National Technical University of Athens

Preparatory lecture for the laboratory exercises

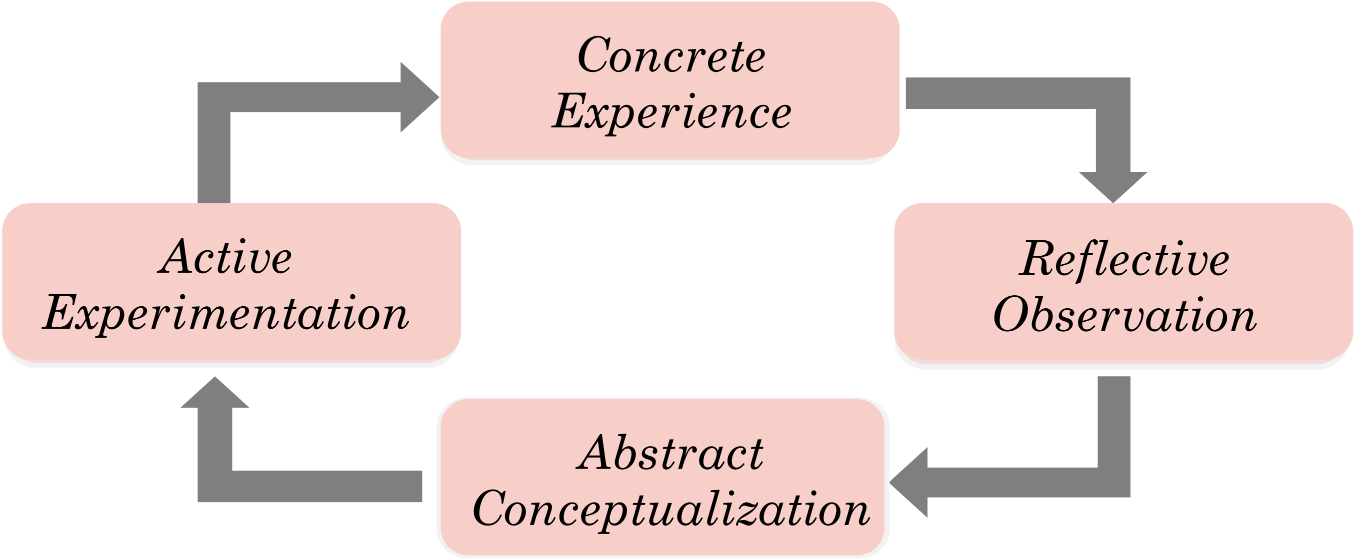
Panos Kotsampopoulos, Marios Maniatopoulos, Dimitris Lagos, Achilleas Markou, Iasonas Kouveliotis-Lysikatos, Vasilis Kleftakis, Nikos Hatziargyriou

Smart Grids Research Unit (Smart RUE)
National Technical University of Athens

Connecting European Smart Grid Infrastructures

Educational Aspects

- *In the past*: simple demonstrations for students were performed in the lab.
- *Now*: hands-on experiments in small groups of students (5-7 each group)
- Experiential learning is applied: educators engage their students directly to the object of knowledge and later on to a focused reflection
- D. Kolb's four stage learning cycle. Extension of "learning by doing" (J. Dewey)



In this Preparatory Lecture

- A short summary of the operation of the traditional power system is provided.
- **Questions are posed** and initial discussions arise concerning the operation of modern power systems with DG
- **The answers to these questions are given directly in the lab, following the experiential learning approach**

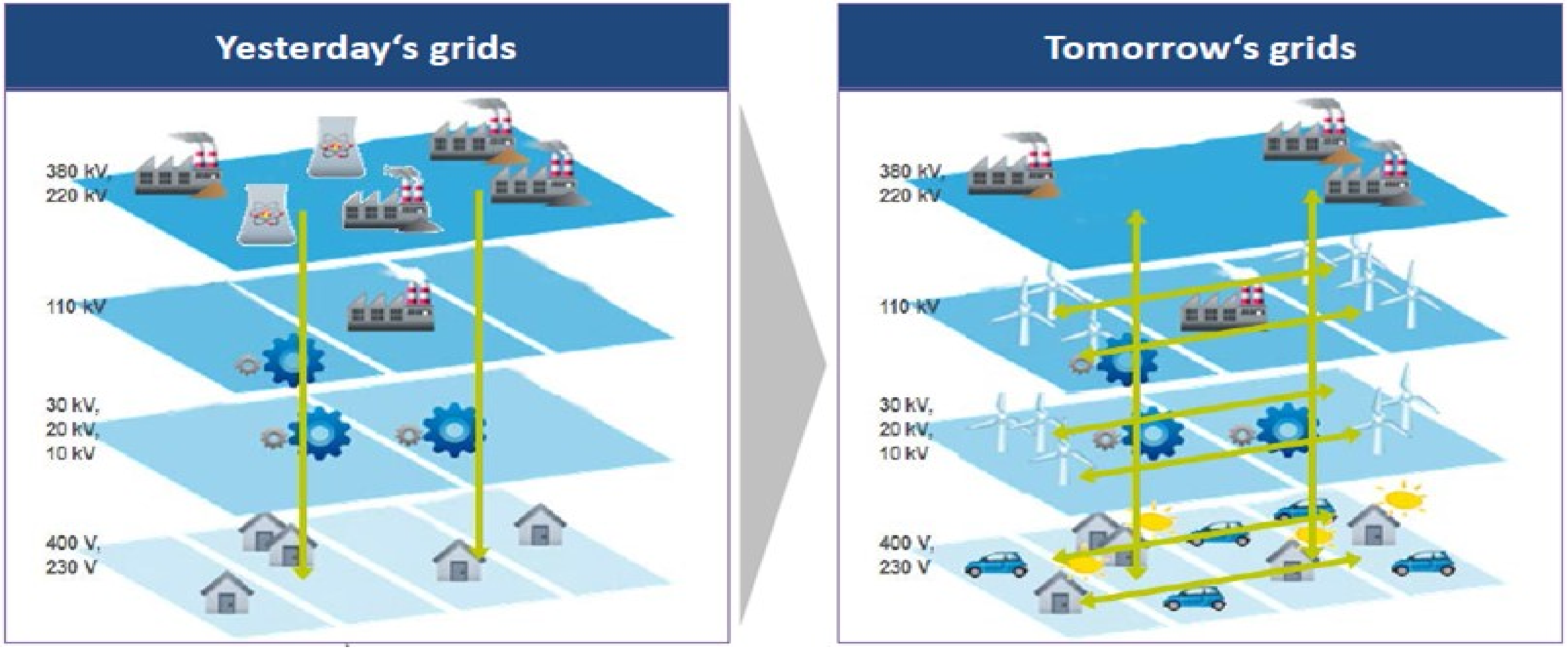
- A detailed description of the laboratory exercises (test set-ups, laboratory steps, results, conclusions etc) can be found at:

P. Kotsampopoulos, V. Kleftakis, N. Hatziargyriou, "Laboratory Education of Modern Power Systems using PHIL Simulation" , IEEE Transactions on Power Systems, Vol. 32, Issue: 5, September 2017

Free download:

http://ieeexplore.ieee.org/document/7801946/

Transformation Of The Power System



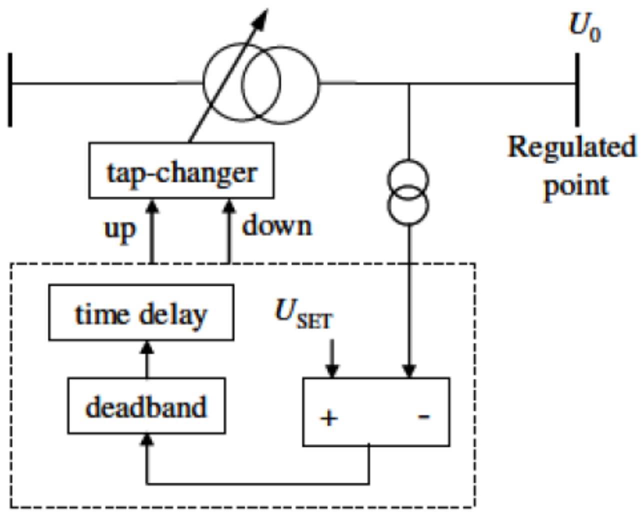
- The centralized, one-way structure of the traditional power system is changing
- Benefits: increased generation from Renewable Energy Sources, reduction of transmission losses, etc
- Challenges: intermittent behavior, stability etc
- Old concept: "fit and forget"
- Distributed Generation (DG) must provide ancillary services:
  - Voltage support in steady state
  - Voltage support in dynamic conditions (e.g. short circuits)
  - Contribution to frequency control

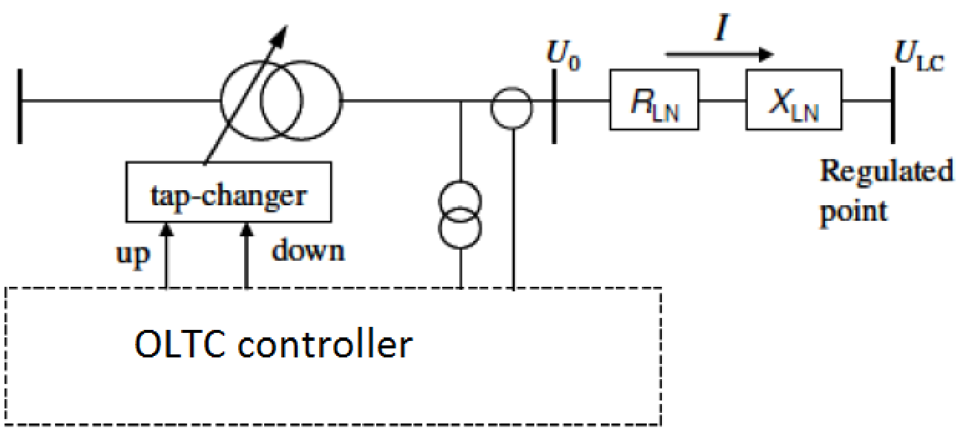
1st Topic: Voltage Control in Distribution Networks

