(COMMELEC)
REAL TIME CONTROL OF DISTRIBUTION NETWORKS

2nd Interdisciplinary Workshop on
Smart Grid Design & Implementation, March 28 - 29
University of Florida.

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joint work with
Mario Paolone, Andrey Bernstein and Lorenzo Reyes, EPFL
Laboratory for Communications and Applications and
Distributed Electrical Systems Laboratory

Contents

Reference

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)

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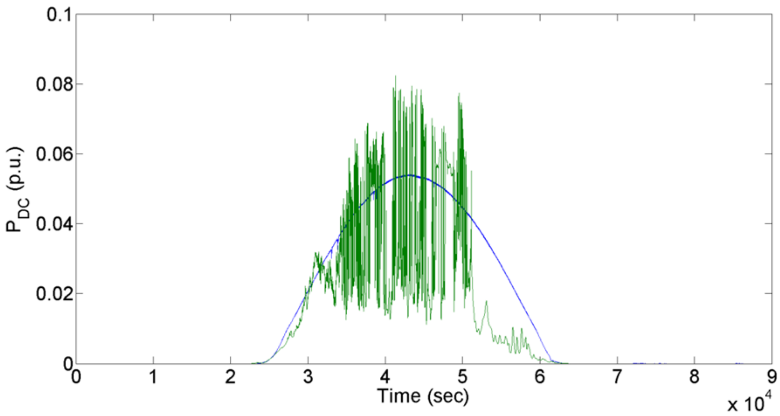
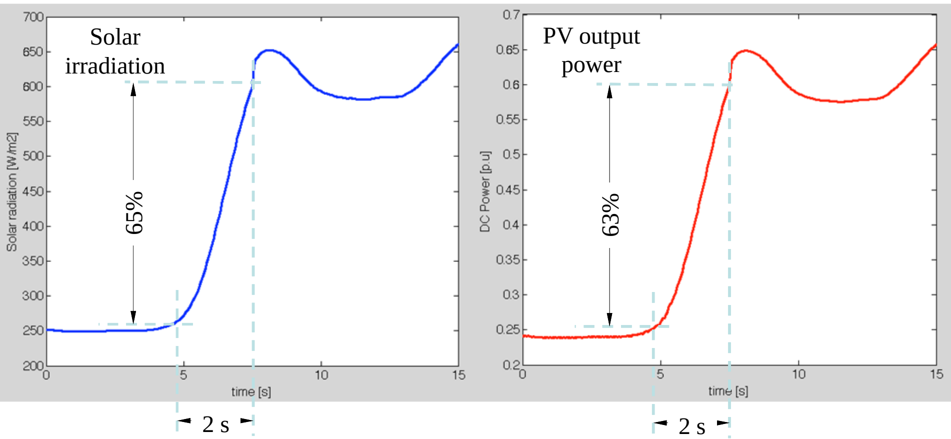
Switzerland 2035: ≥ 30 to 40% generation will be distributed and volatile

Example of daily measured power injected by solar arrays at EPFL



source: Prof. Mario Paolone, Distributed Electrical Systems Lab, EPFL

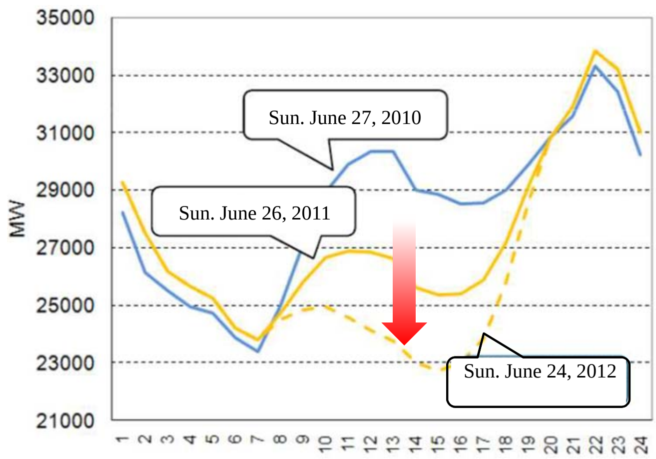


source: Prof. Mario Paolone, Distributed Electrical Systems Lab, EPFL

- $\geq$ 30 to 40% generation will be distributed and volatile

Remark#1: possibility to have phases along the day with large reduction of the net power flow on the transmission network.

Remark#2: need of faster ramping in the evening hours



Source: Terna S.p.A.

