SEMINAR: System Frequency Response considering Integration of Wind Power

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Seminar Agenda

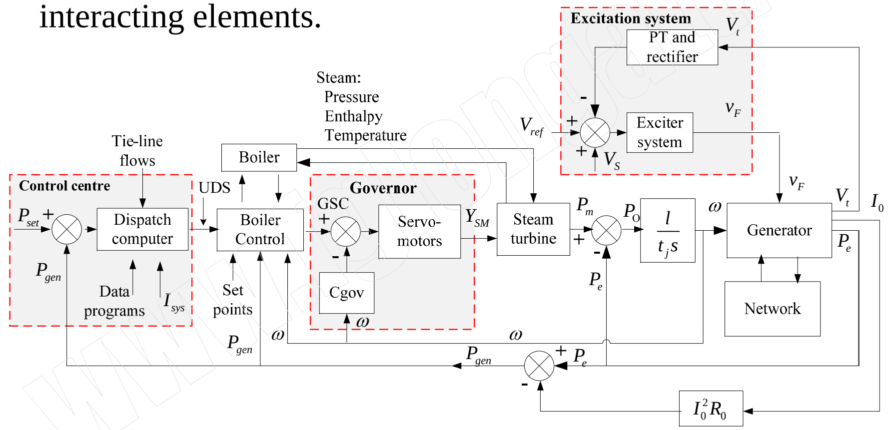
1. Introduction
2. Frequency control in classical power systems
3. System Frequency Response
4. Synthetic or Artificial Inertia
5. Frequency Response of Wind Turbines/Farms
6. Conclusions

1. INTRODUCTION

Power System Dynamic
Electromechanical Processes
Stability
Frequency Stability

Power System Dynamic: Complexity & Dimension

- Process dynamic in electric utility system cover a very wide **spectrum of phenomena** and a **wide range of disciplines.**
- The **dimensions and complexity** of power system dynamics can well be appreciated when one realize that there are hundreds of interacting elements.

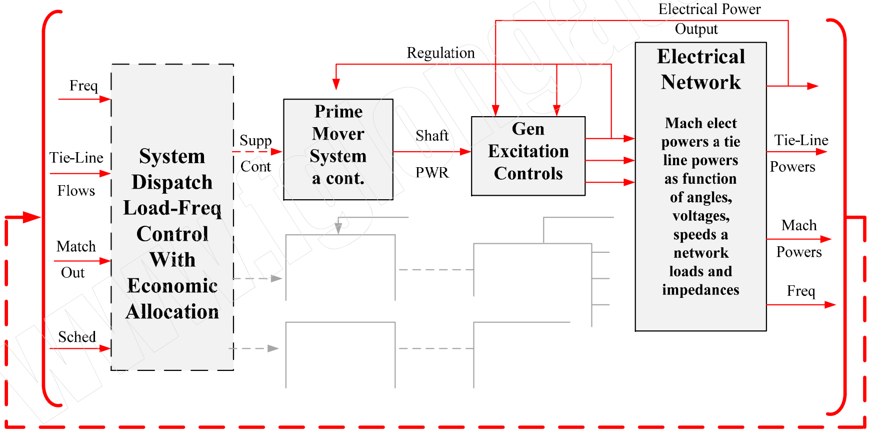


Block Diagram of a Synchronous generator control system

Source: P.M. Anderson "Power System and control

Power System Dynamic: Complexity & Dimension

- There are **hundreds of interacting elements** such ad generator with their controls, energy supply system and controls, and that the **mathematical representation** of each element generally involves many independent variables described by set of **high order, non linear differential equations**.



Power System Dynamic: Classification

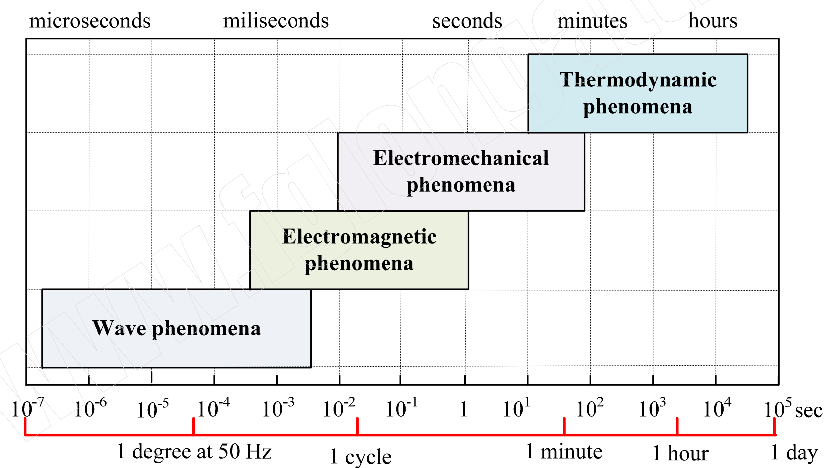
- Because of the interconnection of various elements a large variety of dynamic interactions are possible.
- System **dynamic effects** can be divided based on:
  - Cause
  - Consequence
  - **Time scales**
  - **Physical character**
  - Place in the system that they occur
- The prime concern: **System response to** change in power demand and to **various types of disturbances.**

Dynamic Effects: Change in Power

- Dynamic processes have effect over different time-scales.
  - **The fastest:** Associated with the transfer of energy between the rotating masses in the generators and the loads. **(ms-seconds)**
  - **Slower:** Due to voltage and frequency control actions needed to maintain system operating conditions. **(seconds - minutes)**
  - **Very slow:** Corresponding to the way in which the generation is adjusted to meet the slow daily demand variations. **(seconds - hours)**

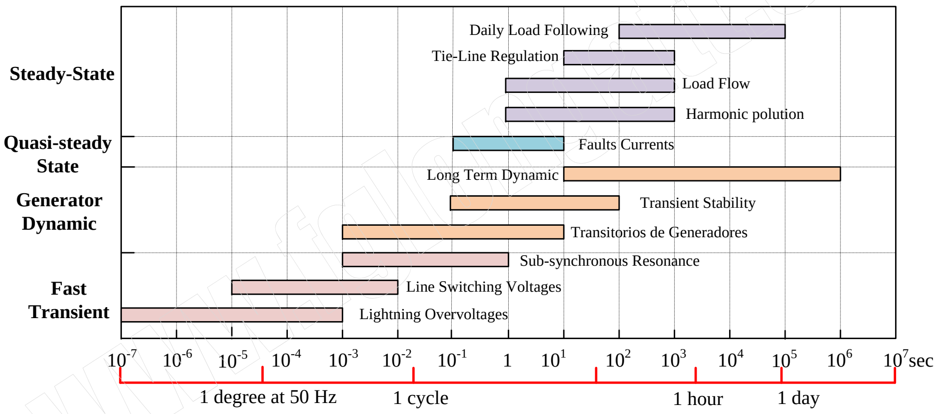
Physical Character

- Wave **(μs - ms)**
- Electromagnetic **(ms - 1s)**
- Electromechanical **(1s - several seconds)**
- Thermodynamic **(several seconds - hours)**



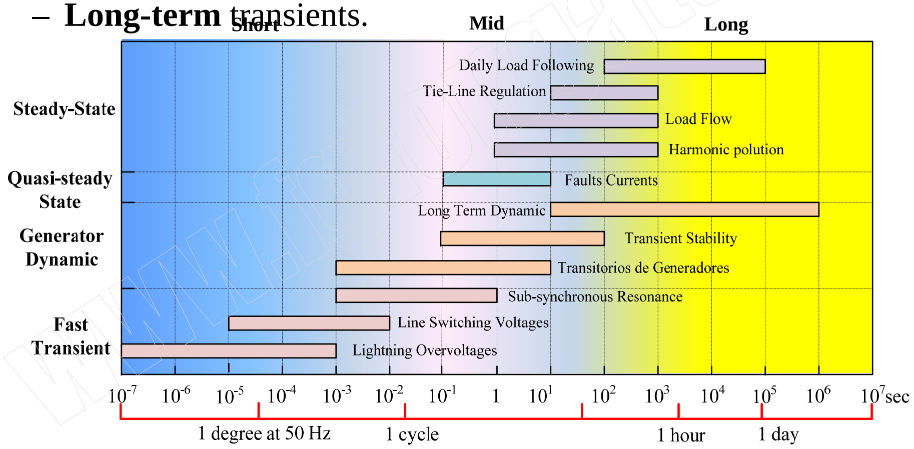
Time Scales

- Dynamic process in electrical power system can be characterized by various areas of consideration and their characteristic **time scales or frequency bands**.



Time Scales

- In general way, the transients in electrical power systems are classified according to three possible timeframes:
  - **Short-term**, or electromagnetic transients;
  - **Mid-term**, or electromechanical transients;
  - **Long-term** transients.



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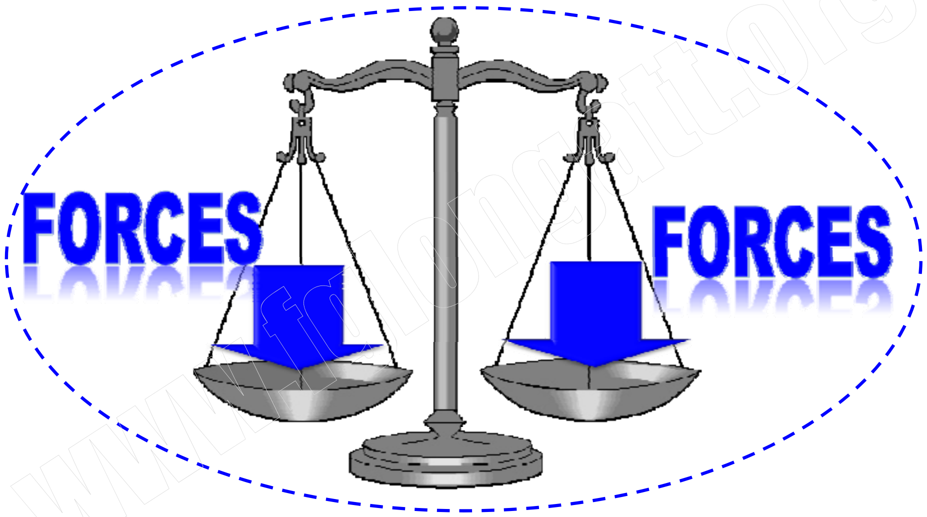
Fundamentals of PS Stability

- **Stability is a problem of balance**



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Stability: Definition

- Power system stability may be broadly defined as that **property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions ad to regain an acceptable state of equilibrium after being subjected to a disturbance** [1]

[1] P. Kundur, *Power System Stability and Control*. New York: McGraw- Hill, 1994.

