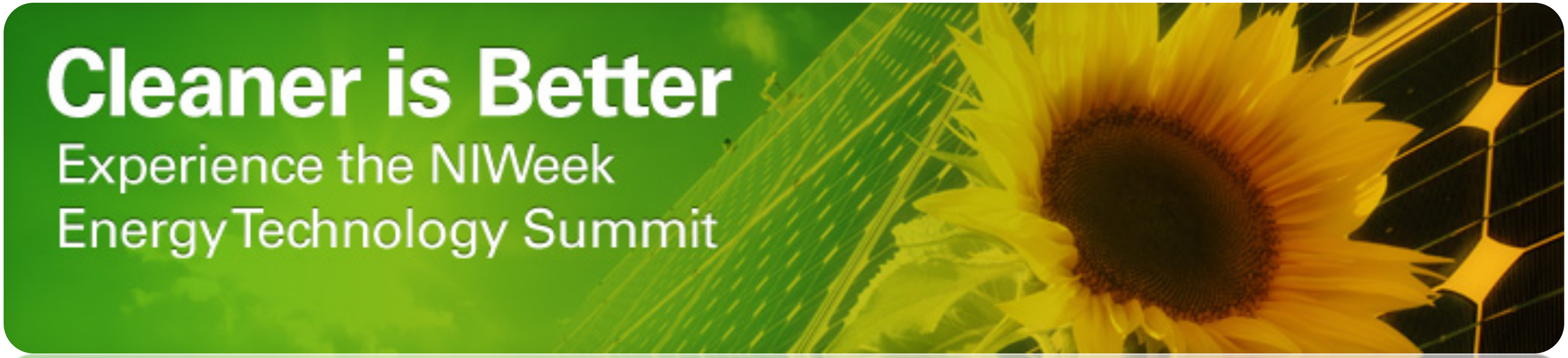
NIWeek Energy Technology Summit

Designing the Smart Grid

August 2–3, 2011 Austin, Texas



Developing PMU Technology for Dynamic Conditions in Distribution

- NI Tools for PMUs
  - Jack Arnold, NI
- PMU Algorithm for Distribution
  - Mario Paolone, EPFL
- Creating PQA and PMU Devices
  - Daniel Kaminsky, ELCOM

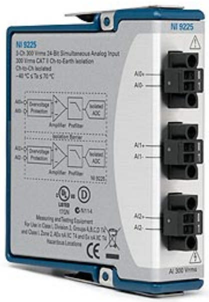
NI PMU Tools

Jack Arnold
Sr. Systems Engineer

Measuring Voltage

NI 9225:

300 Vrms



NI 9239:

+/-10 Vpk

Voltage

Measuring Current

NI 9227:

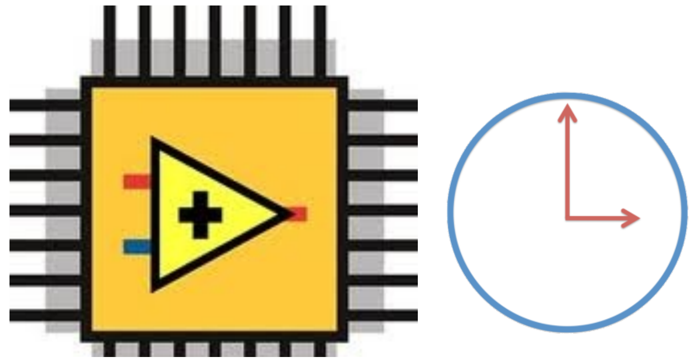
5 Arms

Current or Voltage

NI 9239:

+/-10 Vpk

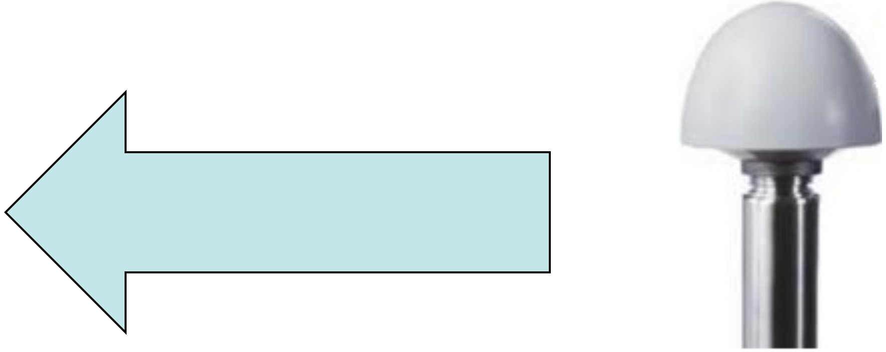
Distributed Time Keeping Tools



FPGA Timekeeper - NILabs

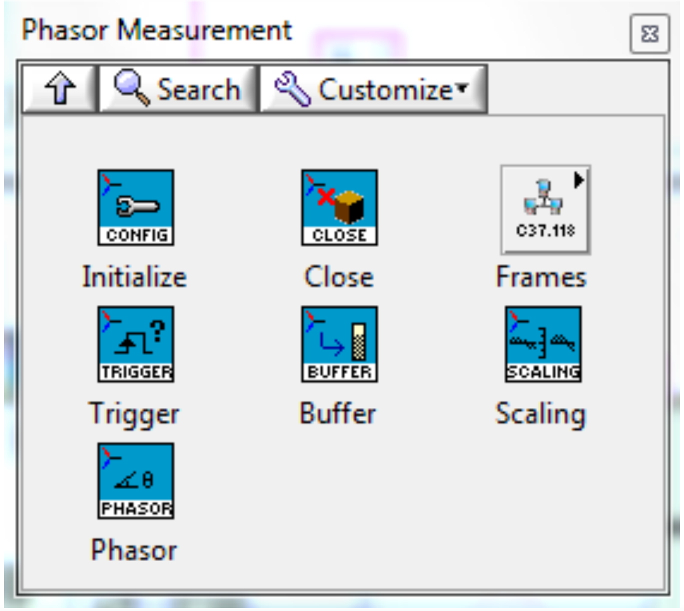
NI GPS

(Q4 2011)

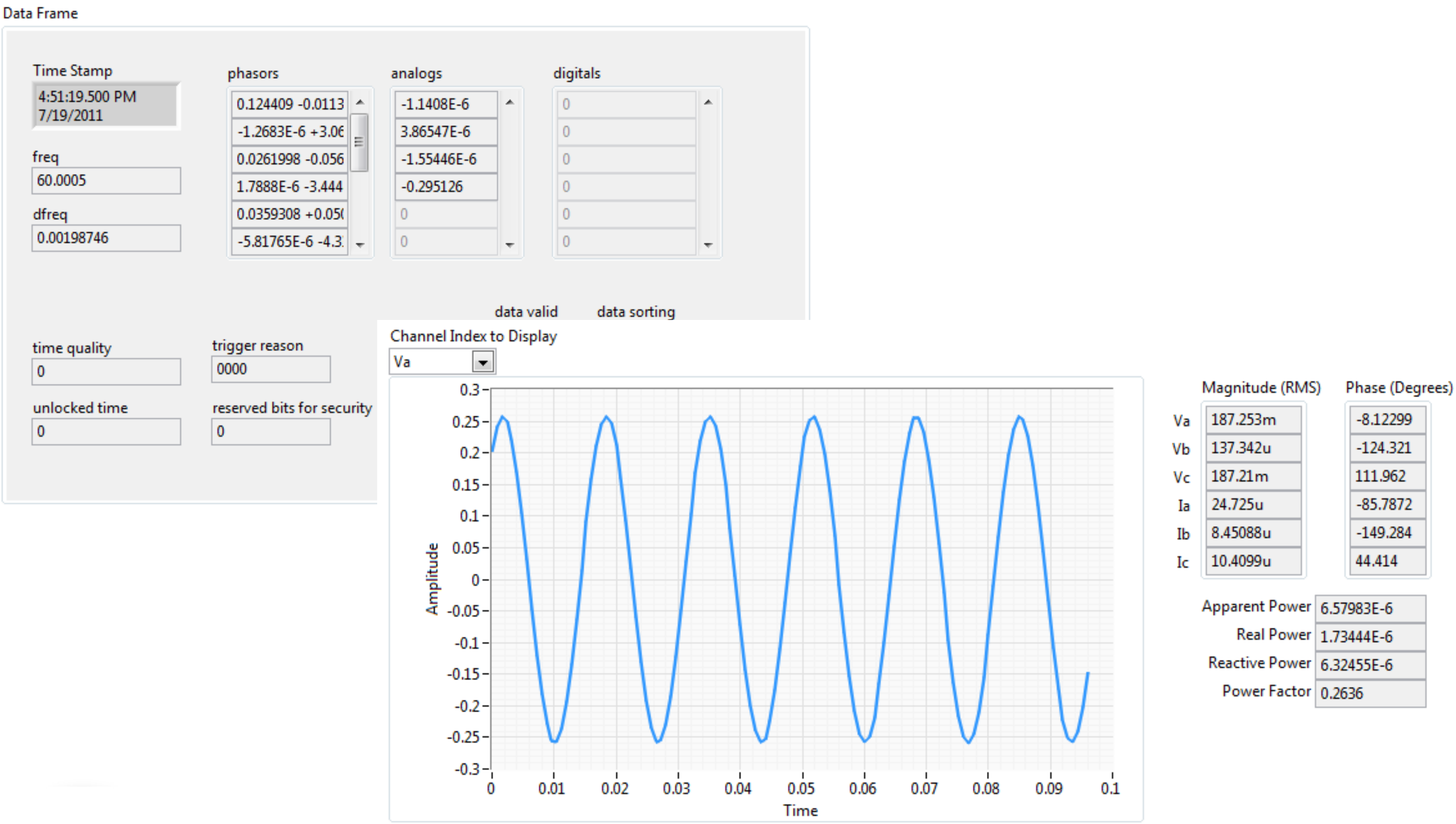


Phasor Measurement Unit (PMU) Toolkit

- IEEE C37.118.1 and C37.118.2
  - Measurement accuracy requirements
  - Communications protocol



Putting it all together



NI week 2011
Austin Tx, USA
Aug. 2-6, 2011

Developing PMU Technology for Dynamic Conditions in Distribution Power Networks

Mario Paolone
Swiss Federal Institute of Technology of Lausanne, Switzerland

Carlo Alberto Nucci
Power Systems Laboratory – University of Bologna, Italy

Outline

- Introduction
- PMU requirements for power distribution network applications
- Proposed algorithm for the synchrophasor estimation
- PMU prototype based on the NI Compact Rio
- Application examples and experimental activities
- Conclusions

Introduction

Evolution of distribution networks **passive** → **active**

- major changes in their operational procedures;
- main involved aspects is the network monitoring;
- massive use of advanced and smarter monitoring tools that result into faster and reliable real-time state estimation;
- distributed measurement of synchrophasors based on the use of phasor measurement units (PMUs).

PMU requirements for power distribution network applications

In transmission networks WAMS are typically based on the measurements of bus voltages synchrophasors realized by means of Remote Terminal Units typically synchronized by means of the Universal Time Code – Global Positioning System.