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Outlook for 2035

Challenges for grids

- quality of service in distribution networks
- participation of distributed generation to frequency and voltage support *(Virtual Power Plant)*
- autonomous small scale grids with little inertia

Solutions

- fast ramping generation (fossil fuel based)
- local storage, demand response
- *real time control* of local grids

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Real Time Control of Grids

- Typically done with droop controllers
- Problems:
  - system does not know the state of resources (e.g. temperature in a building, state of charge in a battery)
  - all problems made global
- Alternative: *explicit control of power setpoints*

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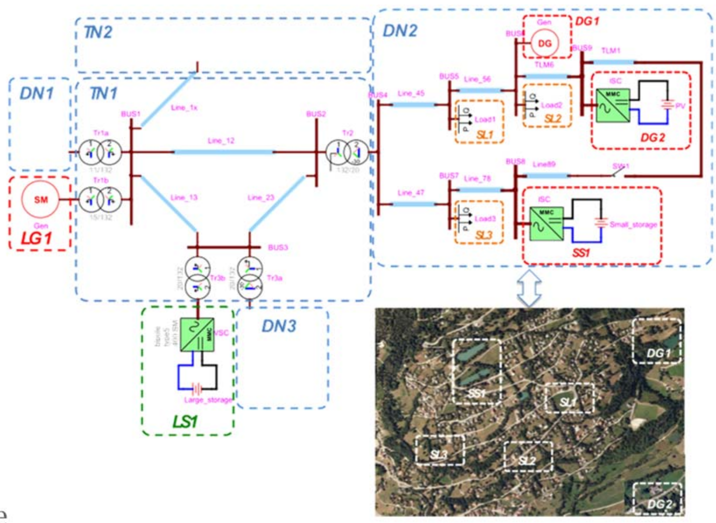
Requirements for an Explicit Control Method



1. Real time
2. Bug free (i.e. simple)
3. Scalable
4. Composable

   e.g. TN1 can control DN2; DN2 can control SS1

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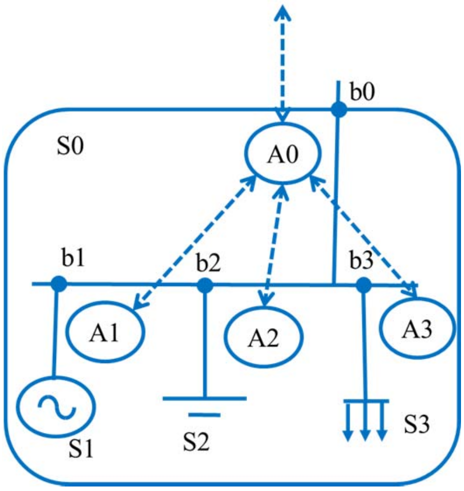
2. COMMELEC's Architecture

- Software Agents associated with devices
  - load, generators, storage
  - grids
- Grid agent sends explicit ***power setpoints*** to devices' agents



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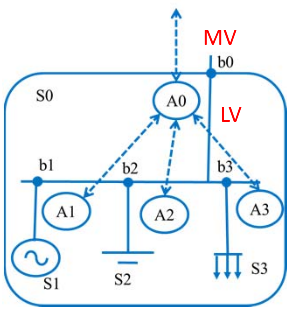
Resources and Agents

- Resources can be
  - controllable (sync generator, microhydro, battery)
  - partially controllable (PVs, boilers, HVAC, freezers)
  - uncontrollable (load)
- Each resource is assigned to a resource agent
- Each grid is assigned to a grid agent
- Leader and follower
  - resource agent is follower or grid agent
  - e.g. LV grid agent is follower of MV agent



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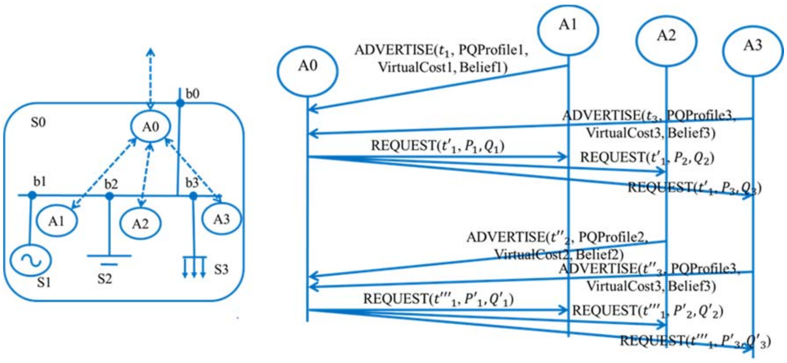
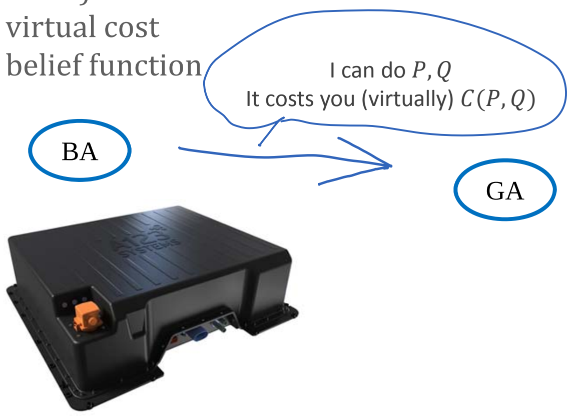
The Commelec Protocol