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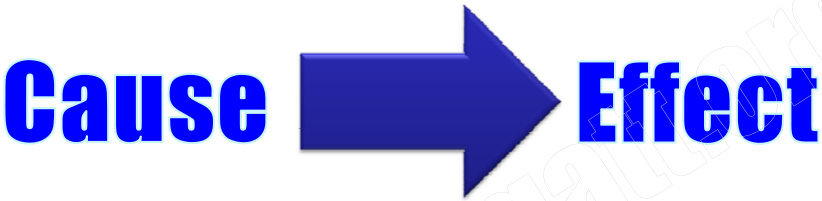
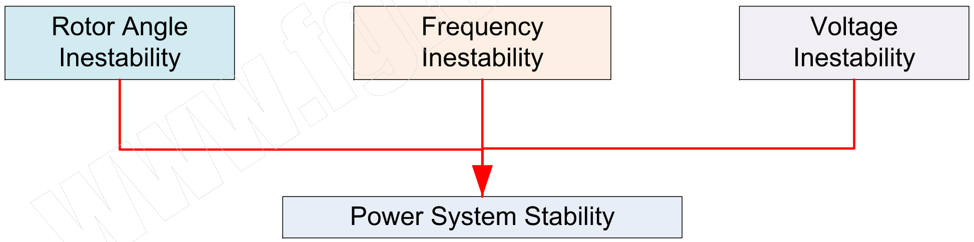
Instability Phenomena

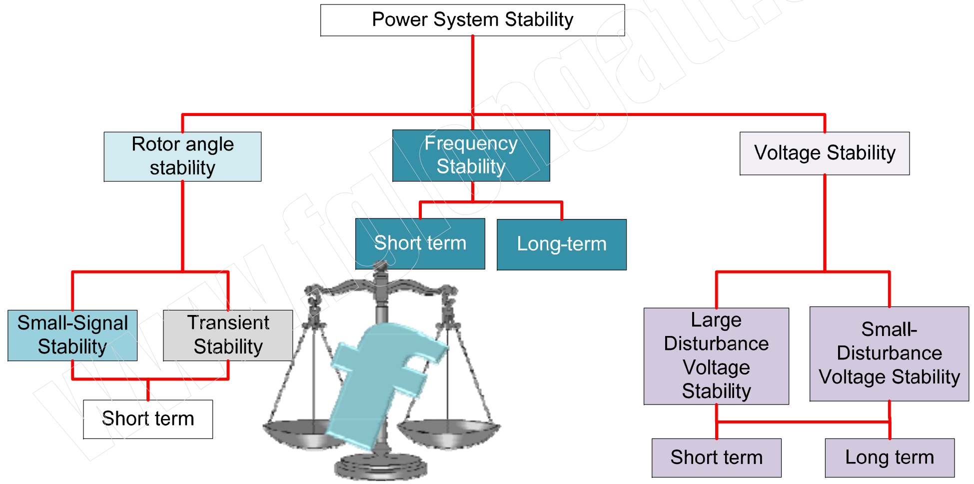


Different phenomena that lead to power system instability



Frequency Stability

- IEEE-CIGRE classification (IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, "Definition and Classification of Power System Stability", *IEEE Trans. Power Systems and CIGRE Technical Brochure 231, 2003):*



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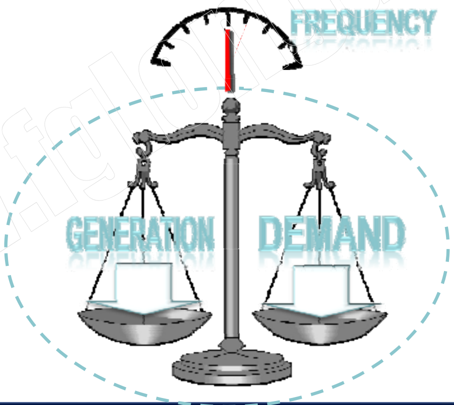
Frequency Stability

- ***"Frequency stability refers to the ability*** **of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load."**
- Frequency stability analysis concentrates on studying the overall system stability for sudden **changes in the generation-load balance.**



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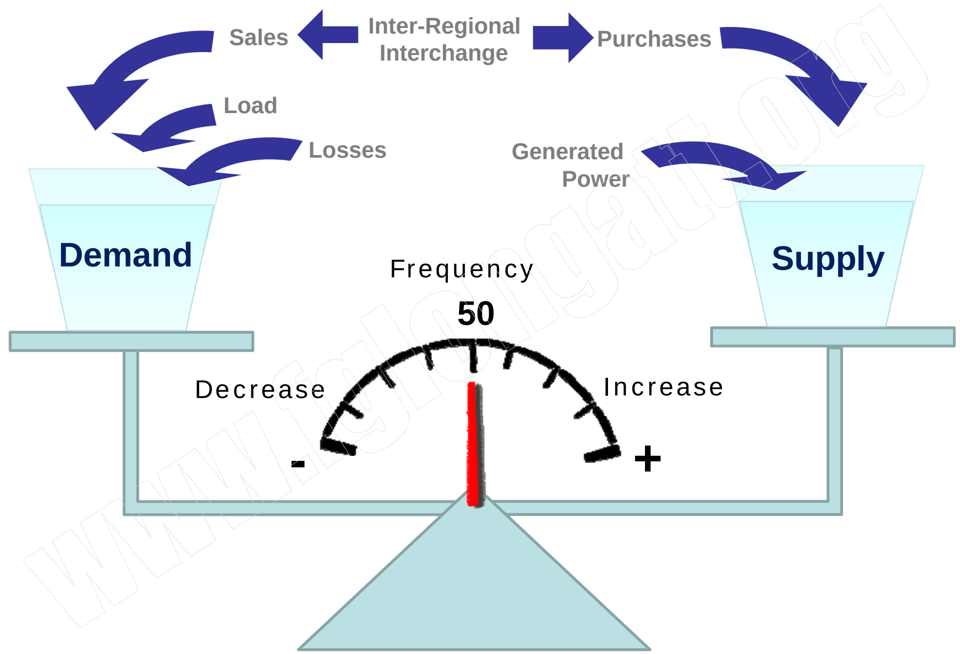
General Picture of Frequency Stability



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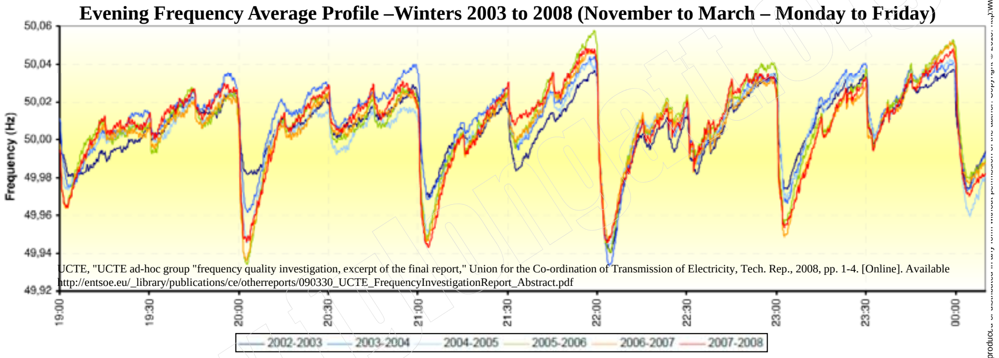
Quality of Frequency Stability

- **Gradually declining in many locations around the world – but not due to wind power!!!**

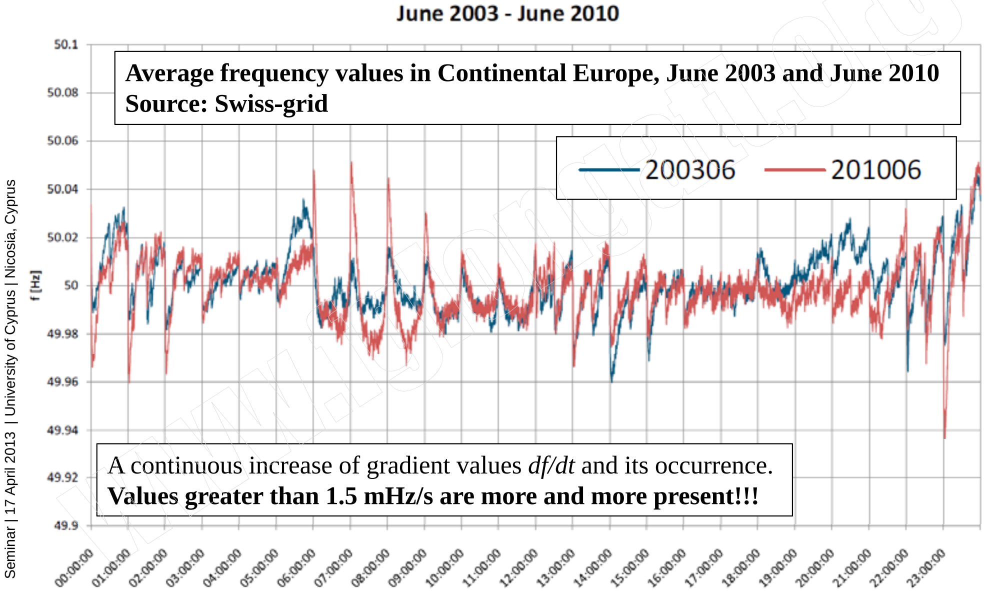


- Market imperfections around full hour shift (*frequency erosion*)
- Systems operated closer to their limits
- Decreased damping of oscillations
- Looking forward – e.g. UK - nuclear units increasing - 1300 to 1800 MW

(*) P. W. Christensen. "Wind Power Plants and future Power System Frequency Stability". Event on Future Power System Operation, Lund University, Sweden, June 12, 2012