Voltage Control at "Traditional" Distribution Networks

- The loads (resistive-reactive) cause voltage drops along the lines

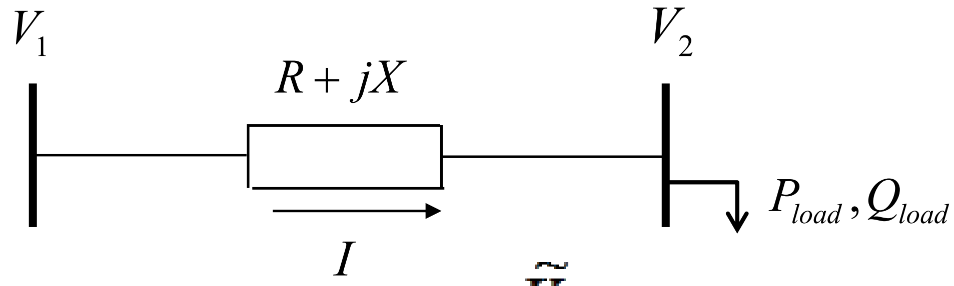
- On-Load Tap Changers (OLTC) on HV/MV Transformers:
  - They regulate the voltage of the secondary winding
  - Line drop compensation (not always used)

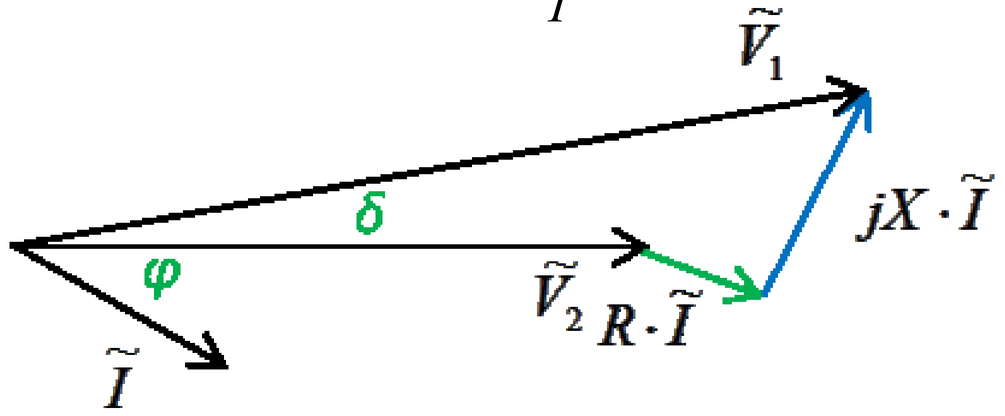




- Capacitor banks
- Static Var Compensators (SVC), etc

Approximate Formula For The Voltage Drop Calculation





$$\tilde{V}_1 = \tilde{V}_2 + \tilde{I} \cdot (R + jX)$$

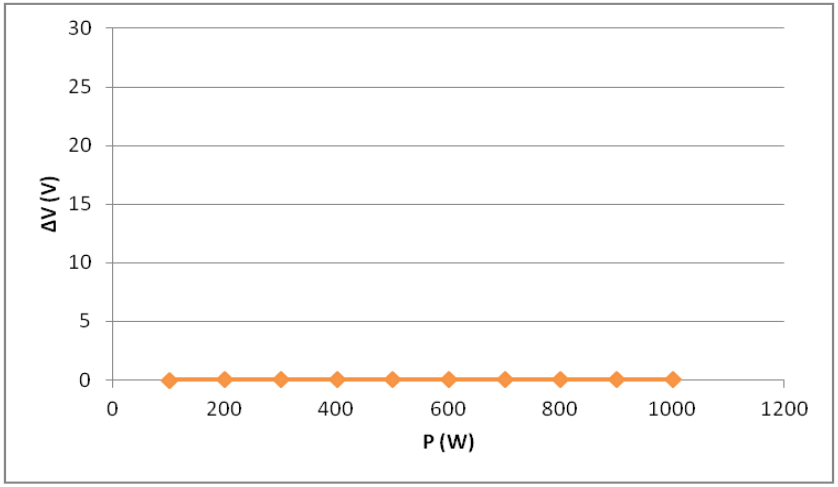
For a small angle δ:

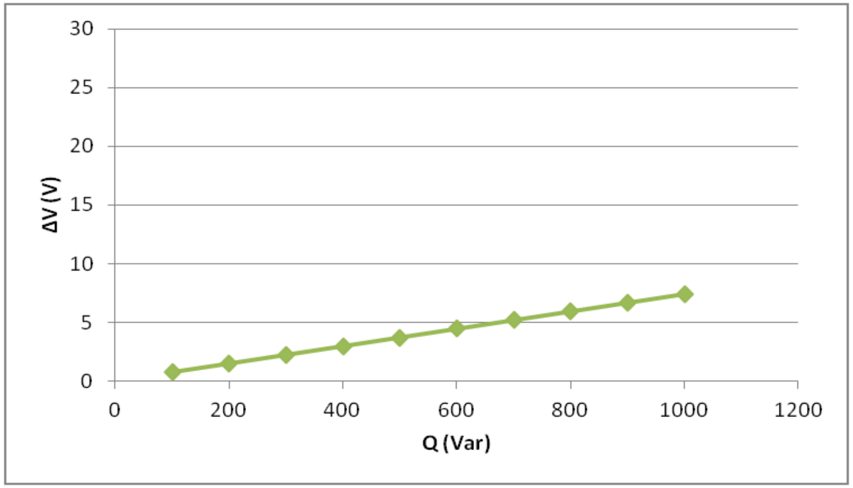
$$\Delta V \approx I \cdot R \cdot \cos\phi + \mathrm{I} \cdot \mathrm{X} \cdot \sin\phi = \frac{P_{load} \cdot R + Q_{load} \cdot X}{V_2}$$

IMPACT OF THE RATIO R/X

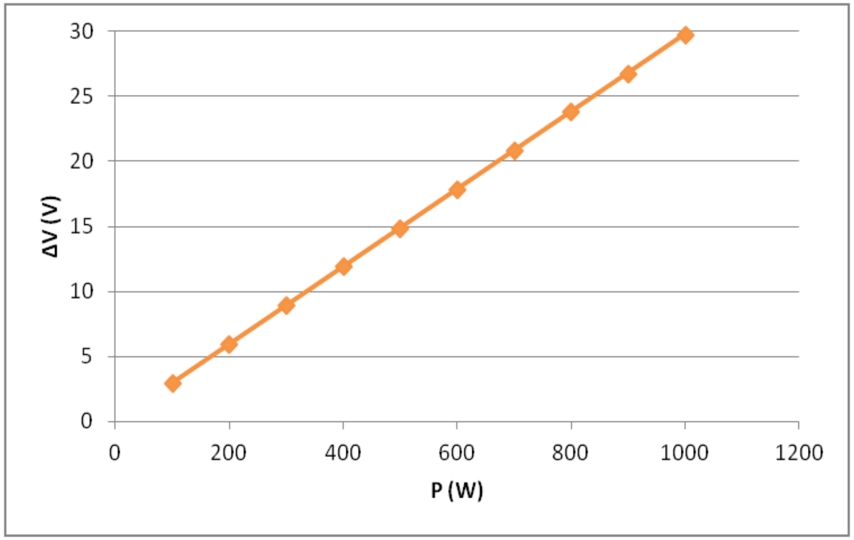
$$\Delta V \approx \frac{P_{load} \cdot R + Q_{load} \cdot X}{V_2}$$

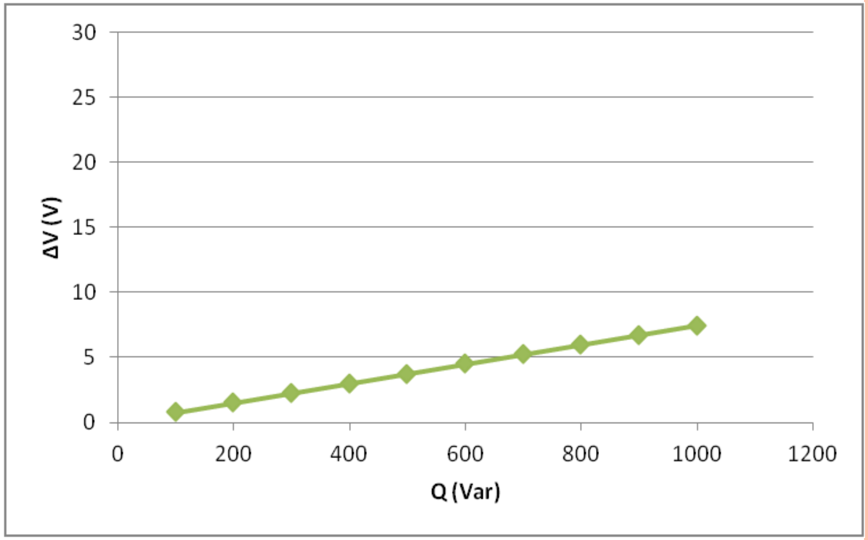
- R/X≈0.01 (overhead HV line)



