Νέες τεχνολογίες για παρακολούθηση του ηλεκτρικού δικτύου και βέλτιστη ένταξη ΑΠΕ για ενδυνάμωση της ευστάθειας του συστήματος

Ηλίας Κυριακίδης

Αναπληρωτής Καθηγητής

Τμήμα Ηλεκτρολόγων Μηχανικών και Μηχανικών Υπολογιστών

Ερευνητικό Κέντρο Αριστείας «Κοίος»

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Presentation Outline

- KIOS Research and Innovation Center of Excellence
- Power system monitoring in real time
- Grid integration of RES and storage
- EMPOWER: Large integrated project in Cyprus

KIOS Research Center - Background

- **KIOS Research and Innovation Center of Excellence**
- **Founded in 2008**
- **The KIOS Research Center is part of the University of Cyprus**
- **Housed (mainly) at the KIOS Center Building (600 m^2)**
- **Web site: www.kios.ucy.ac.cy**
- **TEAMING/H2020 (KIOS/Imperial – funding of ~40 m€)**
- **About 100 researchers (goal to reach 200 by 2020)**
    - ***9 faculty members***
    - ***~30 post-doctoral fellows***
    - ***~50 Ph.D. students***
    - ***Several M.Sc. students and non-degree researchers***

Technical Focus of the KIOS CoE

- **Intelligent monitoring, management and security of complex, large-scale dynamical systems**
- **Application domain: *Critical Infrastructure Systems***

Power Systems

- Increase stability, fault tolerance
- Reduce emissions, energy consumption, generation costs
- Integrate renewable energy sources

Water Networks

- Increase security, water quality, resilience
- Reduce water losses, energy usage, non-revenue water

Telecommunications

- Improve network coverage and mobility, reliability, secrecy, data-rates
- Reduce energy consumption

Transportation Networks

- Increase mobility and productivity
- Reduce accidents, fuel consumption, emissions, congestion cost

Emergency Response

- Reduce damage of ecosystem, damage to property and destruction of critical infrastructures

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Research Areas of Power Systems Group

- **Operation and control of the power system**
- **Wide area monitoring and control**
- **Grid integration of renewables**
- **Control of power electronic converters**
- **Economic dispatch**
- **Micro-grids and Smart-grids**
- **Load shedding**
- **Load modelling**
- **Storage**

Electric Power Systems

- **Similar to all critical infrastructure systems, power systems are crucial for everyday life and well-being**
  - **Citizens expect/rely that they will *always* be available (24/7)**
  - **Citizens expect that they will be managed efficiently (low cost)**

- **Power systems malfunction (frequently) or fail (occasionally)**
  - **Natural disasters (earthquakes, floods)**
  - **Accidental failures (equipment failures, software bugs, human error)**
  - **Malicious attacks (directly, remotely)**

- **When power systems fail, the consequences are tremendous**
  - **Societal consequences**
  - **Health hazards**
  - **Economic effects**

Electric Power Grid

- **Current electric grid: built about a century ago, and has been growing in size and capacity**
- **Transmission lines connect power sources to the grid**
  - ✓ **Technologically updated with automation and human monitoring over the last few decades**
- **Distribution lines, no significant changes**
  - ✓ **They have been mostly taken as user end-points of service**

In the last few years:

- **Steady growth of distributed generation**
- **Higher penetration of renewable energy sources**
- **Policies on electricity distribution have been supporting needs for a “smart grid”**
- **Centralized power plants have enormous economic constraints, and utilities have been trying to use their assets more efficiently**

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Key Challenges for the Power Grid

- Load and system conditions change continuously
  - Quasi-steady state conditions most of the time
  - Dynamically changing conditions occasionally
- Integration of distributed energy resources (DER), renewables, microgrids
- Management of the evolving integrated infrastructure including its ties/interdependencies with massively deployed sensors, communication infrastructure and intelligent software agents
- Ensure system stability, robustness, reliability, security and efficiency

How?

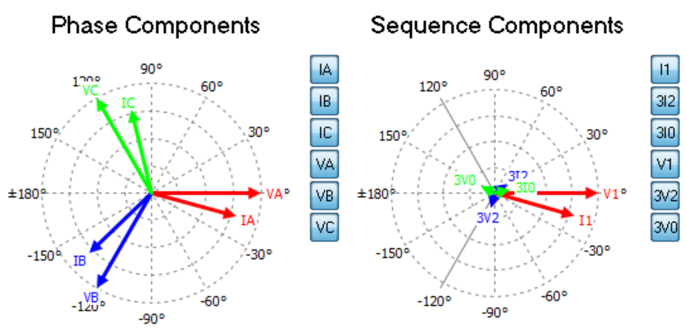
(a) Wide area monitoring and control

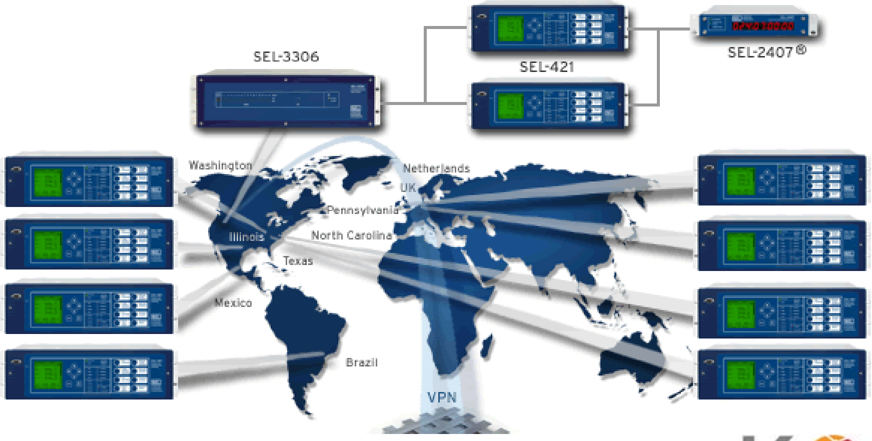
(b) More accurate modeling/validation of models

(c) Improved integration of renewables/storage

Synchronized Phasor Measurements

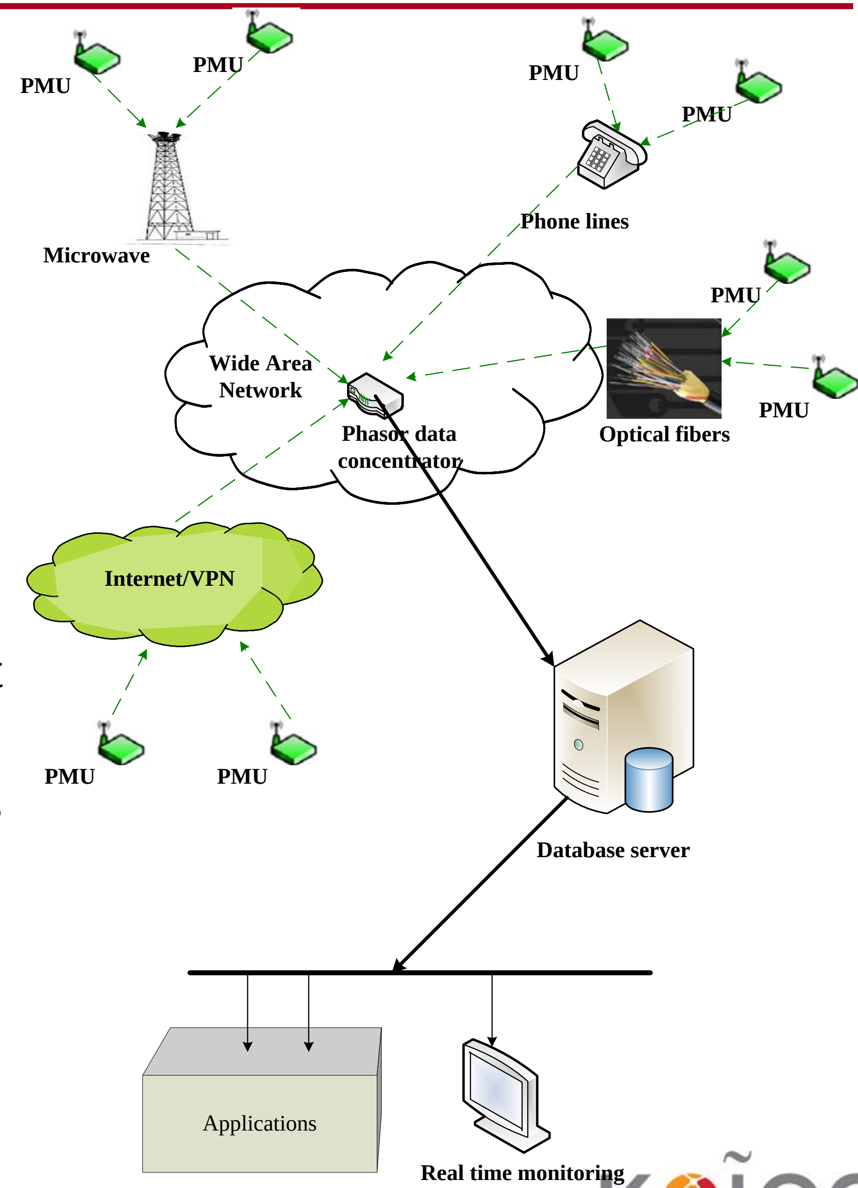
- **The Phasor Measurement Unit (PMU) is the key element of the synchronized phasor measurement technology**
- **PMU measurements are time-aligned to a common reference via a GPS signal. Thus, voltage and current phasor measurements at dispersed locations may be sampled simultaneously.**
- **Synchronized phasor measurements are distinguished by their high fidelity, in comparison to the conventional measurements (i.e., real and reactive power injections and flows, voltage magnitudes)**





Synchronized Measurement Technology

PMU measurements are sampled at a high speed (30-120 samples per second); measurements from conventional technology meters are sampled once every 4 seconds.



