

National Technical University of Athens



Preparatory lecture for the laboratory exercises

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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



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

For a small angle δ : $\Delta V \approx I \cdot R \cdot \cos \phi + I \cdot X \cdot \sin \phi = \frac{P_{load} \cdot R + Q_{load} \cdot X}{V_2}$



• R/X≈0.01 (overhead HV line)



• R/X≈4 (underground LV cable)







VOLTAGE CONTROL AT DISTRIBUTION NETWORKS WITH DISTRIBUTED GENERATION



• 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.



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



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



Distributed Generation connected through Power Electronics: Behavior at Short Circuits



- How do the inverters of DG behave during shortcircuits?
- 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





PHOTOVOLTAICS



•SMA SUNNY BOY 1100E:1.1KW



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





WIND TURBINE



BATTERY ENERGY STORAGE SYSTEM

SW



• 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



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)

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

> 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

> PV inverter testing according to standards



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)

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



• Contribution of Distributed Generation to voltage control



• Parallel operation of synchronous generators and distributed generation



• Microgrid operation and control



TWO WORK BENCHES AT THE LAB EXERCISES



$1^{\rm st}$ Work bench





 2^{nd} 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?

<u>www.smartrue.gr</u> <u>www.erigrid.eu</u>



Home News Laboratory Education Research Publications People Contact Welcome Links Welcome to the Website of Smart RUE (Smart grids Research Unit of the Electrical and Computer Engineering School) of NTUA. 16PEEN6rid About Us Smart RUE is one of the Research Groups of the Institute of Communication and Computer sustain able Systems (ICCS). It belongs to the Electric Energy Systems Laboratory (EESL) of the School of Electrical and Computer Engineering of the National Technical University of Athens. It was founded in 1996 by Professor Nikos Hatziargyriou and operates under his supervision. It is Smart_{Kve} composed of Professors, post-doctoral scientists, postgraduate students and highly specialized researchers and collaborators. It is technically and administratively supported by the personnel of EESL. The main activities of Smart RUE focus in research and technology development in the area of FAST IN CHARGE Smart Grids. Smart Grids have been defined by the European Technology Platform of Smart Grids as "electricity networks that can intelligently integrate the actions of all users connected to them - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies". According to this definition, the main Smart Rue activities deal with planning and operation of modern power systems characterized by high penetration of renewable energy sources, distributed generation and flexible loads. For the efficient solution of related problems advanced control and ICT technologies are employed. Smart RUE has coordinated and participated in a large number of European and national R&D projects and studies. It has organized several international Conferences, Seminars and workshops and it has published numerous papers in international journals and conference proceedings. Its members are active in several EU and international organizations. It maintains excellent connections with many Universities, Research Centers, Utilities and Power Industries

The National Technical University of Athens is among the 100 (98) best Faculties of Engineering and Technology of the world and its School of Electrical Engineering in the positions (51-100) according to the QS Top Universities Rankings.

active in the area of Smart Grids both at national and international level.