REAL-TIME CONTROL OF ELECTRICAL GRIDS WITH EXPLICIT POWER SETPOINTS

INRIA-EPFL Workshop

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joint work with

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Laboratory for Communications and Applications and
Distributed Electrical Systems Laboratory

References

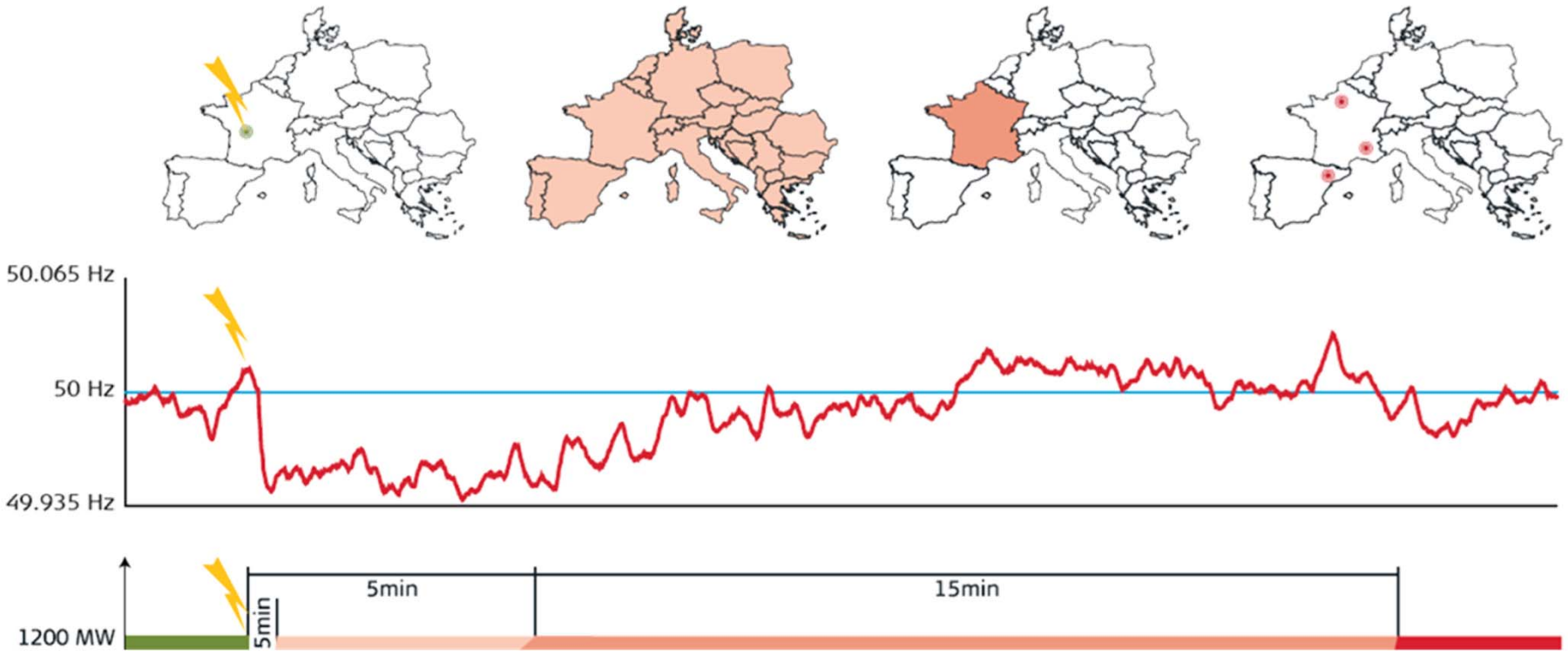
[Commelec] Andrey Bernstein, Lorenzo Reyes-Chamorro , Jean-Yves Le Boudec , Mario Paolone, “A Composable Method for Real-Time Control of Active Distribution Networks with Explicit Power Setpoints”, arXiv:1403.2407 (http://arxiv.org/abs/1403.2407)

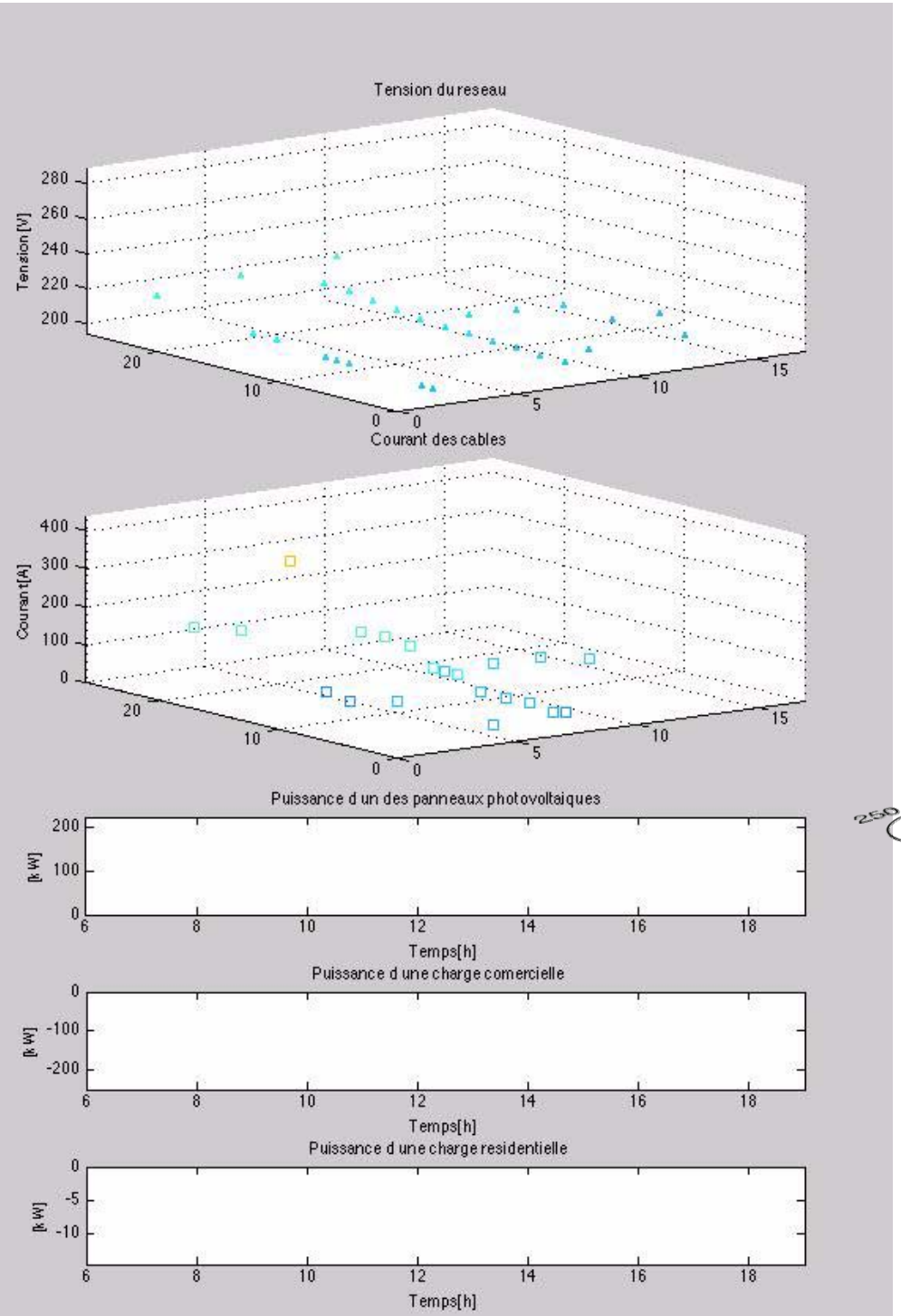
http://smartgrid.epfl.ch

[Campus smart grid] M. Pignati et al ,“Real-Time State Estimation of the EPFL-Campus Medium-Voltage Grid by Using PMUs”, to appear at Innovative Smart Grid Technologies (ISGT2015)

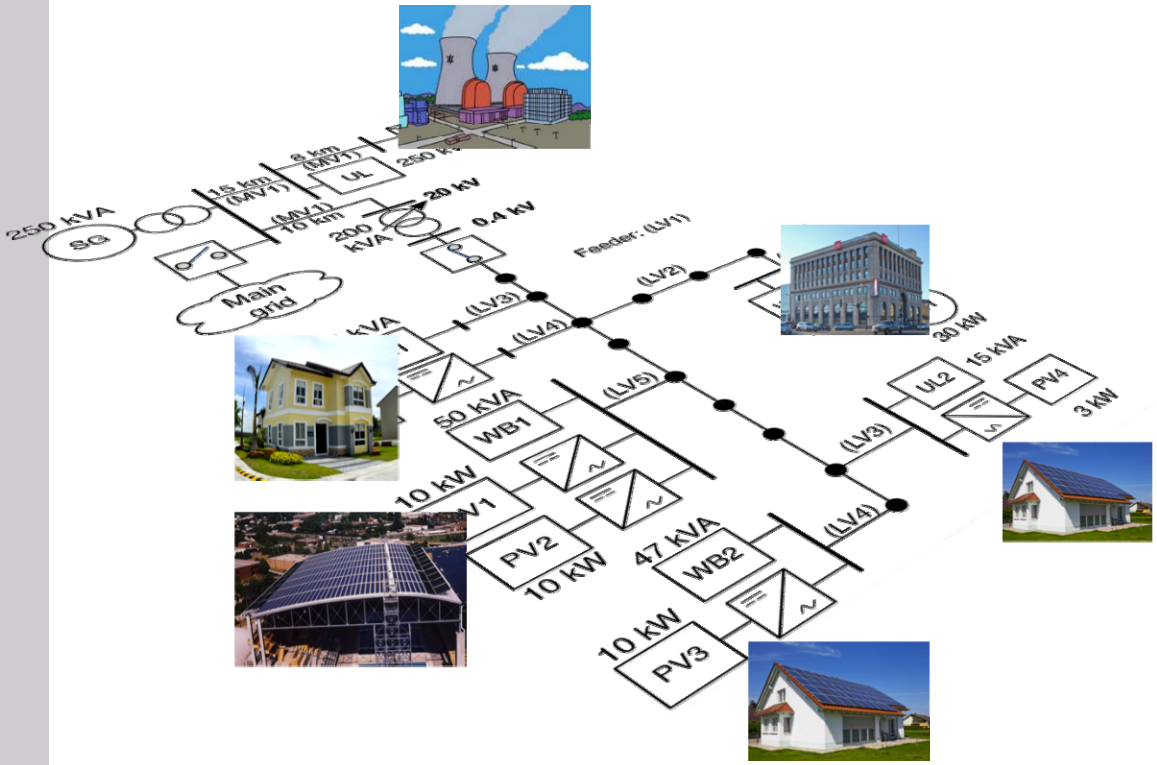
1. Motivation: Real Time Control of Electrical Grids