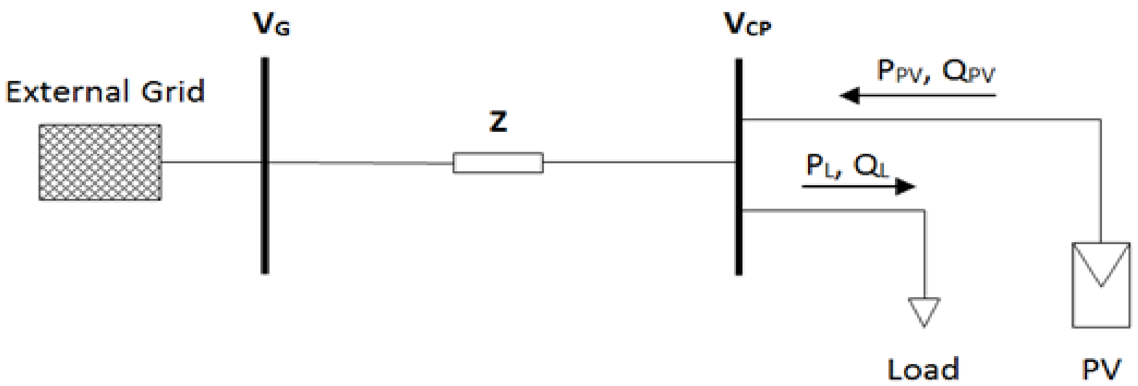


- R/X≈4 (underground LV cable)



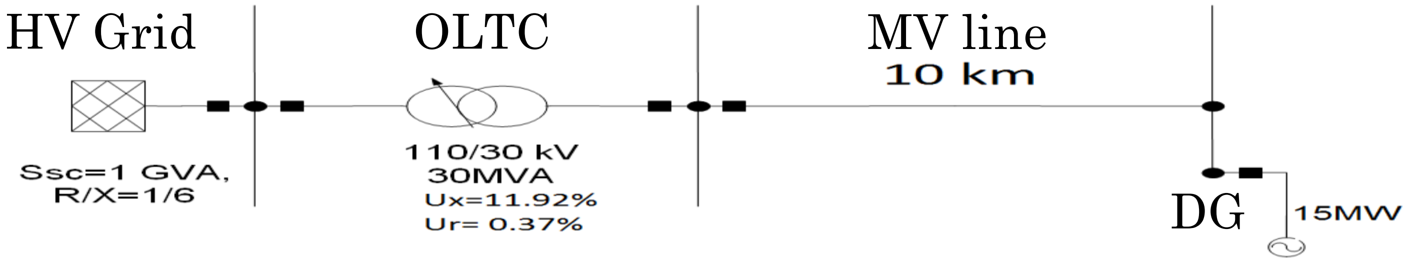


Voltage Control at Distribution Networks with Distributed Generation



$$\Delta V \approx \frac{P_{load} \cdot R + Q_{load} \cdot X}{V_2}$$

- How does Distributed Generation affect the grid voltage?
- How can voltage problems caused by DG penetration be mitigated?

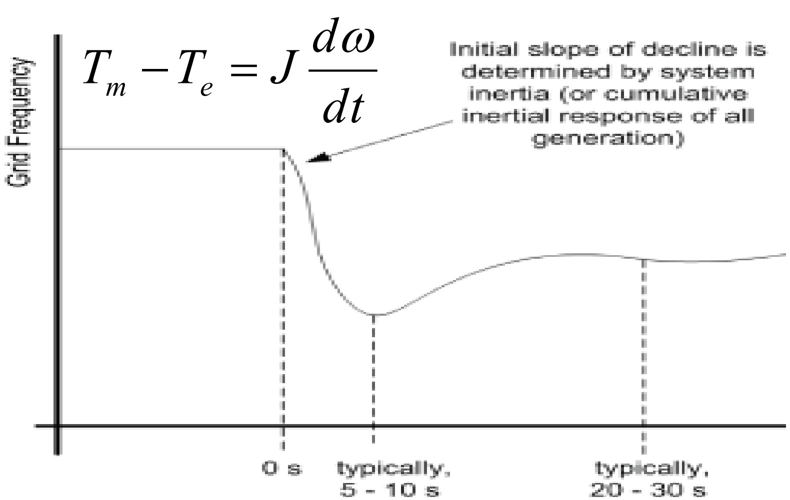


- Is the cooperation with traditional voltage regulation methods (e.g. OLTC) always harmonious?

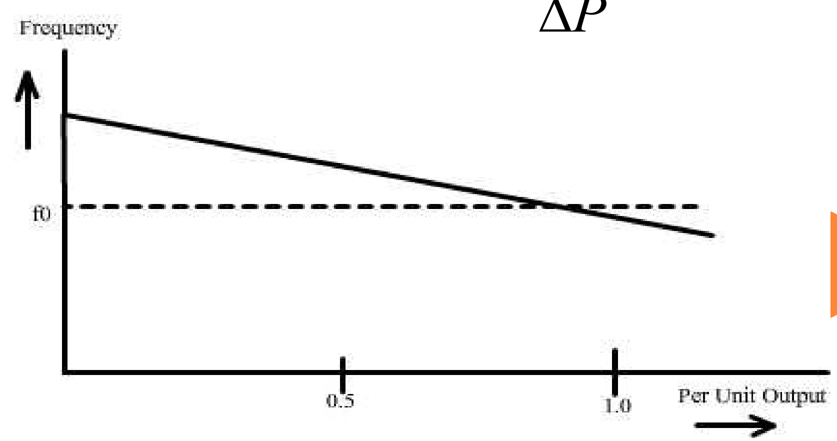
2nd Topic: Frequency Control in Modern Power Systems

Primary Frequency Control at Traditional Power Systems

- Simple system consisting of synchronous generator (with prime mover, governor etc) and load.
- As the load increases, part of the kinetic energy of the rotor is used to support the load, which slows down the generator and reduces the frequency. This is not performed uncontrollably (as it would lead to great frequency reduction etc).
- The generator's governor detects the reduction of the rotational speed and increases the mechanical torque (e.g. by feeding more steam to the turbine).
- As a result, a new equilibrium is achieved at which the generator provides more power to support the increased load.



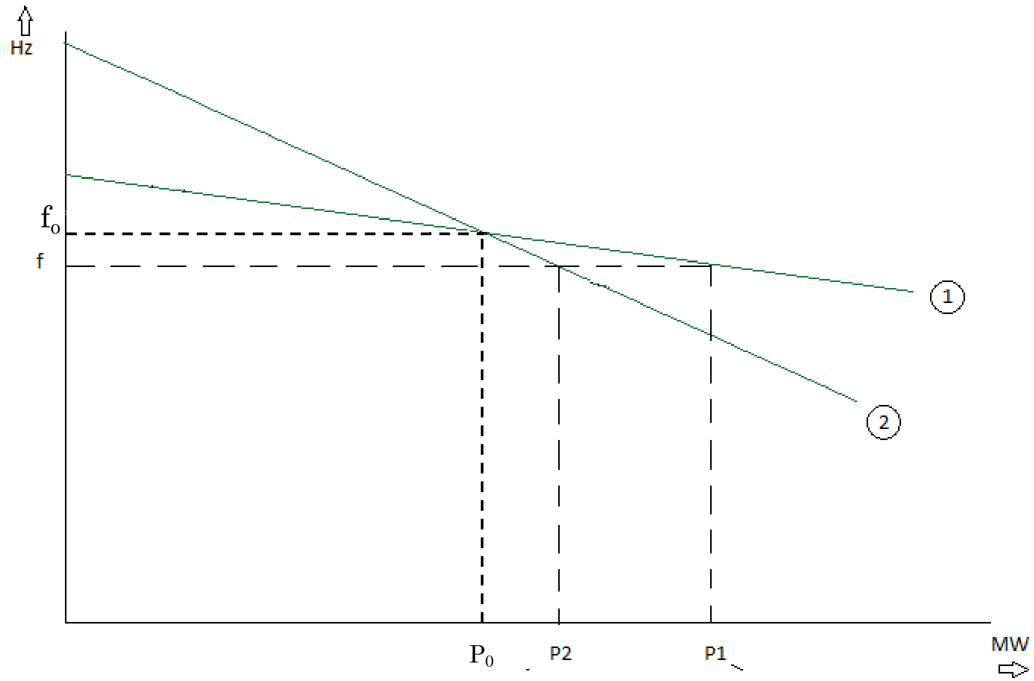
Droop coefficient: $R = -\frac{\Delta\omega}{\Delta P}$ $(p.u.)$



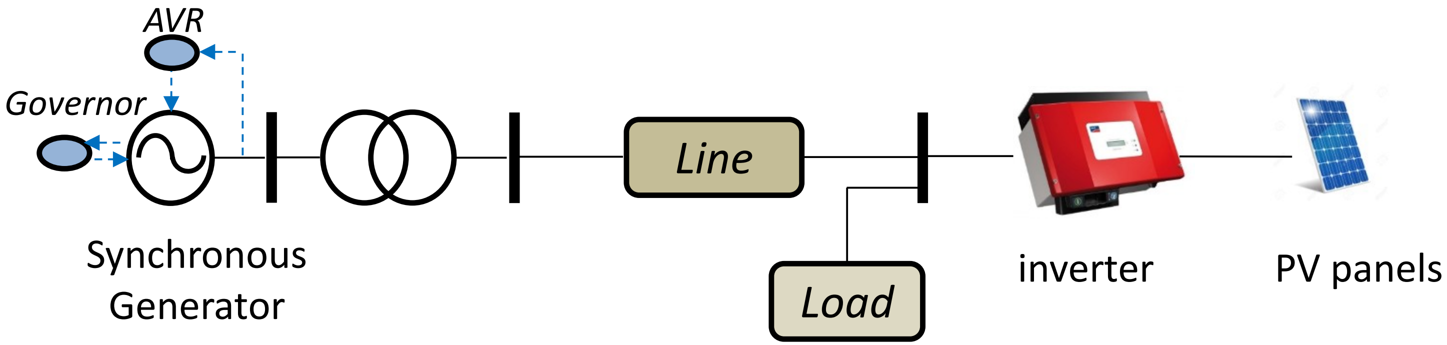
Load Sharing Between 2 Synchronous Generators

