THE VISION OF COMMELEC: REAL-TIME CONTROL OF ELECTRICAL GRIDS BY USING EXPLICIT POWER SETPOINTS

Andrey Bernstein, Niek J. Bouman

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

EPFL, Lausanne, Switzerland

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Outline

1. Motivation
2. Commelec Framework
3. Experimental Validation
4. Overview of Other Aspects

Power Grids and Renewable Energy

Challenges

- Increasing penetration of distributed, intermittent generation (PV, wind farms)
- Legacy grid infrastructure
- Stability problems

Opportunities

- Storage:
  - advances in battery technology (also, the advent of electric vehicles),
  - virtual batteries; demand response & thermal storage (buildings, freezer warehouses)
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Goal

- Droop-less real-time control of power flows in local electrical grids, replacing frequency control by explicit control of power setpoints.
- A scalable solution for the integration of renewable sources into the grid (as an attempt to avoid costly grid re-inforcements).

Expected Benefits

- Optimise operation while keeping the grid safe (voltages, currents, device ratings).
  - Optimal usage of storage and demand response.
  - Maximum utilization of intermittent generation (PV, wind).
- Inherent support for inertia-less grids.
- Provide real-time support to the grid by operating as virtual power plant (VPP).
- Automatic configuration (no manual tuning of parameters)

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Why Droop-less?

Problems with droop control:

- System does not know the internal state of resources (e.g. temperature in a building, state of charge of a battery).
- Use of a frequency signal that supposed to be linked with the power imbalance – assumption that is no-longer true in small inertia systems.

Alternative: Explicit control of power setpoints (P, Q).

How to achieve this in a scalable and universal way?

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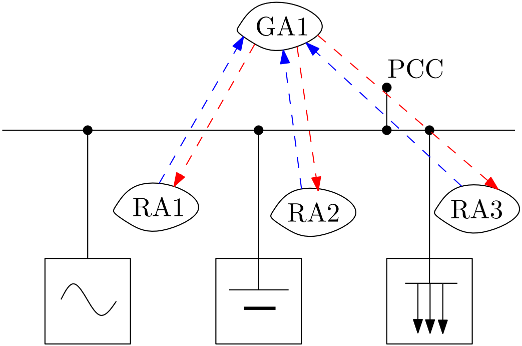
Every 100 ms:

- Resource agent (RA) sends a device-independent representation of its internal state to the GA;
- Grid agent (GA) monitors grid (PMUs) and computes setpoint-requests for the RAs.



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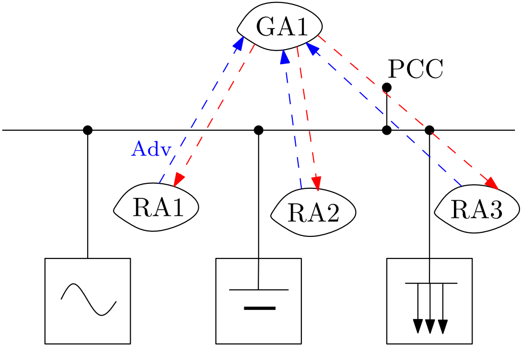

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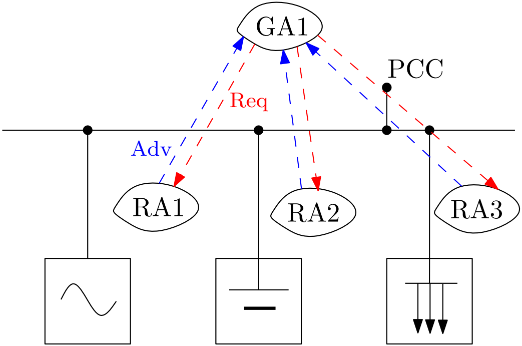
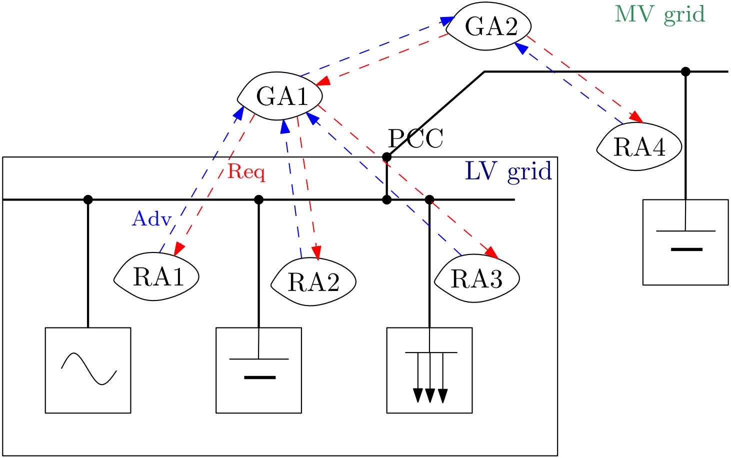


