operational limit

Emergency actions:
- frequency control
- deploy storage systems
- starting gas turbines
- change to active production and uploading of hydro units
- emergency actions on the DC links

- tripping of CHP units
- tripping of pumped-storage units

- Load shedding

- Tripping of interconnection lines
- Tripping of HVDC systems
- Tripping of wind farms

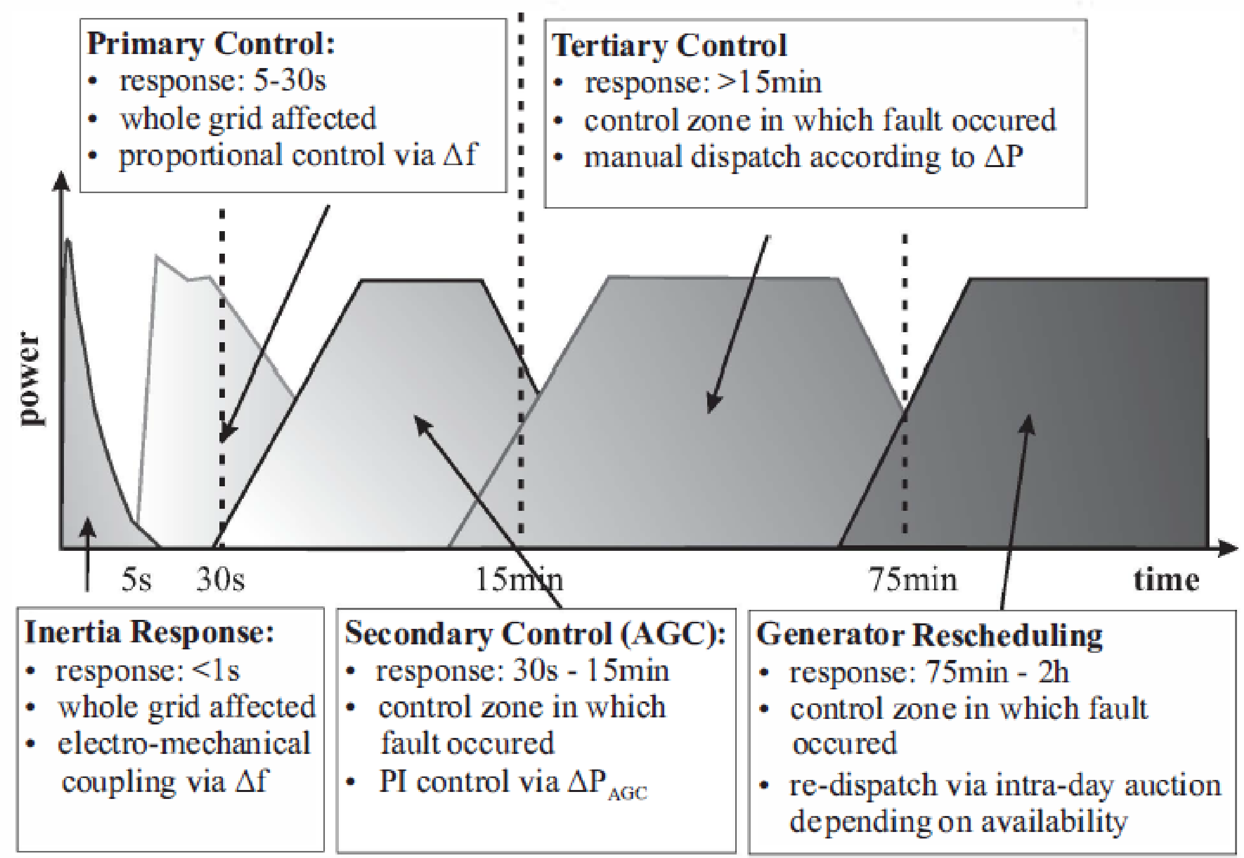
Tripping of large thermal power plants

Operation outside predefined thresholds results in triggering various control actions to prevent system or equipment malfunction!

HIERARCHICAL FREQUENCY CONTROL

	Primary Control (Frequency Containment)	**Secondary Control (automatic Frequency Restoration)**	**Tertiary Control (manual Frequency Restoration)**
Why is this control used?	To stabilize the frequency in case of any imbalance	To restore the frequency and the interchange programs to their target	To restore the secondary control reserve, to manage eventual congestions, and to bring back the frequency and the interchange programs to their target if the secondary control reserve is not sufficient
How is this control achieved?	Automatically		Manually
Where is this control performed?	Locally	Centrally (TSO)	
Who sends the control signal to the source of reserve?	Local sensor	TSO	Gencos, Consumers or other TSOs (after receiving instructions from the TSO)
When is this control activated?	Immediately	Immediately (seconds)	Depends on the system
What sources of reserves can be used?	Depends on the system: partially loaded units, loads, fast/slow starting units, changes in exchange programs		

HIERARCHICAL FREQUENCY CONTROL



Primary Control:
- response: 5-30s
- whole grid affected
- proportional control via Δf

Tertiary Control
- response: >15min
- control zone in which fault occured
- manual dispatch according to ΔP

Inertia Response:
- response: <1s
- whole grid affected
- electro-mechanical coupling via Δf

Secondary Control (AGC):
- response: 30s - 15min
- control zone in which fault occured
- PI control via ΔP_{AGC}

Generator Rescheduling
- response: 75min - 2h
- control zone in which fault occured
- re-dispatch via intra-day auction depending on availability

HIERARCHICAL FREQUENCY CONTROL

Usual time reactions of the frequency and power balancing levels

No.	Control Name	Time frame	Control objectives	Function
1	Inertial response	0-5 secs	Power balance and transient frequency dip minimization	Transient frequency control
2	Primary control (Frequency Containment), governor	1-20 secs	Power balance and transient frequency recovery	Transient frequency control
3	Secondary control, AGC (automatic Frequency Restoration)	2 secs to 3 mins	Power balance and steady-state frequency	Regulation
4	Real-time market (manual Frequency Restoration)	Every 5 mins	Power balance and economic-dispatch	Load following and reserve provision
5	Day-ahead market	Every day	Power balance and economic-unit commitment	Unit commitment and reserve provision

The inertial response

INERTIAL RESPONSE

The dynamic behavior of the synchronous machines is governed by the swing equation

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = \frac{1}{2H}\left(P_m - P_e - D\omega\right)$$

electrical power output (on the stator side)

mechanical power input (on the rotor side)

inertia constant

$$P_e = P_{\max} \sin\delta$$

internal angle of the generator

maximum electrical power that can be provided by the generator from stability point of view

INERTIAL RESPONSE

The rotating **kinetic energy** is:

$$E_{kin} = \frac{1}{2} J \omega_{0m}^2 = \frac{1}{2} J (2\pi f_m)^2$$

J – moment of inertia of the rotating mass, in kg·m^2
ω_{0m} – nominal speed of rotation, in mec.rad/s
f_m – rotating frequency of the machine

$$\omega_{0m} = \underset{\text{pairs of poles}}{p} \quad \underset{\text{el.rad/s}}{\omega_{0s}}$$

$$\omega_{0s} = 2\pi f_n$$

$$f_n = 50\,\text{Hz or } 60\,\text{Hz}$$

The **inertia constant** – the time in seconds a generator can provide the rated power using only the kinetic energy stored in the rotating mass, is:

$$H = \frac{E_{kin}}{S_b} = \frac{1}{2} \frac{J \omega_{0m}^2}{S_b} = \frac{J \left(2\pi f_m\right)^2}{2S_b} \left[\frac{\text{MW} \cdot \text{s}}{\text{MVA}} \right]$$

S_b – MVA rating of the machine

INERTIAL RESPONSE

The inertial response of the synchronous machine can be described by the change in the rotational speed or rotational frequency

$$\frac{\mathrm{d}(E_{kin})}{\mathrm{d}t} = \frac{\mathrm{d}(J\omega_{0m}^2/2)}{\mathrm{d}t} = J(2\pi)^2 f_m \frac{\mathrm{d}f_m}{\mathrm{d}t} = \frac{2HS_b}{f_m}\frac{\mathrm{d}f_m}{\mathrm{d}t} = (P_m - P_e)$$

$$\omega = 2\pi f$$

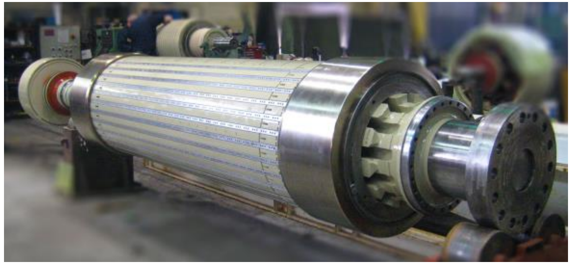
The rate of change of frequency is proportional to

$$\frac{\partial f}{\partial t} \cong \frac{\Delta P}{2H}$$

The greater the inertia, the less acceleration will be observed and the less will be the frequency deviation. Inertia is proportional to the total rotating mass.

INERTIAL RESPONSE

Turbo-generator



Small diameter
Large rot. speed

Large torque
Large inertia constant

H = 3 ÷ 7 MWs/MVA

non-condensing nuclear

Hydro-generator

Large diameter
Small rot. speed

Small torque
Small inertia constant

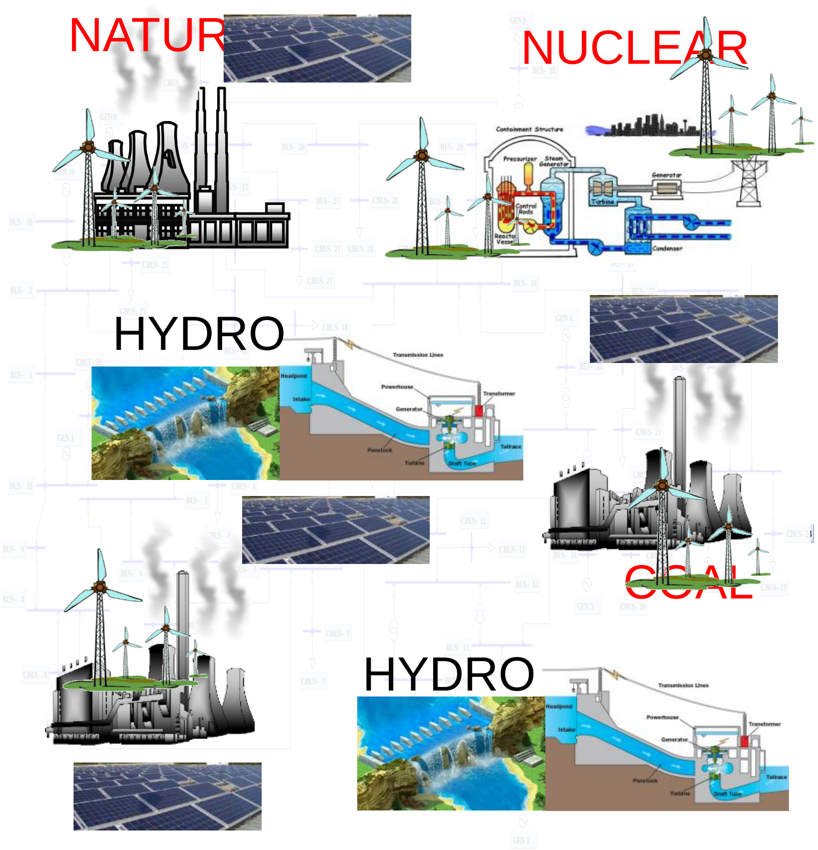
H = 2 ÷ 4 MWs/MVA

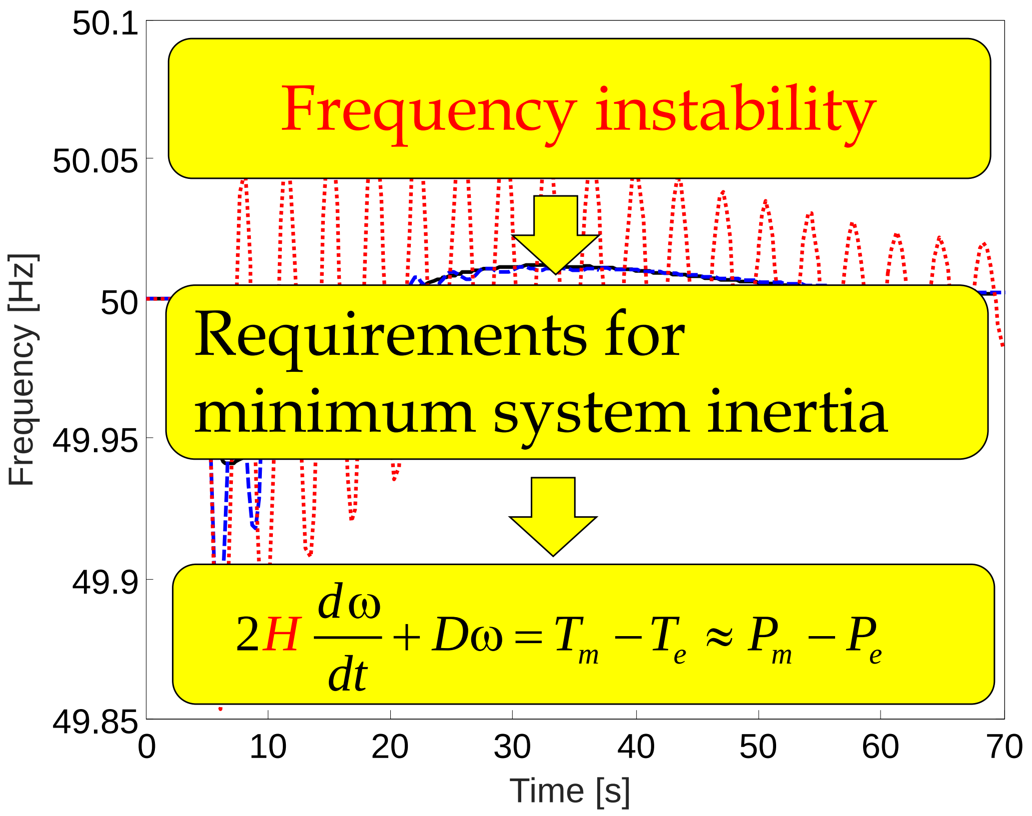
Sync. condenser

No driving system
Small inertia constant

H = 1 ÷ 1.25 MWs/MVA

THE NEED FOR INERTIA COMPENSATION SOLUTIONS



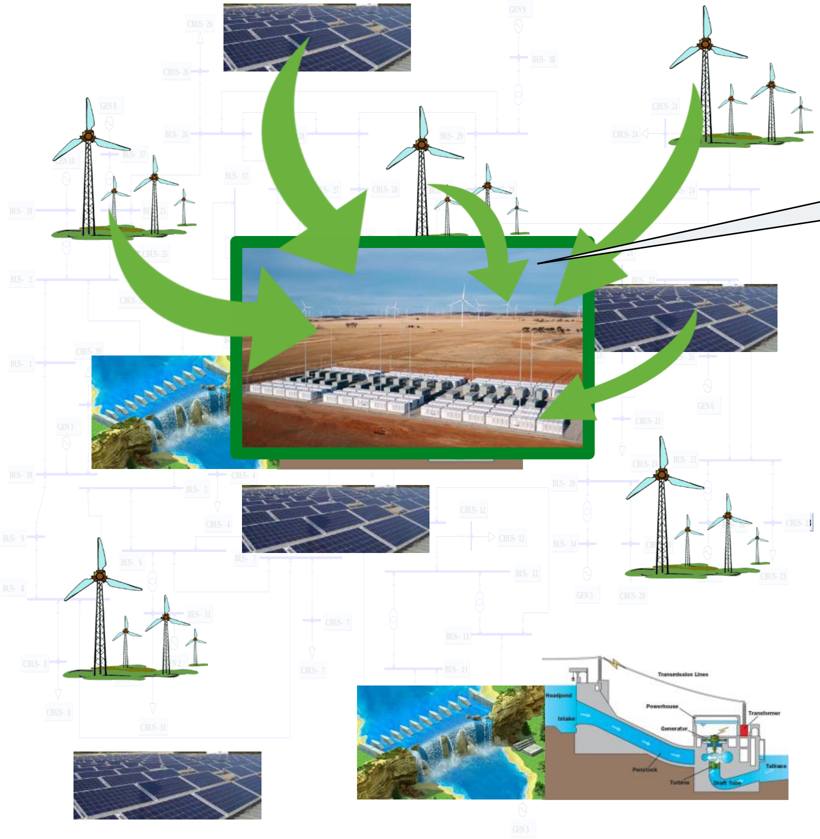


Frequency instability

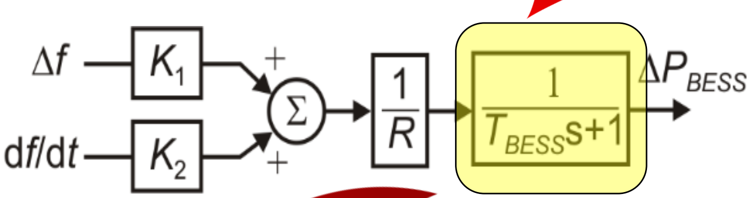
Requirements for minimum system inertia

$$2H\frac{d\omega}{dt}+D\omega=T_m-T_e\approx P_m-P_e$$

THE NEED FOR INERTIA COMPENSATION SOLUTIONS



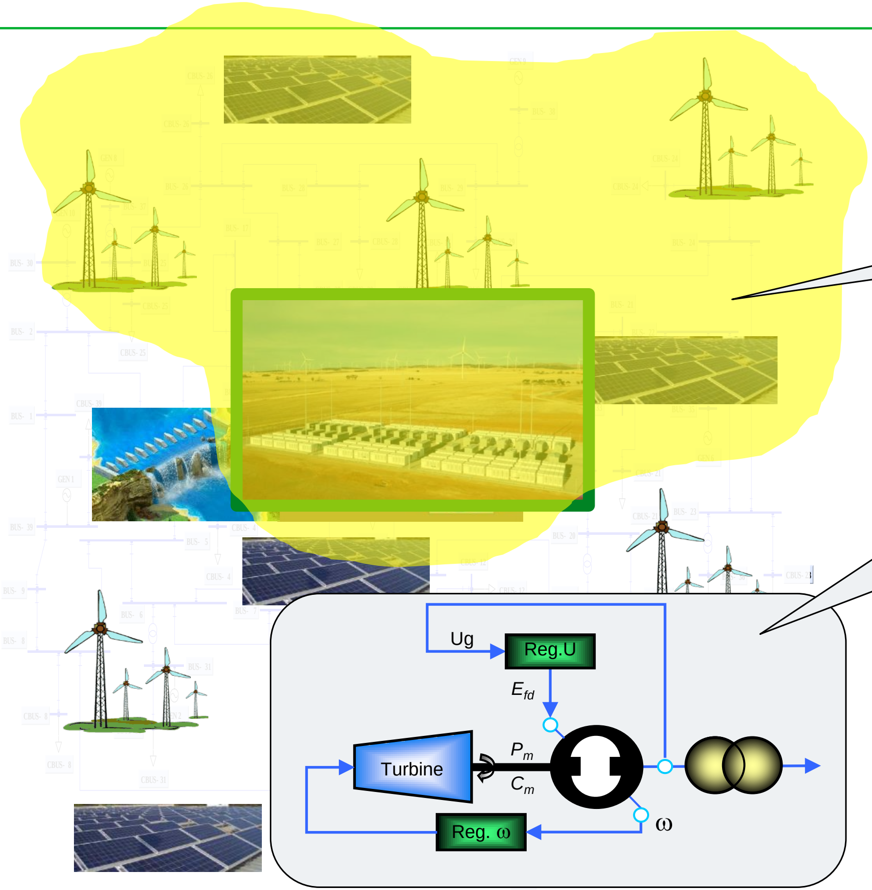
Requirements for power converter-based **Energy Storage Systems** (ESSs) connected to the electrical network in a new network code



RoCoF control

$$2H\frac{d\omega}{dt}+D\omega=T_m-T_e\approx P_m-P_e$$

THE NEED FOR INERTIA COMPENSATION SOLUTIONS



Expanding the frequency control strategy to allow using small-sized and/or intermittent energy resources

