EPFL

Integration of renewable energy sources in the power electric network of the future

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Outline

- Introduction
- Issues and challenges of renewables
- From passive to active distribution networks
- Advanced operation of distribution networks
- Conclusions

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Introduction

A brief historical background (U.S.)

- Edison designed the entire electrical system down to the wall outlet and in 1881 established the first power company
- In the 1930s, isolated power systems melded into interconnected systems
- In the 1950s and 1960s, isolated systems were converted to large regional pools:
  - bulk delivery over long distances
  - large generating plants
- With economies of scale, prices declined and demands increased

Introduction

Traditional power system infrastructure

- Vertically integrated companies
- Regulated prices that guaranteed a fair rate of return on invested capital
- Electricity service was considered a natural monopoly:
  - capital intensive: generating plants, transmission network, and distribution network
  - efficiency: the larger the generating capacity, the more efficient
  - regulation: public

Introduction

Natural monopoly no more applies

- Higher fuel costs and environmental concerns required more diversified generation portfolios
- Emergence of new technologies challenged the natural monopoly:
  - rated power is not the only determining factor in generation, transmission and distribution
  - distributed generation (locally installed)
  - efficiency

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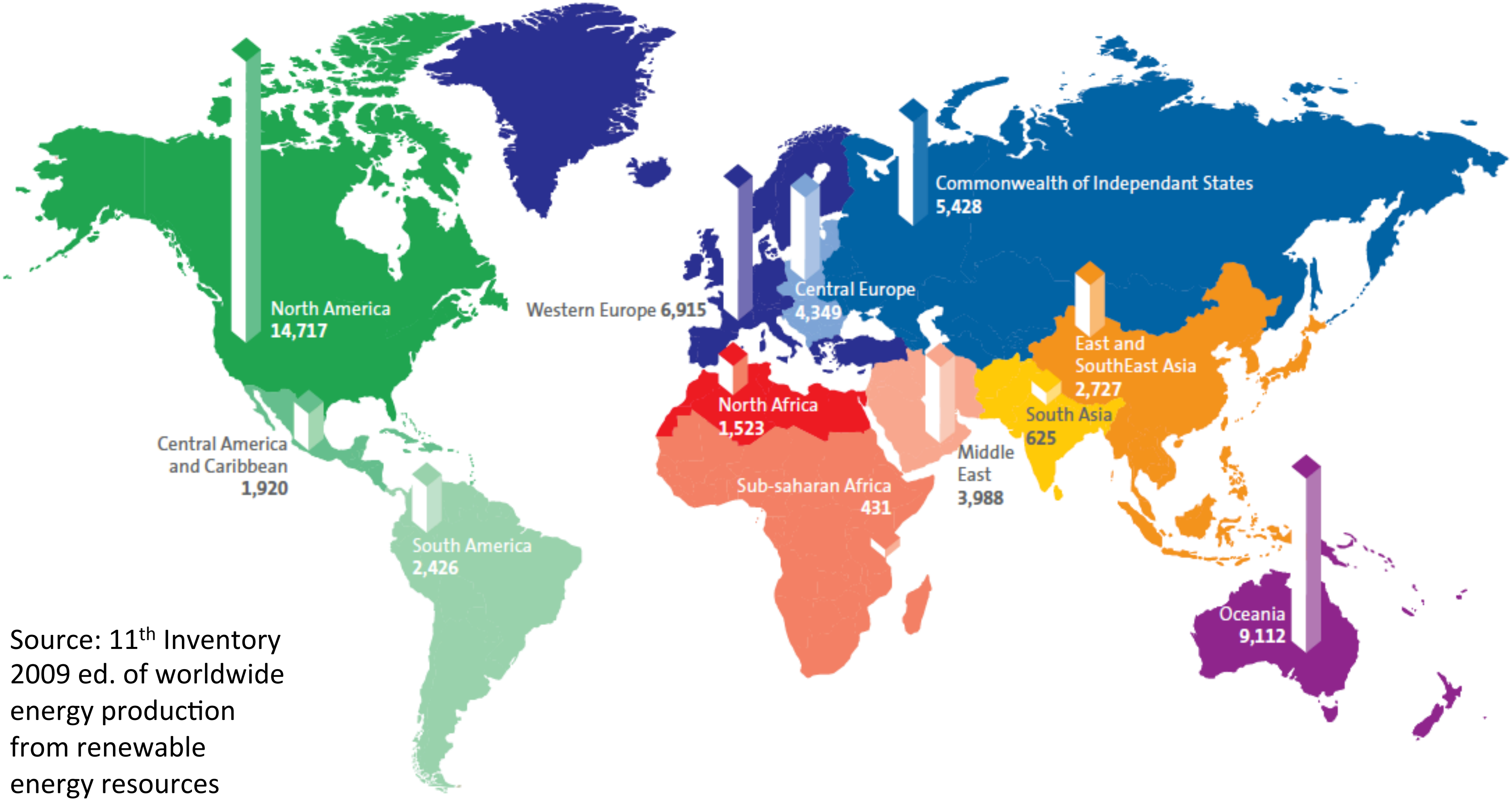
Issues and challenges of renewables

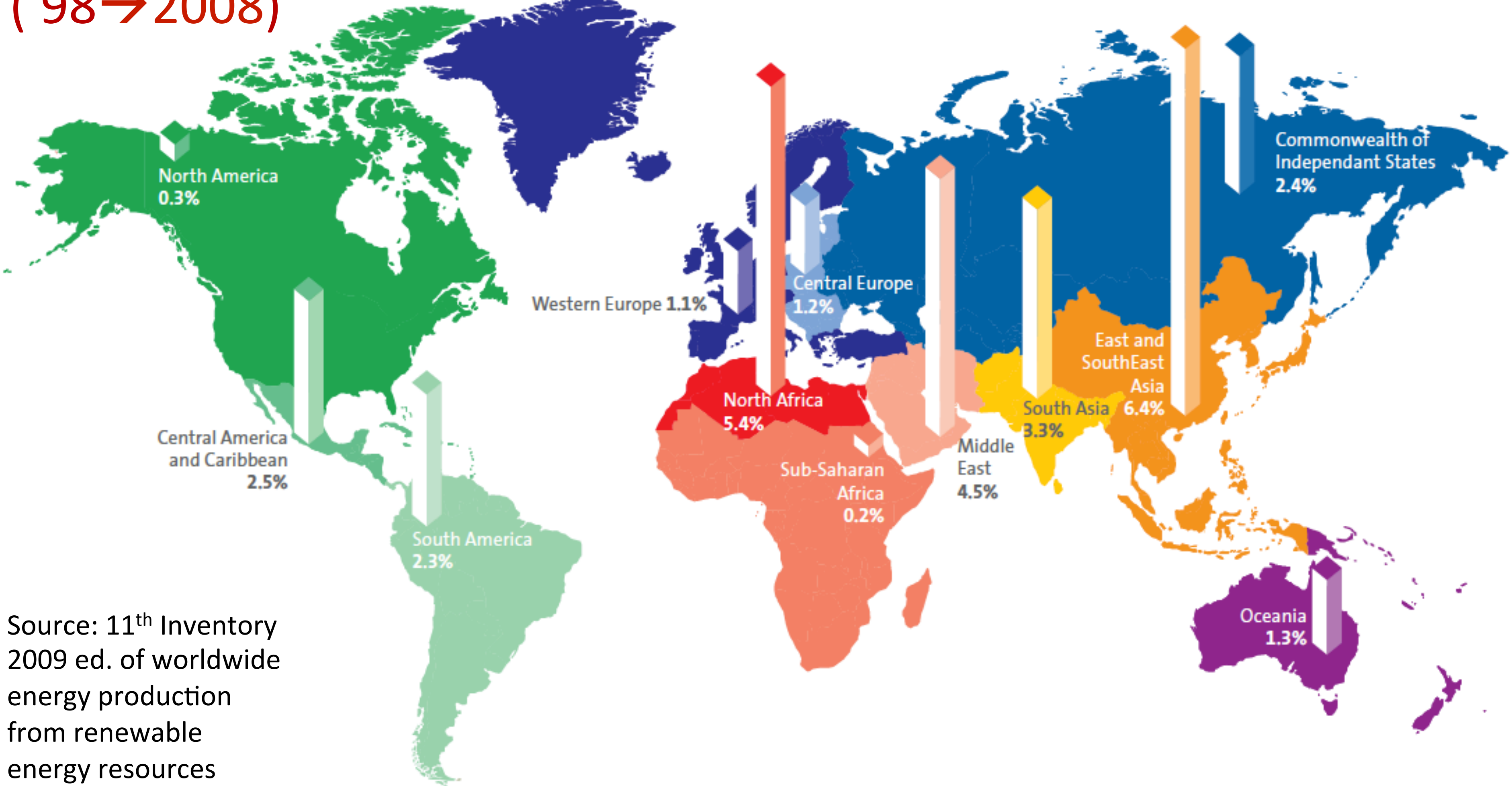
Electricity production per-capita in 2008 (kWh)