- Electrical grids are controlled in real-time to ensure Energy balance + Quality of Service
- Generators react to frequency variations (droop control)
- Issue: inertia-less systems (DC/AC converters : wind mills, PVs)

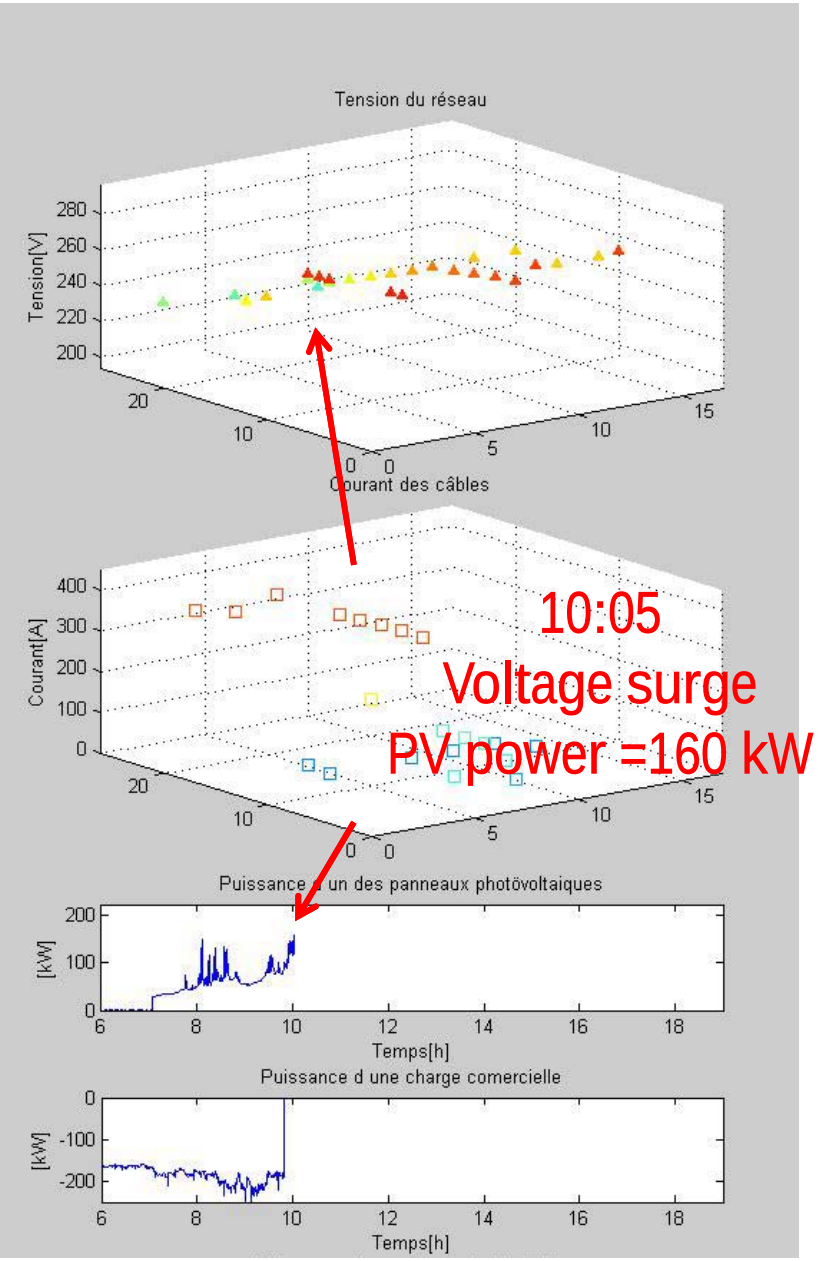


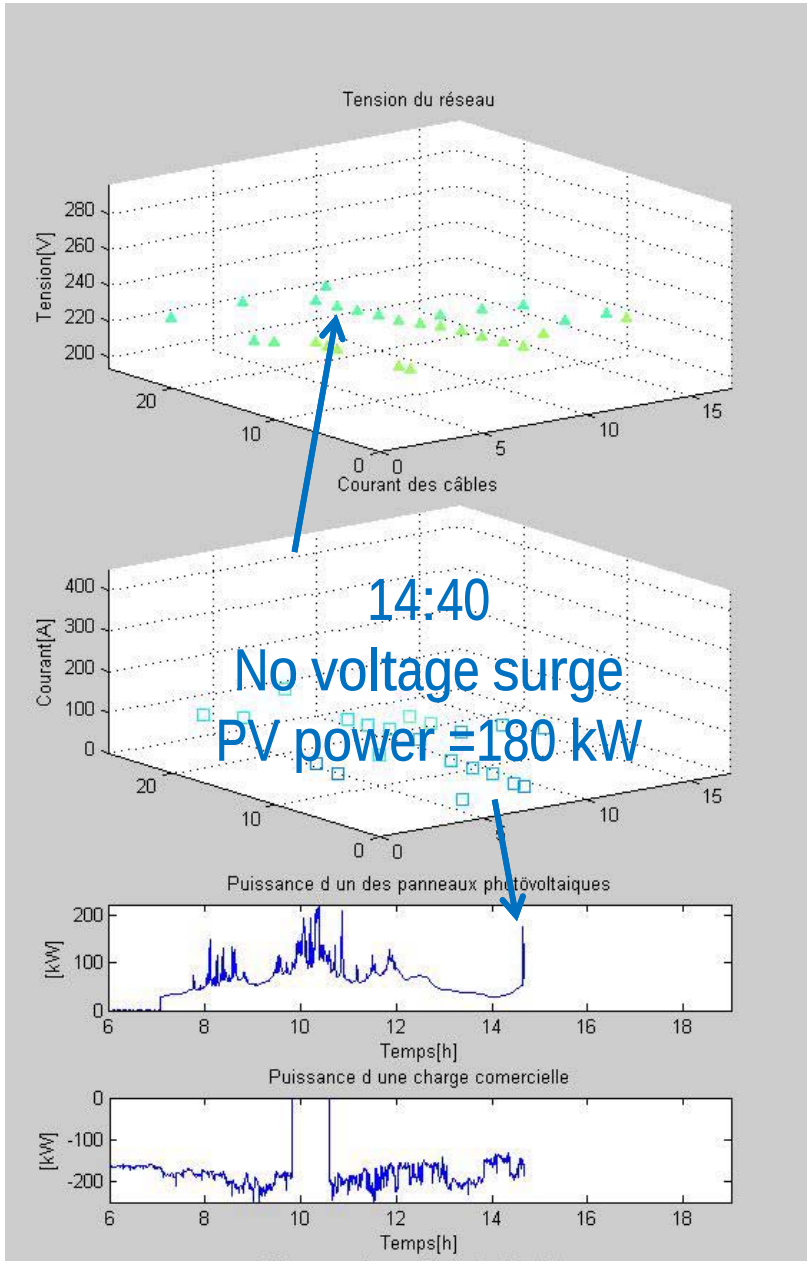


Current methods for real time control of electrical grids do not work well with a high penetration of intermittent distributed generation (e.g. solar photovoltaics, combined heat and power)



The same PV peak does not always have the same effect…





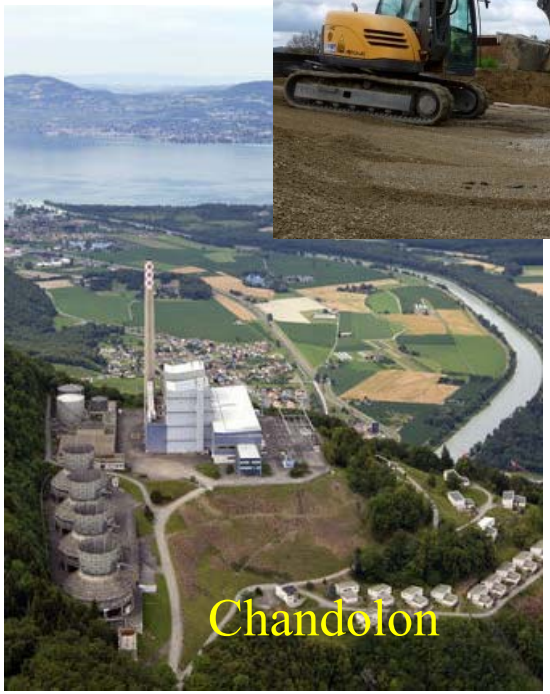
10:05: consumption is small

14:40 load absorbs the peak

Solutions…

Traditional

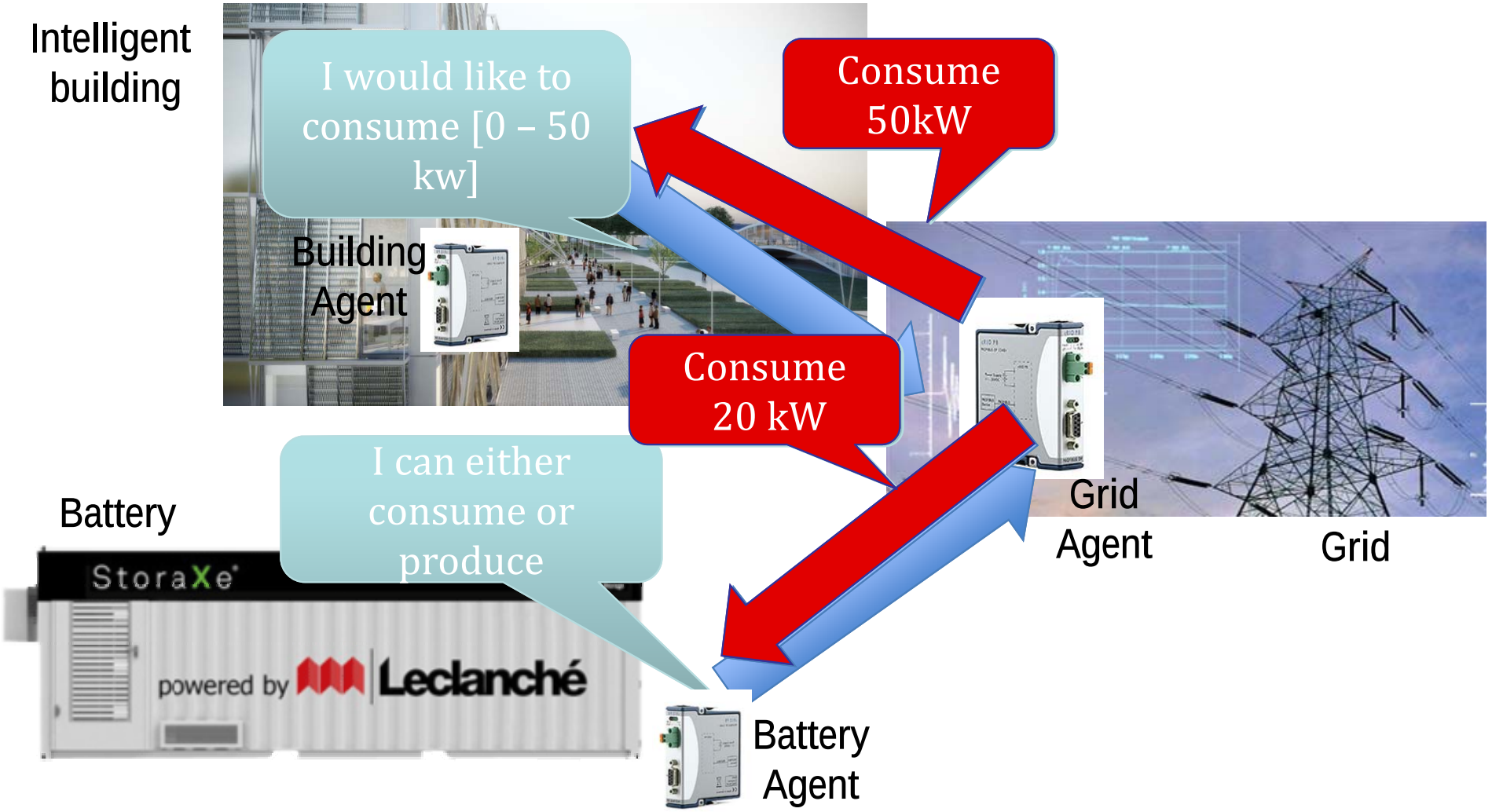
- Upgrade lines and transformers
- Fast ramping gas plants



