ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Microgrid EPFL – Méthodes innovantes issues de la recherche

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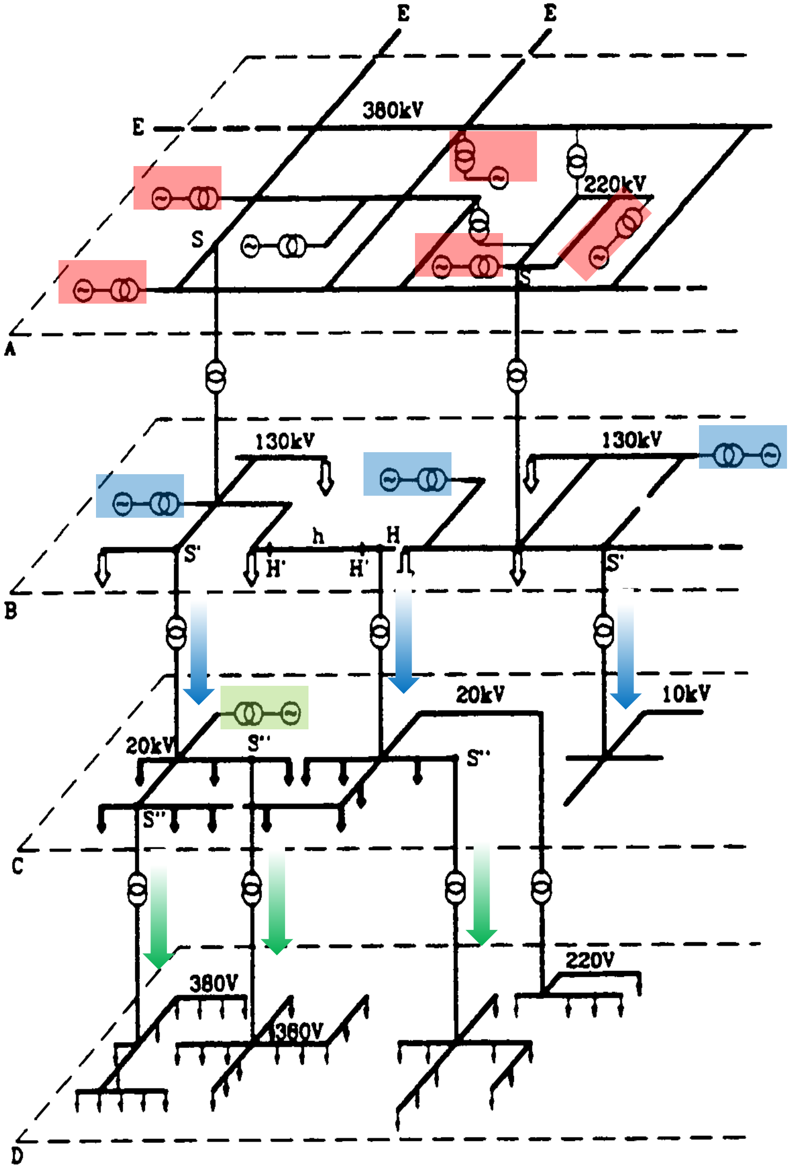
Distributed Electrical Systems Laboratory

Smart Grids –
Solutions intelligentes pour les sites et les villes
Mardi 5 décembre 2017, Berne

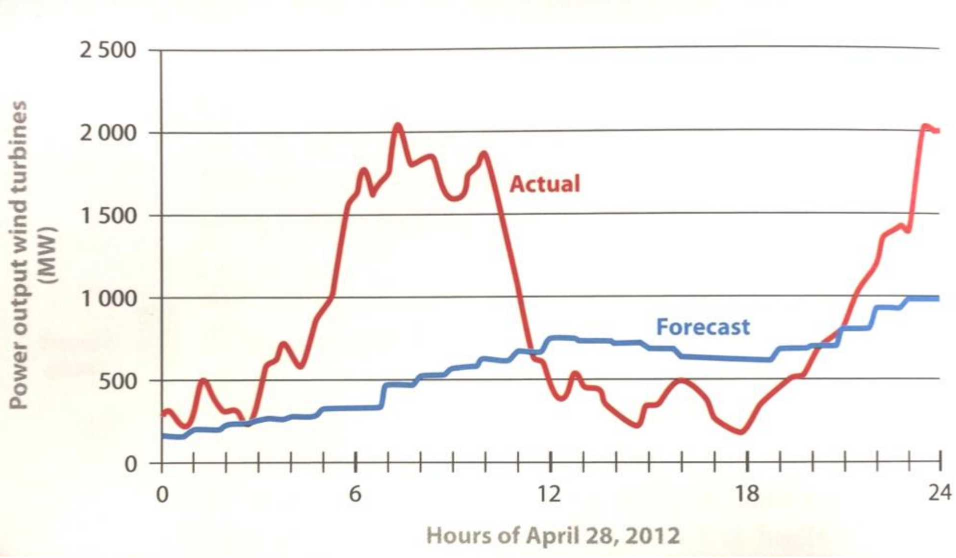
Classical ctrl approaches in energy systems



In traditional power systems, the **sources of uncertainties** are represented by the **loads**.

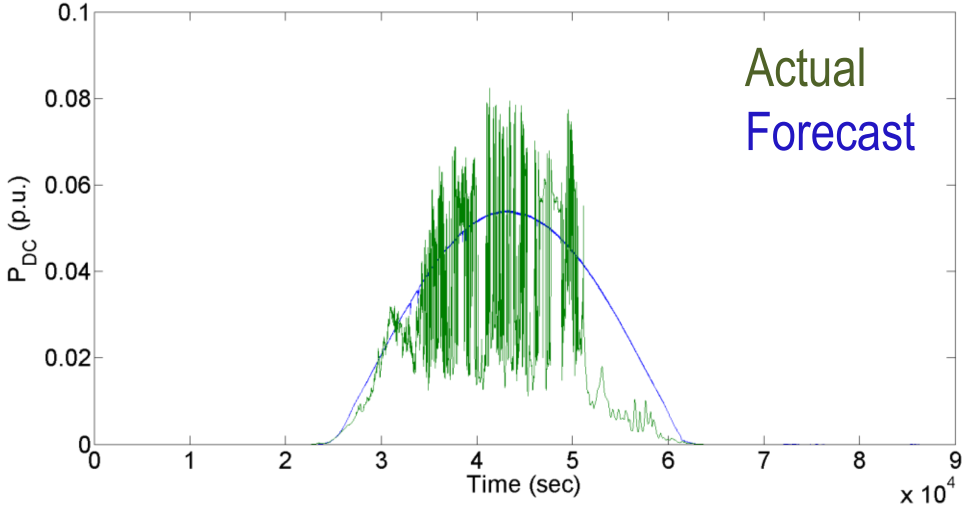
Majority of the control problems are solved in the **planning (years)** or **dispatching (day)** stages.