Source: 11th Inventory 2009 ed. of worldwide energy production from renewable energy resources

Issues and challenges of renewables

Year average growth of the per-capita electricity production ('98→2008)

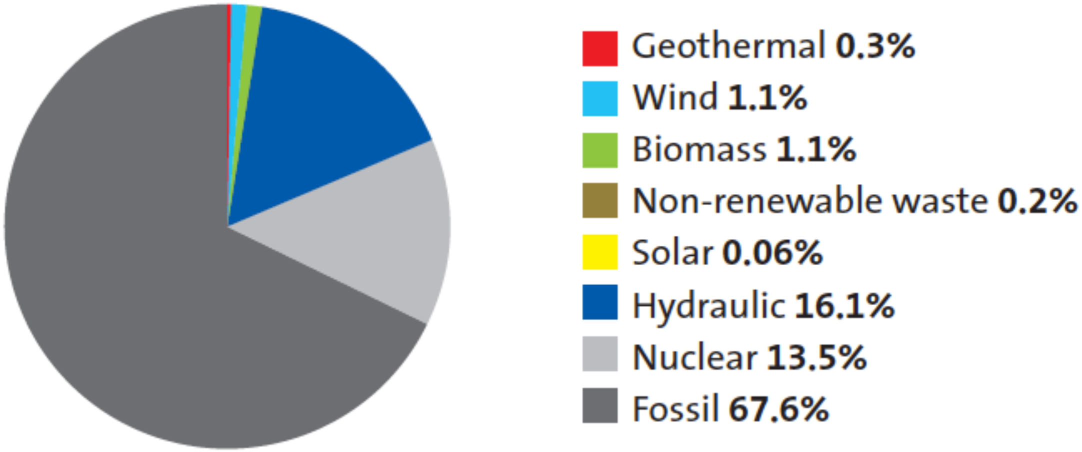


Source: 11th Inventory 2009 ed. of worldwide energy production from renewable energy resources

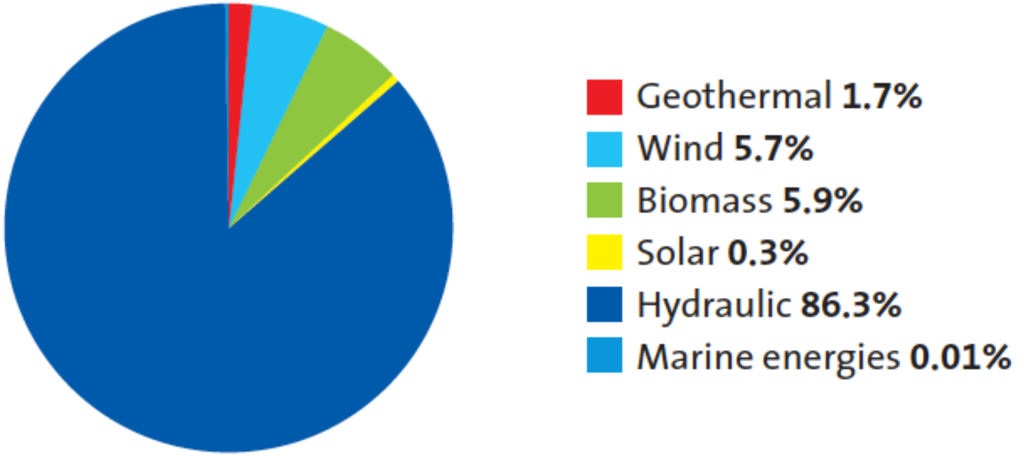
Issues and challenges of renewables

World energy production by source (2008)

Total



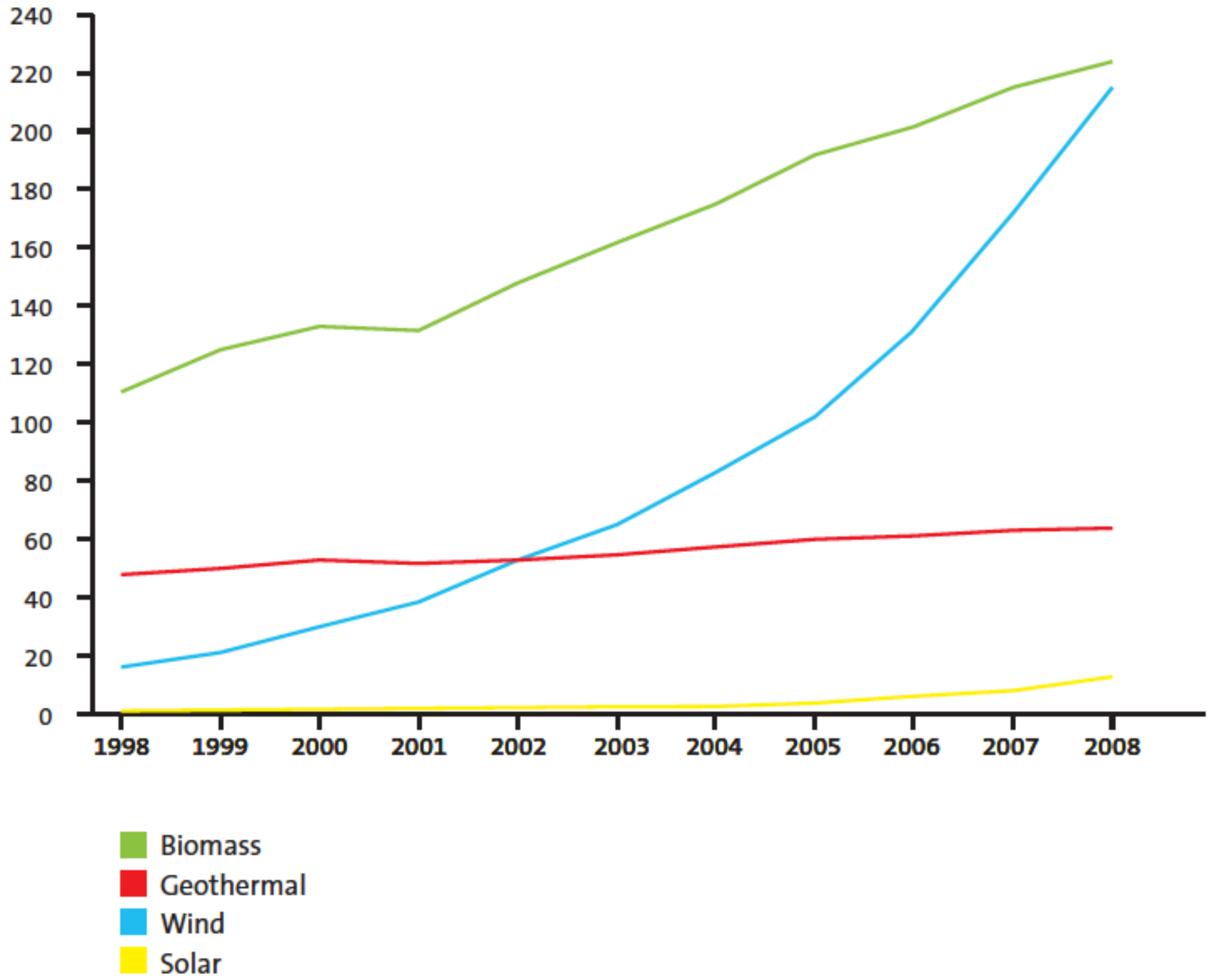
Renewables only



Source: 11th Inventory 2009 ed. of worldwide energy production from renewable energy resources

Issues and challenges of renewables

Renewables production trend excluding hydro (TWh)



Source: 11th Inventory 2009 ed. of worldwide energy production from renewable energy resources

Issues and challenges of renewables

2010		2030
• 3 % renewable (non-hydro) • 16% hydro • 13% nuclear • 68% fossil	Changing Supply Mix	• Renewables increasing • Nuclear • Fossil fuels decreasing • Energy storage increasing • Carbon constrained future Carbon
• Limited transmission capacity • Constrained regions- reliability concerns	Demand Requirements	• Load curves – increased peaking • Balancing with energy storage • More electrically sensitive equipment • Higher power quality demand • Transition to plug-in hybrids
• Control areas • Transmission lines • Millions of DG units	Complexity of Grid	• More transmission lines needed • Highly interconnected structure • More on-site generation • Wide-area monitoring and real-time control
• Aging Infrastructure • Vulnerabilities – cyber • Age of Workforce	Vulnerability of Energy Infrastructure	• Increased interdependencies • Material and resource limitations • Increased use of IT, communications, and controls • Multi-discipline workers

