ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Real-Time Control of Electrical Distribution Grids

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Credits

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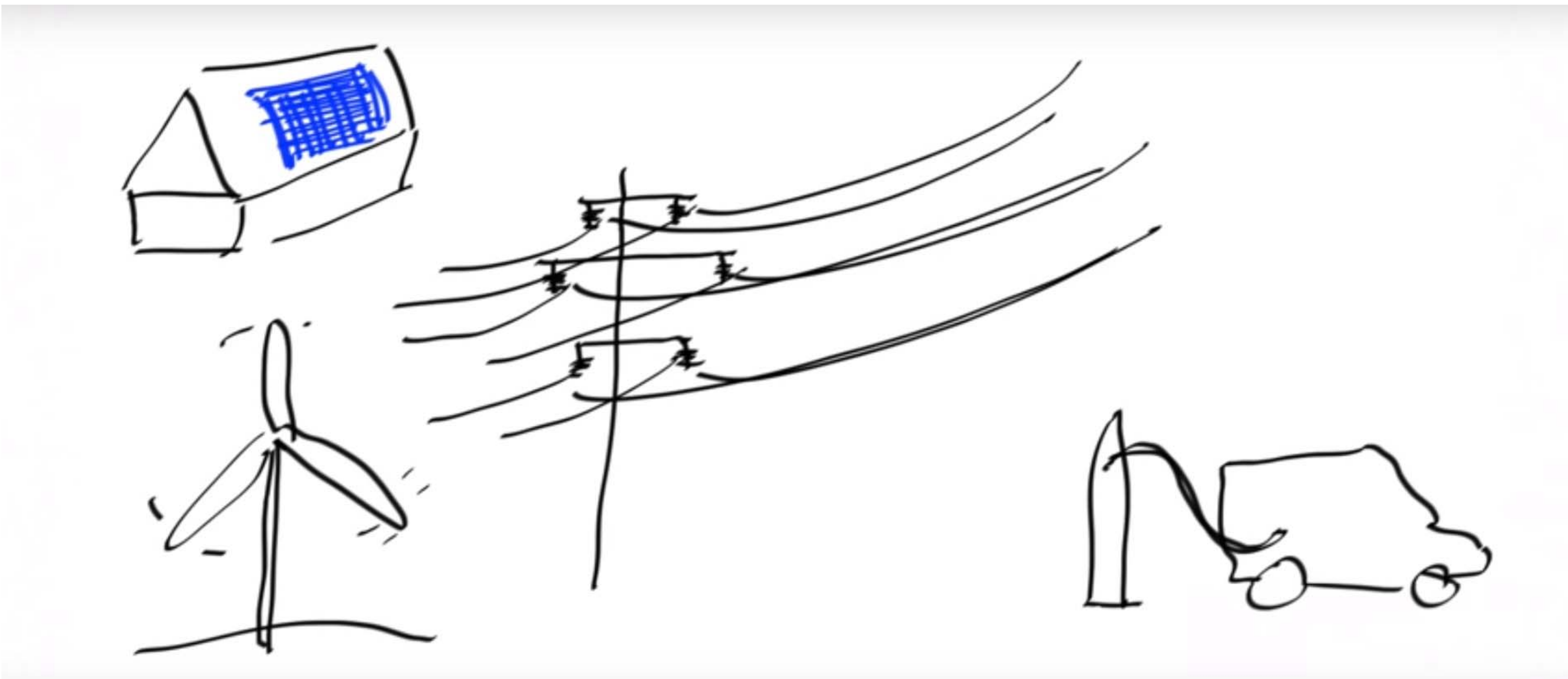
Abstract

What would happen today if we would instantly add a very large amount of renewables to the electricity mix? First, many distribution grids would face power quality problems such as over- and under-voltages and excessive line-currents. Second, the existing reserve mechanisms that are required to maintain power balance at all times would not be able to cope with the high variability and uncertainty of renewables. These problems can be solved if we are able to control the huge number of electrical resources that are located in distribution grids, which poses a number of new challenges in terms of scalability and reliability. In this talk we discuss these challenges and how they can be addressed by innovative information technology solutions, which involve in particular a scalable and composable framework (Commelec) for the development of real-time control agents .

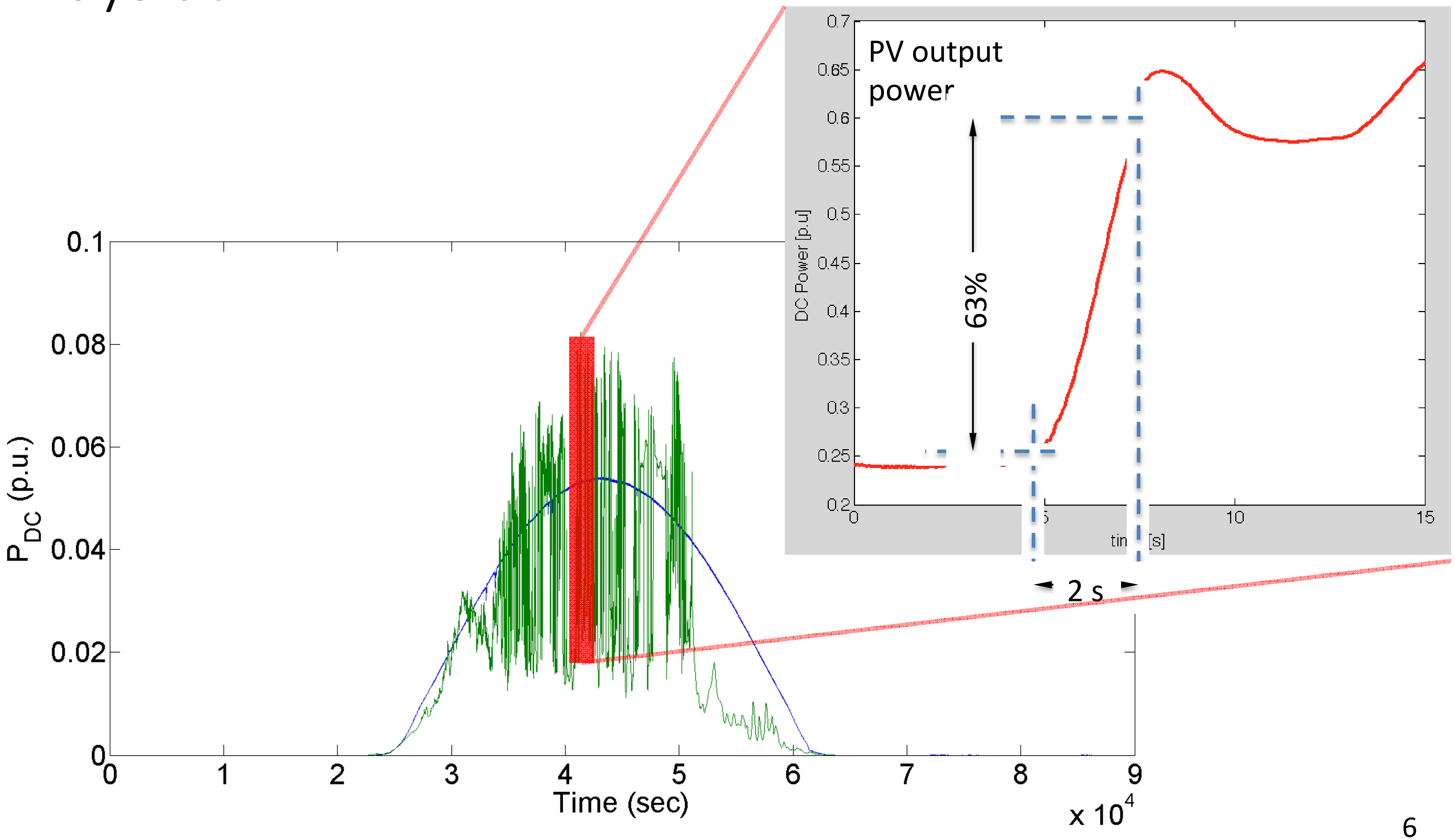
Contents

What would happen if we had 100% renewables in the grid ?



Short-term volatility

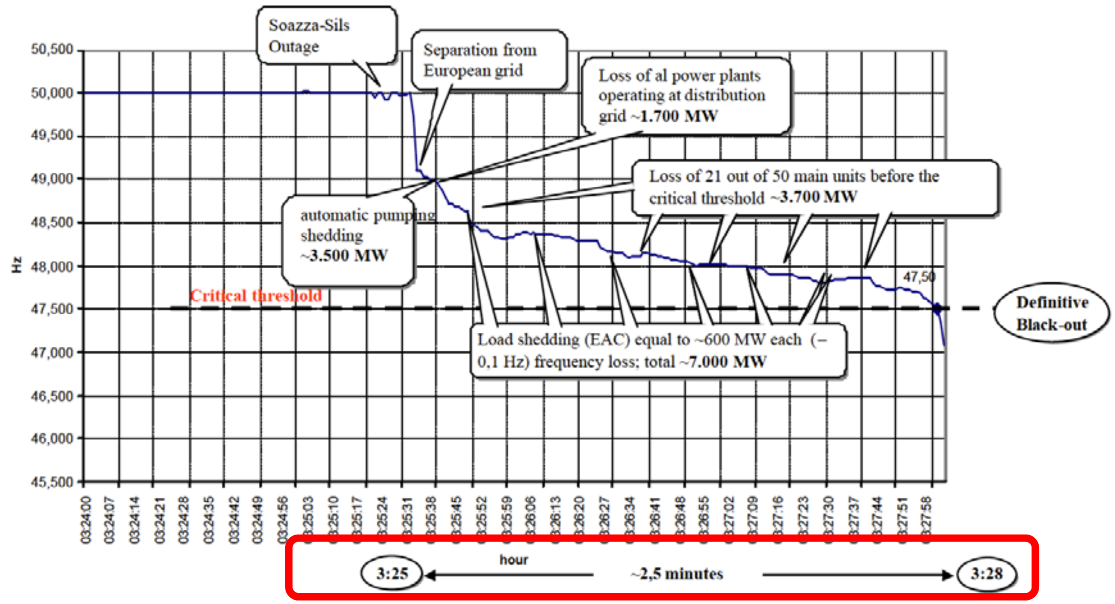
Example of daily measured power injected by solar arrays at EPFL



Absence of inertia in distribution grids

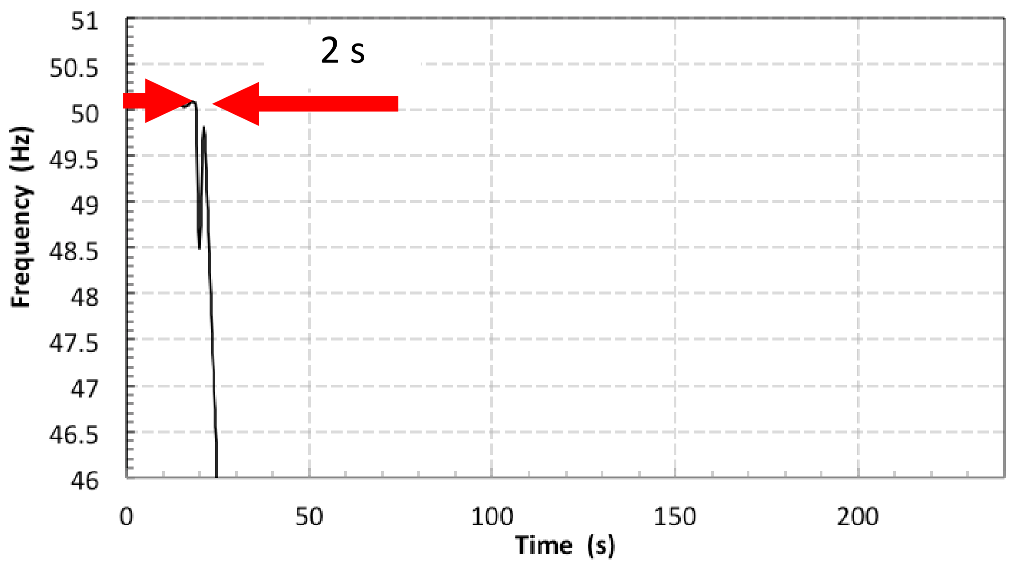
2003 blackout in Italy frequency trend

Source: UCTE Interim Report of the Investigation Committee on the 28 September 2003 Blackout in Italy



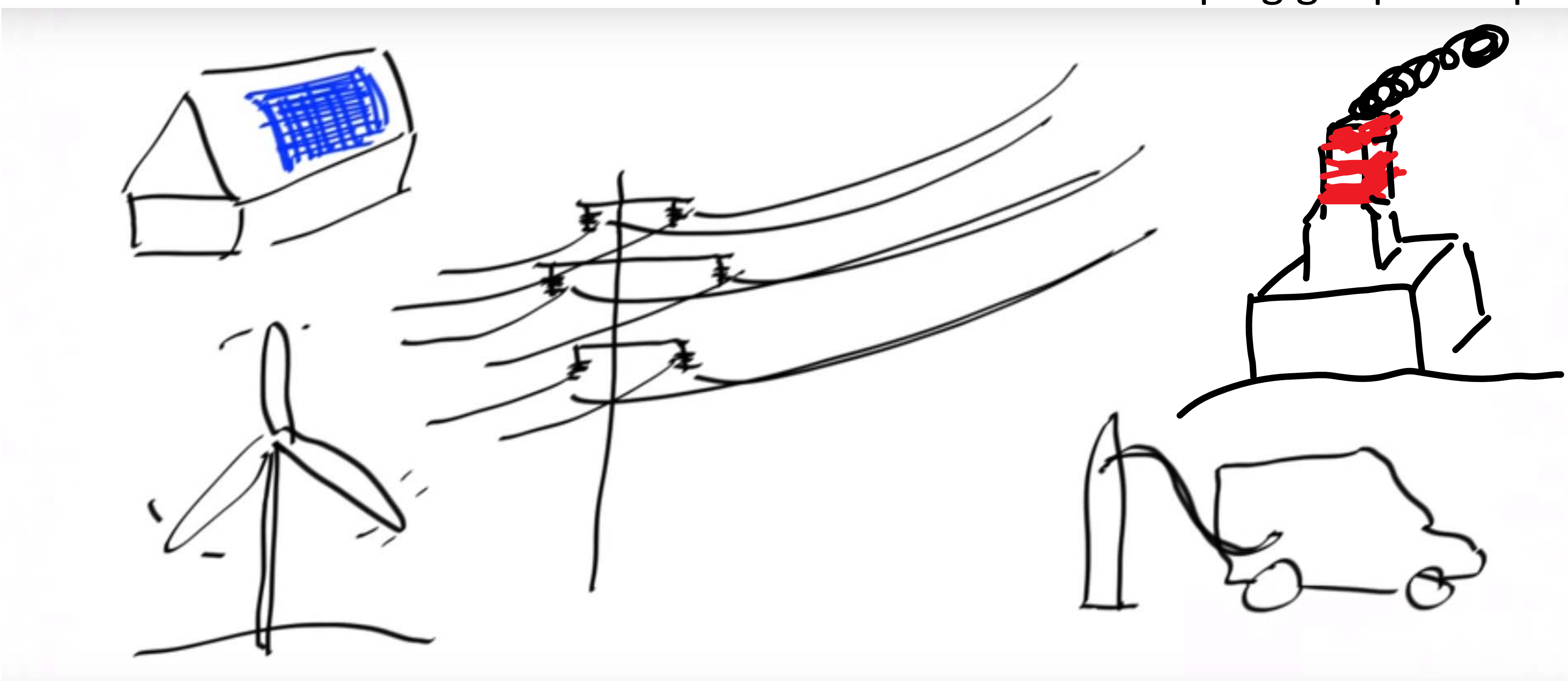
2009 blackout during the islanding maneuver of an active distribution network

Source: A. Borghetti, C. A. Nucci, M. Paolone, G. Ciappi, A. Solari, "Synchronized Phasors Monitoring During the Islanding Maneuver of an Active Distribution Network", IEEE Trans. On Smart Grid, vol. 2 , issue: 1, march, 2011, pp: 70 – 79.