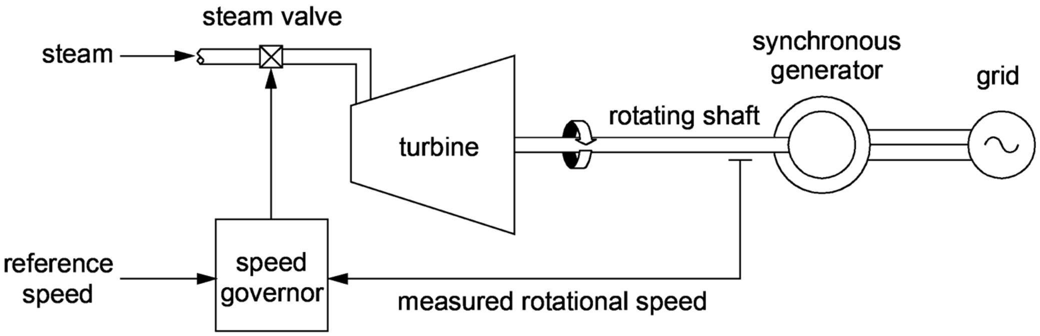
Recommended settings for the controlled units

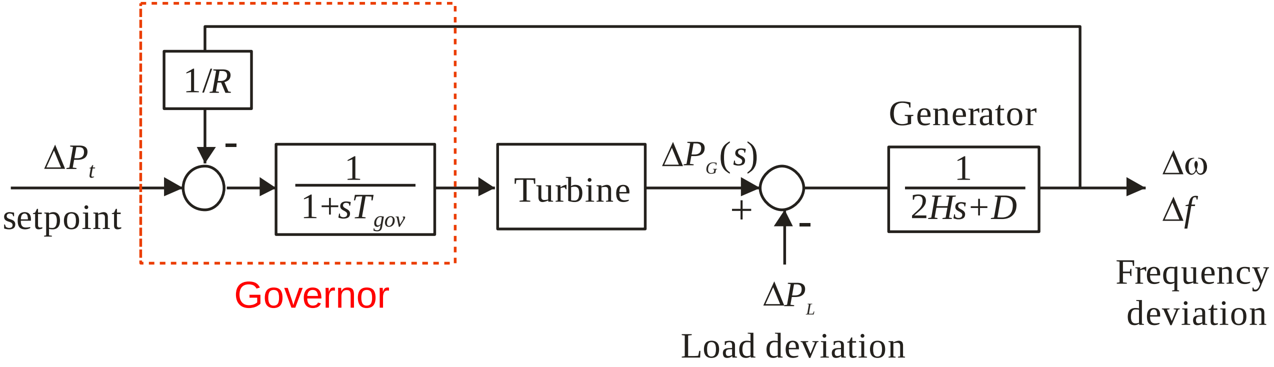
Requirements for the DSOs

The frequency containment control

PRIMARY FREQUENCY CONTROL

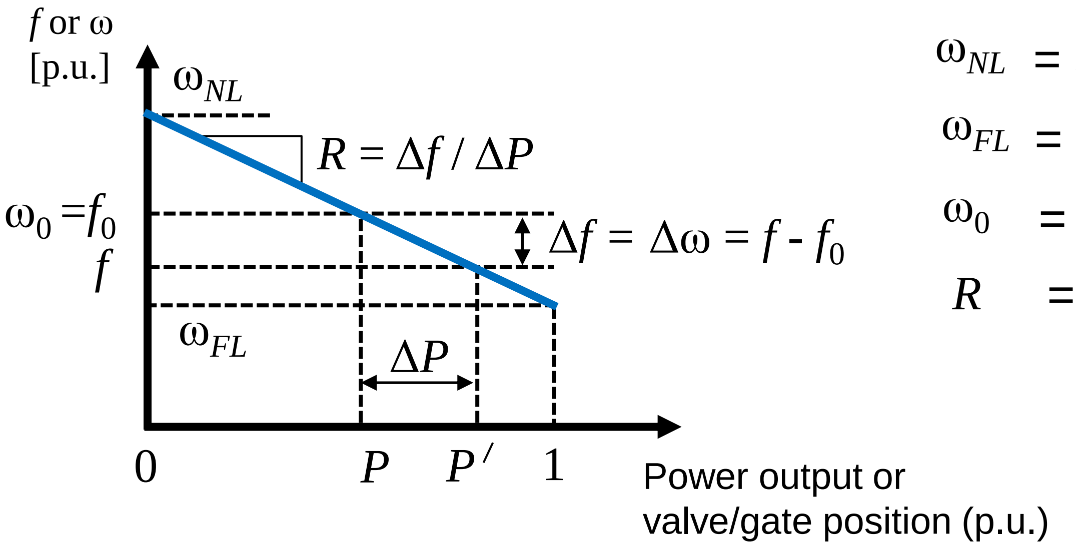
Speed governor control of a generating unit:





PRIMARY FREQUENCY CONTROL

Steady-state characteristic of f/P control



ω_{NL} = steady-state speed at no load

ω_{FL} = steady-state speed at full load

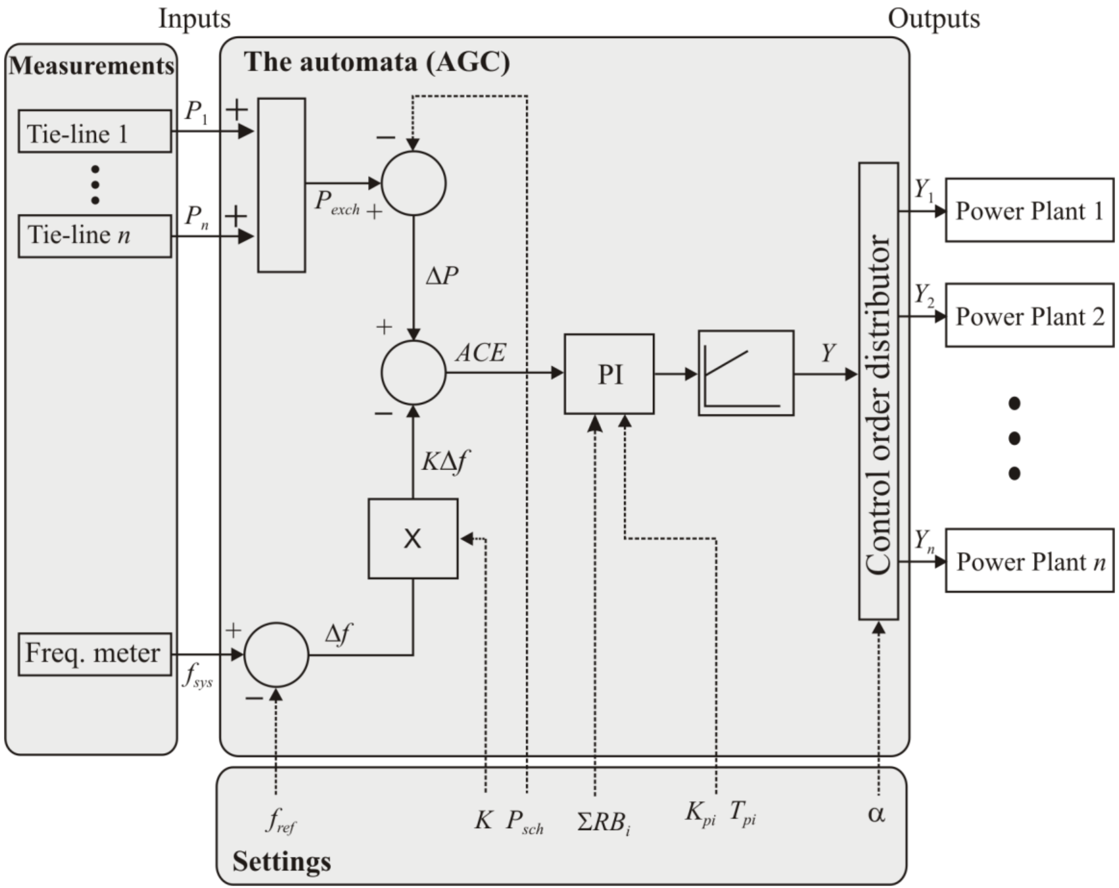
ω_0 = nominal or rated speed

R = percent speed regulation or droop

- A 5% droop or regulation means that a 5% frequency deviation cause 100% change in valve position of power output

Automatic Generation Control

AUTOMATIC GENERATION CONTROL (AGC)



Area Control Error

$$ACE = (P_{exch} - P_{sch}) + K(f_{sys} - f_{ref})$$

The active power required for system balancing:

$$Y = -\beta \cdot ACE - \frac{1}{T_r}\int ACE\,\mathrm{d}t$$

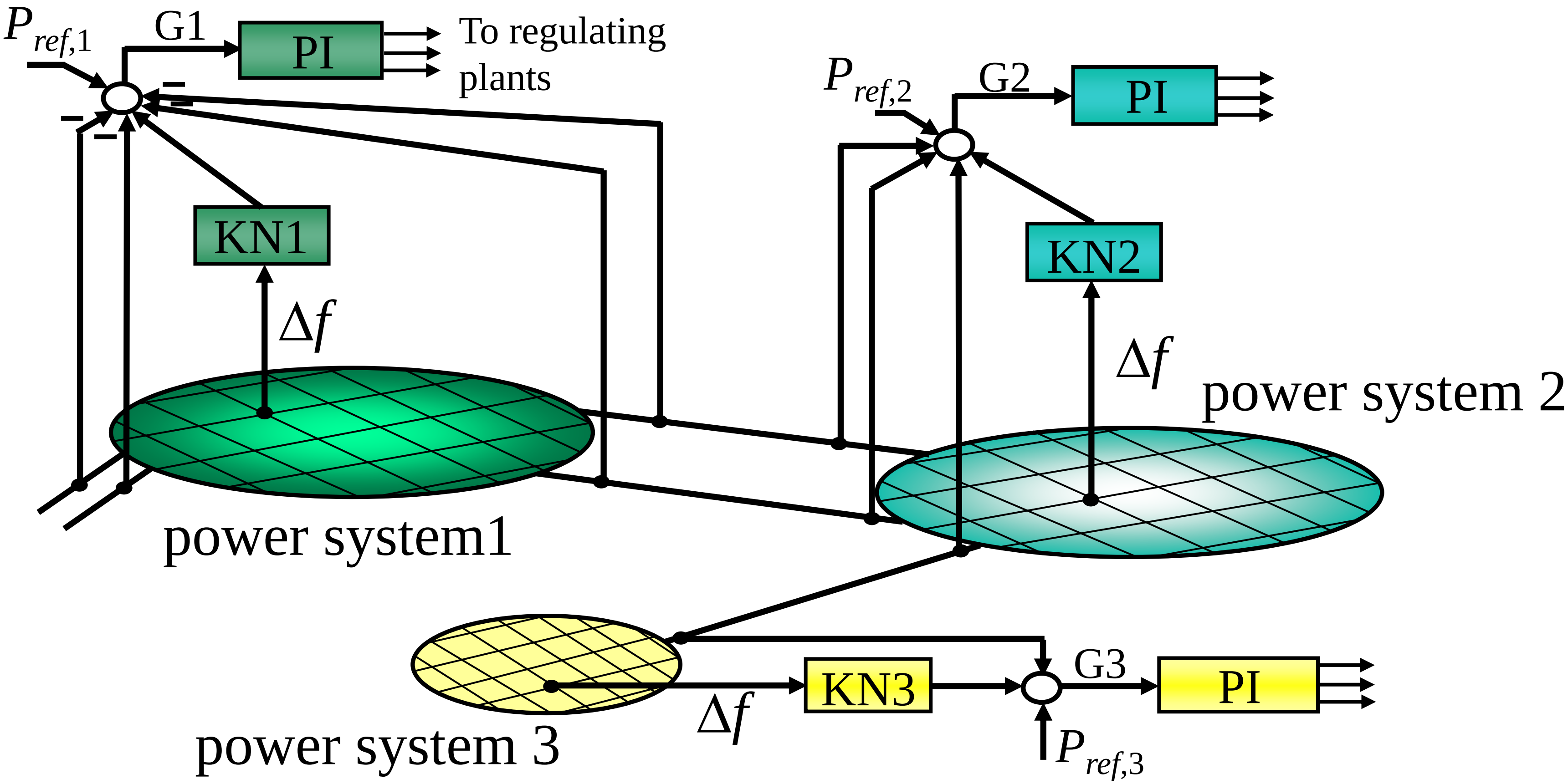
β - proportional factor (gain)
T_r - integration time constant

The control order

$$Y_1, Y_2, \ldots, Y_n \ (\pm\mathrm{MW})$$

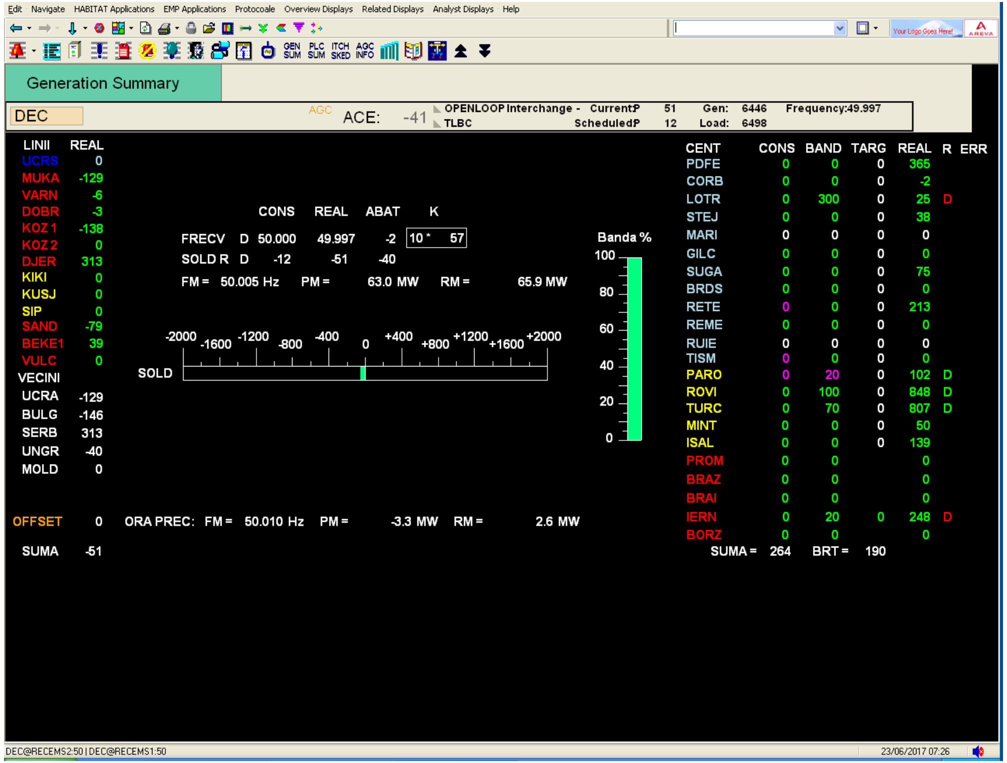
set according to market rules

AUTOMATIC GENERATION CONTROL (AGC)



AUTOMATIC GENERATION CONTROL (AGC)

Snapshot of AGC operation is Romania



Generation Summary

DEC AGC ACE: -41

OPENLOOP Interchange - CurrentP 51 Gen: 6446 Frequency:49.997
TLBC ScheduledP 12 Load: 6498

LINII	REAL
UCRS	0
MUKA	-129
VARN	-6
DOBR	-3
KOZ 1	-138
KOZ 2	0
DJER	313
KIKI	0
KUSJ	0
SIP	0
SAND	-79
BEKE1	39
VULC	0
VECINI	
UCRA	-129
BULG	-146
SERB	313
UNGR	-40
MOLD	0

OFFSET 0

SUMA -51

		CONS	REAL	ABAT	K
FRECV	D	50.000	49.997	-2	10 * 57
SOLD R	D	-12	-51	-40	

FM = 50.005 Hz PM = 63.0 MW RM = 65.9 MW

ORA PREC: FM = 50.010 Hz PM = -3.3 MW RM = 2.6 MW

CENT	CONS	BAND	TARG	REAL	R	ERR
PDFE	0	0	0	365		
CORB	0	0	0	-2		
LOTR	0	300	0	25	D	
STEJ	0	0	0	38		
MARI	0	0	0	0		
GILC	0	0	0	0		
SUGA	0	0	0	75		
BRDS	0	0	0	0		
RETE	0	0	0	213		
REME	0	0	0	0		
RUIE	0	0	0	0		
TISM	0	0	0	0		
PARO	0	20	0	102	D	
ROVI	0	100	0	848	D	
TURC	0	70	0	807	D	
MINT	0	0	0	50		
ISAL	0	0	0	139		
PROM	0	0		0		
BRAZ	0	0		0		
BRAI	0	0		0		
IERN	0	20	0	248	D	
BORZ	0	0		0		

SUMA = 264 BRT = 190

DEC@RECEMS2:50 | DEC@RECEMS1:50 23/06/2017 07:26

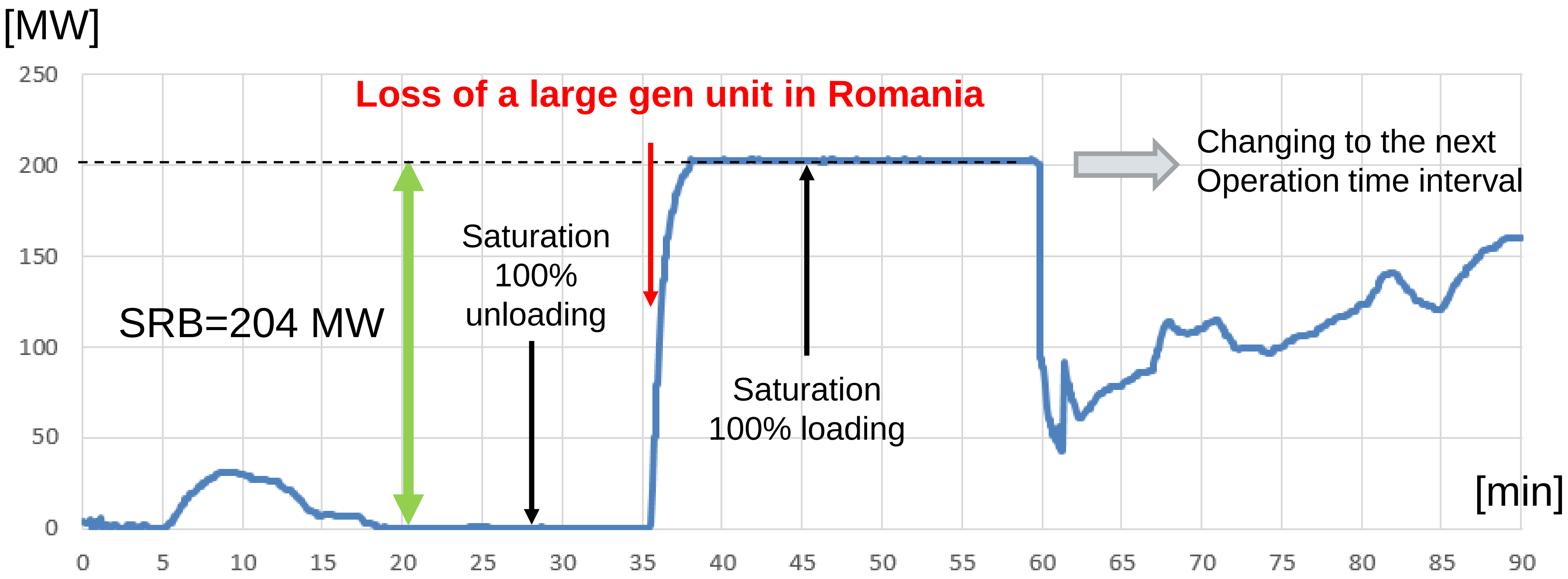
- Power flow on the interconnection lines (lest side);
- Power exchange deviation (SOLD, in the centre);
- The actual band used in secondary control (BAND column, on the right side). One can observe that is a special case when the total secondary reserve was fully used;
- Total power generation of all power plants integrated into the AGC scheme;
- The area control error (=-41, for this instant);
- Power system frequency;
- Total generation and load.