Main parts of a synchronized measurement system:

-- Synchronized measurement units (SMU), such as PMUs

-- Phasor data concentrators

-- Application software and servers

-- A wide area network

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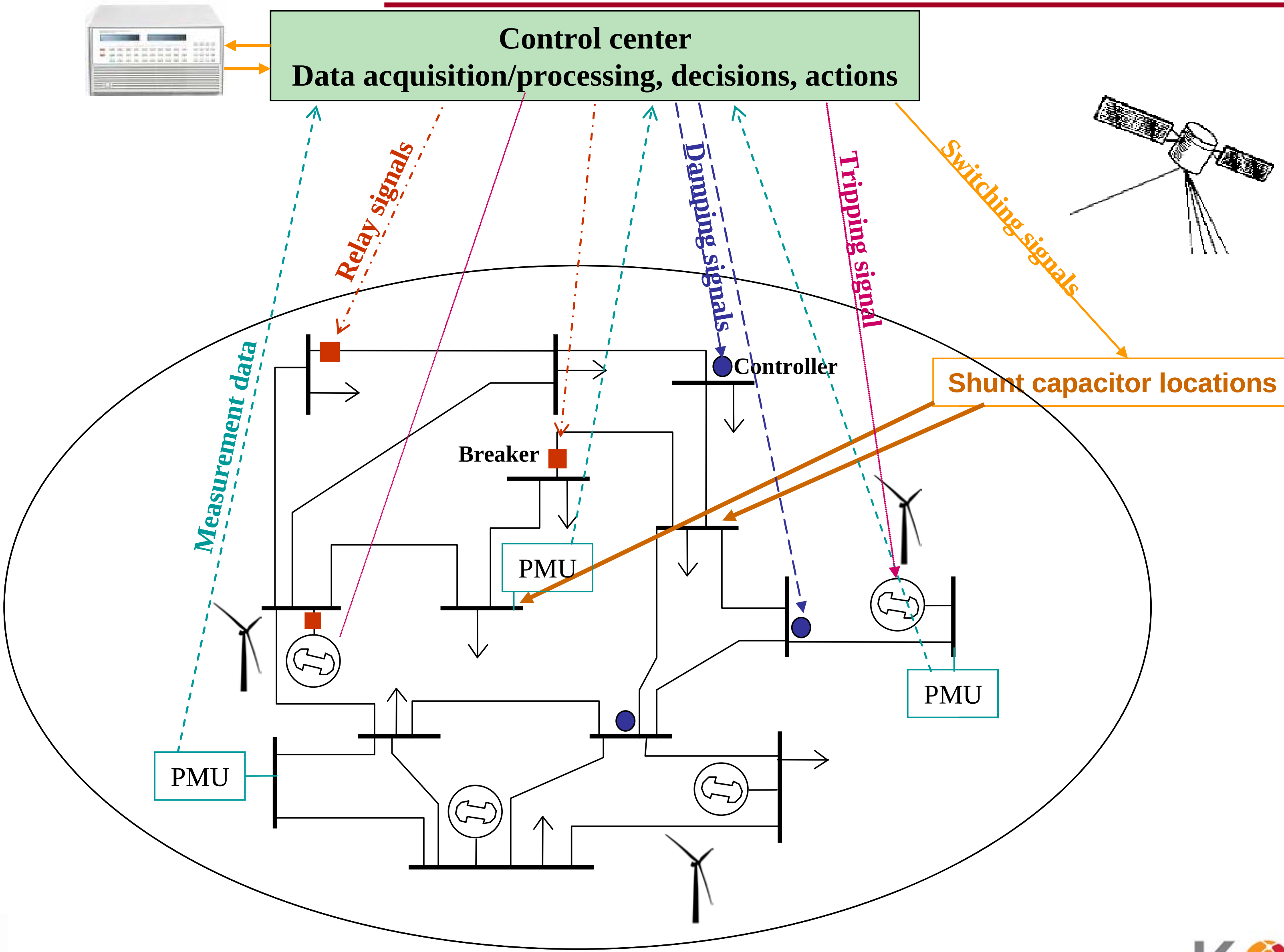
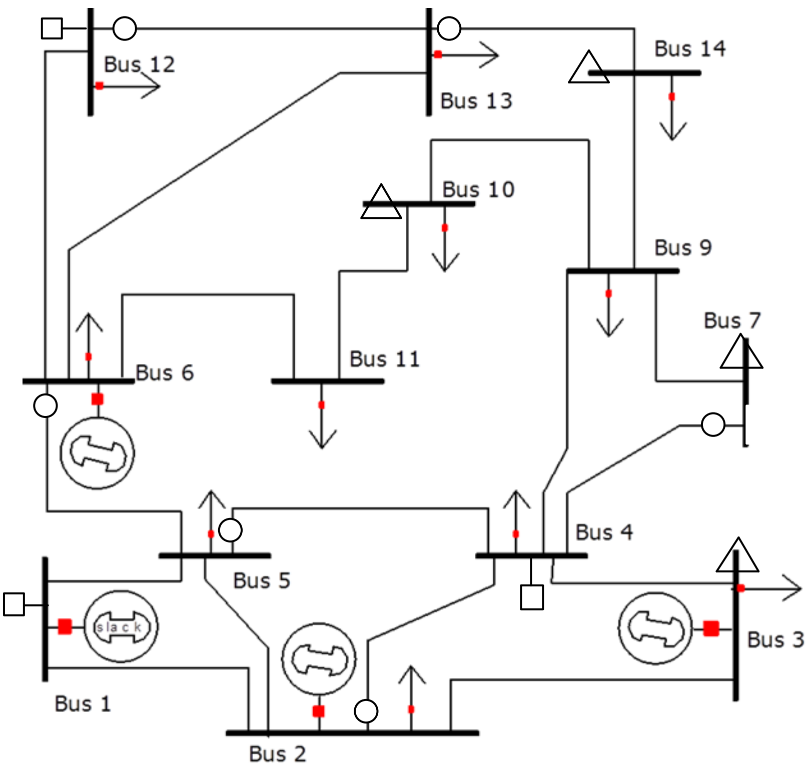
Why do we Need Synchronized Measurements?

- **Investigation for the cause of the recent blackouts found the following:**
  - **Lack of wide area visibility**
  - **Lack of time-synchronized data**
  - **Inability to monitor system dynamic behavior in real-time**
- **Phasor technology addresses these shortcomings**
- **Phasor technology facilitates the move from wide area measurement systems to wide area control systems**

The Vision


Control center
Data acquisition/processing, decisions, actions
Relay signals
Measurement data
Damping signals
Tripping signal
Switching signals
Shunt capacitor locations
Controller
Breaker
PMU
PMU
PMU

State Estimation in Electric Power Systems



○ Active/reactive power flow measurement
□ Active/reactive injection measurement
△ Voltage magnitude measurement

Measurements every 5-30 s
Not synchronized

State Estimation (SE) executed every 1-5 min using asynchronous measurements

Goal of state estimation: Obtain an estimate of the "state" of the system (V and δ at every bus)

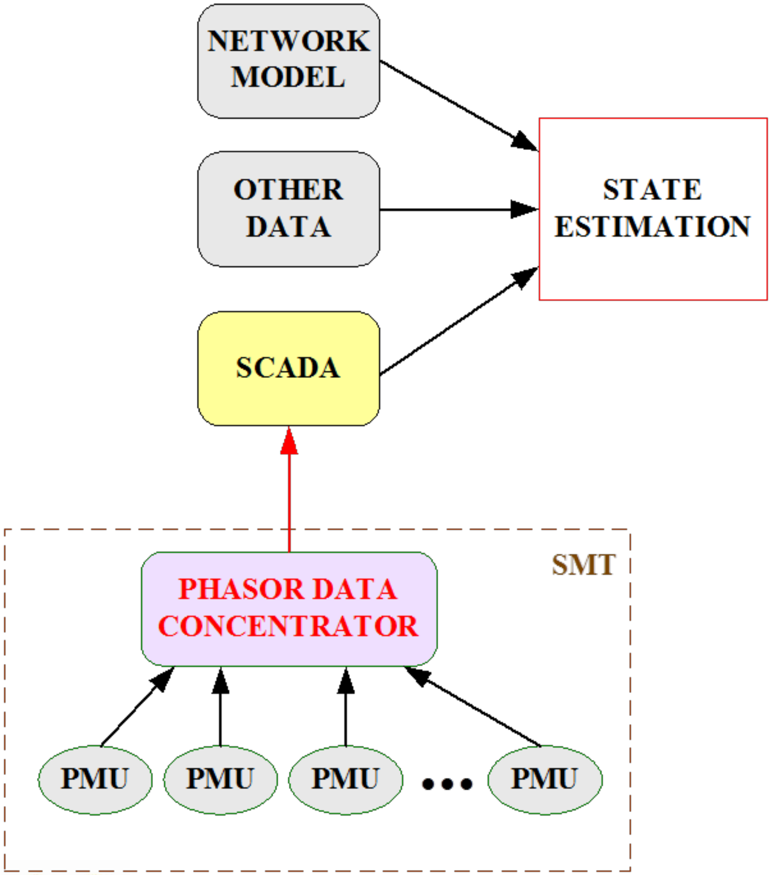
When the state is known, all MW and MVAr flows can be calculated.