Source: prof. M. Shahidehpour, IIT

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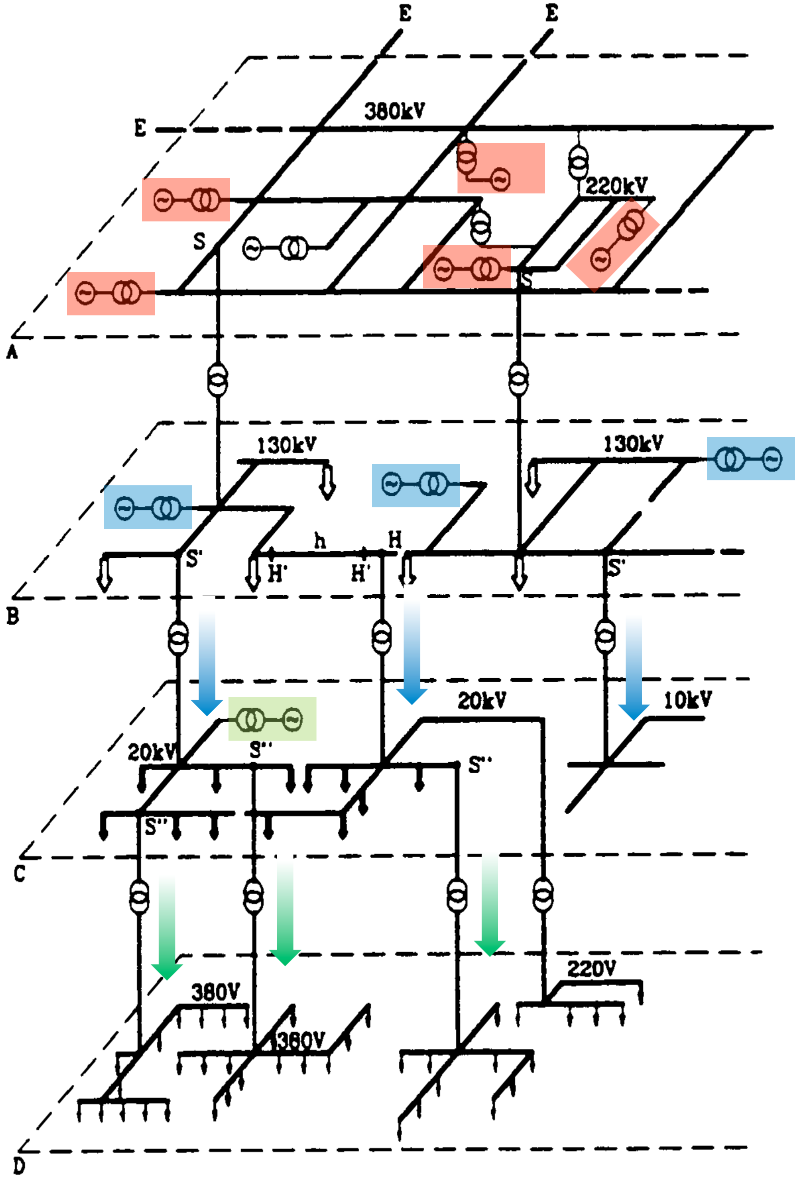
From passive to active distribution networks

Transmission

Sub-transmission

Distribution (medium voltage)

Distribution (low voltage)



Without **distributed generation**

Unidirectional powerflows

from transmission to distribution networks.

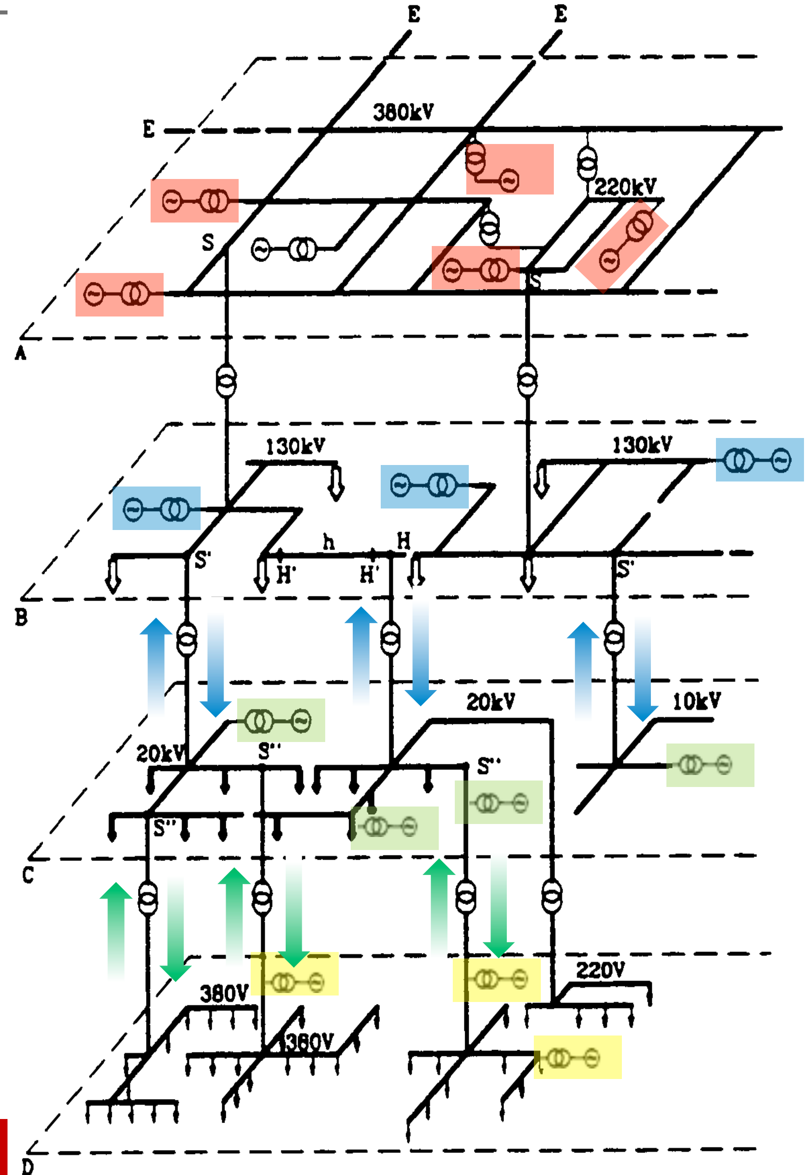
From passive to active distribution networks

Transmission

Sub-transmission

Distribution (medium voltage)

Distribution (low voltage)



With **distributed generation**

Bidirectional powerflows

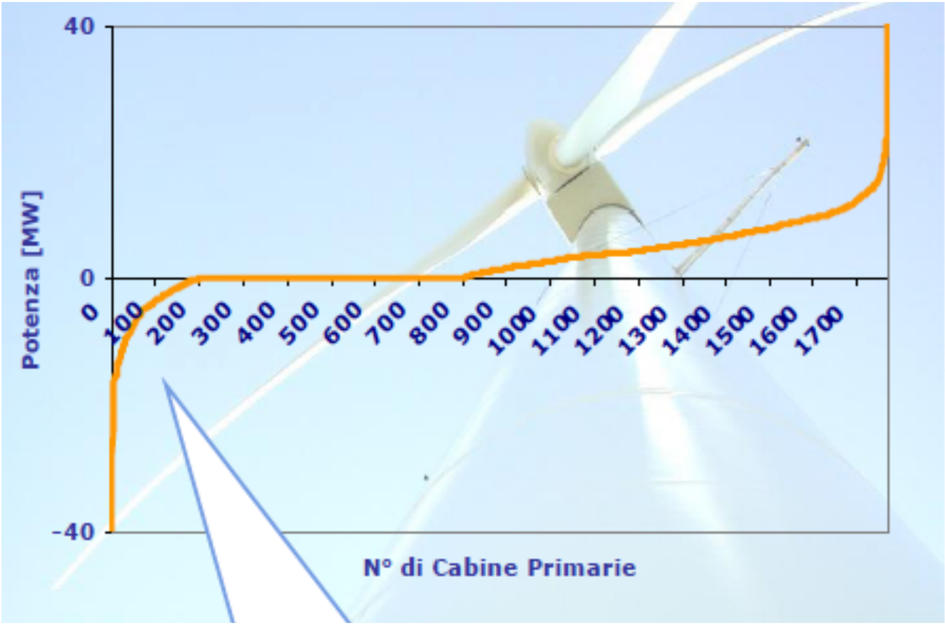
between the transmission to distribution infrastructures.