Importance of uncertainties of renewables

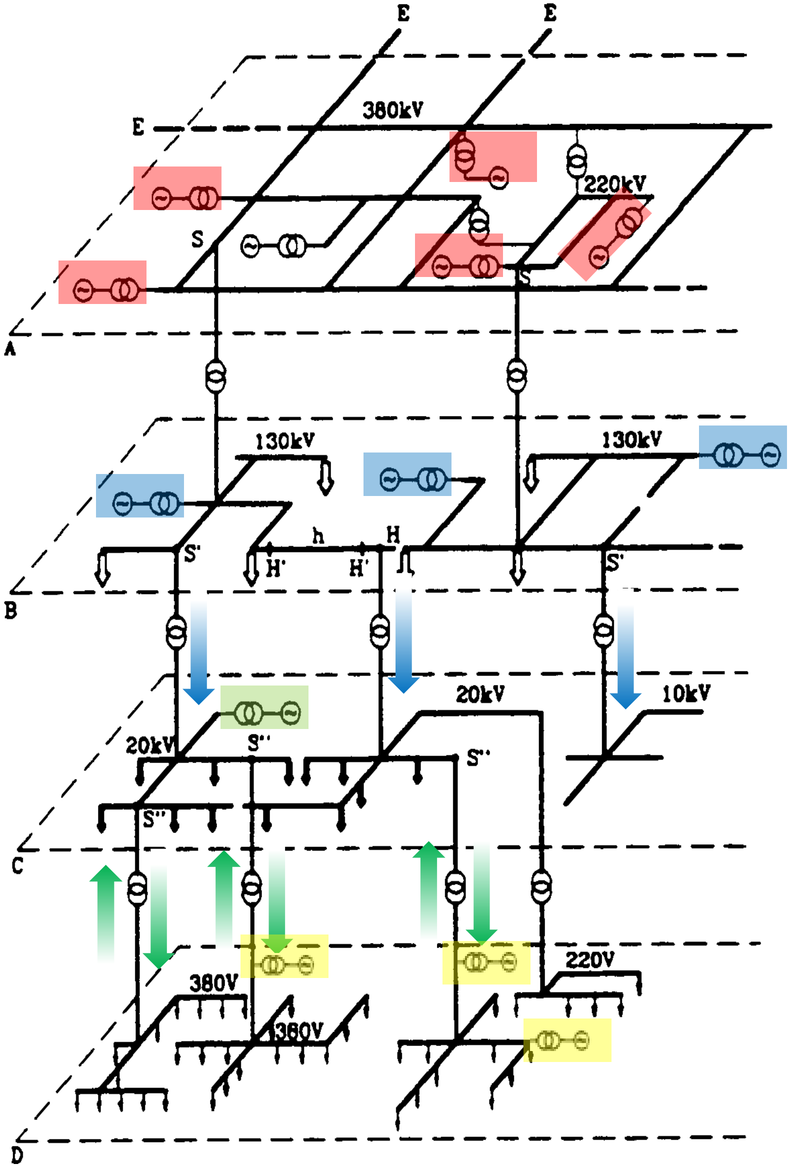


Example of deviation from predicted and actual power output from wind turbines in the German Amprion TSO region, April 28, 2012.

Example of deviation from predicted and actual power power injected by solar arrays at EPFL



Classical ctrl approaches in energy systems



Transmission

Sub-transmission

Distribution (medium voltage)

Distribution (low voltage)

Massive deployment of distributed energy resources → **large uncertainties come from injections**

Control problems are solved in the planning (years), dispatching (day) and **real-time**.

Methodological/technological challenges in smart grids

ms

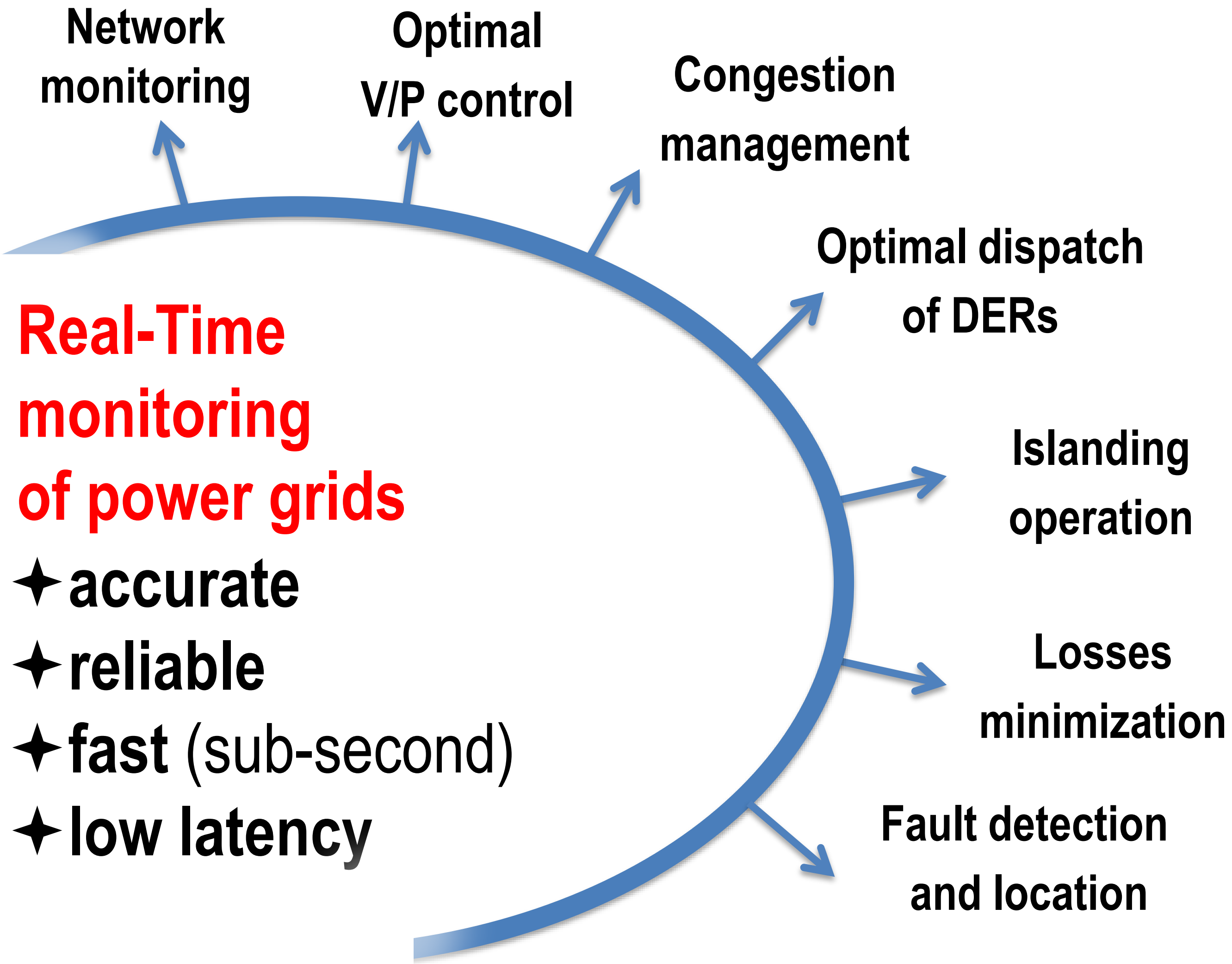
secs-mins

time

months

Problem	Required methods	Required technologies
Renewables short-term volatility	Real-time knowledge of the system state	**Distributed sensing (e.g. PMU)** Real-time state estimators
Grid congestions Voltage control	Exact optimal power flow Explicit control methods Stability assessment of complex systems (low inertia)	Distributed storage
Heterogeneous resources aggregation Ancillary services (system stability)	Real-time estimation of system flexibility Robust optimization Short-term forecast	Agent-based software frameworks Demand response New technologies in pumped hydro