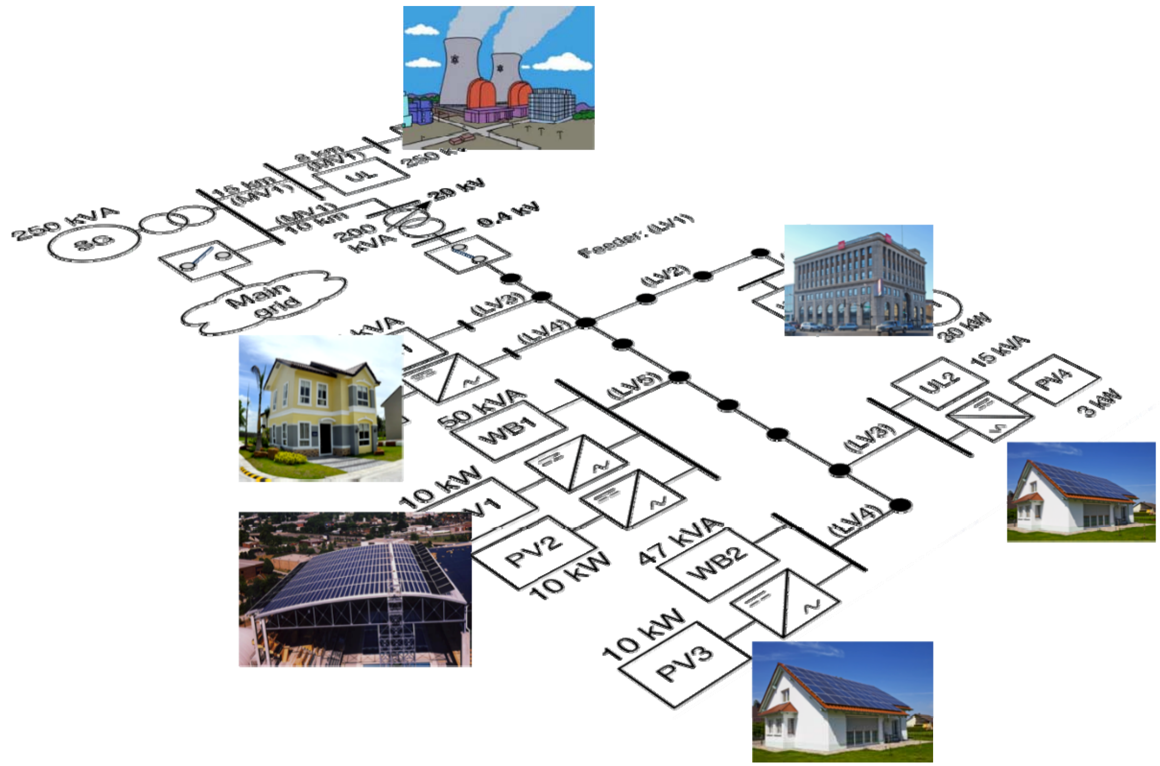
What would happen if we had 100% renewables in the grid ?

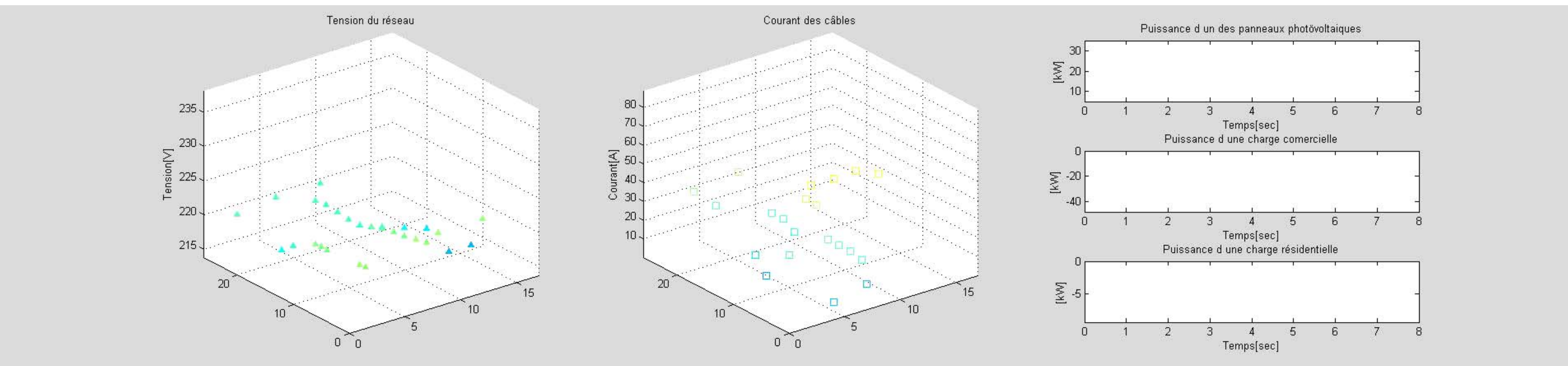
fast ramping gas power plant



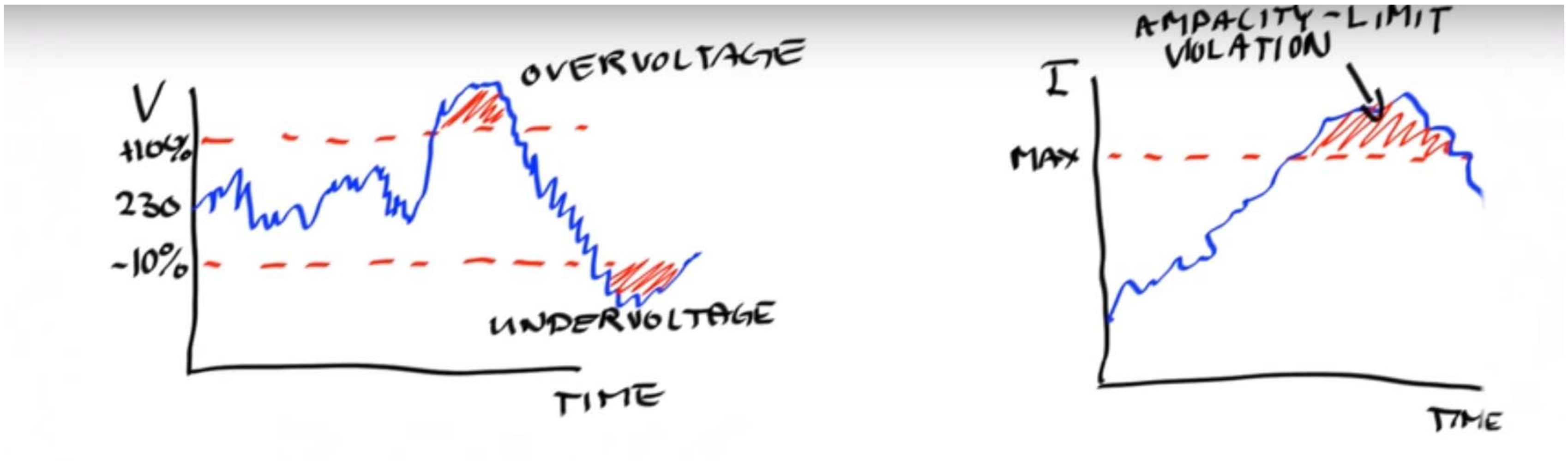
1. We would need very large reserves for power balance and reliability.

Quality of Service problems in distribution grids





What would happen if we had 100% renewables in the grid ?



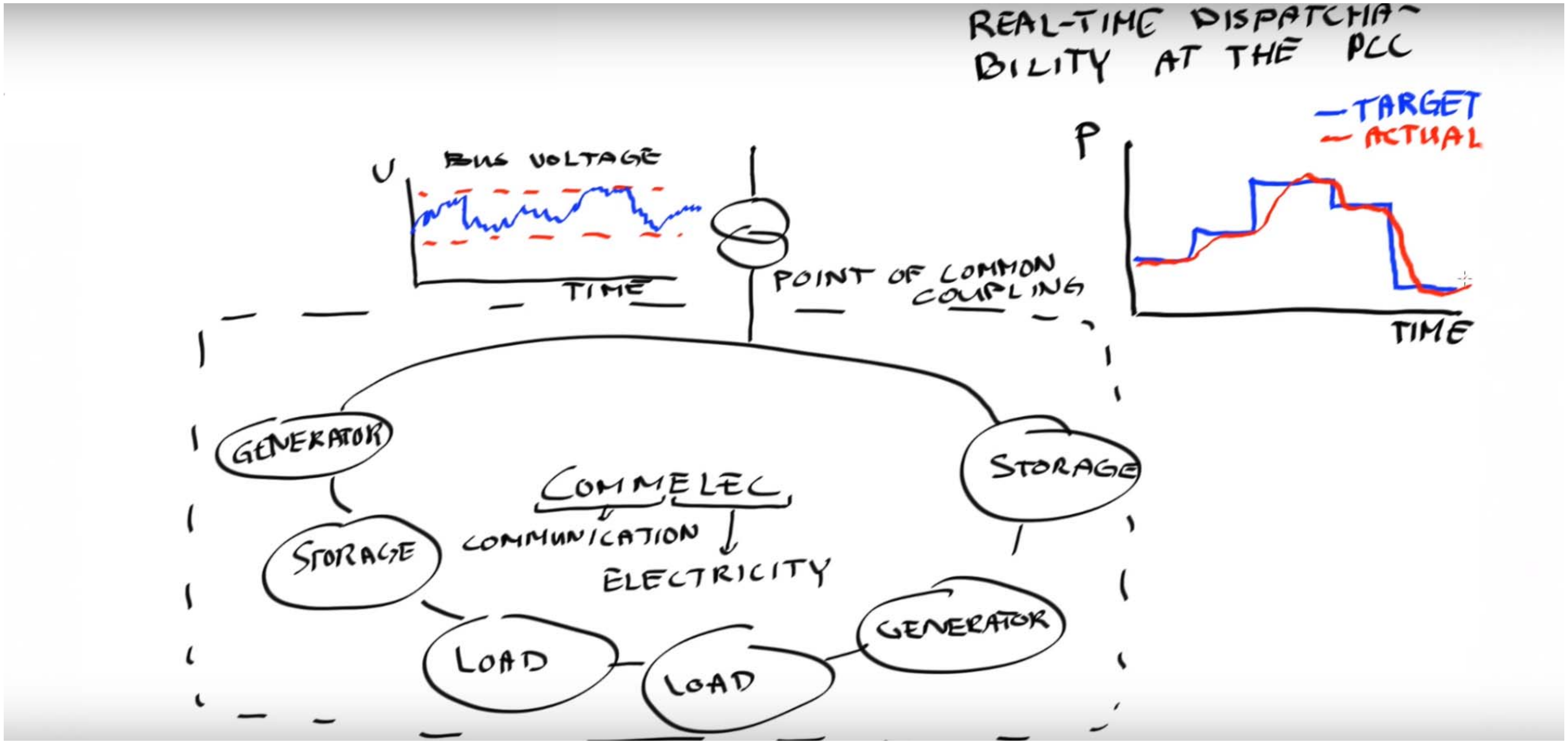
2. Grid re-enforcement would be needed in many distribution networks

We can do better with real-time control of electrical distribution grids with storage and demand-response

Goals of control:

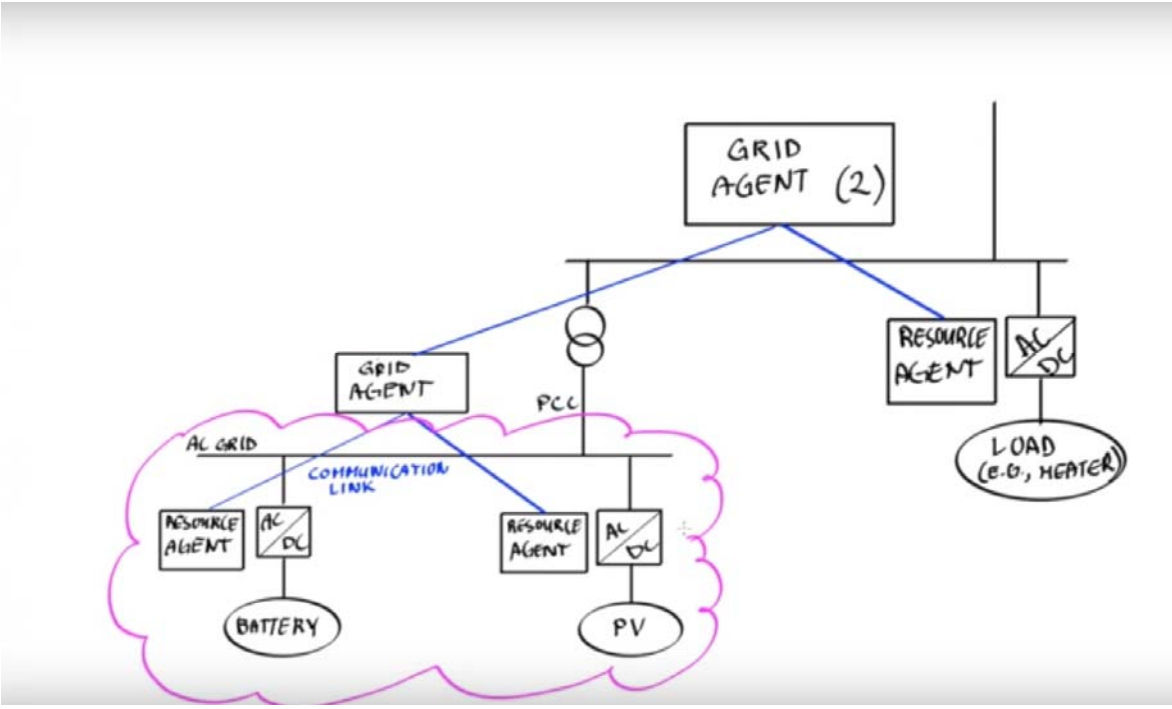
- Distribution grid supports main grid
- Local solution of quality of service issues