- The load is equal to the sum of the power of the synchronous generators $P_L = P_1 + P_2$
- The frequency is the same

$$\omega - \omega_o = -R_1 \cdot (P_1 - P_0) = -R_2 \cdot (P_2 - P_0) \quad (p.u.)$$



Parallel Operation of Synchronous Generators and Distributed Generation



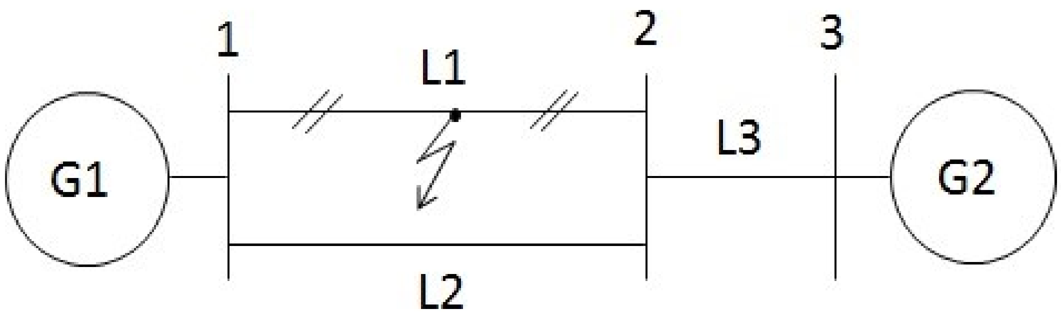
- How does Distributed Generation affect the frequency of isolated systems?
- How can the penetration of DG help mitigate frequency deviations?

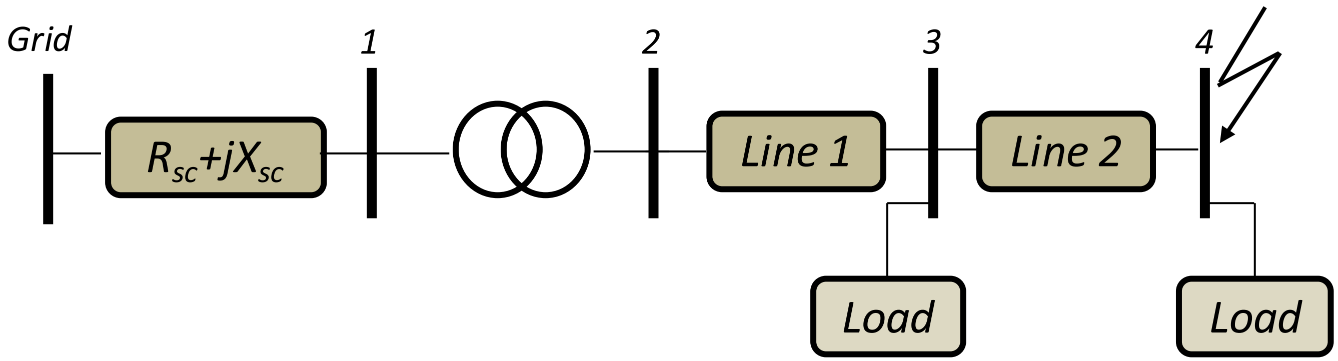
- «The 50.2 Hz problem» in Germany: simultaneous disconnection of several GW of DG.

3rd Topic: Short-Circuit Contribution of Inverter-Based DG

SHORT-CIRCUIT STUDIES

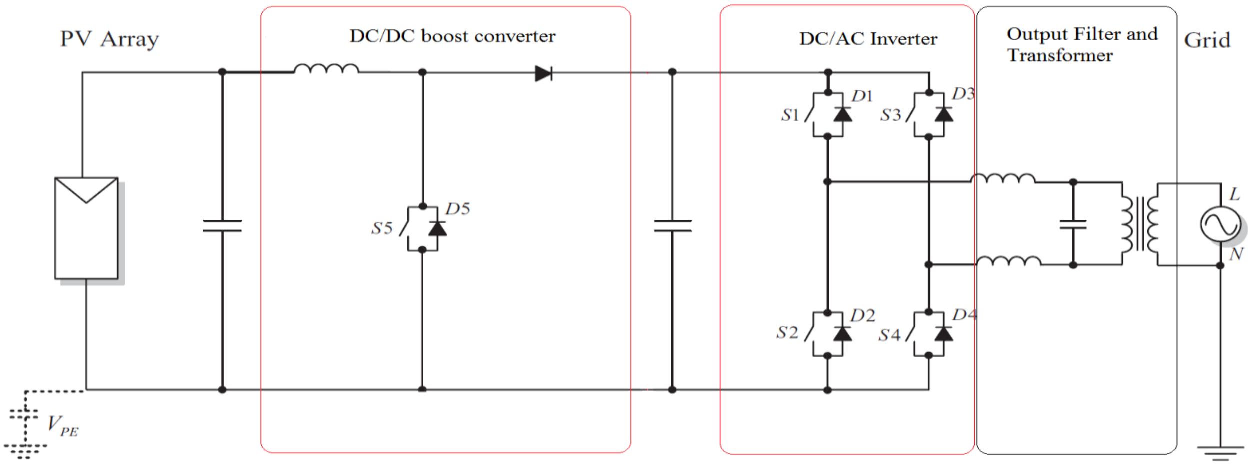
- Traditional power system:
  - Thevenin equivalent, current dividers, etc.
  - Y_{bus}, Z_{bus}, etc.