Sensing: situation awareness and functions



Network monitoring

Optimal V/P control

Congestion management

Optimal dispatch of DERs

Islanding operation

Losses minimization

Fault detection and location

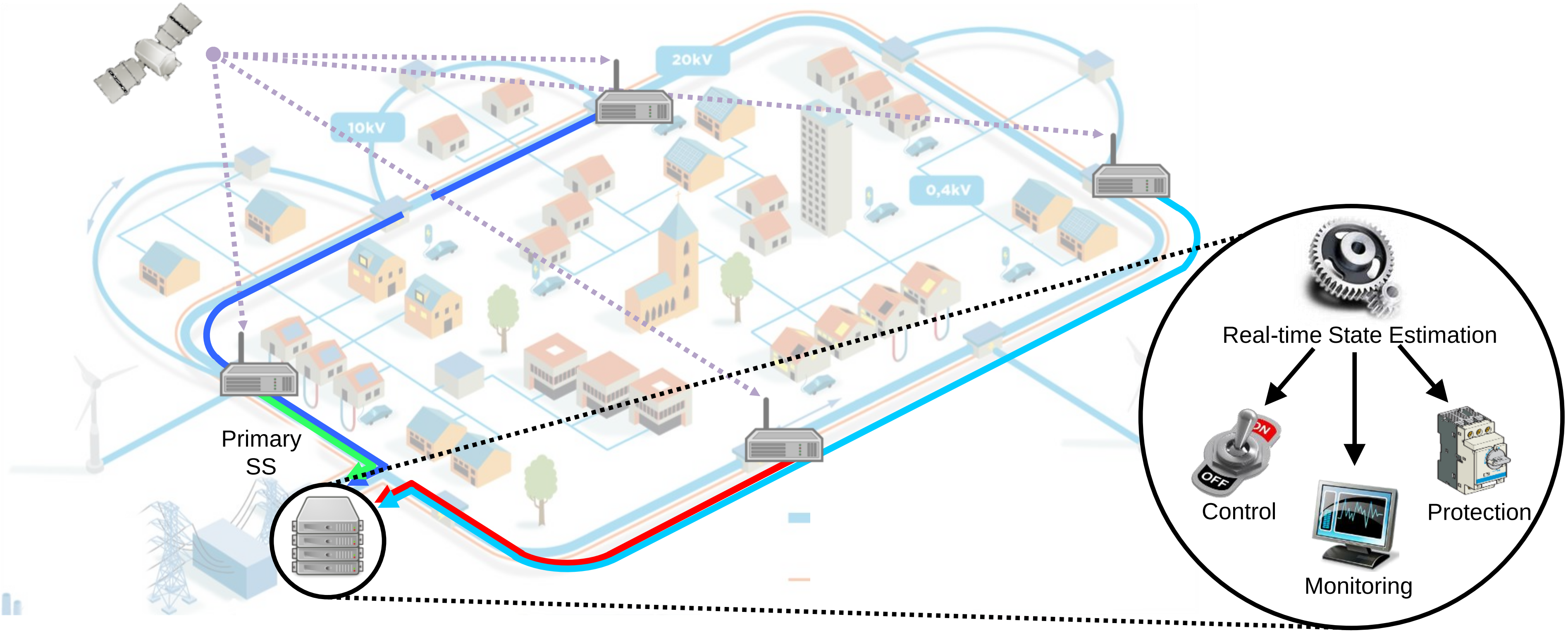
Real-Time monitoring of power grids

- **accurate**
- **reliable**
- **fast** (sub-second)
- **low latency**

Sensing: technologies and time synchronisation

Drivers **Availability of new technologies (e.g., precise time dissemination)**

→ Enable new situation-awareness and control schemes in power grids



Sensing: real-time state estimation via PMUs

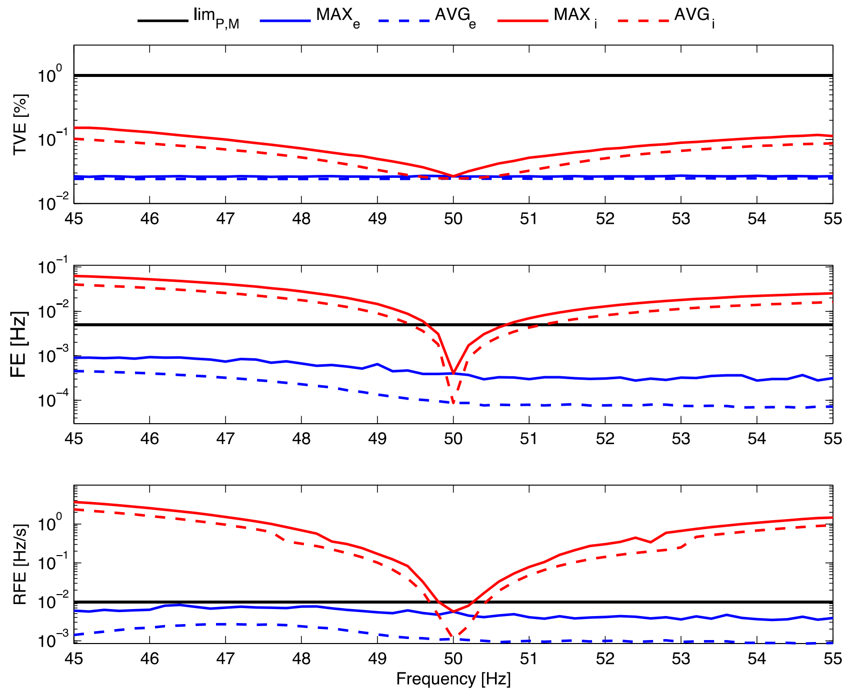
Definition

Phasor Measurement Unit
(IEEE Std.C37.118-2011)

"A device that produces **synchronized measurements of phasor** (i.e. its **amplitude** and **phase**), **frequency**, **ROCOF** (**Rate of Change Of Frequency**) from voltage and/or current signals based on a **common time source** that typically is the one provided by the **Global Positioning System UTC-GPS**."

Sensing: the EPFL PMU metrological performances

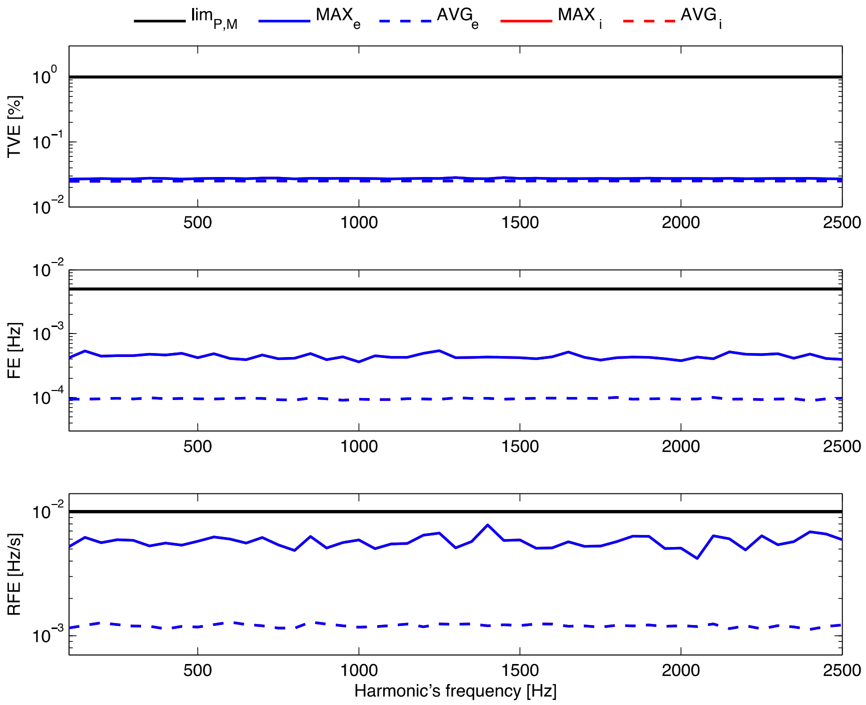
SINGLE TONE SIGNALS



Comments:

- TVE_{max} = 0.027 % – TVE_{avg} = 0.024 % **(1.5 µrad)**
- FE_{max}= $4{\cdot}10^{-4}$ – FE_{avg}= $9{\cdot}10^{-5}$
- RFE_{max}= $6{\cdot}10^{-3}$ – RFE_{avg} = $1{\cdot}10^{-3}$

MULTI TONE SIGNALS



Comments:

- Identical performances w.r.t. single tone signals
- Perfect harmonic rejection

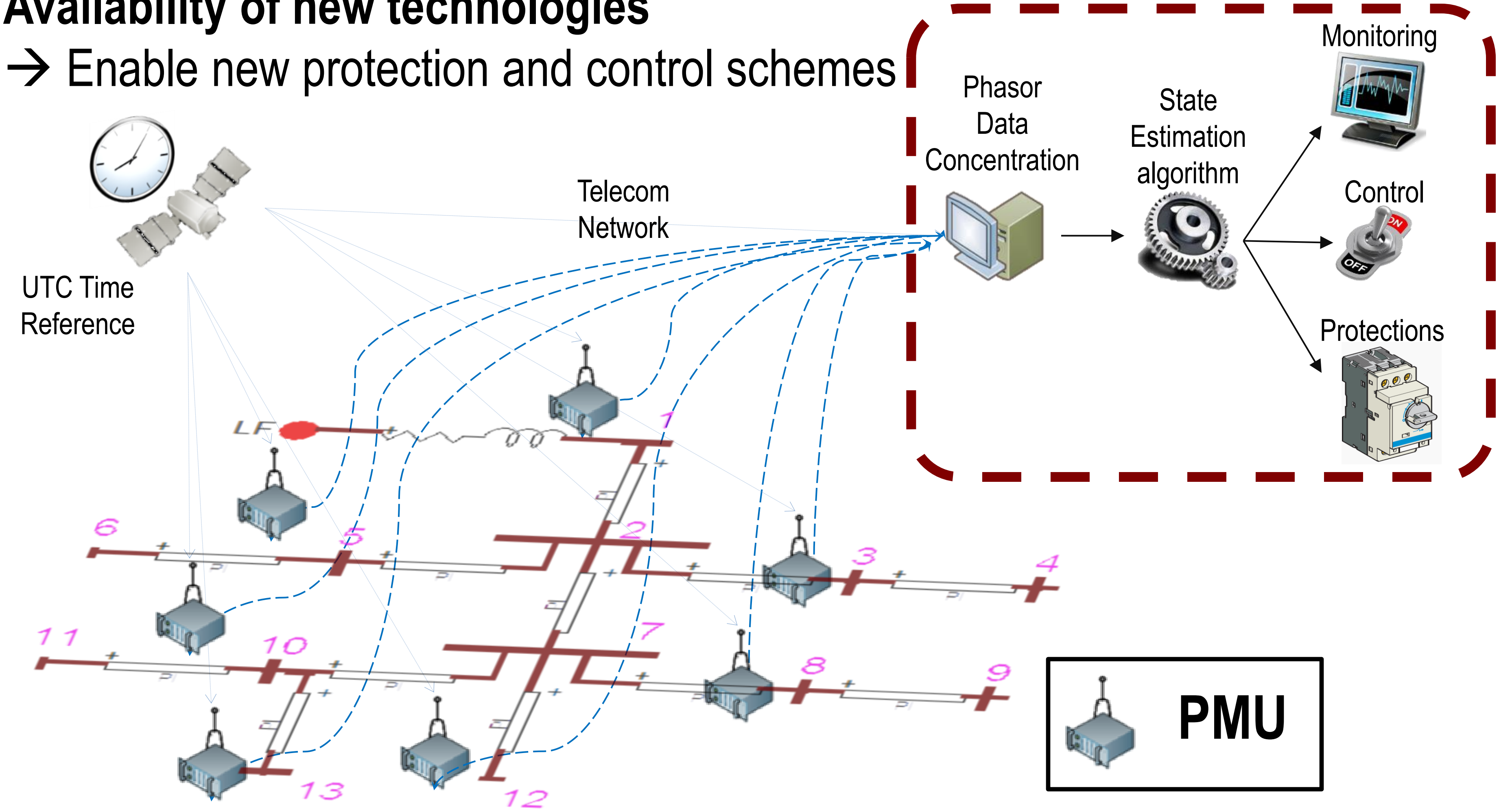
Methodological/technological challenges in smart grids

months time - secs-mins ms

Problem	Required methods	Required technologies
- Renewables short-term volatility	- **Real-time knowledge of the system state**	- Distributed sensing (e.g. PMU) - **Real-time state estimators**
- Grid congestions - Voltage control	- Exact optimal power flow - Explicit control methods - Stability assessment of complex systems (low inertia)	- Distributed storage
- Heterogeneous resources aggregation - Ancillary services (system stability)	- Real-time estimation of system flexibility - Robust optimization - Short-term forecast	- Agent-based software frameworks - Demand response - New technologies in pumped hydro

Real-Time State Estimation via PMUs

Availability of new technologies
→ Enable new protection and control schemes



Real-Time State Estimation via PMUs

Definition 1/2

To fix the ideas, in what follows with the term

Real-Time State Estimation – RTSE

we make reference to the process of **estimating the network state** (i.e., **phase-to-ground node voltages**) with an **extremely high refreshing rate** (typically of **several tens of frames per second**) enabled by the use of **synchrophasor measurements**.

Real-Time State Estimation via PMUs

Use cases

Monitoring

- Real-time visualization and alarming
- Real-time State Estimation
- Post-event analysis
- Planning of grid reinforcement due to excessive DER penetration
- Asset management
- Equipment misoperation
- System health monitoring
- …

Protection

- Fault identification
- Fault location
- Fault isolation

Control

- Voltage control
- Line congestion management
- Distributed resources control (e.g., electrochemical storage)
- Network islanding (and reconnection)
- System restoration

Methodological/technological challenges in smart grids

ms
secs-mins
time
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▪ Grid congestions ▪ Voltage control	▪ **Exact optimal power flow** ▪ **Explicit control methods** ▪ Stability assessment of complex systems (low inertia)	▪ Distributed storage
▪ Heterogeneous resources aggregation ▪ Ancillary services (system stability)	▪ Real-time estimation of system flexibility ▪ Robust optimization ▪ Short-term forecast	▪ Agent-based software frameworks ▪ Demand response ▪ New technologies in pumped hydro

Optimal real-time explicit control

The COMMELEC control framework – Main features

- inexpensive platforms (embedded controllers)
- scalability
- do not build a monster of complexity - bug-free