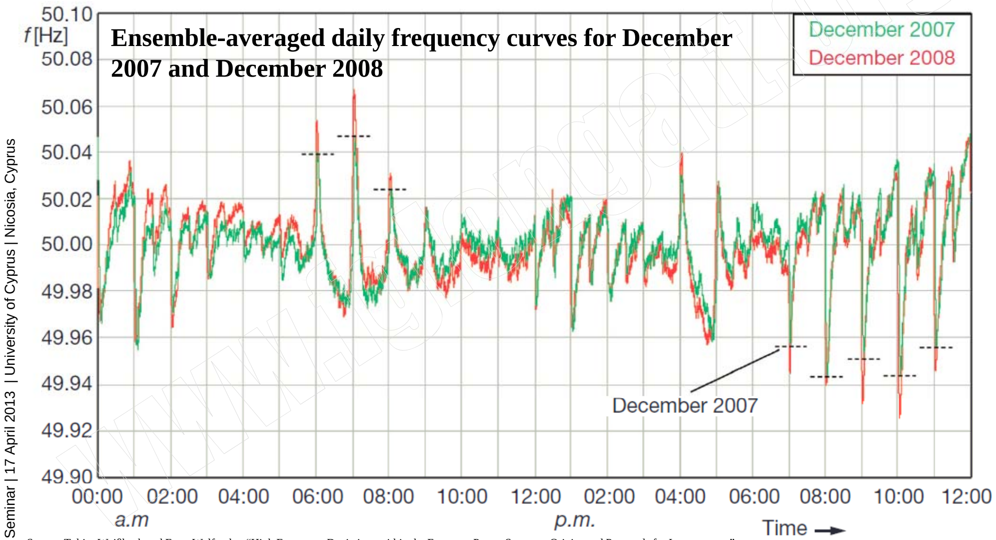
Quality of Frequency Stability

- Example - Europe (frequency erosion)



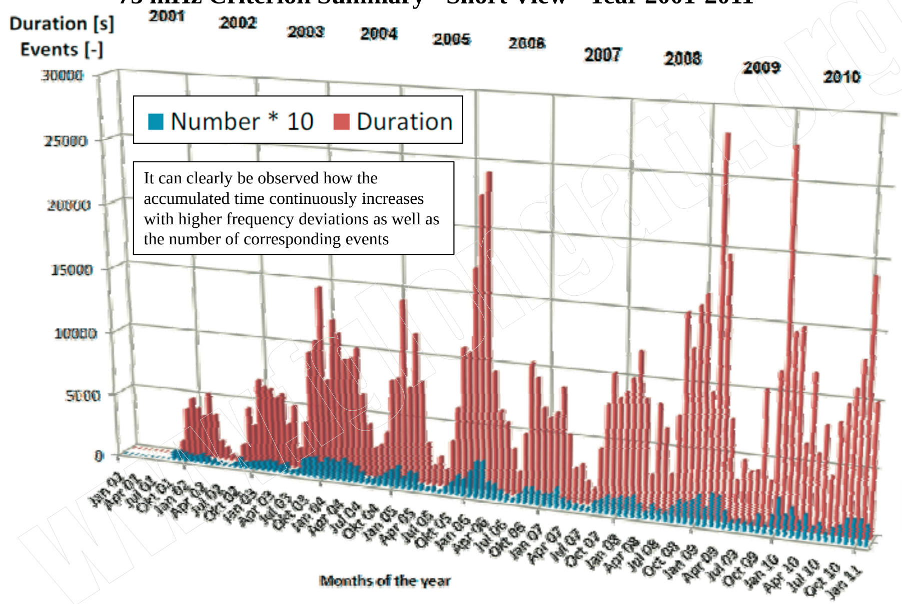
Quality of Frequency Stability

- A **remarkable increase** of the **ensemble-averaged magnitude** of the frequency deviations during the winter



Source: Tobias Weißbach and Ernst Welfonder. "High Frequency Deviations within the European Power System – Origins and Proposals for Improvement"

Quality of Frequency Stability



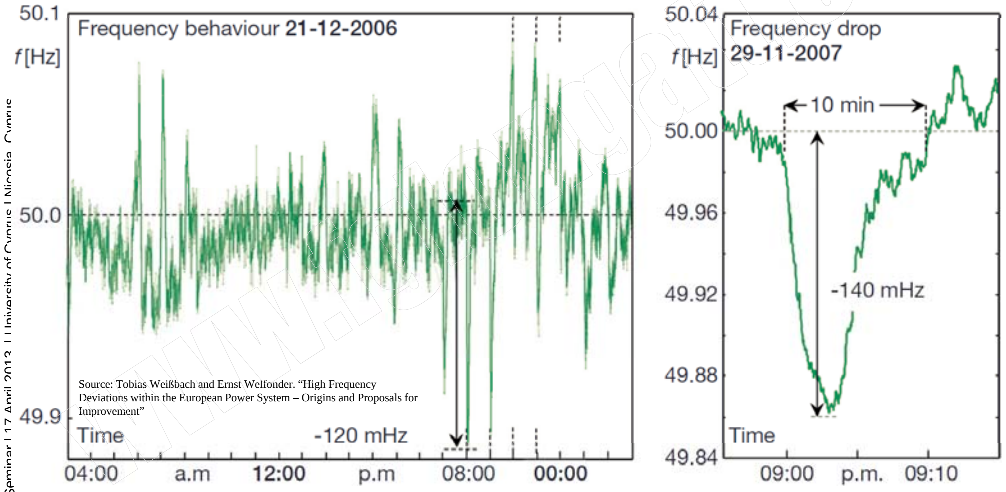
Frequency quality behaviour in Continental Europe during the last ten years. Source: Swissgrid

Quality of frequency stability

- Example - Europe (frequency erosion)

Current operational frequency behaviour, almost similar every day

An increase both of their occurrence and their durations in the long-run



(*) P. W. Christensen. "Wind Power Plants and future Power System Frequency Stability". Event on Future Power System Operation, Lund University, Sweden, June 12, 2013

2. Frequency Control in Power Systems

What is Inertia?

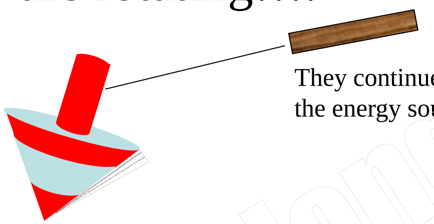
Definition of H

Swing Equation

Total System Inertia (HT)

What is Inertia?

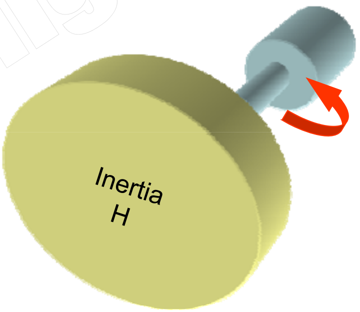
- It is the energy stored in generators because they are rotating….



They continue to rotate after the energy source is removed

H

Large spinning machines provide stored energy due to the **rotating mass of their rotor**, driving turbine shafts etc.



Engineers model this as a number of rotating masses.

Definition of H

- The inertia constant of a rotating system (H), or individual generator, is used to **define the energy stored in its rotating mass** (E_{c0}).
- It can be understood as **the time, in seconds, that it would take to replace this stored energy when operating at rated mechanical speed** (ω_{sm}) **and rated apparent power output** (S_{base})

$$H = \frac{1}{2}\frac{J\omega_{sm}^{2}}{S_{base}}$$

where: J is the **total moment of inertia** in kg.m^2, ω_{sm} is the **rated mechanical speed** in rad/s, and S_{base} is the **selected base apparent power** in MVA.

Swing Equation

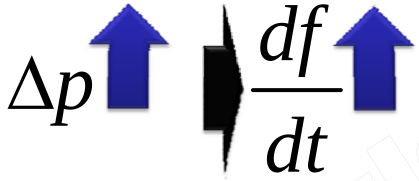
- The relationship between the power imbalance at the terminals of the i-th generator in p.u. (Δp_i) and its frequency (f_i), can be expressed as:

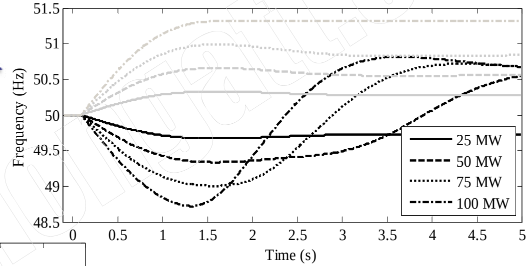
$$\frac{2H}{f_n}\frac{df}{dt} = p_m - p_e = \Delta p$$

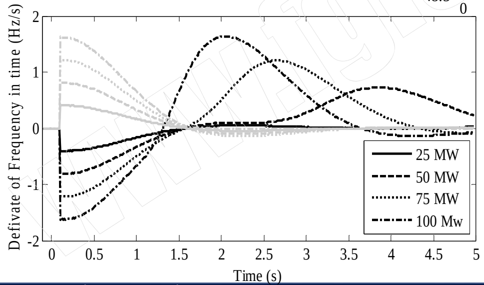
where: $p_{m,i}$ is the mechanical turbine power in p.u., $p_{e,i}$ is the electrical power in p.u., Δp_i is the load generation imbalance in p.u., H_i is the inertia constant in s, f_i is the frequency in Hz, f_n is the nominal system frequency in Hz and df_i/dt is the rate of change of frequency in Hz/s.

Swing Equation

- **If the balance between generation and demand is not reached, the system frequency will change** at a rate initially determinate by the total system inertia (H).







$$\frac{2H}{f_n}\frac{df}{dt} = p_m - p_e = \Delta p$$

Total System Inertia (HT)

- The **total system inertia** (H_T) comprises the combined inertia of most of spinning generation and load connected to the power system.

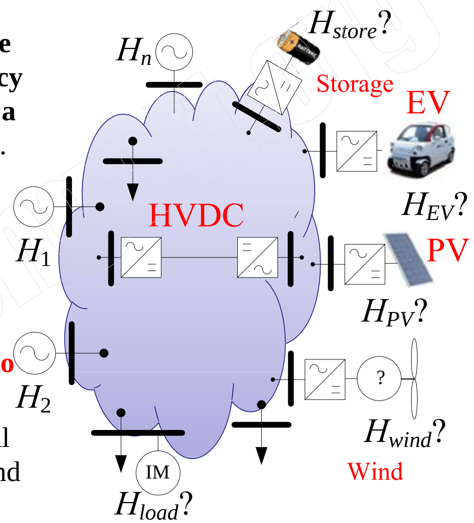
$$H_T = \sum_{i=1}^{N} H_i \qquad H_i = \frac{1}{2}\frac{J_i \omega_{sm}^2}{S_{base}}$$

- The contribution of the system inertia of one load or generator depend **if the system frequency causes change in its rotational speed and, then, its kinetic energy**

$$H_T = H_1 + H_2 + \ldots H_n$$

Total System Inertia (HT)

- Inertia is the stored **rotating energy** in the system
- Following a System loss, **the higher the System Inertia (assuming no frequency response) the longer it takes to reach a new steady state operating frequency**.
- **Modern Generation Technologies** employing power electronic converters currently **do not contribute to System Inertia.**
- Further growth is expected in **HVDC which currently does not contribute to System Inertia**
- The implications of this are a substantial erosion in *System Frequency Control* and **consequent required increases in additional reserve and response**.