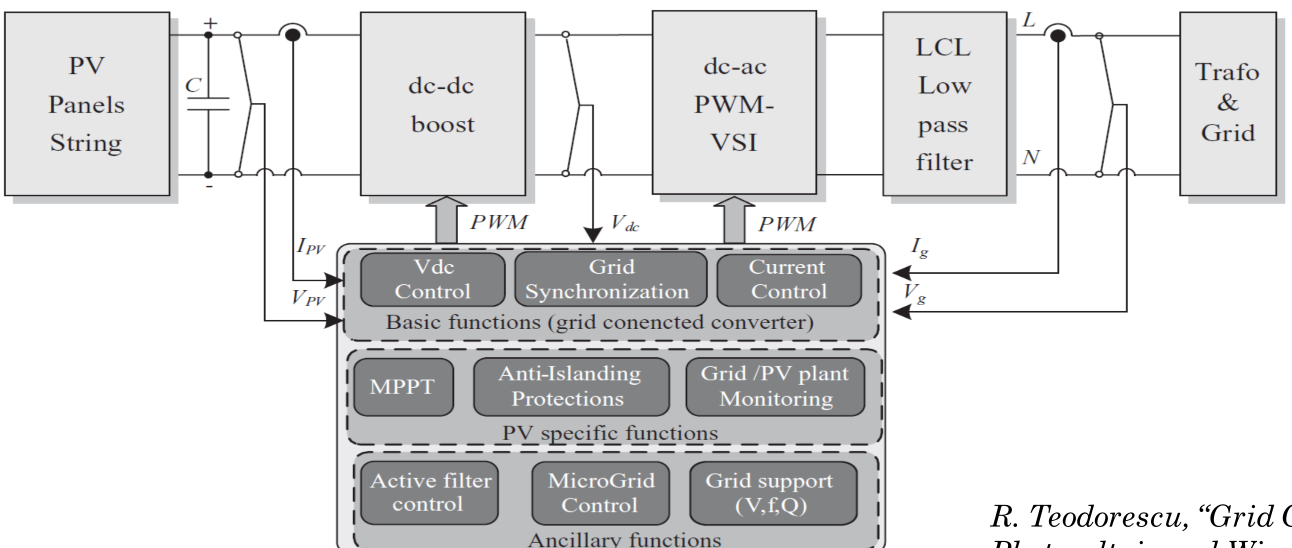




Inverter-Based Distributed Generation

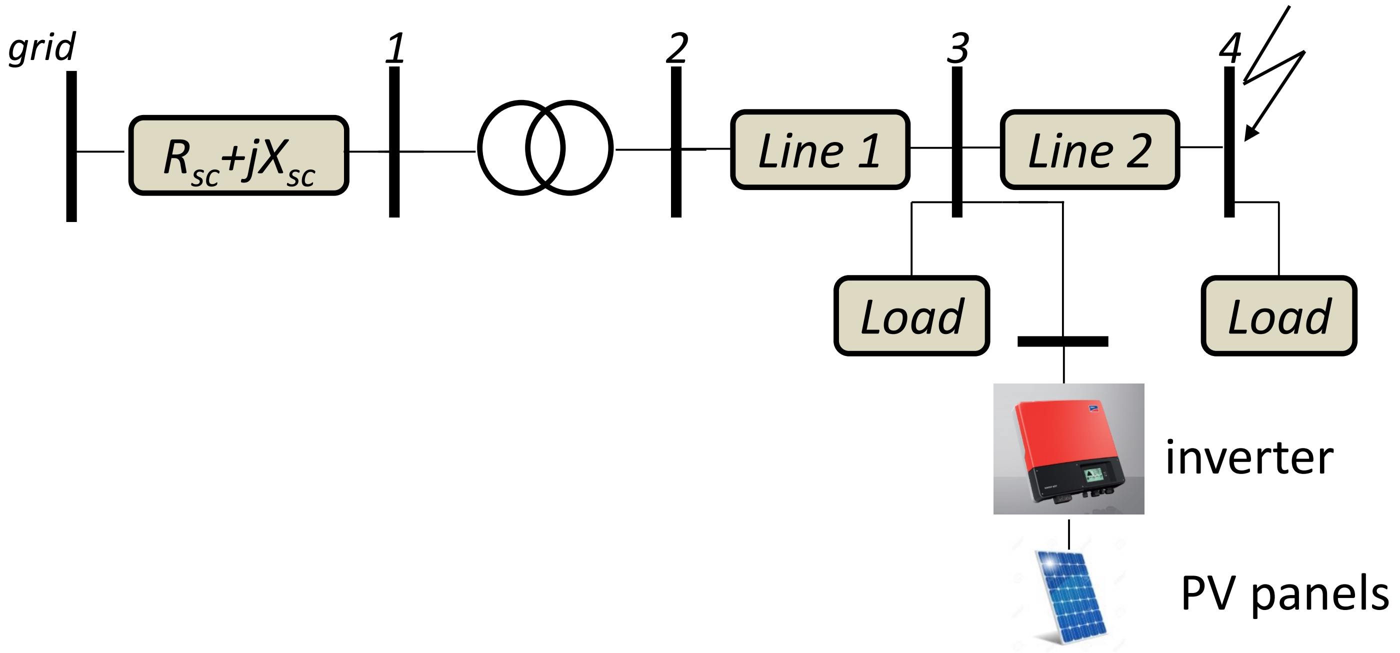
- E.g. Photovoltaics, variable speed synchronous wind generators





R. Teodorescu, "Grid Converters for Photovoltaic and Wind Power Systems", 2011

Distributed Generation connected through Power Electronics: Behavior at Short Circuits

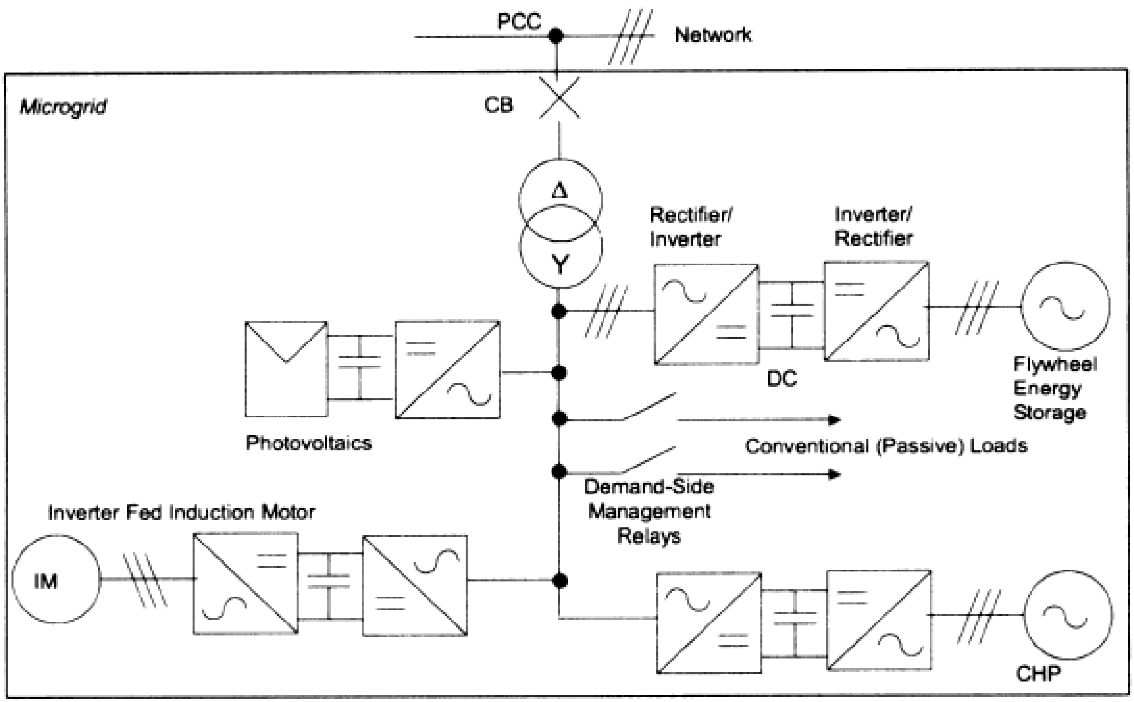


- How do the inverters of DG behave during short-circuits?
- How can we make short-circuit studies at power systems with inverter-based DG?

4th Topic: Microgrids

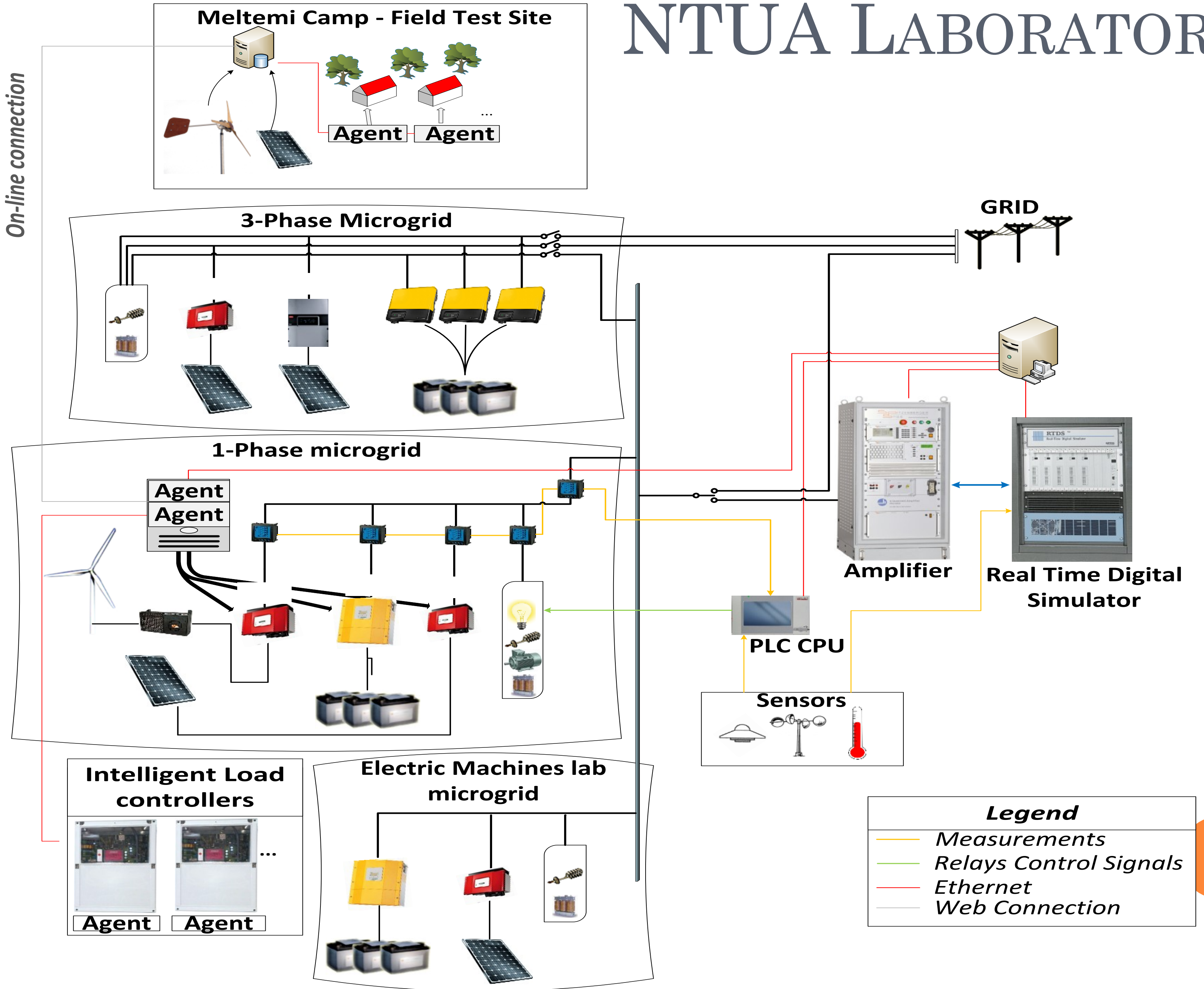
Microgrids

- A part of the network that can also operate isolated from the main grid (e.g. by utilizing energy storage).
  - Grid-connected operation
  - Stand-alone (islanded) operation



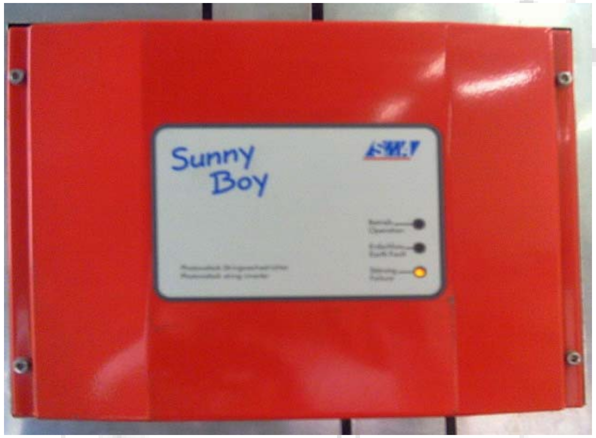
Laboratory Equipment-Experimental Setups