Google-Car-like

- Explicit control of what can be controlled: storage, intelligent buildings, e-cars

The EPFL Commelec Project



Problems with Explicit Control

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

We address these issues at the root by developing a system that is

scalable

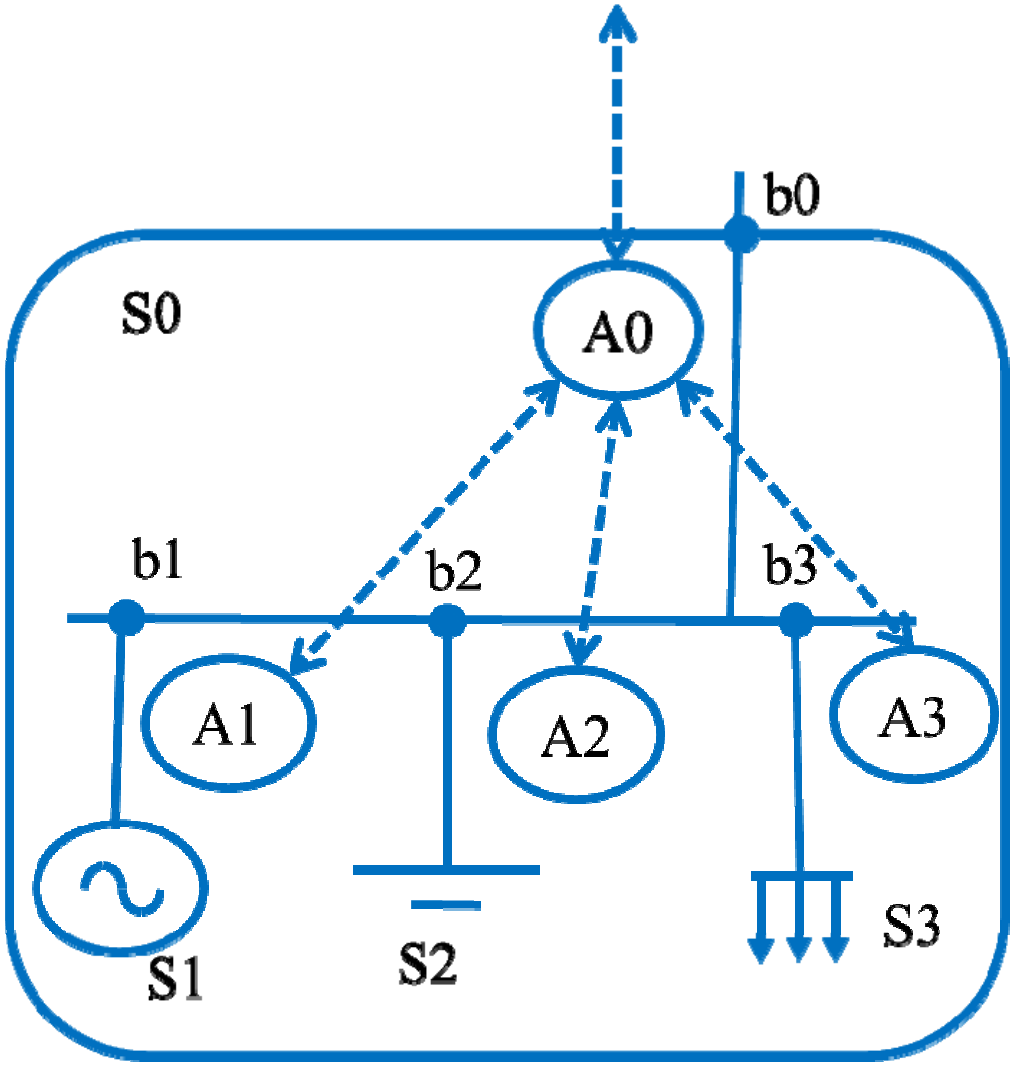
and

composable

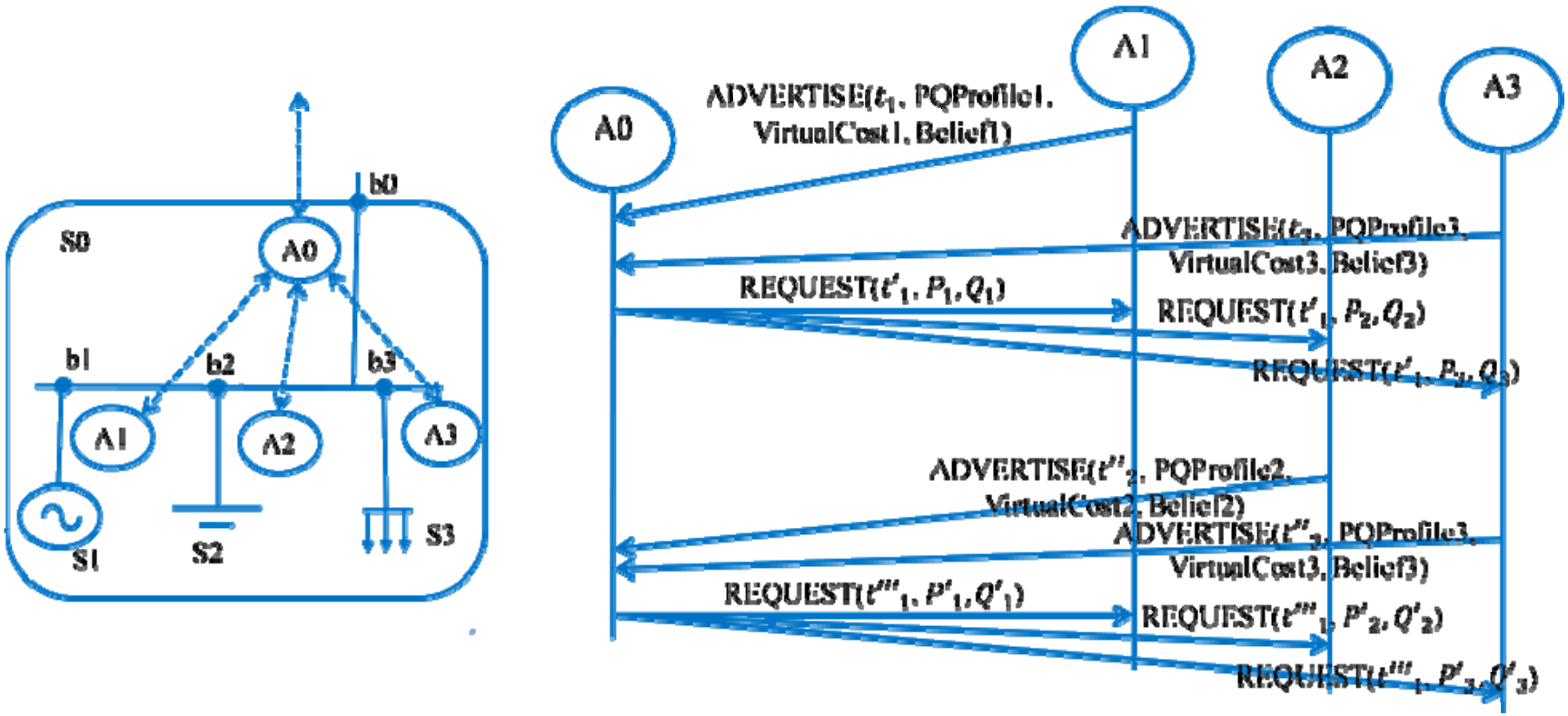
(i.e. built with identical small elements)

2. COMMELEC's Architecture

- Software Agents associated with devices
  - load, generators, storage
  - grids
- Grid agent sends explicit ***power setpoints*** to devices' agents
- Leader and follower
  - resource agent is follower or grid agent
  - e.g. LV grid agent is follower of MV agent