Peculiar characteristics of distribution networks

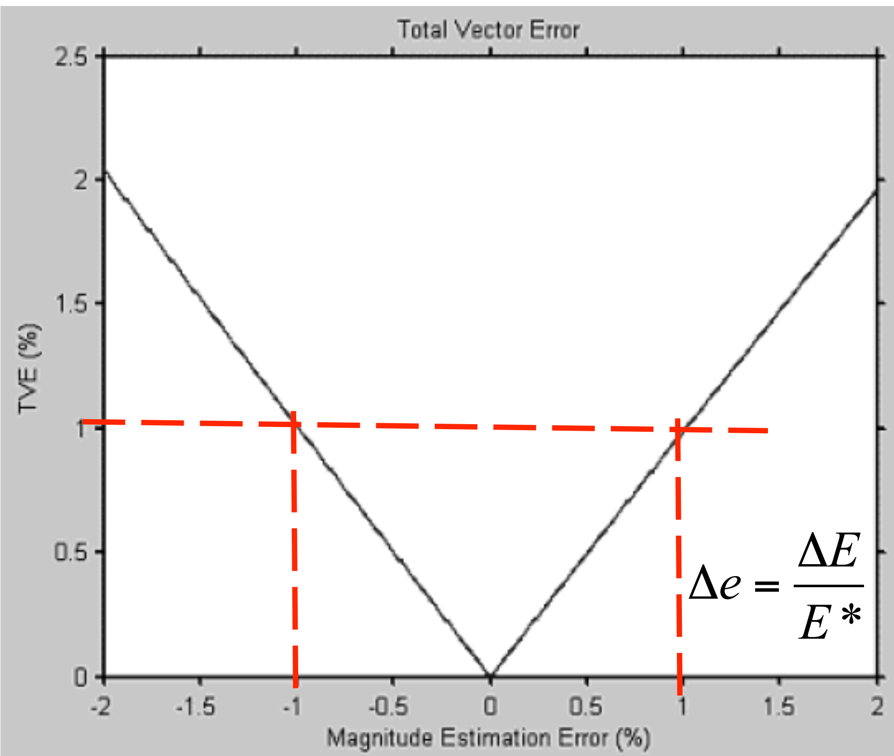
- high feeder impedances;
- low power flows values;
- high harmonic distortion levels.

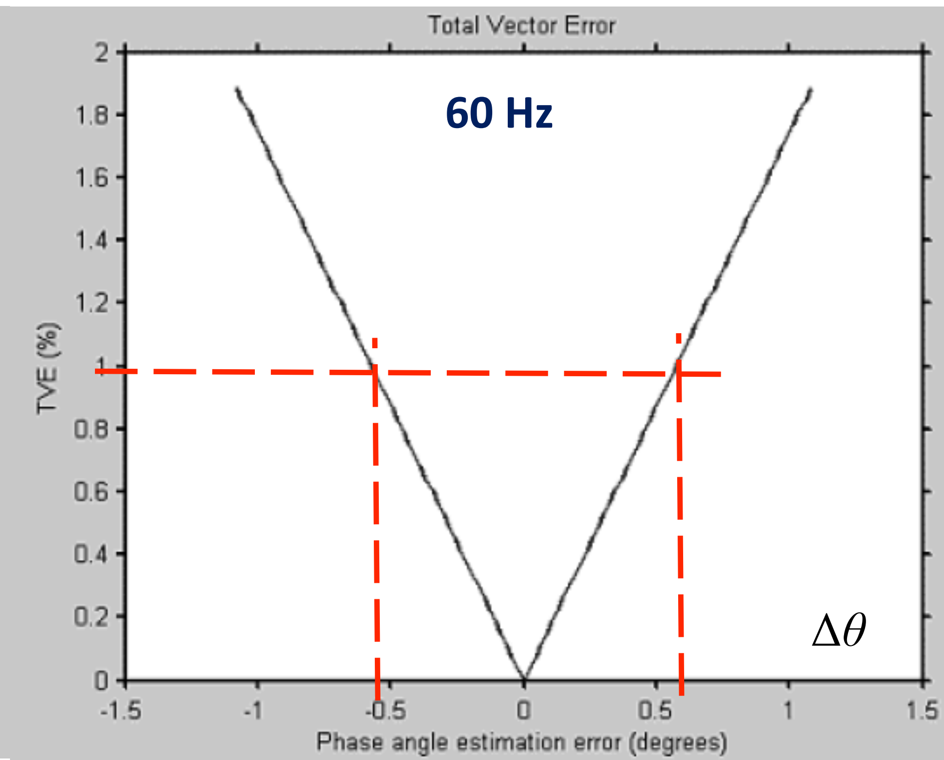
Improved accuracy of synchrophasors measurements

PMU requirements for power distribution network applications

$$TVE = \sqrt{\frac{\left(X_r(n) - X_r\right)^2 + \left(X_i(n) - X_i\right)^2}{X_r^2 + X_i^2}}$$

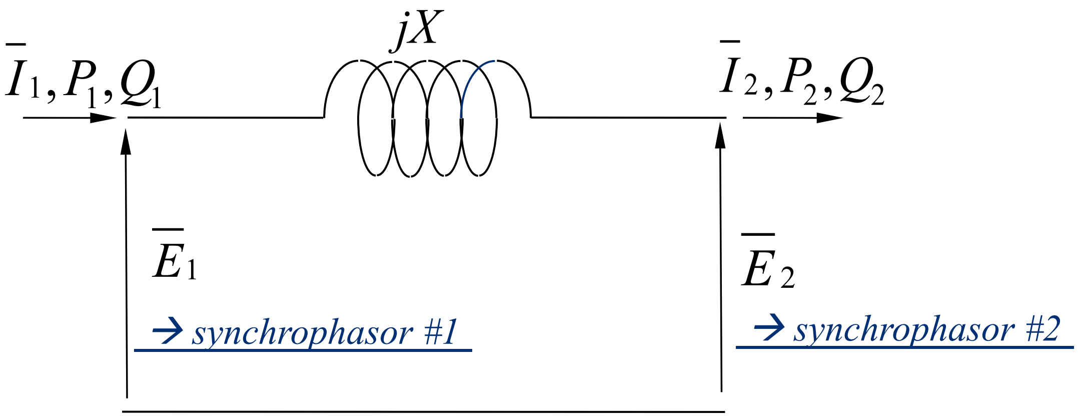
Total Vector Error (TVE) (**): magnitude of the difference between the theoretically true phasor and the estimated one, in per unit of the true phasor magnitude.





(**) IEEE Standard for Synchrophasors for Power Systems, IEEE Std. C37.118, 2005

PMU requirements for power distribution network applications



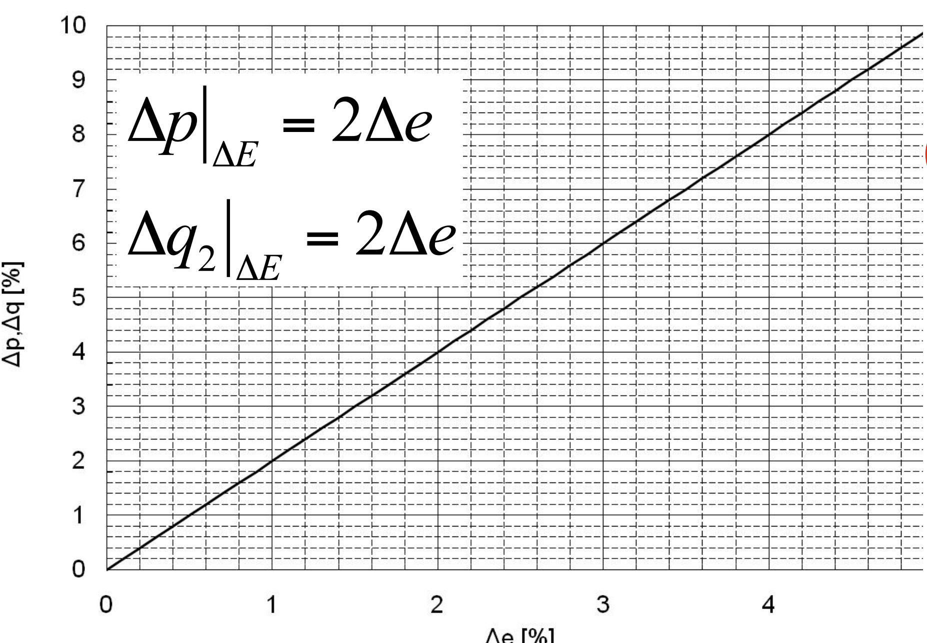
Estimated phasor errors:

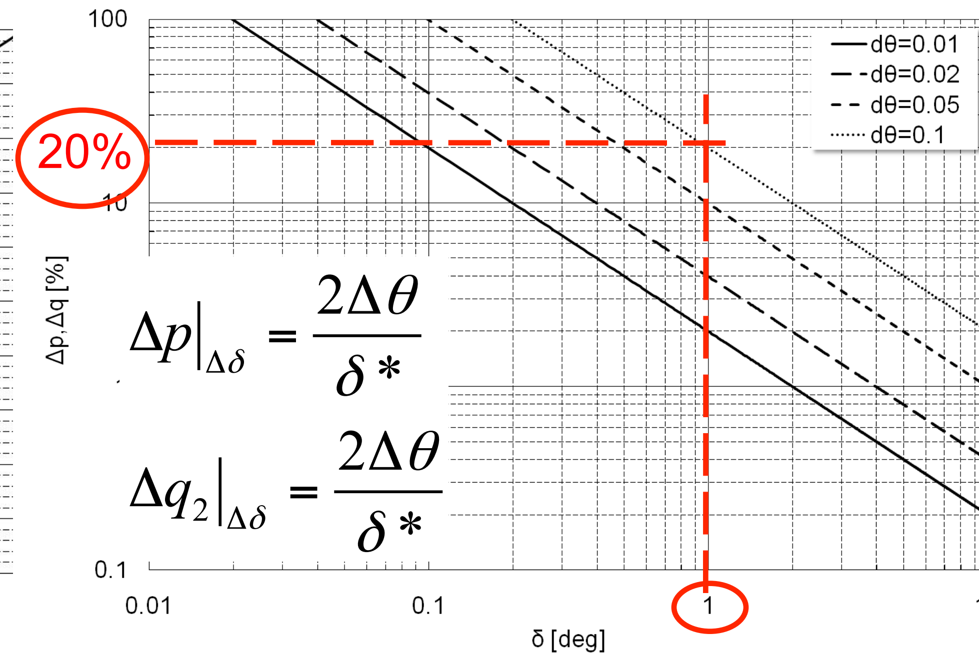
RMS: ΔE

phase: $\Delta\theta$

phase angle difference between phasors $\overline{E}_1, \overline{E}_2 : \delta$

→ $\Delta\delta = 2 \cdot \Delta\theta$





Proposed algorithm for the synchrophasor estimation

Structure of the developed algorithm for the synchrophasor estimation

I. sampling of the waveforms (voltage/current), within a sliding-time window T (e.g. 80 ms, i.e. 4 cycles at 50 Hz), starting in correspondence of the trigger signal wave-front.

II. Identification of the fundamental frequency tone within a specific frequency window Δf (i.e. $f_0 \pm \Delta f$).

III. Reconstruction in time-domain of the identified fundamental frequency tone and improved estimation of the dynamic phasor amplitude, phase and frequency.

Proposed algorithm for the synchrophasor estimation

Input signal:

$$s(t) = \tilde{s} + \sum_{h=1}^{n} s_h \cos(h\omega_0 t + \varphi_h) + \varepsilon_t,\ \tilde{s} = DC\left[s(t)\right]_{t\in[0,T]},\ \varepsilon_t = Gaussian\ noise$$

Discrete Fourier Transform

$$G(k\Delta f) = \sum_{h=1}^{n} S_h\, D_N\left[(k\Delta f - f_h)\,T\right],\ \text{being}\ D_N(\vartheta) = \frac{\sin(\pi\vartheta)}{N\sin(\pi\vartheta/N)} e^{-\pi\, i\, \vartheta \frac{(N-1)}{N}}$$

Problems related to the identification of the fundamental frequency tone:

a. leakage;
b. identification of the correct frequency value that may fall between two subsequent frequency values provided by the DFT.