AUTOMATIC GENERATION CONTROL (AGC)

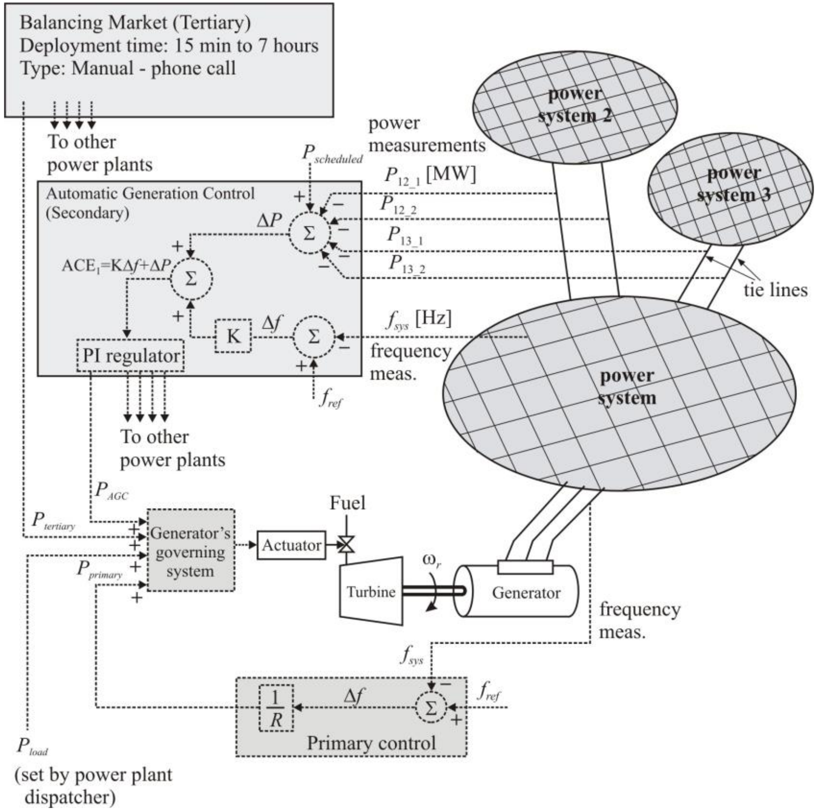
	Activation	Full availability	Utilization	Controller cycle	Controller type
ENTSO-E	≤ 30 s	≤ 15 min	As long as required	1-5 s	I or PI
Germany	Immediately or ≤ 5 min	≤ 15 min	As long as required	1-2 s	PI
France	≤ 30 s	≤ 430 s or ≤ 97 s	As long as required	5 s	I
Spain		≤ 300-500 s	≥ 15 min	4 s	P or PI, depending on the regulation zone
Netherlands	30 s – 1 min	≤ 15 min	≥ 15 min and by consensus	4s	PI, with additional heuristics
Belgium	≤ 10 s	≤ 10 min	As long as required	5s	PI
Romania	≤ 30 s	≤ 15 min	As long as required	4 s	PI

AUTOMATIC GENERATION CONTROL (AGC)

Example of hydro-generator reaction to control order



HIERARCHICAL FREQUENCY CONTROL

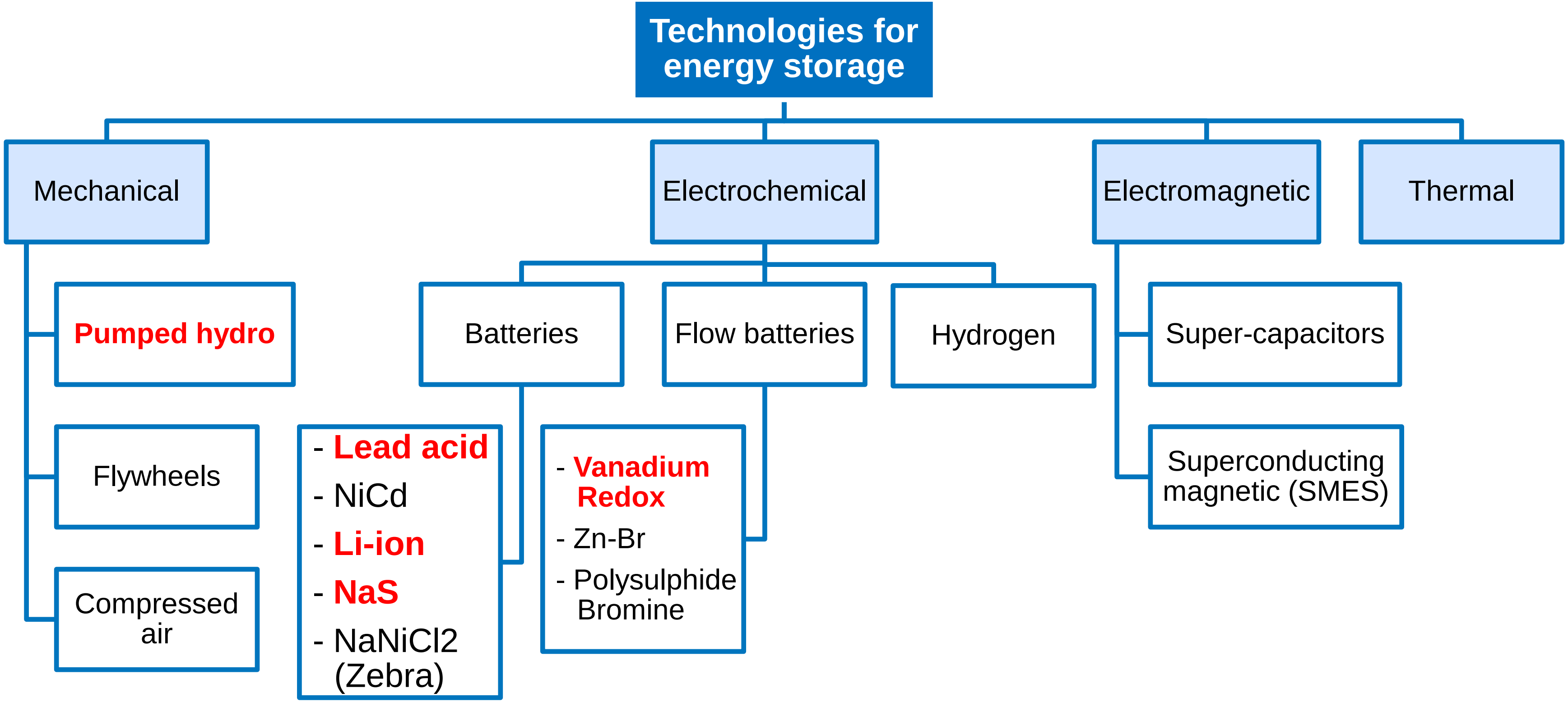


The active power produced by a generator is the results of:

- Load setting (DAM and BC)
- Frequency Containment response
- AGC response
- Manual orders changes

Storage is essential to support 100% renewables

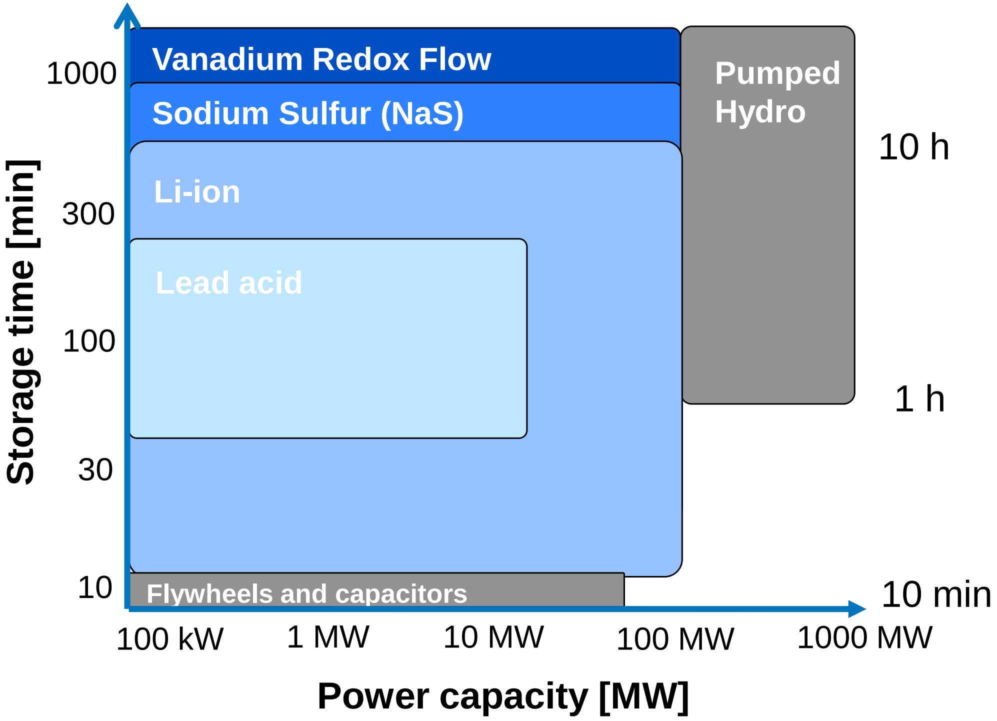
ENERGY STORAGE TECHNOLOGIES



Technologies for energy storage

- Mechanical
  - **Pumped hydro**
  - Flywheels
  - Compressed air
- Electrochemical
  - Batteries
    - **Lead acid**
    - NiCd
    - **Li-ion**
    - **NaS**
    - NaNiCl2 (Zebra)
  - Flow batteries
    - **Vanadium Redox**
    - Zn-Br
    - Polysulphide Bromine
  - Hydrogen
- Electromagnetic
  - Super-capacitors
  - Superconducting magnetic (SMES)
- Thermal

ENERGY STORAGE TECHNOLOGIES



Source: ABB

Deployed

- Pumped hydro (synch)
- Compressed Air Energy Storage (CAES) (synch)
- Batteries (NaS, Li-ion, Pb-Acid) (asynch)
- Flywheels (asynch)

Demonstration

- Advanced Pb-acid and Flow batteries (asynch)
- Superconducting Magnetic Storage (SMES) (asynch)
- Electrochemical Capacitors (asynch)

Early stage technologies

- Adiabatic (CAES) (synch)
- Hydrogen (synch)
- Synthetic Natural Gas (synch)

ENERGY STORAGE TECHNOLOGIES

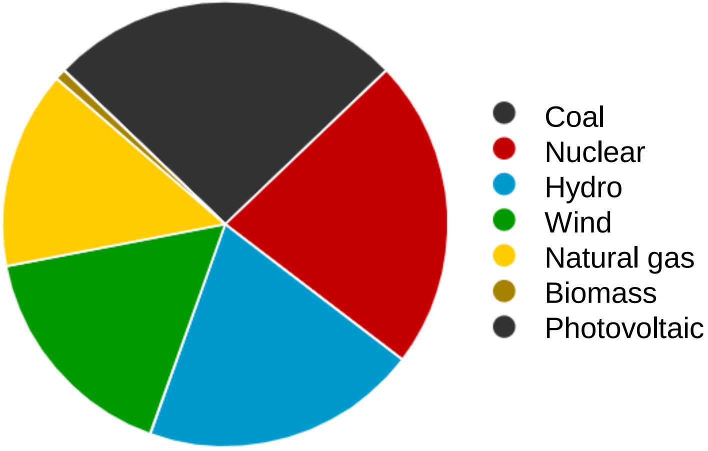
Ancillary Service	Storage system
RoCoF Control Response time = 10 - 100 ms	Li-ion, Flow, Lead-acid, Super-cap, Flywheels, loads, HVDC
FCR (primary control) Response time <30 sec. Deployment – up to 15 min.	Li-ion, Flow, Lead-acid, Pumped hydro, CAES, HVDC
FRR (secondary control) Response time >30 sec. Deployment – as long as necessary	Pumped hydro, CAES, HVDC

Source: AEM

ENERGY STORAGE - ROMANIA CASE

Example of power generation in Romania

(night operation)



Energy transition in Romania

100% CO2 free	Storage
08.06.2017	2 GW / 14.8 GWh
29.05.2017	4 GW / 26 GWh
100% renewables	
08.06.2017	4 GW / 20.8 GWh
29.05.2017	4.5 GW / 32 GWh
23.01.2017	8 GW / 42 GWh

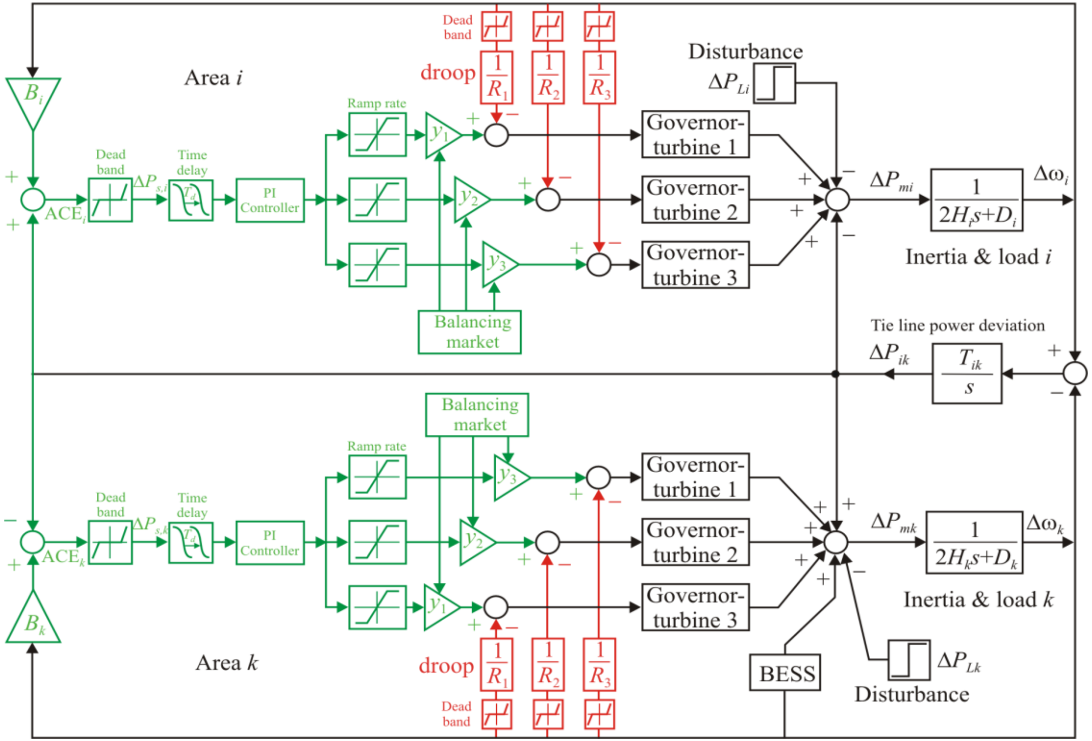
Average load = 6800 MW
Peak load = 9500 MW
Low load = 3600 MW

Simulations based frequency analysis

SIMULATION OF FREQUENCY CONTROL

Simulating primary and secondary frequency controls

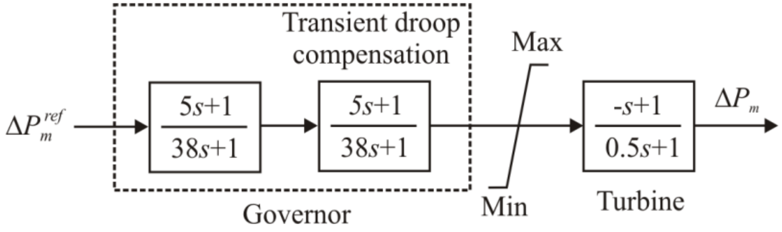
- Two area interconnected
- Three types of turbines considered
- Droop and AGC controls simulated
- BESS to provide inertial response



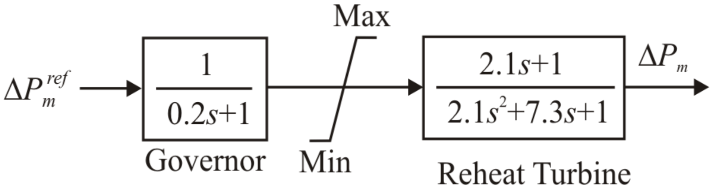
SIMULATION OF FREQUENCY CONTROL

Governor-turbine models

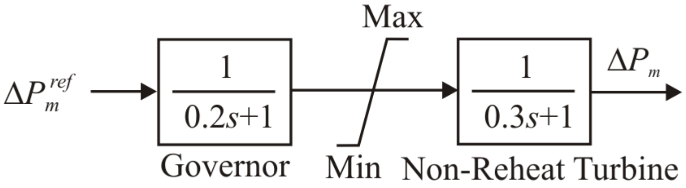
hydraulic unit



reheat unit

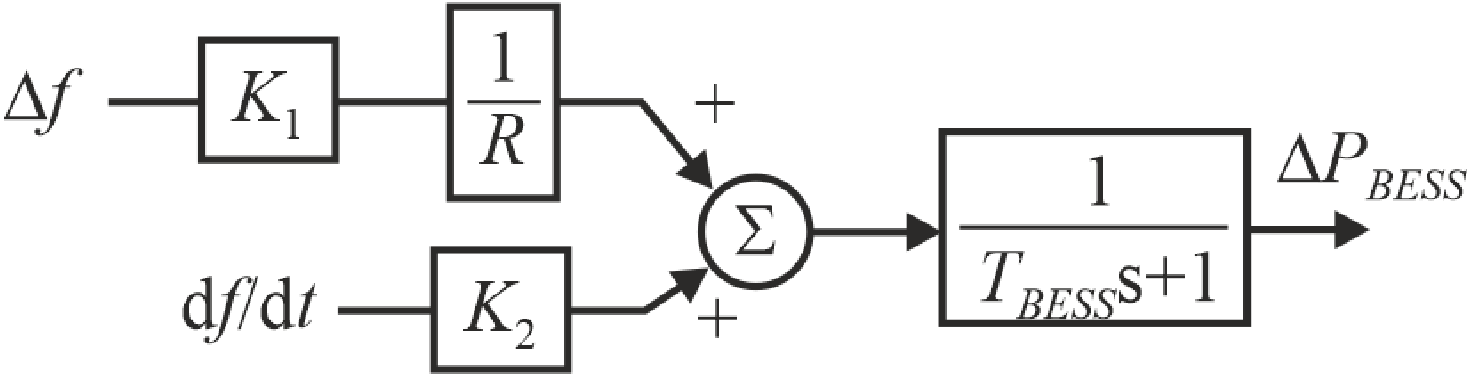


non-reheat unit



SIMULATION OF FREQUENCY CONTROL

Battery Energy Storage System model

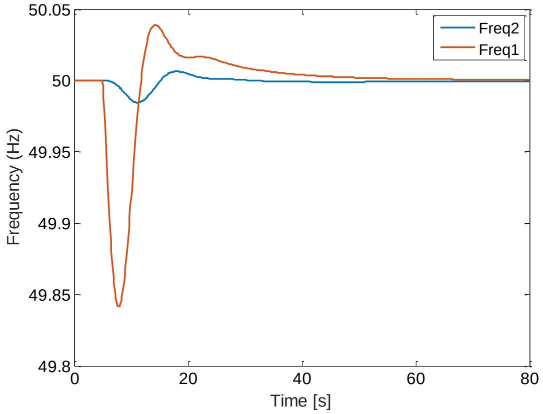


K_1 and K_2 are weighting factors of the signal inputs

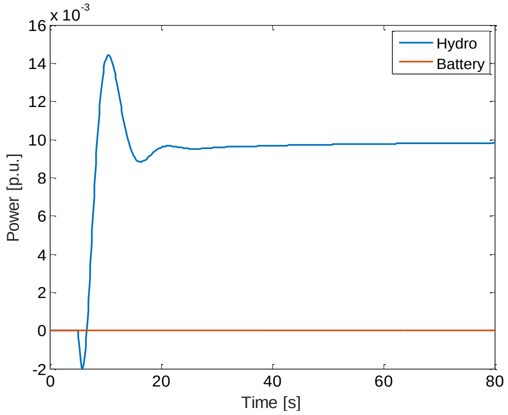
T_{BESS} is the simulated time reaction of the BESS

SIMULATION OF FREQUENCY CONTROL

Hypotheses: *Inertia constant H = 6.5 s; only hydroelectric units are considered for frequency control*.