Explicit control of power flows



- instruct battery, heat pump, EV charging station…
- manages quality of service in grid
- respond to main grid's signals

Challenges for explicit control of power flows

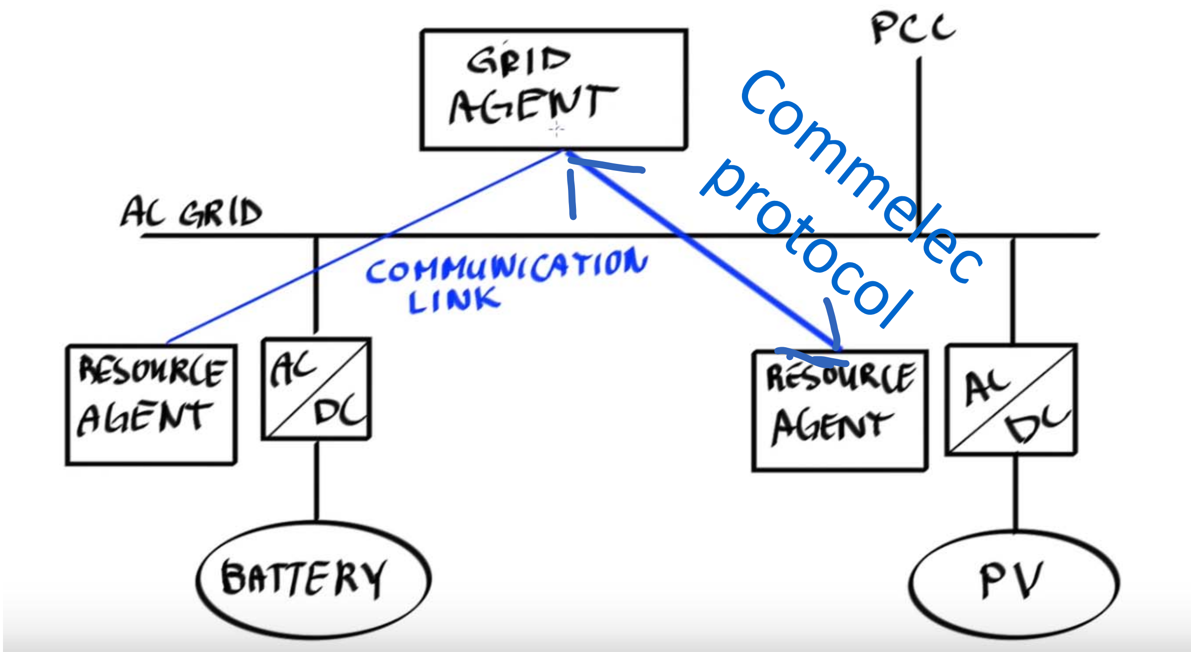


- Inexpensive platforms (embedded controllers)
- Real-time
- Scalability
- Simple and re-usable code
- Reliability

Contents

1. Motivation
2. The Commelec framework for real-time control of electrical grids
   [Bernstein et al 2015, Reyes et al 2015]
3. Networking Issues

Commelec design principle #1: resource independent control

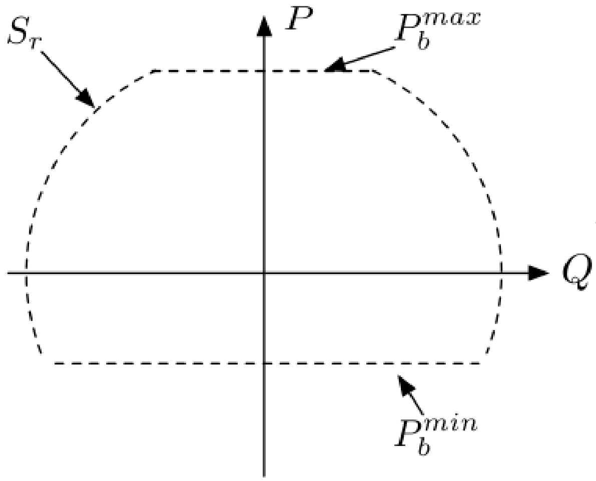


Every 100 msec

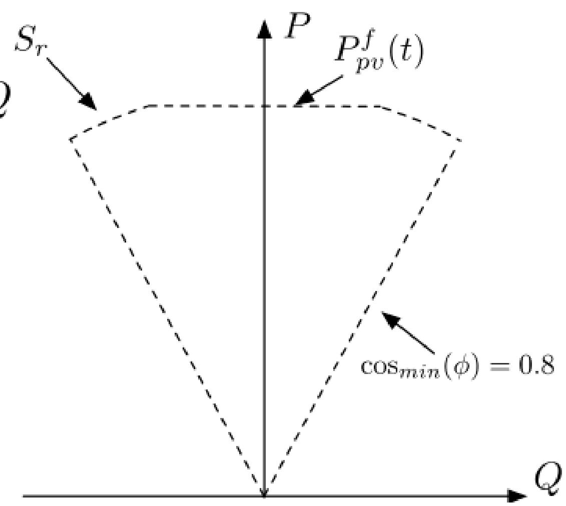
- Resource agent sends to grid agent a PQ profile, Virtual Cost and uncertainty sets (Belief Function)
- Grid agent sends power setpoints

Examples of PQ profiles

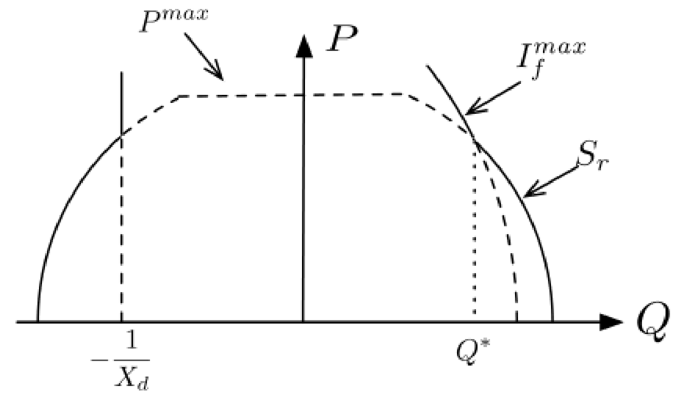
Battery



PV plant



Synchronous Generator



Virtual cost act as proxy for internal constraints

Battery used for regulation:

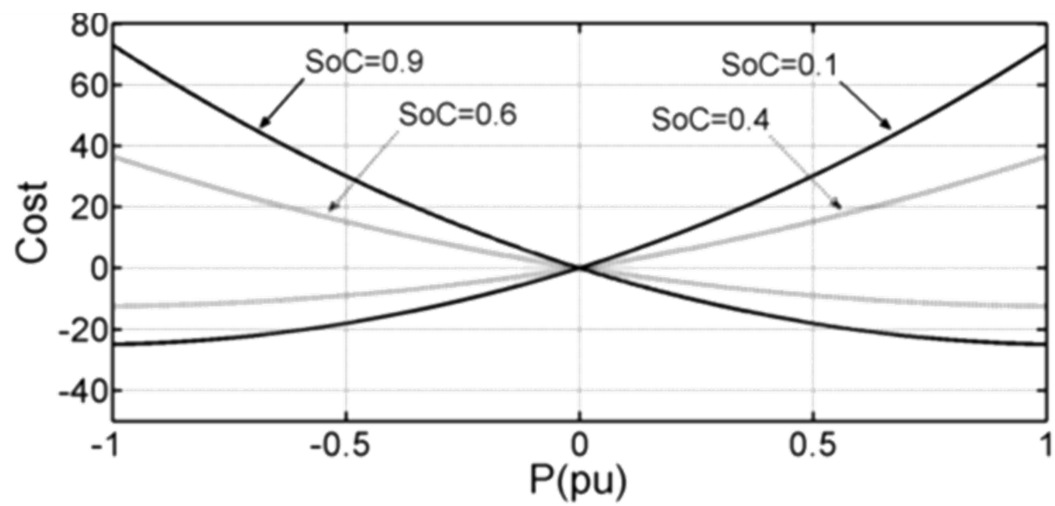
If state of charge is 0.7,
I am willing to inject power

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

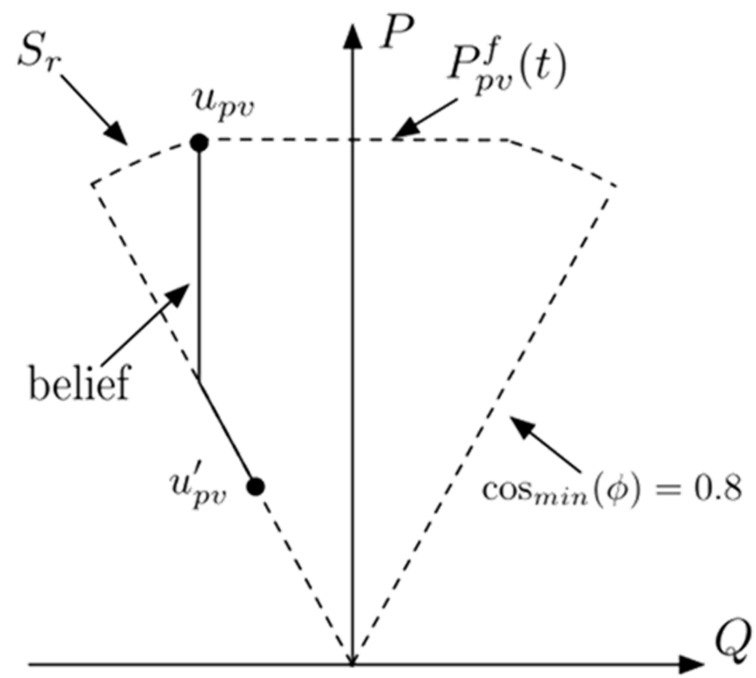
GA



$$C_b(Q) = 0$$

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 $(P, Q) \in BF(P_{\text{set}}, Q_{\text{set}})$

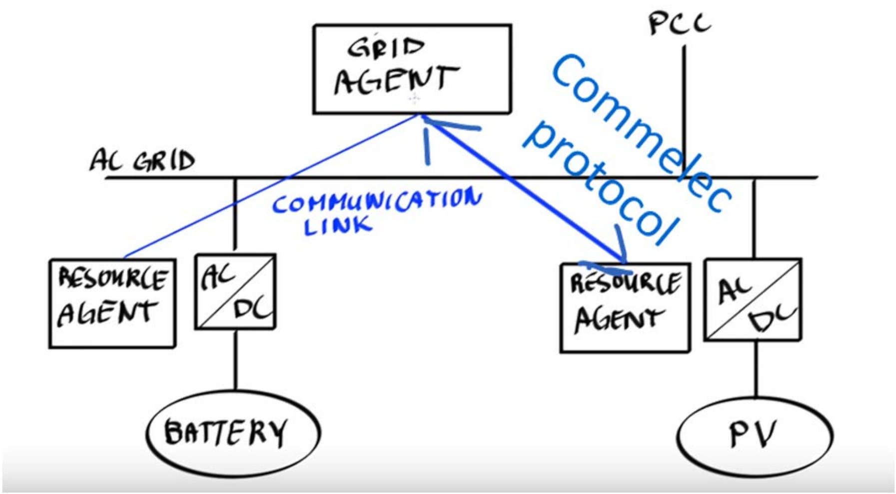


Belief Function
for a PV resource

Essential for safe operation

Grid Agent computes setpoints for resource agents based on

- Electrical state estimation
- Advertisements received
- Request from main grid



Grid Agent minimizes

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

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)

Cost of power flow at point of common connection

Grid Agent does not see the details of resources;

Problem solved by grid agent is always the same

Given estimated (measured) state $\hat{x} = (\hat{P}_i, \hat{Q}_i)$ grid agent computes next setpoint as

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

where

- Δx is a opposed to gradient of overall objective
- Proj{} is the projection on the set of safe electrical states

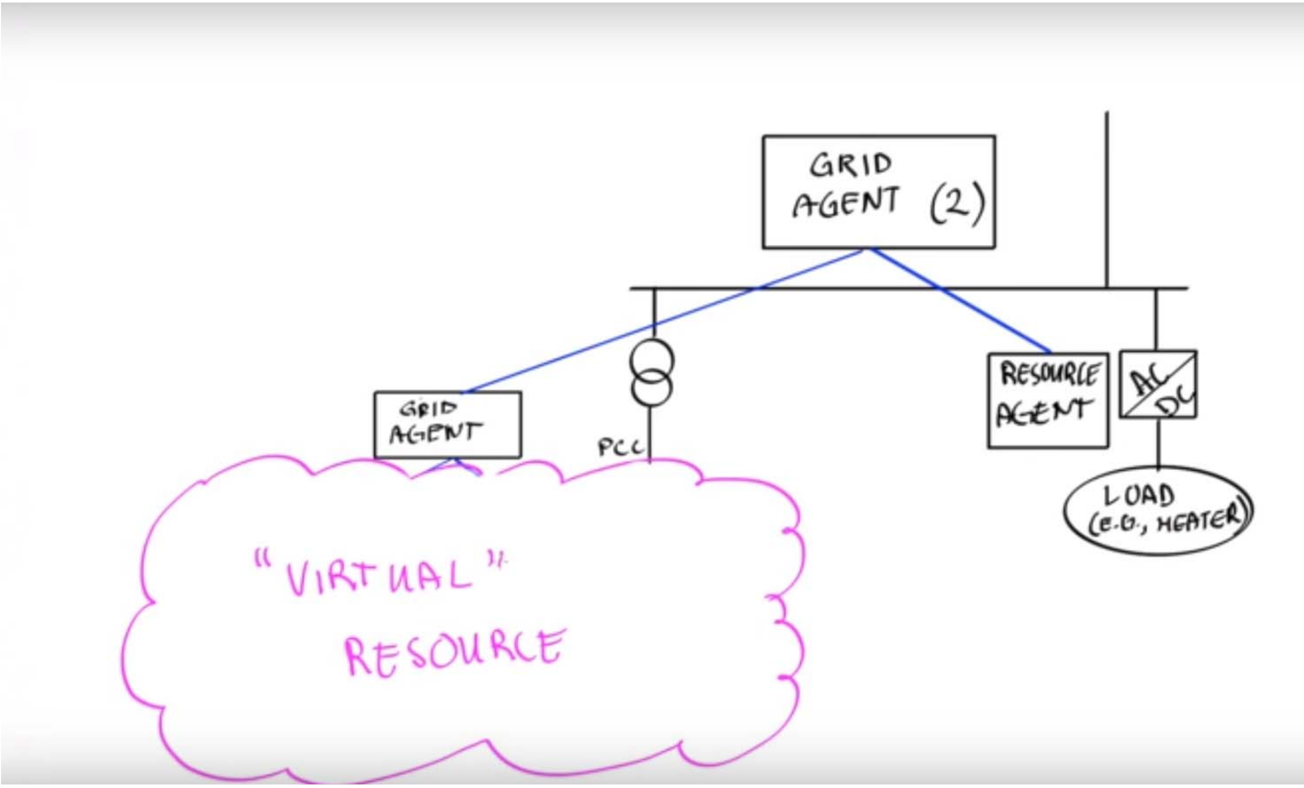
This is a randomized algorithm to minimize $E(J(x))$