Proposed algorithm for the synchrophasor estimation

Problem *a:* simple solution by applying a proper windowing

$$G_H\left(k\Delta f\right)=\sum_{h=1}^{n}S_h H_N\left[\left(k\Delta f-f_h\right)T\right],\;\; H_N(\vartheta)=\frac{1}{2}\left[D_N(\vartheta)-\frac{D_N(\vartheta+1)+D_N(\vartheta-1)}{2}\right]$$

Problem *b*:

$$f_0=\left(m+\Delta bin\right)\Delta f,\;\; 0\le\Delta bin\le 1,\;\; m\in\mathbb{N}$$

HP: since the number of samples N per time window T is very large ($f_{sampling}$=100 kHz >> f_0=50-60 Hz); → the sine function in the denominator of the Dirichlet kernel $D_N(\vartheta)$ can be approximated by its argument and, also, the following approximation applies:

$$e^{-\pi i\frac{N-1}{N}}\approx -1+i\frac{\pi}{N}$$

Proposed algorithm for the synchrophasor estimation

These assumption led to a linear expression of $G_H(k\Delta f)$ that allows to express Δbin as:

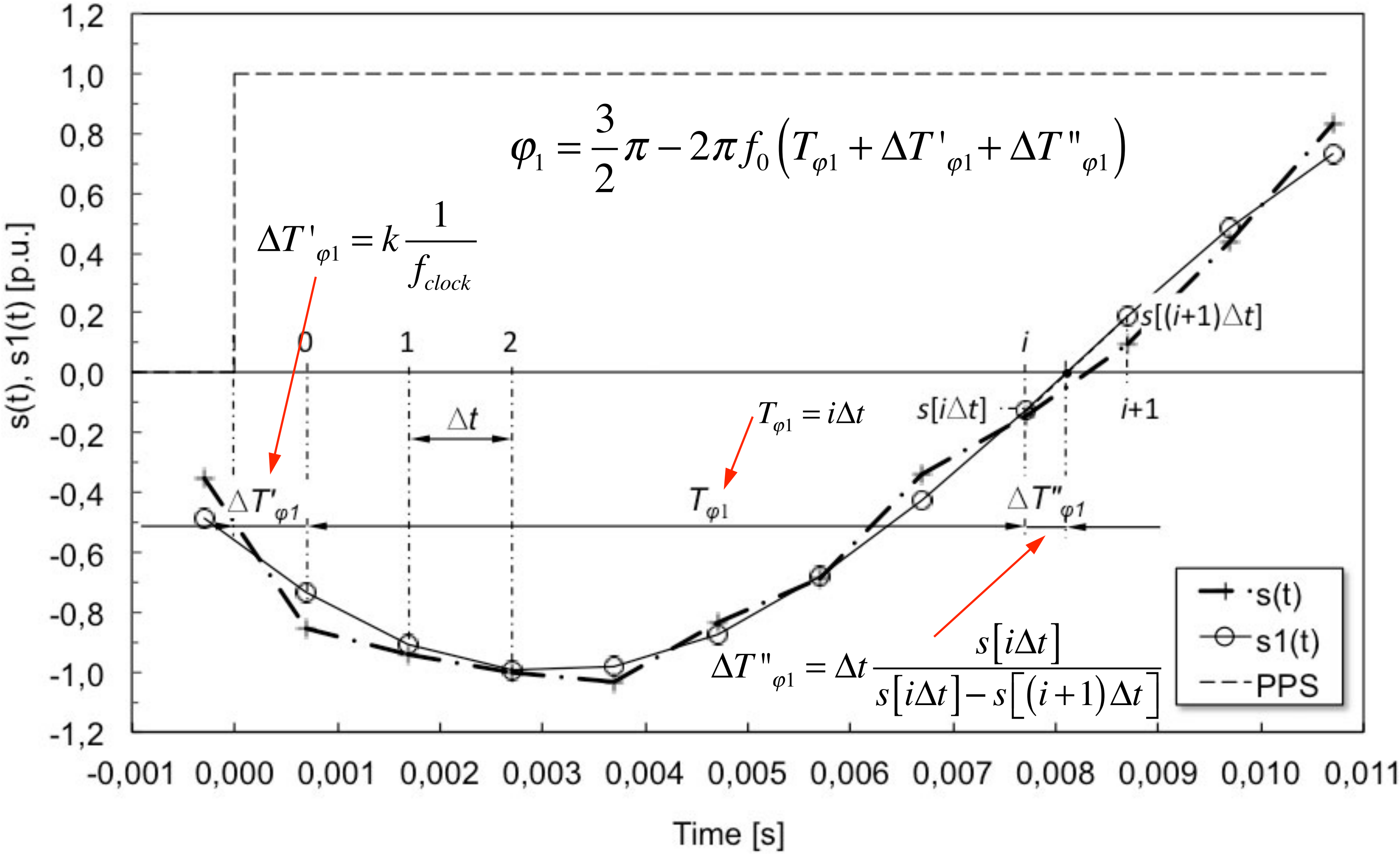
$$\Delta bin = \pm \frac{a-2b}{a+b}$$

Where *a* e *b* are the highest and the second highest tone magnitudes in the discrete spectrum G_H. Once Δbin is known, the complex amplitude of the fundamental frequency tone S_1 at frequency f_0 is given by:

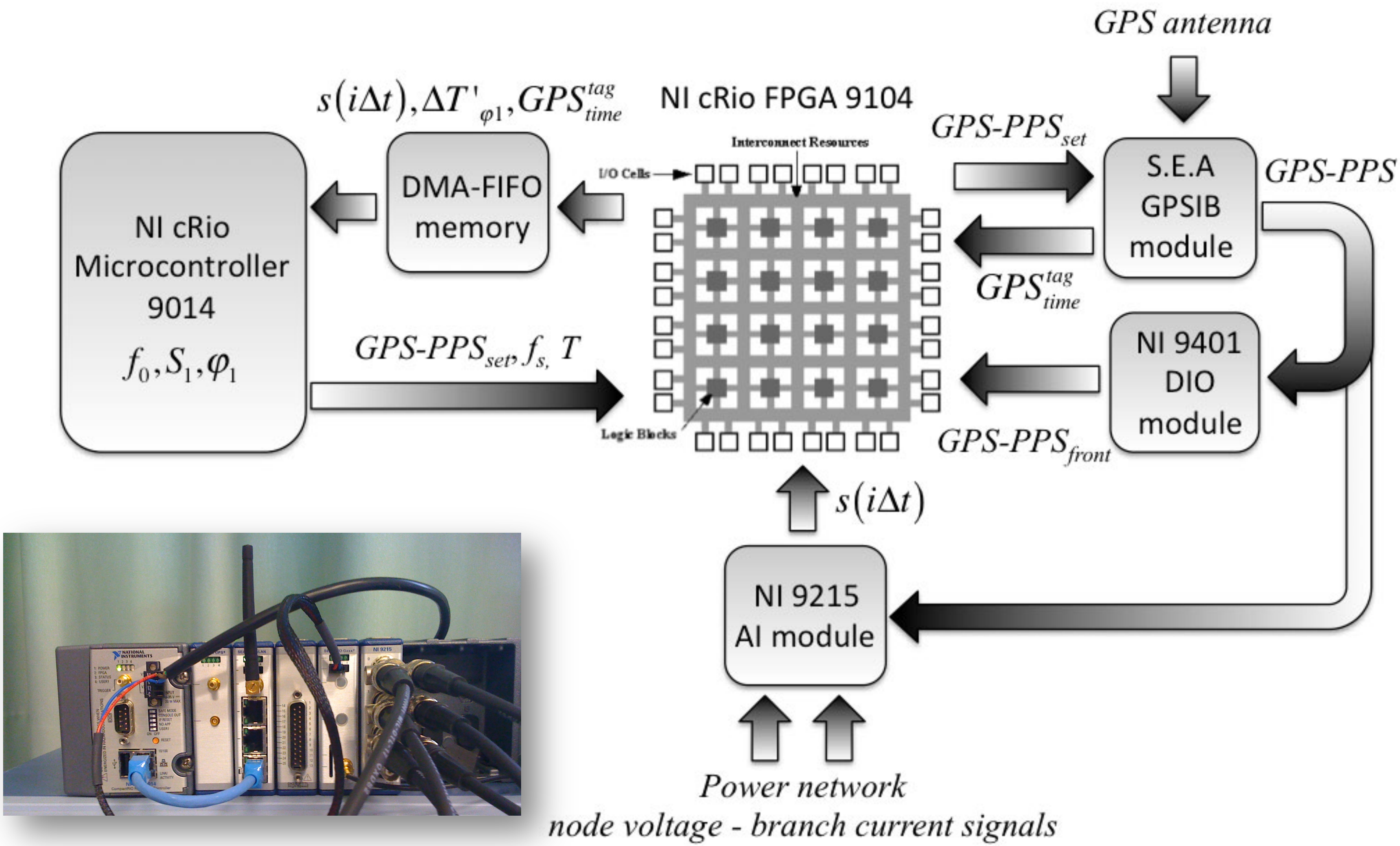
$$S_1 = \frac{2\pi \, \Delta bin \left(1-\Delta bin\right)}{\sin\left(\pi \Delta bin\right)} e^{-\pi i \Delta bin} \left(1+\Delta bin\right) G_H \left(m\Delta f\right)$$

The knowledge of f_0 and S_1 allows to reconstruct the fundamental frequency tone in the time domain in order to improve its phase estimation.