From passive to active distribution networks

Impact of embedded generation on distribution networks

- ❑ Voltage control
- ❑ Secure network operation after transients subsequent to the loss of major dispersed generation and subsequent reconnection
- ❑ Protections and short circuit levels
- ❑ Detection and operation in islanding conditions

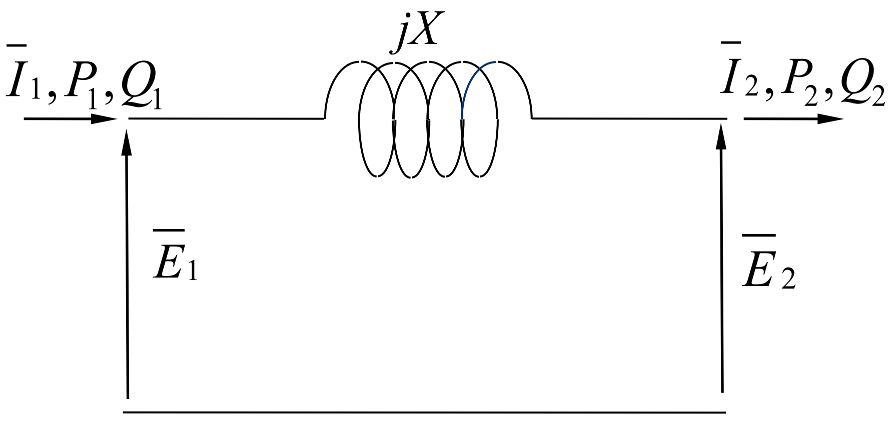
Primary substation minimum power

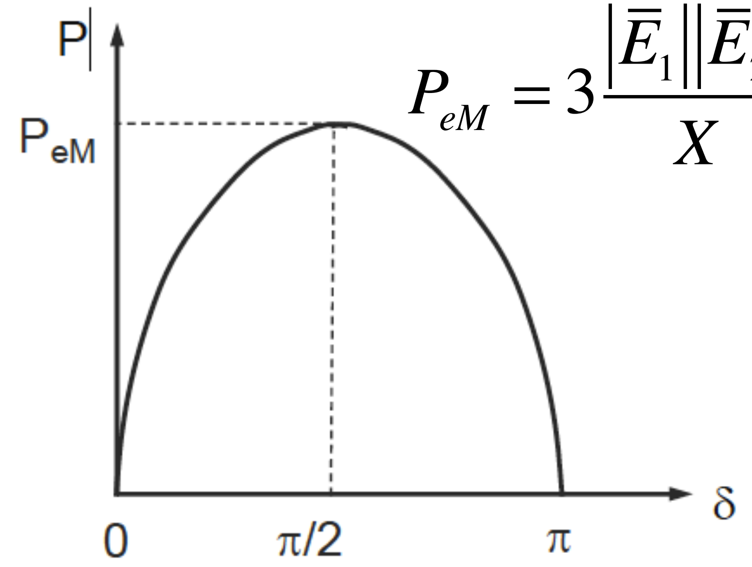


16 % of the Italian primary substations experience power flow inversions to the sub-transmission network (courtesy of ENEL)

From passive to active distribution networks

Impact of embedded generation on the distribution network operation constraints → AC line power flow limit





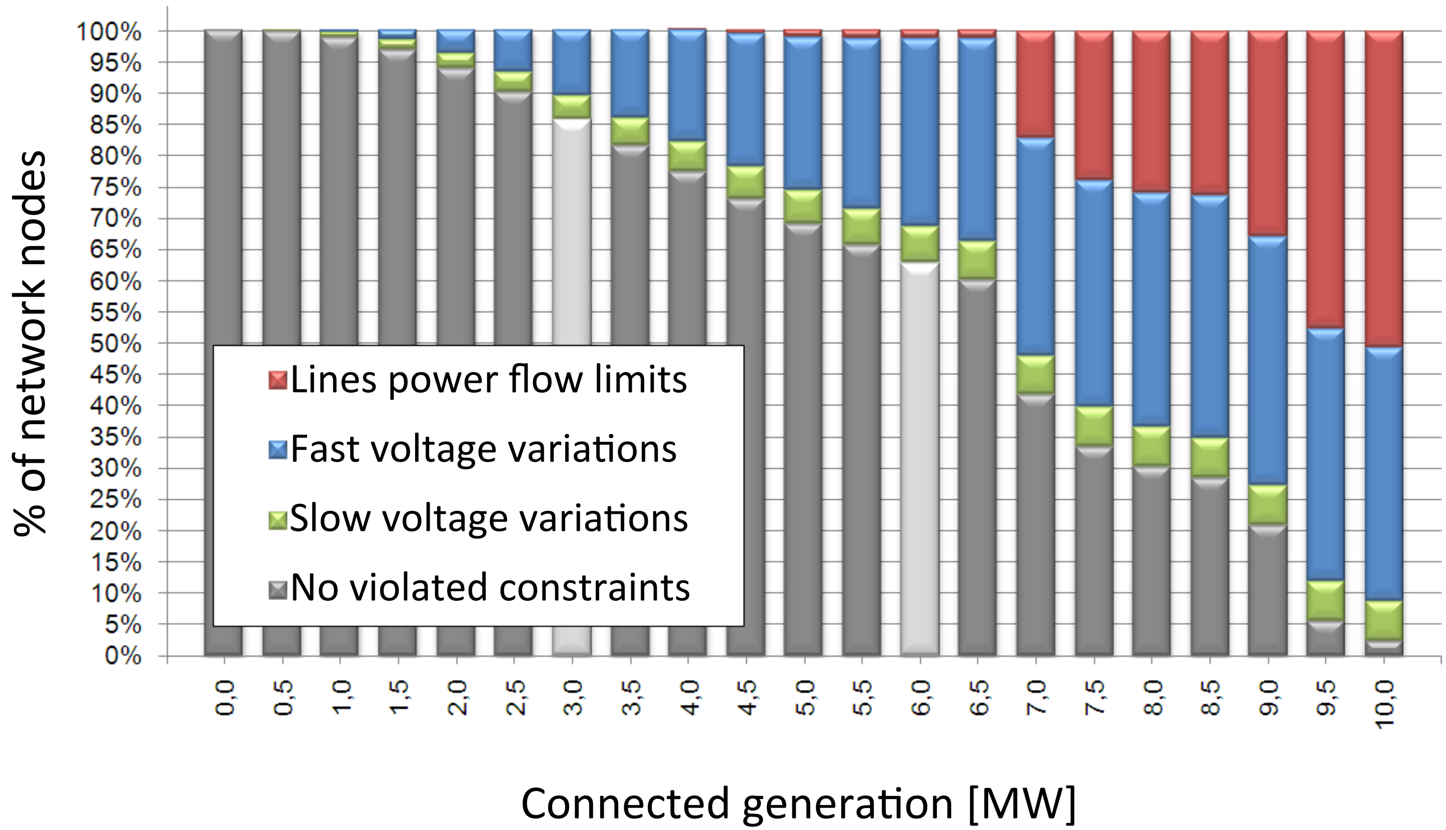
$$P_{eM} = 3\frac{|\bar{E}_1||\bar{E}_2|}{X}$$

$$P_1 = P_2 = 3\frac{|\bar{E}_1||\bar{E}_2|}{X}\sin\delta$$

$$Q_2 = \frac{3|\bar{E}_2|}{X}\left(|\bar{E}_1|\cos\theta - |\bar{E}_2|\right), Q_1 = \frac{3|\bar{E}_1|}{X}\left(|\bar{E}_1| - |\bar{E}_2|\cos\theta\right)$$

From passive to active distribution networks

Impact of embedded generation on the distribution network operation constraints



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Operation and control

- **network advanced monitoring**;
- stochastic generation and changes in load behavior;
- **advanced control** (incl. hierarchical levels redefinition);
- demand side management and active customer integration;
- storage management;
- power quality;
- protection;
- emergency condition management (faults, blackouts, islanding).
- market (local) constraints.