3. System Frequency Response

Frequency Response
Frequency Control Processes
System Frequency Model
Example I

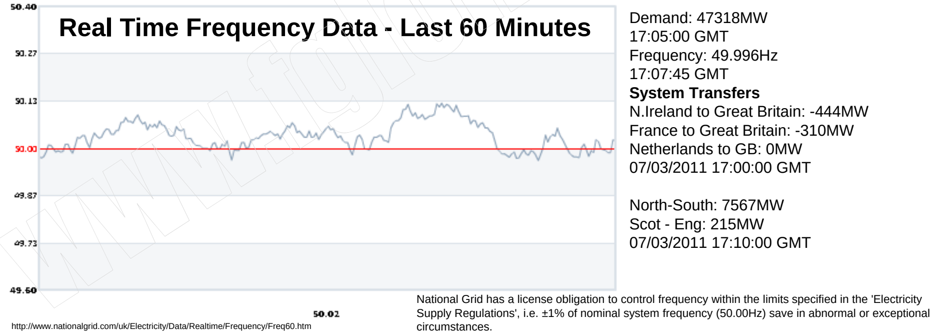
Frequency Response

What is it?

- an automatic **change in active power output or demand in response to a frequency change**

Why we need it?

- to **maintain system frequency within statutory and operational limits**

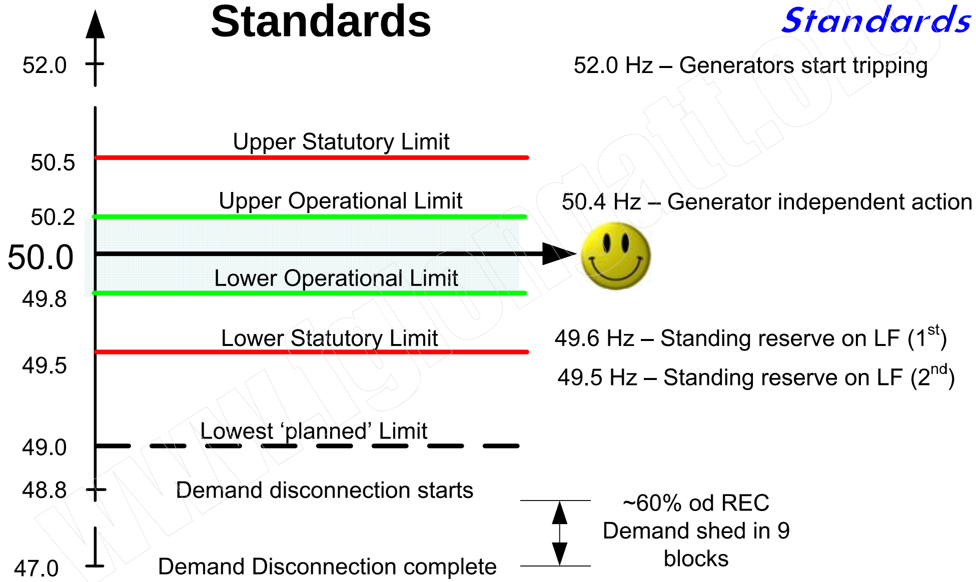


National Grid has a license obligation to control frequency within the limits specified in the 'Electricity Supply Regulations', i.e. ±1% of nominal system frequency (50.00Hz) save in abnormal or exceptional circumstances.

http://www.nationalgrid.com/uk/Electricity/Data/Realtime/Frequency/Freq60.htm

Steady-State Frequency

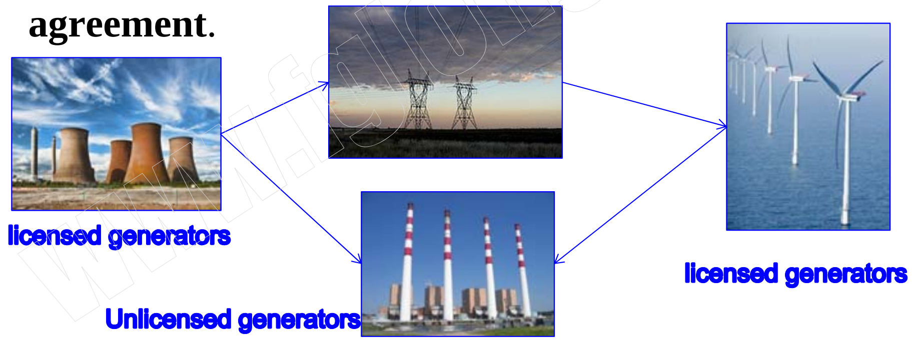
Obligations, Statutory, Code and Operational Standards



Frequency Response

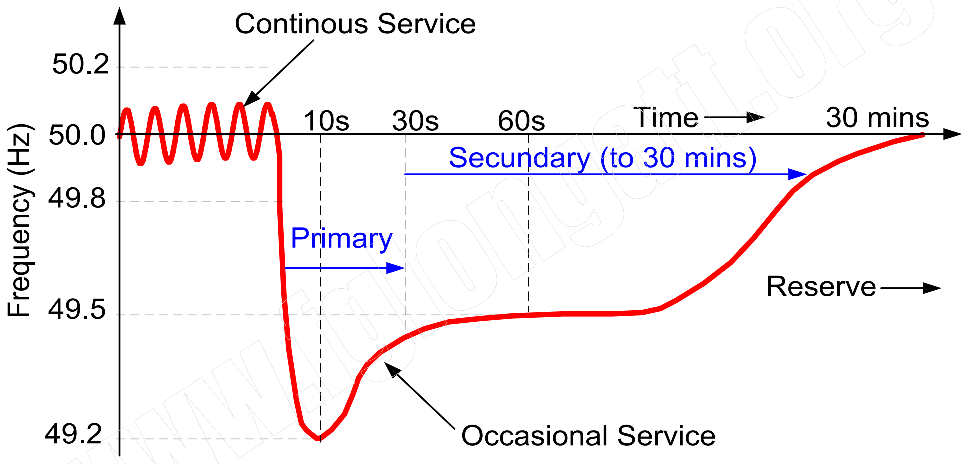
Who can provide it?

- **All licensed generators** in accordance with Grid Code mandatory requirements generators offering enhanced commercial services
- **Demand tripping by low frequency relay**
- **Unlicensed generators with a commercial agreement.**



Frequency Control

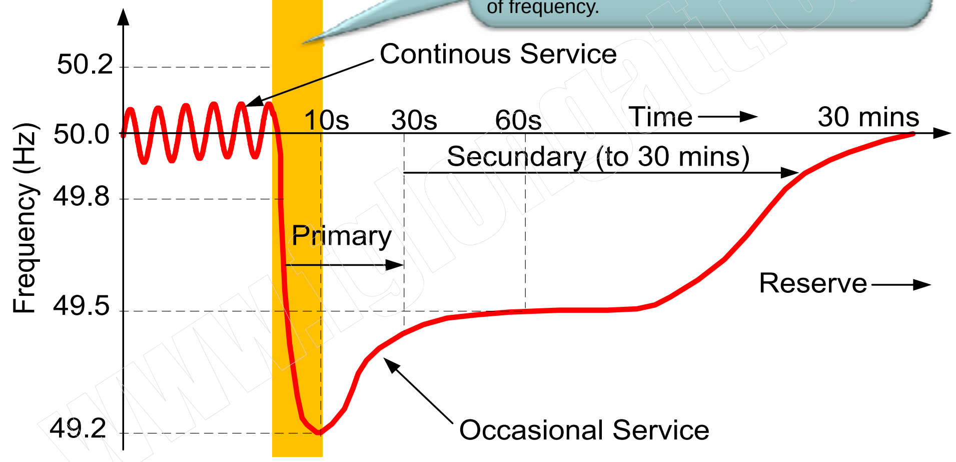
- Frequency Control processes



Frequency Control Processes

Frequency Control Phases

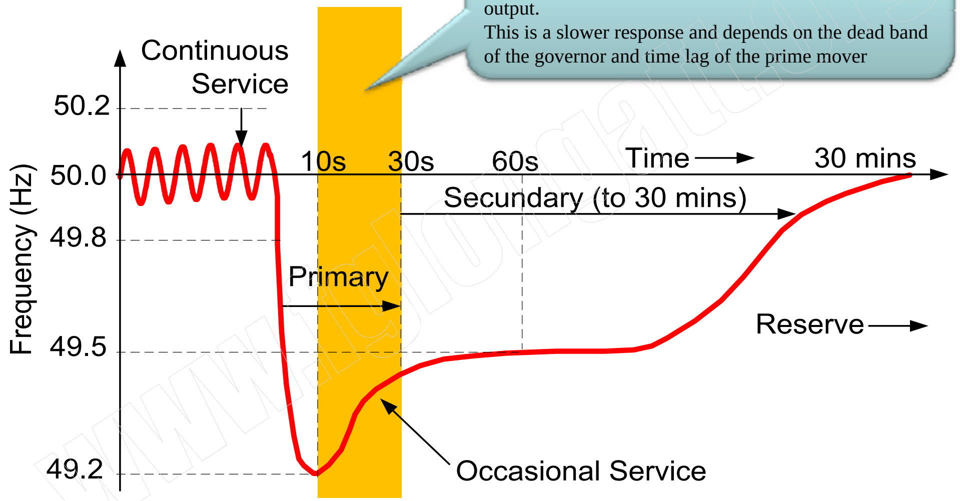
INERTIAL RESPONSE: The speed of the synchronous generators also reduces and some of the kinetic energy stored in the rotating mass is released as electrical energy. This is a fast response and proportional to the rate of change of frequency.