Grid agent's main job involves

- Testing whether a given collection of power setpoints is feasible, given uncertainties of belief functions and given the characteristics of the grid
- This is known as a robust load flow

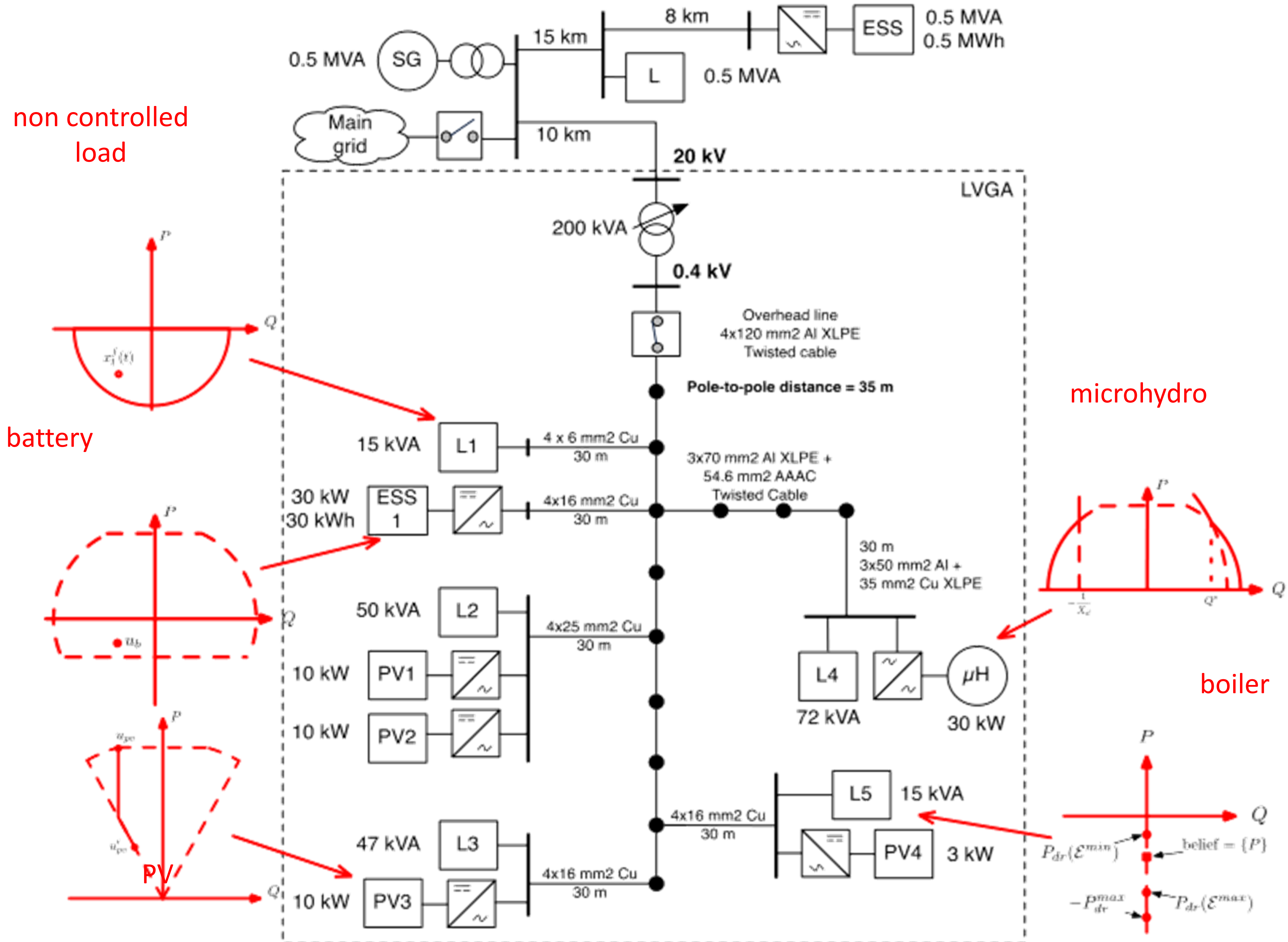
We have developed a very fast innovative method adapted to distribution networks (linear complexity, sub ms run time) [Wang et al. 2016]

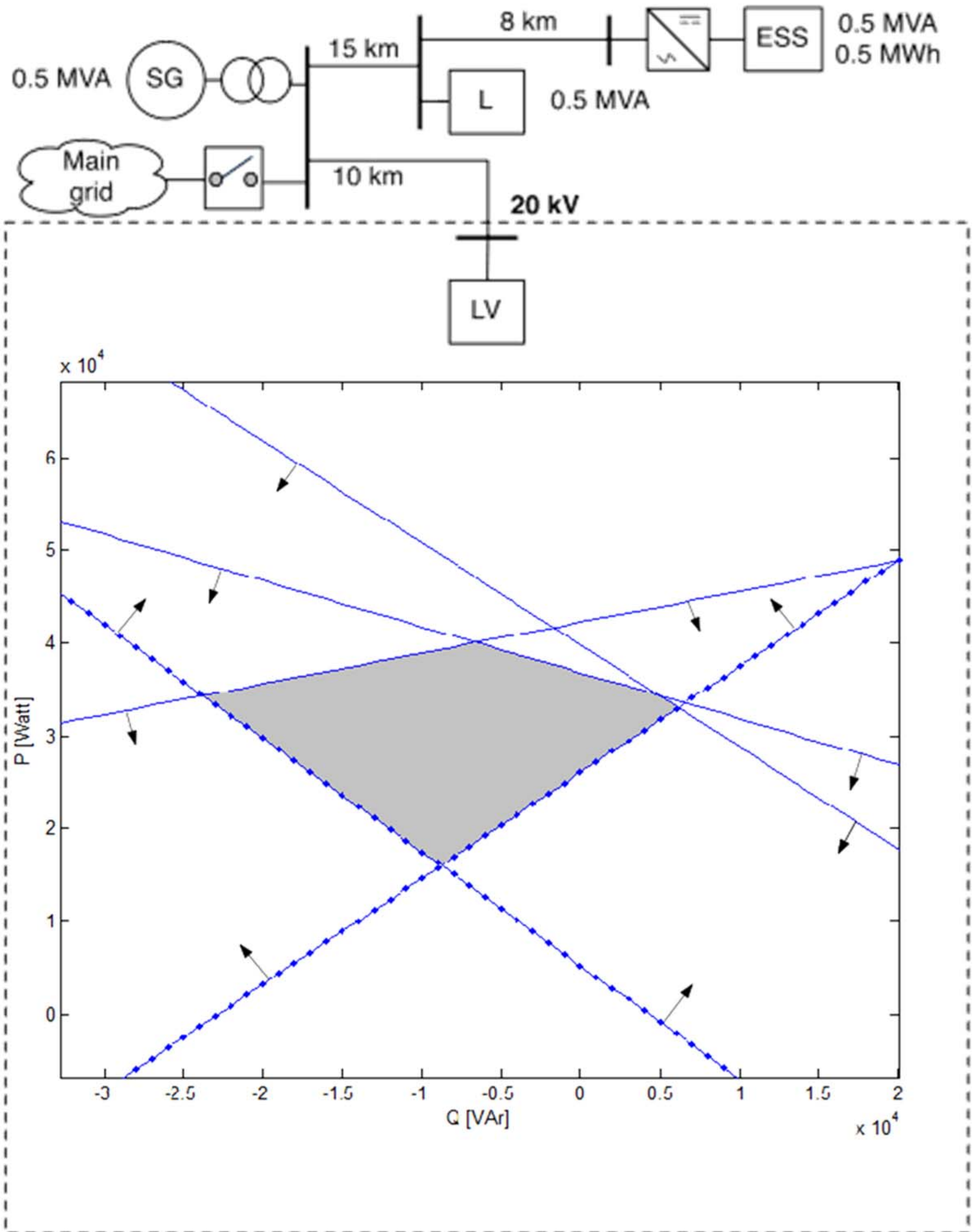
Commelec design principle #2: composability



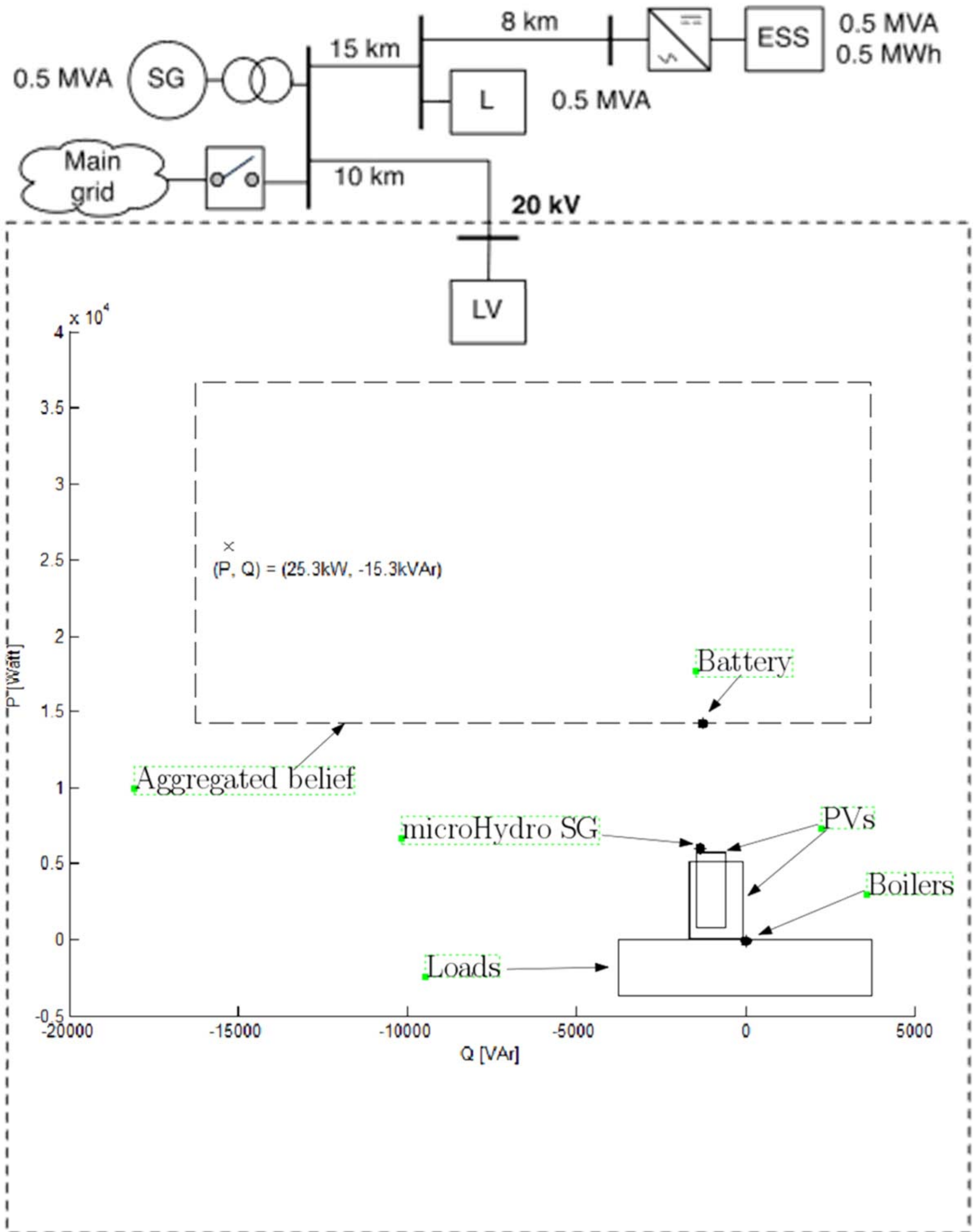
- an entire sub-grid can be abstracted as a single resource