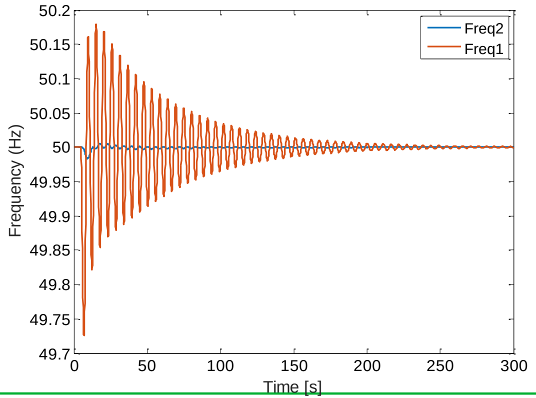


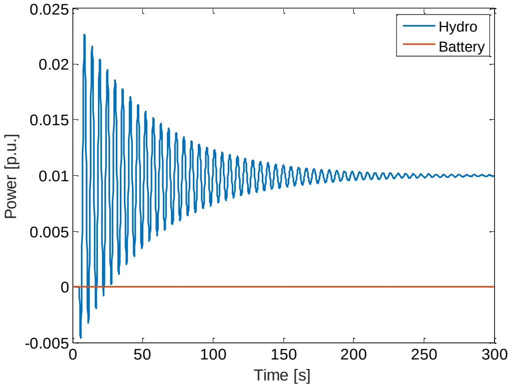
a) Frequency variation



b) Power contribution

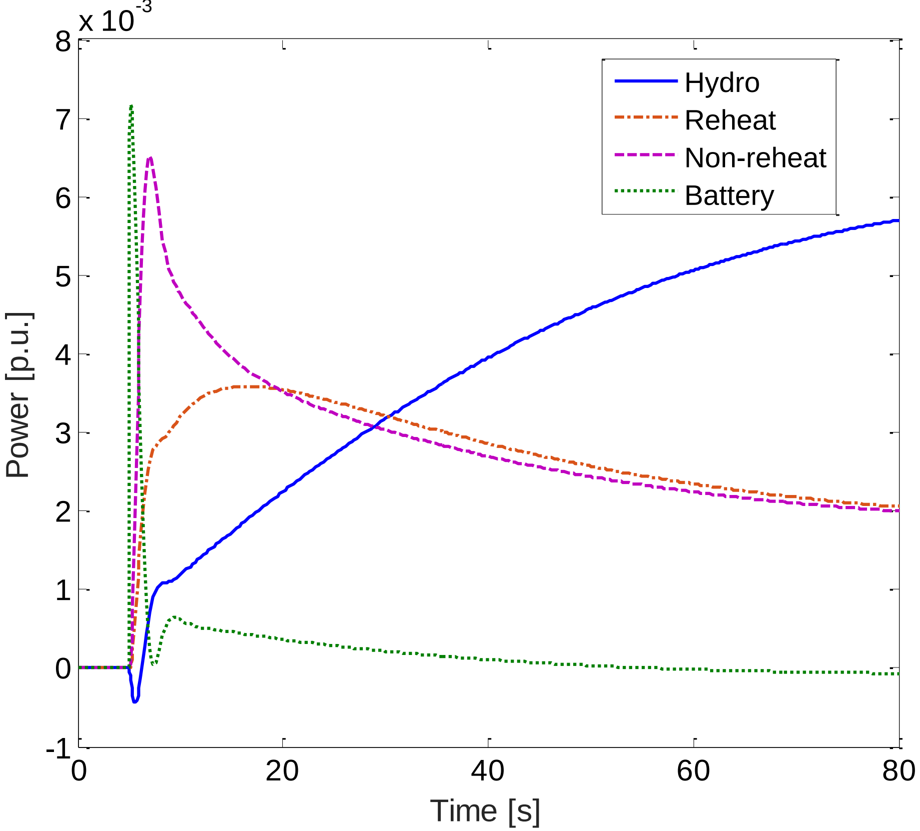
Hypotheses: *Inertia constant H = 3 s; only hydroelectric units are considered for frequency control.*





SIMULATION OF FREQUENCY CONTROL

Base case scenario (2*H* = 6.5 s)



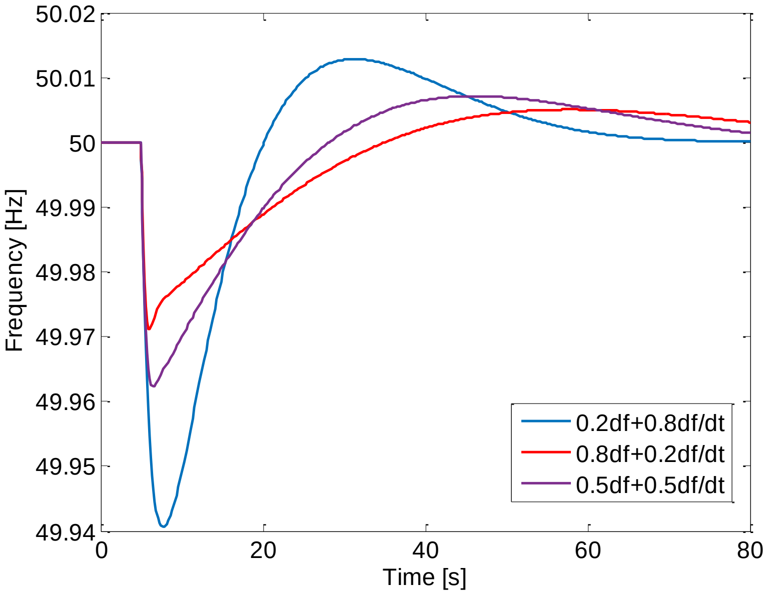
! reference step power imbalance in area *k* of 0.01 p.u. occurring at 5 seconds from the simulation start.

Power contribution under normal inertia value; all types of generation units considered for frequency control

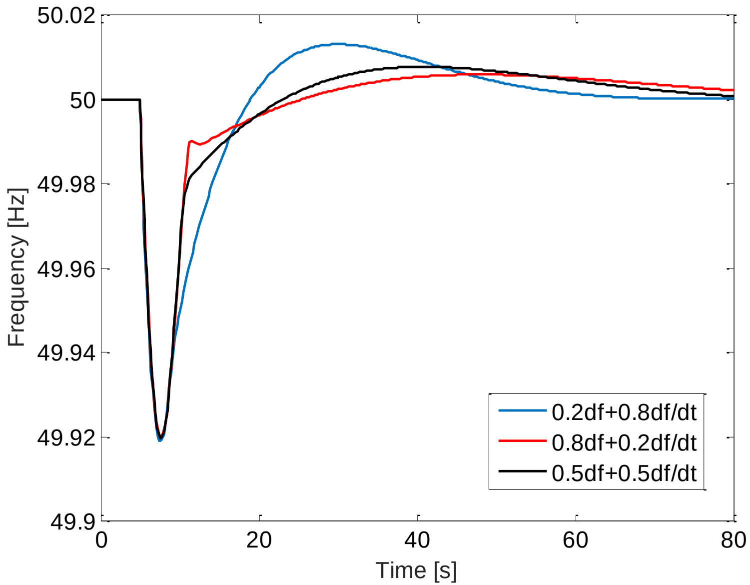
[Hydro and reheat units are slower in primary frequency control level than battery and non-reheat units]

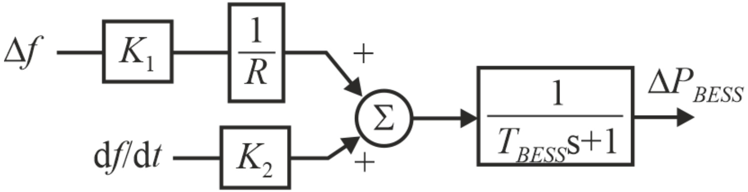
SIMULATION OF FREQUENCY CONTROL

Frequency response for unlimited battery power.



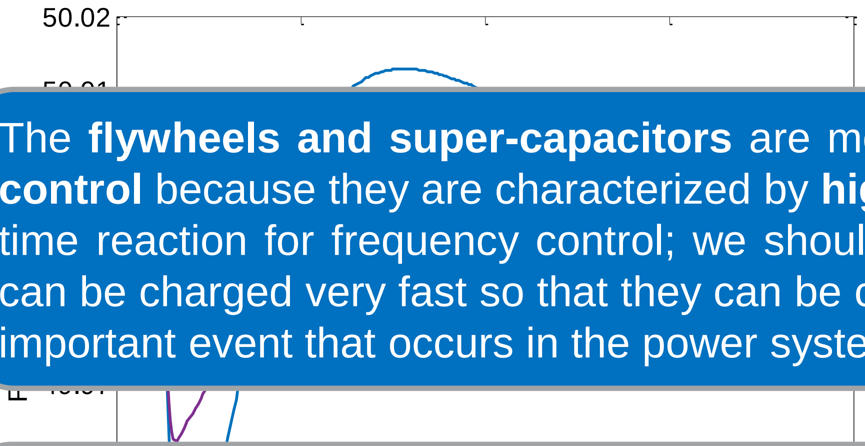
Frequency response for limited battery power



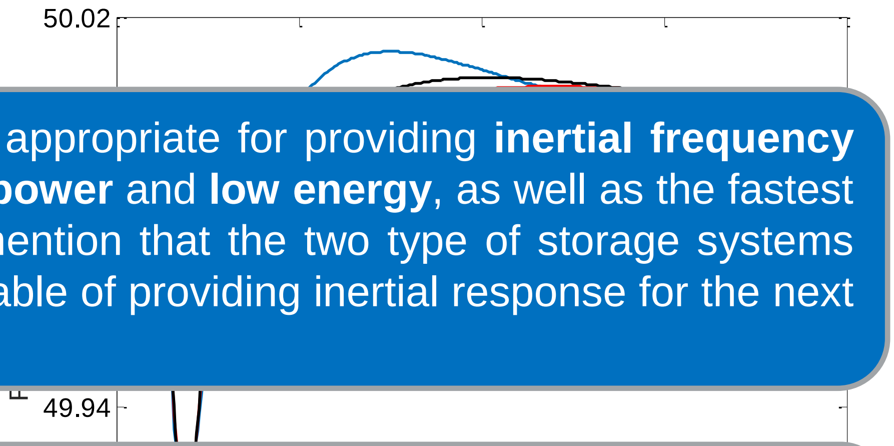


BESS USED FOR FREQUENCY CONTROL

Frequency response for unlimited battery power.



Frequency response for limited battery power



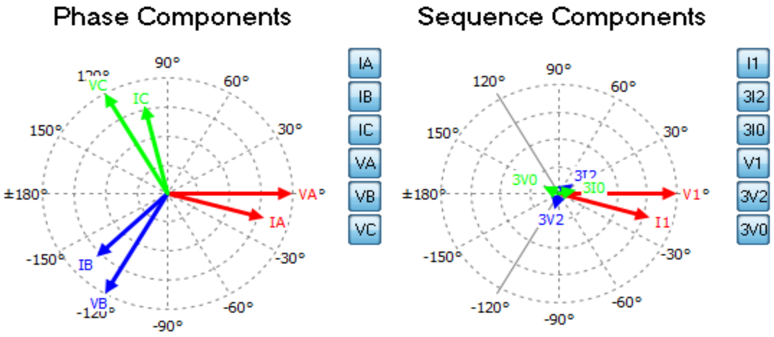
The **flywheels and super-capacitors** are more appropriate for providing **inertial frequency control** because they are characterized by **high power** and **low energy**, as well as the fastest time reaction for frequency control; we should mention that the two type of storage systems can be charged very fast so that they can be capable of providing inertial response for the next important event that occurs in the power system.

The **Li-ion batteries** are more appropriate for **primary frequency control** because they are characterized by **low power** and **high energy**; if batteries are used for inertial control, their energy capability will not be efficiently used from economic point of view. On the other hand, for the actual technology of the Li-ion batteries, the fast change in the operation mode (switching from charging to discharging and vice versa) may significantly reduce their lifetime.

Frequency measurement

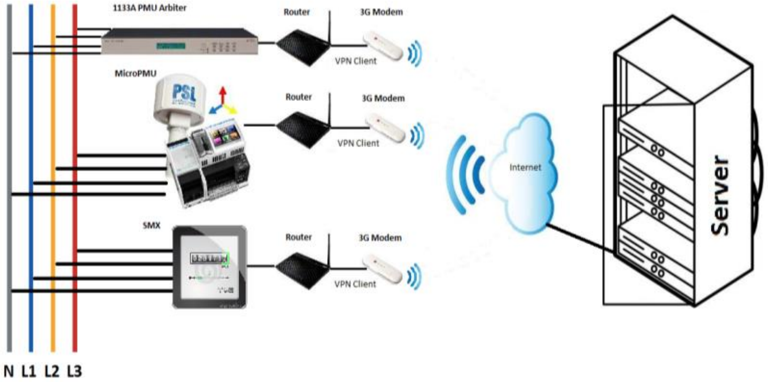
PMU MEASUREMENTS BY UPB

- **phasor:** A complex **equivalent**, in polar or rectangular form, of a **sinusoidal wave quantity**.
- **synchronized phasor or synchrophasor**: A phasor calculated from data samples using a **standard time signal as the reference** for the measurement.
- **phasor measurement unit** (PMU): a device that **measures** and **reports** synchronized phasor, frequency, and ROCOF **estimates** from voltage and/or current signals *and* a time synchronizing signal.
- **phasor data concentrator (PDC)**: **A function** that **collects** phasor data, and discrete event data from PMUs and possibly from other PDCs, and **transmits** data to other applications.



PC37.118.1a™/D1 Draft Standard for IEEE Standard for Synchrophasor Measurements for Power Systems – specifies maximum errors (FE and RFE) for different reporting rates.

PMU MEASUREMENTS BY UPB



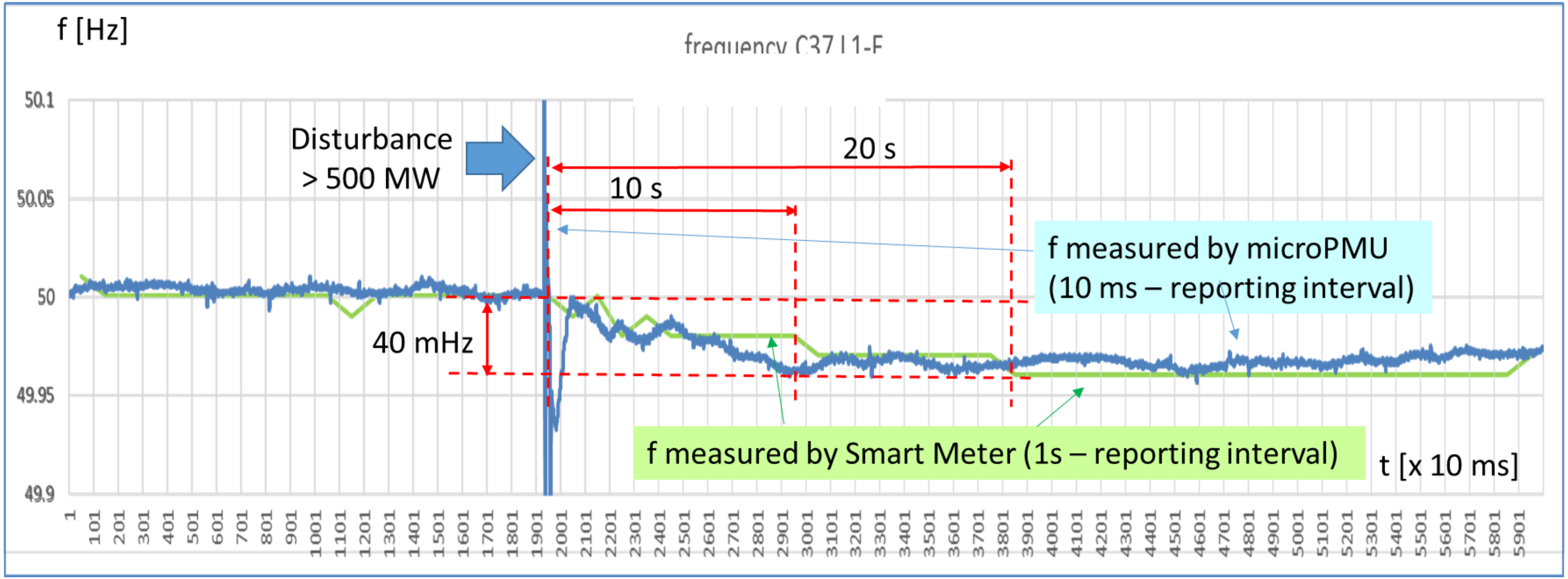
Three devices, of deferent reporting rate:

- PMU - 50 frames/s (successive data frames every 20 ms),
- µPMU -100 frames/s (successive data frames every 10 ms),
- USM - 1 frame/s (successive data frames every 1s).

Location: Faculty of Electrical Engineering - UPB

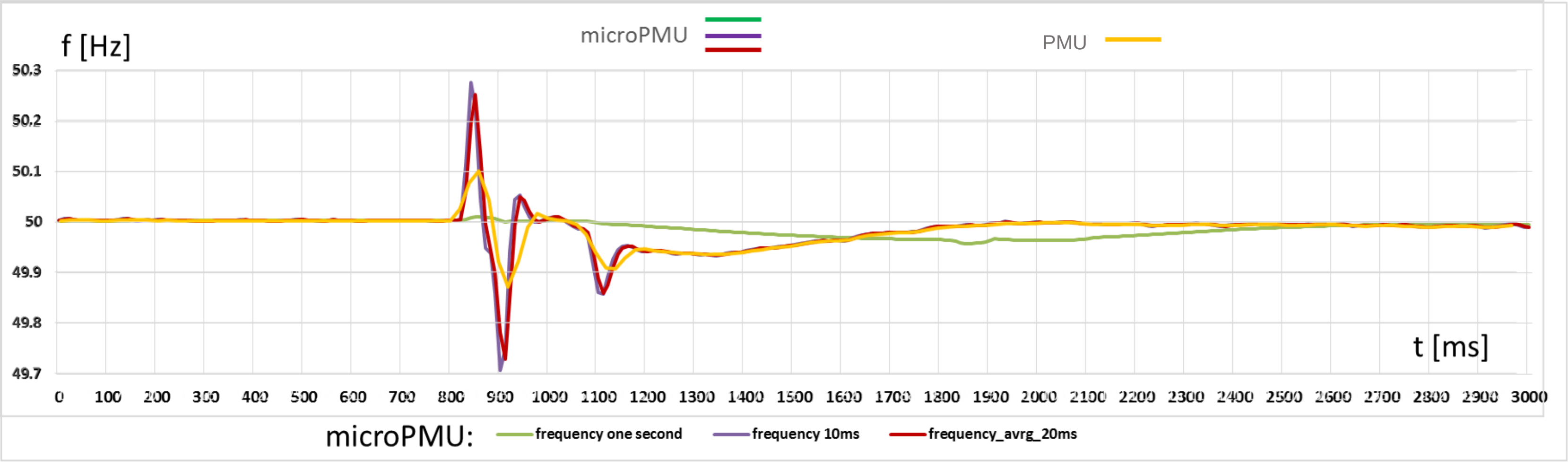
Description	**PMU**	**Micro PMU**	**RTU/ BCU/ IED**	**Classic Energy meter**	**Unbundled Smart Meter**
Synchronisation requirements	<1 µs	<1 µs	1 – 2 s	1 – 5 s	≤ 1 s
Reporting rate (typical) [frames/s]	50	100	1	1 – 0.2	> 1
Freq. resolution in steady state conditions [mHz]	<0.01	<0.01	10… 100	10..3 100	10
Accuracy	Spec.	Spec.	Not spec.	Not spec.	≈0.2%
Measurement capabilities	Dynamic state	Dynamic state	Steady state	Steady state	Steady state

PMU MEASUREMENTS BY UPB



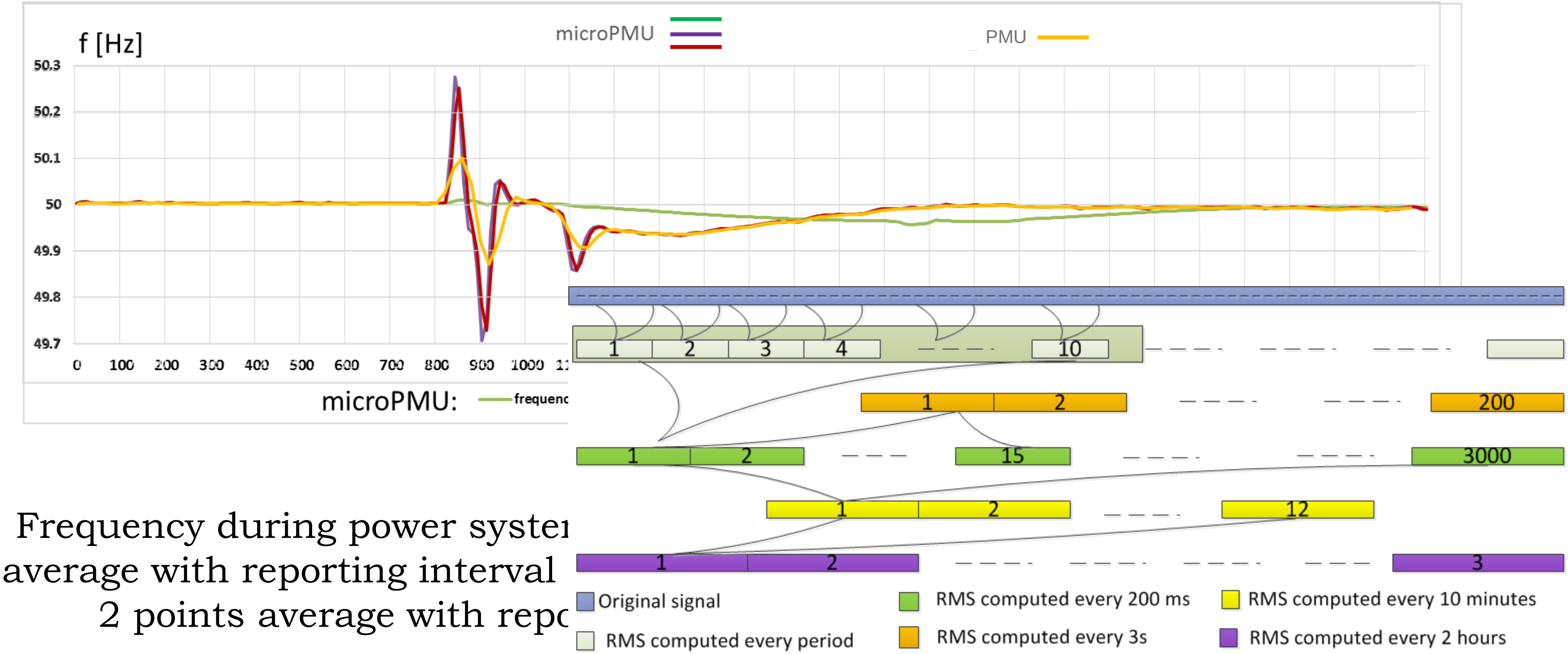
Frequency during power system disturbance: microPMU data aggregated (asynchronous 100 points average) and USM data (original measurements)