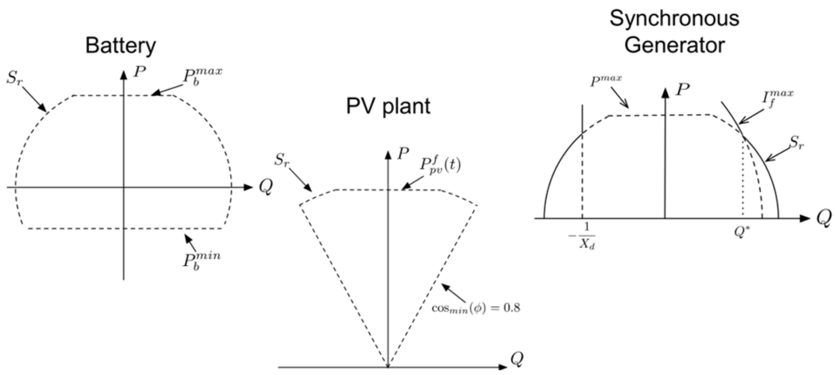
- Every agent advertises its state (every≈ 100 ms) as PQt profile, virtual cost and belief function
- Grid agent computes optimal setpoints and sends setpoint requests to agents

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



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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

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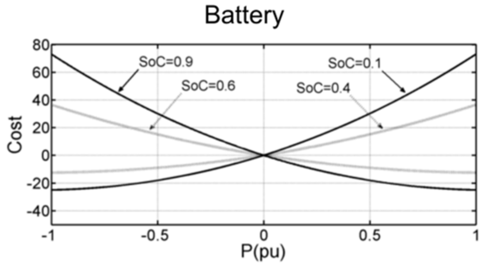
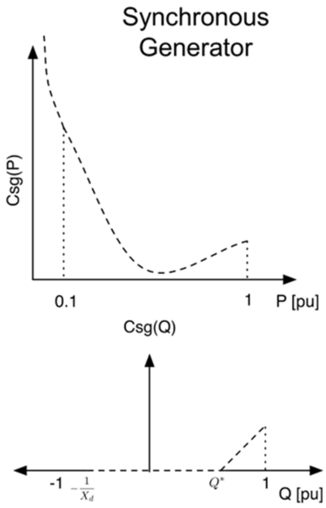
Examples of Virtual Costs



$C_b(Q) = 0$



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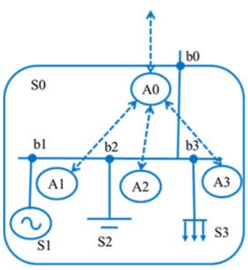
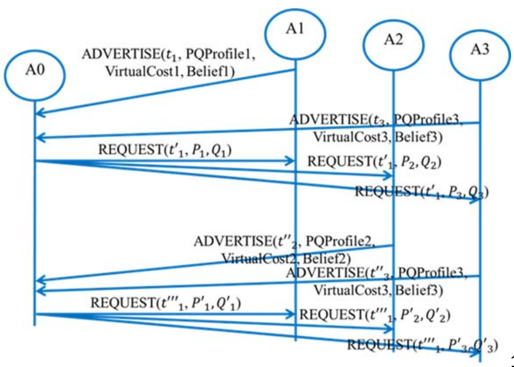
Commelec Protocol: Belief Function

- 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





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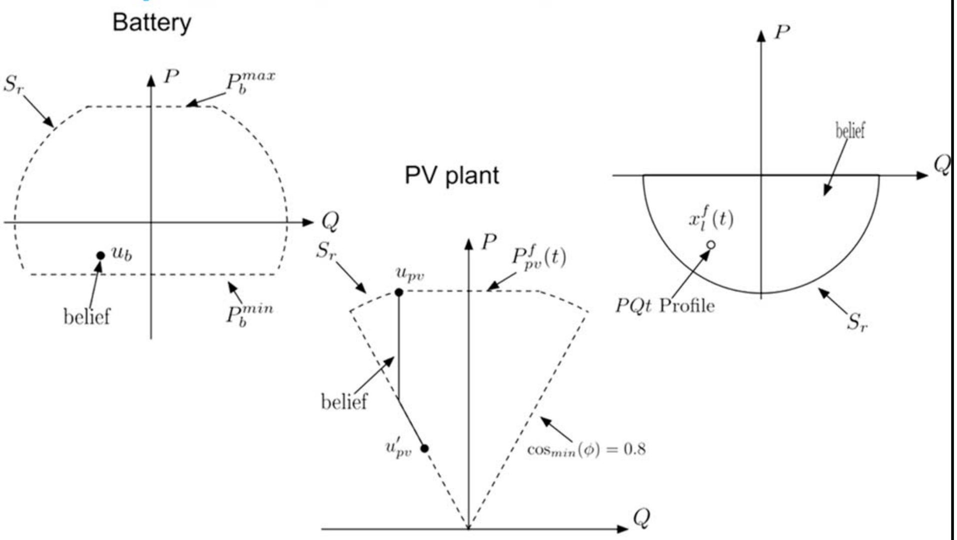
Examples of Belief Function