Proposed algorithm for the synchrophasor estimation

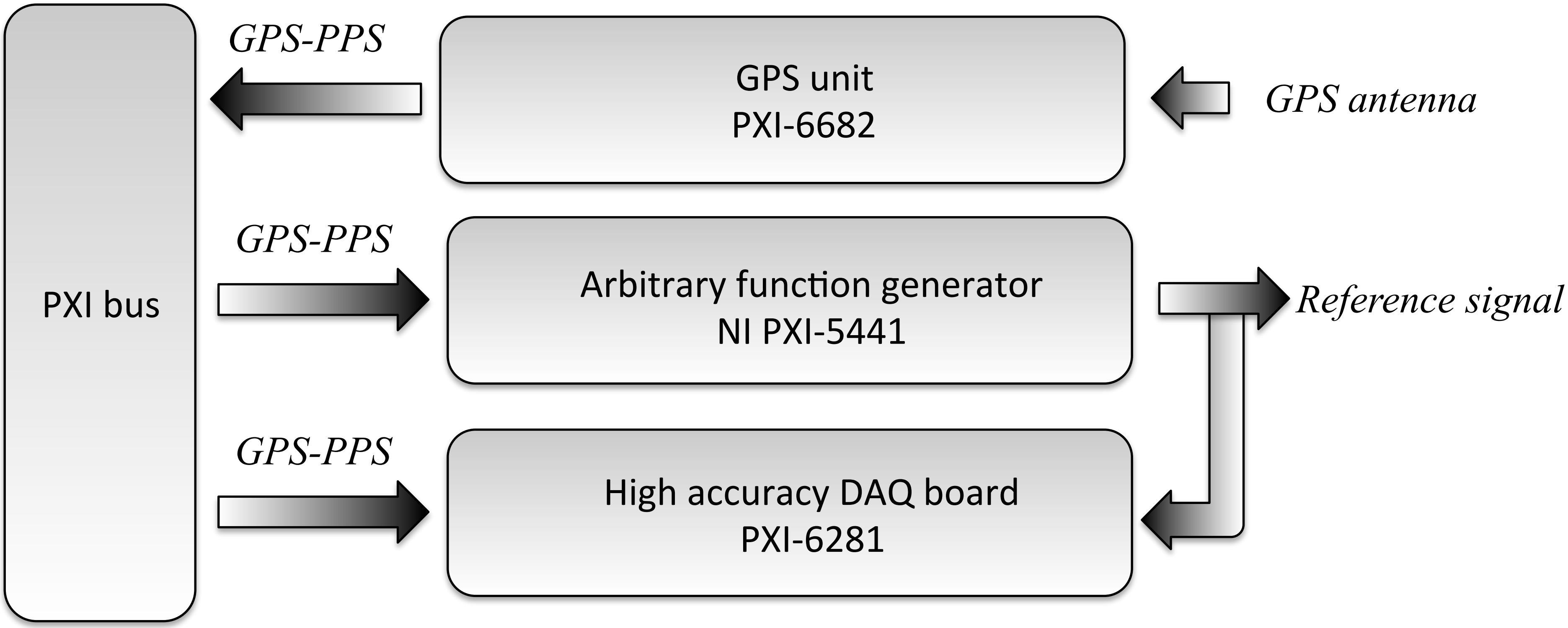


PMU prototype based on the NI Compact Rio



Application examples and experimental activities

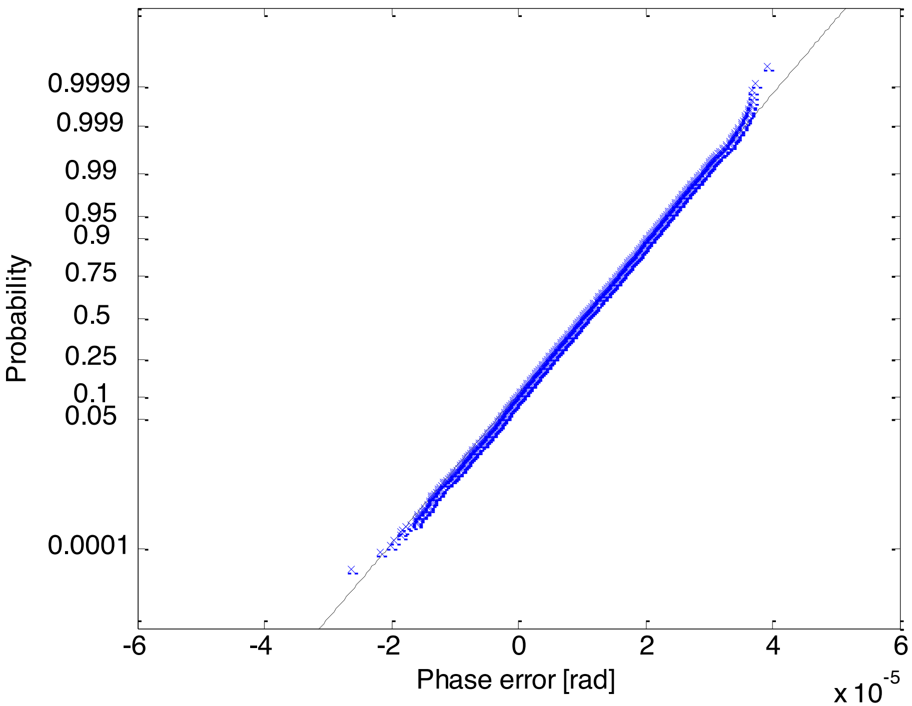
PXI-based system for the generation of reference signals used for the experimental characterization



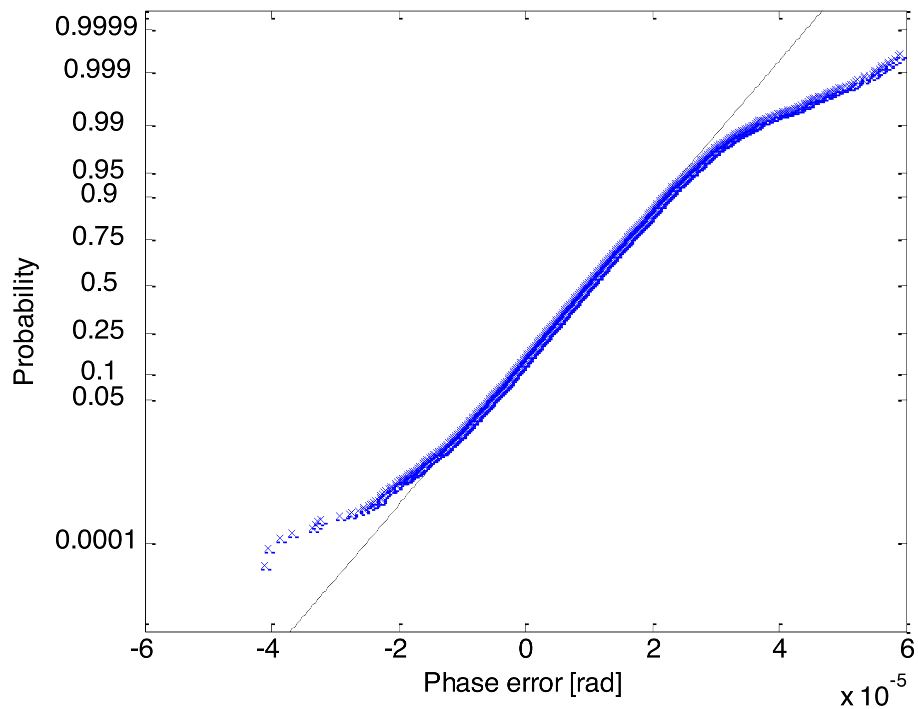
Application examples and experimental activities

Accuracy assessment with reference to steady-state signals (phase error)

Single tone signal
(50 Hz)



Distorted signal
(spectrum of std. EN 50160)



Application examples and experimental activities

Steady-state signals (single-tone and distorted)

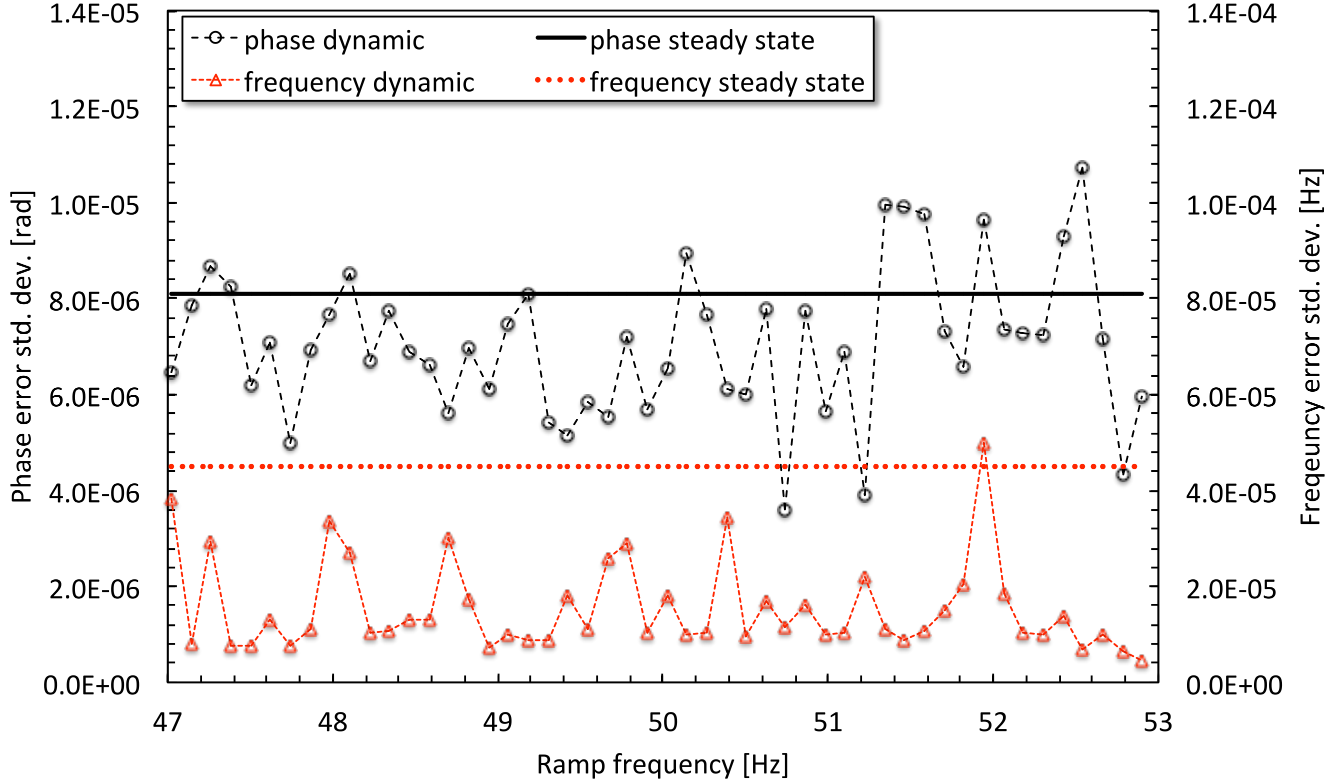
Quantity	Single tone signal	
	μ	σ
Phase error	$10.0\cdot10^{-6}$ [rad]	$8.1\cdot10^{-6}$ [rad]
RMS error	$120.0\cdot10^{-6}$ [p.u.]	$9.3\cdot10^{-6}$ [p.u.]
TVE	$117.0\cdot10^{-6}$	$9.3\cdot10^{-6}$
Frequency error	$20.0\cdot10^{-5}$ [Hz]	$4.5\cdot10^{-5}$ [Hz]

Quantity	Distorted signal	
	μ	σ
Phase error	$9.4\cdot10^{-6}$ [rad]	$9.9\cdot10^{-6}$ [rad]
RMS error	$250.0\cdot10^{-6}$ [p.u.]	$12.0\cdot10^{-6}$ [p.u.]
TVE	$250\cdot10^{-6}$	$12.0\cdot10^{-6}$
Frequency error	$20.0\cdot10^{-5}$ [Hz]	$3.8\cdot10^{-5}$ [Hz]

Application examples and experimental activities

Frequency-varying signals

Std.dev of the synchrophasor phase estimation with reference to 10 s frequency sweep ramp from 47 Hz to 53 Hz

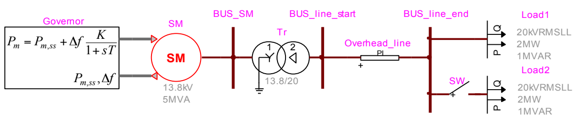


Application examples and experimental activities

Accuracy assessment with reference to electromechanical transients

Procedure:

1. Calculation of signal waveforms (bus voltages) within the EMTP-RV environment;
2. analog-generation of fault transient waveforms by means of the PXI reference signal generator system.