PMU MEASUREMENTS BY UPB



Frequency during power system disturbance: microPMU (asynchronous 100 points average with reporting interval of 1s; original data with 100 frames/s; asynchronous 2 points average with reporting interval of 20ms); PMU data (50 frames/s)

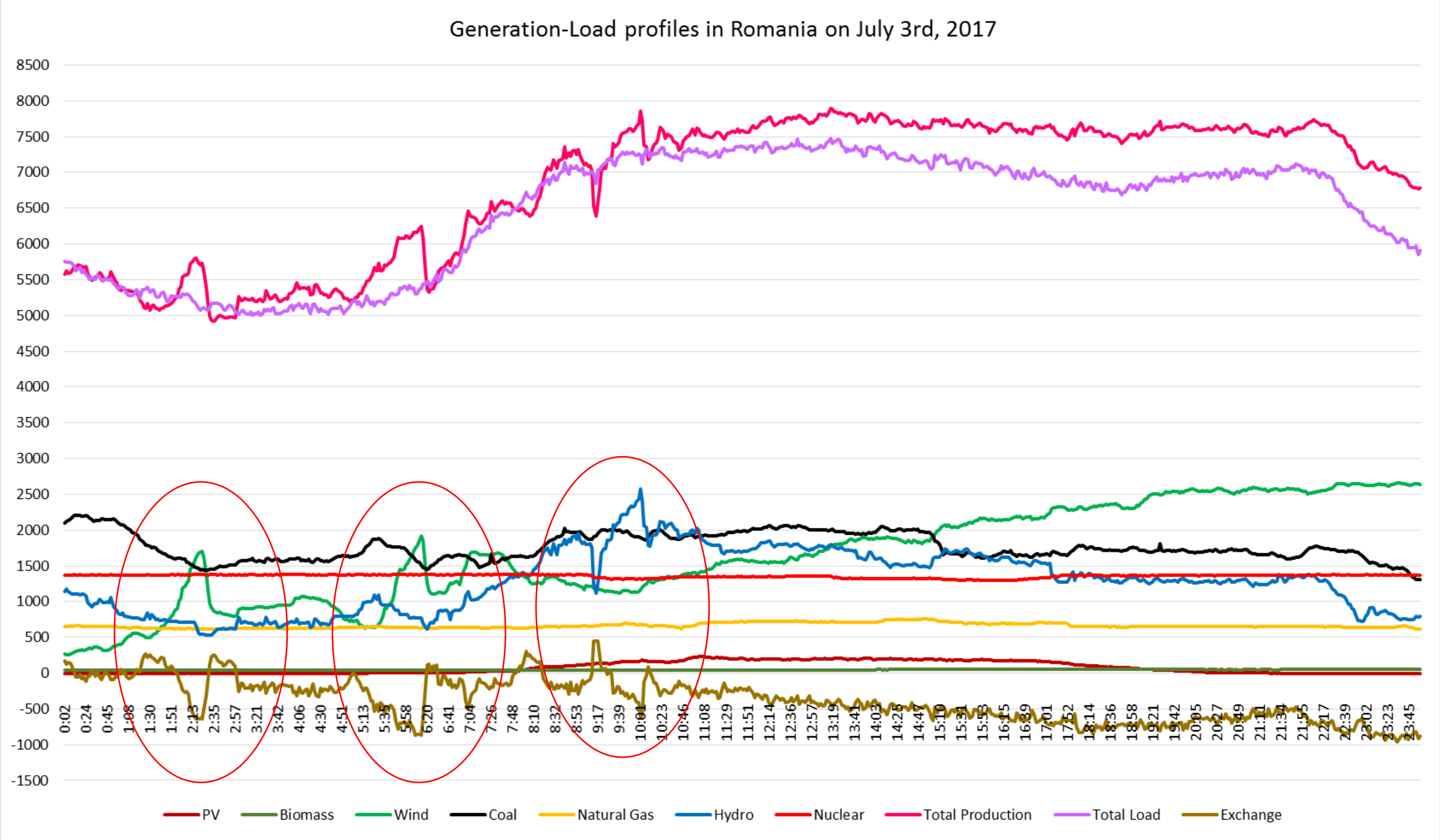
PMU MEASUREMENTS BY UPB



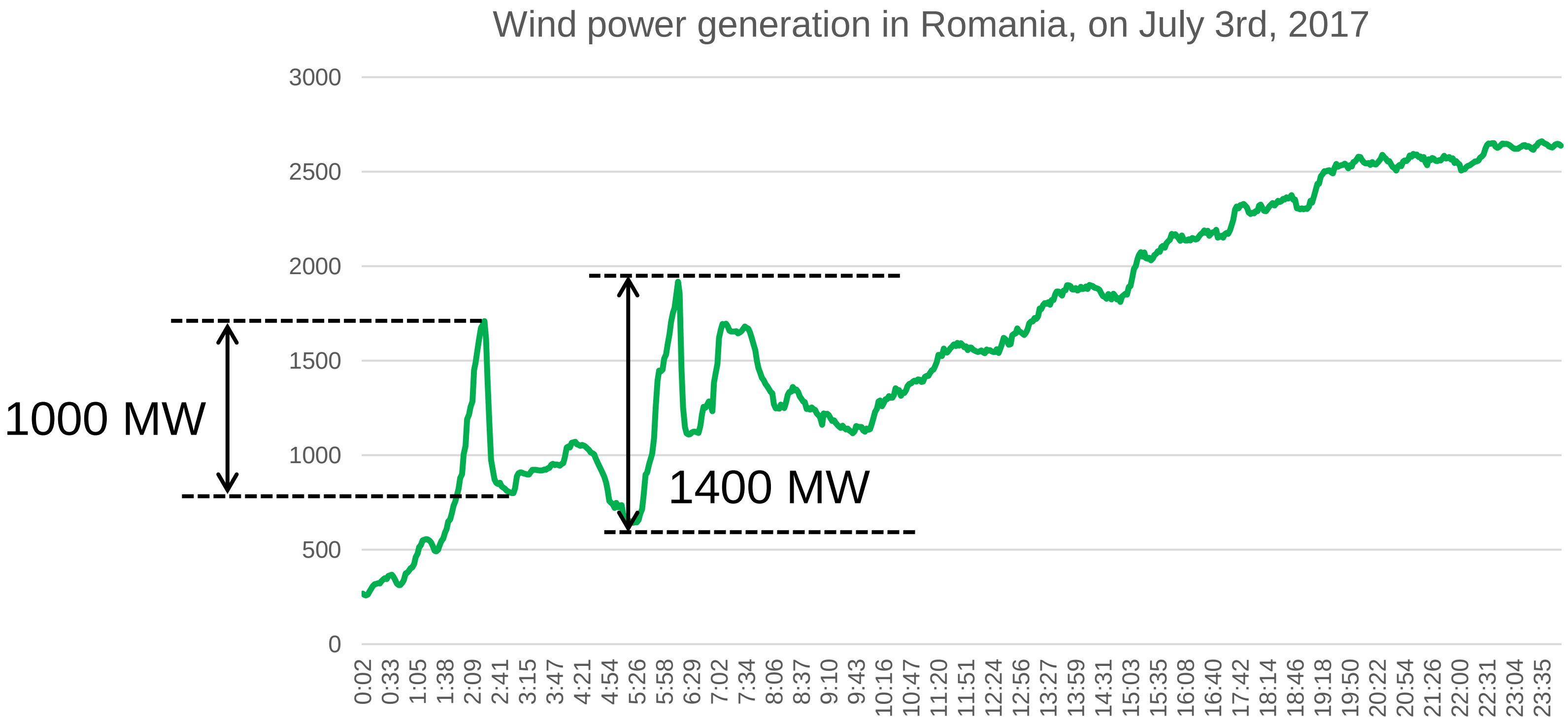
Frequency during power syste
average with reporting interval
2 points average with repo