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

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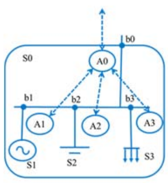
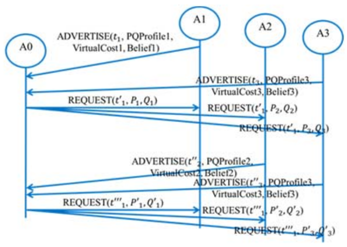
Grid Agent's job

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





- Grid Agent attempts to minimize

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

virtual cost of resource i

penalty function of grid electrical state z keeps voltages close to 1 p.u and currents within bounds

- 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

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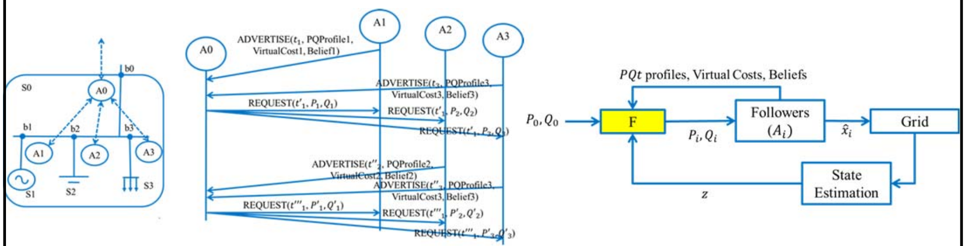
Grid Agent's algorithm



- 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 $E(J(x))$

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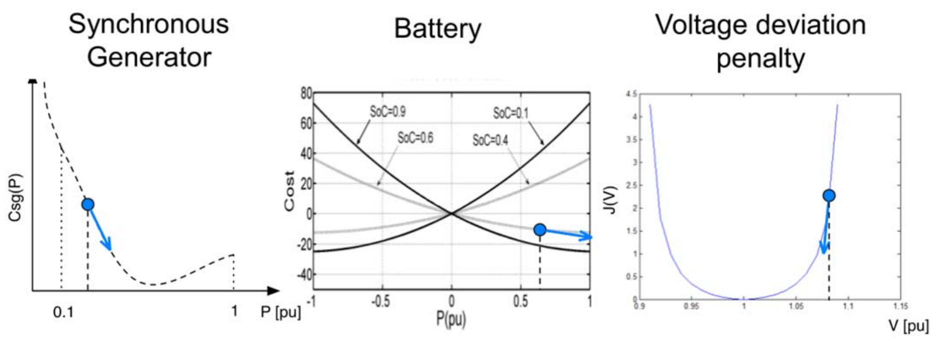
Setpoint Computation by Grid Agent involves gradient of overall objective = sum of virtual costs + penalty



+ line congestion penalty

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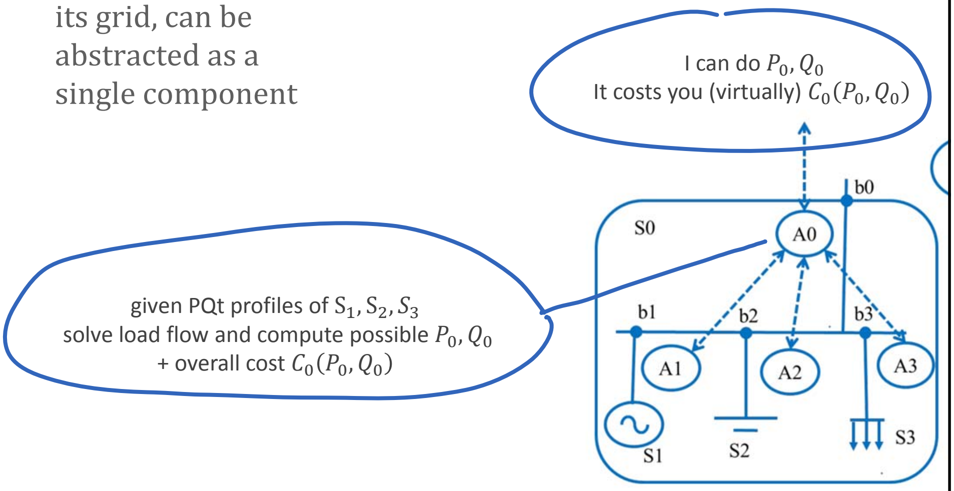
Aggregation (Composability)