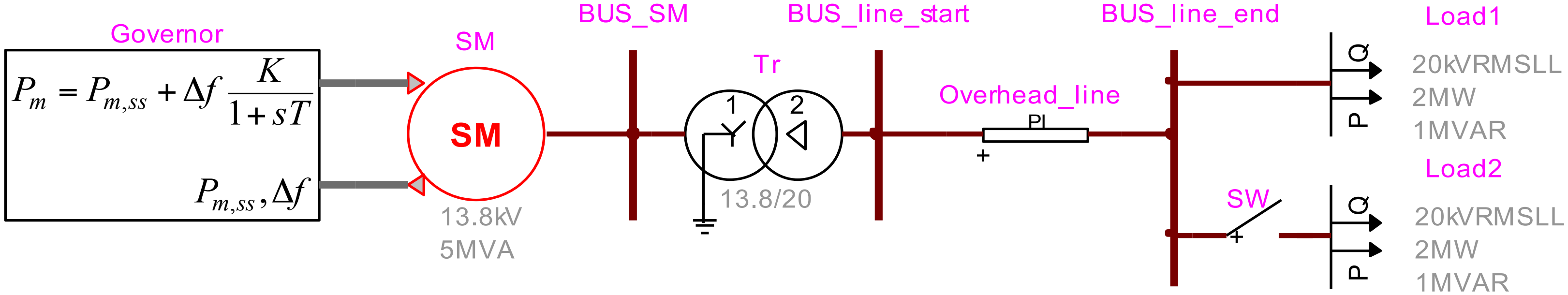


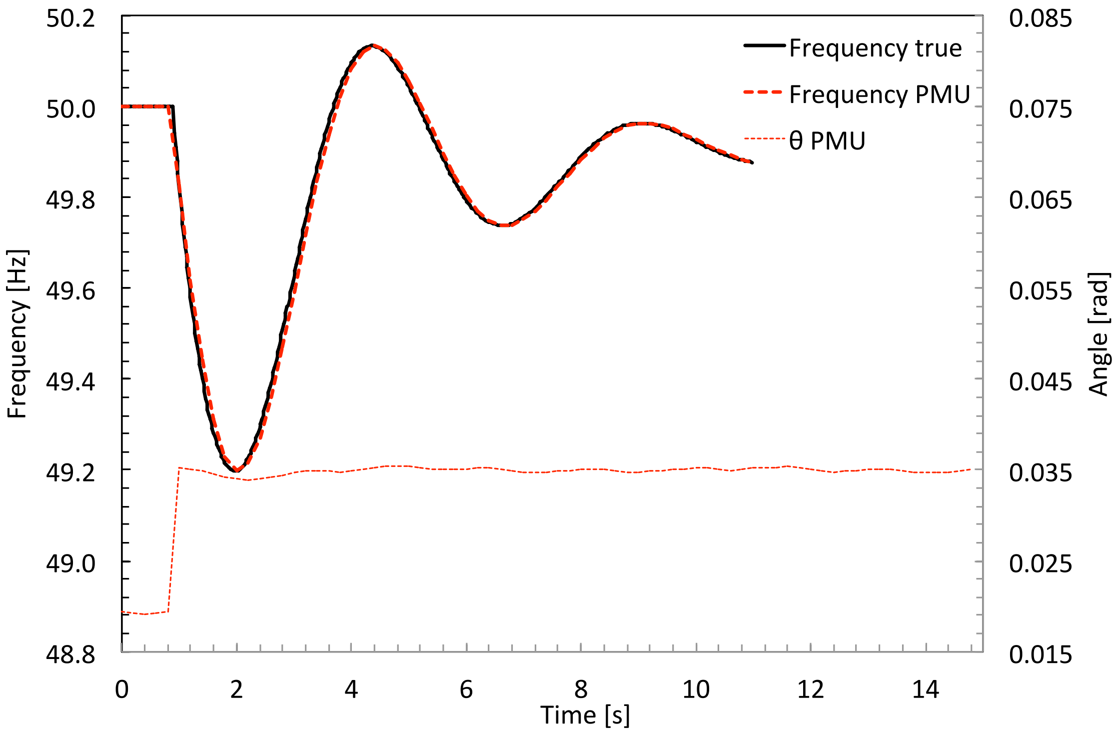
EMTP-RV network model

→ National Instruments PXI Arb 6289

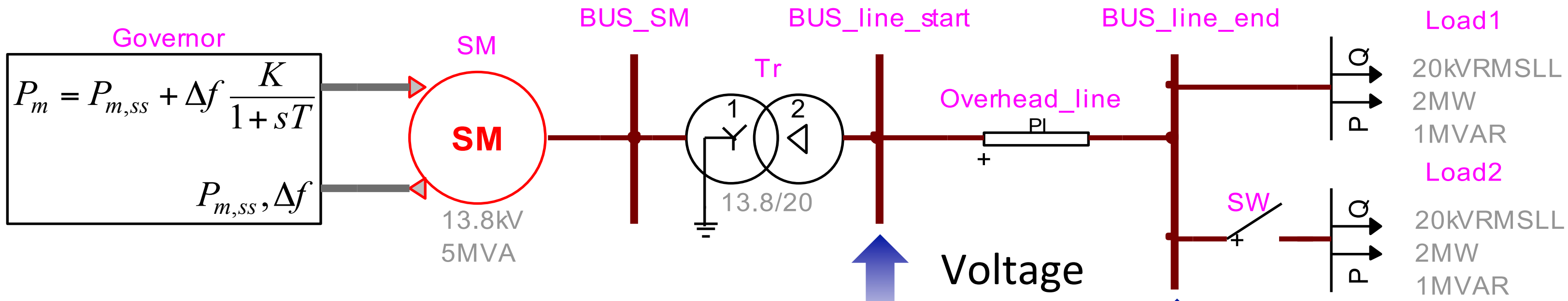
→ cRio PMUs

Application examples and experimental activities

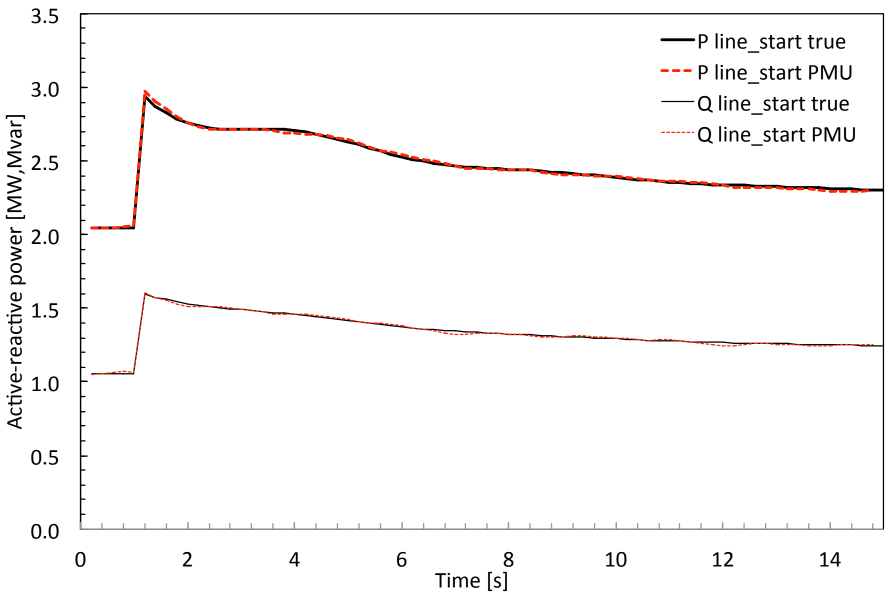


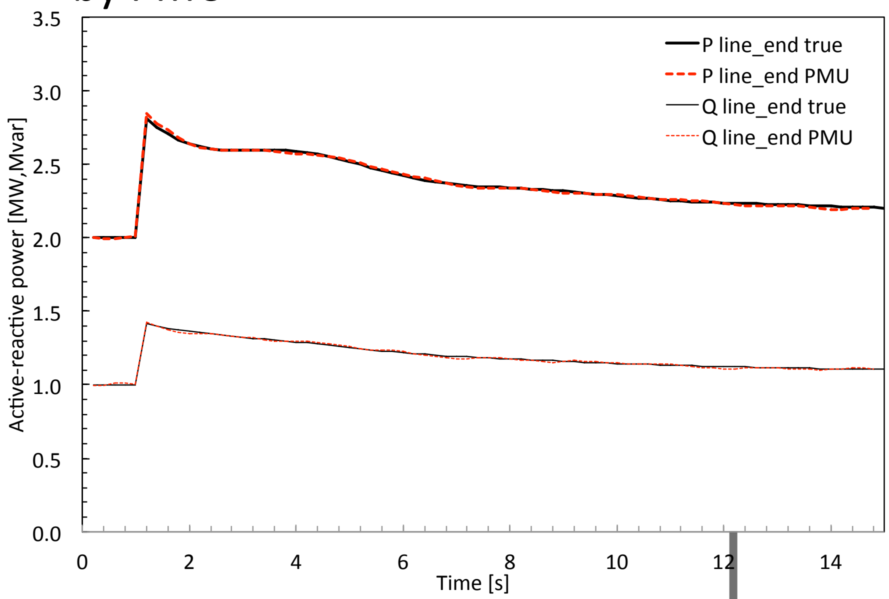


Application examples and experimental activities



Voltage phasors measured by PMU

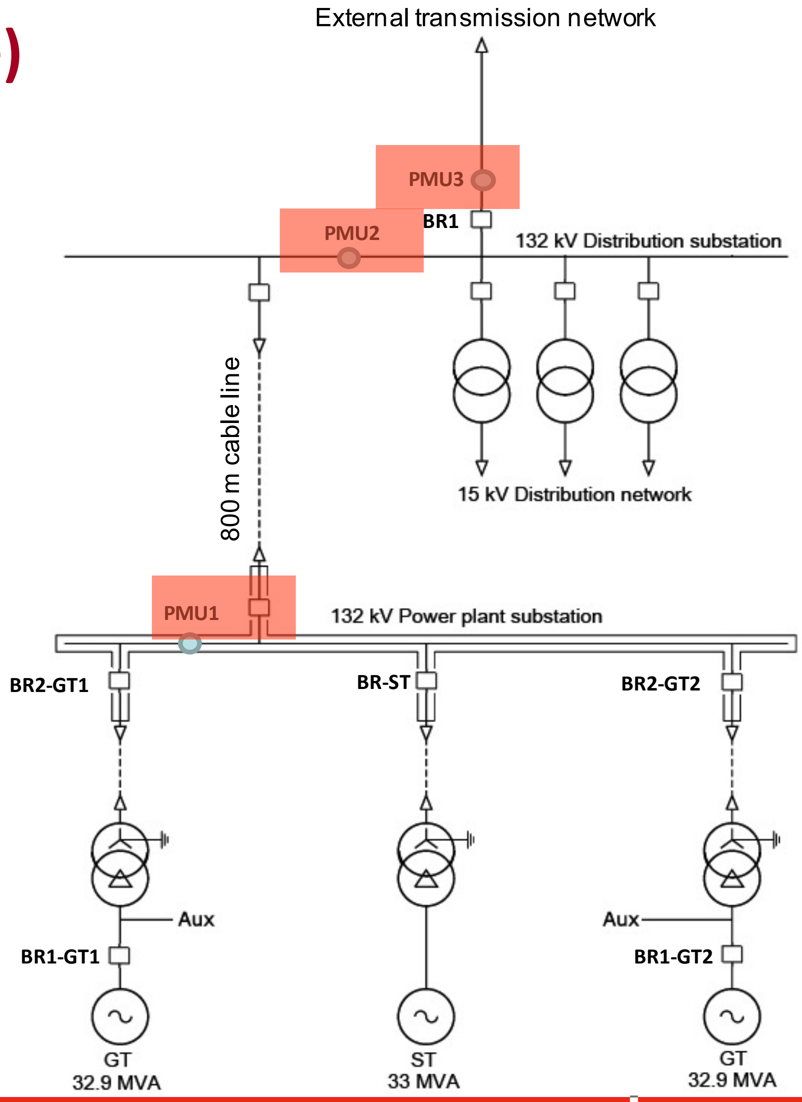




Application examples and experimental activities

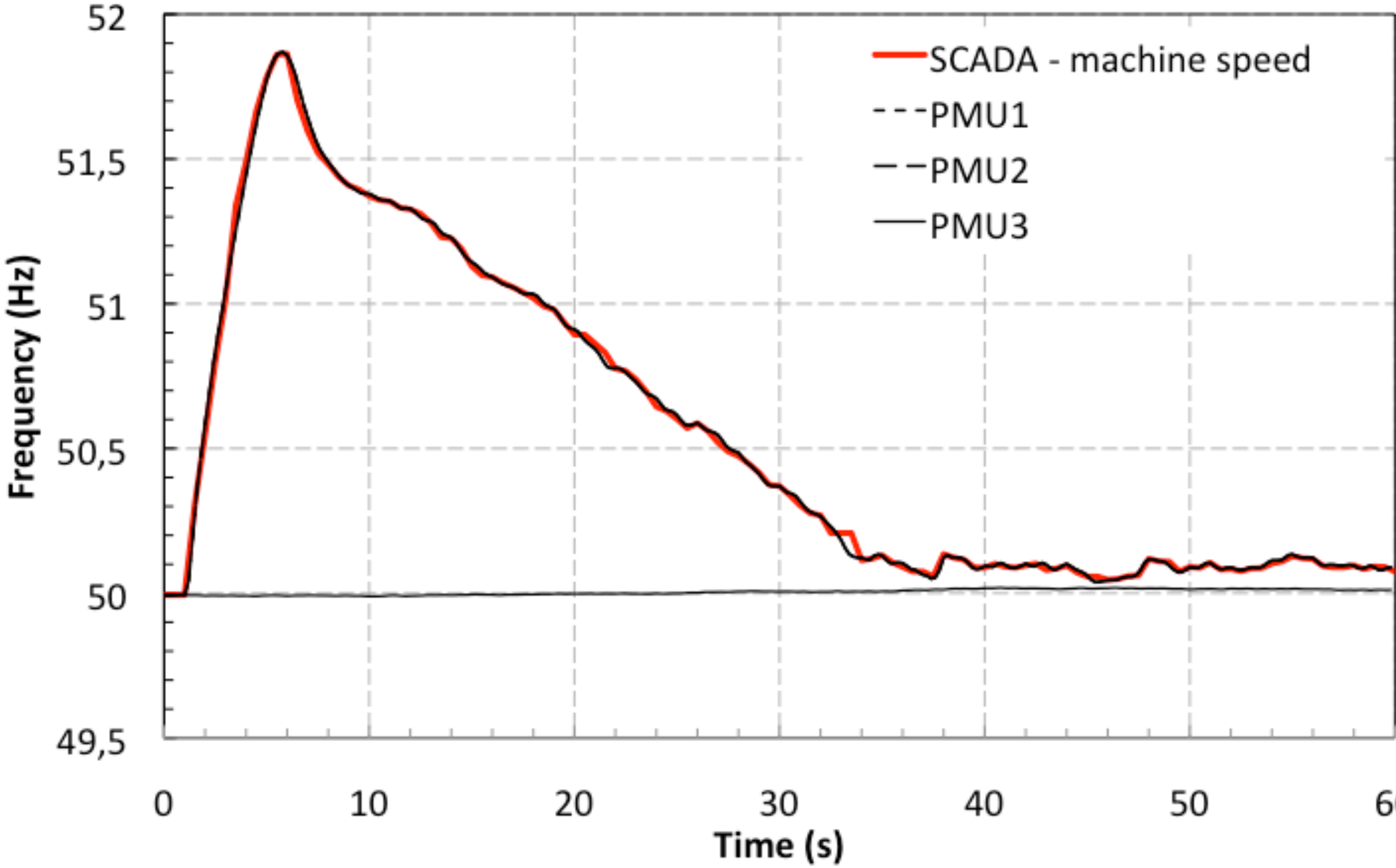
PMU application example (real scale)