Advanced network monitoring by means of phasor measurement units

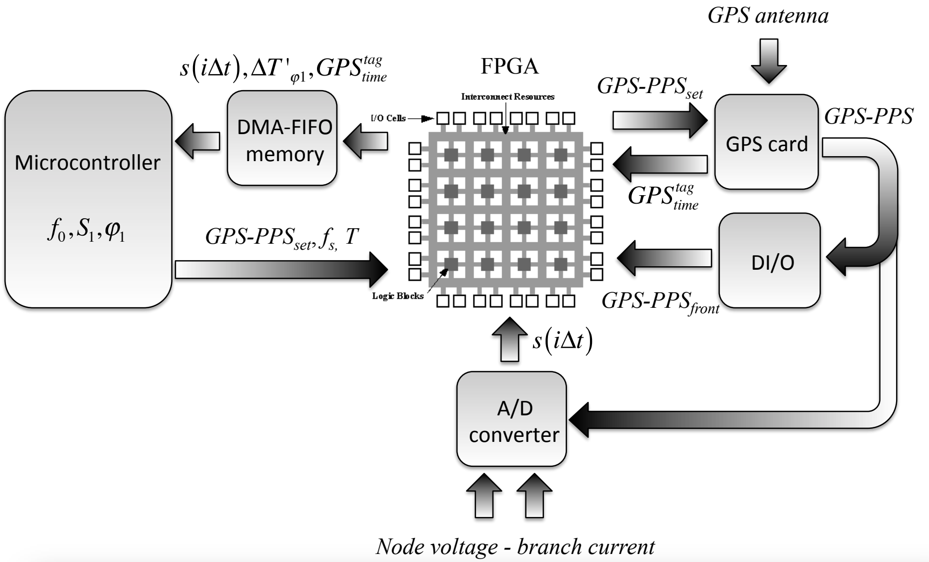
- Phasor Measurement Units – Mature Hardware, Emerging Networks and Applications
  - Supplements 50-year old SCADA technology
  - GPS time synchronized high resolution data
  - Wide coverage
- Provides MRI of Power System Compared to the X-ray Quality for the Visibility of Traditional SCADA
  - Wide-area situational awareness
  - System dynamics monitoring
  - Improved modeling

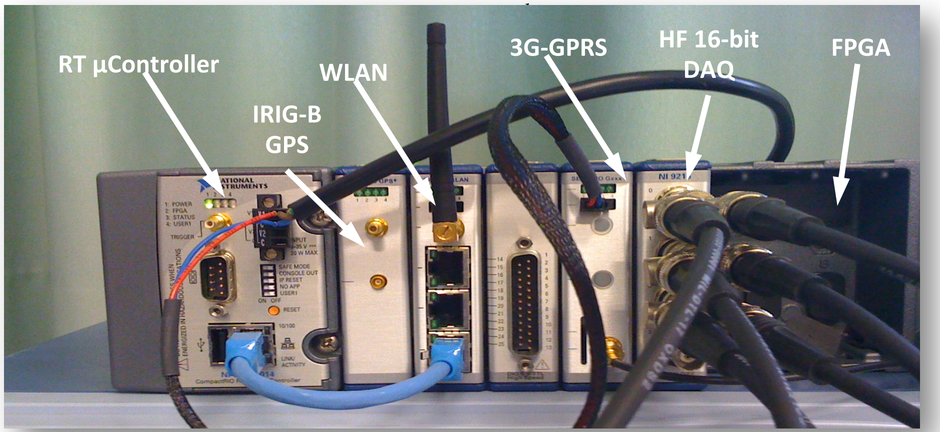
Advanced network monitoring by means of phasor measurement units

- Addresses Current Industry Problems
  - Blackout prevention – early warning - and restoration
  - Visualization – wide area, common data, common displays
  - Reliability standards monitoring
  - Security Assessment – safe operating zones
  - Renewables integration

Advanced operation of distribution networks

PMU prototype for distribution network applications



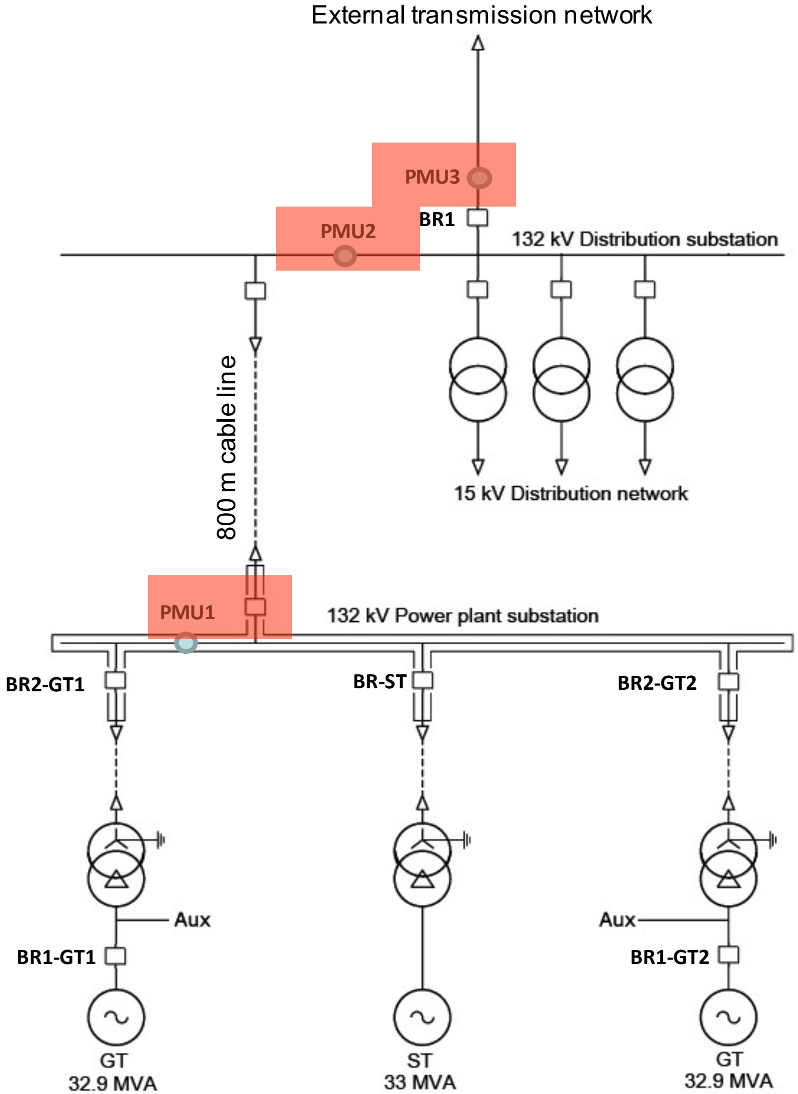


Quantity	Single tone signal μ	Single tone signal σ
Phase error	$10.0\cdot10^{-6}$ [rad]	$8.1\cdot10^{-6}$ [rad]
RMS error	$120.0\cdot10^{-6}$ [p.u.]	$9.3\cdot10^{-6}$ [p.u.]
TVE	$117.0\cdot10^{-6}$	$9.3\cdot10^{-6}$
Frequency error	$20.0\cdot10^{-5}$ [Hz]	$4.5\cdot10^{-5}$ [Hz]
Quantity	**Distorted signal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