Frequency Control Processes

Frequency Control Phases

GOVERNOR ACTION: The automatic droop control loop of the governor acts on the change in frequency and opens the governor vaive to increase the turbine's output.
This is a slower response and depends on the dead band of the governor and time lag of the prime mover

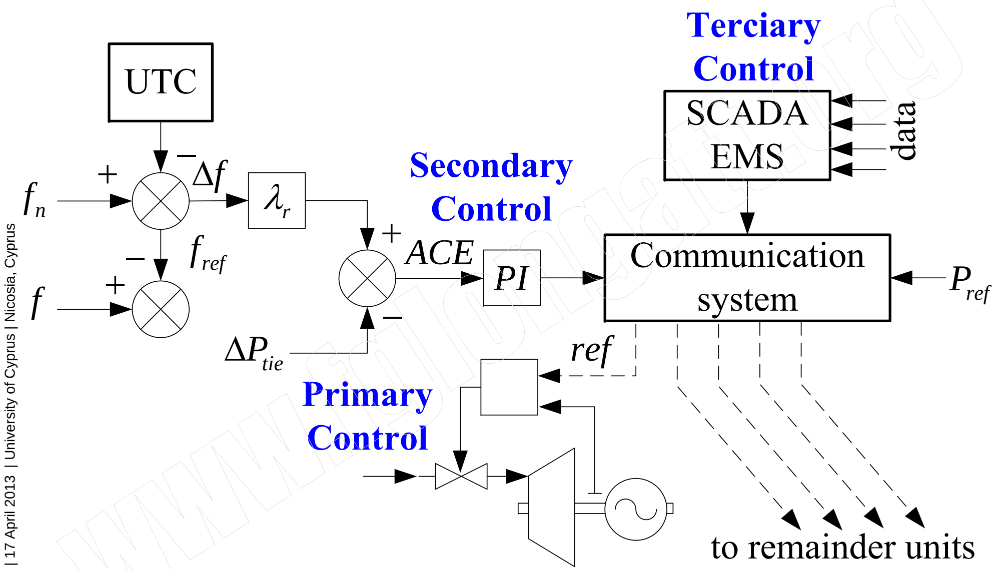


Frequency Control Processes

Summary of Frequency Controllers

- **Primary Control:** The action of turbine governors due to frequency changes when reference values of regulators are kept constant.
- **Secondary Control:** The restoration of the rated frequency followed to the primary control action, but now at the required increased value of power demand.
- **Tertiary control**: Objective depends on the organizational structure of a given power system and the role that power plants play in this structure

Frequency Control Processes



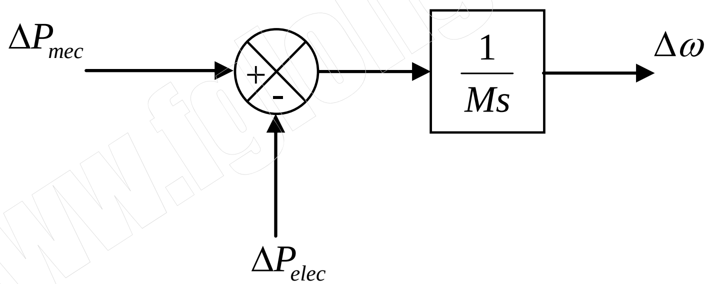
System Frequency Response Model

- Low order System Frequency Response (SFR) model that can be used for **estimating the frequency behavior of a large power system**, or islanded portion thereof, to sudden load disturbances.
- The SFR model is a **simplification** of other models used for this purpose, but it is believed to include the **essential system dynamics**.

System Frequency Response Model

- When there is a demand change (ΔP_{mec}), it is reflected instantaneously as a change in the electrical Power Output P_e of the generator.

$$\Delta P_{mec} - \Delta P_{elec} = M \frac{d(\Delta\omega)}{dt}$$



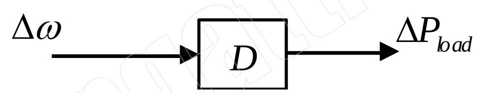
Transfer function relating speed and power

System Frequency Response Model

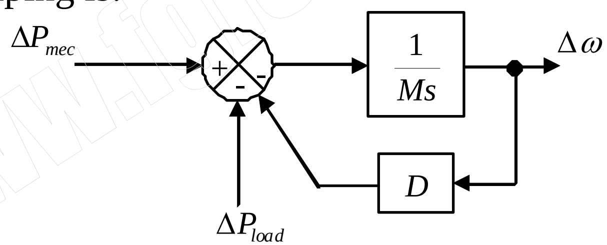
Load response to frequency deviation

- The overall frequency-dependent characteristic of a composite load may be expressed as:

$$D = \frac{\Delta P_{load}(\omega)}{\Delta\omega}$$

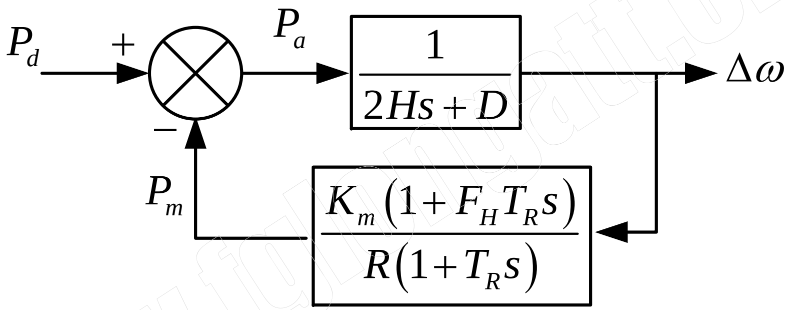


- The system block diagram including the effect of the load damping is:



System Frequency Response Model

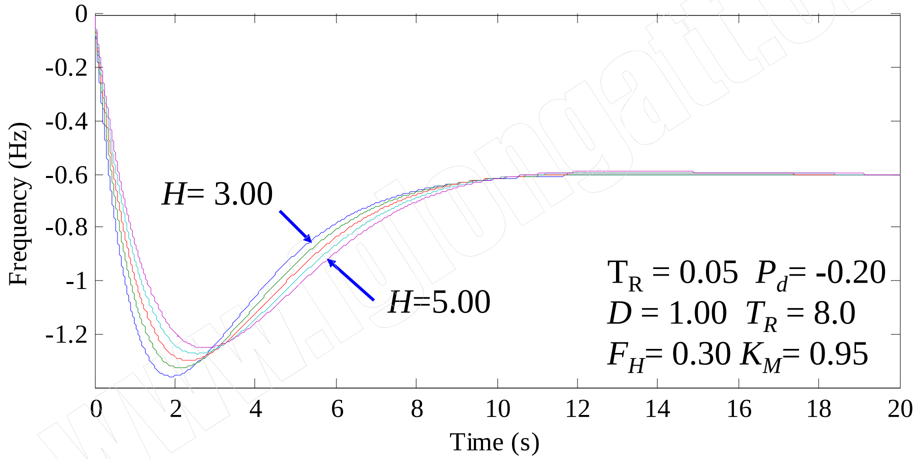
- **System Frequency Model of the Typical Reheat Turbine Governor Model.**



F_H = Fraction of total power generated by the HP turbine
T_R = Reheat time constant, seconds
H = Inertia constant, seconds
D = Damping Factor
K_m = Mechanical Power Gain Factor

SRF Model: *Example I*

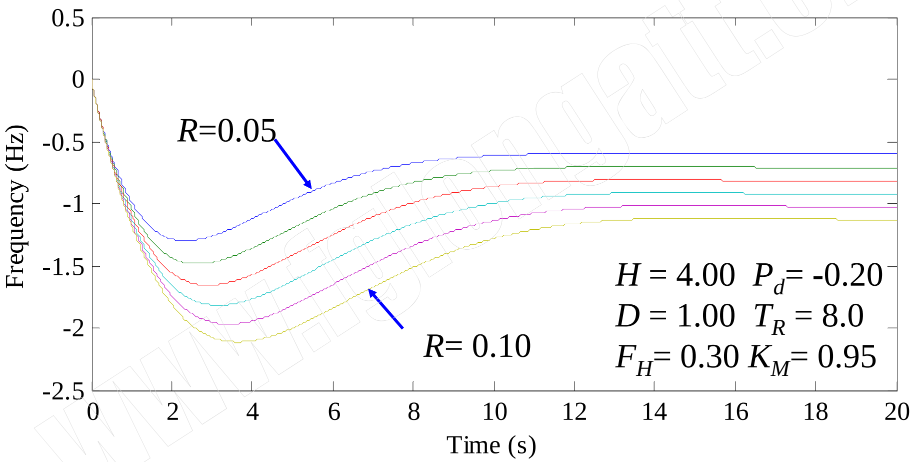
- System frequency response variation of H increments of 0.5



Frequency Response for Varying Values of *H*

SRF Model: *Example I*

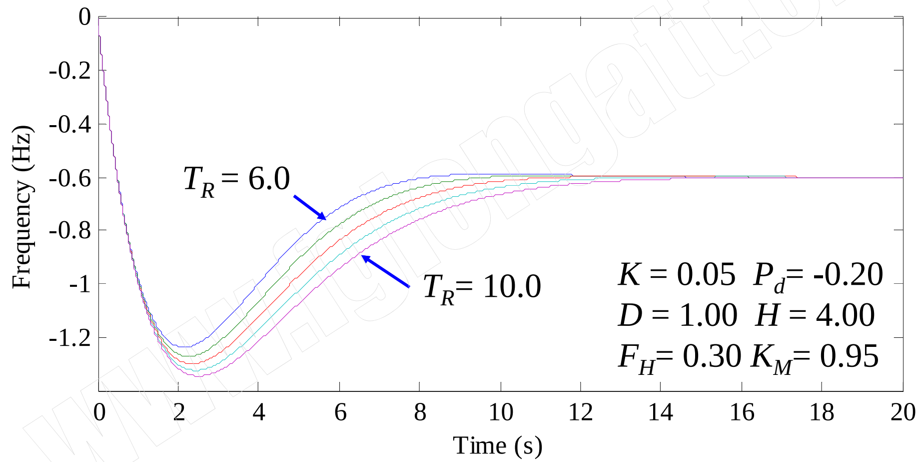
- System frequency response variations of R with increments of 0.01.



Frequency Response for Varying Values of *R*

SRF Model: *Example I*

- System frequency response variations of T_R with increments of 1.0



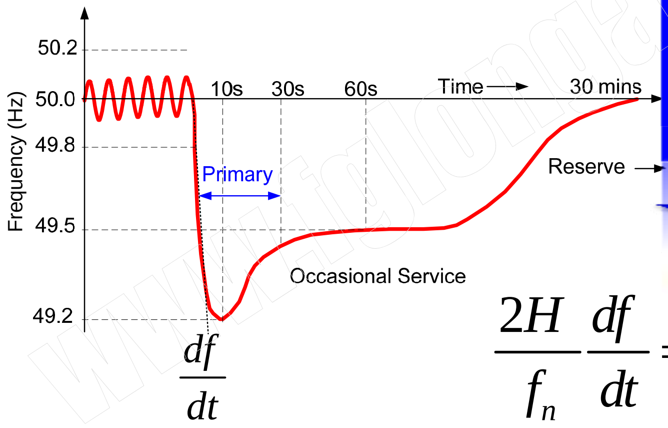
Frequency Response for Varying Values of T_R

4. Synthetic Inertia

System Frequency Dynamic
Releasing Kinetic Energy
Inertial Response
Synthetic Inertia: Objective
Commercial Implementations

System Frequency Dynamic

- During a **system frequency disturbance** the balance between **generation-demand is not reached**, then the system frequency will change at a rate initially determinate by the **total system inertia** (H_T).