- 80 MW power plant:
  two aeroderivative gas turbine (GT) units and a steam turbine unit (ST) in combined cycle;
- PP connected to a 132 kV substation feeding a urban medium voltage (MV) distribution network;
- PP substation is linked, by means of a cable line, to the 132 kV substation that feeds 15 feeders of the local medium voltage (15 kV) distribution network and provides also the connection with the external transmission network throughout circuit breaker BR1.



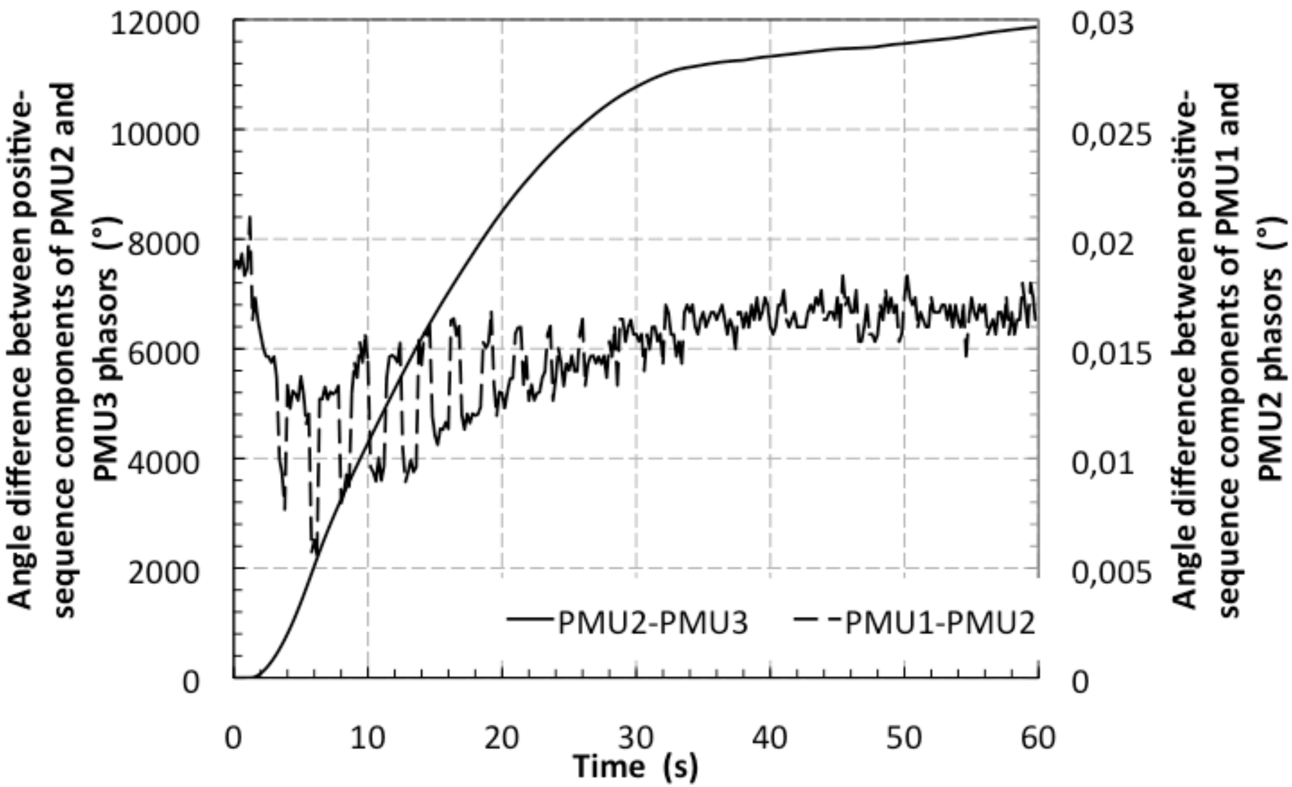
Application examples and experimental activities

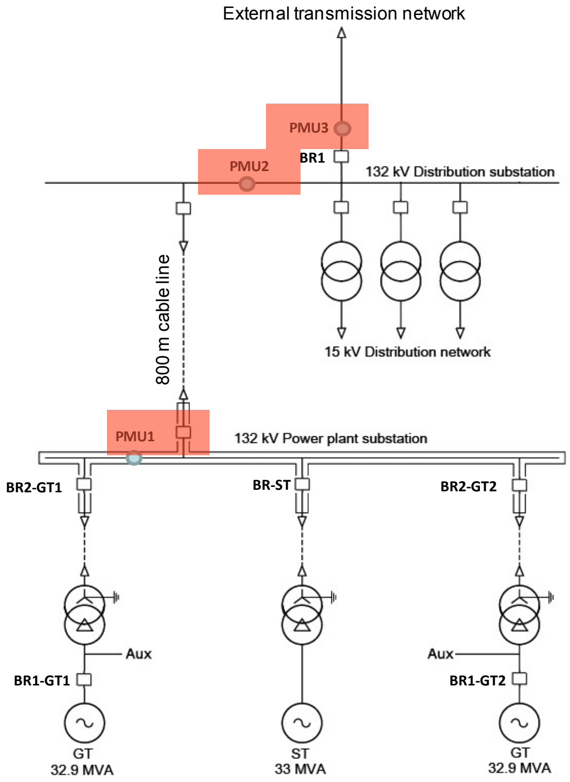
Distribution network frequency transient after the islanding



Application examples and experimental activities

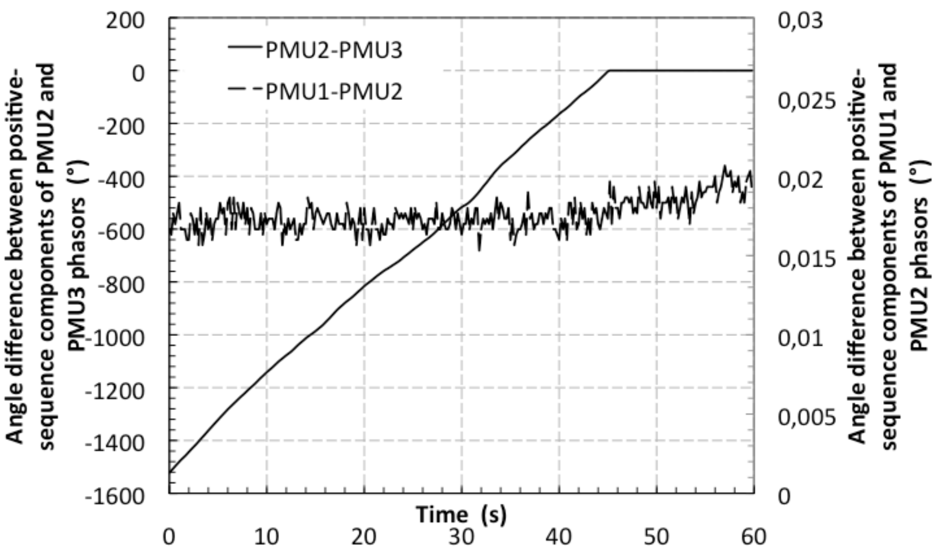
Distribution network voltage phasors angles differences during the islanding

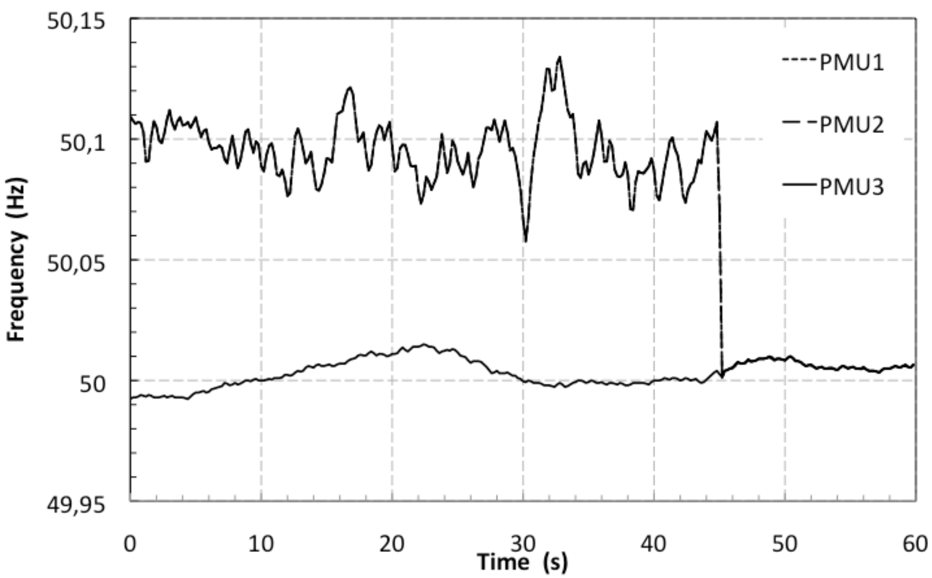




Application examples and experimental activities

Islanded network voltage phasors during the reconnection with the external grid





Conclusions

- The use of PMUs in active distribution networks requires the definition of improved performances of these devices compared to those available in the international standard (e.g. IEEE C37.118).
- The developed PMU prototype based on the NI cRio architecture allows to:
  i) identify the fundamental frequency tone with accuracy levels adequate for distribution network applications;
  ii) obtain accuracy levels not influenced by the harmonic distortion of the analysed signals and by their time-varying characteristics.

Creating PQA and PMU Devices for Smart Grids

Dr. Daniel Kaminsky
Dr.Petr Bilik
Dr. Jiri Hula

ELCOM, a.s.