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



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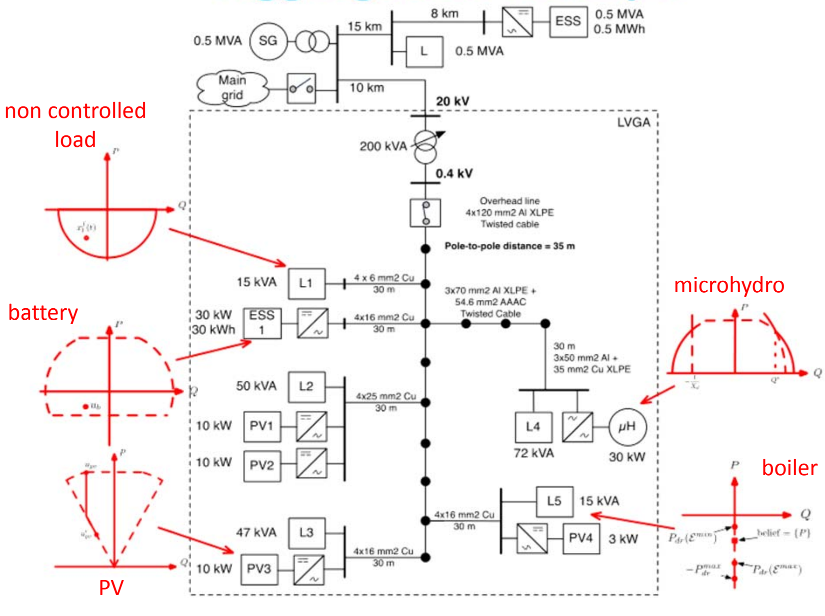
Aggregation Example



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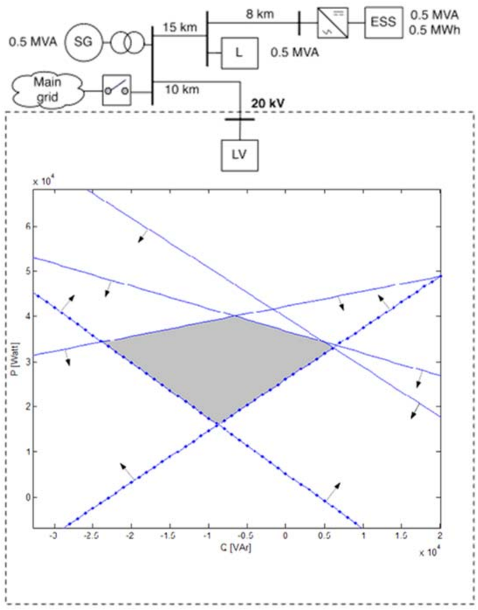
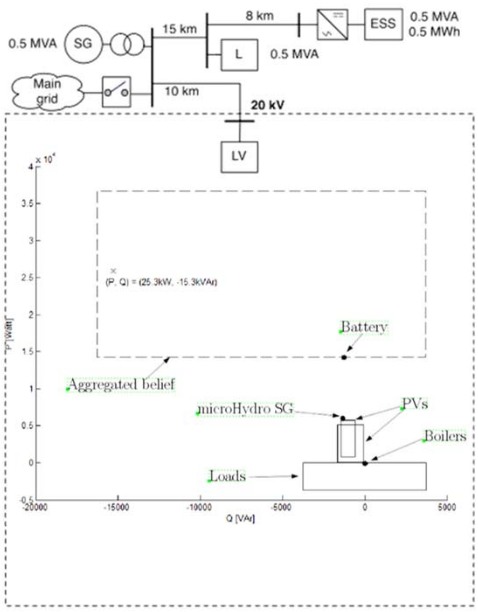


Aggregated PQt profile

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

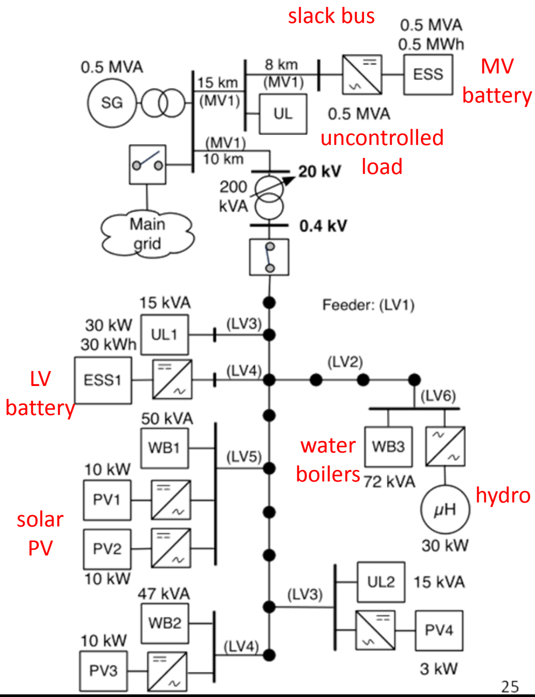


Aggregated Belief

safe approximation (*superset* of true aggregated belief)