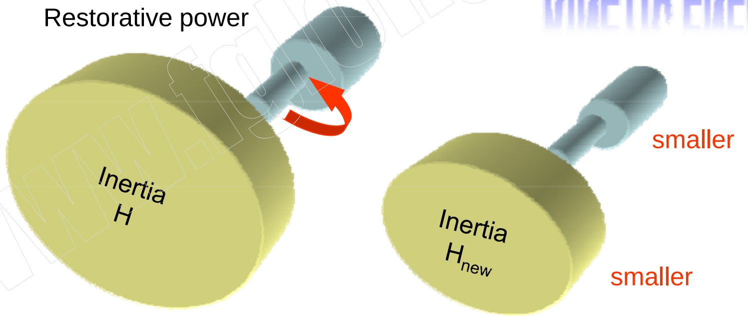


$$\frac{2H}{f_n}\frac{df}{dt} = p_m - p_e = \Delta p$$

Releasing Kinetic Energy

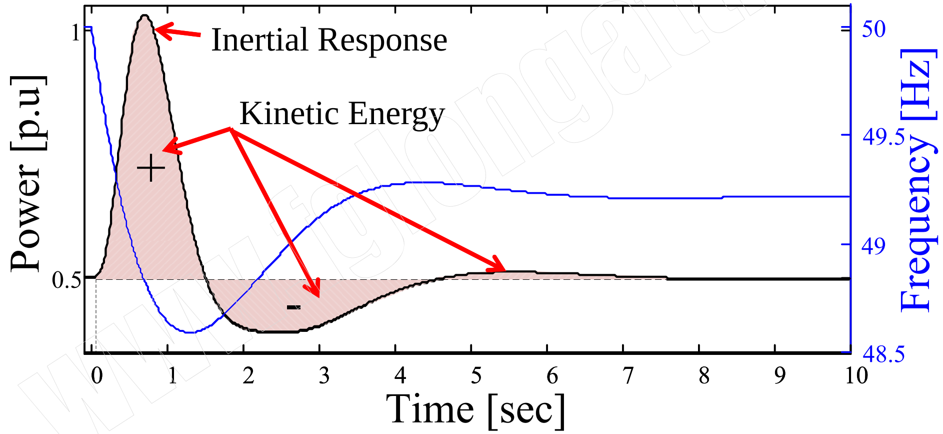
- The contribution of the system inertia of one load or generator depend if the system frequency causes change in its rotational speed and, then, its **kinetic energy**.

$$H_T = \sum_{i=1}^{N} H_i \Leftarrow H_i = \frac{1}{2}\frac{J_i \omega_{sm}^2}{S_{base}}$$



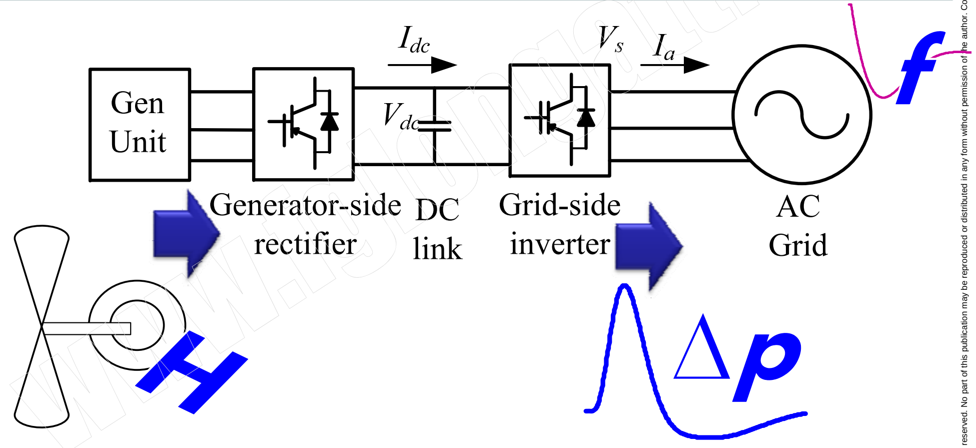
Inertial Response

- The **power associated with this change in kinetic energy** is fed or taken from the power system and is known as the **inertial response.**



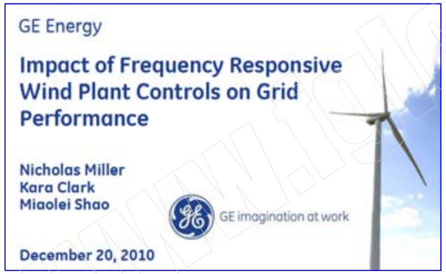
Synthetic Inertia: Objective

- The objective of the synthetic inertia control is extracting the stored inertial energy from the moving part on WTGs.



Commercial Implementations

- There are several names for this control system that enable inertial responses on a WTG: **Artificial, Emulated, Simulated, or Synthetic Inertial.**
- Examples of synthetic inertia controlled commercially available for WTG are: **General Electric WindINERTIA™, ENERCON Inertia Emulation.**


GE Energy

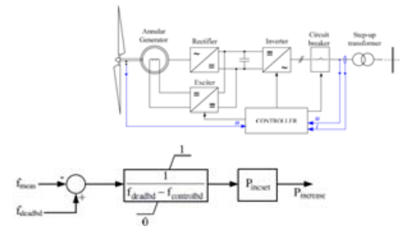
Impact of Frequency Responsive Wind Plant Controls on Grid Performance

Nicholas Miller
Kara Clark
Miaolei Shao

GE imagination at work

December 20, 2010

ENERCON ENERGIE FÜR DIE WELT



4. Frequency Control of Wind Power

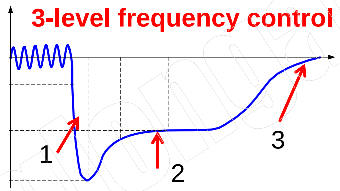
Controllers

Overview

Problems

Increasing wind power Penetration
Wind turbines provide small or even no response to frequency changes

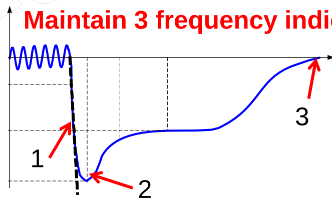
Methods



A. Wind Turbine
B. Wind Farm Level
C. Power System Level

1. **Primary Control:** <30s, automatic, local
2. **Secondary Control:** 30s~30min, artificially or by AGC, global
3. **Tertiary Control:** economic dispatch

Objectives



1. ROCOF
2. Transient Frequency Nadir
3. Steady state Frequency deviator

Possible Solutions

Traditional Solutions

- Reduce wind penetration during low system load
- Modify reserve policy
- More static reserve at times of high wind and low system inertia

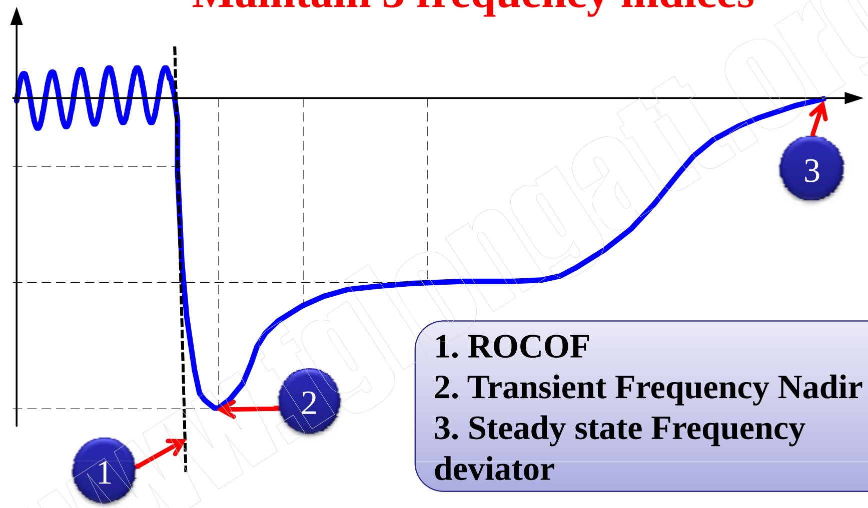
Modern Solutions

- Modify existing technology
- **Inclusion of supplementary control loop in the Wind Turbine Generators.**

Controllers to Provided Frequency Response!!!

Objective of Control

Maintain 3 frequency indices



1. ROCOF
2. Transient Frequency Nadir
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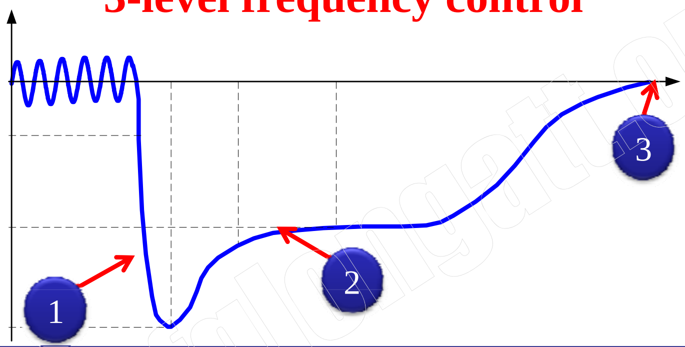
Control Layers

3-level frequency control

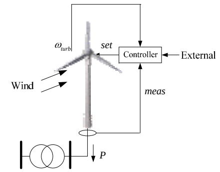


1. **Primary Control:** <30s, automatic, **LOCAL**
2. **Secondary Control:** 30s~30min, artificially or by AGC, **GLOBAL**
3. **Tertiary Control:** economic dispatch, **GLOBAL**

Control Layers

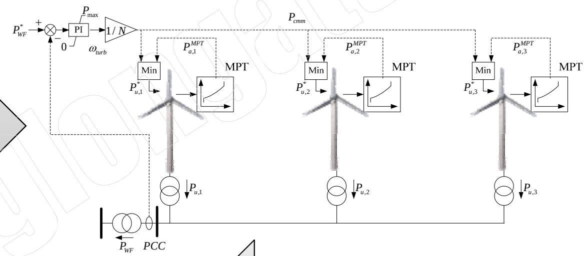
- **A. Wind Turbine**
- **B. Wind Farm Level**
- **C. Power System Level**