Effects of wind variation

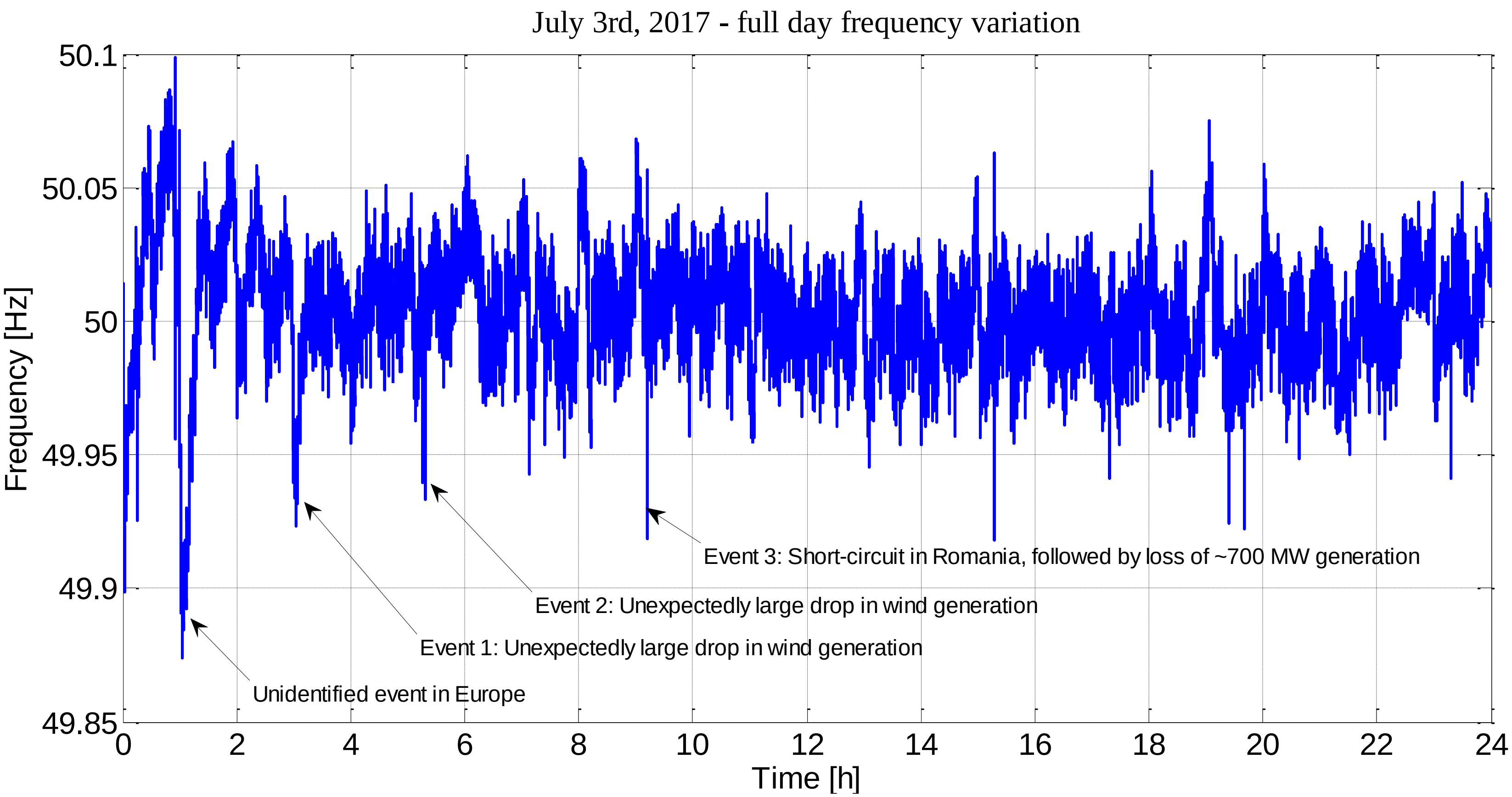
EFFECTS OF WIND VARIATION


Generation-Load profiles in Romania on July 3rd, 2017

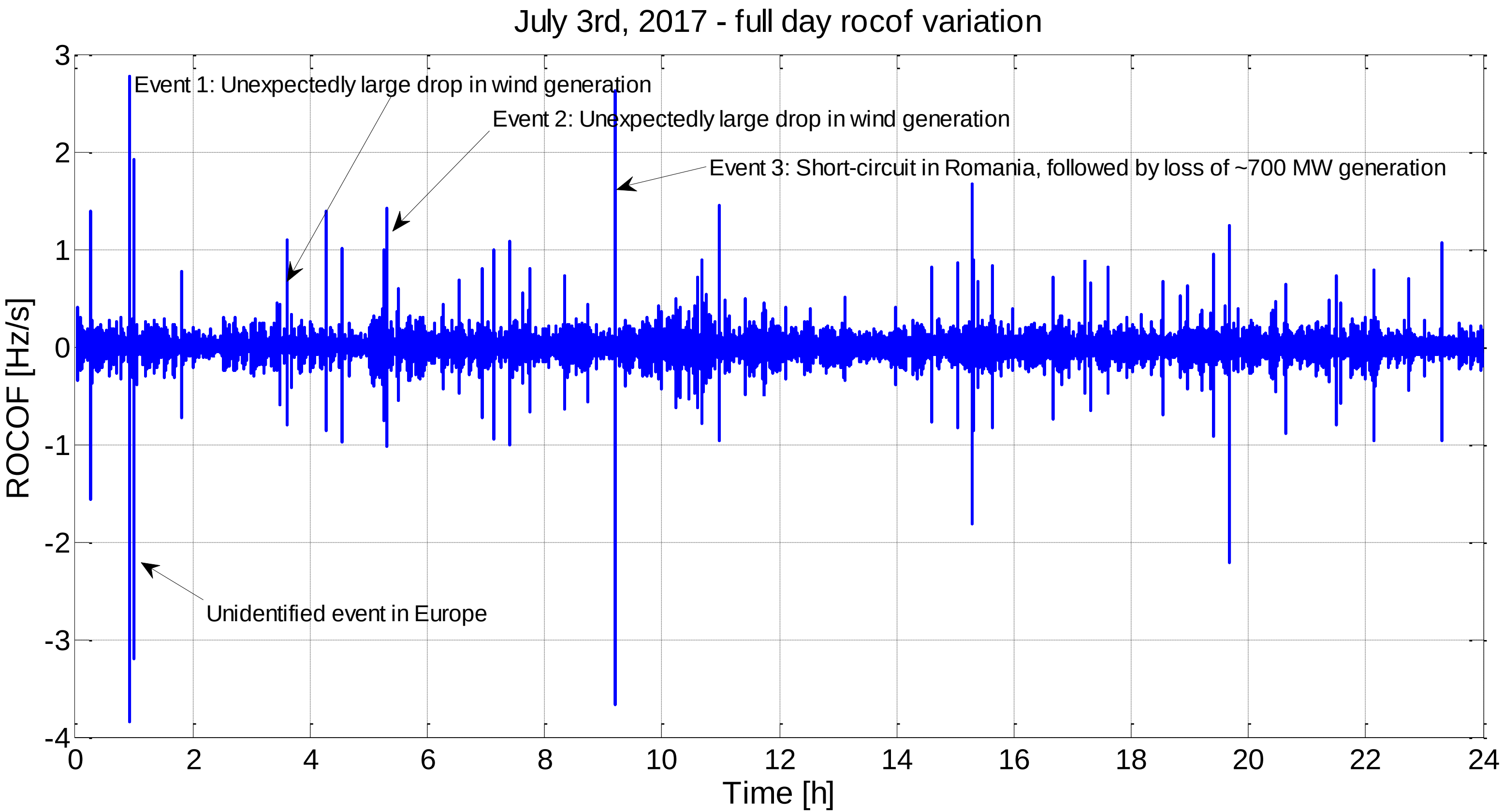
EFFECTS OF WIND VARIATION



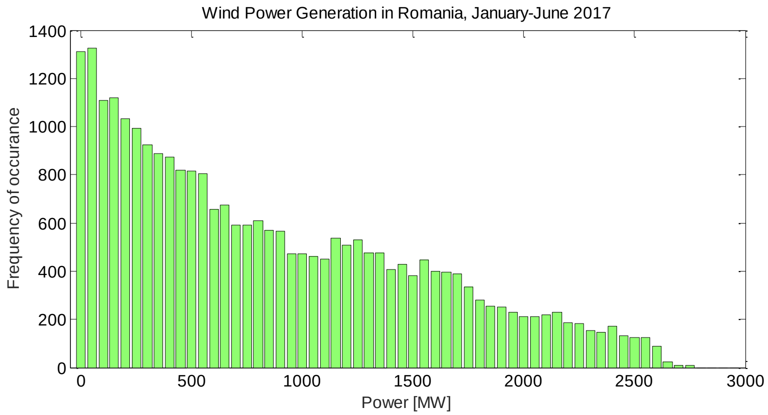
EFFECTS OF WIND VARIATION

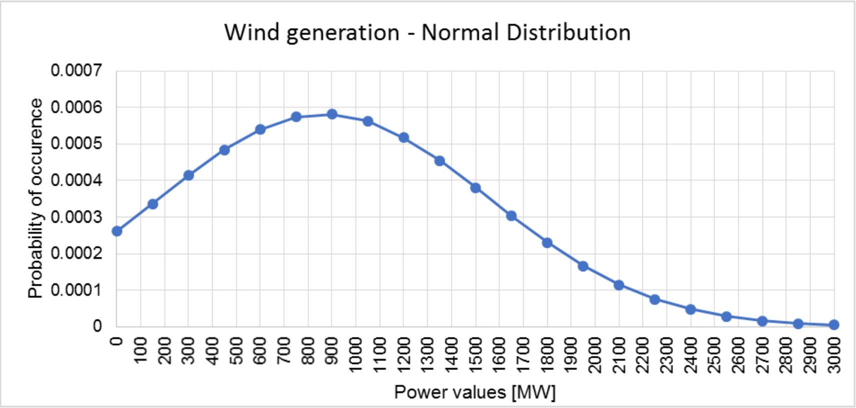


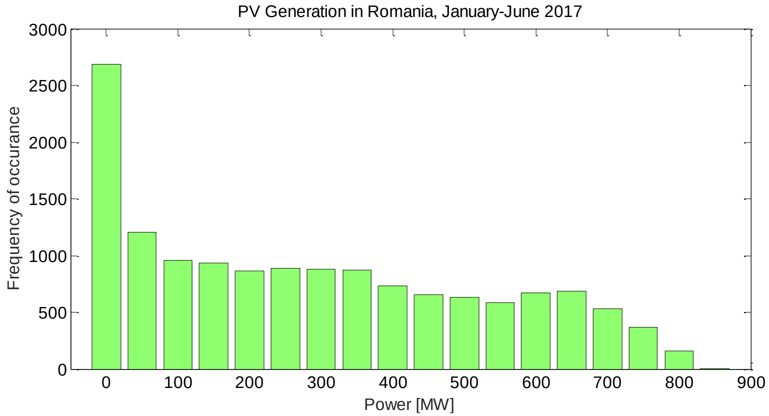
EFFECTS OF WIND VARIATION

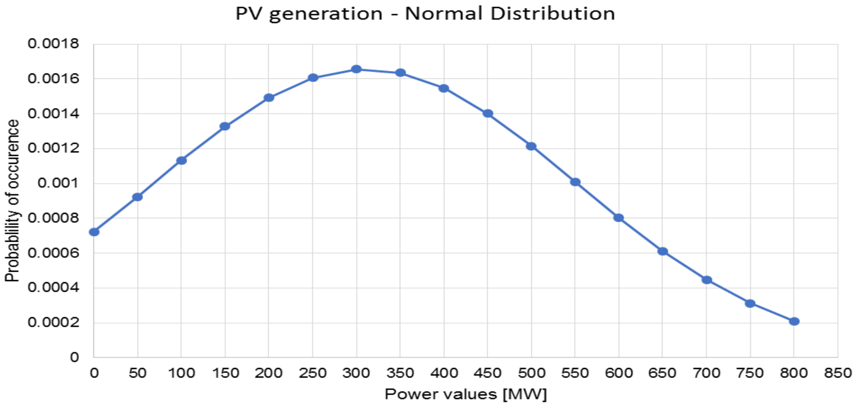


POWER GENERATION FROM RES IN ROMANIA


Wind Power Generation in Romania, January-June 2017


Wind generation - Normal Distribution

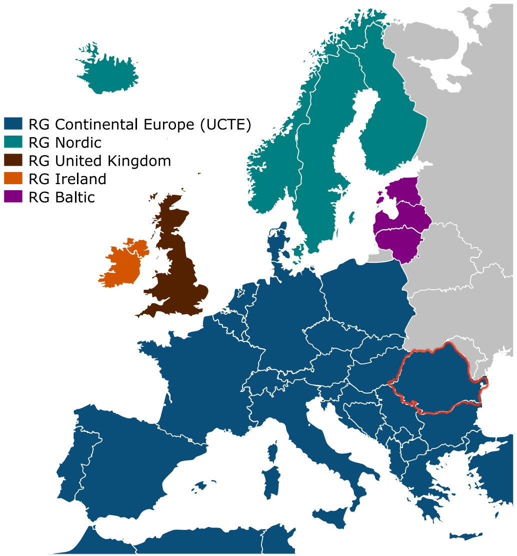

PV Generation in Romania, January-June 2017


PV generation - Normal Distribution

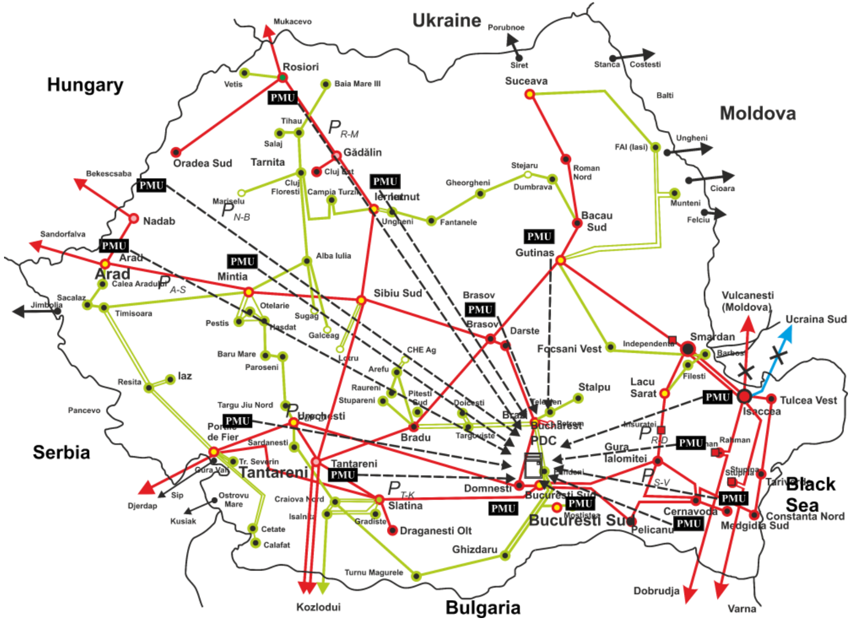
Analysis of various frequency events in Romania

THE WIDE AREA MEASUREMENT SYSTEM IN ROMANIA

ENTSO-E System



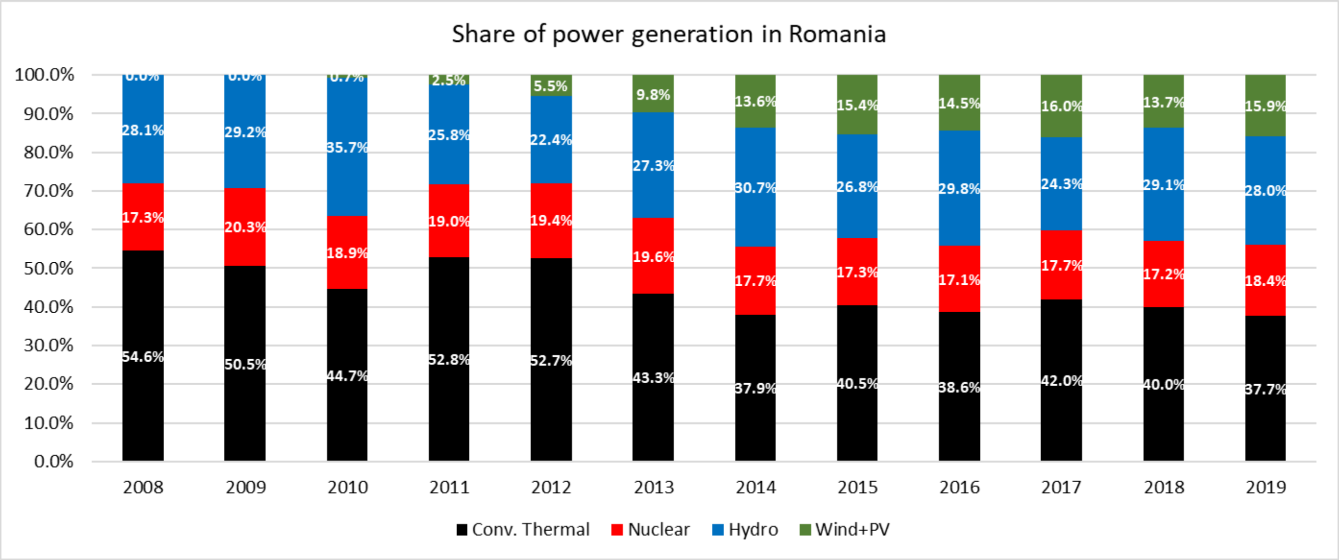
Romanian Transmission System



WAMS in Romania

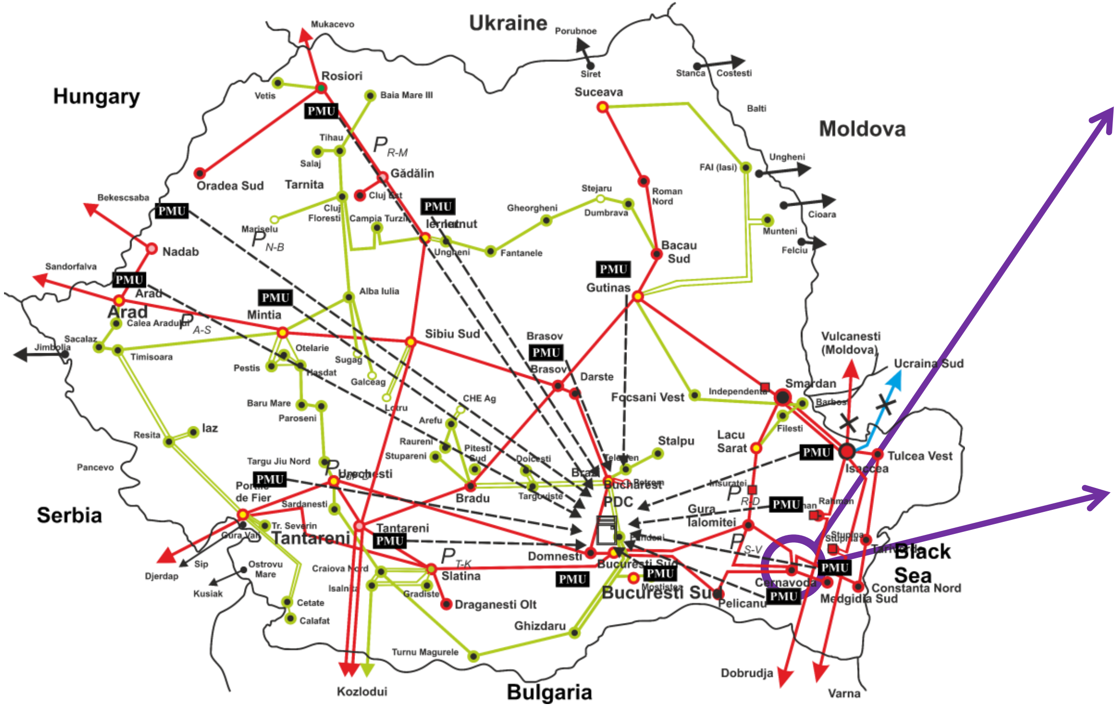
- 15 PMUs + 1 central PDC
- manufactured by Schweitzer Engineering Laboratories (SEL)
- Located at border buses and at the most important power plants
- Reporting rate: 25 values per second (40 ms time interval)

THE WIDE AREA MEASUREMENT SYSTEM IN ROMANIA



Type of plant	H [MWs/MVA]
Nuclear	6-7
Coal and Natural Gas	3-6
Large Hydro	2-4
Small Hydro	1
Synch. Condenser	1
PV and Wind	0-1

A. FREQUENCY VARIATIONS CAUSED BY THE DISCONNECTION OF LARGE MECHANICAL INERTIA



Cernavoda Nuclear Power Plant
2 x 700 MW

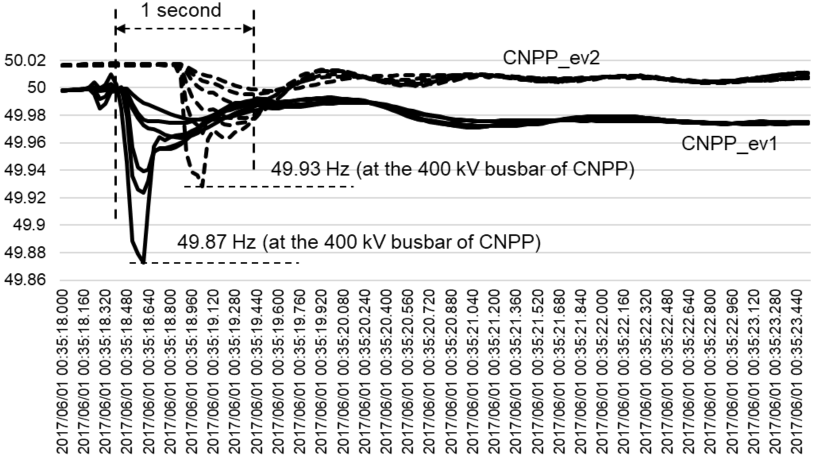
CNPP_ev1: 1st June 2017

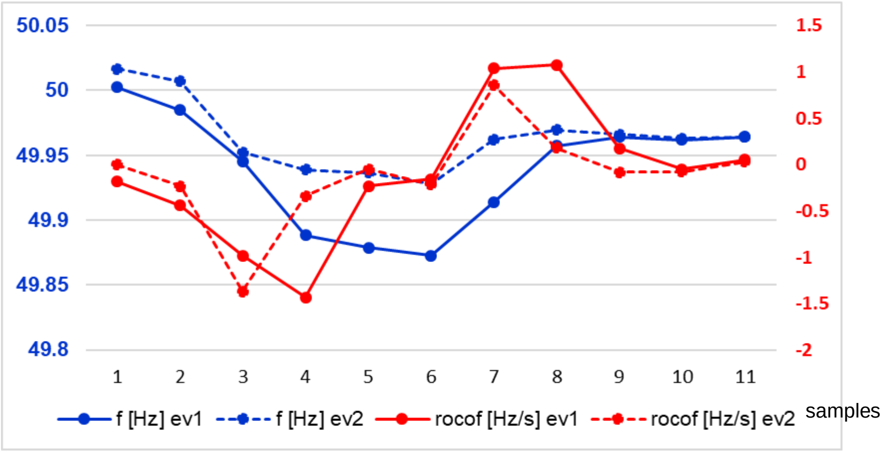
- One unit was under planned maintenance (half inertia available)
- Sudden full disconnection of the unit (no inertia remained)
- The instant of perturbation:
  - 18% wind generation
  - 17% power export

CNPP_ev2: 16 August 2018

- Both units in operation
- Sudden full disconnection of the unit
- The instant of perturbation:
  - 4.4% wind generation
  - 6% power export

A. FREQUENCY VARIATIONS CAUSED BY THE DISCONNECTION OF LARGE MECHANICAL INERTIA

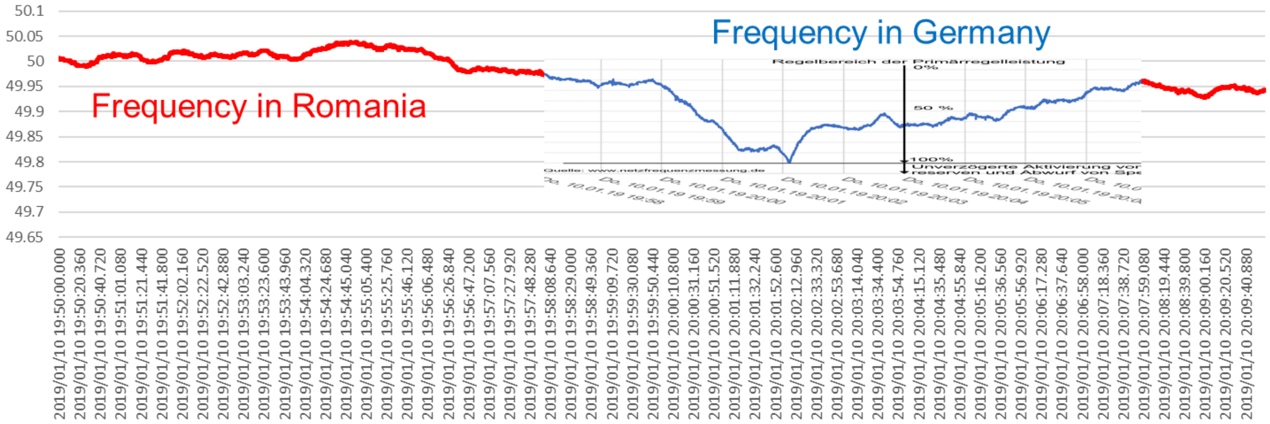




- The local mechanical inertia determines the frequency dip, which is double when both units of CNPP are disconnected
- The frequency is stabilized within 1 second, earlier than the time delay specific to the primary frequency control
- the frequency reaches the nadir value after 5 reporting intervals (200 ms), then the frequency is stabilized after 10 reporting intervals (400 ms).
- The mechanical inertia is deployed after 2-3 reporting intervals (80-120 ms), when RoCoF starts decreasing

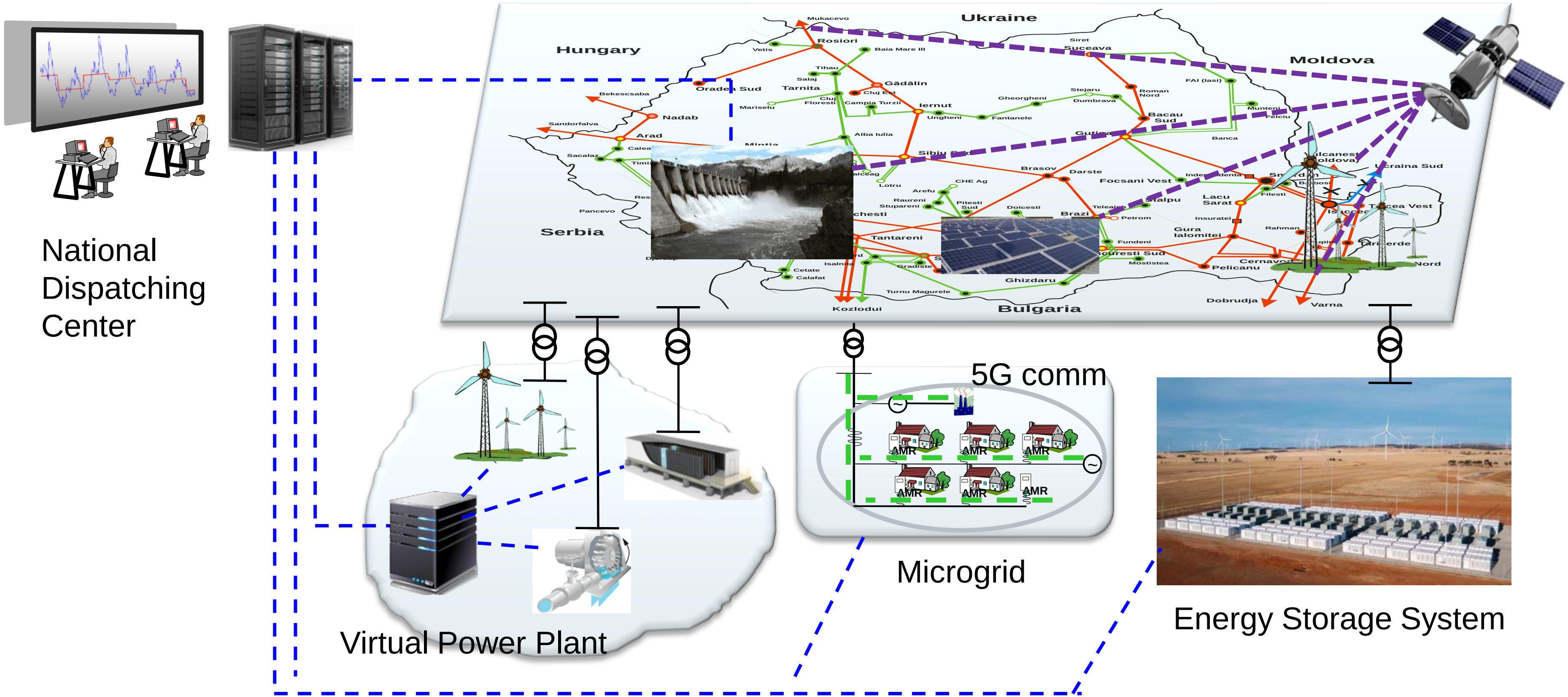
B. FREQUENCY VARIATIONS CAUSED BY SLOW LONG-TERM UNBALANCES

- On 10 January 2019, 21:02 CET, a new critical situation was recorded in the Continental Europe power system. The frequency dropped to 49.8 Hz for nine seconds, as compared to 49.0 Hz in 2006, during the desynchronization of the ENTSO-E power system.
- The frequency was almost identical in both Germany and Romania showing that, under the current operating conditions of the European Continental power system, with large mechanical inertia available across the system, the generators maintain synchronism with each other.