3. Simulation Results

- Microgrid benchmark defined by CIGRÉ Task Force C6.04.02
- Islanded operation



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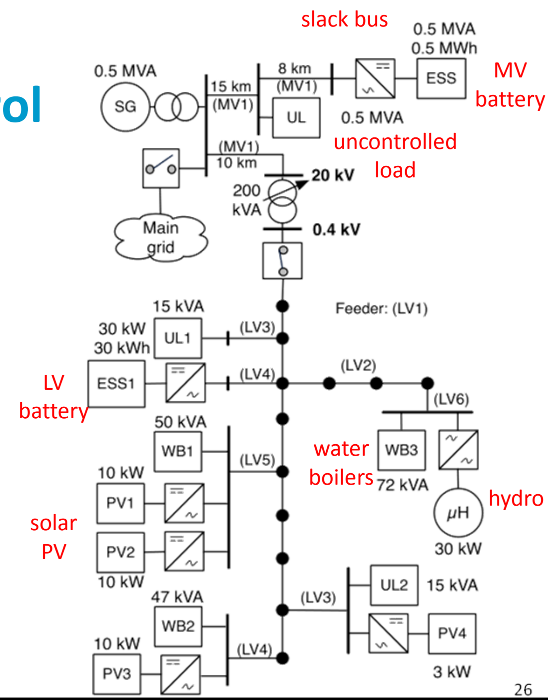
Droop versus Commelec control

- We studied 3 modes of operation
  - Droop control at every power converter ; Frequency signal generated at slack bus with only primary control
  - Droop control at every power converter : Frequency signal generated at slack bus with secondary control
  - Commelec



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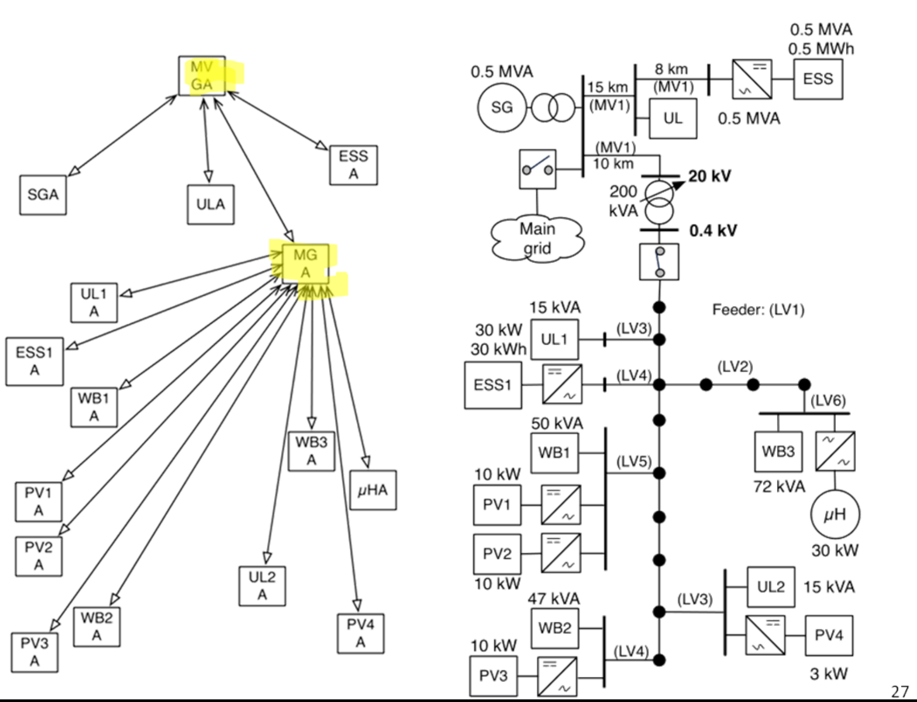
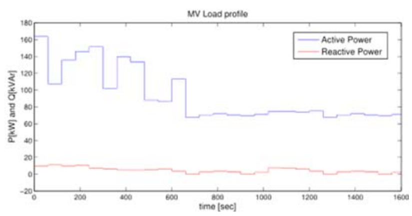
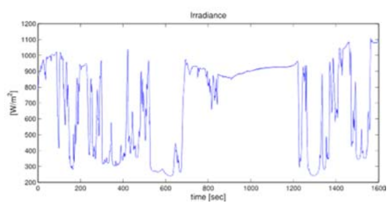


- Sources of randomness are
  - solar irradiation
  - uncontrolled load
- Storage provided by
  - batteries
  - water boilers
- Data: We used traces collected at EPFL in Nov 2013
- Performance Metrics
  - distance of node voltages to limits
  - state of charge
  - renewable curtailed
  - collapse/no collapse