Aggregation example



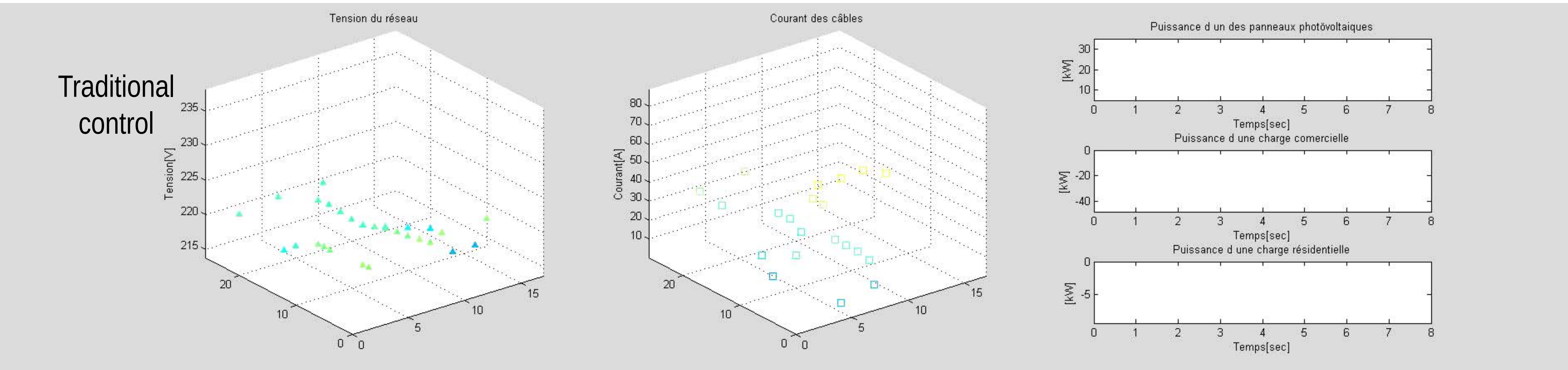


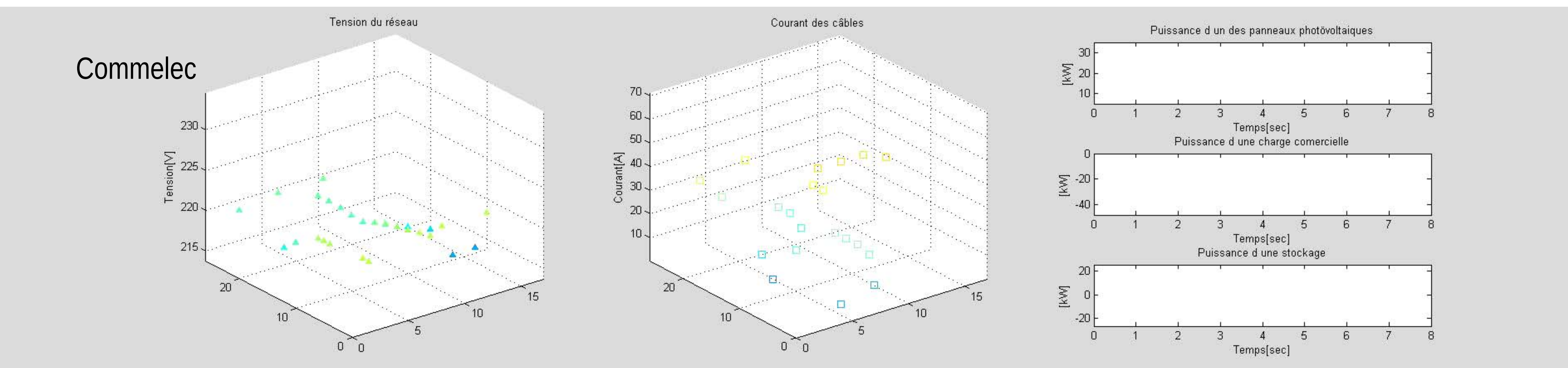
Aggregated PQt profile



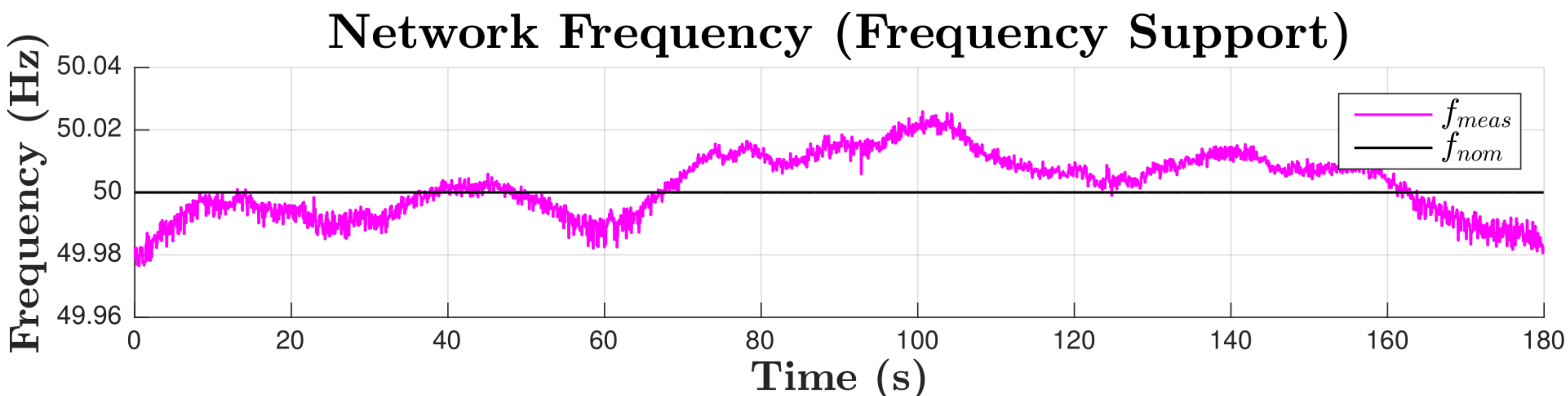
Aggregated Belief Function

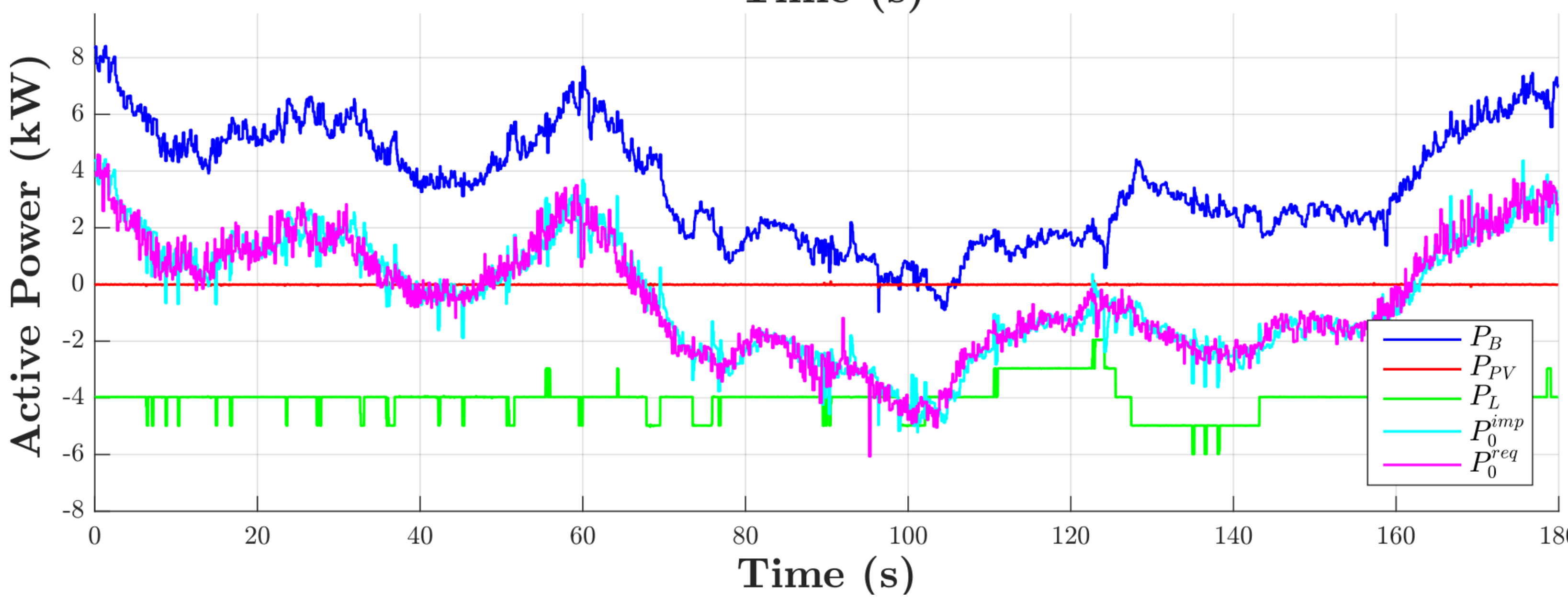
Commelec grid integrates all resources to keep grid safe