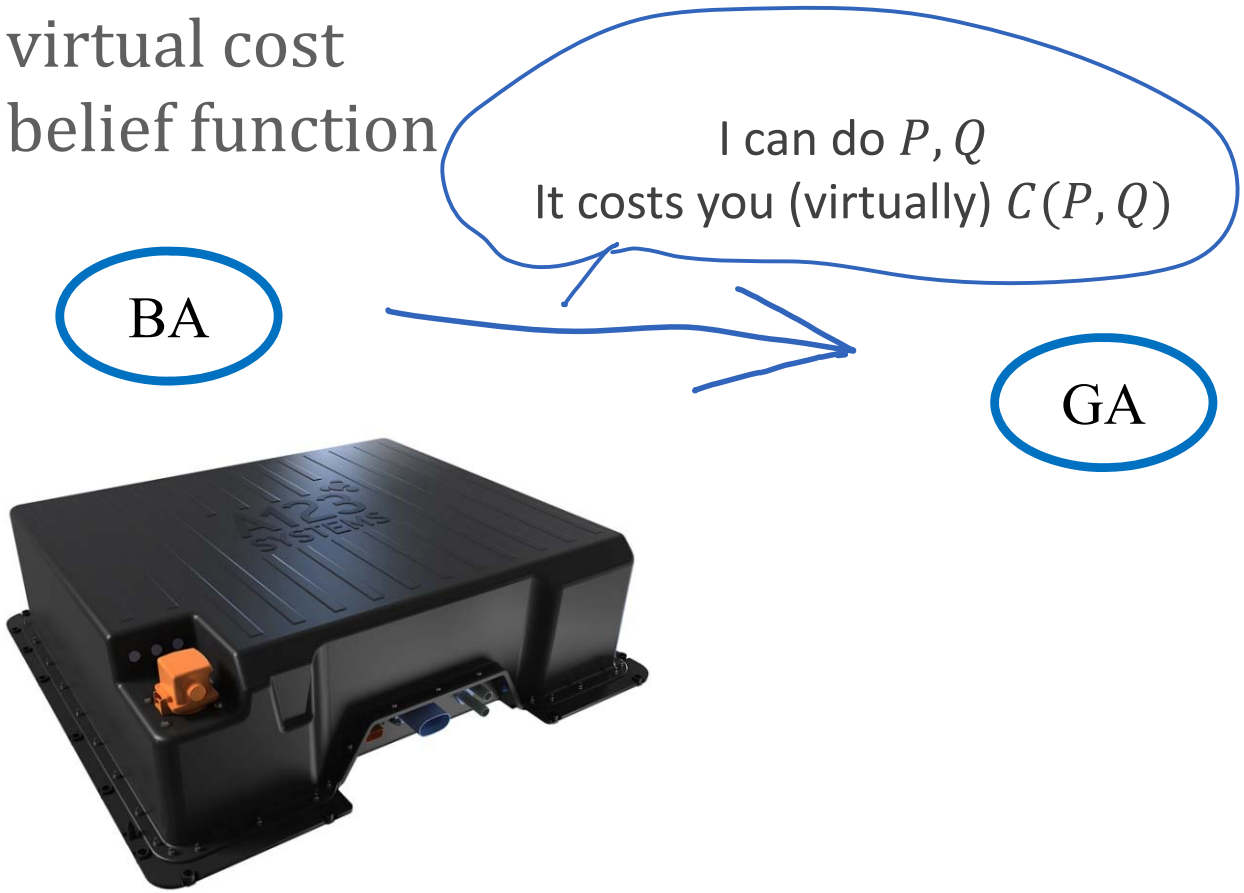
The Commelec Protocol



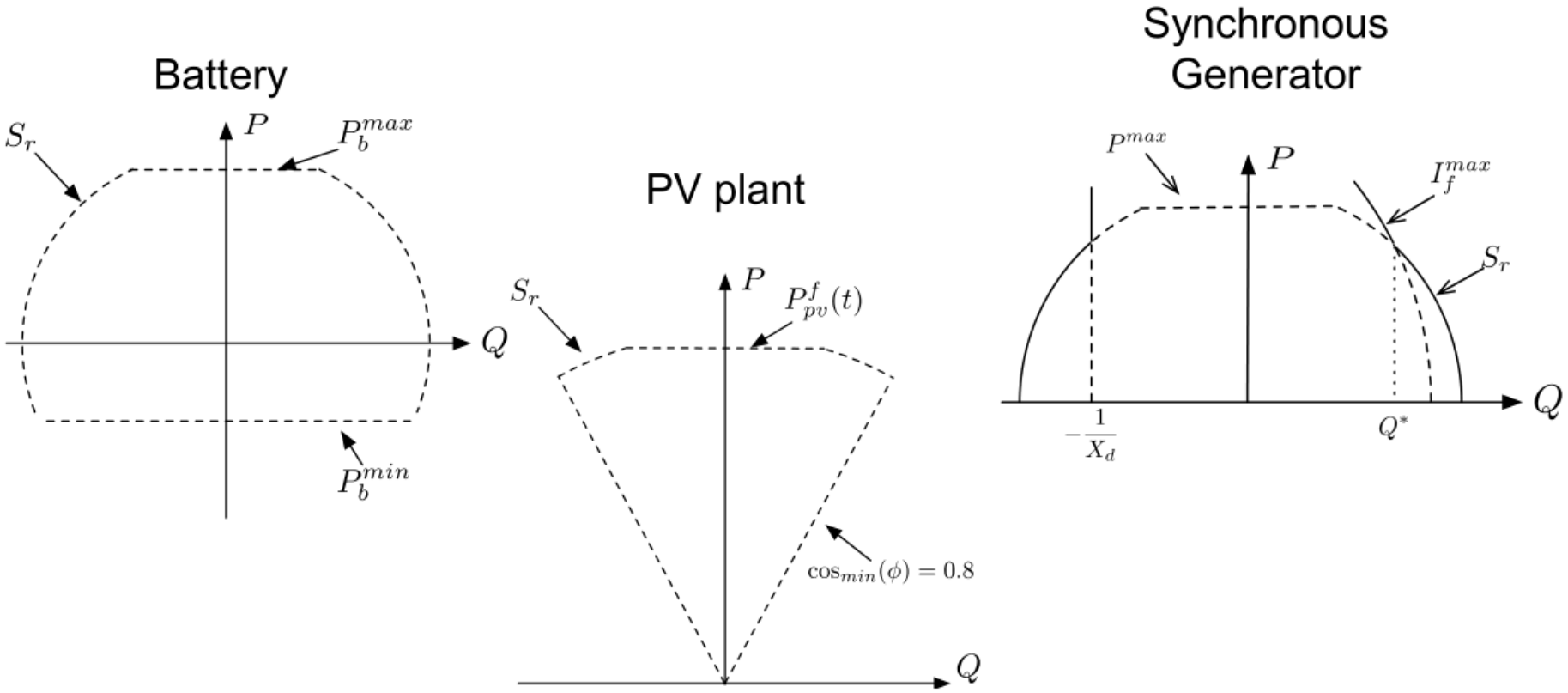
- Every agent advertises its state (every≈ 100 ms) as PQt profile, virtual cost and belief function
- Grid agent computes optimal setpoints and sends setpoint requests to agents
- Communication is over D-TLS and IPRP – details not discussed today

A Uniform, Simple Model

- Every resource agent exports
  - constraints on active and reactive power setpoints P, Q (PQt profile)
  - virtual cost
  - belief function



Examples of PQt profiles



Virtual cost act as proxy for Internal Constraints

If state of charge is 0.7,
I am willing to inject power

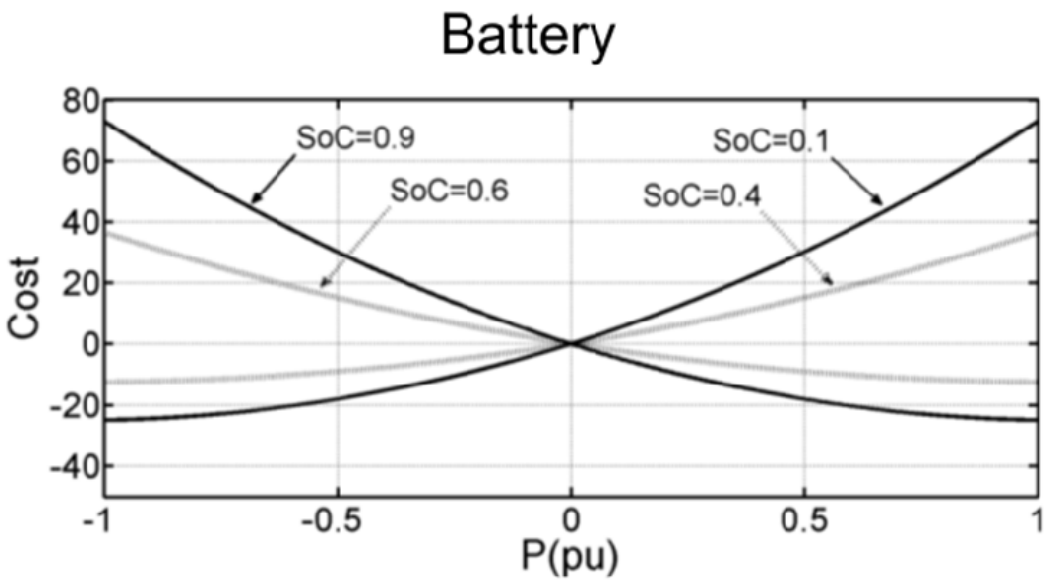
If state of charge is 0.3,
I am interested in consuming power