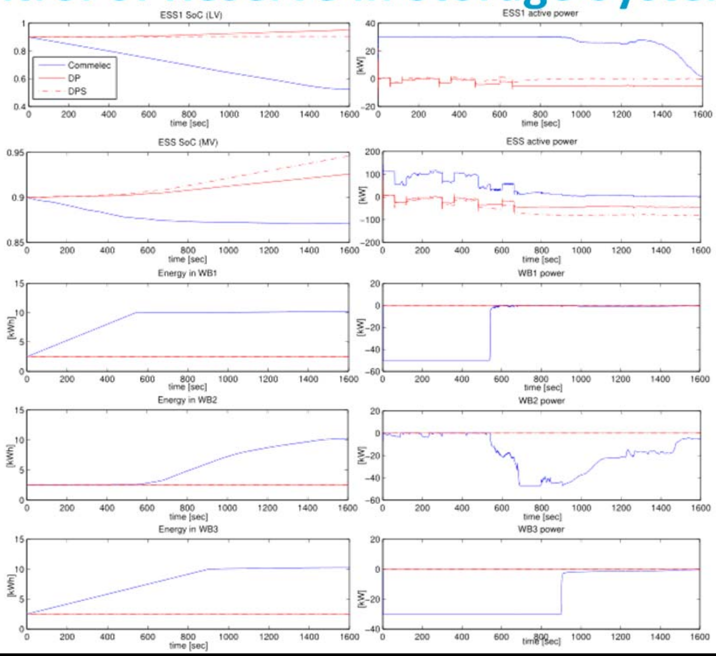




Control of Reserve in Storage Systems

ESS1 and ESS2 are driven to their midpoints

boiler 2 charged only when feasible



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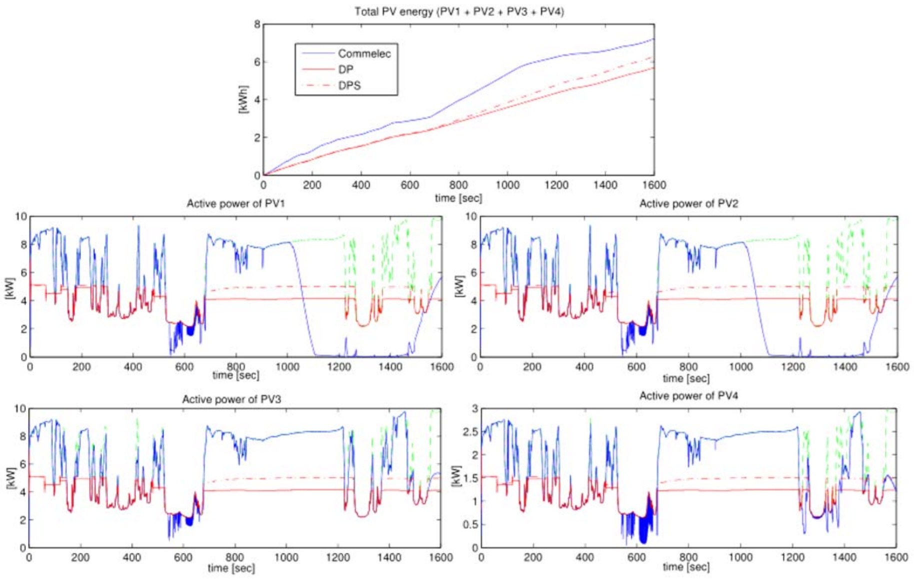
Reduced Curtailment of Renewables



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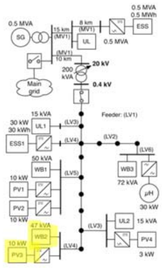
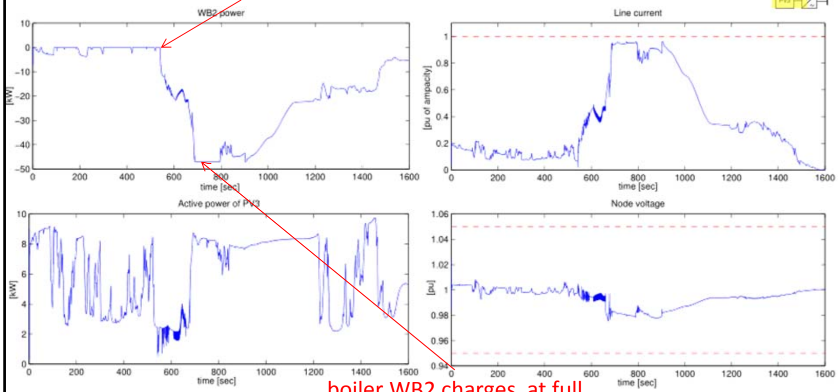
Local Power Management



boiler WB2 starts because WB1 stops at mid power due to line current



boiler WB2 charges at full power because PV3 produces

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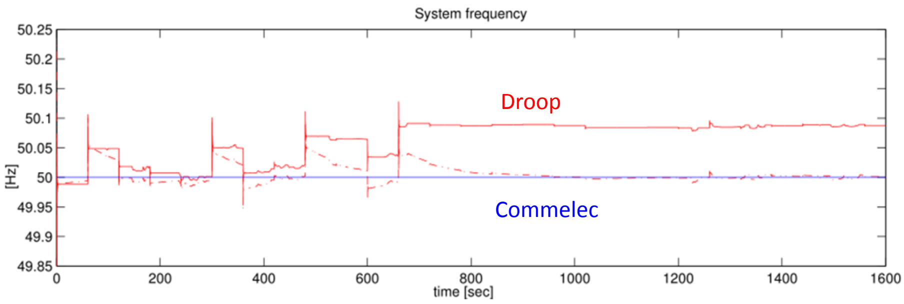
System Frequency