Principle of Operation # 2: Composability

GA1 aggregates a collections of its own resources, including its grid, and makes it appear to GA2 as a single (virtual) resource.



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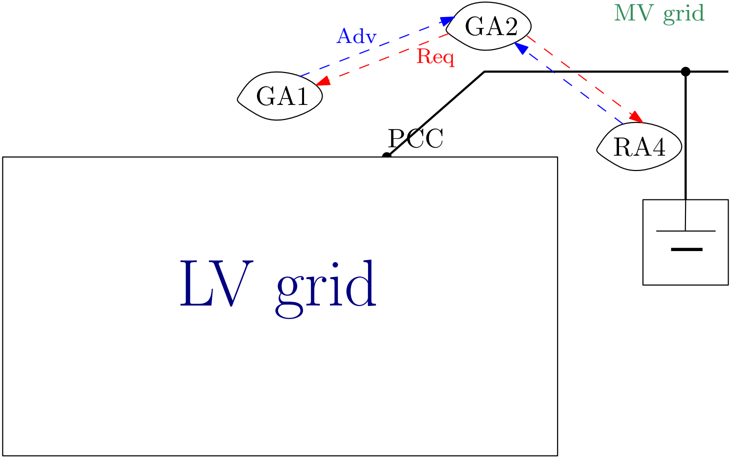

Device-Independent Protocol

Every resource agent advertises:

- *PQ* profile: A convex set $\mathcal{A} \subseteq \mathbb{R}^2$ that represents constraints on active and reactive power setpoints (P, Q).
- Virtual cost: A continuously differentiable function $CF : \mathcal{A} \to \mathbb{R}$ that exposes the preference of the resource to stay in particular zones of the PQ profile.
- Belief function: A set-valued function $BF : \mathcal{A} \to 2^{\mathbb{R}^2}$ that quantifies the uncertainty in resource operation.

Benefits for online control

- Simple GA optimization: continuous, robust.
- Same GA process for any grid.

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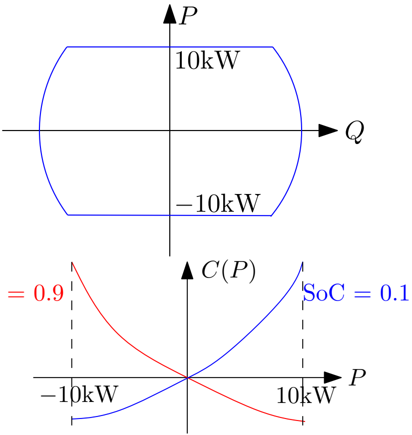
Example: PQ Profile and Virtual Cost

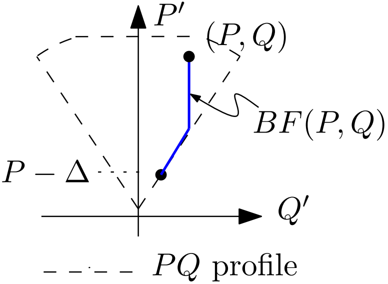
PQ profile: battery says to its GA that it can implement any active power from −10kW (charging) to 10kW (discharging), and any reactive power under converter limitations.

Virtual cost: battery close to be fully charged gives higher cost to charging than to discharging, and vice versa.