Control Layers

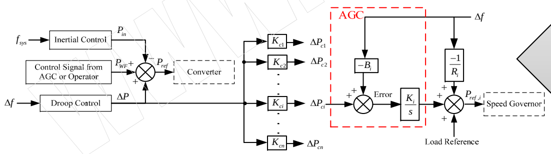


A. Wind Turbine

B. Wind Farm Level

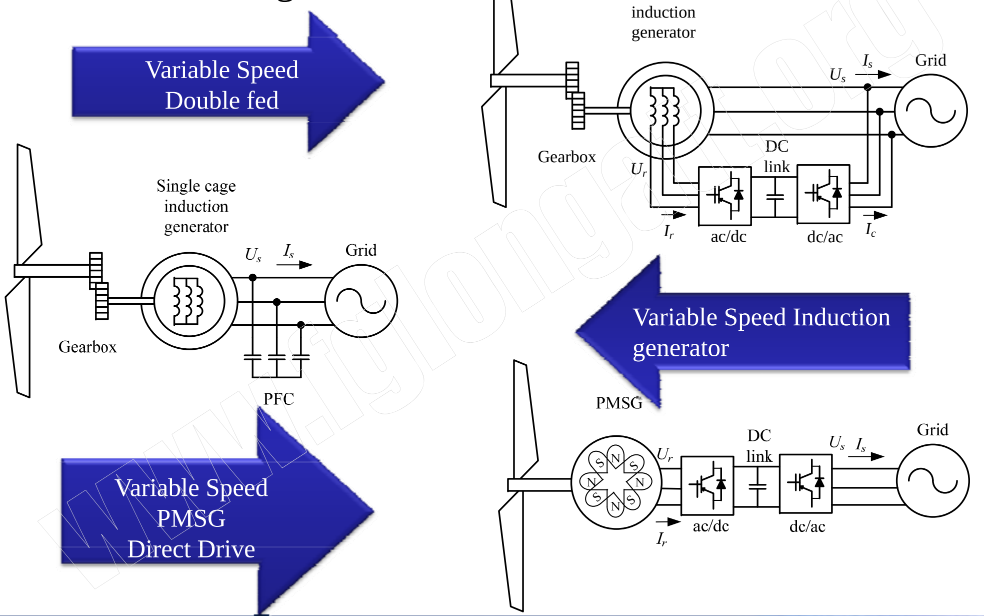


C. Power System Level



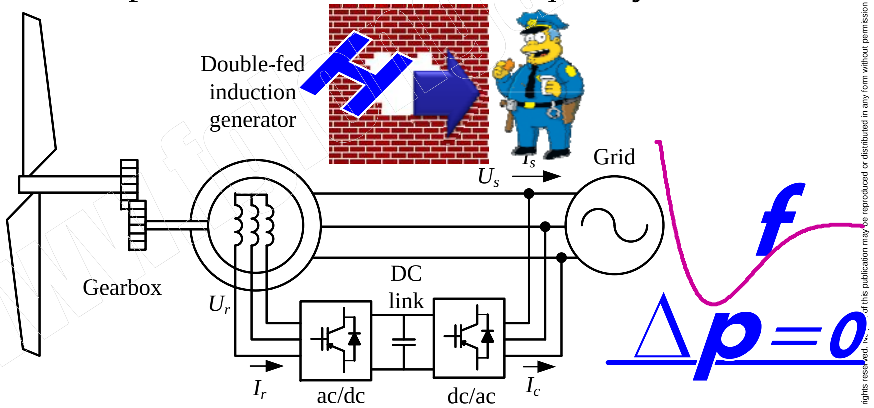
WT Technologies

- WT Technologies



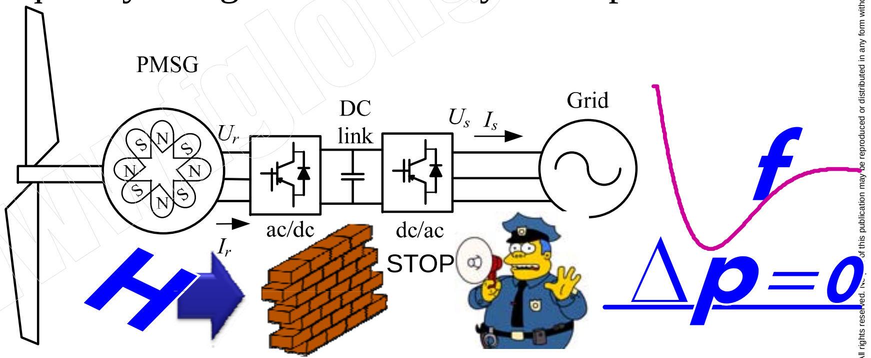
Frequency Response: DFIG

- **Wind turbines provide small or no response to frequency changes**
- **DFIG(doubly fed induction generator):** the rotor is connected to the grid through an AC/DC/AC converter which decouples the rotor from the frequency.



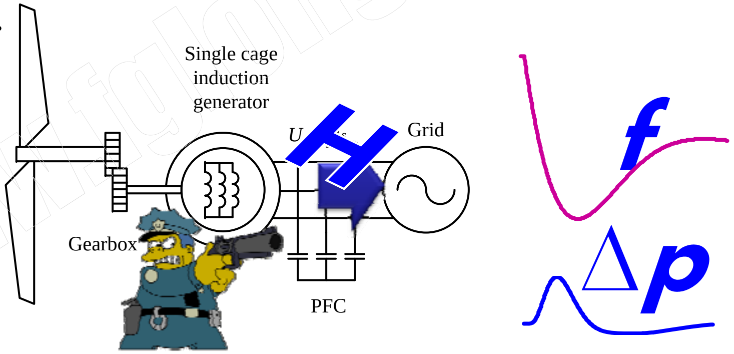
Frequency Response: PMSG

- **Wind turbines provide small or no response to frequency changes**
- **PMSG (permanent magnet synchronous generator):** contains a multi-pole magnet rotor and an AC/DC/AC converter attached to the stator.
- Consequently the generator is fully decoupled from the grid.



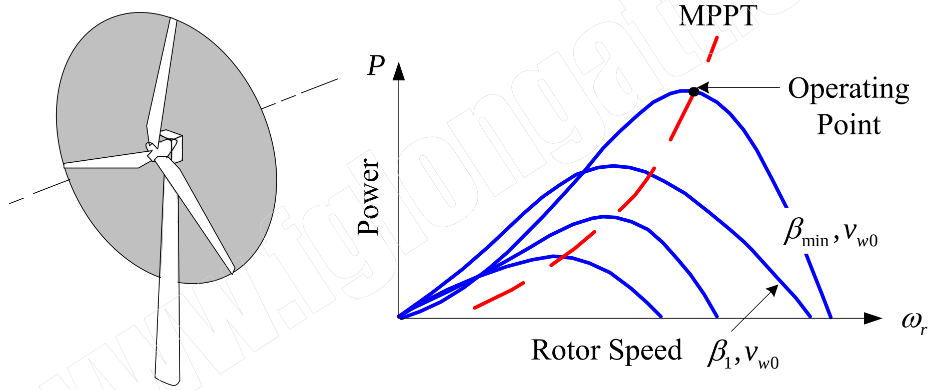
Frequency Response: FSWT

- **Wind turbines provide small or no response to frequency changes**
- **Fixed speed wind turbine:** can provide inertial response to the frequency fluctuation, however, the inertial response is generally smaller and slower than that of synchronous generators due to allow normal slip of 1%-2%.



Frequency Response

- Traditional wind turbines **store no power reserves**.
- They always **operate at the maximum power point tracking(MPPT).**

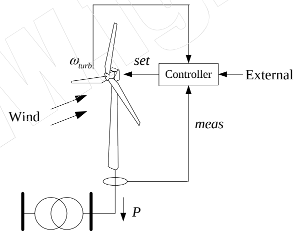


Additional controllers are needed!

Wind Turbine Level Control

Wind Turbine Level Control

- 1. Inertial Control
  - a. Hidden Inertia Emulation
  - b. Fast Power Reserve Emulation
- 2. Droop Control
- 3. De-loading Control
  - Pitch Angle Control
  - Rotational Speed Control

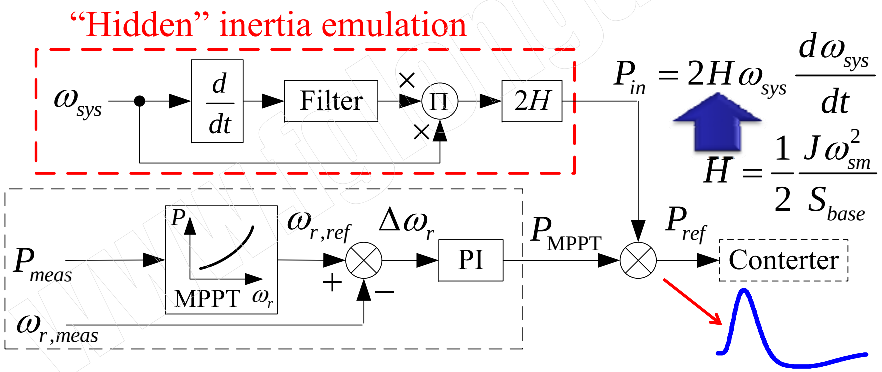


1. Inertial Control

a. "Hidden" Inertia Emulation

- **Functions:**
  - For variable speed wind turbines.
  - To reduce the maximum frequency change rate.
  - To increase the transient frequency nadir.

- Comparison with fixed speed wind turbines and conventional generators:
  - Releasing considerably larger kinetic energy.
  - Responding faster because of the PWM technology



$$P_{in} = 2H\omega_{sys}\frac{d\omega_{sys}}{dt}$$

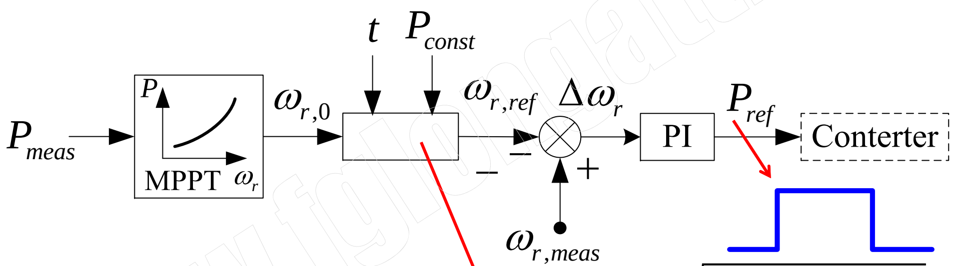
$$H = \frac{1}{2}\frac{J\omega_{sm}^2}{S_{base}}$$

G. Ramtharan, J. B. Ekanayake, and N. Jenkins, "Frequency support from doubly fed induction generator wind turbines," lET Renew. Power Gener., vol. I, pp. 3-9,2007.
J. Ekanayake, and N. Jenkins, "Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency," IEEE Trans. Energy Convers., vol. 19, no. 4, pp.800--802, Dec. 2004.
J. Morren, S W. H. de Haan, W. L. Kling, and J. A. Ferreira, "Wind turbines emulating inertia and supporting primary frequency control," IEEE Trans. Power Syst., vol. 21, no. I, pp. 433-434, Feb. 2006.