NTUA Laboratory



Laboratory Equipment

Photovoltaics



- SMA SUNNY BOY 1100E:**1.1KW**

- Danfoss : **2kW**
- SMA Sunny Boy 3000 TL: **3kW**

Wind Turbine

- SMA WINDYBOY 1700
- 1.7KW

WISPER WIND GENERATOR H80HV

Battery Energy Storage System

- SMA SUNNY ISLAND 4500
  3.3KW Nominal Power
- Voltage source in islanded operation:
  -voltage and frequency regulation
- P-Q source in grid-connected operation

- LEAD ACID SOLAR OPzS
- 30X2V
- 250Ah

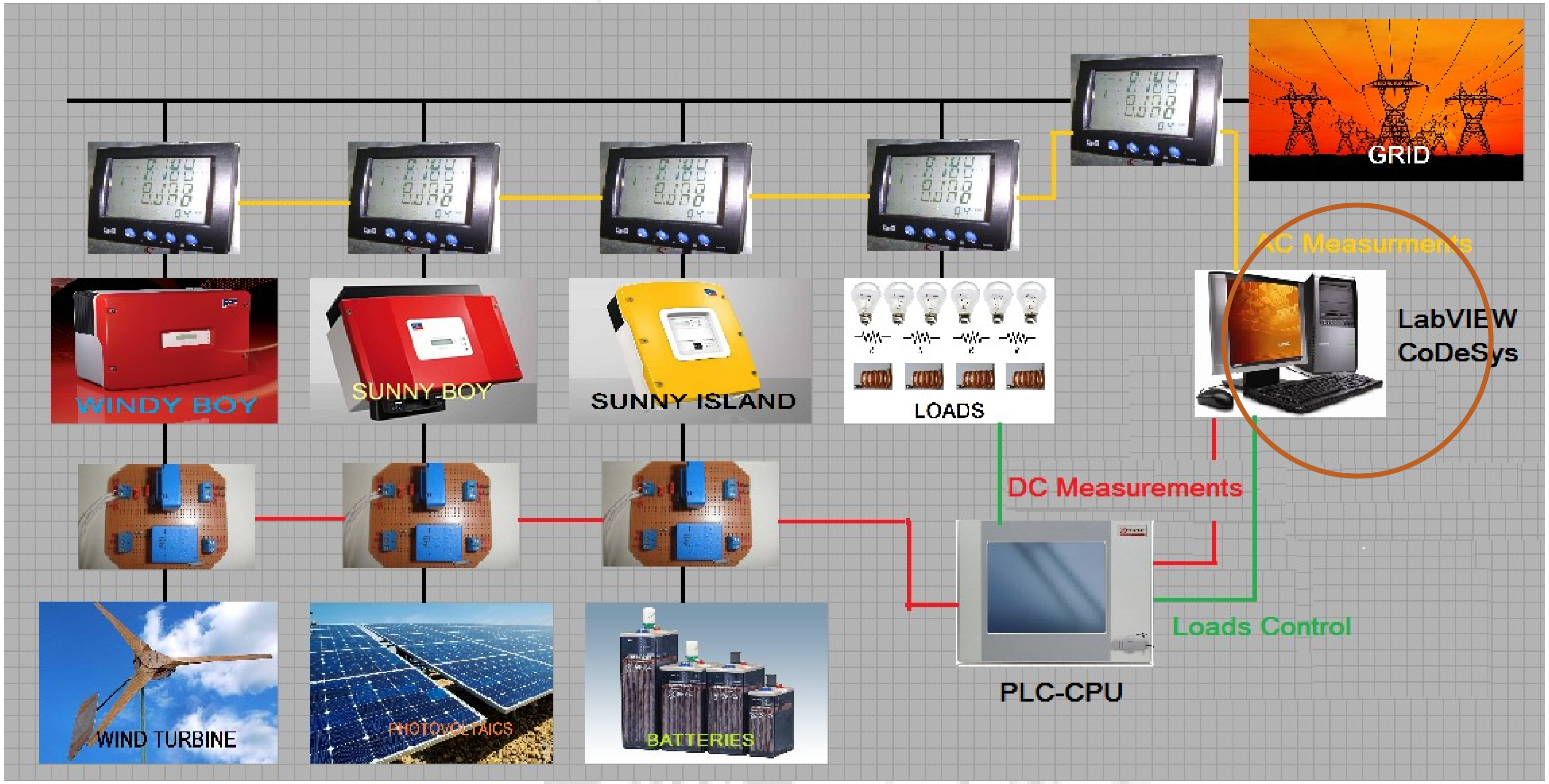
Controllable Loads

Resistors: 15KW
Fans: 300W

Light bulbs: 1000 W
Motor: 0.5 HP

Inductors: 2,5KVar

MICROGRID SCADA



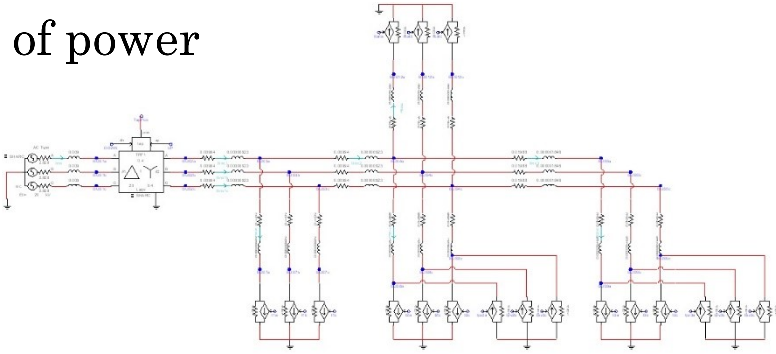
Sources and Load Monitoring/Control

- AC Measurements
- DC Measurements
- Environmental measurements (e.g. irradiation)

LABORATORY EQUIPMENT

- Real Time Digital Simulator (RTDS®)

- Real-time simulation of power systems
- Parallel processing
- Analog and Digital Inputs/Outputs



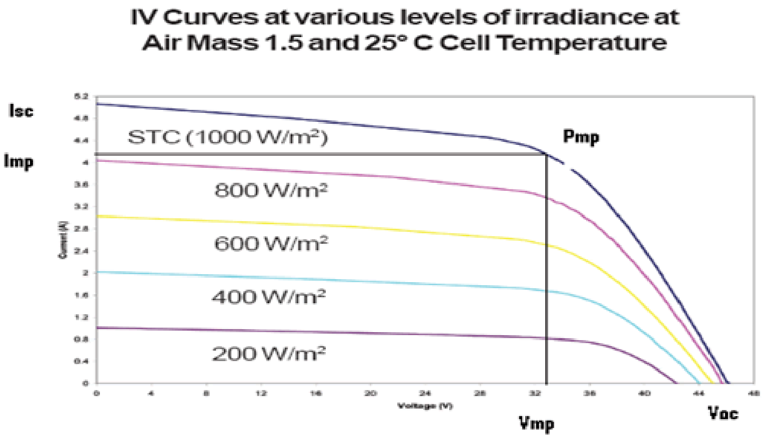
- Controllable and customizable power electronics (by Triphase)

- Flexibility and various possible topologies (DC/DC, DC/AC, AC/DC/AC)
- Applications: PV/Battery converter, power amplifier and more
- Fully and easily programmable using Matlab/Simulink

Laboratory Equipment

- PV Simulator

- Controllable DC source
- Simulates I-V characteristic curves of PV panels
- Provides independency from environmental conditions during testing

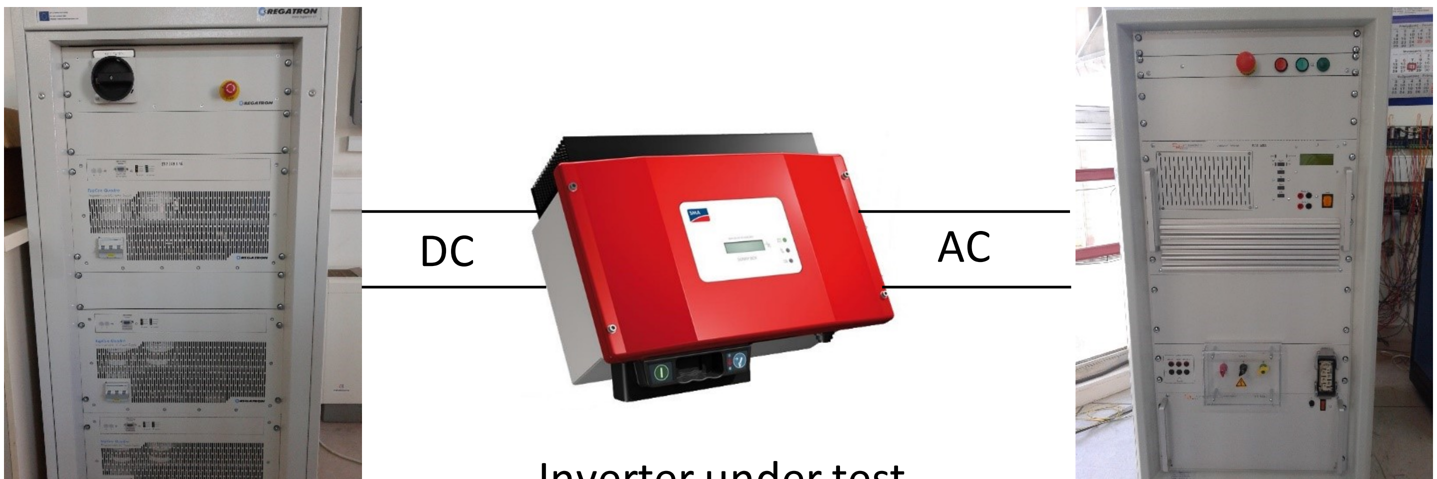


- AC Grid Simulator – Linear Amplifier

- Controllable voltage and frequency source
- 4-Quadrant operation
- 5 kVA nominal power