SE assumptions:

- **Balanced system**
- **Line parameters perfectly known**
- **No time-skew between measurements**
- **Topology known**

Hybrid State Estimation

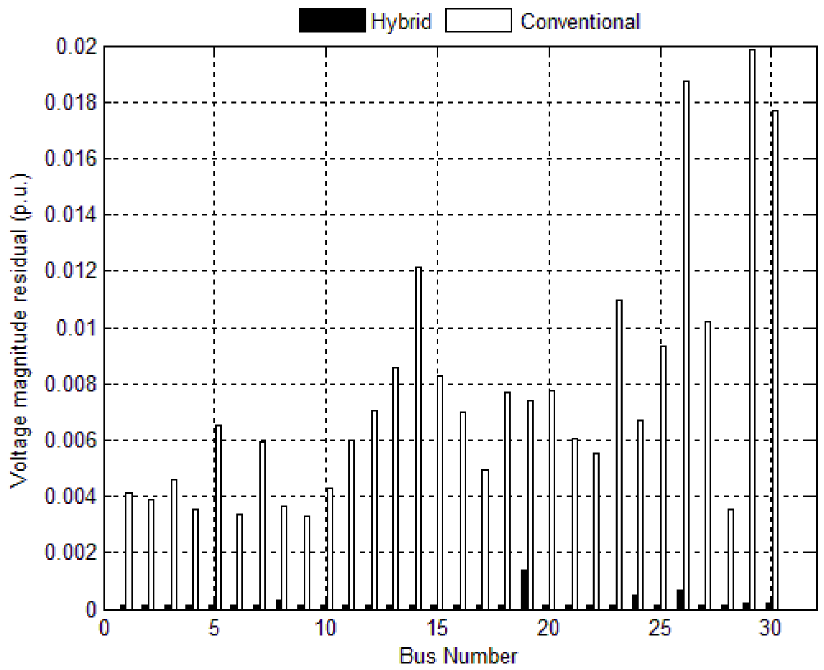
Idea: Take advantage of voltage and current phasor measurements from PMUs
Incorporate these measurements into the existing state estimator
Emergence of a new state estimator: The Hybrid State Estimator

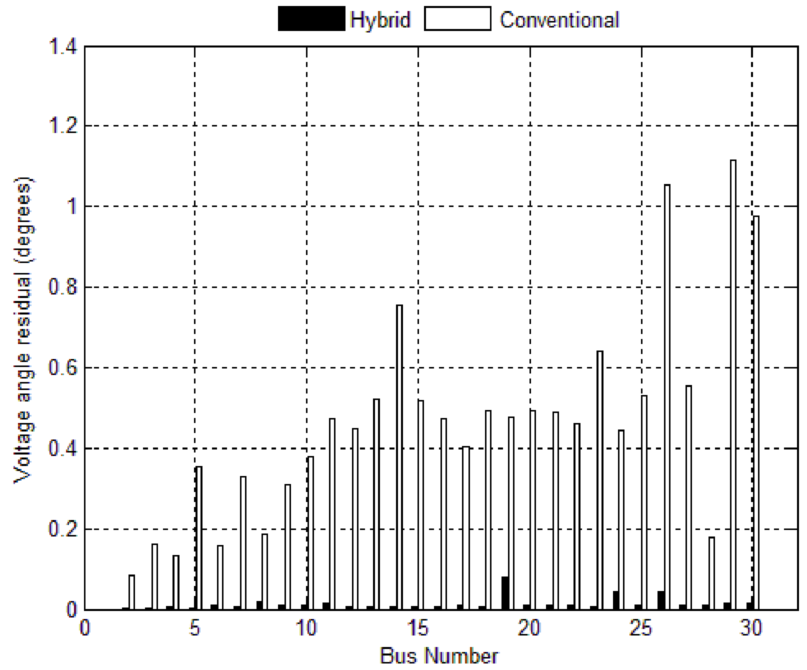


$$z_{hyb} = \begin{bmatrix} P_{flow} \\ P_{inj} \\ Q_{flow} \\ Q_{inj} \\ \theta_{Vpmu} \\ V_{pmu} \\ \theta_{Ipmu} \\ I_{pmu} \end{bmatrix}$$

$$H_{hyb}(x) = \begin{bmatrix} \frac{\partial P_{flow}}{\partial \theta} & \frac{\partial P_{flow}}{\partial V} \\ \frac{\partial P_{inj}}{\partial \theta} & \frac{\partial P_{inj}}{\partial V} \\ \frac{\partial Q_{flow}}{\partial \theta} & \frac{\partial Q_{flow}}{\partial V} \\ \frac{\partial Q_{inj}}{\partial \theta} & \frac{\partial Q_{inj}}{\partial V} \\ \frac{\partial \theta_{Vpmu}}{\partial \theta} & \frac{\partial \theta_{Vpmu}}{\partial V} \\ \frac{\partial V_{pmu}}{\partial \theta} & \frac{\partial V_{pmu}}{\partial V} \\ \frac{\partial \theta_{Ipmu}}{\partial \theta} & \frac{\partial \theta_{Ipmu}}{\partial V} \\ \frac{\partial I_{pmu}}{\partial \theta} & \frac{\partial I_{pmu}}{\partial V} \end{bmatrix}$$

Results - IEEE 30 Bus System





Flow measurements locations (bus # - bus #)	Injection measurements locations (bus #)	PMU locations (bus #)
1-3, 2-6, 2-4, 5-7, 4-6, 6-28, 6-8, 6-9, 6-10, 12-13, 12-15, 16-17, 10-20, 10-17, 14-15, 15-23, 15-18, 25-26, 25-27, 28-27, 29-30	1, 2, 4, 6, 10, 11,12, 15, 18, 19, 24, 25,27, 30	1, 5, 10, 12, 15, 27

Line Parameter Uncertainties

- **Many factors can affect the network parameters in the real field**
  - *The resistance of the transmission line can be affected by the ambient temperature, wind, and resistivity of the soil*
  - *Mutual coupling of parallel transmission lines can affect both the resistance and the reactance of the lines*
  - *Actual connection (e.g., joints and transmission lines that have overhead and underground parts) and the effects of maintenance work*

- **Surveys have shown that the line parameters stored in the electric utilities databases can vary up to 30% from their rated values**

- **Important to investigate how the parameter uncertainties impact the state estimator accuracy**

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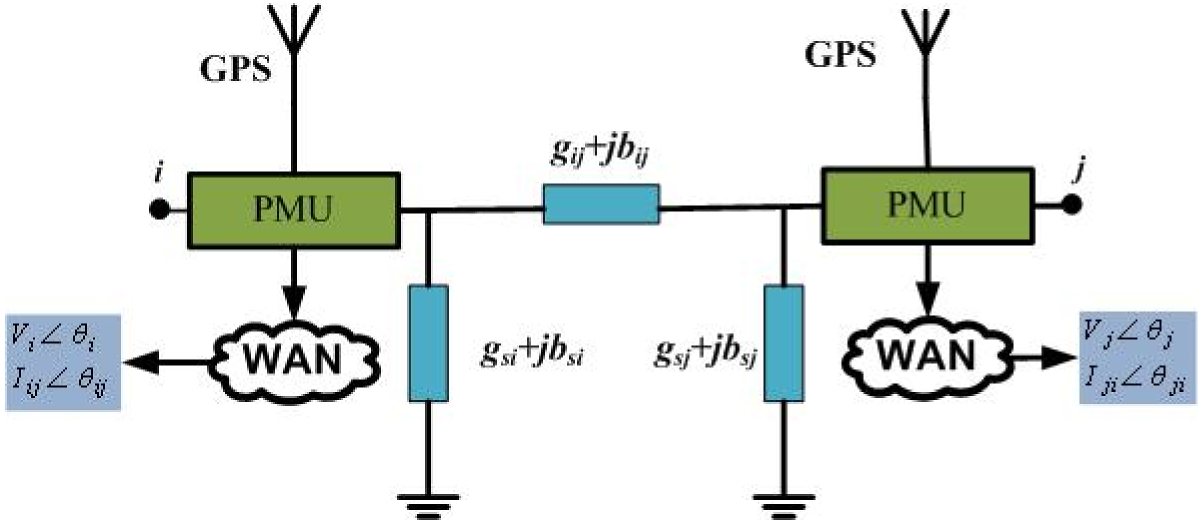
Line Parameter Uncertainties

- **The uncertainty of the line parameters deteriorates the accuracy of the hybrid state estimator more than the measurement uncertainty does.**
- **Important to identify and correct erroneous line parameters (take advantage of synchronized phasor measurements)**
- **With the knowledge of the voltage phasors at the two ends of the line and the line current phasor the line parameters can be calculated.**



* M. Asprou and E. Kyriakides, "Identification and estimation of erroneous transmission line parameters using PMU measurements," IEEE Transactions on Power Delivery, vol. 32, no. 6, pp. 2510-2519, Dec. 2017.