The Virtual Power Plant

AGGREGATED CONTROL



National Dispatching Center

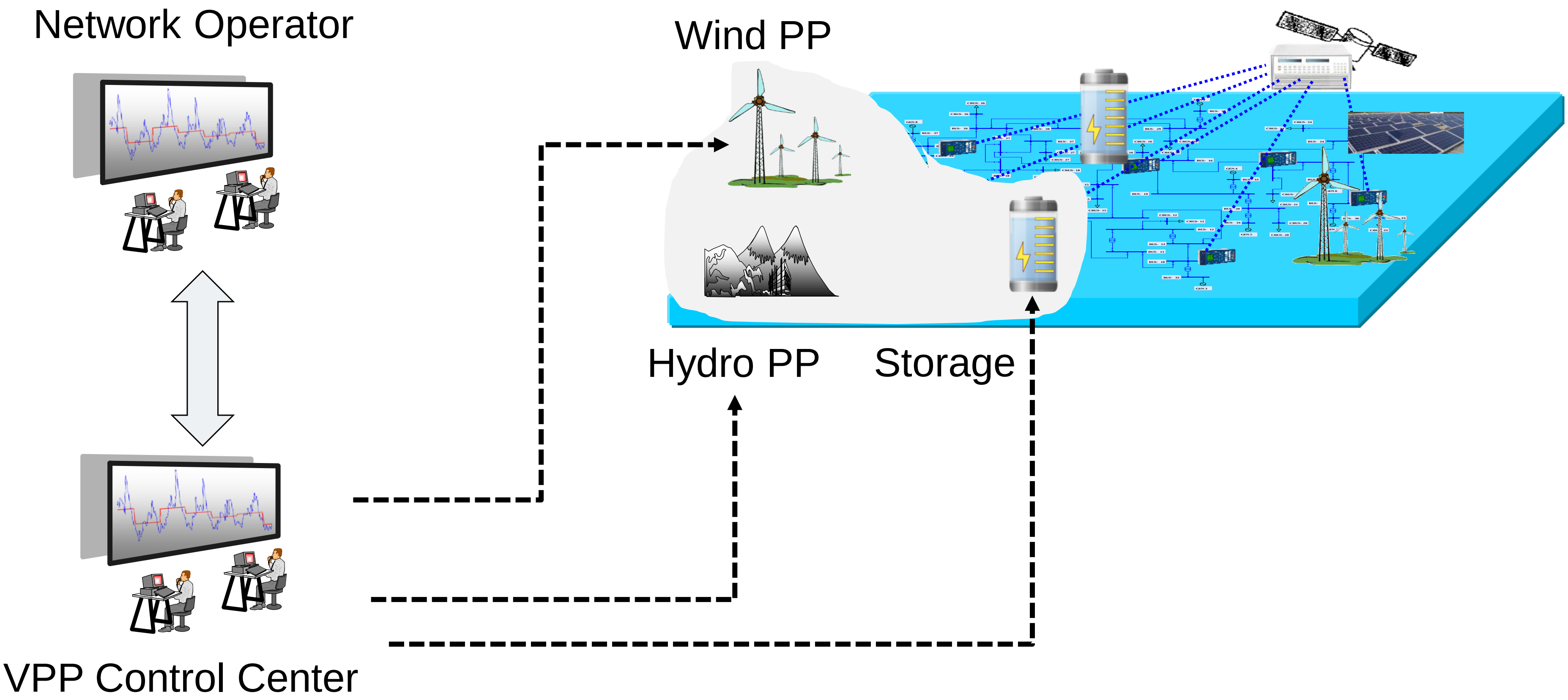
5G comm

Virtual Power Plant

Microgrid

Energy Storage System

VIRTUAL POWER PLANT



Network Operator

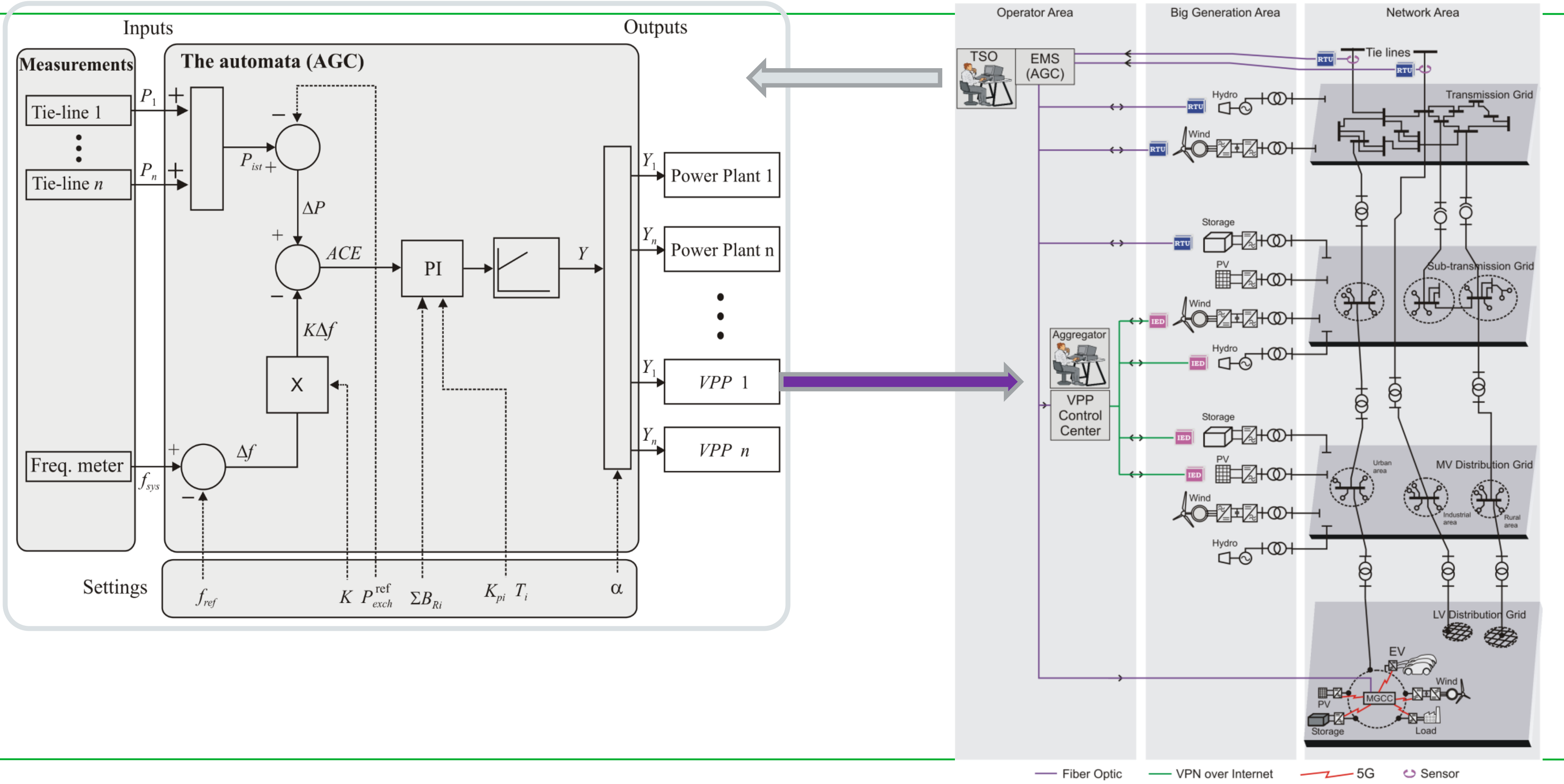
Wind PP

Hydro PP

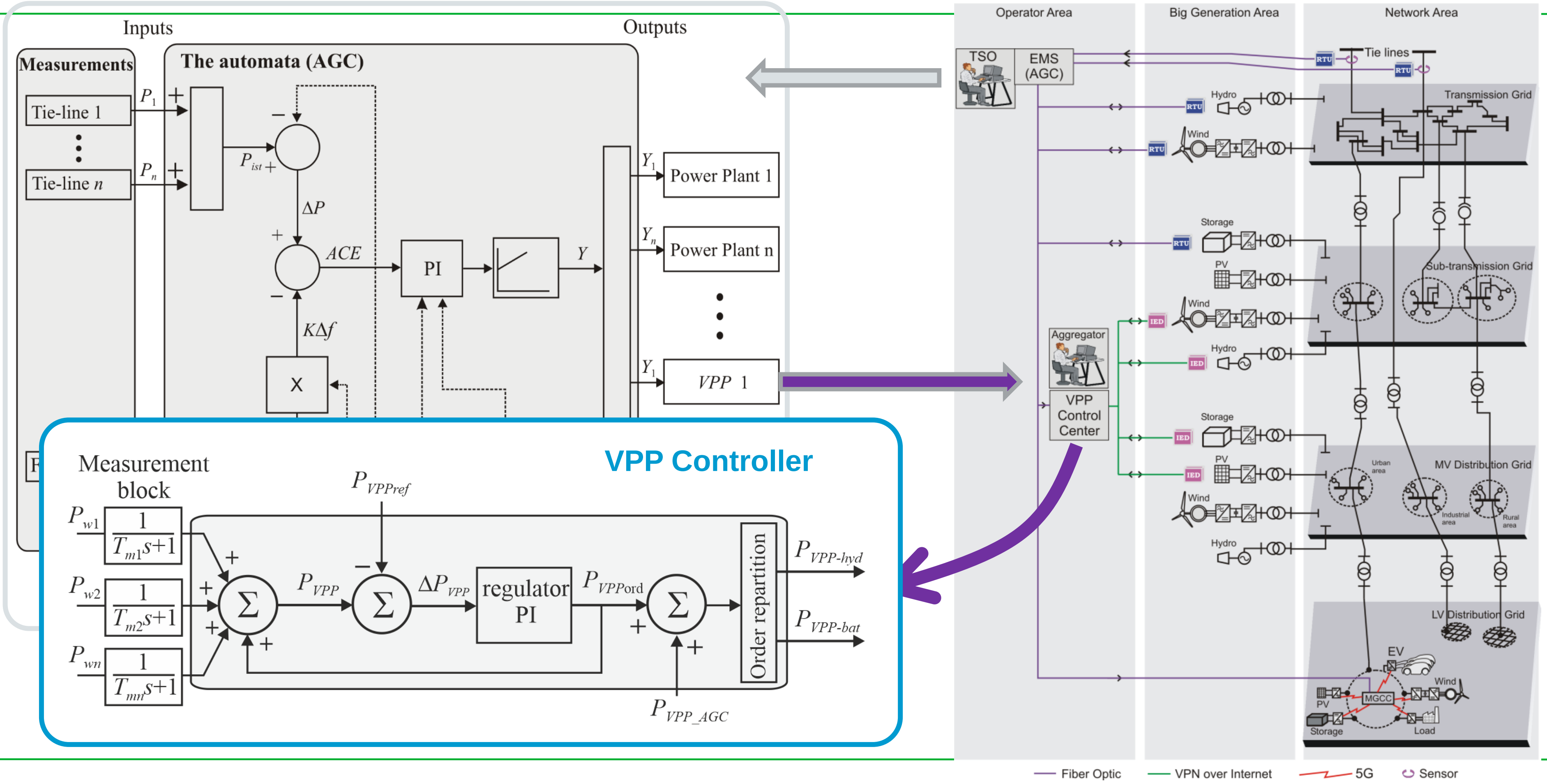
Storage

VPP Control Center

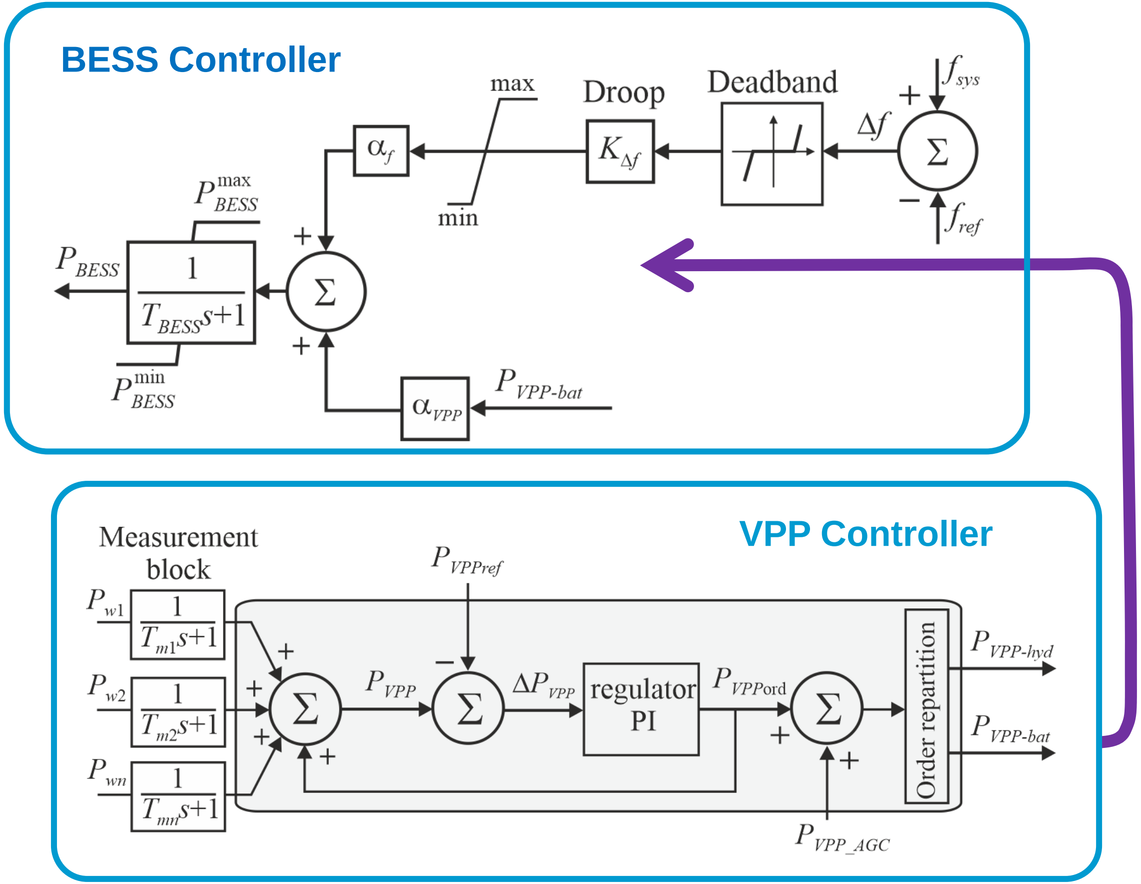
VIRTUAL POWER PLANT

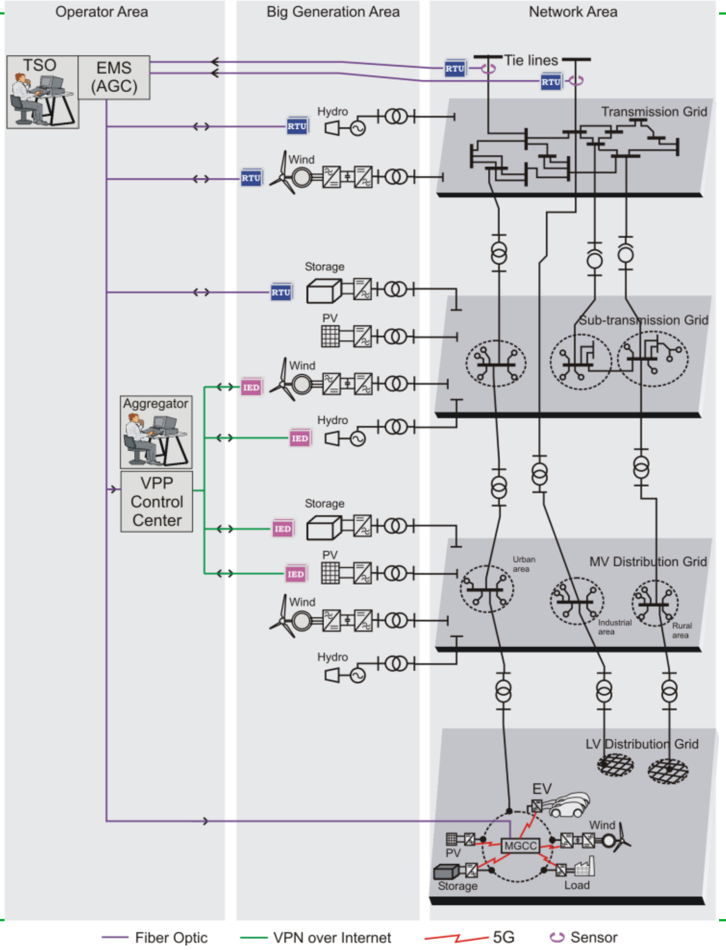


VIRTUAL POWER PLANT



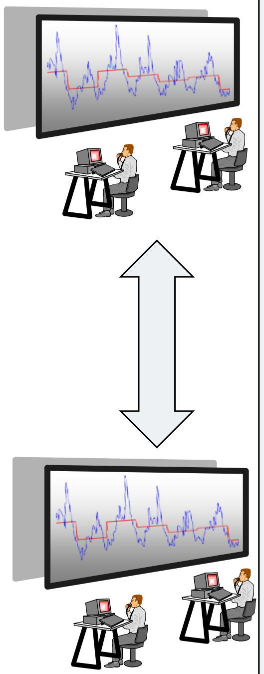
VIRTUAL POWER PLANT

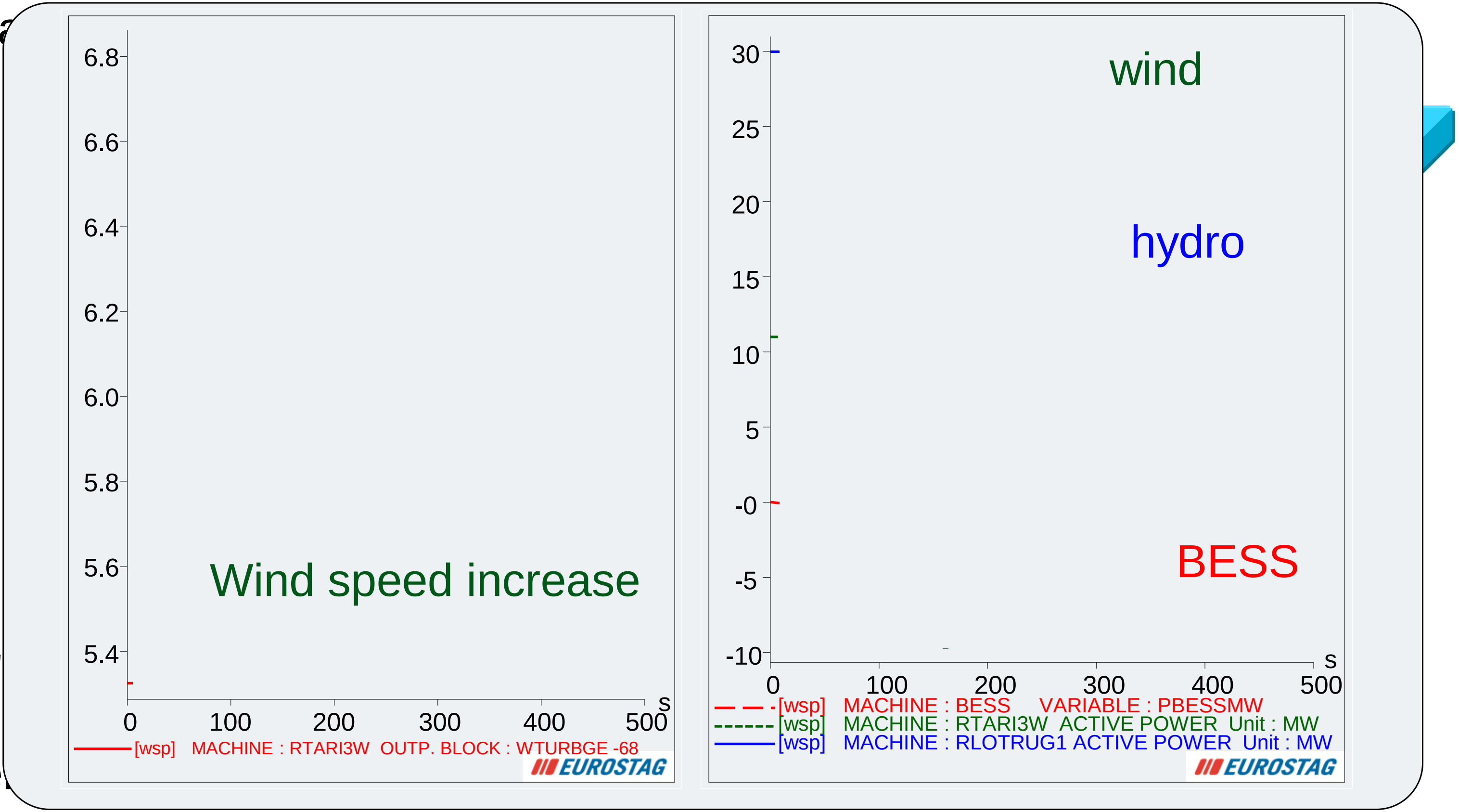




VIRTUAL POWER PLANT – SIMULATION IN EUROSTAG

Network Opera

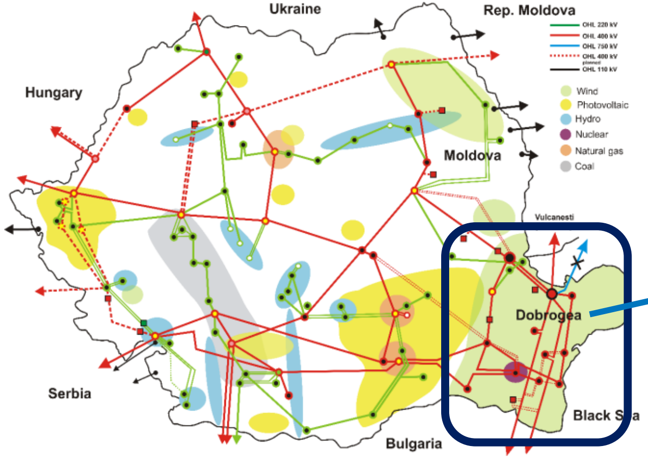


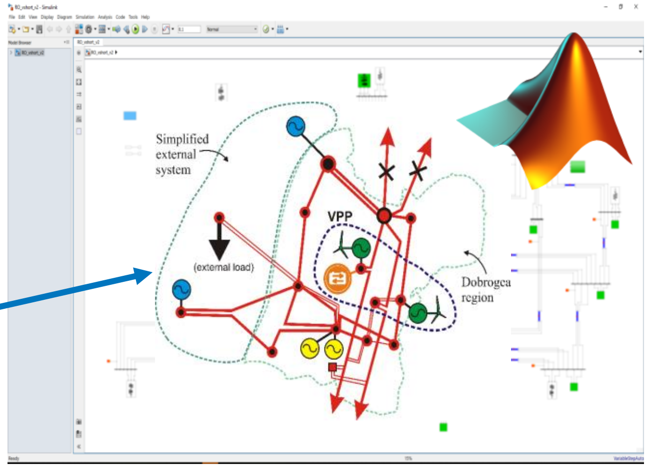


VPP Control Ce

VIRTUAL POWER PLANT – SIMULATION IN SIMULINK

The Romanian power system





Objectives: providing power reserves from Virtual Power Plants for the **Frequency Restoration Control**