Such a control framework must be

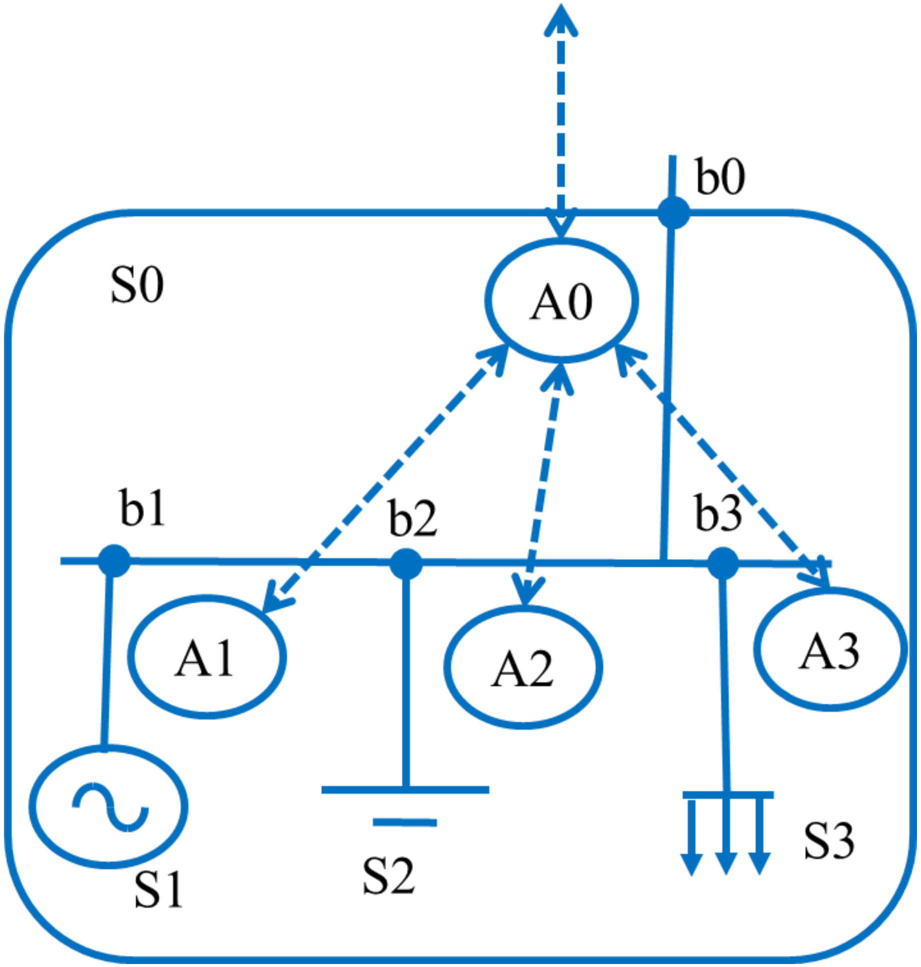
- scalable
- composable

(i.e. built with identical small elements)

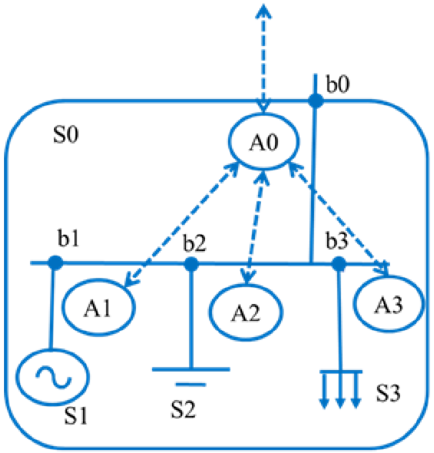
COMMELEC's Architecture

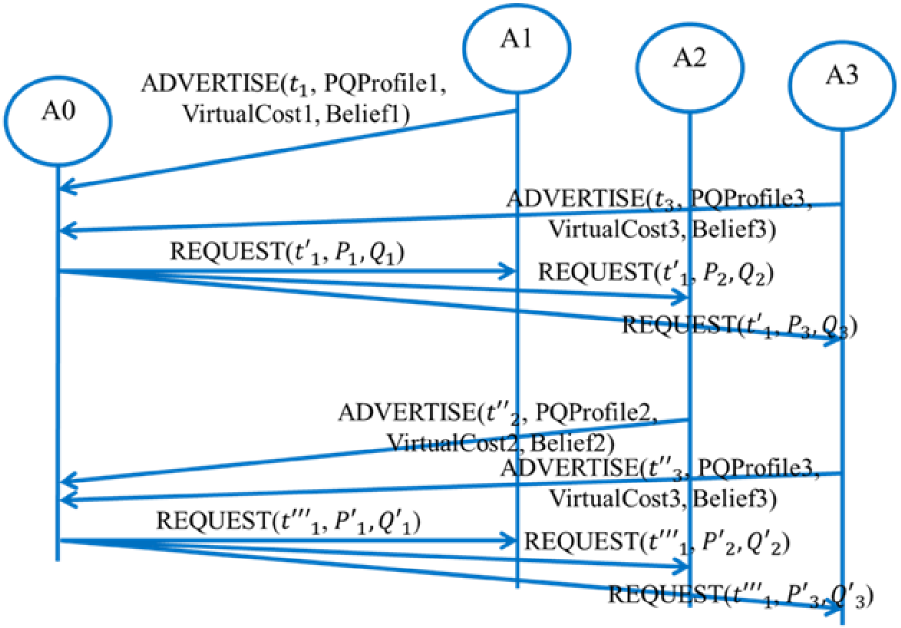
- **Software Agents** associated with devices
  - load, generators, storage
  - grids

- **Grid agent sends** explicit ***power setpoints*** to devices' agents



COMMELEC's Architecture





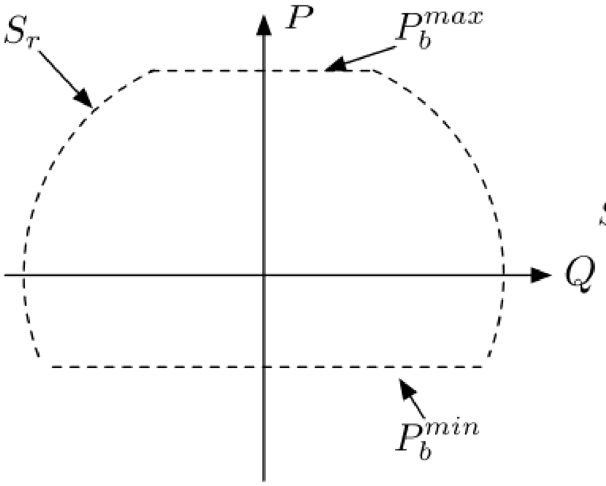
- Every agent **advertises** its state (example each 100 ms) as a ***PQt profile***, a ***virtual cost*** and a ***belief function***
- Each Grid agent computes optimal setpoints and sends them as **requests** to resource agents.

COMMELEC's Architecture – The PQt Profile

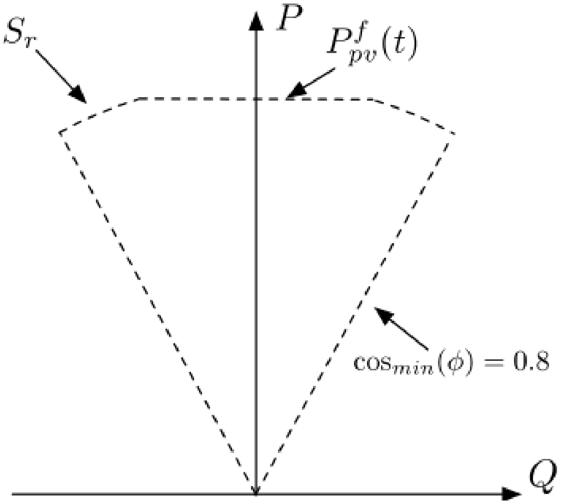
PQt profile: constraints on active/reactive power setpoints