The Effect of Instrument Transformers

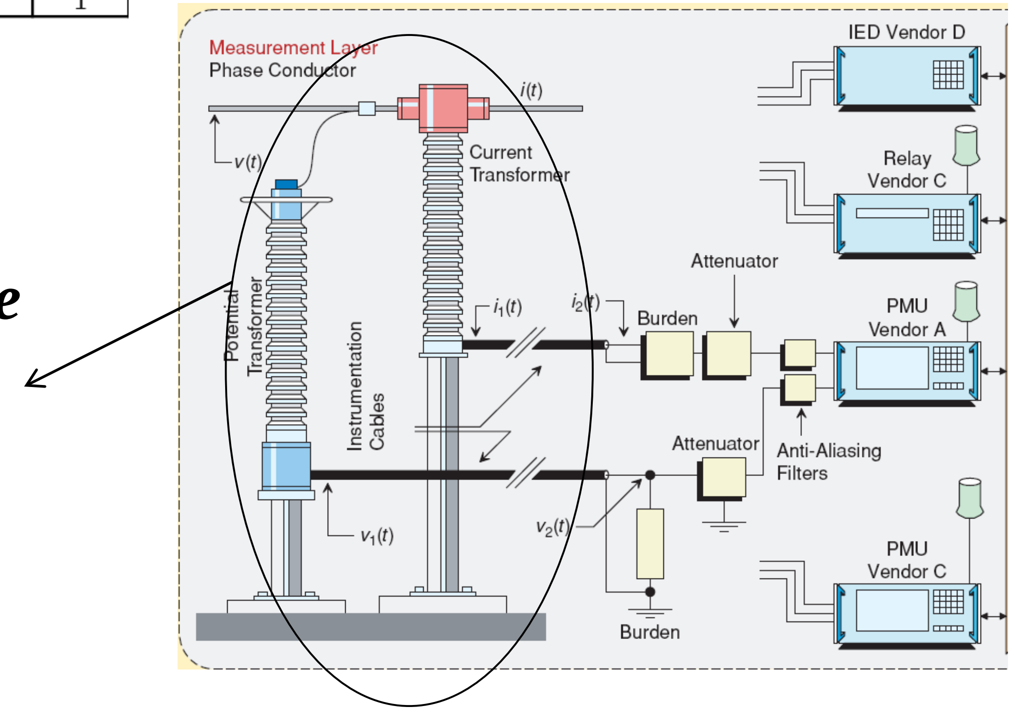
Current transformer maximum errors

Accuracy class	± Percentage of current error at percentage of rated current					± Phase displacement at percentage of rated current (degrees)				
	1	5	20	100	120	1	5	20	100	120
0.1	-	0.4	0.2	0.1	0.1	-	0.25	0.133	0.083	0.083
0.2S	**0.75**	**0.35**	**0.2**	**0.2**	**0.2**	**0.5**	**0.25**	**0.167**	**0.167**	**0.167**
0.2	-	0.75	0.35	0.2	0.2	-	0.5	0.25	0.167	0.167
0.5S	1.5	0.75	0.5	0.5	0.5	1.5	0.75	0.5	0.5	0.5
0.5	**-**	**1.5**	**0.75**	**0.5**	**0.5**	**-**	**1.5**	**0.75**	**0.5**	**0.5**
1	-	3	1.5	1	1	-	3	1.5	1	1

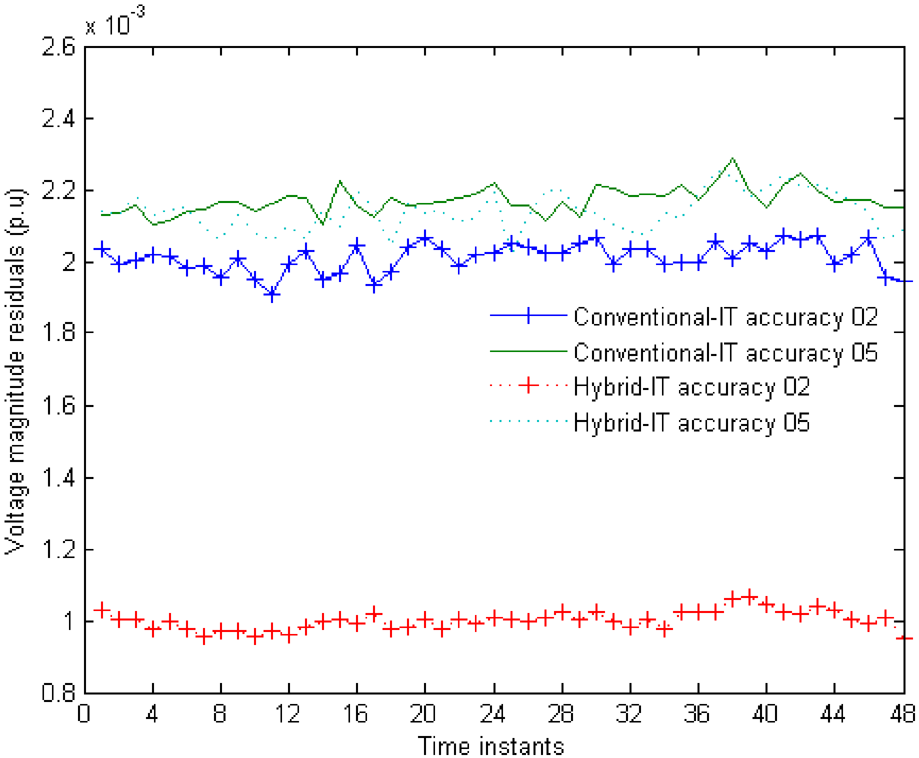
Voltage transformer maximum errors

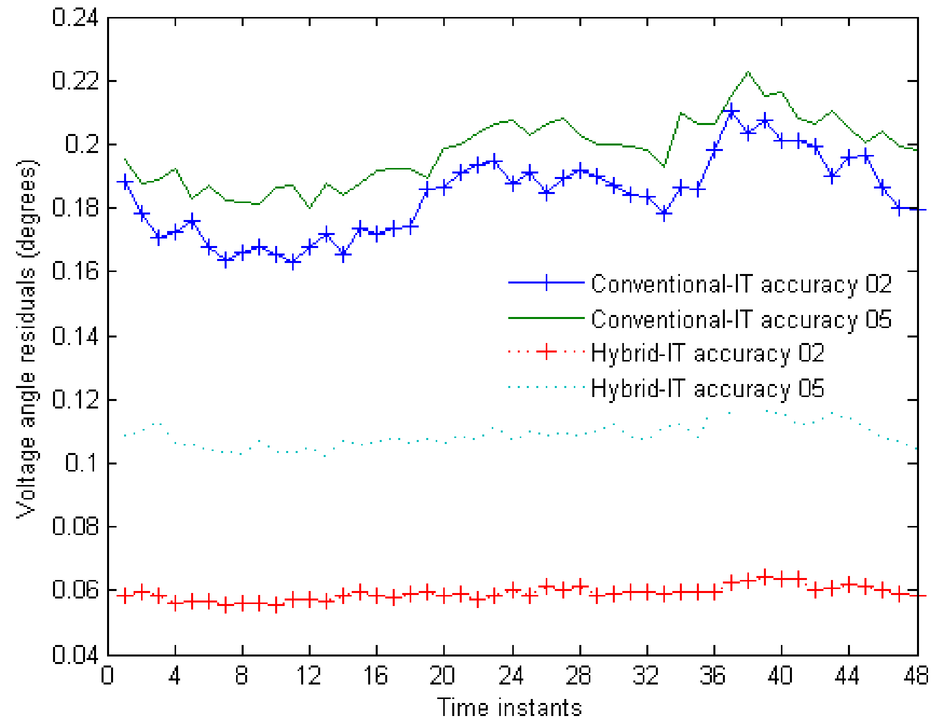
Accuracy class	± Percentage of voltage magnitude error	phase displacement (degrees)
0.2S	**0.2**	**0.167**
0.5	**0.5**	**0.333**
1	1	0.667

Does the accuracy of ITs impact the accuracy provided by the PMU?



Case Studies: The Effect of IT Accuracy Class





The instrument transformer accuracy class impacts only the hybrid state estimator accuracy

***M. Asprou, E. Kyriakides, and M. Albu, "The effect of instrument transformer accuracy class on the WLS state estimator accuracy," IEEE Power and Energy Society General Meeting, Vancouver, Canada, pp. 1-5, July 2013 (Best paper award).**

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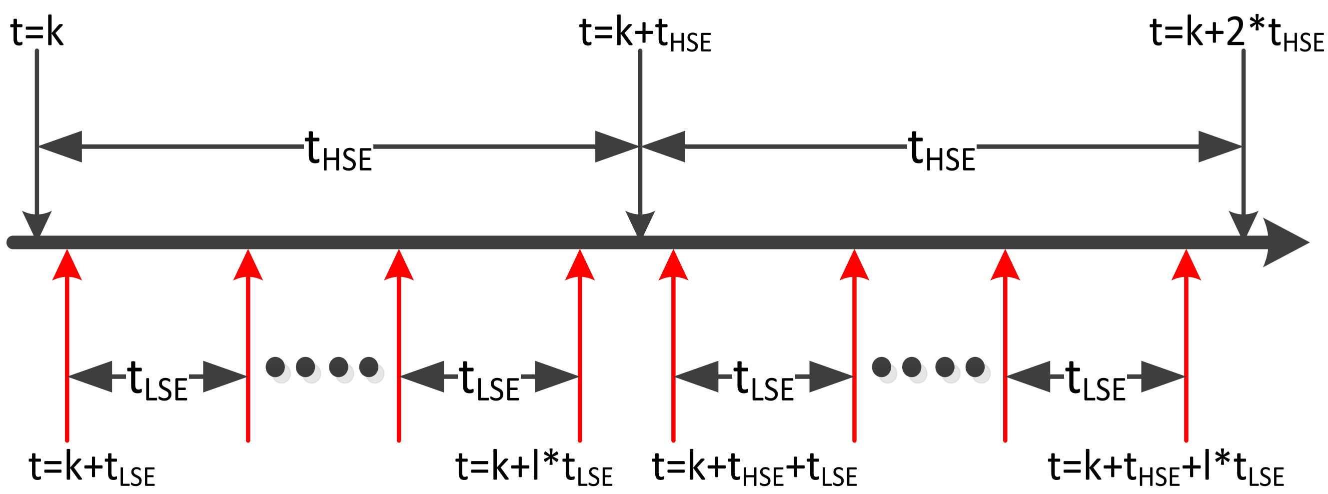
Towards Real Time Monitoring…

- **Tracking the transients is of paramount importance for the power system operators, both for real time actions, as well as for post-mortem analysis.**
- **Electric utilities use fault recorders (mainly at the generator terminals) to track the transients. However, they cannot provide a wide area picture of the power system operating condition.**

A Two-Stage State Estimator



Stage 1:

Execute a hybrid state estimation (both conventional and synchronized measurements).