I can do P, Q
It costs you (virtually) $C(P, Q)$

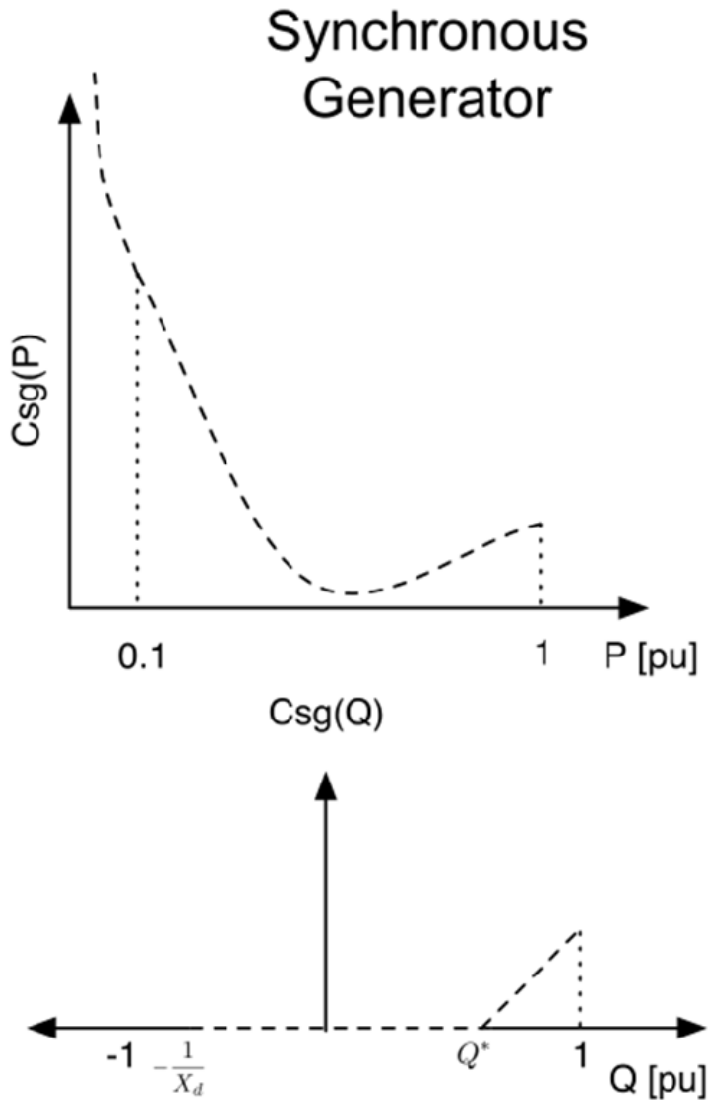
BA

GA

Examples of Virtual Costs

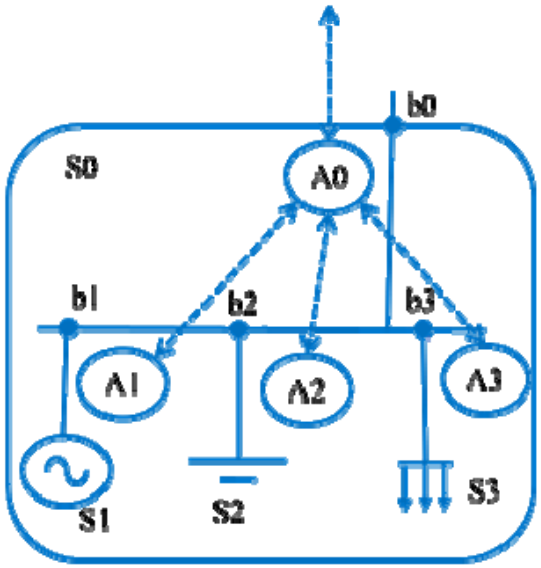


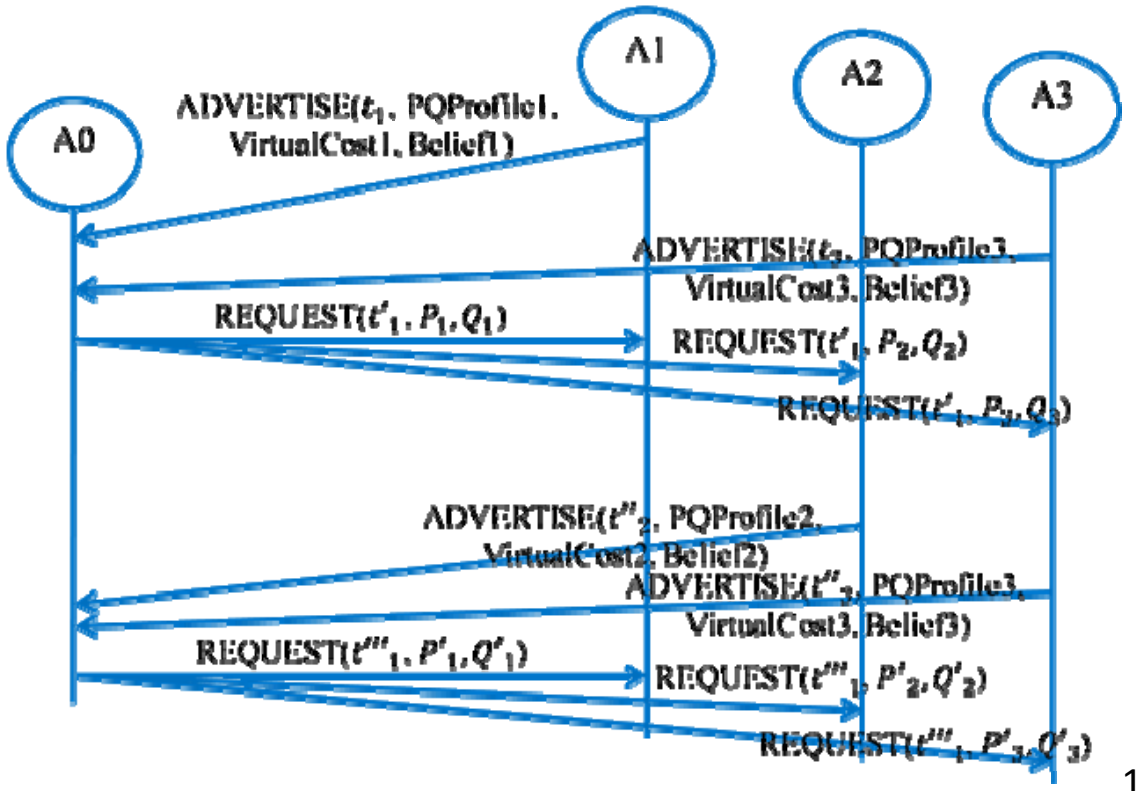
$$C_b(Q) = 0$$



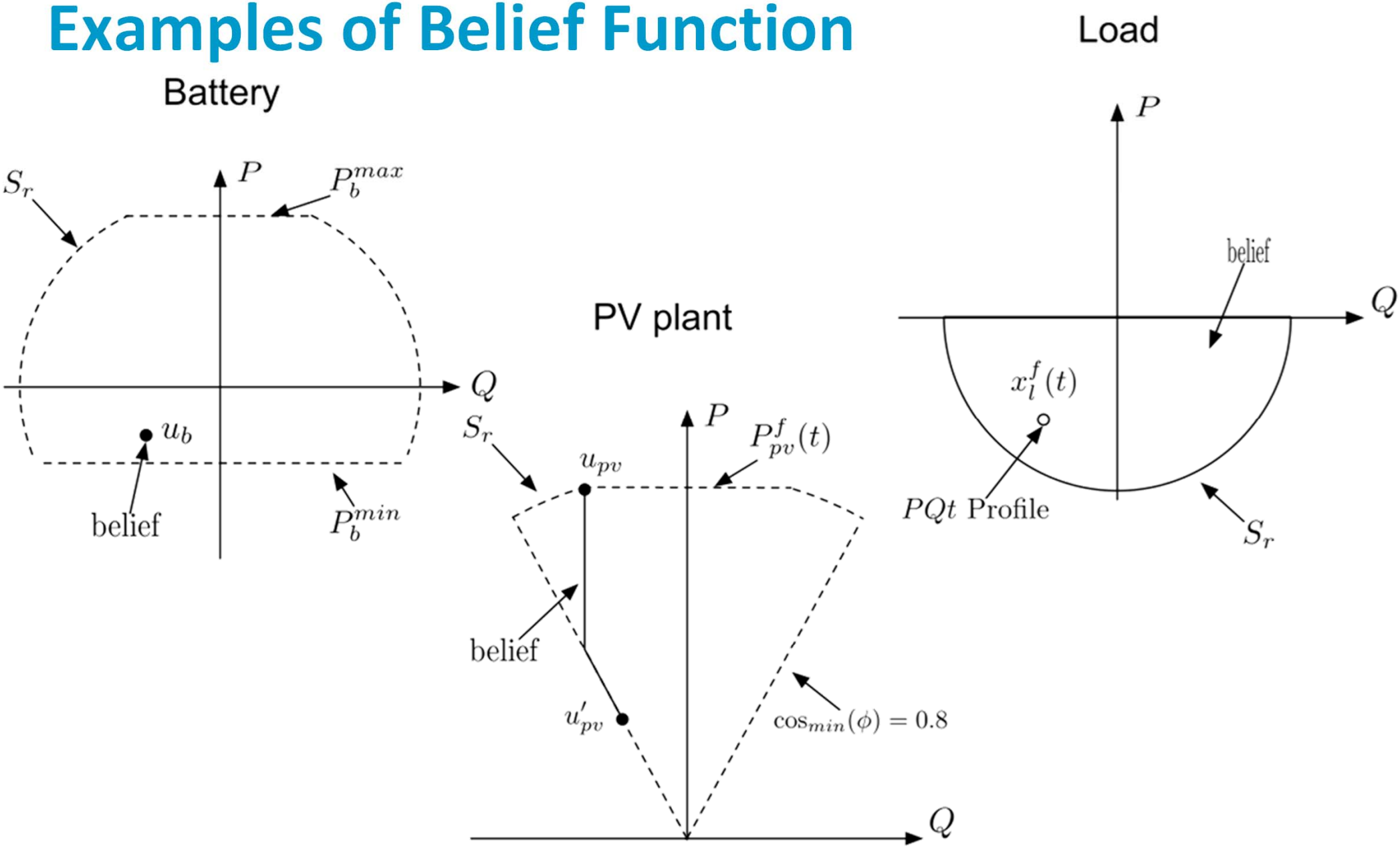
Commelec Protocol: Belief Function

- Say grid agent requests setpoint $(P_{\text{set}}, Q_{\text{set}})$ from a resource; actual setpoint (P, Q) will, in general, differ.
- *Belief function* is exported by resource agent with the semantic: resource implements $(P, Q) \in BF(P_{\text{set}}, Q_{\text{set}})$
- Essential for safe operation





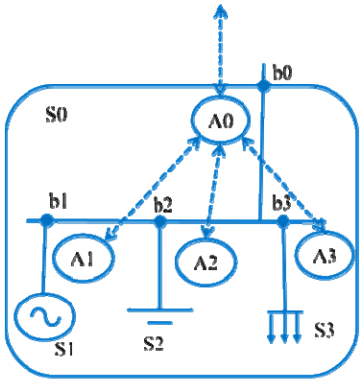
Examples of Belief Function

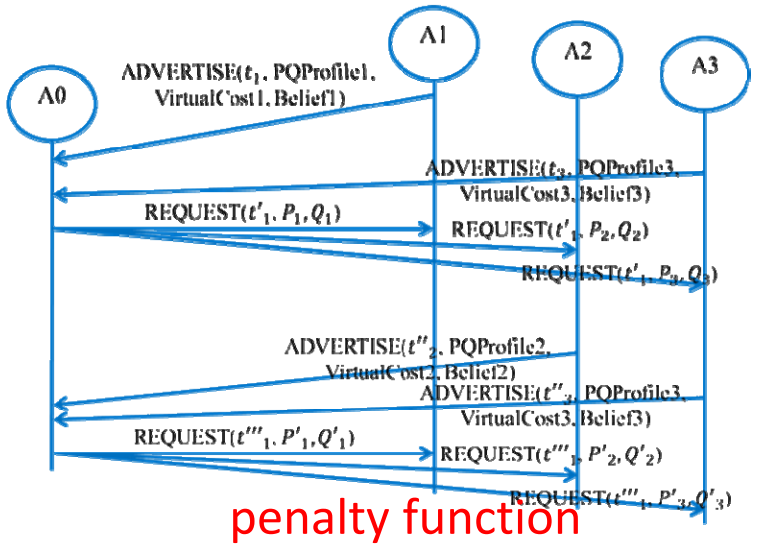


PQt profile = setpoints that this resource is willing to receive
Belief function = actual operation points that may result from receiving a setpoint

Grid Agent's job

- Leader agent (grid agent) computes setpoints for followers based on
  - state estimation
  - advertisements received
  - requested setpoint from leader agent