ELCOM Fact Sheet

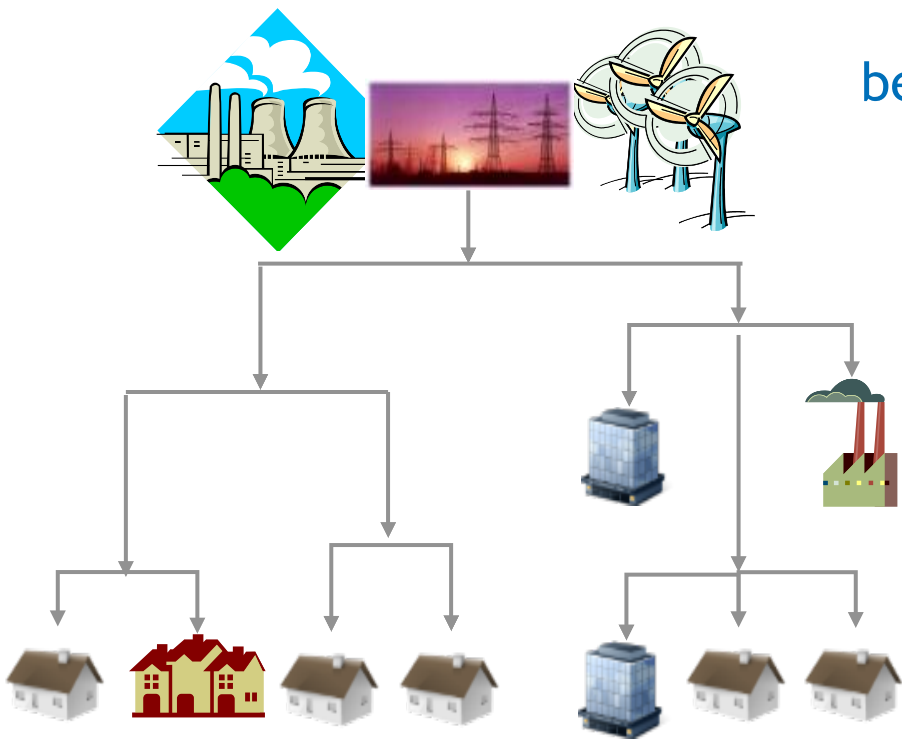
- Founded in 1990
- Based in Czech Republic
- 137 employees
- Annual revenue 16mil €
- Core business is electrical engineering and test & measurement

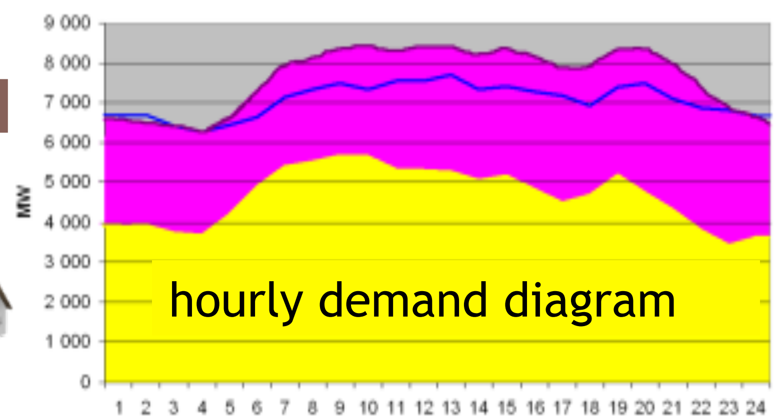
ELCOM Products & Services

- Turnkey Solutions and Products
  - Functional Testers
  - **Power Quality Analyzers, PMUs**
  - Lean Assembly Lines
  - Electrical Drives
  - Special Power Supplies
  - Power Filters and Compensators
- Custom Solutions
  - Laboratory Automation
  - Test & Measurement Software Development
  - Special Electronic and Mechanical Components

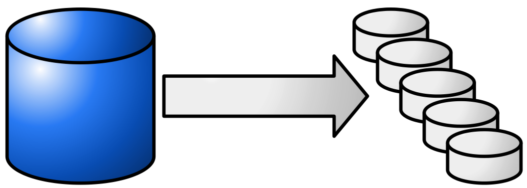
Electrical System Stability

There must exist balance between generated energy and energy demand at any time



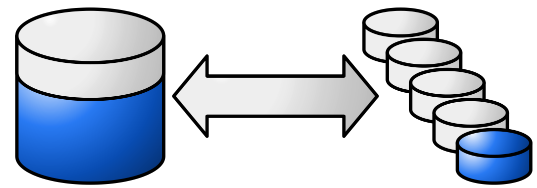


Traditional Power Network vs. Smart Distribution Grid



Central predicable generation

Consumption fully stochastic



Some gener. dispersed & stochastic

Some consumption is controllable

20-th century

power generation is controllable whereas the power consumption is unpredictable

21-st century

part of power generation is clearly unpredictable (renewable power sources) and therefore a part of power consumption should be controllable.

Why Do We Need Smart Grids?

- To handle intermittent energy sources from sun and wind. (Environmental targets)
- To accommodate a greater emphasis on demand response
- To support plug-in hybrid electric vehicles (PHEVS) – new significant load
- To handle distributed generation and storage capabilities.

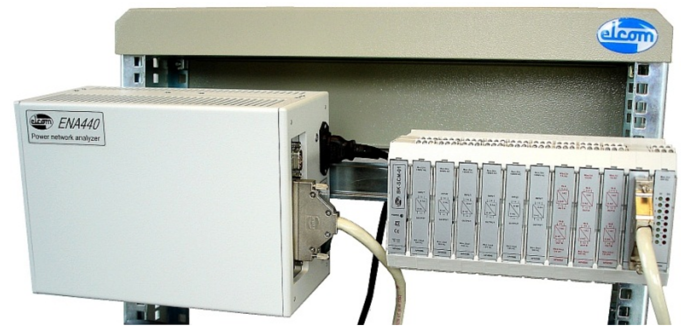
15 years of PQ Analyzers Design and Development at ELCOM

- From the very beginning till now the instrument firmware is fully written in LabVIEW
- From the very beginning till now the NI DAQ boards are used (ISA, PCI, USB, C series for cRIO)
- From the very beginning till now we produce PC-based PQ analyzers
- In 2005 we started to use cRIO and later sb-RIO platform too

ELCOM NI-based PQ Analyzers

ENA450

ENA440

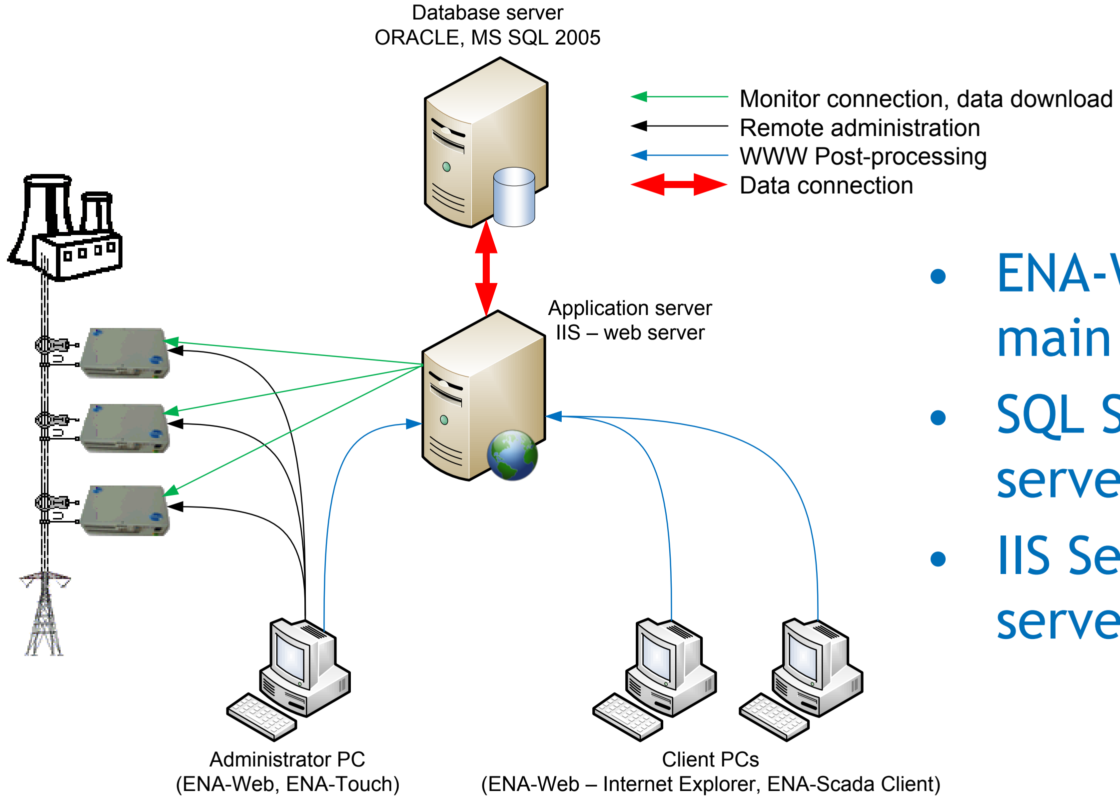


ENA460

ENA330

All ELCOM's PQA are compliant with IEC 61000-4-30 class A

Distributed PQA System Components

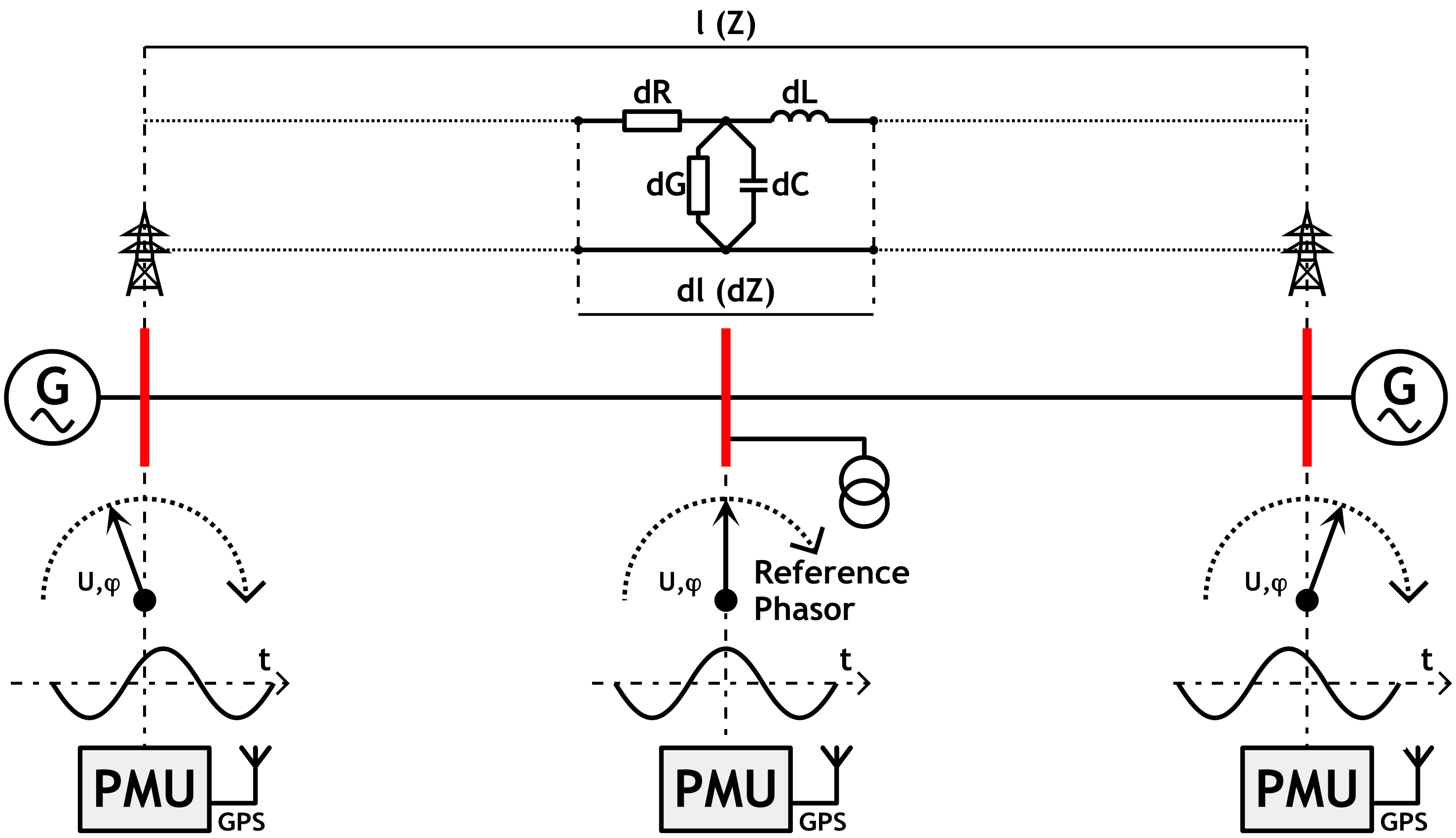


- ENA-Web PostProcessing – main application
- SQL Server – database server
- IIS Server – internet www server

Why to Measure Synchronous Phase

- The phase position of AC voltages and currents in different parts of an electric power system determines the stability and the dynamic performance of the system.
- PMU's are used for Wide Area Monitoring Systems (WAMS). The WAMS supports utilities in making optimal usage of the transmission grid capacity with regard to active power flow and voltage profile.
- Real-time information from WAMS gives early warning of power system disturbances that, if left unattended, could cascade into system wide blackouts

Synchronous Phase Measurements



PMUs

- PMU provides synchronized measurement of U and I signals on different locations, analyses state and dynamic changes for U phasors, I phasors, and frequency.
- Synchronized measurements make possible to directly measure phase angles between corresponding phasors in different locations within the power system.
- Measurements include a time stamp that provides an easy method of correlating values from different locations that take different amounts of time to arrive at a common collection point – Phase Data Concentrator (PDC).