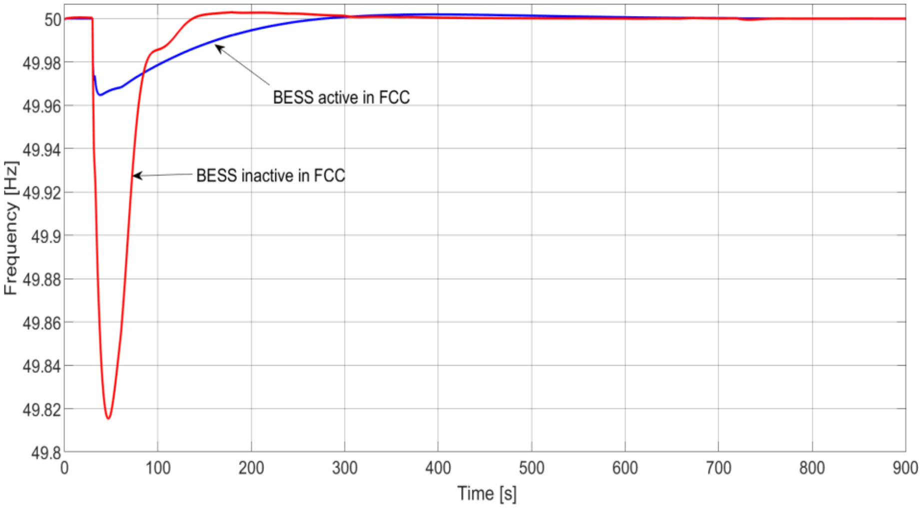
Results: recommendations for designing the VPP control scheme

Network characteristics

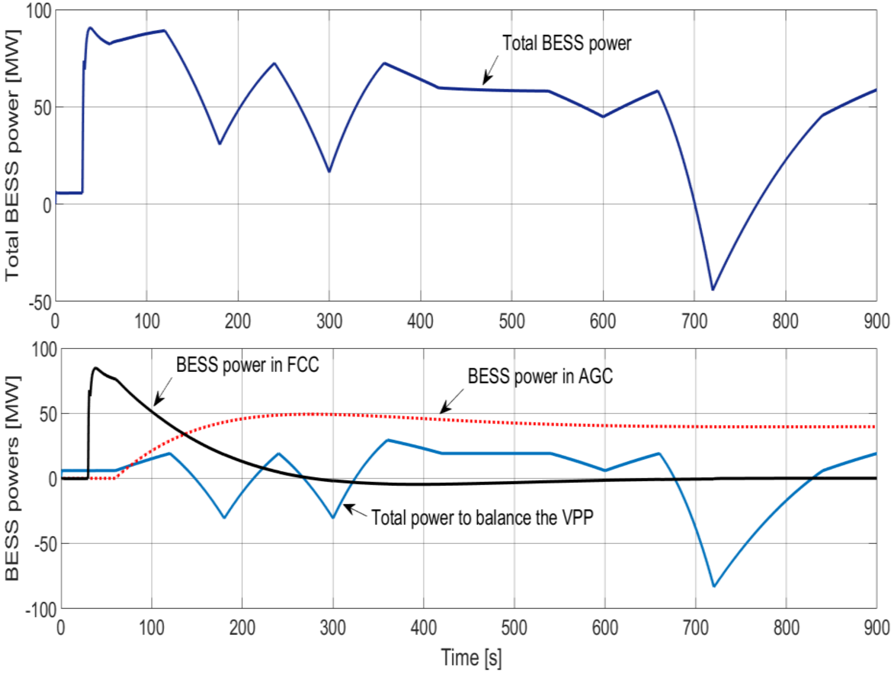
- **2600 MW Wind Power**
- **1400 MW Nuclear Power**
- **Peninsular Configuration**
- **Generation Surplus**

VIRTUAL POWER PLANT

Importance of batteries for frequency stability

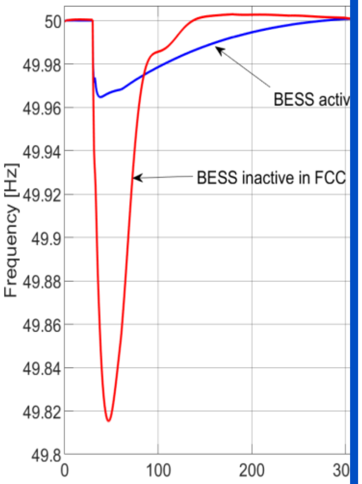


Use of batteries for VPP balancing



VIRTUAL POWER PLANT

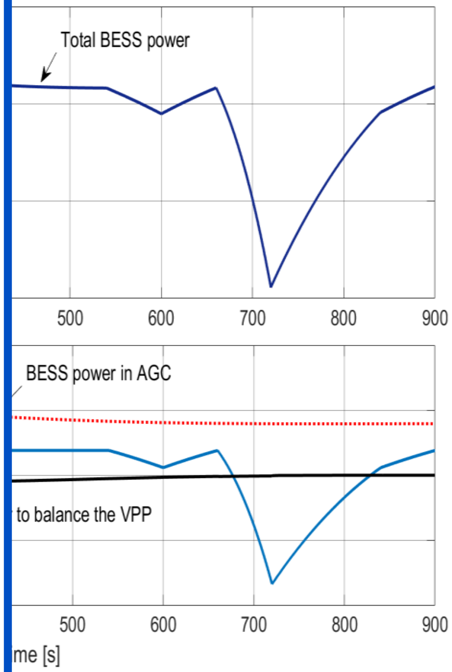
Importance c



Recommendations for VPPs:

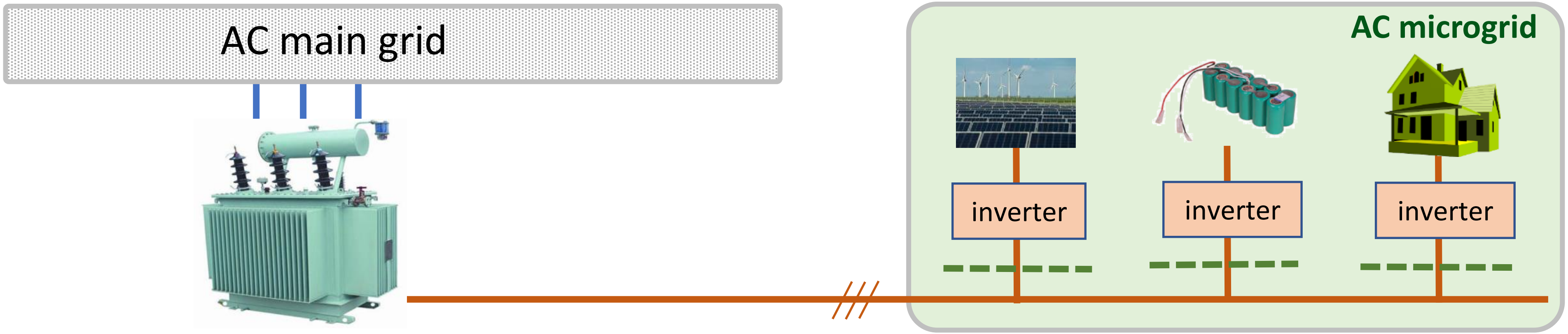
- When a CI-ESS is used for aFRC, delays should be added to the reaction of the CI-ESS in order to avoid the frequency to be restored in a longer time.
- In order to save the energy available for aFRC, some CI-ESSs can be included in the tertiary frequency control level.
- As the share of RES increases, larger CI-ESSs are required
- Standardization of the operation in relation to the network operator in the grid cods, such as: communication type, power reserve monitoring, and Quality of Service (QoS) monitoring

or VPP balancing



Desynchronizing the grids by Solid State Transformer

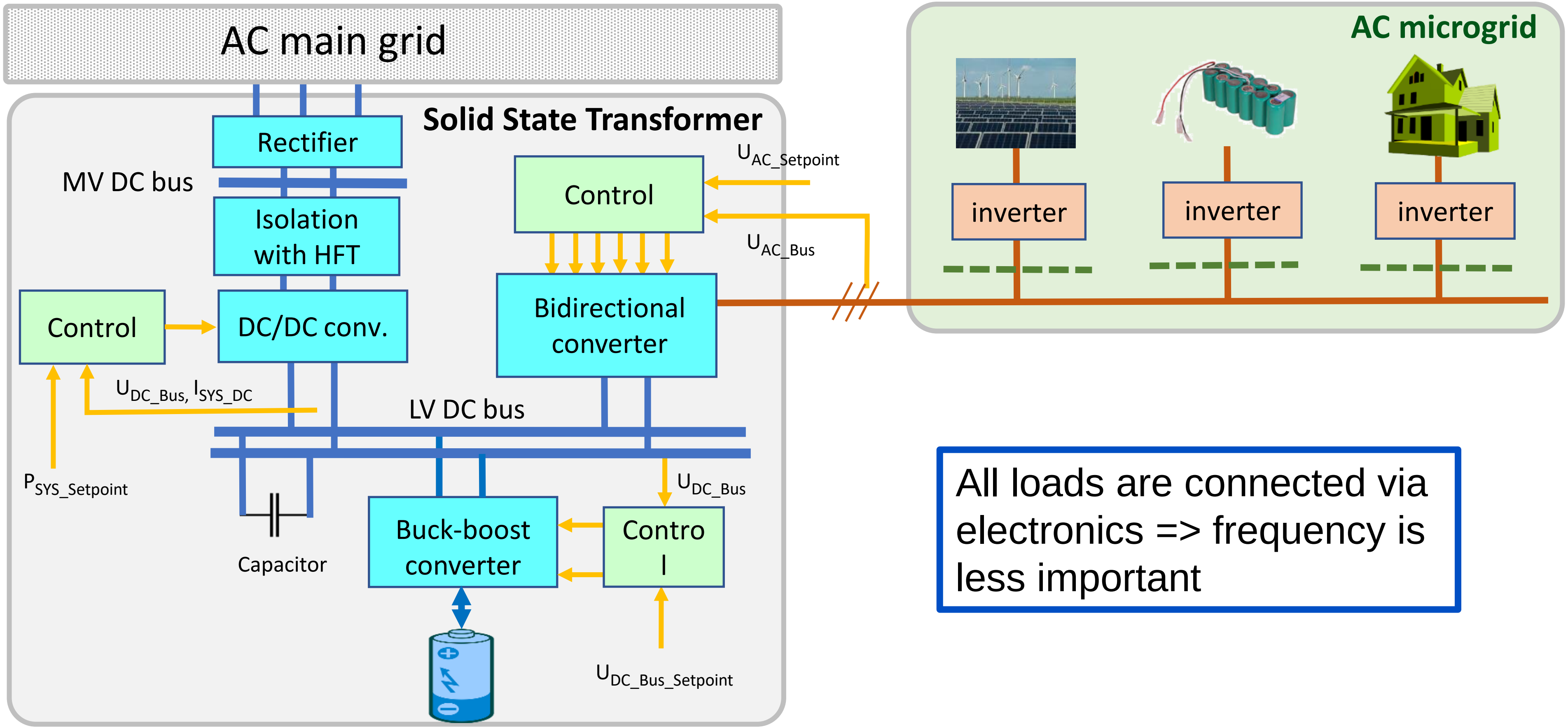
SOLID STATE TRANSFORMER



The distribution grids are subjected to

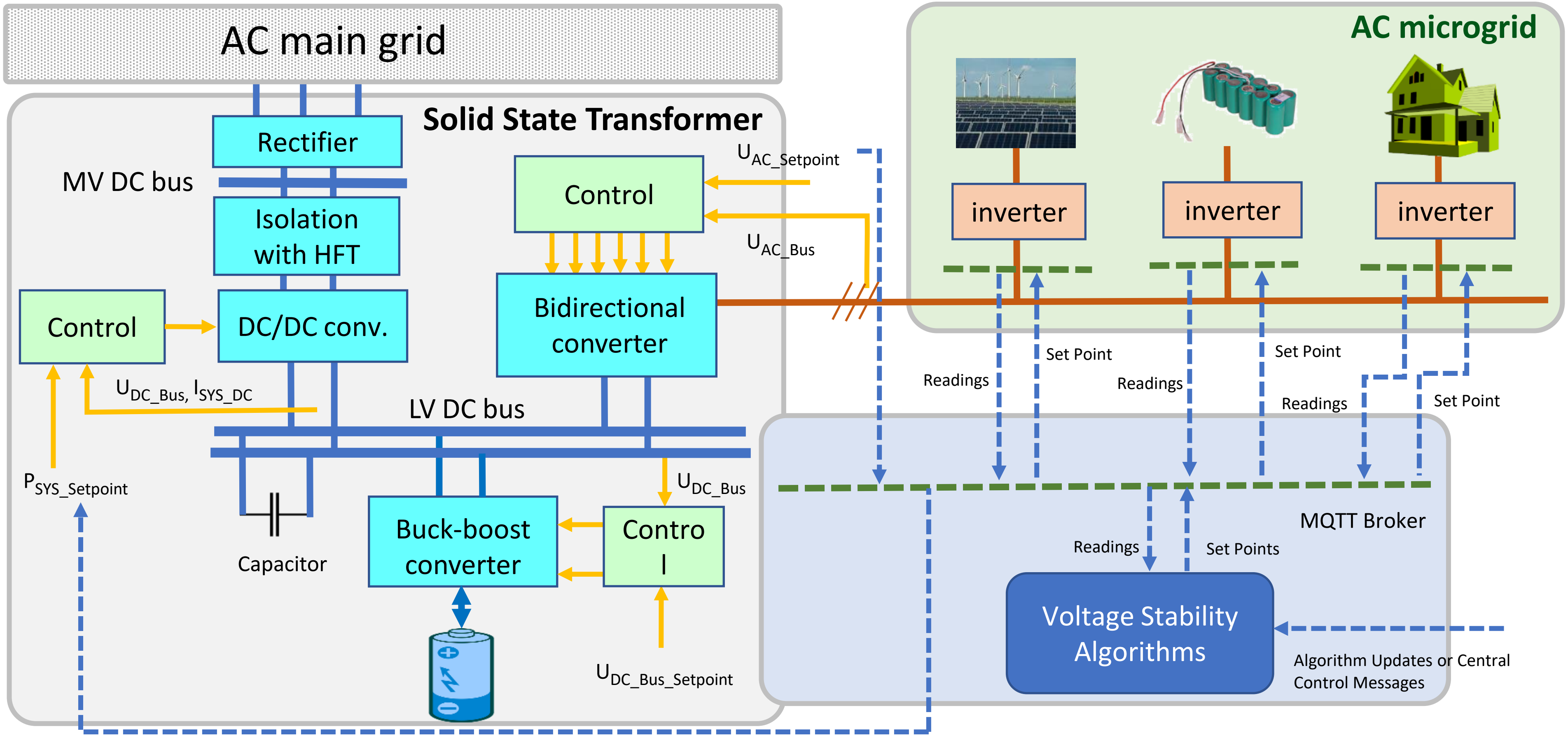
- frequency perturbations
- voltage transients coming from upstream
- voltage fluctuations
- special protections designs

SOLID STATE TRANSFORMER

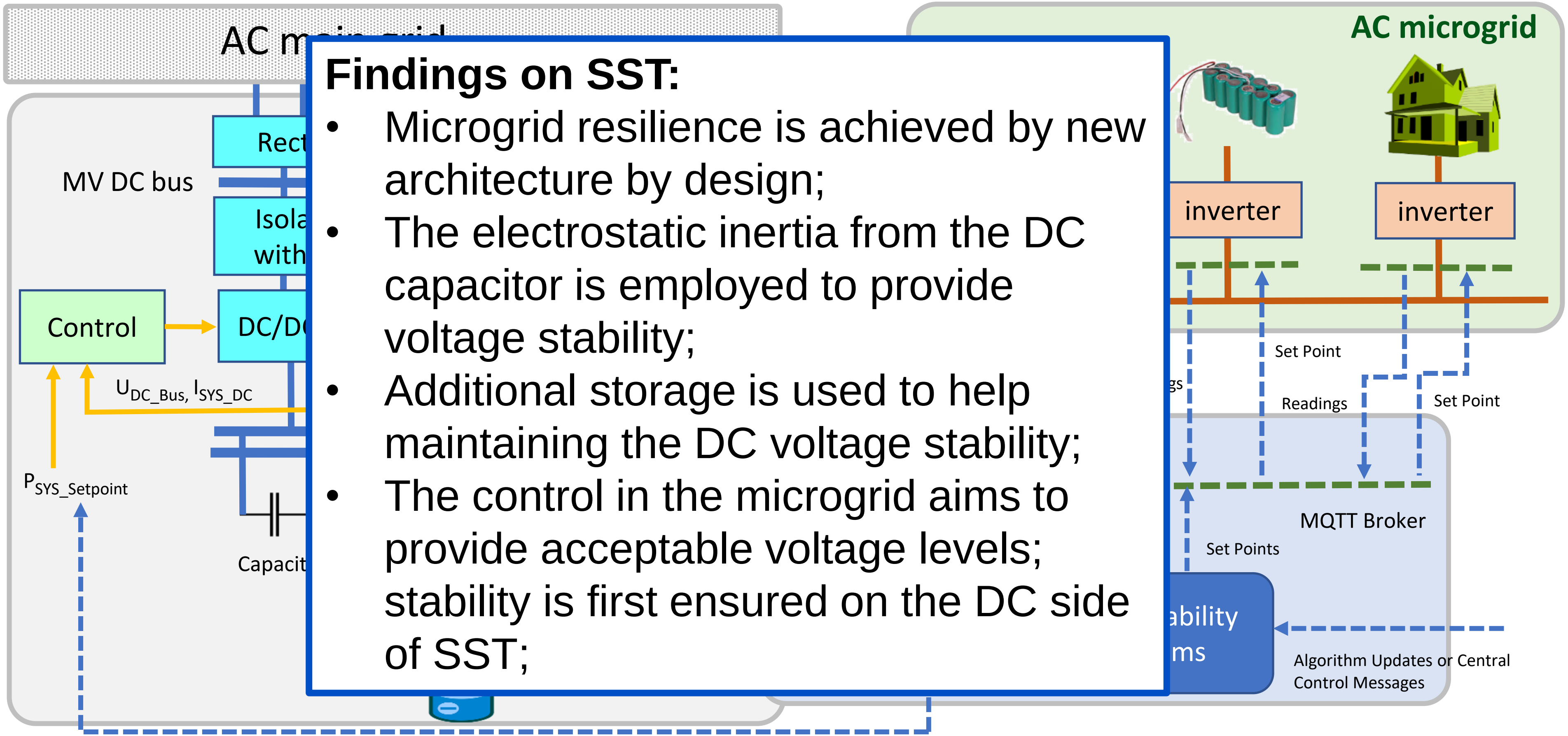


All loads are connected via electronics => frequency is less important

SOLID STATE TRANSFORMER



SOLID STATE TRANSFORMER



Findings on SST:

- Microgrid resilience is achieved by new architecture by design;
- The electrostatic inertia from the DC capacitor is employed to provide voltage stability;
- Additional storage is used to help maintaining the DC voltage stability;
- The control in the microgrid aims to provide acceptable voltage levels; stability is first ensured on the DC side of SST;

Solutions for power system stability under renewables dominated operating conditions

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Measurements based frequency analysis