Examples of *PQt* profiles

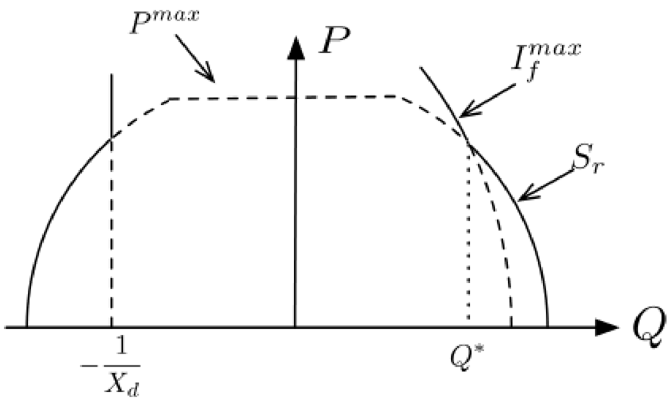
Battery



PV plant



Synchronous Generator



COMMELEC’s Architecture – The Virtual Cost

Virtual cost: proxy for the resource internal constraints

I can do P,Q in the next t

It cost you (virtually) $C(P,Q)$

Example:

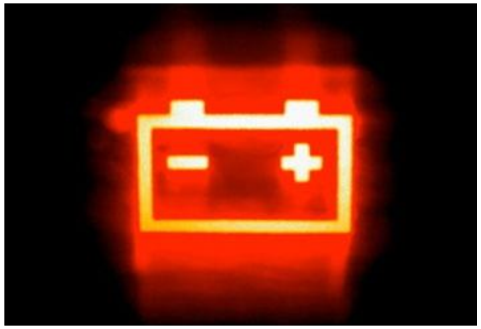
If (State-of-Charge) is 0.7

I am willing to inject power

If (State-of-Charge) is 0.3,

I am interested in absorbing power

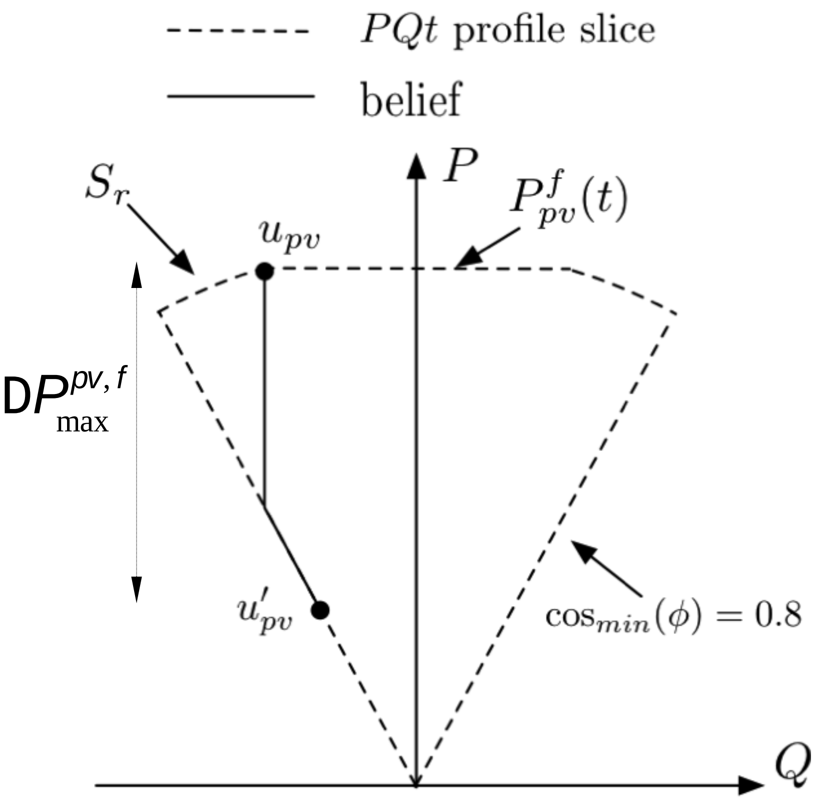
Battery agent



Grid agent

COMMELEC's Architecture – The Belief Function

- Say grid agent requests setpoint (P_{set}, Q_{set}) from a resource
- Actual setpoint **will, in general, differ**
- The ***belief function*** is exported by a resource agent with the semantic: resource implements $(P,Q) \in BF(P_{set},Q_{set})$
- It gives bounds on the actual (P,Q) that will be observed when the follower is instructed to implement a given setpoint.
- Essential for safe operation.



COMMELEC's Architecture – The Grid Agent's Job

Leader agent (grid agent) computes setpoints for followers based on

- the state of the grid
- advertisements received from the resources

The Grid Agent attempts to minimize

Cost of power flow at point of common connection

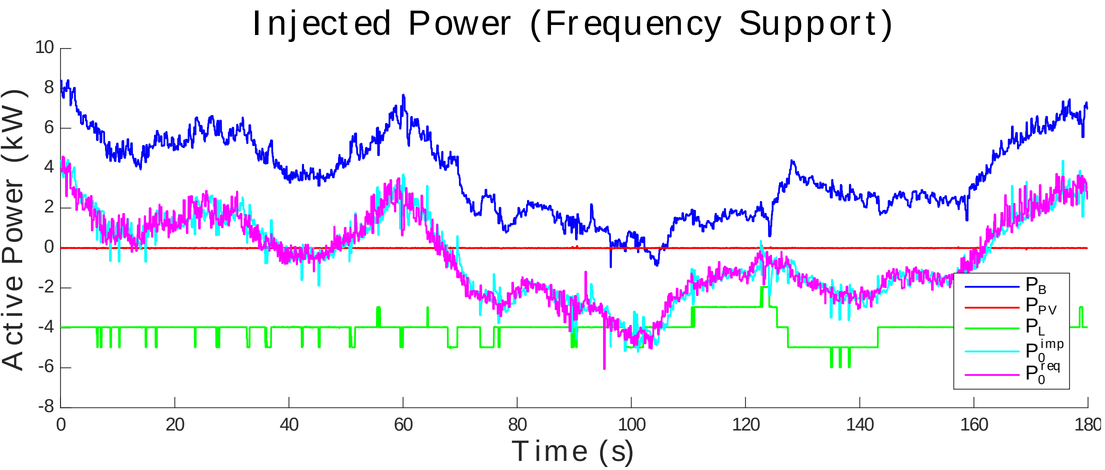
$$J(\mathbf{x}) = \sum_i w_i C_i(x_i) + W(\mathbf{z}) + J_0(\mathbf{x}_0)$$