Advanced operation of distribution networks

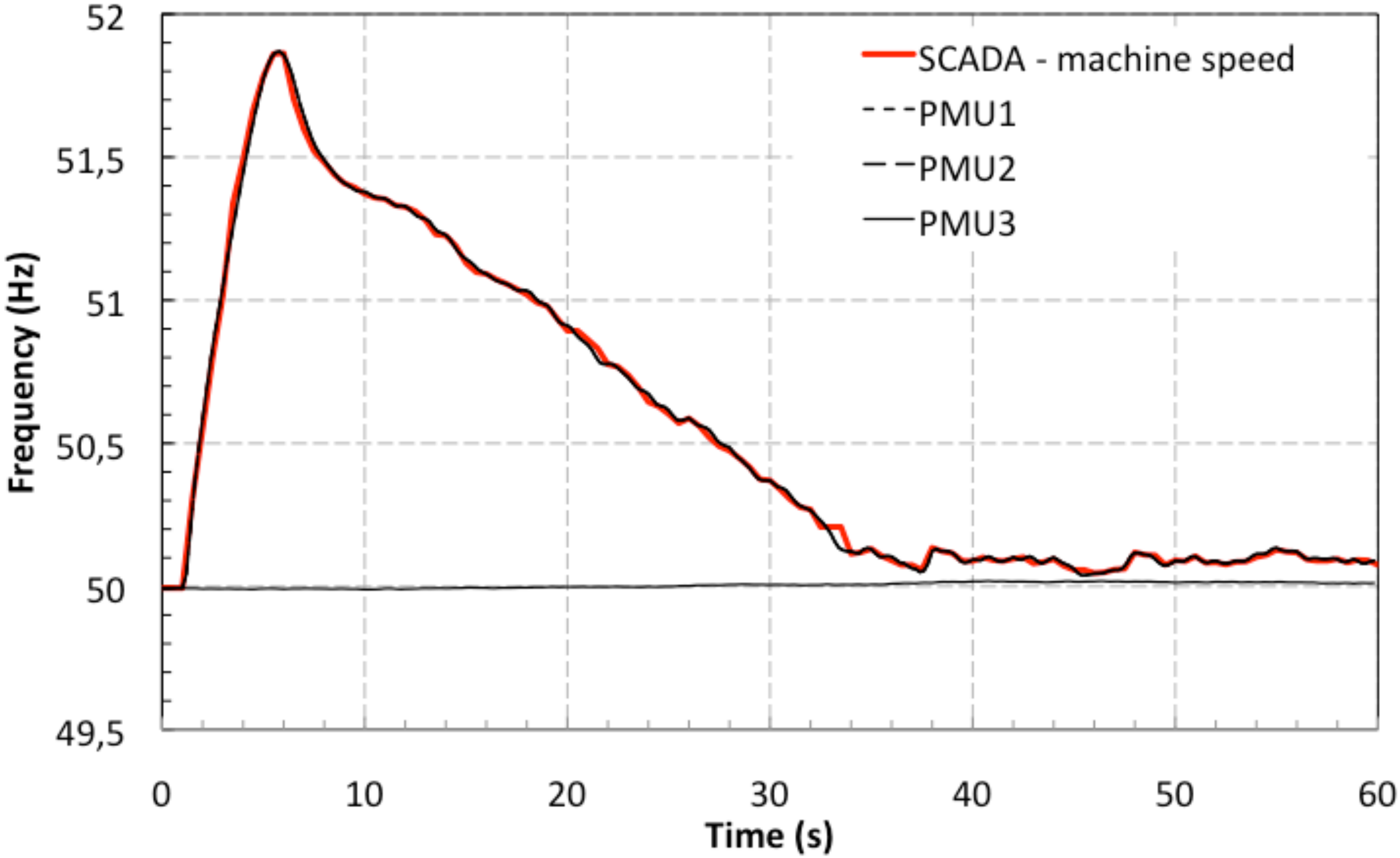
PMU application example

- 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.



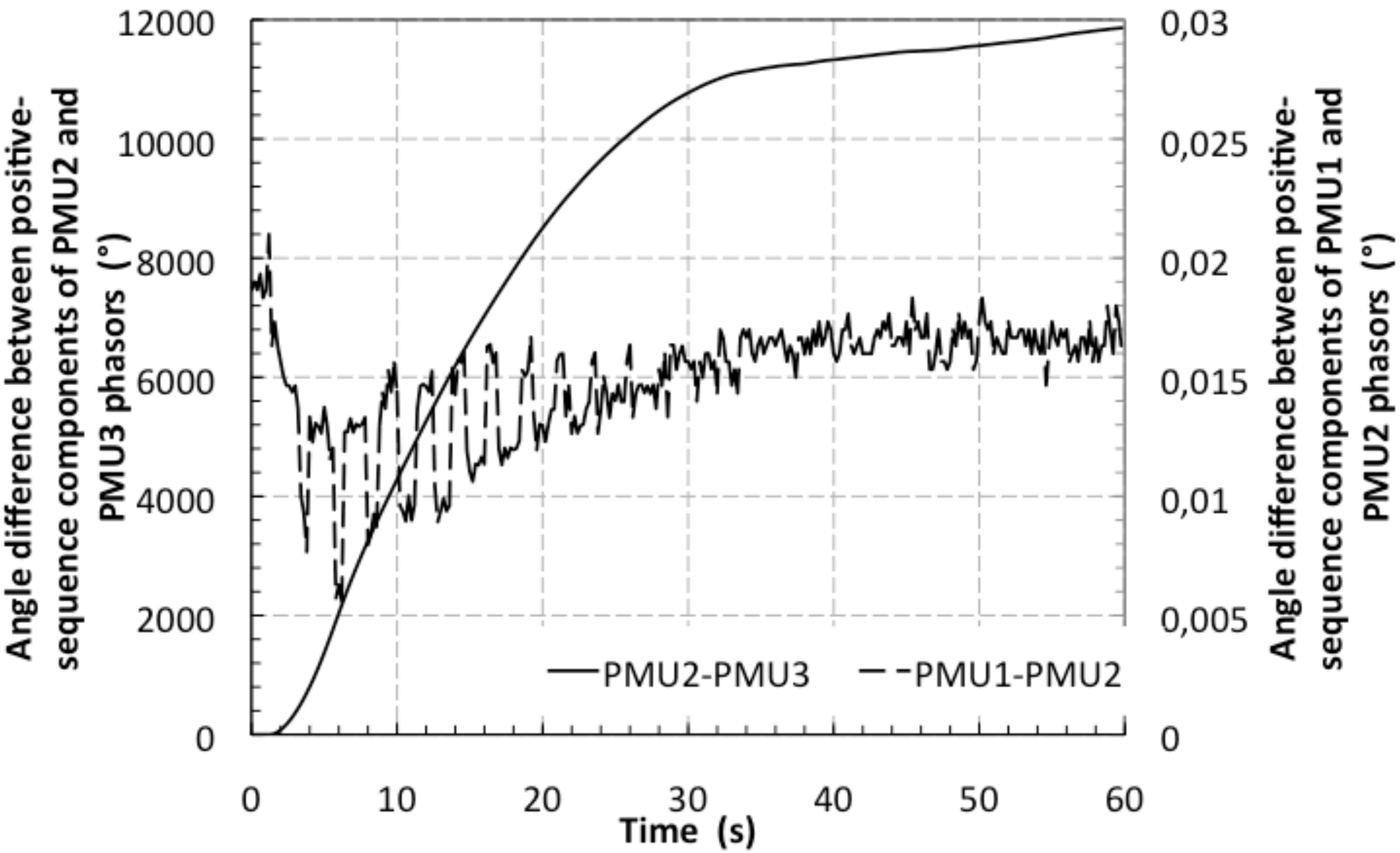
Advanced operation of distribution networks

Distribution network frequency transient after the islanding



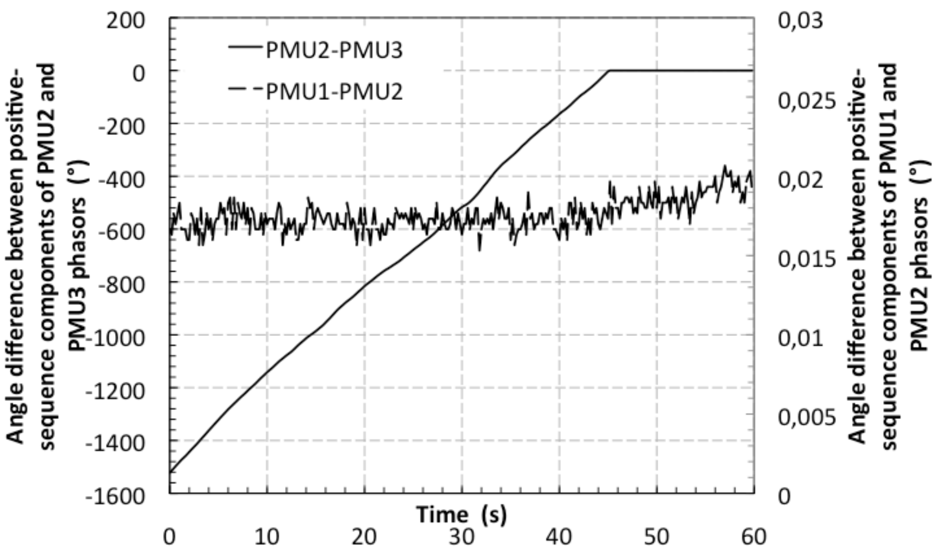
Advanced operation of distribution networks