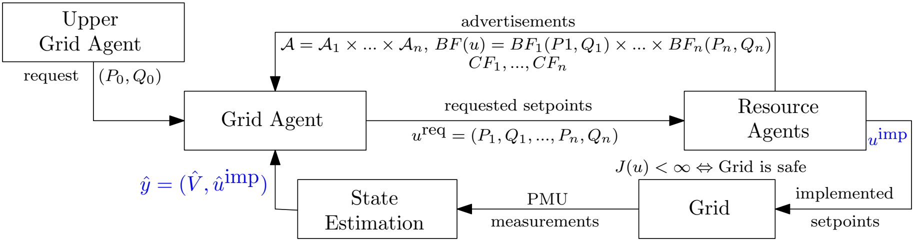


Example: Belief Function

- Recall: Belief function quantifies the uncertainty in resource operation.
- Say, the GA requests a PV to implement (P, Q).
- The actually implemented setpoint $(P', Q') \in BF(P, Q) \subseteq \mathbb{R}^2$.



Grid Agent's Decision Process



Robust online multi-objective optimization:

- Objective function:

$$F(u) = \sum_{i=1}^{n} \omega_i CF_i(P_i, Q_i) + \omega_0 J_0(u, P_0, Q_0) + J(u)$$

- Admissible setpoints:

$$\mathcal{U} = \{u^{\text{req}} \in \mathcal{A} : \forall u^{\text{imp}} \in BF(u^{\text{req}}), J(u^{\text{imp}}) < \infty\}.$$

- Gradient steering algorithm:

$$u^{\text{req}} = \mathcal{P}_{\mathcal{U}} \left[\hat{u}^{\text{imp}} - \alpha \nabla F(\hat{u}^{\text{imp}}) \right].$$

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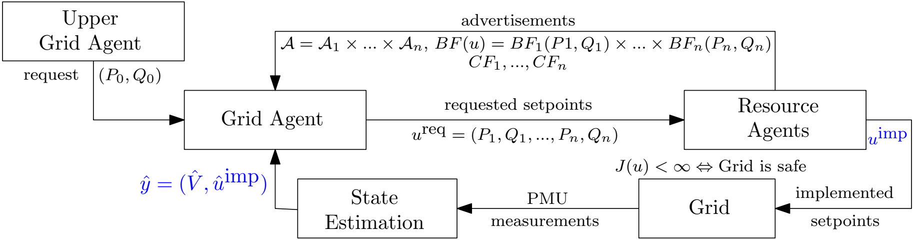

Upper Grid Agent

request (P_0, Q_0)

advertisements

$\mathcal{A} = \mathcal{A}_1 \times \dots \times \mathcal{A}_n,\ BF(u) = BF_1(P1, Q_1) \times \dots \times BF_n(P_n, Q_n)$

$CF_1, \dots, CF_n$

Grid Agent

requested setpoints

$u^{\text{req}} = (P_1, Q_1, \dots, P_n, Q_n)$

Resource Agents

u^{imp}

$J(u) < \infty \Leftrightarrow$ Grid is safe

$\hat{y} = (\hat{V}, \hat{u}^{\text{imp}})$

State Estimation

PMU measurements

Grid

implemented setpoints

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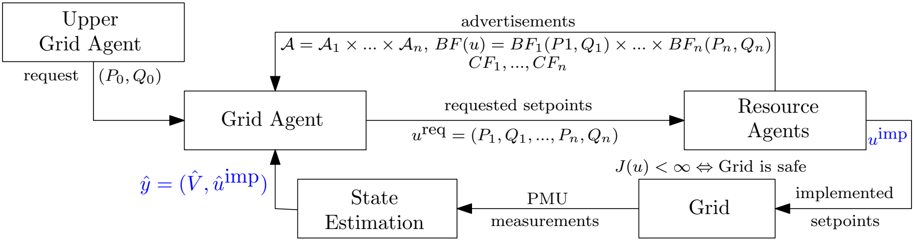

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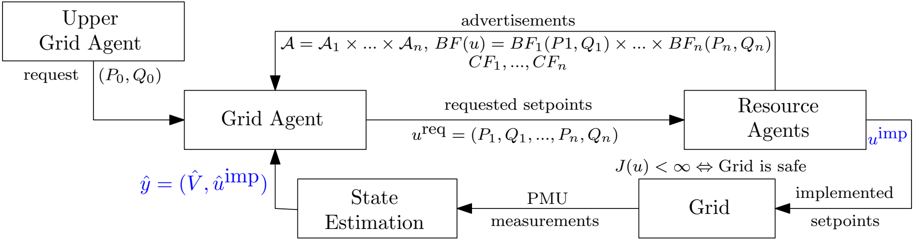