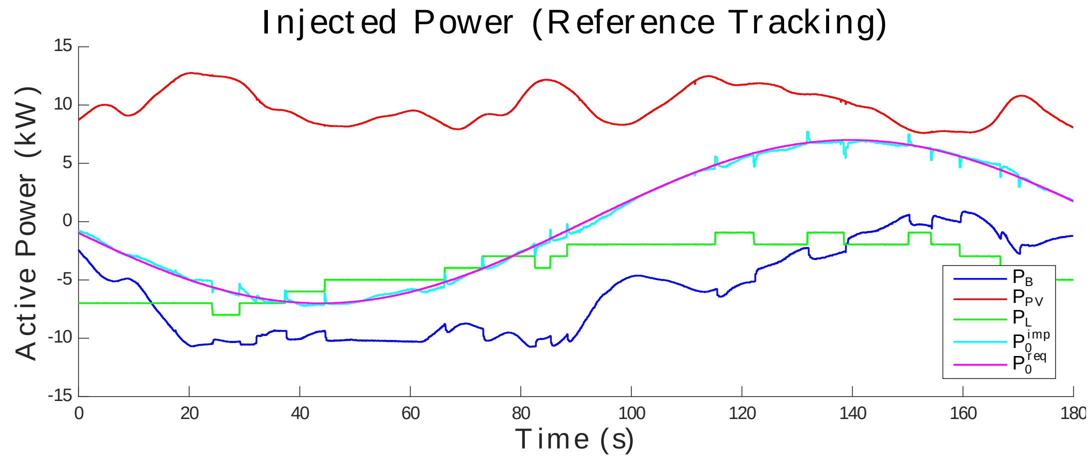
Virtual cost of the resources

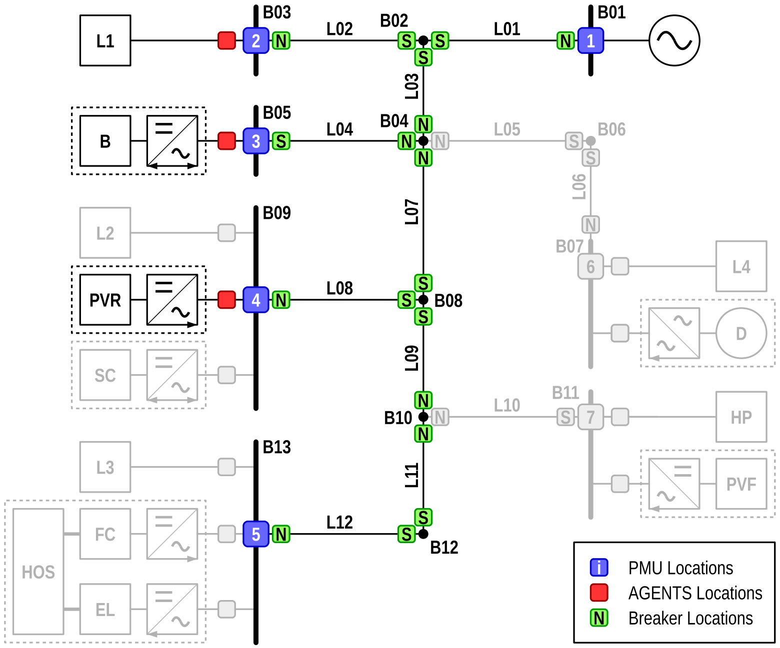
Penalty function of grid electrical state z (e.g., voltages close to 1 p.u., line currents below the ampacity)

The Grid Agent **does not see the details of resources**
a grid is a collection of devices that export *PQt* profiles, virtual costs and belief functions and has some penalty function problem solved by grid agent **is always the same**

COMMELEC's Architecture – Experimental results


Injected Power (Frequency Support)


Injected Power (Reference Tracking)




The EPFL-DESL microgrid

Methodological/technological challenges in smart grids

months - mins-hours

time

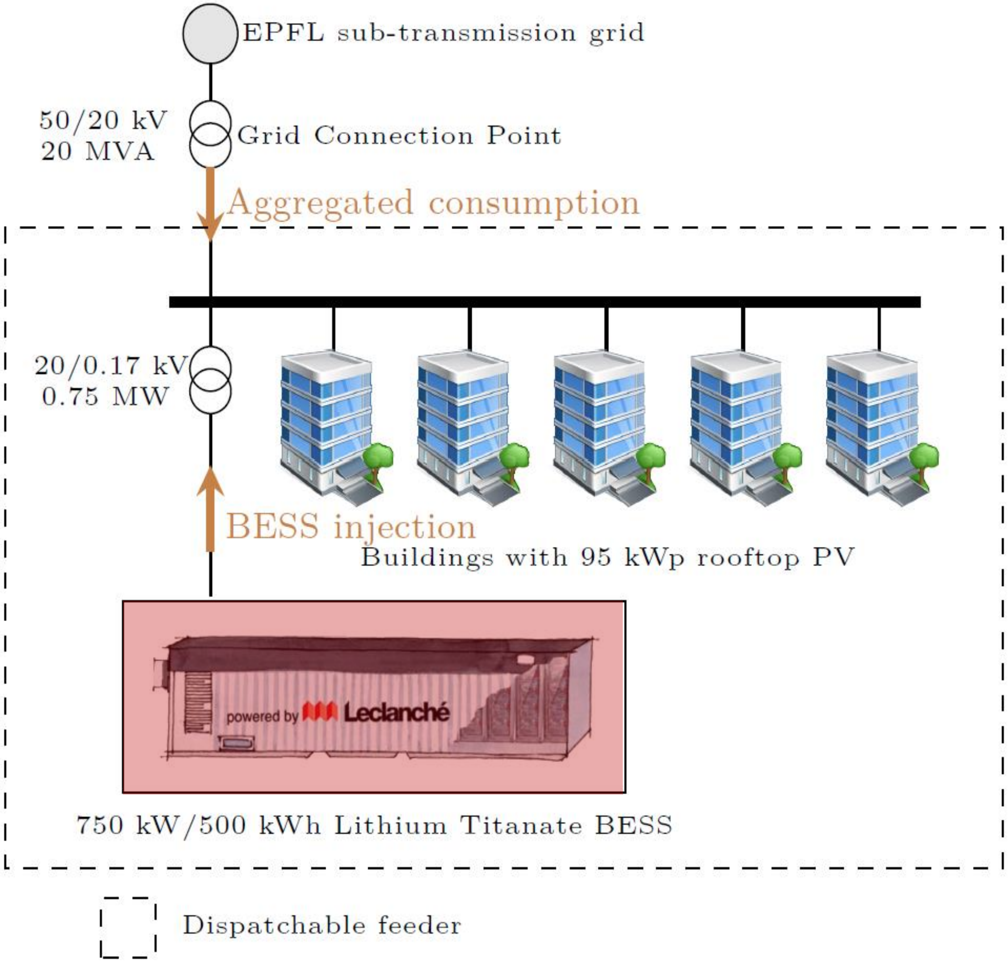
Problem	Required methods	Required technologies
- Renewables short-term volatility	- Real-time knowledge of the system state	- Distributed sensing (e.g. PMU) - Real-time state estimators
- Grid congestions - Voltage control	- Exact optimal power flow - Explicit control methods - Stability assessment of complex systems (low inertia)	- Distributed storage
- Heterogeneous resources aggregation - Ancillary services (system stability)	- **Real-time estimation of system flexibility** - **Robust optimization** - **Short-term forecast**	- Agent-based software frameworks - Demand response - New technologies in pumped hydro

Robust optimization applied to local systems: why ?

- Achieving **dispatched-by-design operation** of traditionally stochastic prosumption allows **reducing grid reserve requirements**.

- The **dispatch plan** is built to satisfy a **local objective**, such as **peak shaving**, **load levelling** or **minimization of the cost of imported electricity**.

The topology of a dispatchable feeder (EPFL campus)