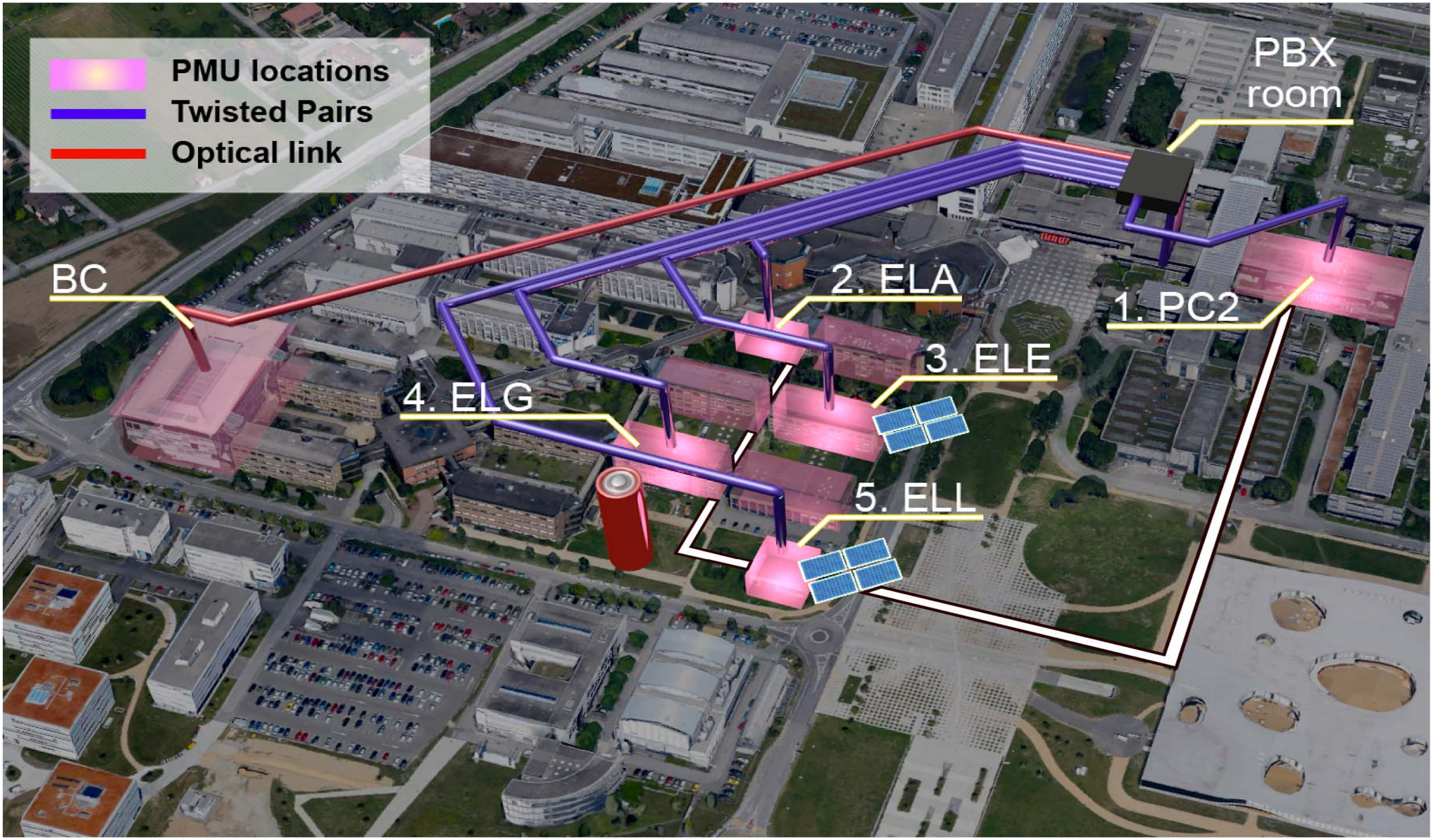


Commelec grid provides frequency support to main grid



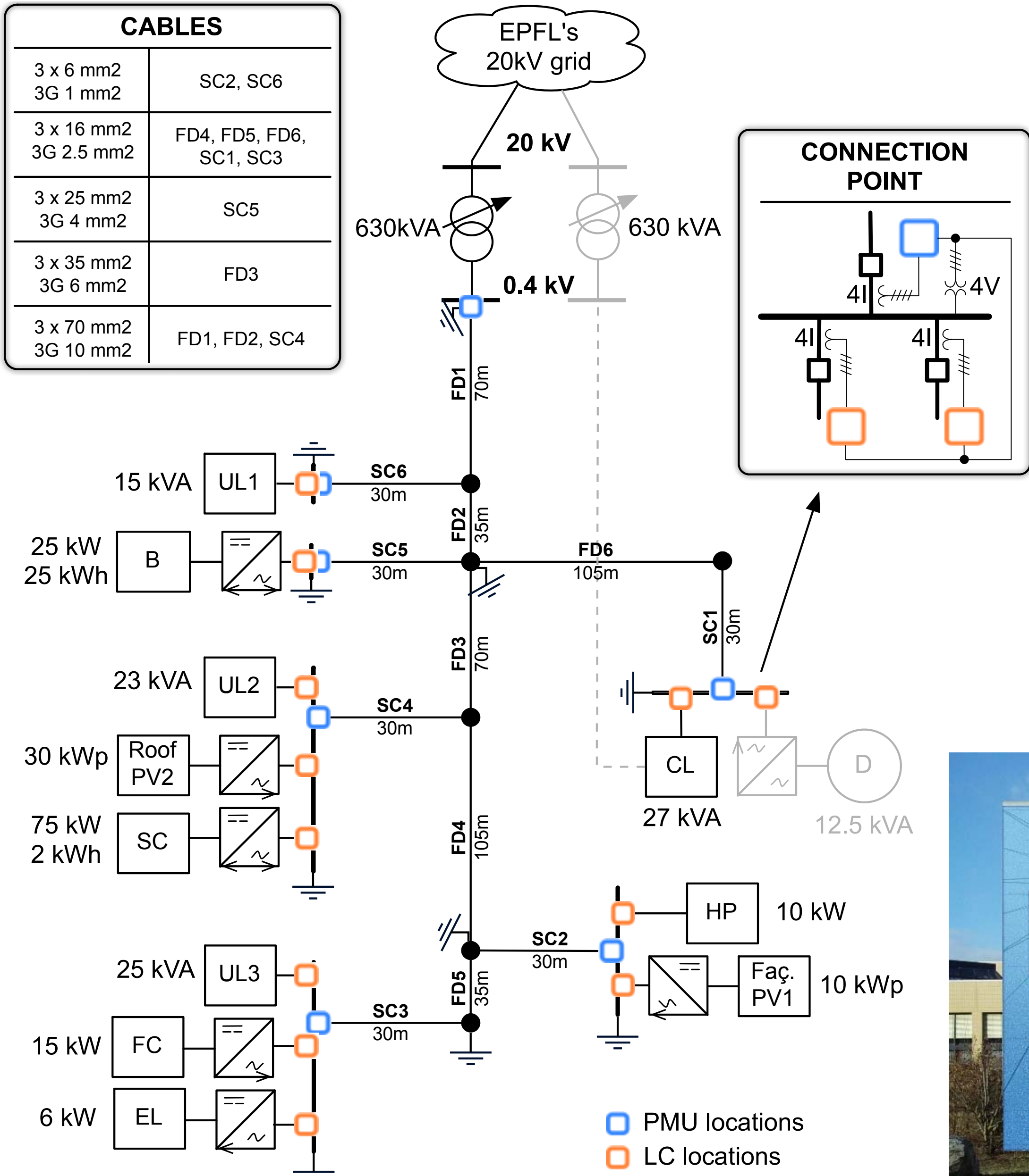


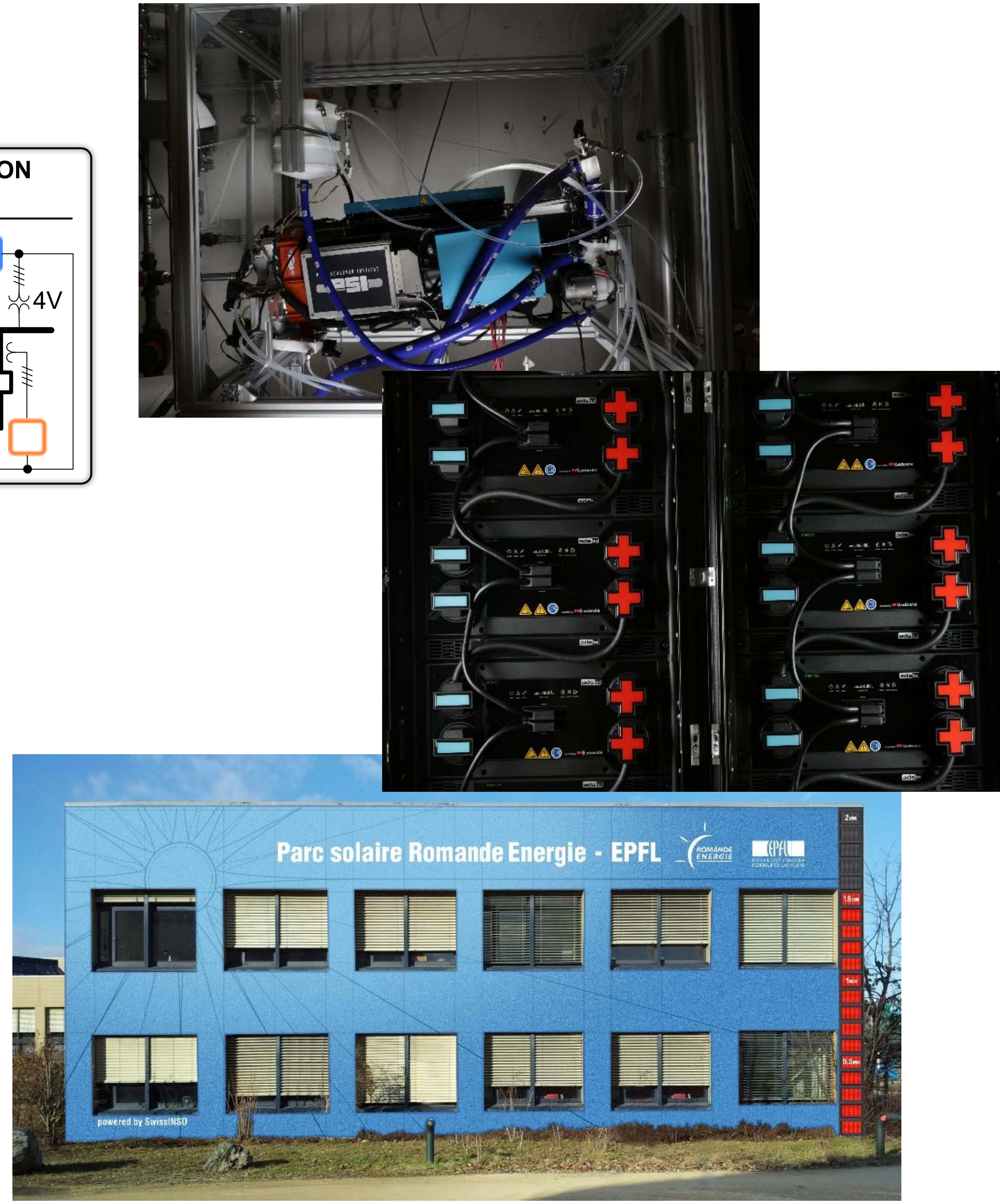
EPFL smart grid deployment



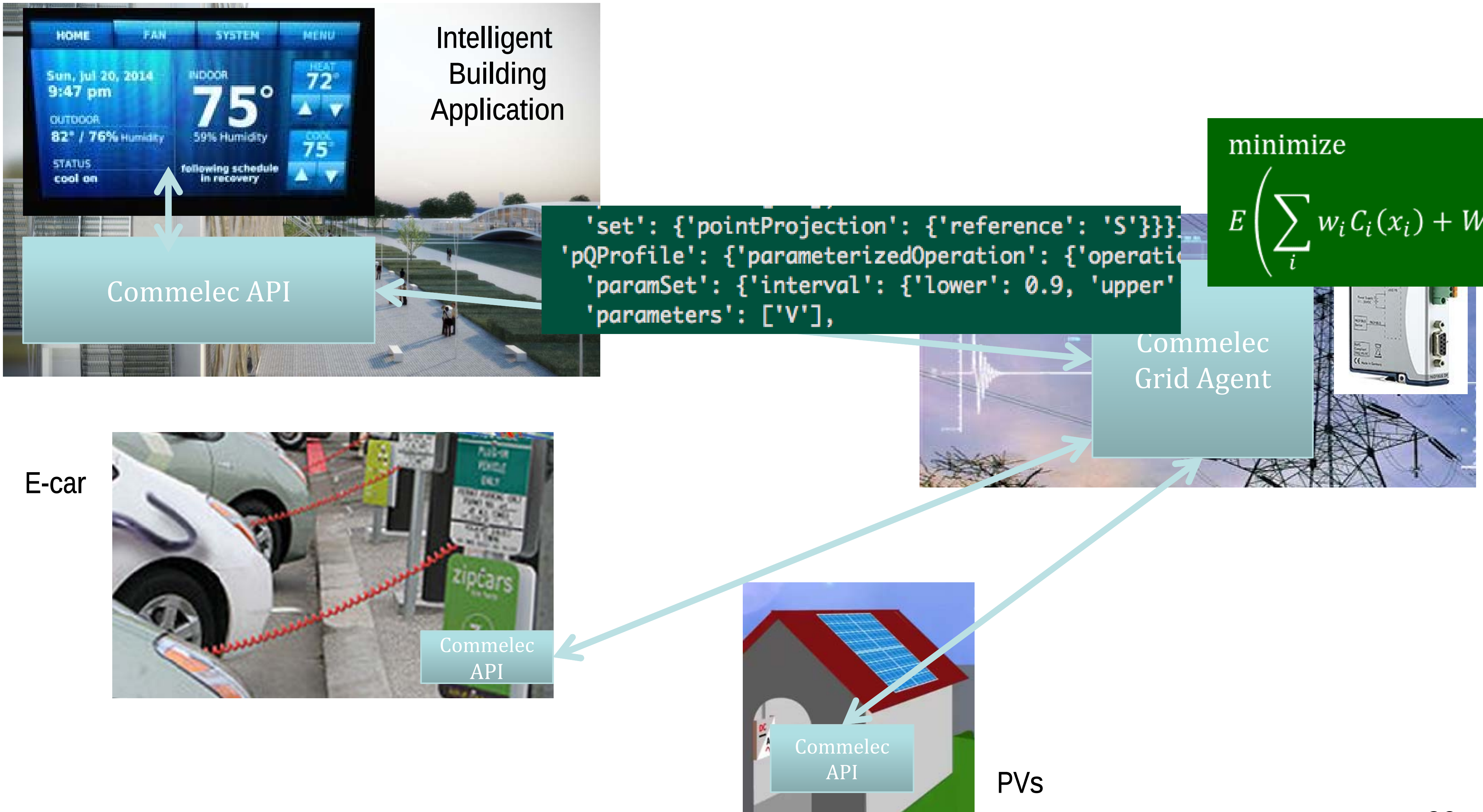
EPFL Microgrid running Commelec

CABLES	
3 x 6 mm2 3G 1 mm2	SC2, SC6
3 x 16 mm2 3G 2.5 mm2	FD4, FD5, FD6, SC1, SC3
3 x 25 mm2 3G 4 mm2	SC5
3 x 35 mm2 3G 6 mm2	FD3
3 x 70 mm2 3G 10 mm2	FD1, FD2, SC4



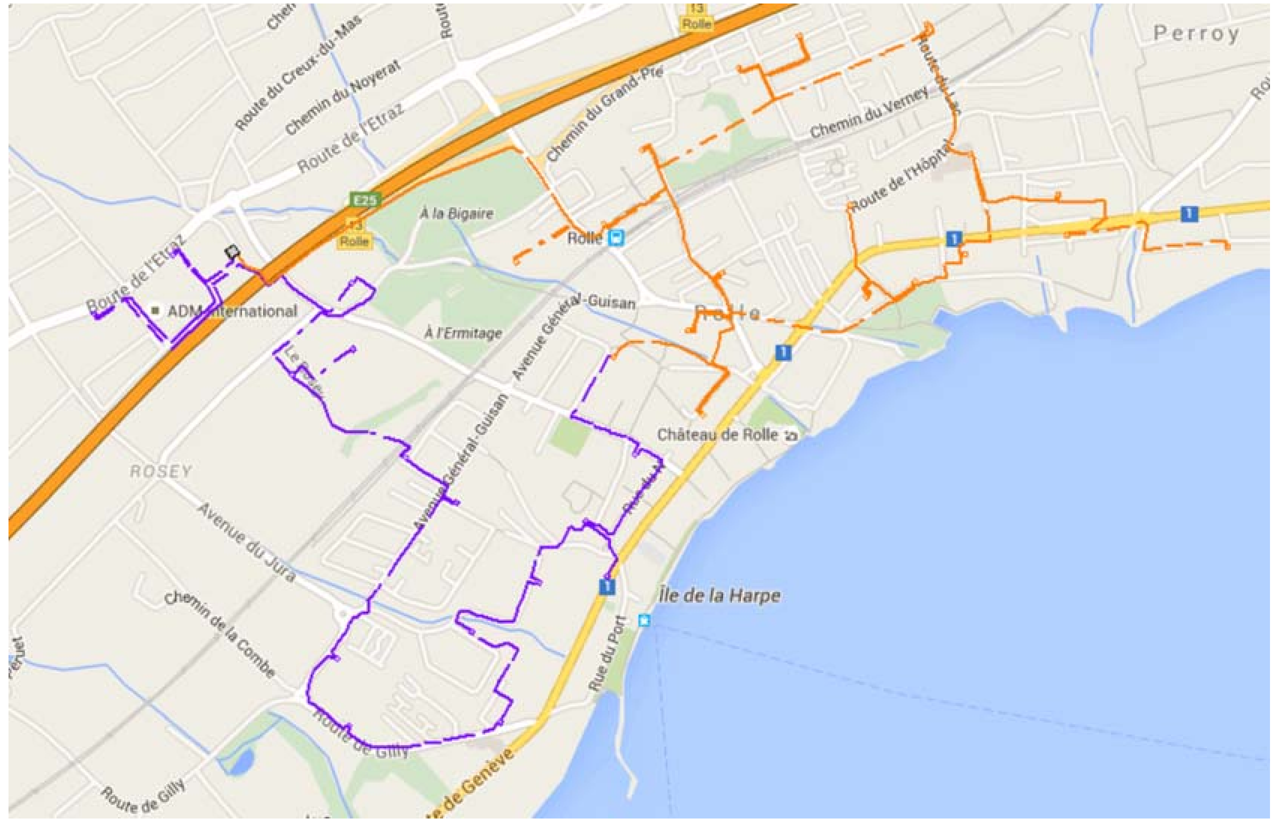


Commelec is implemented in the Commelec API (smartgrid.epfl.ch) for resource agent



Deployment Plans 2017

- Romande Energie grid



- MV: control of batteries to support voltage (large PV penetration) utility communication network
- LV: support main grid with frequency response communication over Internet, Swisscom cellular ?

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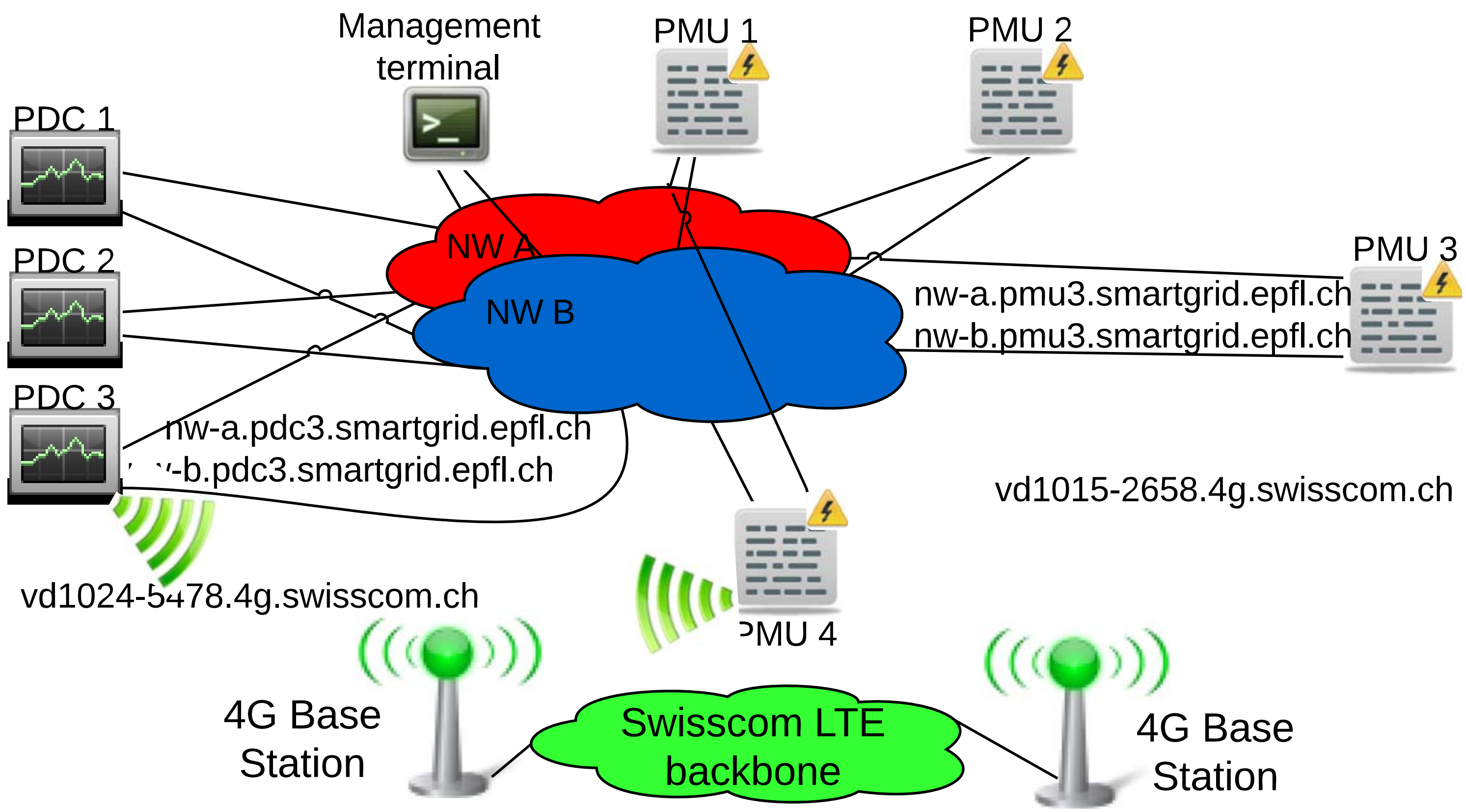
Reliability