Stage 2:

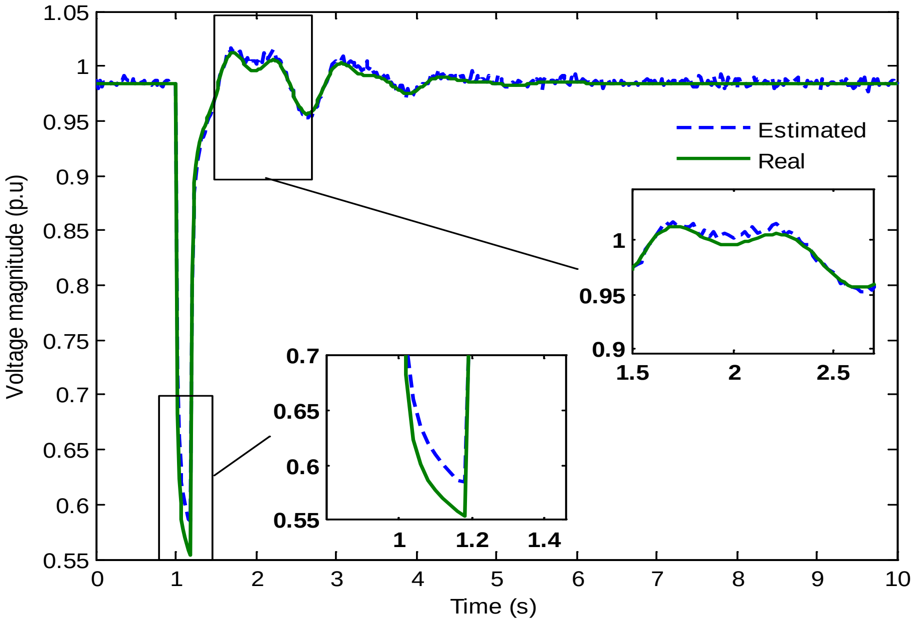
Execute a number of consecutive linear state estimations (use synchronized measurements and pseudomeasurements created using the previously estimated states)

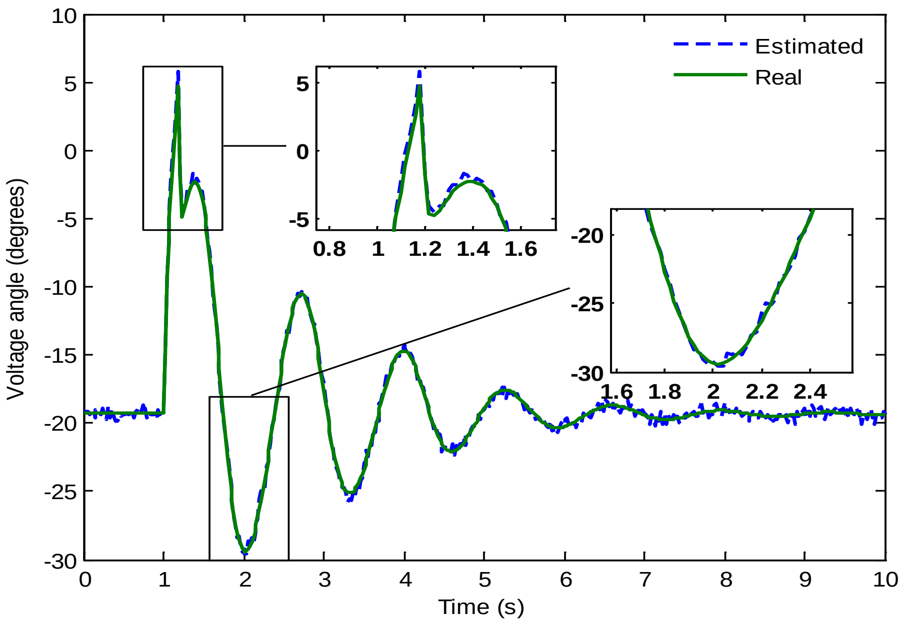
Dynamic Monitoring - Results

IEEE 118 bus system

22 PMUs installed – 32 required for full observability

Bus 14 has the largest average estimation error





* M. Asprou, S. Chakrabarti, and E. Kyriakides, "A two-stage state estimator for dynamic monitoring of power systems," IEEE Systems Journal, vol. 11, no. 3, pp. 1767-1776, Sep. 2017.

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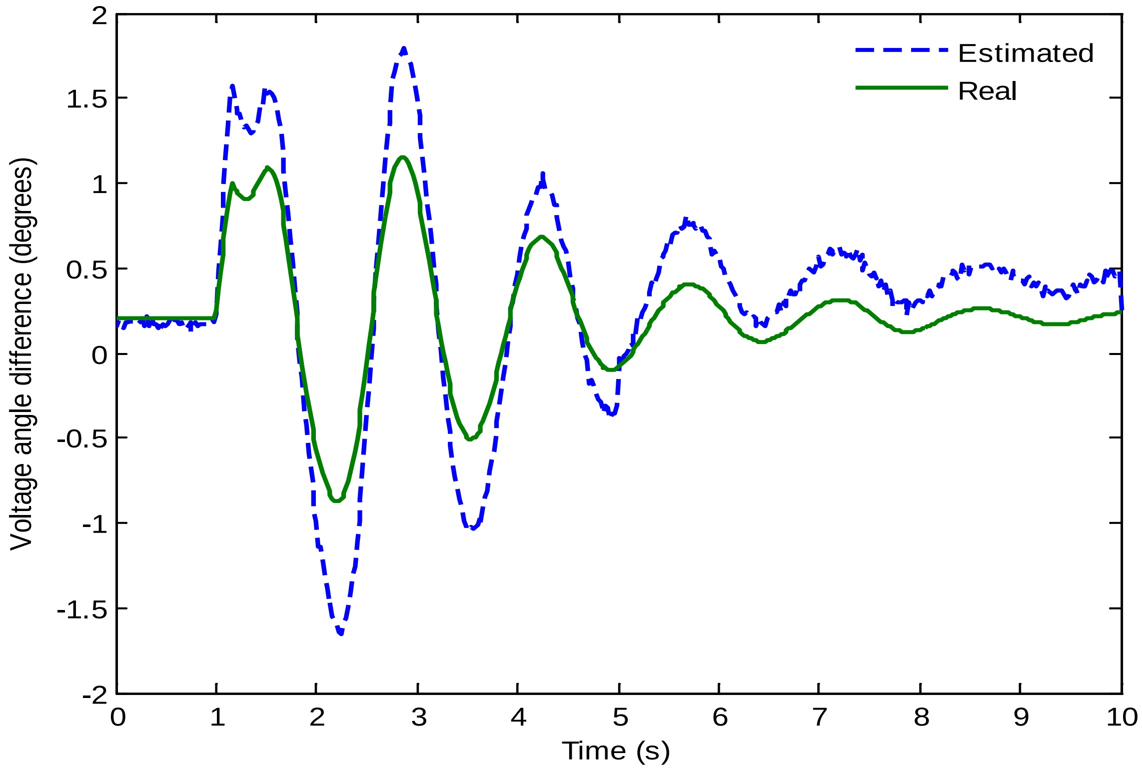
Dynamic Monitoring - Results

The tracking of the angle difference between two buses is extremely important for stability monitoring.

Voltage angle difference between buses 96 and 87



Grid Integration of Renewable Energy

- **Control of power electronic inverters**
- **Storage technologies**

The PV2Grid Project

A next generation grid side converter with advanced control and power quality capabilities

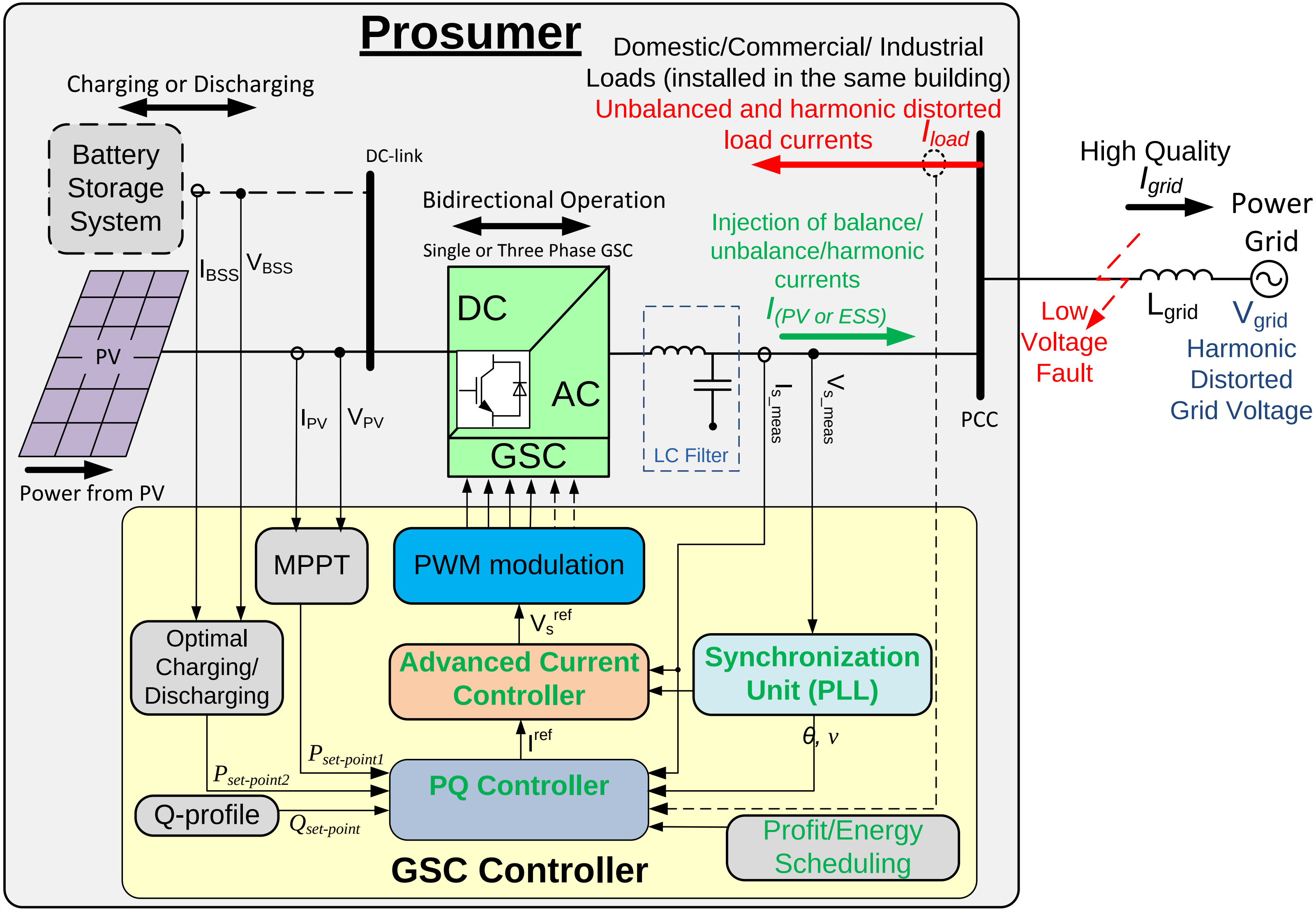
- ➢ **KIOS Research Center – University of Cyprus (Coordinator)**
- ➢ **Department of Energy Technology - Aalborg University**