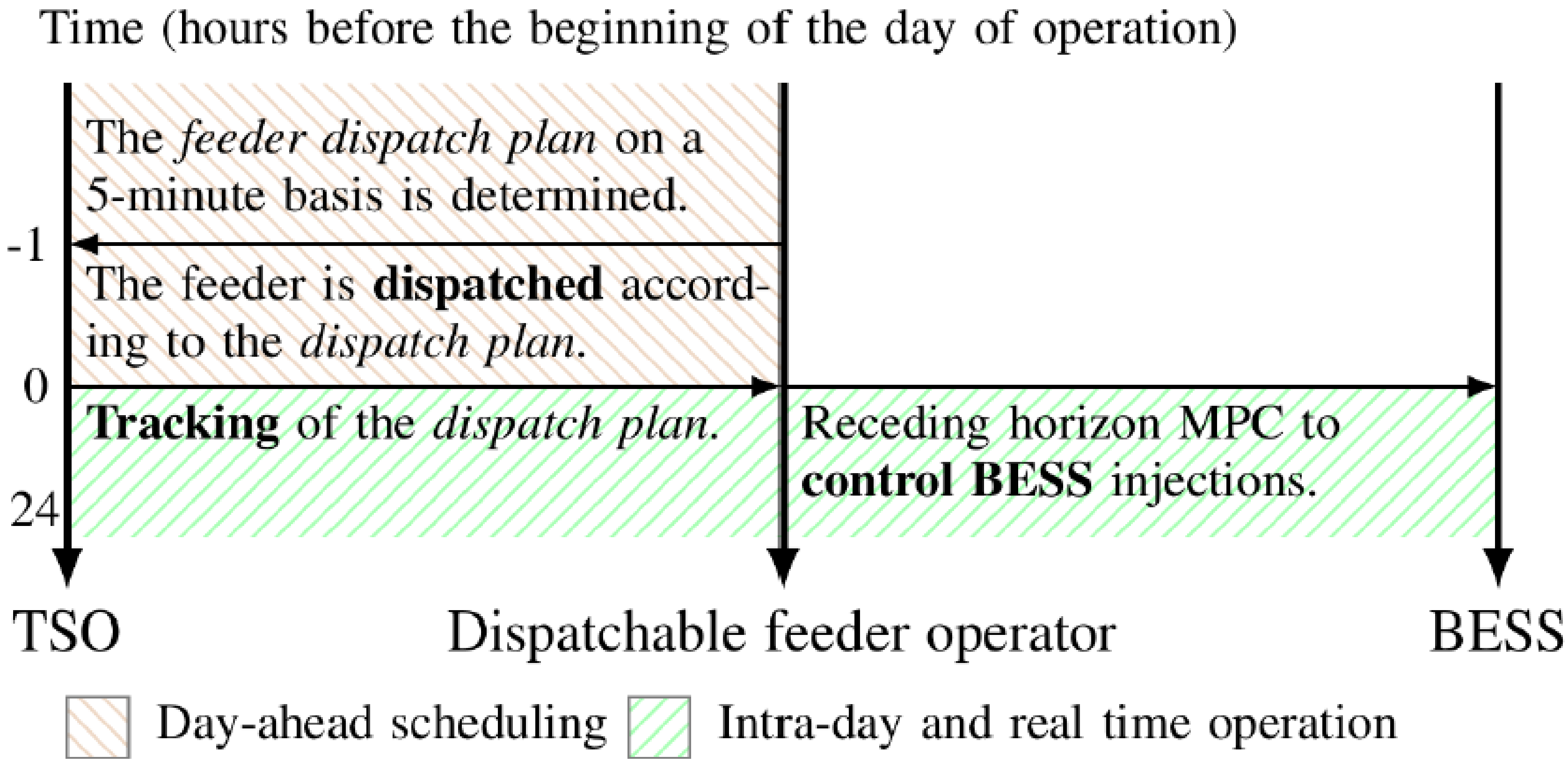


Sources of flexibility:

- **physical energy storage storage systems**

The operation of a group of stochastic prosumers (**generation + demand**) is dispatched according to a profile established the day before operation (called **dispatch plan**) by controlling the real power injection of the battery.

The DF problem formulation – A two stage process



Time (hours before the beginning of the day of operation)

-1

0

24

The *feeder dispatch plan* on a 5-minute basis is determined.

The feeder is **dispatched** according to the *dispatch plan*.

Tracking of the *dispatch plan*.

Receding horizon MPC to **control BESS** injections.

TSO

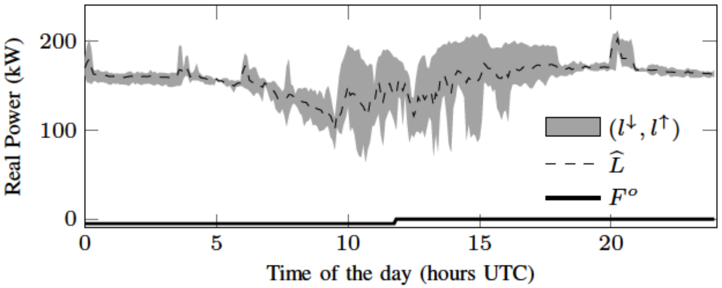
Dispatchable feeder operator

BESS

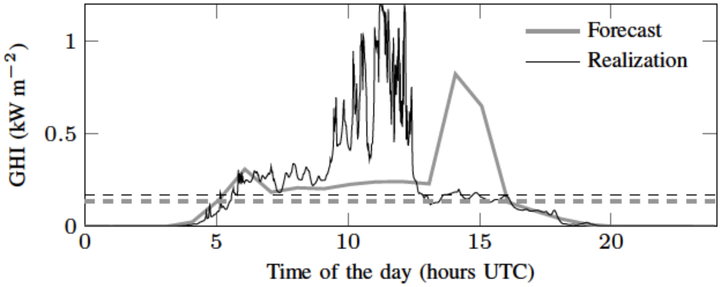
▨ Day-ahead scheduling ▨ Intra-day and real time operation

The DF experimental performances

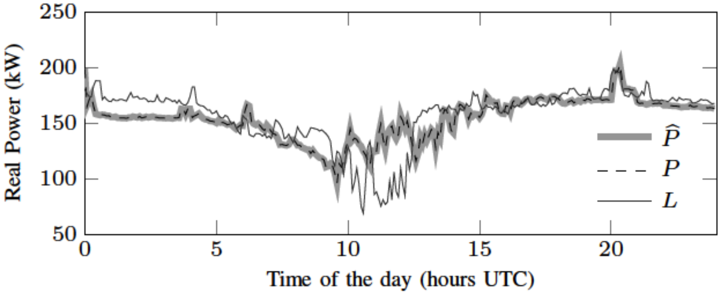
24h dispatch of heterogeneous EPFL campus aggregated resources



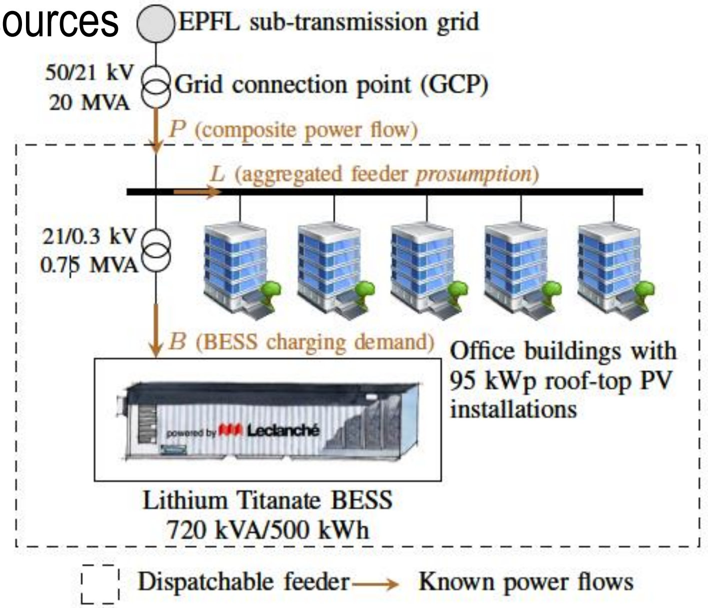
(a) **Day-ahead: prosumption uncertainty sets and expected value, and offset plan.**



(b) **GHI forecast *vs* realization and respective average components.**



(c) **Real-time: *dispatch plan vs* realization of GCP power transit and prosumption.**



Conclusions

The **massive integration of volatile resources** is and will drive **major changes** in modern power systems and future smart grids.

Current Swiss research programs have developed new technologies and methodologies to re-engineer the sensing and control of power grids.

- **Real-time situation awareness of power systems enabling new control schemes.**
- **Seamless aggregation and control of heterogeneous energy resources via abstract control methods.**