- Use the BIP framework
- A single code for all grids
- Network Reliability by iPRP
- Tolerance to delay faults by Axo

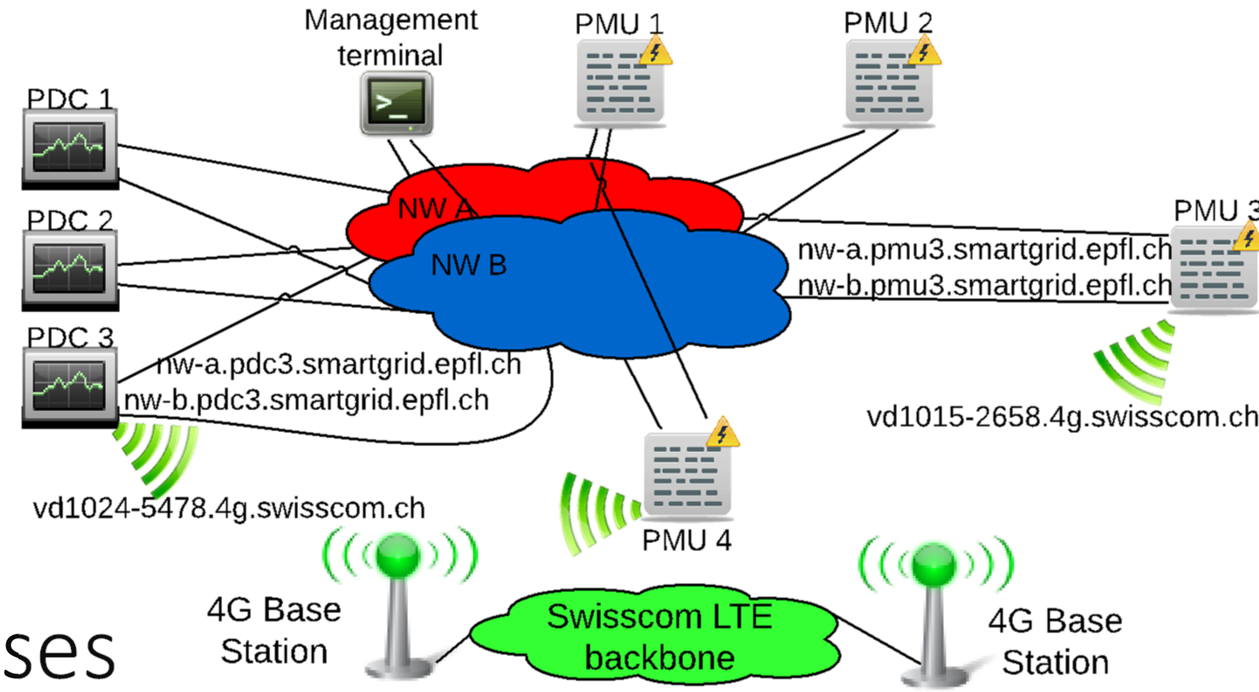
iPRP : reduce packet loss probability for UDP streaming with multi-homed sensors and controllers [Popovic et al 2016]

- Works on IP networks (unlike PRP)

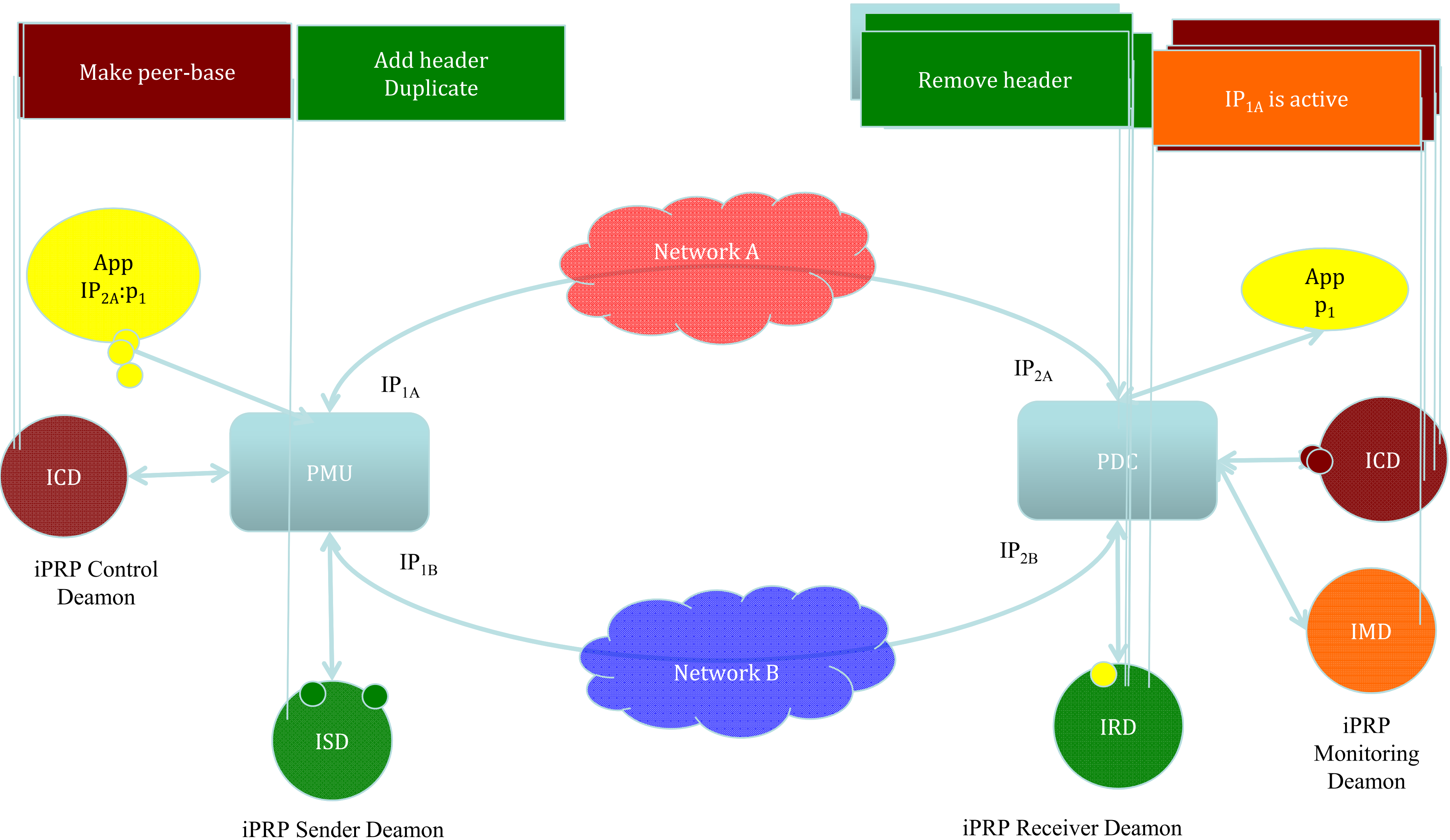


iPRP: transparent to UDP application and to network

- At source packets are replicated on all interfaces
- Matching addresses learnt automatically
- Supports multicast with Biersack-Nonnenmacher’s scheme for backoff
- Soft-state for crash recovery



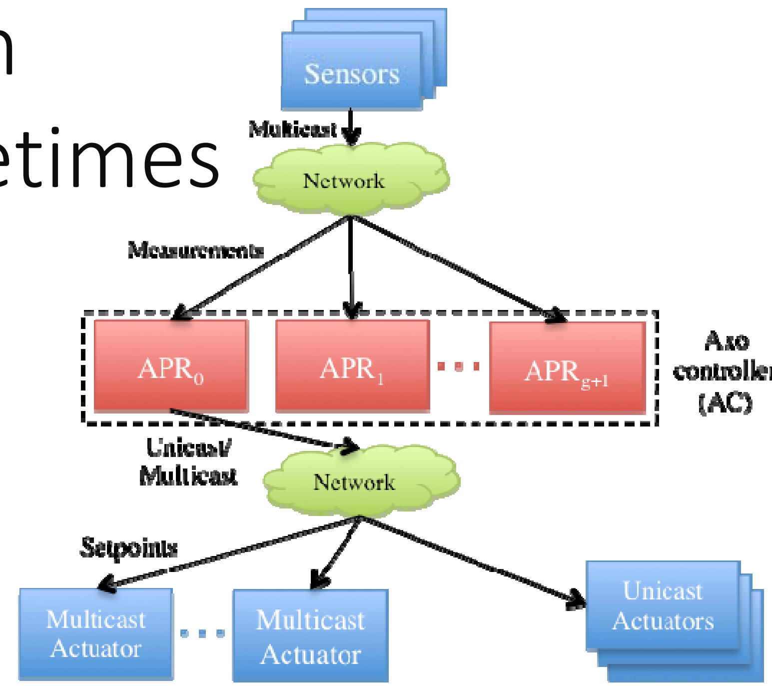
iPRP operation



Axo: handle delay faults in Grid Agents

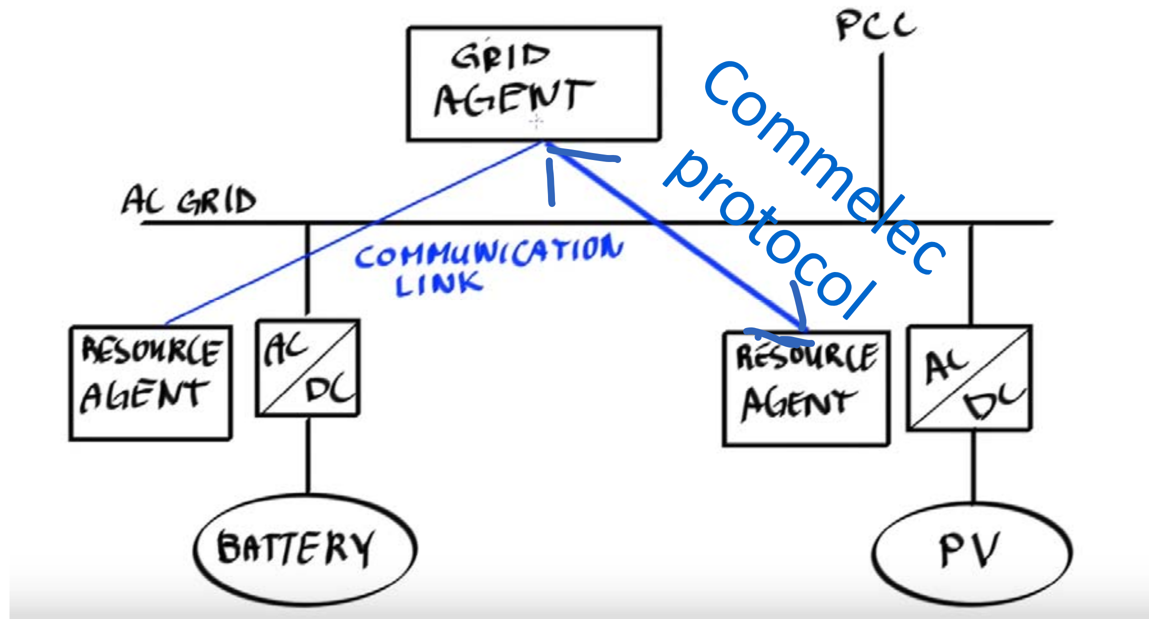
- Controller is replicated for reliability
- Commodity software used in controller (Grid Agent) sometimes exhibits large delays
- Delayed setpoints received by actuator may be invalid
- Axo solution

  1. require soft state approach in controller
  2. tagger and masker in client libraries catch delayed setpoints



Cyber-Security

- Control and sensing messages are authenticated with D-TLS and ECDSA for multicast

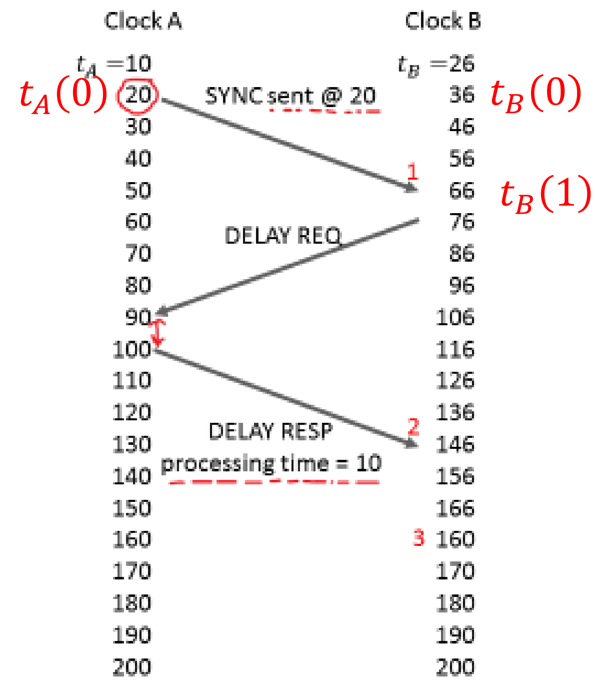


- Timing Attacks:
  Time Sync is used everywhere in smartgrid
  Phasor Measurement Units: require $\leq \mu$sec (GPS- PTP)
  Other sensors / actuators require $\approx$ 1 msec (NTP- PTP)

Network Time Synchronization Protocols (PTP, NTP)

B's goal is to adjust its clock to A's

B receives at $t_B(1)$ a time stamped SYNC message from A, sent by A at $t_A(0)$.



Assume we know the one-way delay d_{AB}. With B's clock, the time $t_B(0)$ at which this message was sent is $t_B(0) = t_B(1) - d_{AB}$.