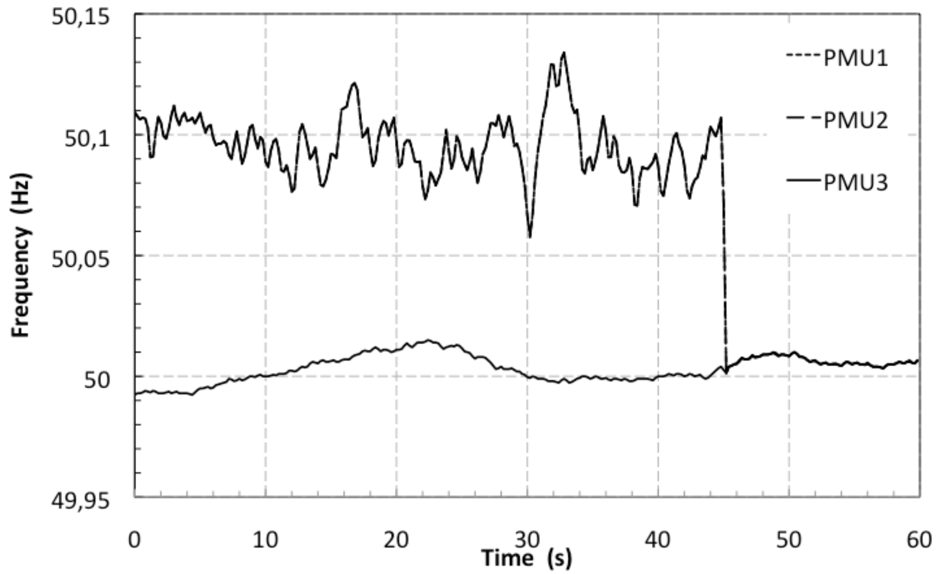
Distribution network phasors angles during the islanding



Advanced operation of distribution networks

Islanded network phasors during the reconnection with the external grid



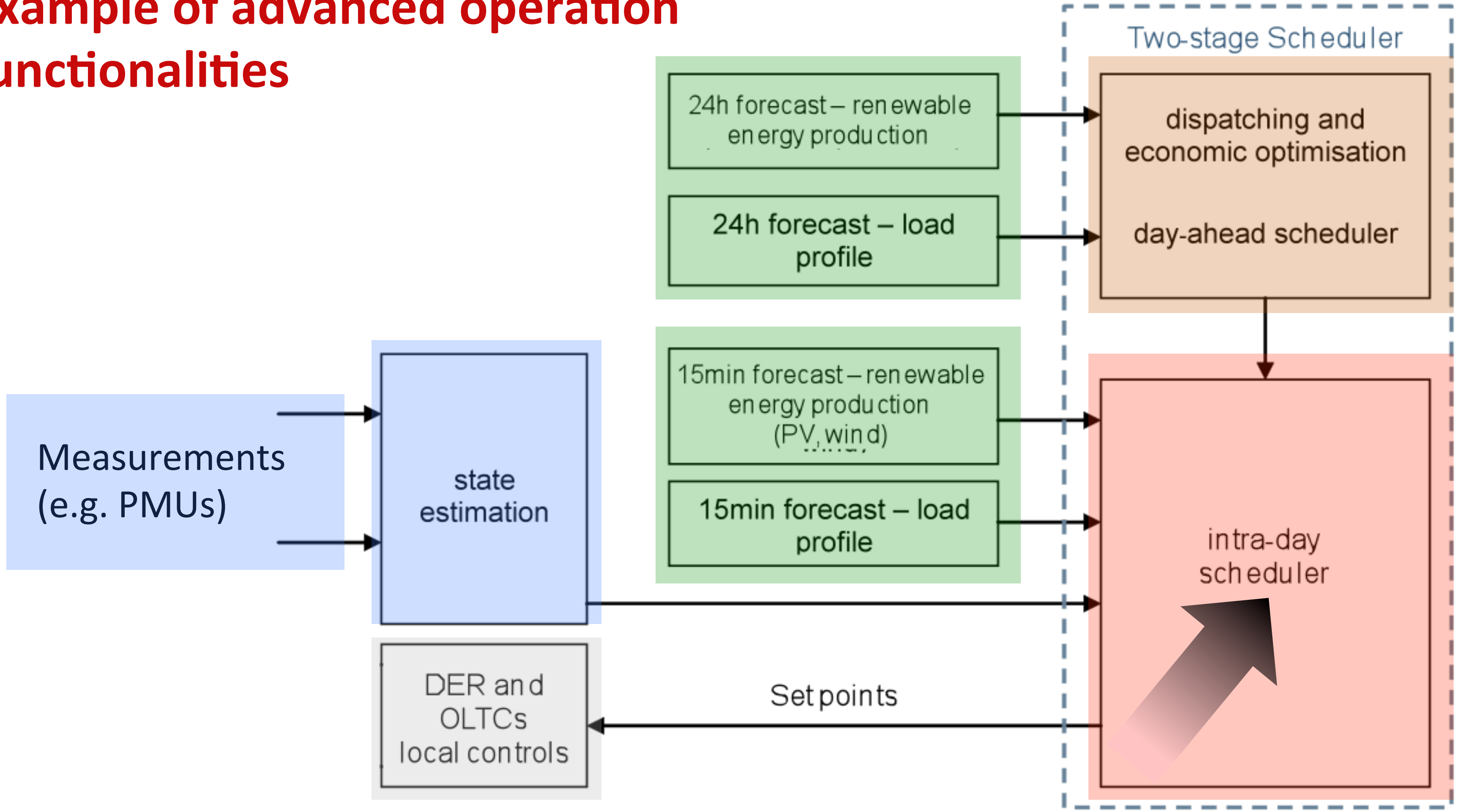


Optimal control - some preliminary remarks

- Improved “connect and forget” approach;
- each distributed energy resource becomes, **within its specific capability limits**, an important control tool (e.g. voltage regulation, frequency control).
- need to define:
  - ✓ local DER and centralized functionalities;
  - ✓ coordinated scheduling of both dispatchable DERs and regulation resources.

Advanced operation of distribution networks

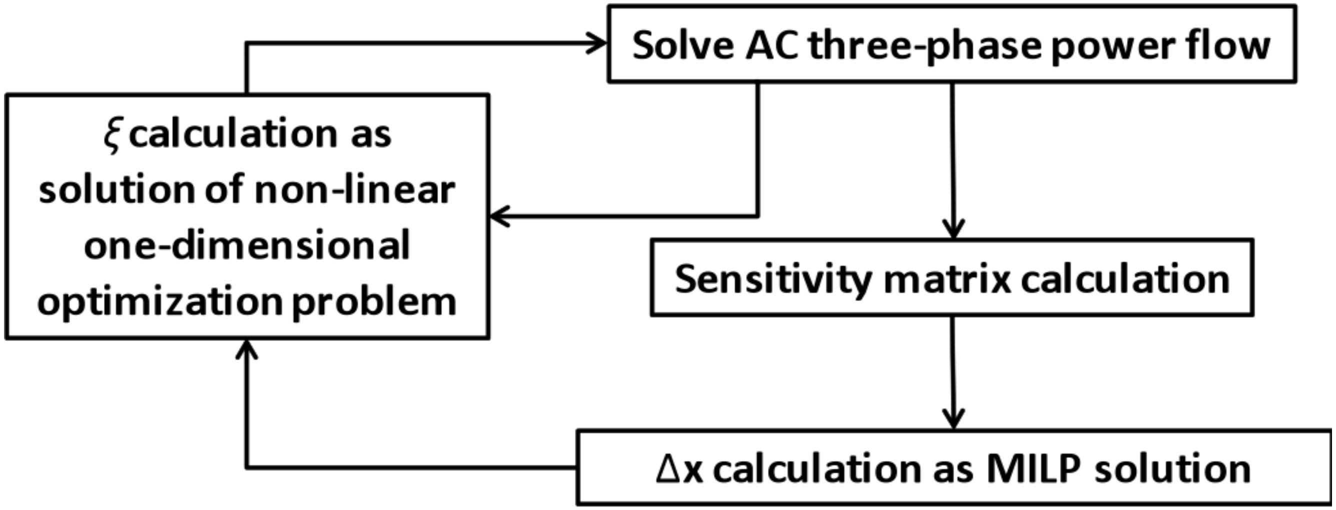
Example of advanced operation functionalities



Advanced operation of distribution networks

The goal of this optima control is the minimization of:

- **voltage deviations** with respect to the rated value;
- **DERs production deviations** with respect the set points;
- **network losses**.