1. Inertial Control

b. Fast Power Reserve Emulation

- Similar functions to "hidden" inertia emulation
  - To compensate the power loss for a short period and save time for other slower generators to participate in the frequency control

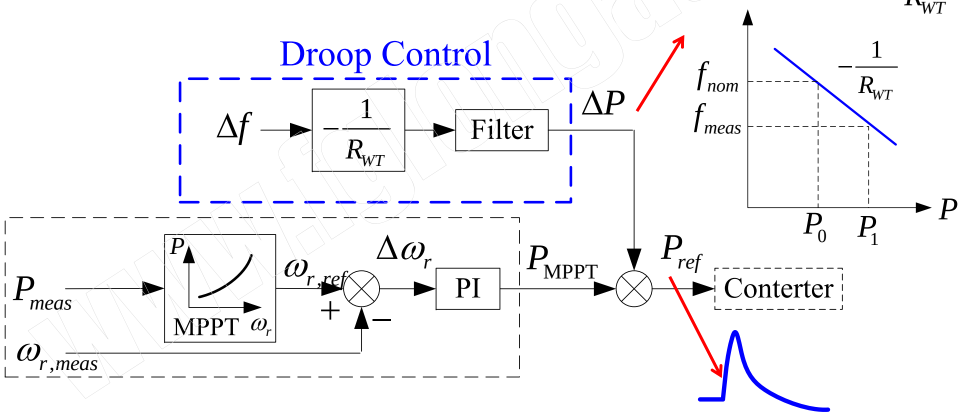


$$P_{const}t = \frac{1}{2}J\omega_{r0}^2 - \frac{1}{2}J\omega_{rt}^2 \Rightarrow \omega_{r,ref} = \omega_{rt} = \sqrt{\omega_{r0}^2 - 2\frac{P_{const}}{J}t}$$

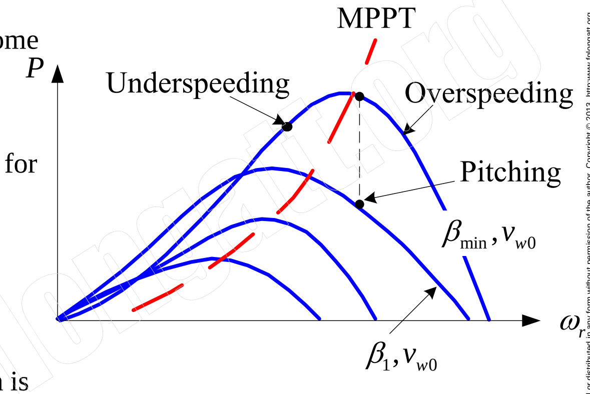
A. Teninge, C. Jecu, D. Roye, S. Bacha, J. Duval, and R Belhomme, "Contribution to frequency control through wind turbine inertial energy storage," lET Renew. Power Gener., vol. 3, pp. 358-370,2009

- Functions:
  - For variable speed wind turbines.
  - To increase the transient frequency nadir.
  - The droop controller should be ended on time to avoid the stalling or
  - coordinated with the deloading control.

$$\Delta P = P_1 - P_0 = -\frac{\Delta f}{R_{WT}}$$



- **Deloading definition:**
  - not MPPT, i.e., abandon some wind energy.
- **Advantages:**
  - Provide sufficient reserves for systems.
  - Save investment of the reserves and storages although the wind energy may be partially lost.
  - The wind power regulation is faster than the thermal power regulation due to the PWM control technology.
  - The system will be more stable than MPPT condition.

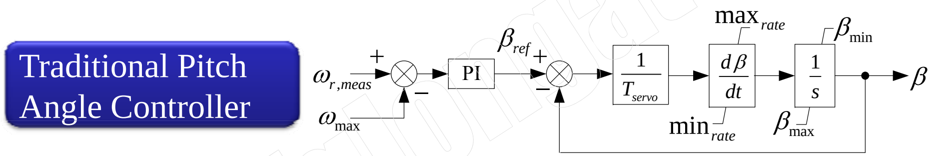


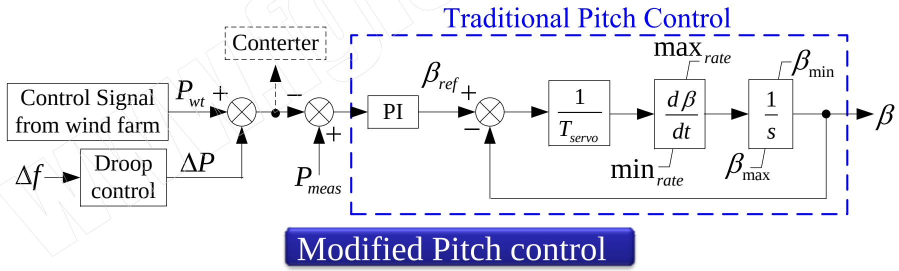
•Deloading possibilities:

Overspeeding: increasing the rotor rotational speed over the MPPT speed.
Pitching: controlling the pitch angle.

a. Pitch angle controller

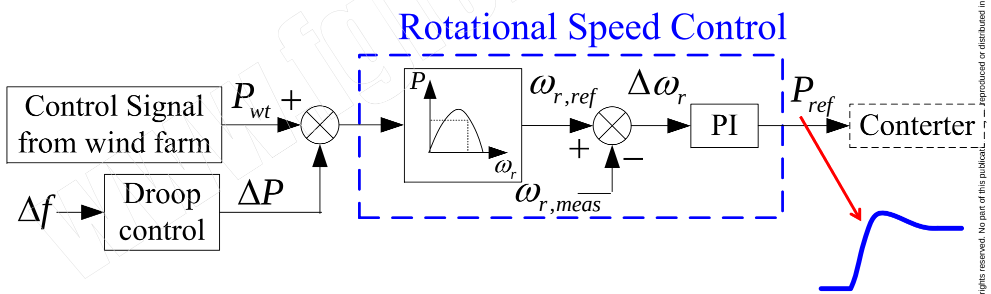
- Functions:
  - For both fixed and variable speed wind turbines.
  - Providing power reserves.
  - Slower than the convertor control due to the mechanical time constant.





b. Rotational Speed Control

- Functions:
  - For variable speed wind turbines.
  - Providing power reserves.
  - Faster than the pitch control due to the PWM technology.
  - Storing more kinetic energy, like a big flywheel energy storage.
  - Pitching increases wear and tear, overspeeding does not.
  - Some research showed that overspeeding can improve the small signal stability.

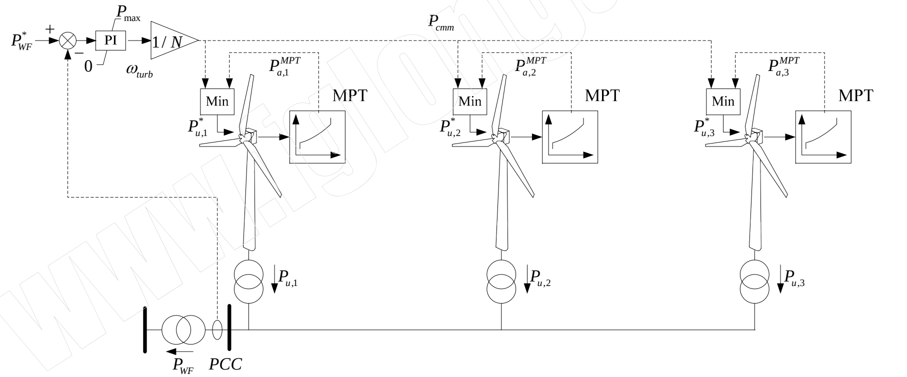


Wind Farm Control Level

Wind Farm Control Level

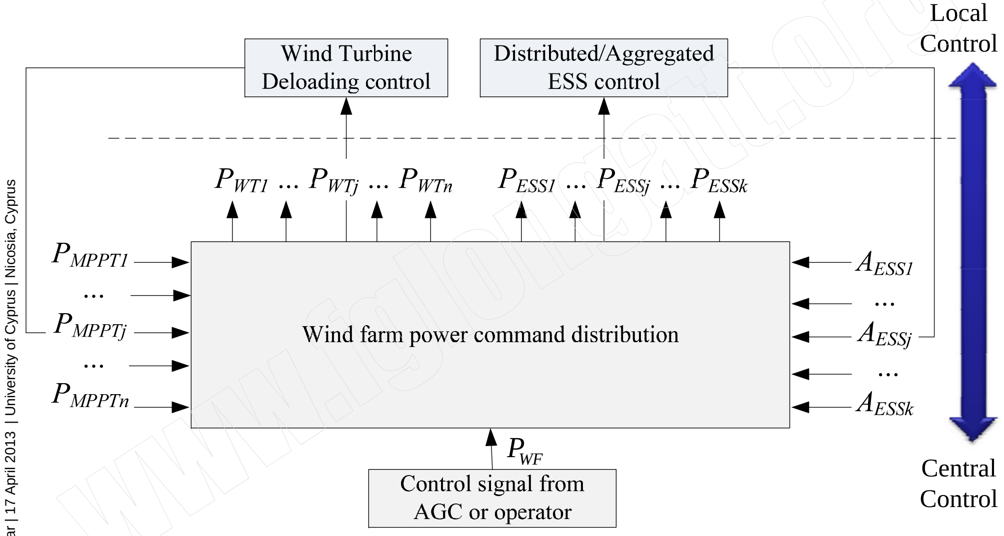
1. Local Control → Wind turbine deloading control; Energy storage system (ESS) control

Central Control



Wind Farm Control Level

a. Central Control

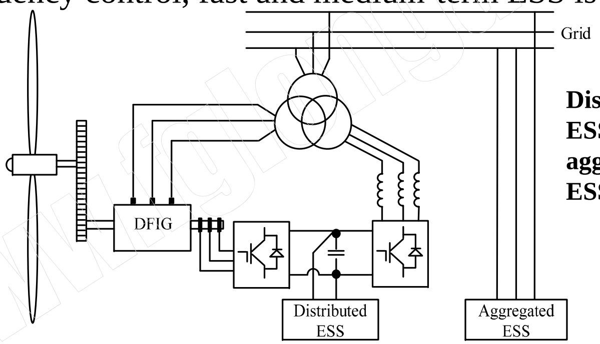


Wind Farm Control Level

b. Local Control

ESS technologies:

- **Aggregated ESS:** battery, compressed-air, pumped hydro.
- **Distributed ESS:** battery, flywheel, supercapacitor
- For frequency control, fast and medium-term ESS is suitable.



Distributed ESS and aggregated ESS

5. Conclusions

Summary and Conclusions

Any Question?

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