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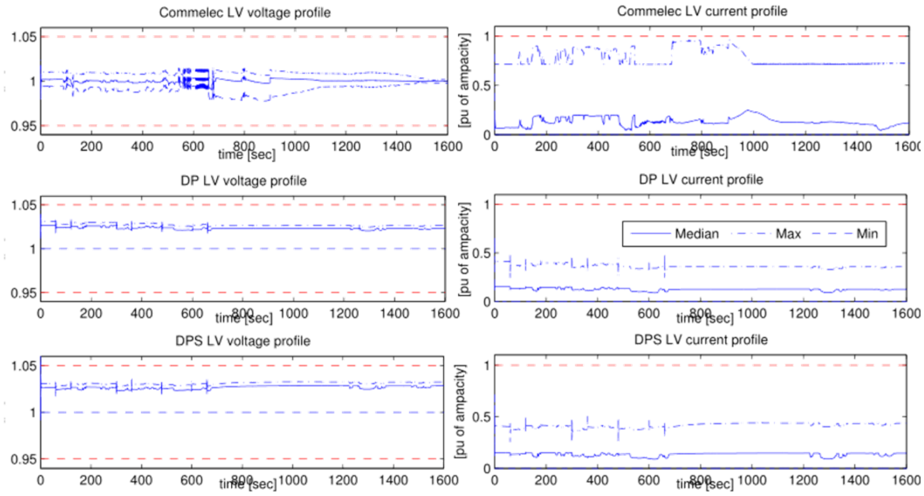
Voltage and Current Profiles



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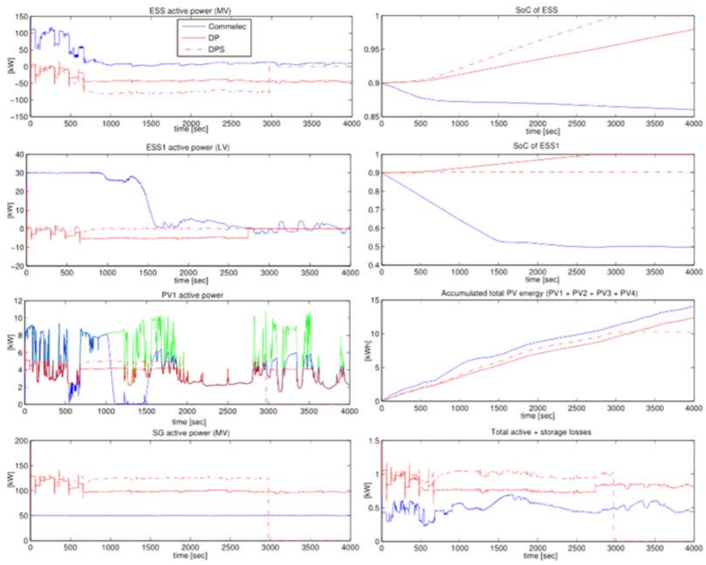
Without manual intervention, droop control with secondary fills the slack bus battery until collapse
Commelec automatically avoids collapse



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4. Discussion

- Implementation on EPFL' grid is underway
  - phase 1 (now) experimental microgrid
  - phase 2: campus feeders with automatic islanding and reconnection
- Implementation of Resource Agents is simple
  - translate device specific info into PQt profile, cost and beliefs
  - implement setpoints
- Implementation of Grid agent is more complex
  - we use the formal development framework (BIP)
  - automatic code generation

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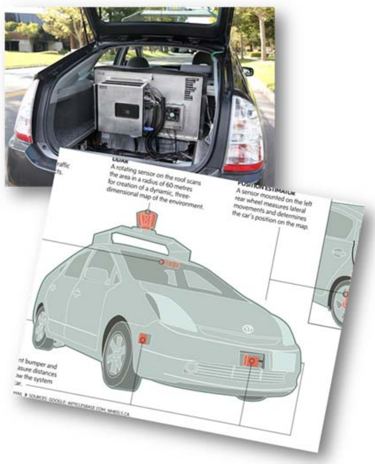
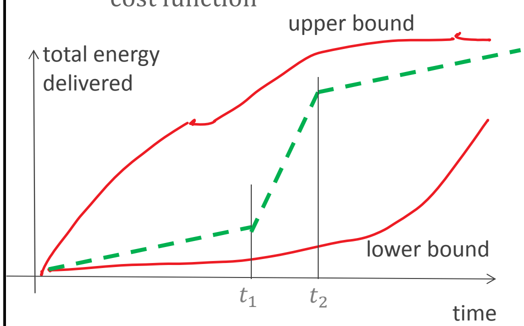
Commelec = Grid Autopilot

- Separation of timescales
  - real time control (grid agent)
  - trip planning
    resource agent translates
    long term objective into current
    cost function





at t_1 load agent exports a cost function that expresses desire to consume energy
at t_2 load agent exports a cost function that expresses desire to stop consuming energy

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Conclusion

- Commelec is a practical method for automatic control of a grid
  - exploits available resources (storage, demand response) to avoid curtailing renewables while all maintaining safe operation
- Method is designed to be robust
  - separation of concerns between resource agents and grid agents
  - 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

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