- Grid Agent attempts to minimize

$$J(x) = \sum_i w_i C_i(x_i) + W(z) + J_0(x_0)$$

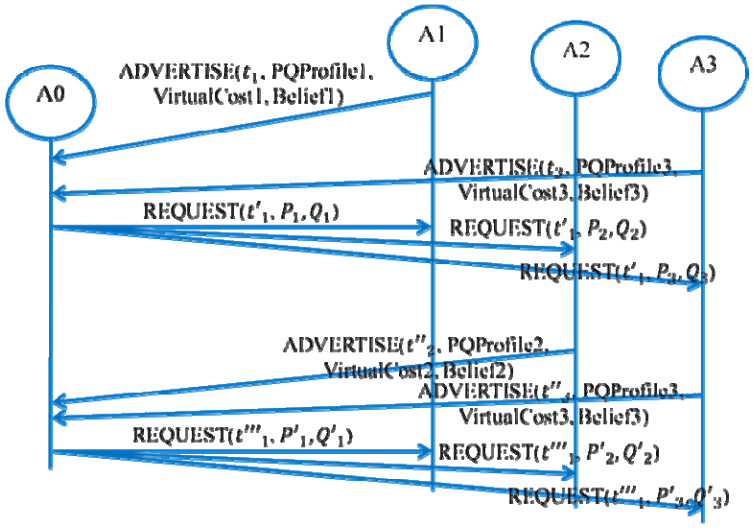
virtual cost of resource i

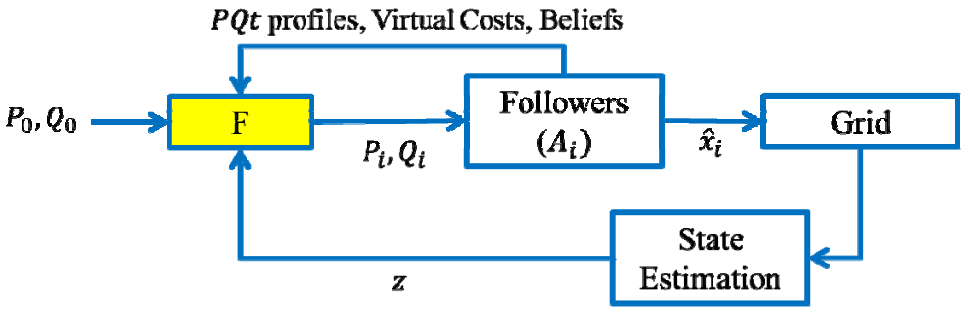
penalty function keeps voltages close to 1 p.u. and currents within bounds

cost of power flow at point of common connection

- 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

Grid Agent's algorithm





- Given estimated (measured) state $\hat{x} = (\hat{P}_i, \hat{Q}_i)$ computed next setpoint is

$$x = \text{Proj}\{\hat{x} + \Delta x\}$$

where

Δx is a vector opposed to gradient of overall objective

Proj{} is the projection on the set of safe electrical states

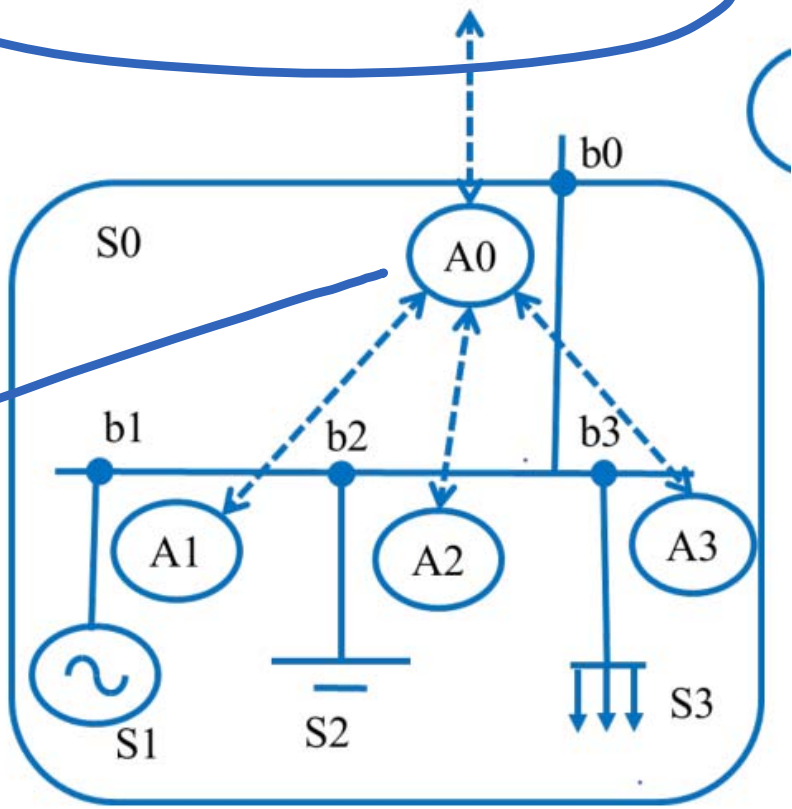
- This is a randomized algorithm to minimize $E(J(x))$

Aggregation (Composability)

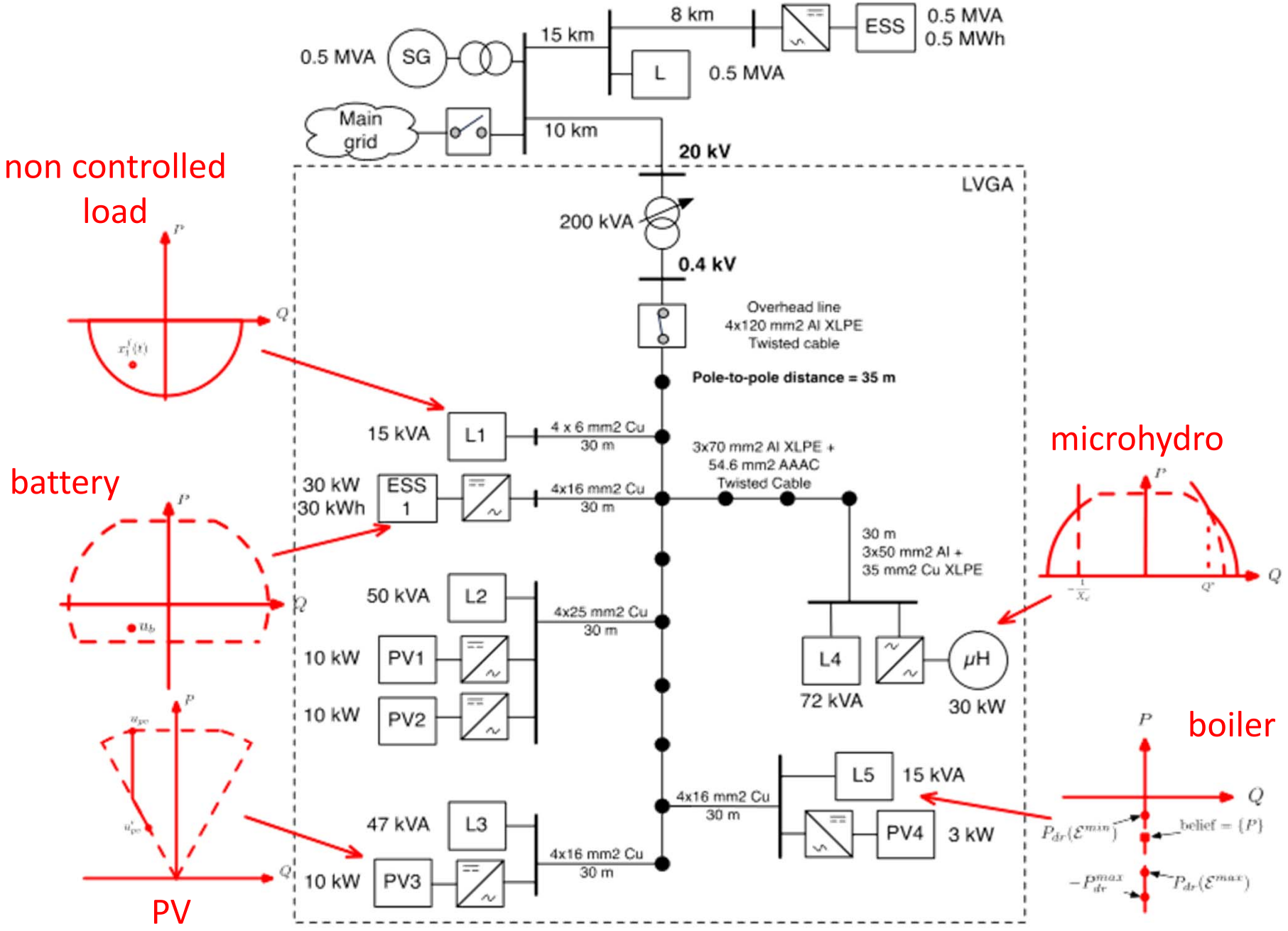
- A system, including its grid, can be abstracted as a single component