Laboratory Equipment

- PV inverter testing according to standards



PV Simulator

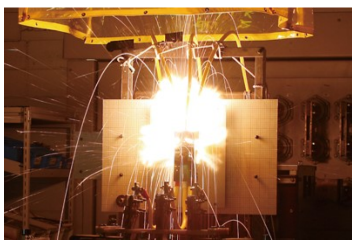
Inverter under test

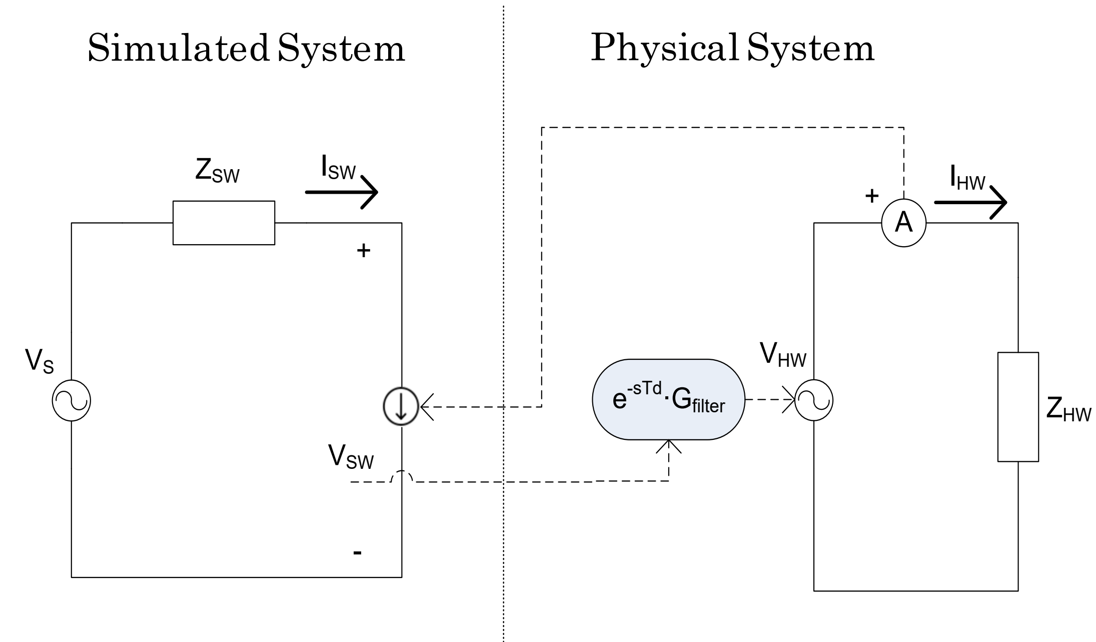
Grid Simulator

Yokogawa WT3000 Power Analyzer

Power Hardware In The Loop Simulation

Real Time Digital Simulator:
RTDS



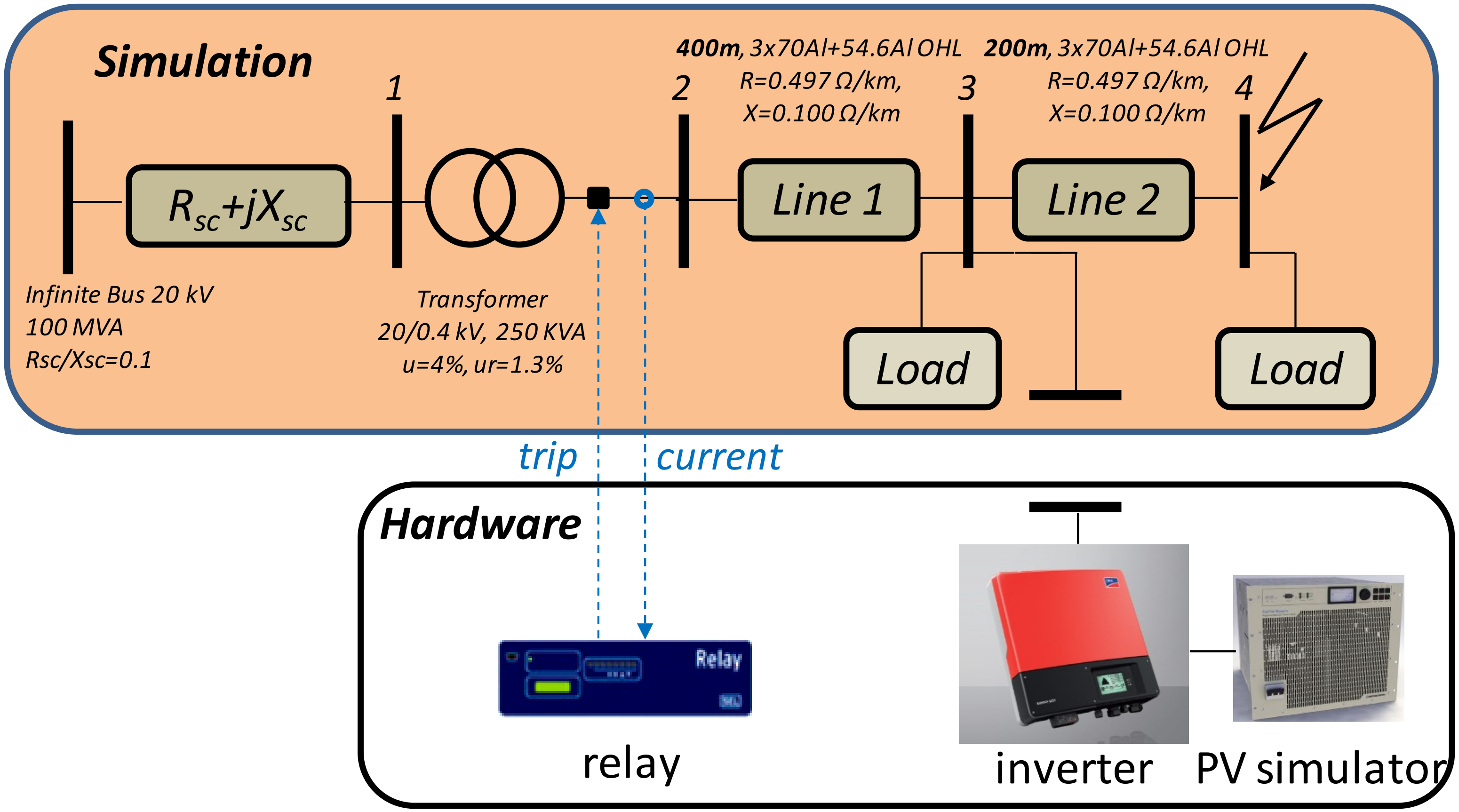


An amplifier is required for interfacing RTDS with the hardware equipment

- Equipment that is not available at the lab can be simulated (e.g. transformer with OLTC, synchronous generator, etc.)
- Difficult tests (e.g. short-circuits) can be made with safety
- Education: Students can familiarize with real hardware laboratory equipment (not just computer simulations)