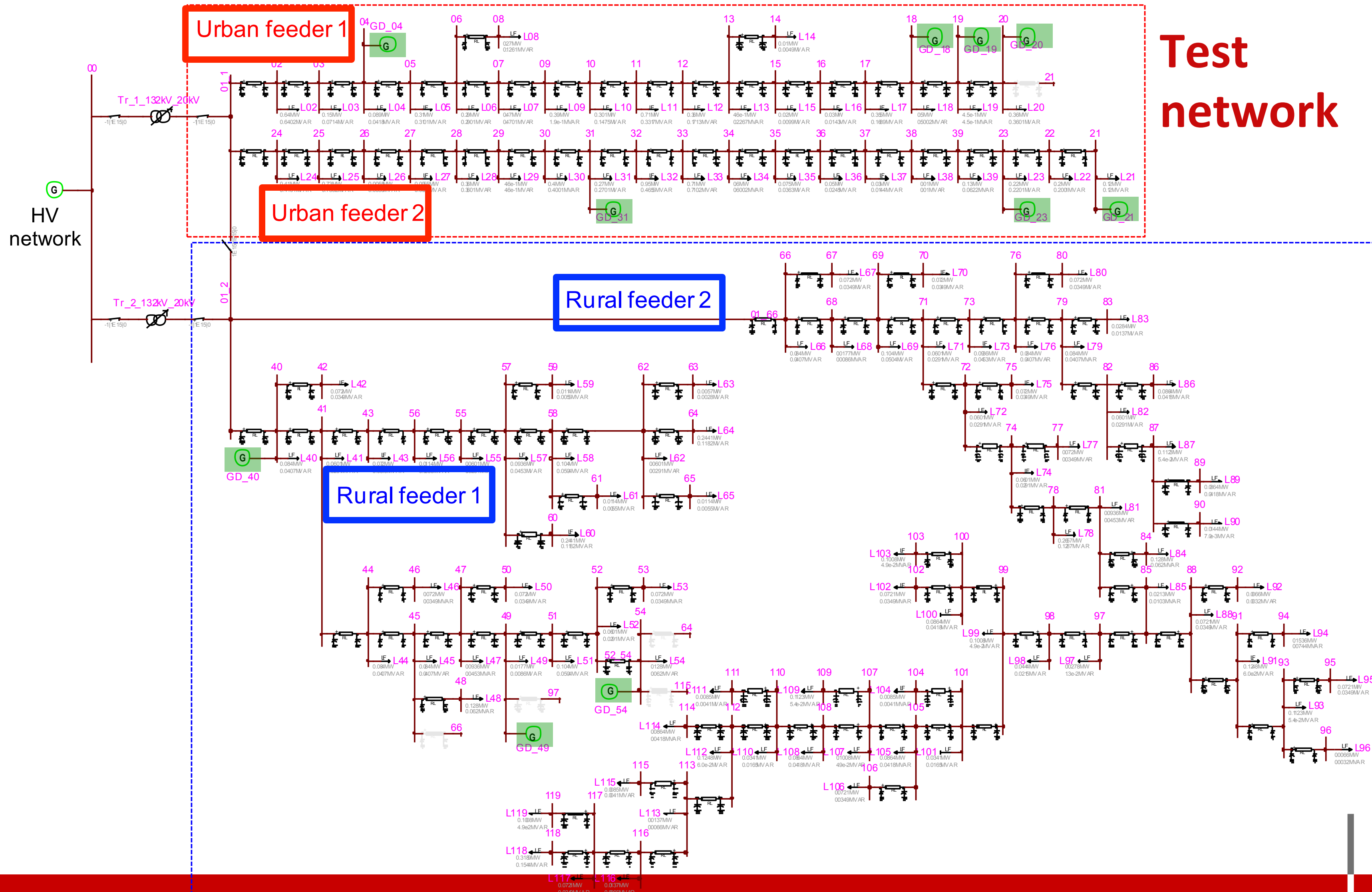
$$\mathbf{x} = [\mathbf{P}_{\text{DER}} \; \mathbf{Q}_{\text{DER}} \; \mathbf{n}_{\text{OLTC}}]$$

Example of objective function

$$\min_{\Delta \mathbf{x}} \left\{ \sum_{j=1}^{N_{bus}} \alpha \mathbf{s}_P + \beta P_{loss} + \sum_{i=1}^{N_{bus}} \gamma \mathbf{s}_V \right\}$$

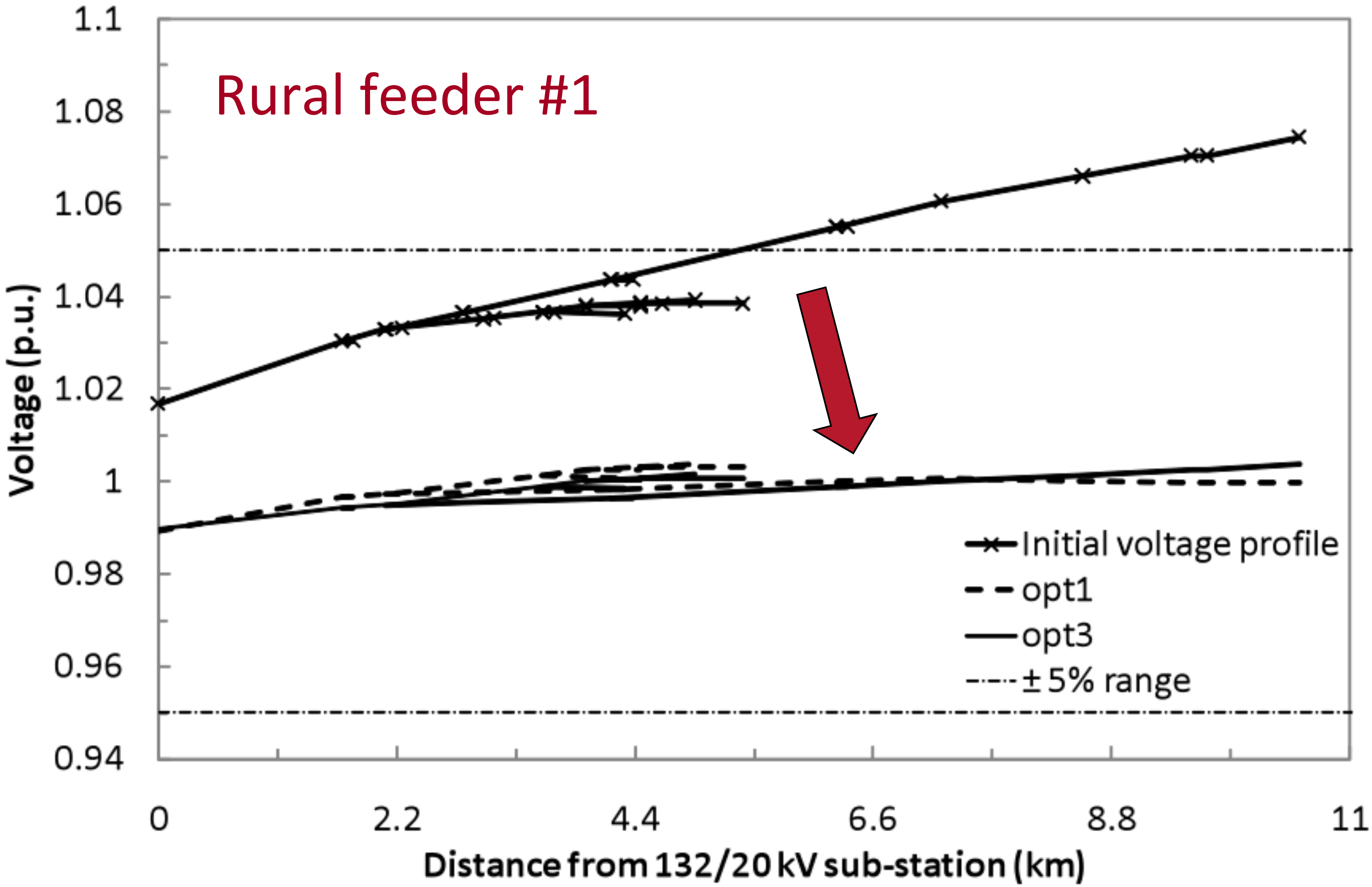
- s_P: vector of the artificial variables representing the differences of DERs power outputs P_j with respect to their references values;
- s_V: vector of the artificial variables representing the differences of bus voltages V_i with respect to their rated value;
- α, β, and γ : weights of each component of the objective function.

Advanced operation of distribution networks



Test network

Advanced operation of distribution networks



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Conclusions

- Deploy new technologies to transform the static grid to a smart and automatically switched network, in particular:
  - advanced monitoring technologies to allow the system operators to have a close real-time network state estimation
  - new control methodologies for mitigating power flow congestions in stressed power systems

- Integrate distributed technologies for generation, storage and control

Conclusions

- Power systems operators need to be involved into the development and, above all, into the selection and implementation of the different technologies and operation procedures. This will drive the rate of change of the distribution network operation in the next years.

- Standardization of component performances, communications, new protection schemes needs to be defined and shared among the research community and industry.