PMU Standardization

- PMU must meet IEEE Std C37.118–2005
- This standard covers synchronized phasor measurement in electric power systems, defines steady state performance and data transmission format for real-time reporting
- In 2011 will be released:
  - C37.118.1 definition of 2 types of PMU classes: P protection and M measurement/monitoring with regard to reporting latency included definition of dynamic behavior requirements
  - C37.118.2 description of communication protocol
  - Testing, calibration, installation guides IEEE PC37.242

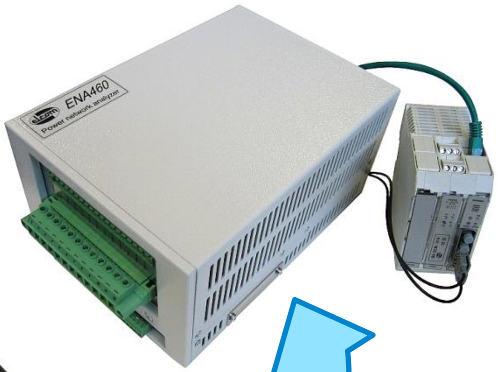
ELCOM sbRIO based PMU ENA460

- NI sbRIO-9612 based
- Aluminum case, DIN rail mountable
- Sampling rate 12kS/s
- 4 voltage inputs 75/150/300/600V, 4.2kV isolation, 600kOhm
- 4 current inputs 1A, 5A, 4.2kV isol.
- 0.1% TVE precision
- 8 digital inputs
- Up to 16 GB of CF data storage

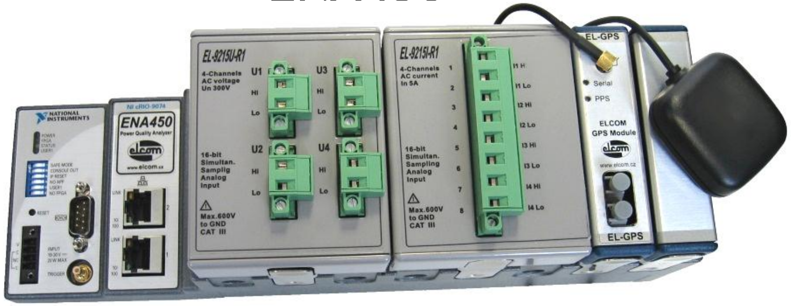
- Advanced corrections of PTs and VTs errors
- Optionally PMU can calculate P,Q
- Communicates with more PDCs concurrently
- Can work as PQA

From PC-based PMU to sbRIO-based PMU

ENA460



ENA450



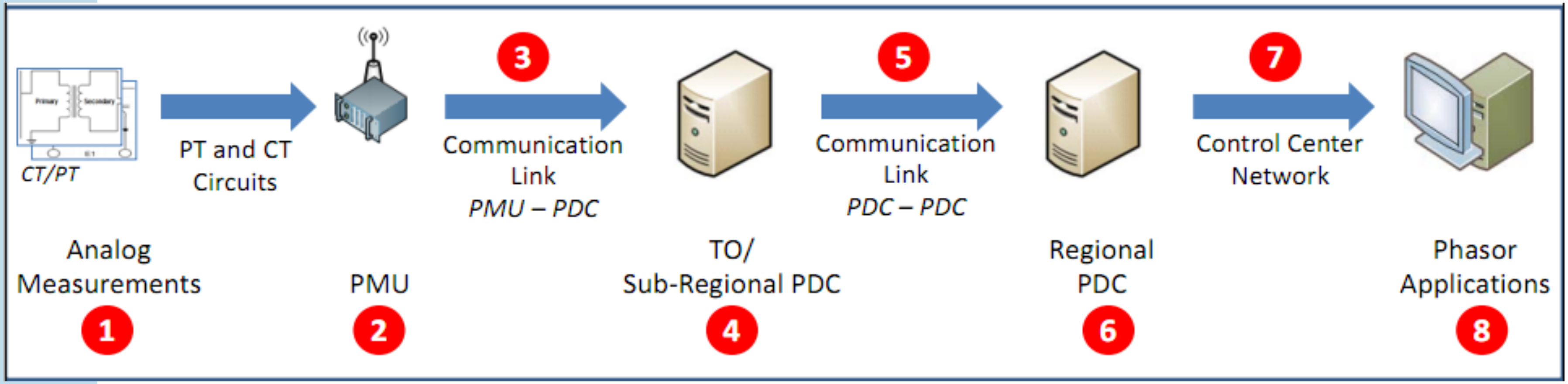
ENA440

ENA510 – Latest Model of Portable PQA/ PMU

- Portable analyzer with two three-phase voltage/current systems and embedded touch screen
- 8 voltage inputs up to 600 V RMS; 8 current inputs using current clamps; 4,2kV isolation
- 16 digital inputs, external GPS receiver
- Uses two NI sbRIO-9612 and one industrial PC with display
- Works as PQ meter and PMU together

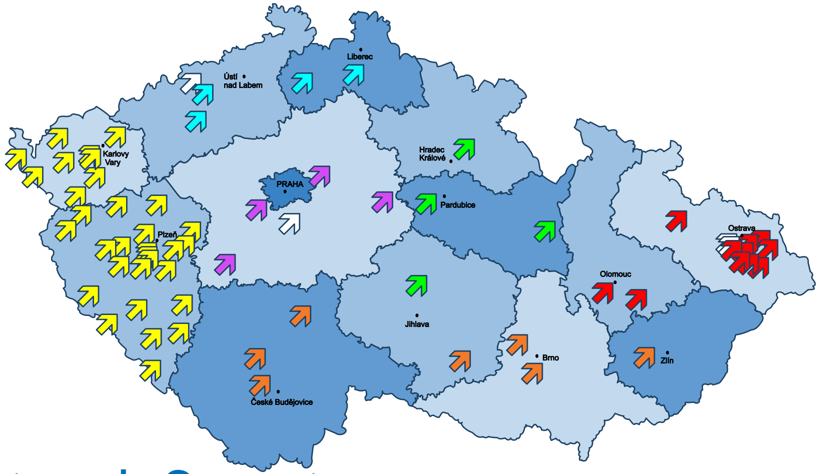
Communication infrastructure at WAMS systems

- Ethernet is the most common way used for communication
- Transport delay between data acquisition and data processing at central server is in tens or maximum hundreds of miliseconds. SF data are time sychronized!

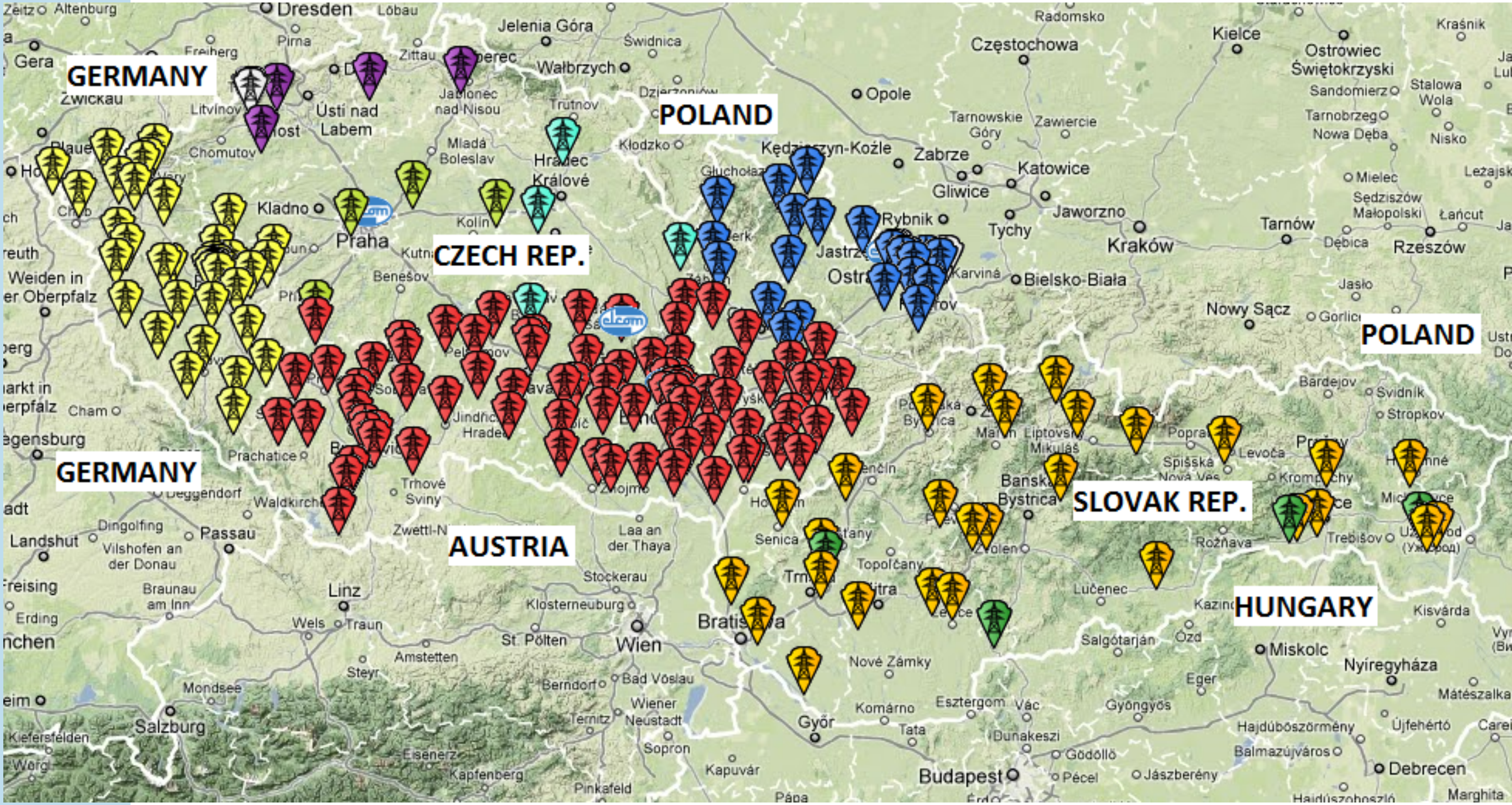


Successful stories

- CEZ Distribution Network Operator
  - 45 multi-system PQAs, 146 monitored 3~ systems
  - 42 single-system PQAs
- E.ON Czech Republic
  - 34 single-system PQAs



- CEPS Czech Transmission Network Operator
  - 2 PMU test project
- SEPS Slovak Transmission Network Operator
  - 36 single and multi system PQAs, 54 monitored 3~ systems
  - 2 portable PMUs, 4 PMUs for fixed installation
- Slovak Technical University
  - 2 portable PMUs


GERMANY
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