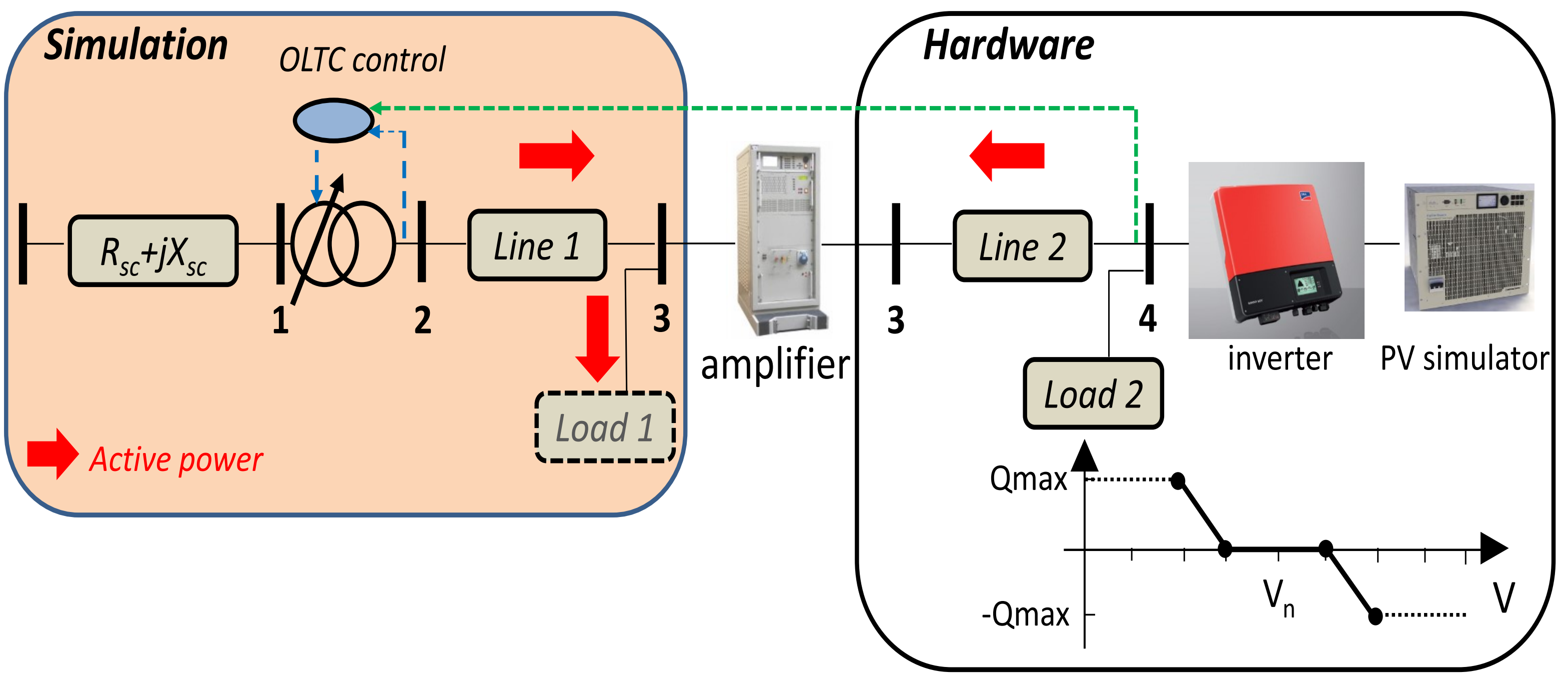
Laboratory Exercises

- Behavior of inverter-based Distributed Generators during short-circuits



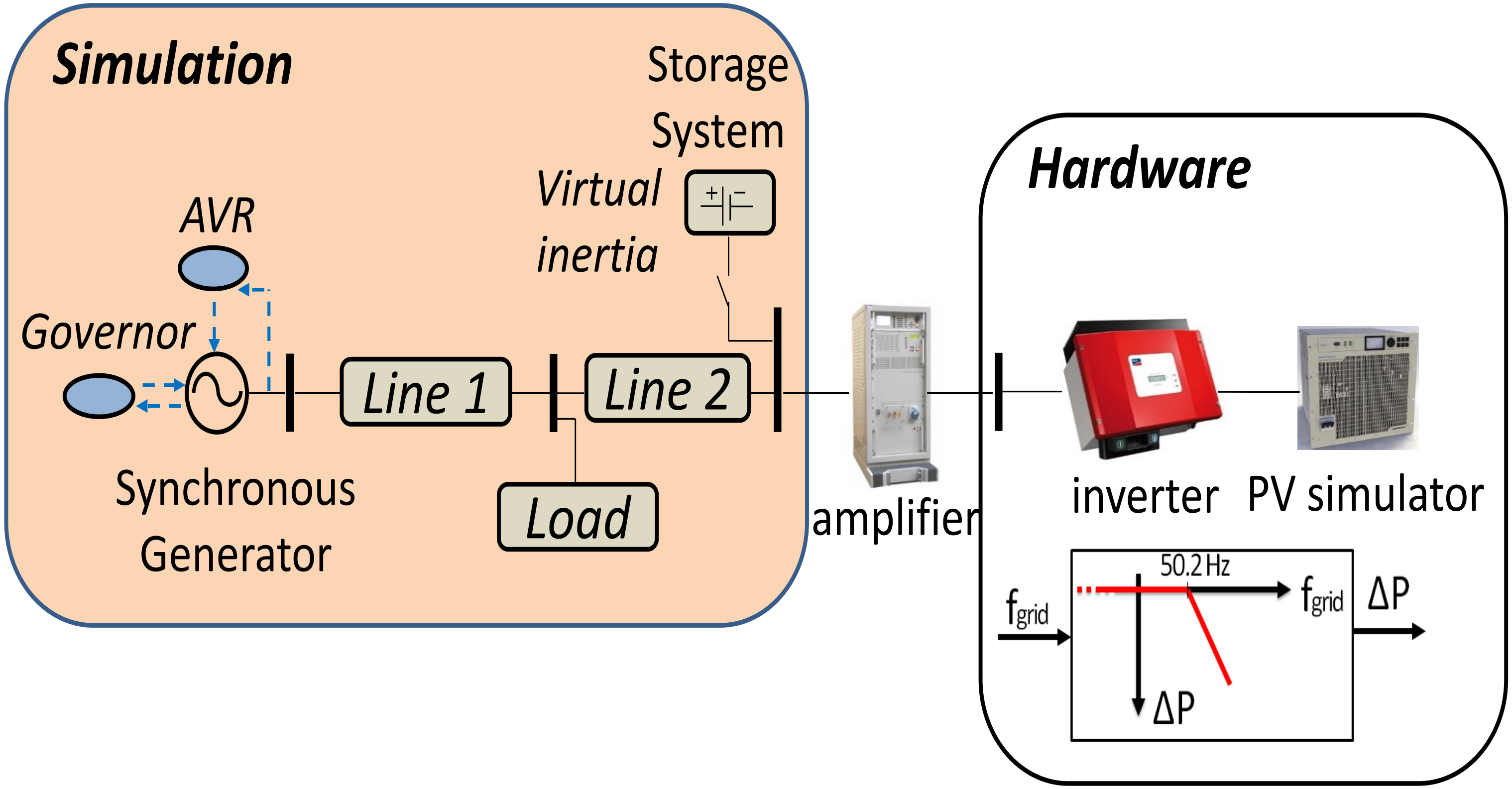
LABORATORY EXERCISES

- Contribution of Distributed Generation to voltage control



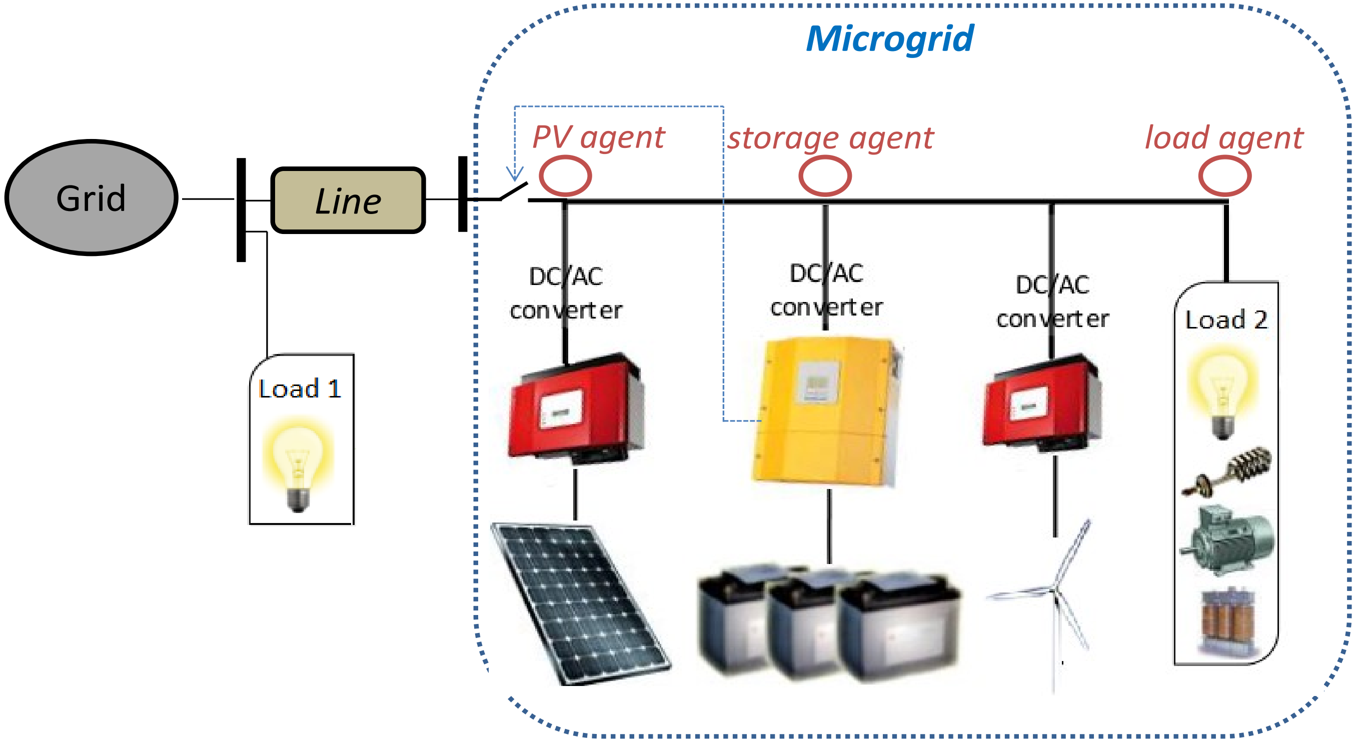
Laboratory Exercises

- Parallel operation of synchronous generators and distributed generation

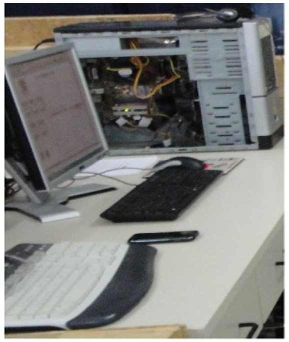


Laboratory Exercises

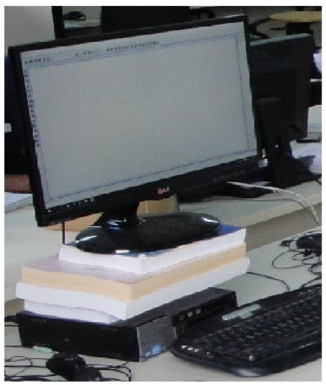
- Microgrid operation and control



Two Work Benches at the Lab Exercises



1st Work bench



2nd Work bench

Each bench:

- PV Inverter
- Oscilloscope or power analyzer
- PC which connects with:
  - RTDS (power system: measurements, control)
  - PV Simulator (set irradiation values)
  - PV Inverter (set reactive power set-points, droop control etc)

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Questions?

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