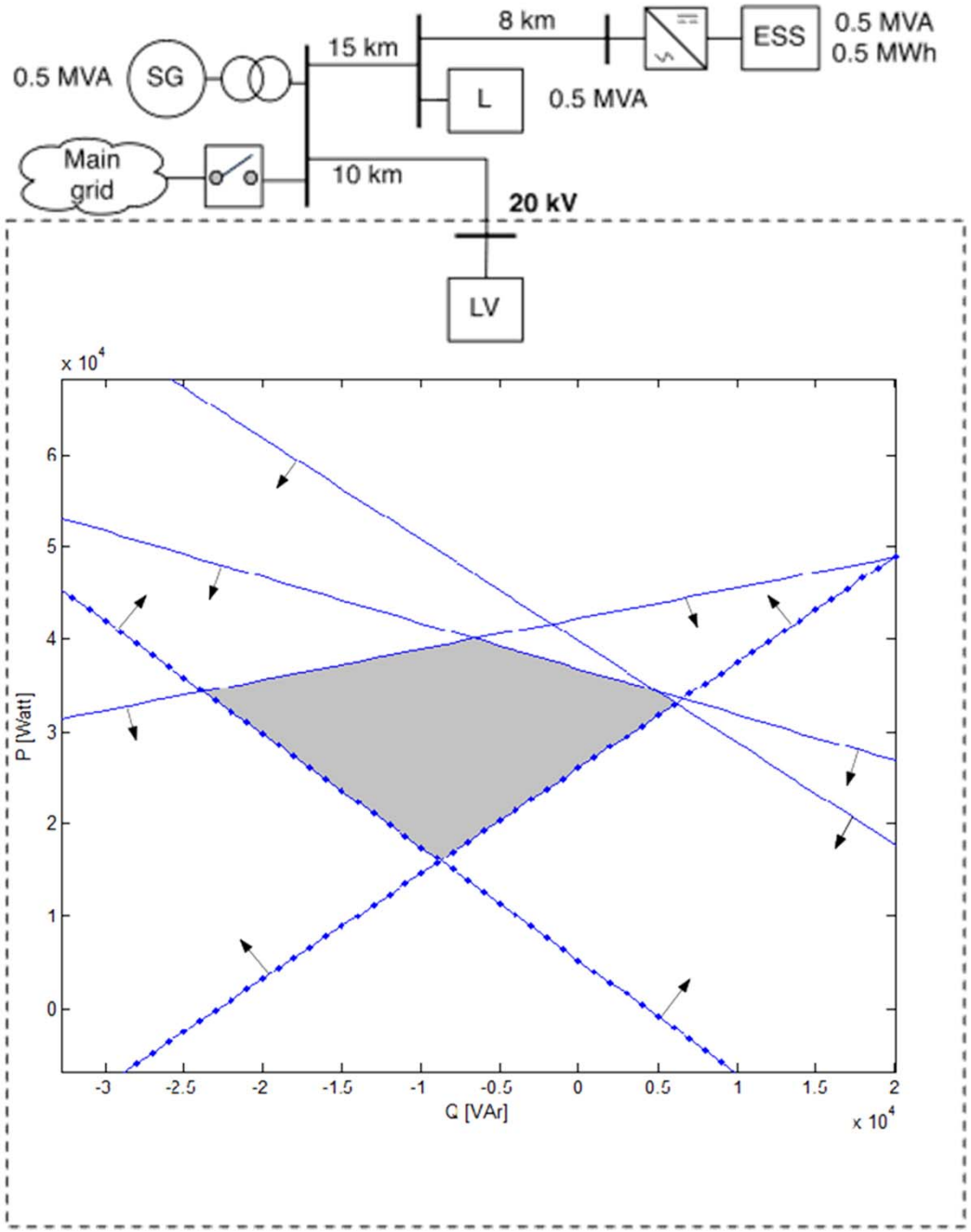
I can do P_0, Q_0
It costs you (virtually) $C_0(P_0, Q_0)$

given PQt profiles of S_1, S_2, S_3
solve load flow and compute possible P_0, Q_0
+ overall cost $C_0(P_0, Q_0)$



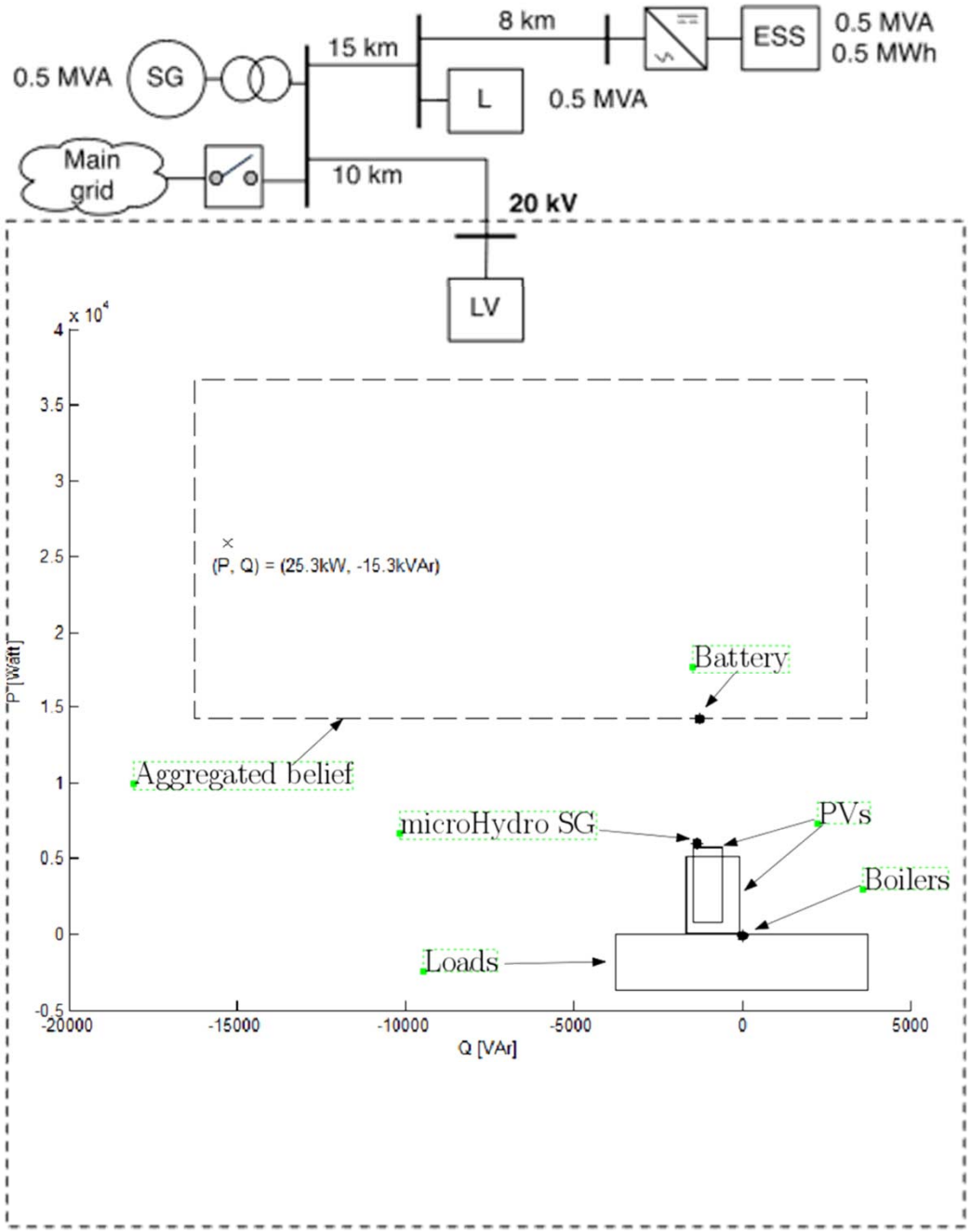
Aggregation Example





Aggregated PQt profile

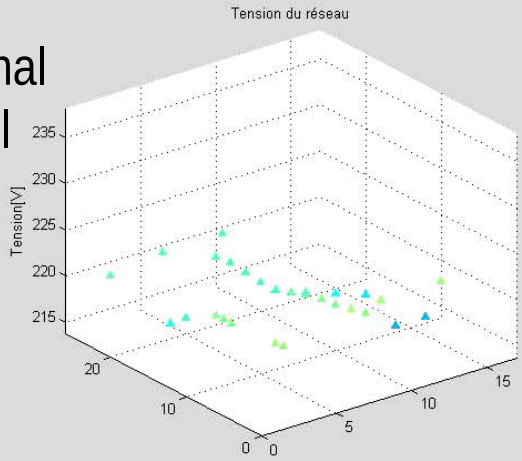
safe approximation (*subset* of true aggregated PQt profile)

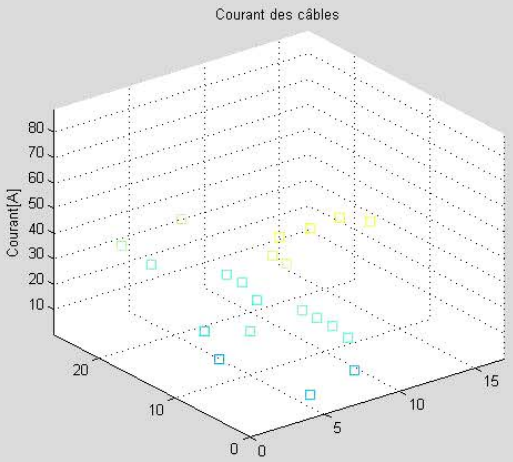


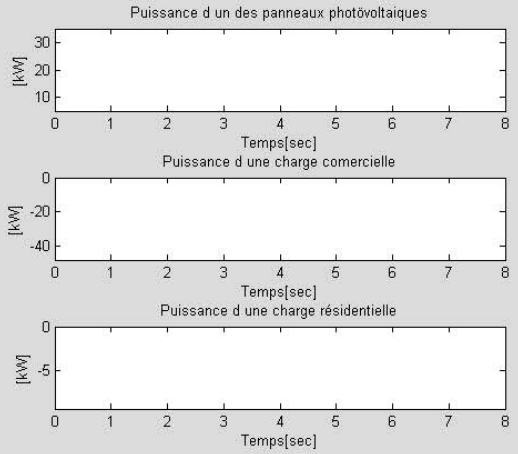
Aggregated Belief

safe approximation (*superset* of true aggregated belief)