- ✓ **This project aims to advance the technology related to the seamless grid integration of photovoltaic (PV) systems.**
- ✓ **Development of next generation power electronic Grid Side Converters (GSC) with advanced capabilities and innovative operational management approaches.**

The PV2Grid Project – Objectives

- **Design and develop new generation Grid Side Converters (GSCs) equipped with advanced control capabilities and novel operational mode approaches:**
  - ✓ **providing support to the grid when needed**
  - ✓ **enhancing the power system stability**
  - ✓ **improving the power quality of the grid**
  - ✓ **reducing the network losses**
- **Design new current controllers: inject positive, negative (in case of three-phase GSCs) and harmonic-free currents under normal or abnormal voltage conditions.**
- **Develop experimental prototypes of GSCs including the current control techniques and the PQ controllers.**

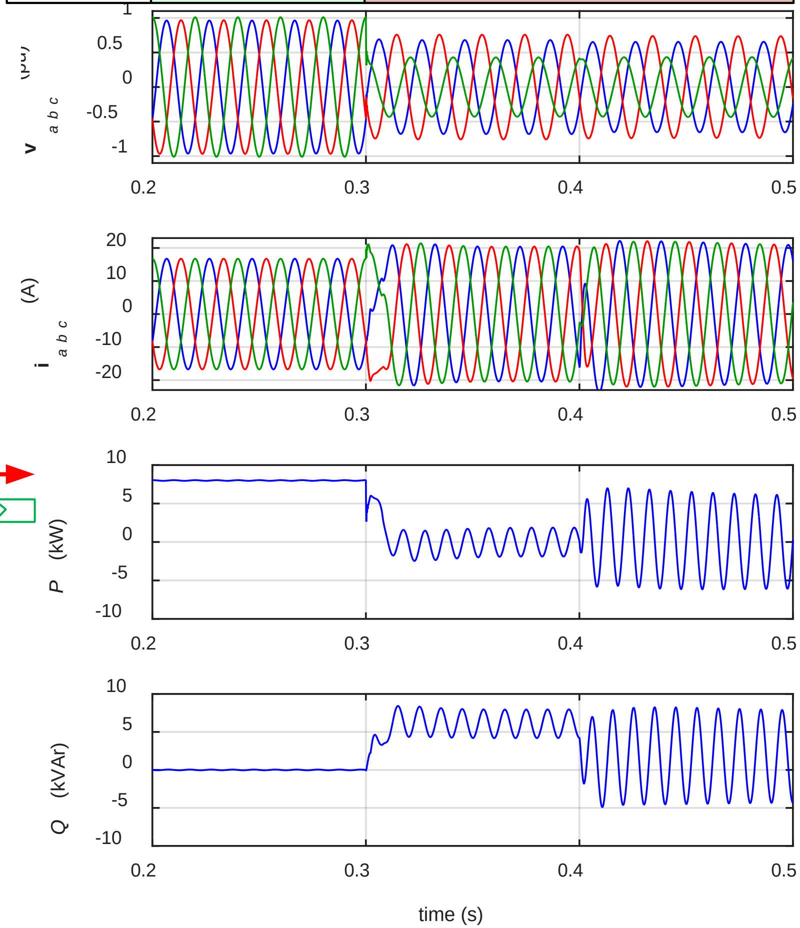
Architecture of the Proposed GSC

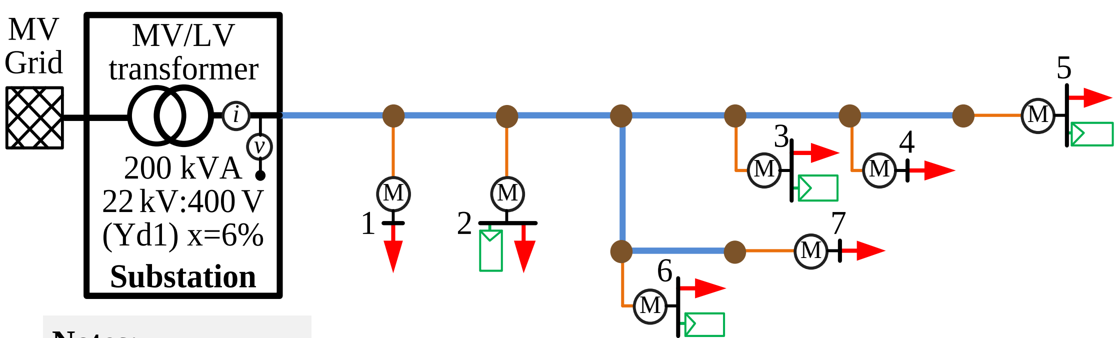


FRT operation of residential PVs

- **Provide both positive and negative sequence FRT support**
- **Investigate effect on a realistic LV distribution grid**

GSC	Normal Operation (P=8 kW, Q=0 kVAr)	**FRT** with **positive** sequence injection	**FRT** with **negative** sequence injection
Grid Conditions	Normal Voltage Conditions	Unbalanced Grid Fault (Type F)	





Notes:

4x100 mm^2 OH Aluminum line (Wasp)

(2 or 4)x22 mm^2 OH Aluminum line (Midge)

10 m wooden poles

Consumer's Meter

Consumer's Load

Consumer's PV

ENHANCE

The ENHANCE project

Enhanced rooftop PV integration through kinetic storage and wide area monitoring

Partnering with Chakratec Ltd and PowerCom Ltd in Israel

Funded by:

- **Research Promotion Foundation of Cyprus (RPF, Cyprus)**
- **Ministry of National Infrastructures, Energy and Water Resources (Israel)**
- **SOLAR-ERA.NET (EU-FP7)**