B's clock offset ω_{AB} with respect to A is

$$\omega_{AB} = t_B(0) - t_A(0) = t_B(1) - t_A(0) - d_{AB}$$

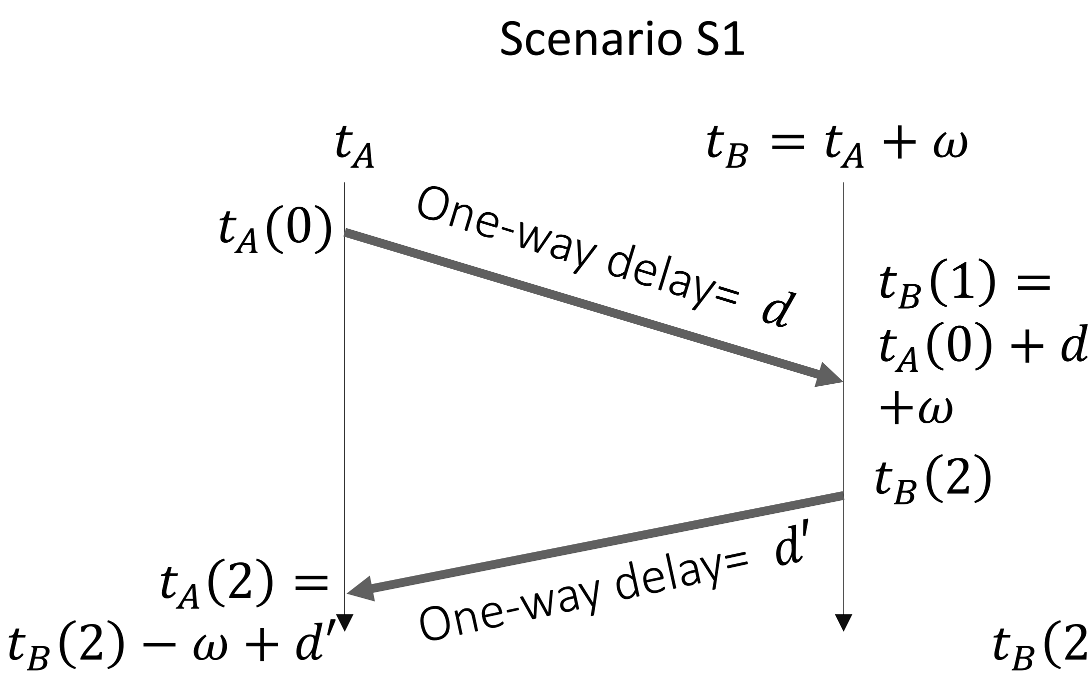
NTP and PTP measure the round-trip delay and do:

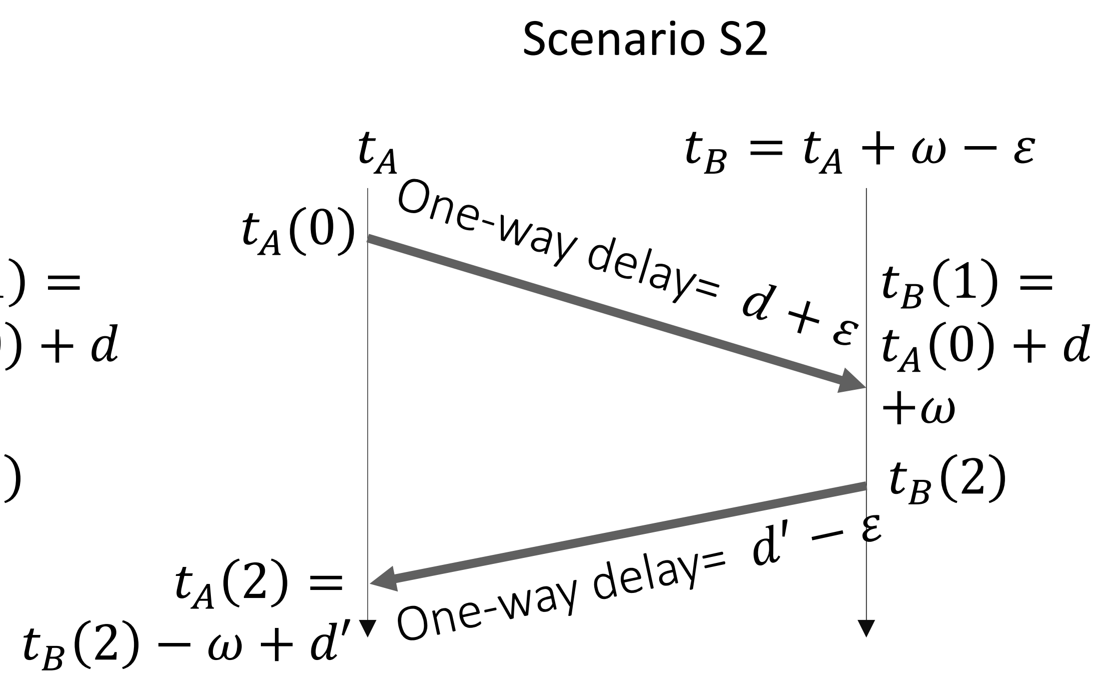
one-way-delay = $\frac{1}{2}$ round-trip delay.

Can we Measure One-Way Delays?

No. It is impossible.

Consider a simple scenario with two nodes. It is impossible for node B to distinguish between scenarios S1 and S2





Theorem [Gurewitz 2006] In a general network with N nodes and L unidirectional links, the number of delays that can be measured by timestamping protocols (such as NTP and PTP) is $\leq L - N + 1$.

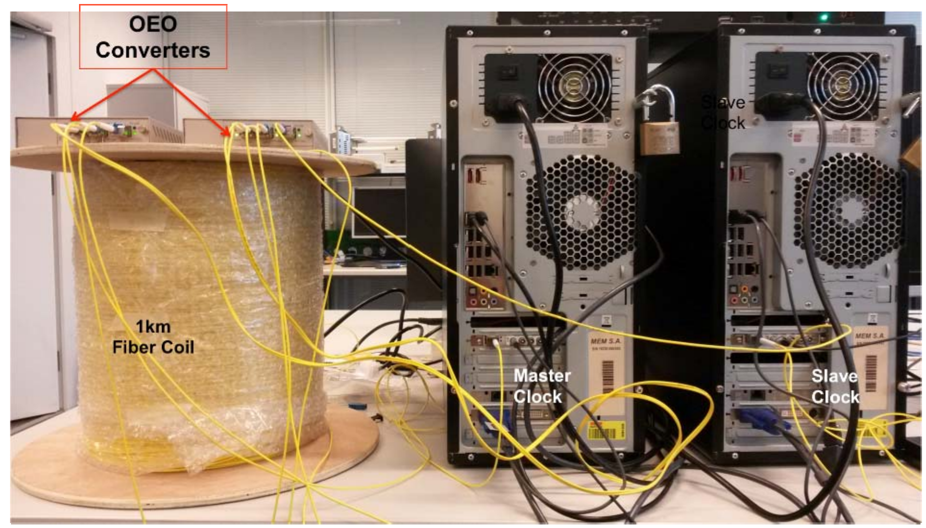
The bound (called *cyclomatic number)* is always less than L, so it is not possible to measure all unidirectional link delays.

It is possible to account for link asymmetries (one-way-delay $\neq \frac{1}{2}$ round trip delay) only by external information. For example, if asymmetry is due to different speed of light in optical fibers, the ratio between forward and backward delay is known and can be used to estimate delays correctly.

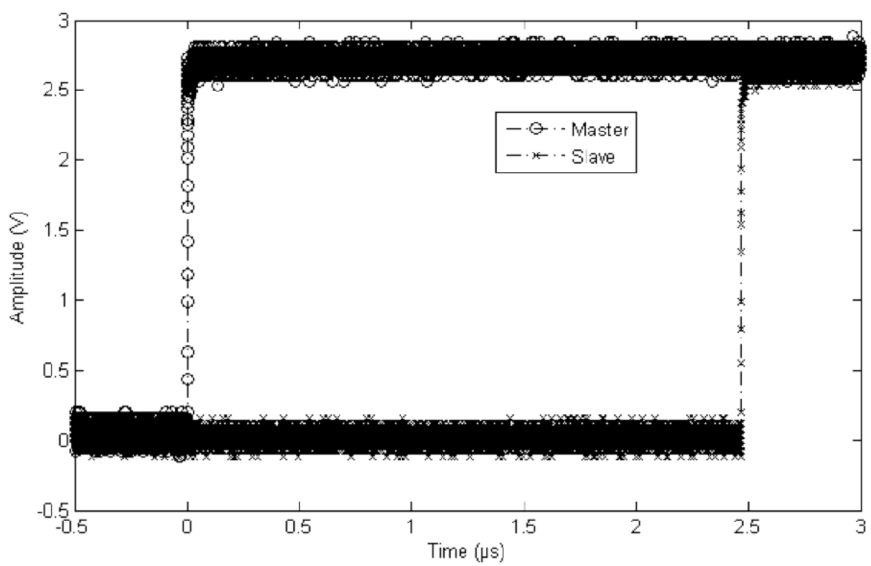
[Gurewitz 2006] Gurewitz, Omer, Israel Cidon, and Moshe Sidi. "One-way delay estimation using network-wide measurements." *IEEE/ACM Transactions on Networking (TON)* 14.SI (2006): 2710-2724.

The Undetectable Delay Box

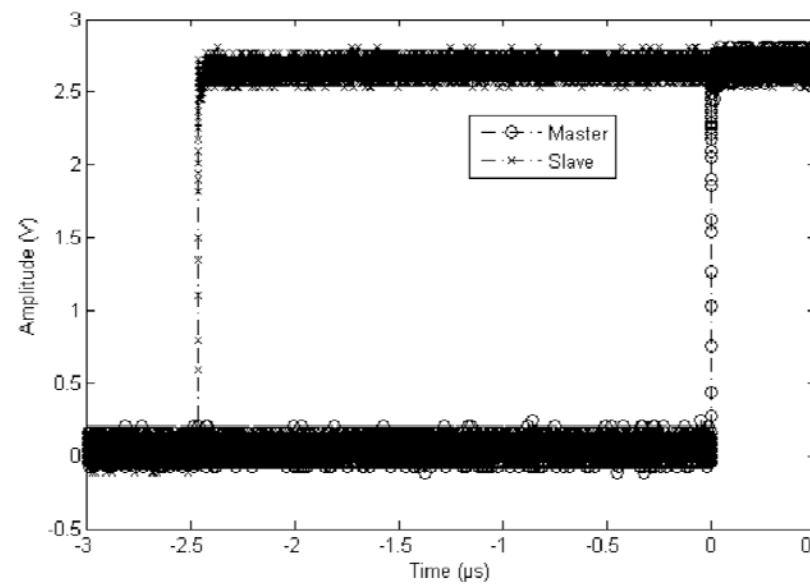
- Introduce OEO repeater in an optical line
- Insert different delays in each direction



- PTP slave clock computes wrong offset



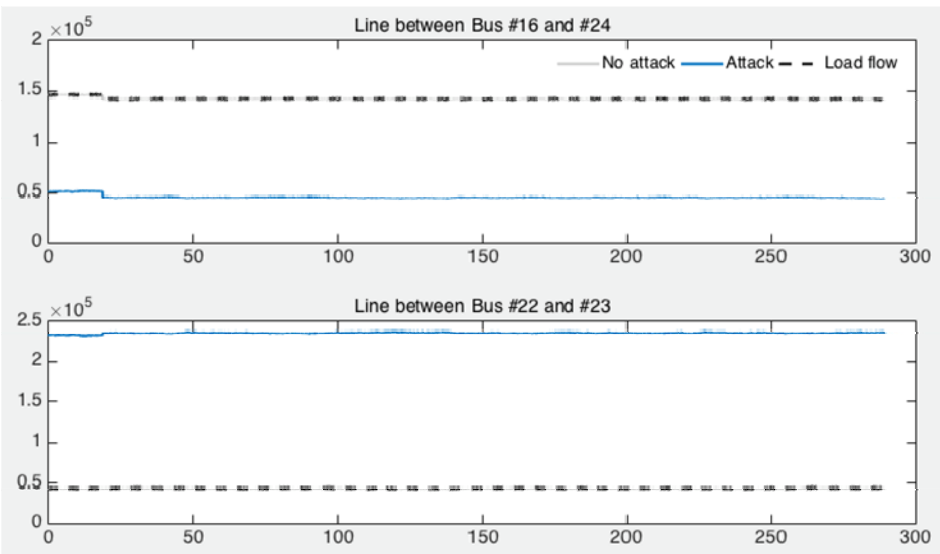
Delay attack in M-S direction with $D = D^* = 4.98\mu s$

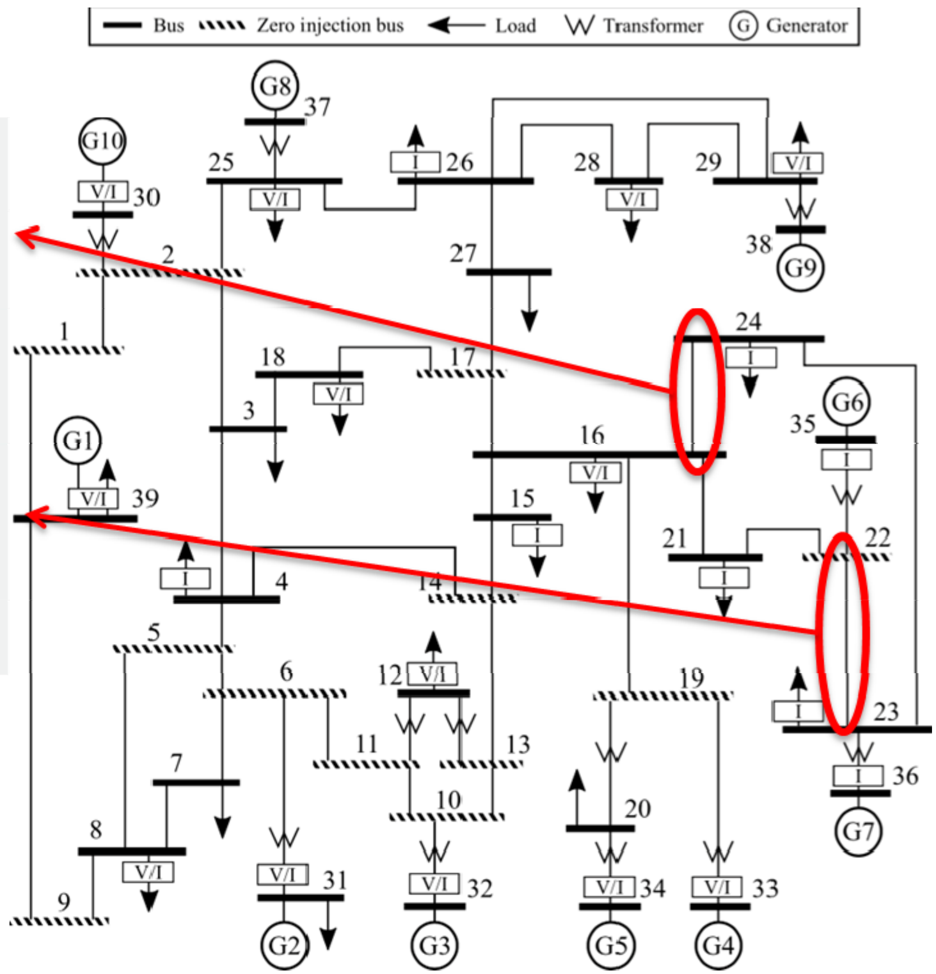


Delay attack in S-M direction with $D = D^* = 4.98\mu s$

Attack against grid control using a delay box

- modify measured phasor angles, undetectably
- induce grid control into under- or over-estimating power flows.





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Conclusion

- Real time control of power flows will enable integration of large amounts of renewables
- IT Challenges are similar to those of autonomous vehicles