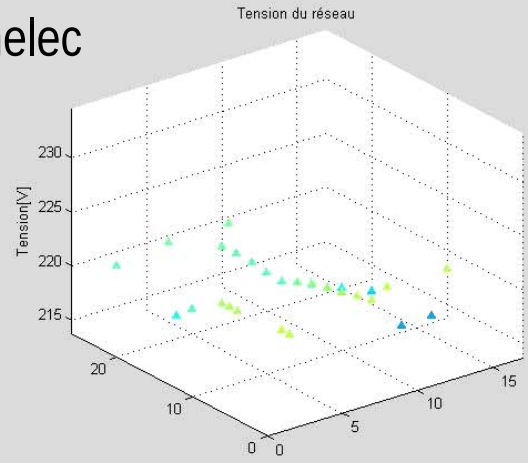
Traditional control

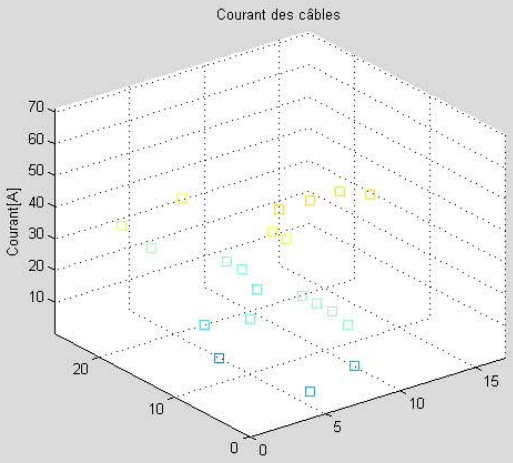


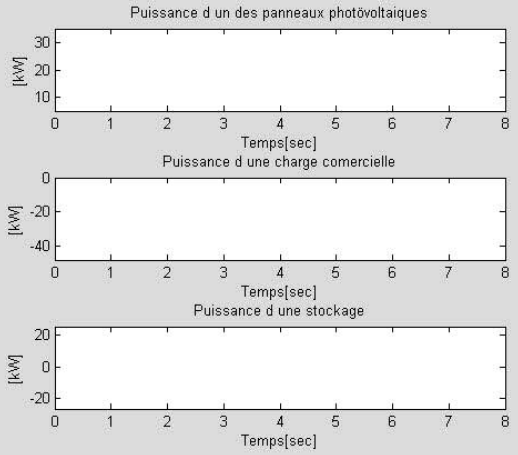




Commelec







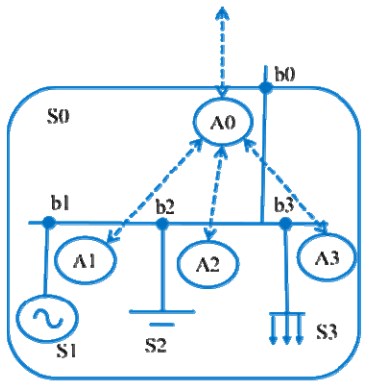
Separation of Concerns

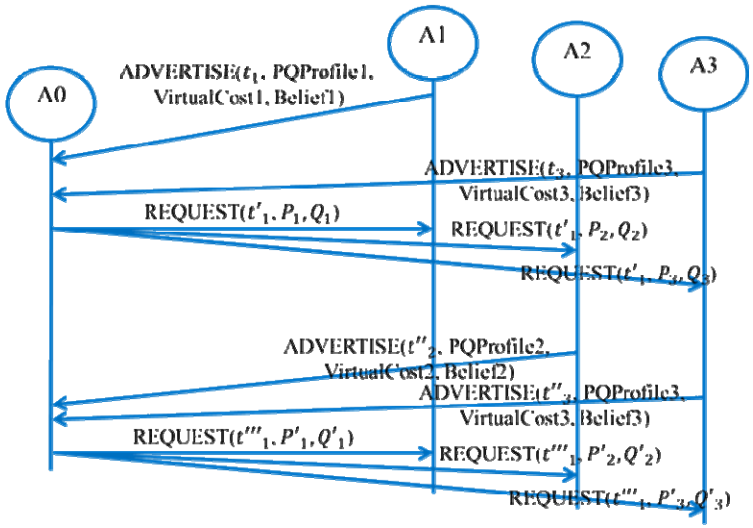
Resource Agents

- Device dependent
- Simple:
  - translate internal state (soc) into virtual cost
  - Implement setpoint received from a grid agent

Grid Agents

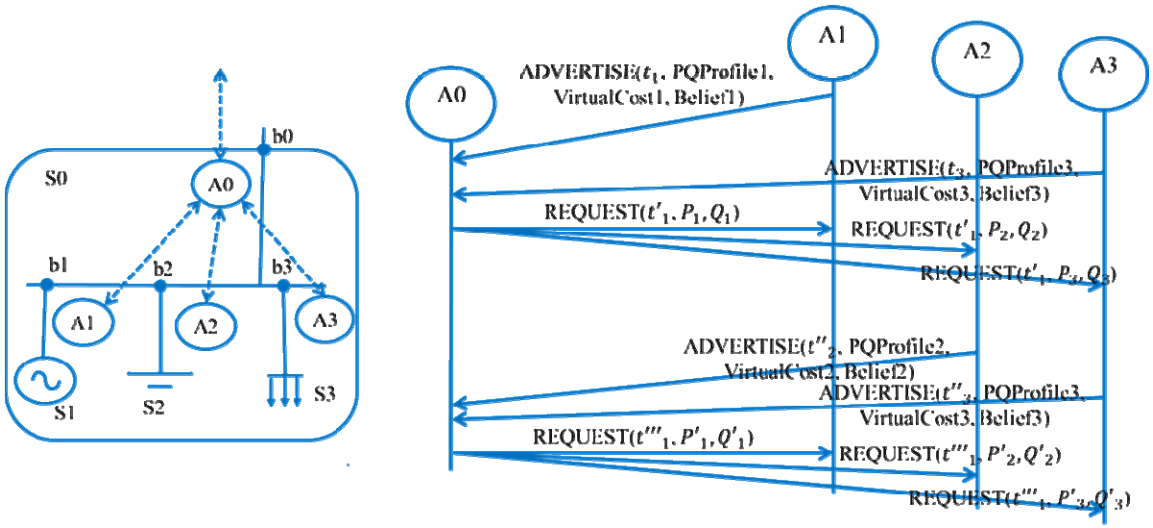
- Complex and real time
- But: all identical





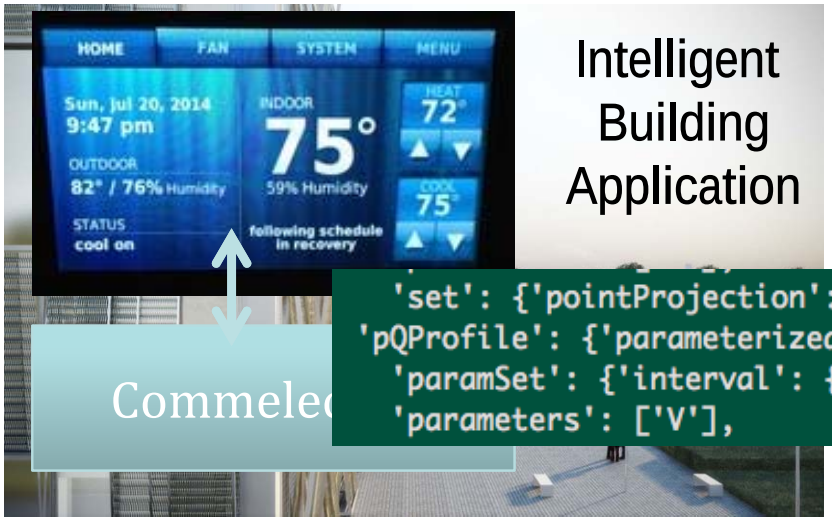
Reliability and Security

- Grid Agent development uses Prof Sifakis's rigorous system development approach and the BIP framework
- Grid Agent are triplicated, Resource Agents use voting
- Communication used authentication (D-TLS) and real time reliability protocols



An Operating System for Electrical Grids

- Resource control uses the Commelec API and does not need to be aware of the grid

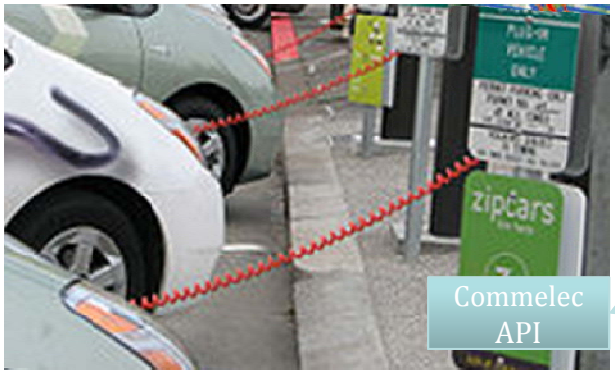


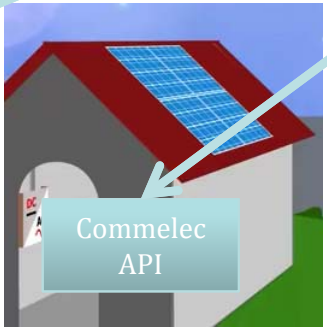

```
  'set': {'pointProjection': {'reference': 'S'}}}}
'pQProfile': {'parameterizedOperation': {'operati
  'paramSet': {'interval': {'lower': 0.9, 'upper'
  'parameters': ['V'],
```

minimize

$$E\left(\sum_i w_i C_i(x_i) + W\right.$$

E-car





PVs

- Implementation on EPFL' grid is underway
  - experimental microgrid
  - campus feeders with automatic islanding and reconnection

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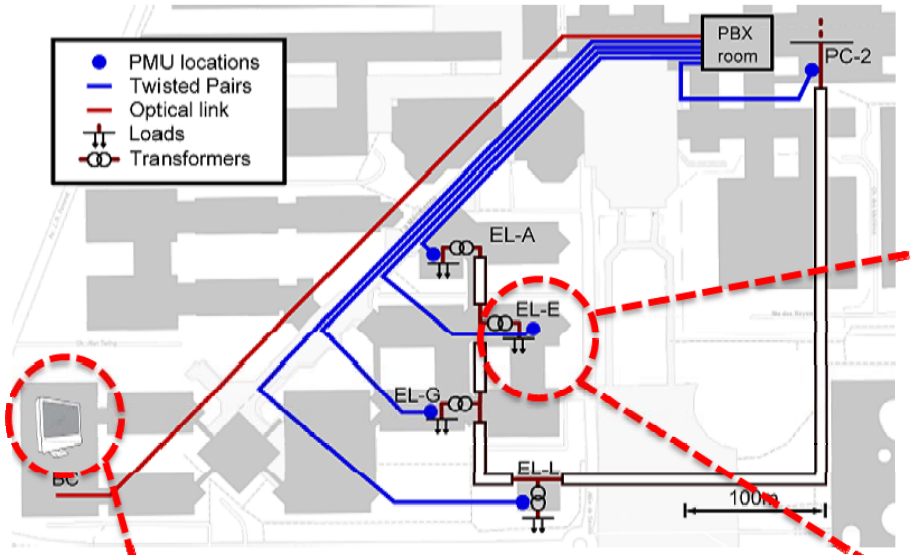
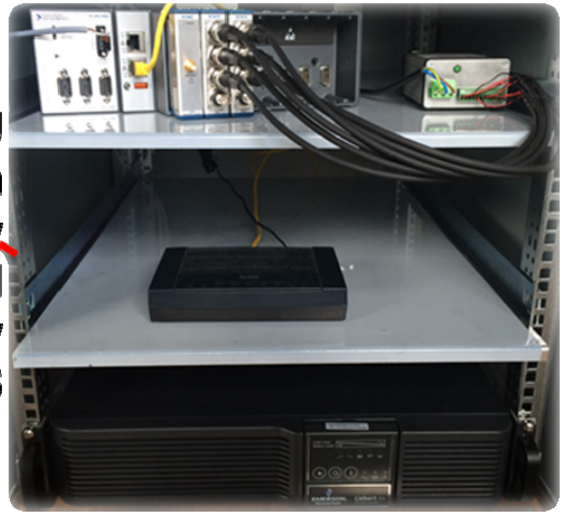
nano-tera.ch

smartgrid.epfl.ch



12 kV sensors

PMU
ADSL network with
Internet Parallel Redundancy
Protocol
D-TLS security
UPS



State
Estimator
PMU data
concentrator

Conclusion

- Commelec is a practical method for automatic control of a grid
  - exploits available resources (storage, demand response) to avoid curtailing renewables while maintaining safe operation
- Method is designed to be robust and scalable
  - separation of concerns between resource agents (simple, device specific) and grid agents (all identical)
  - a simple, unified protocol that hides specifics of resources
  - aggregation for scalability
- We have started to develop the method on EPFL campus to show grid autopilot