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SEVENTH FRAMEWORK PROGRAMME

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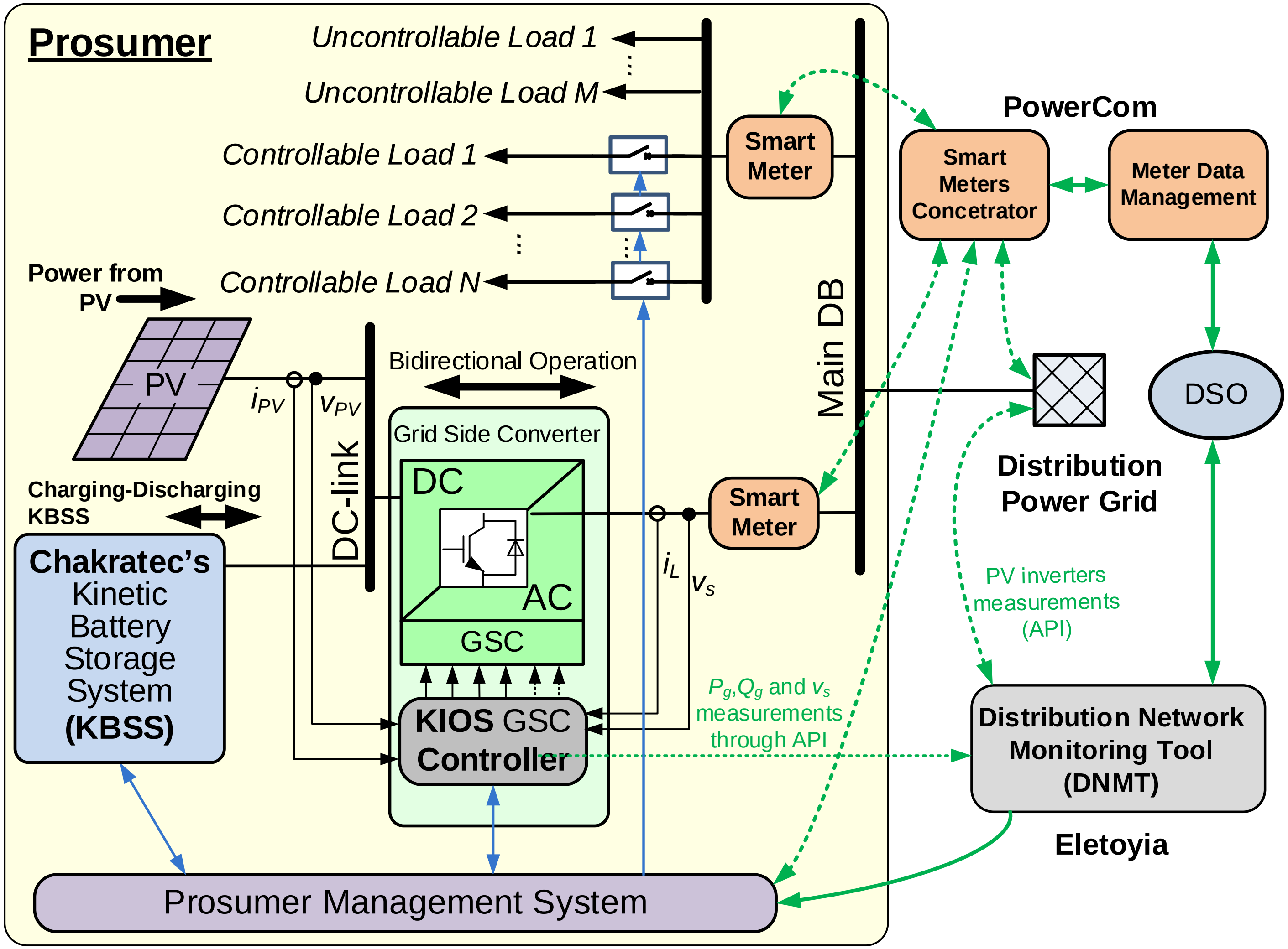
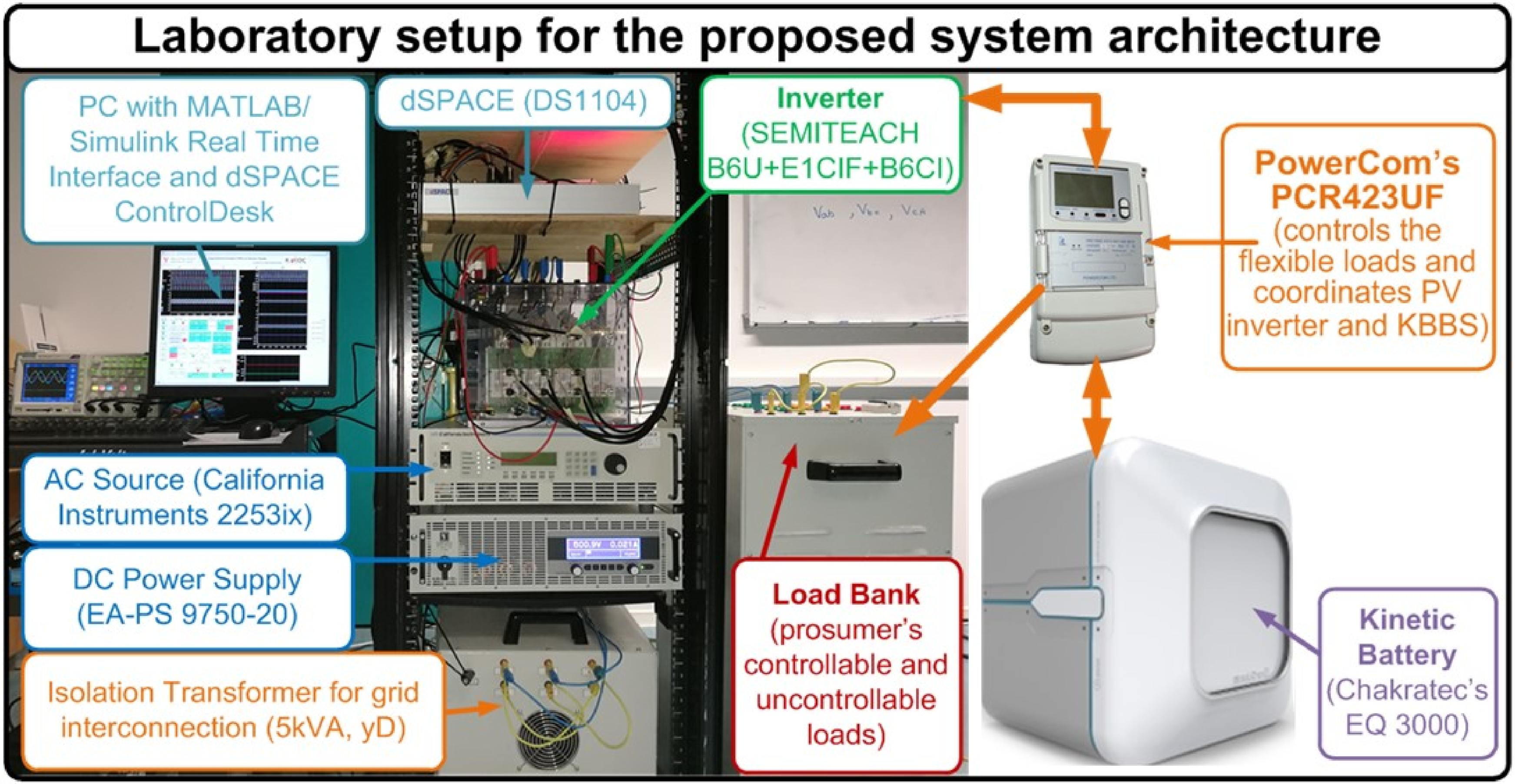
Development of a novel PV system architecture



Prototype development and pilot testing

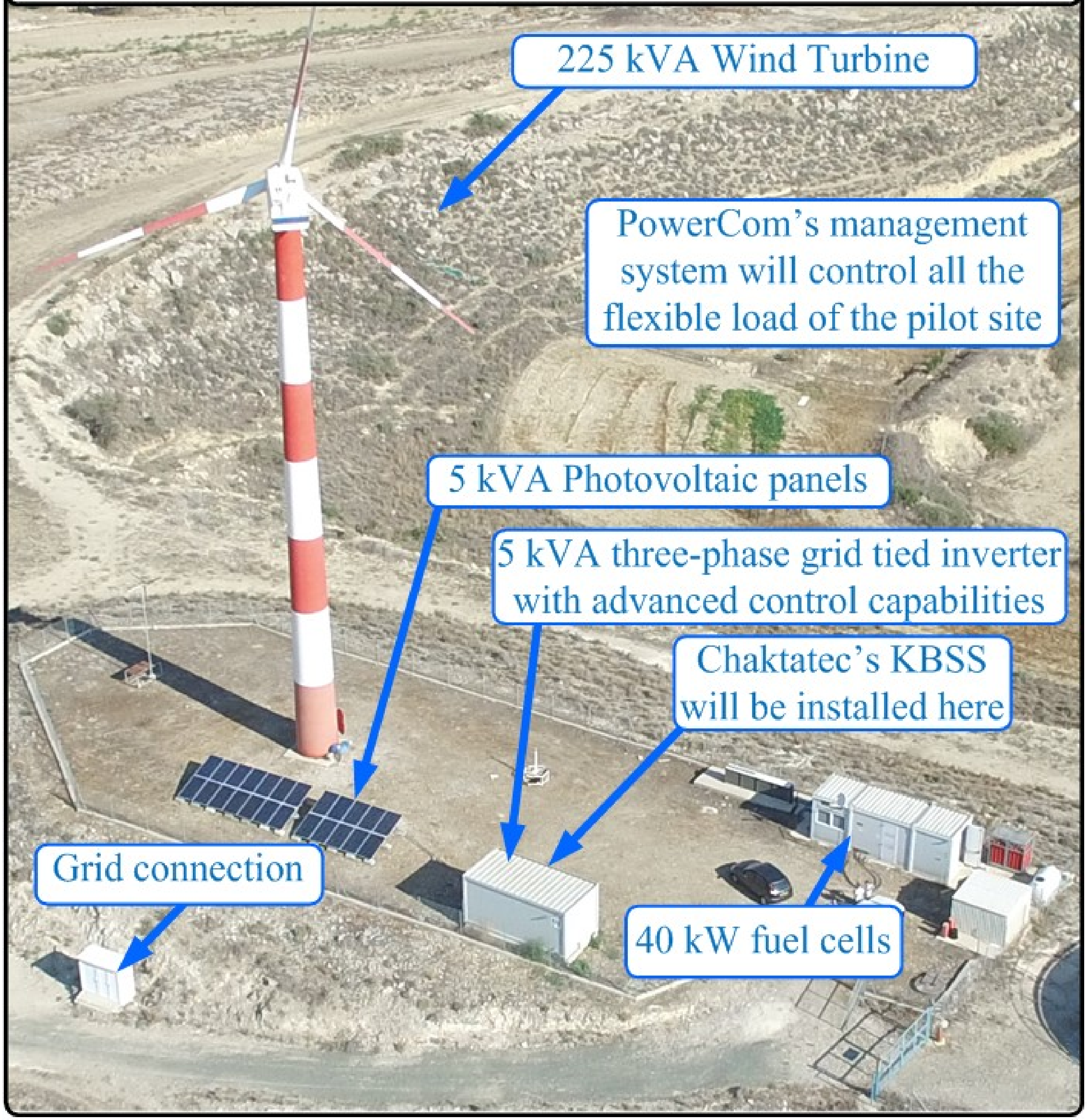
All concepts and methodologies will be tested and validated in both laboratory and grid-connected conditions



Prototype development and pilot testing

Prototype development and pilot testing

Pilot site setup



Inverter-less connection of PVs to the grid

- **Perform the dc/ac conversion through a set of interconnected electrical machines and a custom-made patented controller => Avoid the use of conventional inverters for the dc/ac conversion (expensive, harmonics).**
- **Ability to fully control active and reactive power injection.**
- **Provision of inertia to the grid – extremely important for isolated networks.**
- **Can compensate for the variability of the dc source.**

Empowering the Cyprus Power System with Sustainable and Intelligent Technologies

The consortium of EMPOWER covers the *quadruple helix* of the Cyprus economy

Research Centers and Higher Academic Institutions

University of Cyprus

KOIOS – Research and Innovation Center of Excellence

Enterprises

Electricity Authority of Cyprus

Deloitte.

PHOEBE RESEARCH & INNOVATION

Aeolian-Dynamics

EMPOWER

Public/User organizations and non-profit organizations

OEB

Cyprus Energy Agency

Public entities

MINISTRY OF ENERGY COMMERCE INDUSTRY AND TOURISM

ΔΣΜΚ – Διαχειριστής Συστήματος Μεταφοράς Κύπρου – Transmission System Operator - Cyprus

ρυθμιστική αρχή ενέργειας κύπρου – cyprus energy regulatory authority

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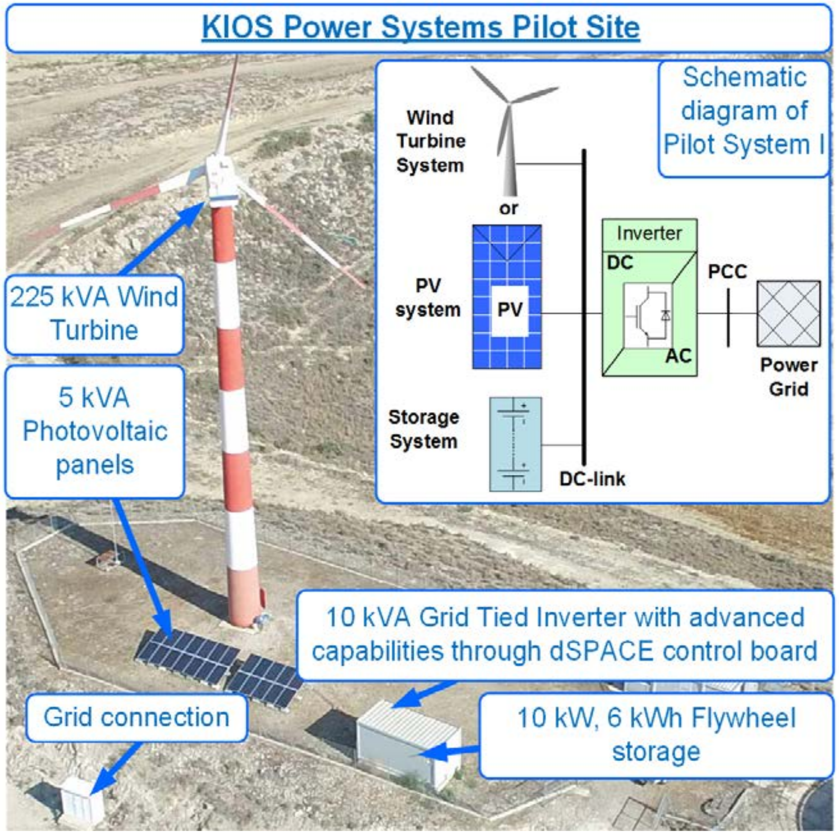
Objectives

1. Deploy at least 15 Phasor Measurement Units (PMUs) in the Cyprus power system to achieve full observability
2. Develop and evaluate a dynamic state estimator for real-time (every 20 ms) and accurate monitoring of the Cyprus power system
3. Design a wide area controller for the Cyprus system for the reduction of the power system oscillations
4. Increase the accuracy of the dynamic models by 15%, to achieve a precise determination of the power system stability margins
5. Extend the maximum allowable installed capacity of RES in the energy mix of Cyprus by 20% through the incorporation of different storage solutions

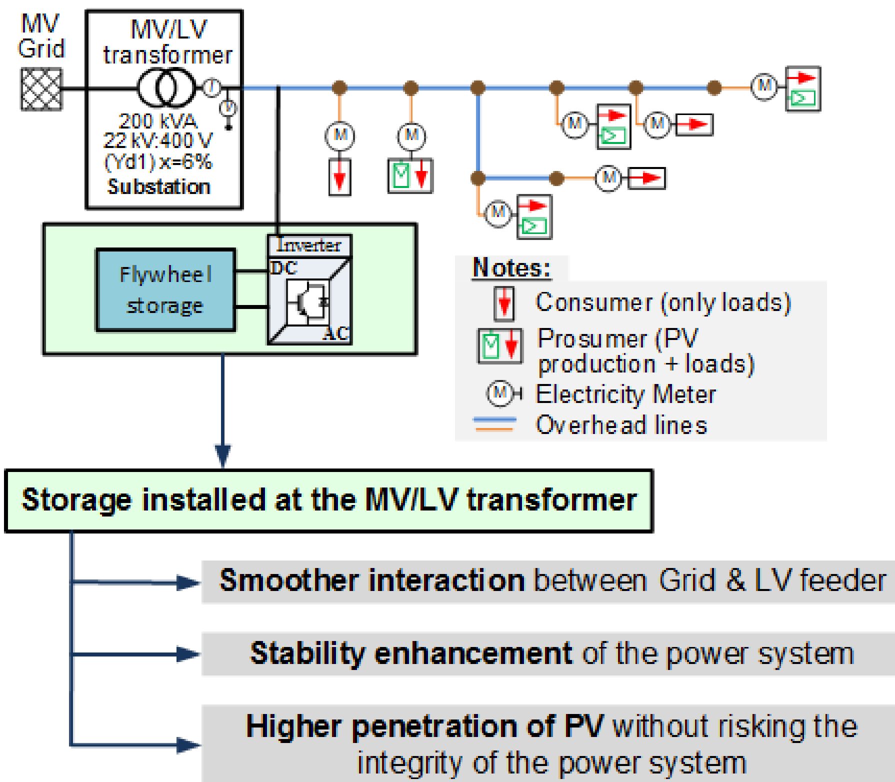
Pilot System I: Large scale storage for RES



Storage solution (battery and/or flywheel) combined with a hybrid wind/PV system

- ✓ **Higher penetration of RES**
- ✓ **Smoother power exchange/interaction between RES and grid**
- ✓ **RES support to power system under grid disturbances (by providing both active and reactive power)**

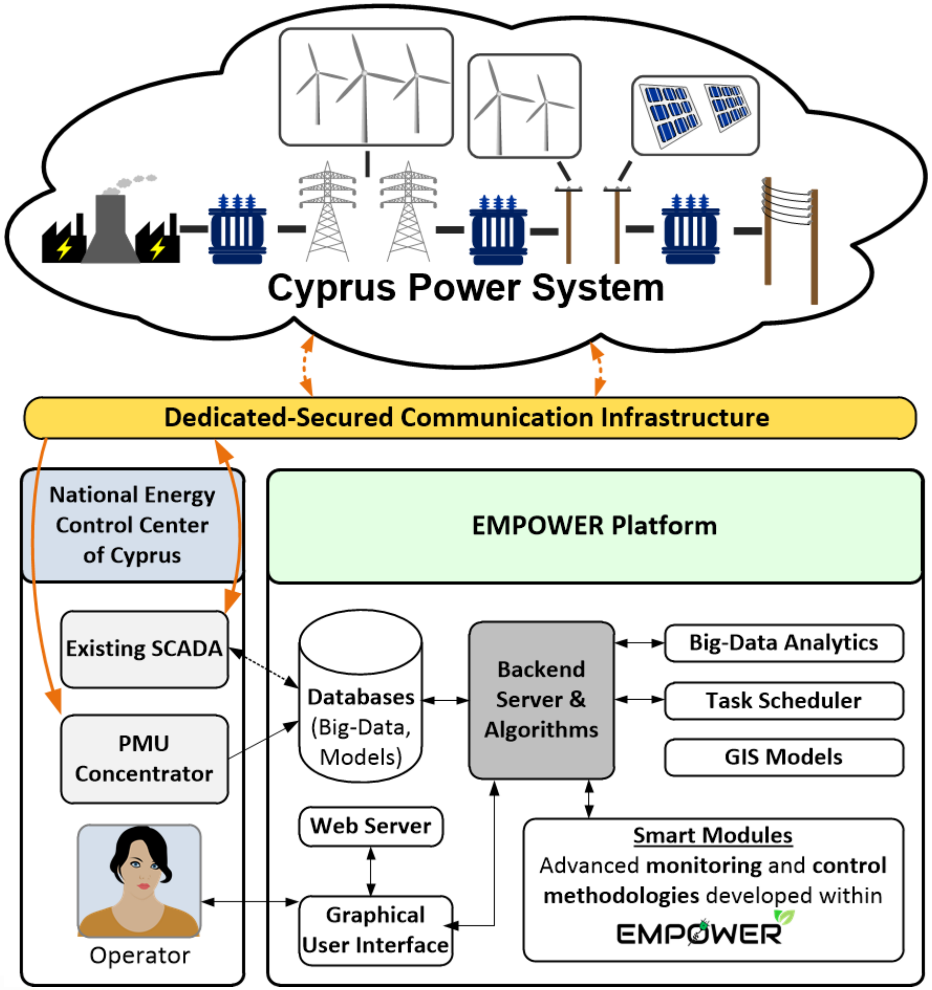
Pilot System II: Cost-effective storage at distribution substation for supporting residential PVs



Cost-effective storage unit at a MV/LV substation for considering all the PVs installed within the specific LV feeder

- ✓ **Mitigate the aggregate impact of all the installed rooftop PVs within the LV feeder (reverse power flows, voltage drops)**
- ✓ **Support the grid when faults occur**

Pilot System III: Deploy and test the EMPOWER platform



- Installation of the software tool at the National Energy Control Center of Cyprus
- Connection with the databases of the Control Center and the Open Platform Communication (OPC)
- Testing phase (quantitative and qualitative feedback by the operators)
- Correction of any inconsistencies with the initial design requirements

Limassol, Cyprus

ENERGYCON 2018

IEEE International Energy Conference

3 - 7 June, 2018

Towards Self-healing, Resilient and Green Electric Power and Energy Systems

Contact: elias@ucy.ac.cy **http://www.kios.ucy.ac.cy**

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