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Summary of Commelec's Main Features

- **Abstract framework:**
  - Applies to all electrical subsystems
  - Uses a universal device-independent language
- **Composition of subsystems:**
  - Can aggregate a set of interconnected elements into a single entity
  - Uses the same common language to advertise its internal state to its leader, allowing for scalability
- **Separation of concerns:**
  - Grid agents are smart, but manipulate only data expressed by means of the abstract framework – same grid agent software for all instances of grid agents
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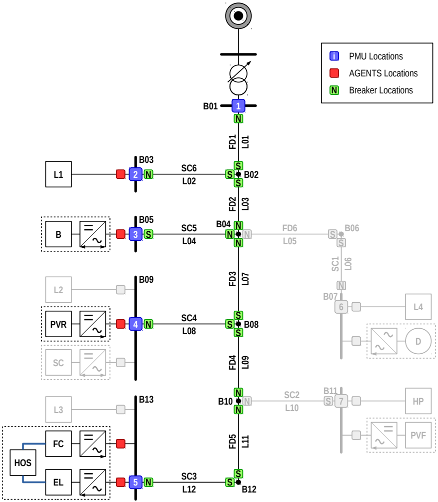
Commelec in EPFL's Microgrid Lab

Microgrid EPFL

- Replica of CIGRÉ's low-voltage microgrid benchmark TF C6.04.02
- Real-time monitoring:
  - Phasor Measurement Units (PMUs): voltage/current synchrophasors
  - Phasor Data Concentrator
  - Kalman-Filter-based State Estimation
  - Update rate: 50 Hz



EPFL's Microgrid Lab: Battery

Battery

- Lithium–titanate technology
- Manufacturer: Leclanché
- 25 kW max. active power
- Energy: 25 kWh
- Fully controllable (4 quadrants) power converter interface @ 100 ms pace

EPFL's Microgrid Lab: PV

Rooftop Photovoltaic Plant

- Mono-crystalline panel technology (rooftop deployment)
- 79 modules × 255 W ≈ 20 kW Lithium–titanate technology
- 20 kW @ full irradiance
- MPTT mode (currently not controllable in PQ-mode)

EPFL's Microgrid Lab: Electronic Load

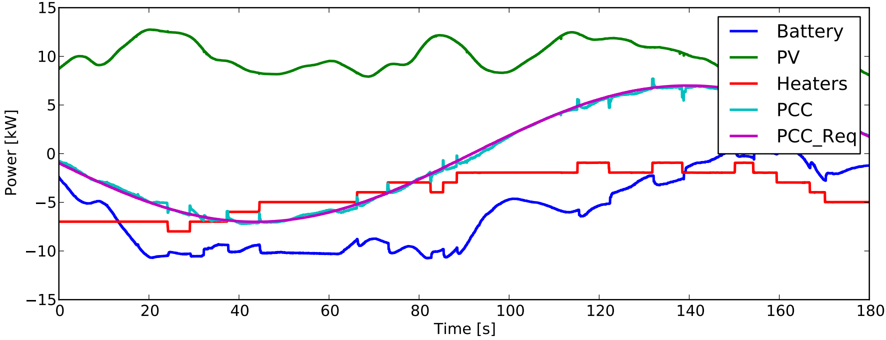
AC Electronic Load Emulators

- Rated power: 30 kVA
- Fully controllable power converter (4 quadrants)
- Bandwidth: 2 kHz
- Used to simulate heating system with a discrete set of power setpoints

Commelec in EPFL's Microgrid Lab: Experiments

Providing Real-Time Dispatchability

- Sinusoidal-like reference signal for P and Q (power factor: 0.9)
- In particular:
  - Resources jointly (and fairly) absorb intermittence (due to PV)
  - When a resource disconnects, the system responds almost instantly (the next timestep) by re-dispatching power to remaining resources
- Dispatchable reactive power $\triangleq$ secondary voltage support (MV)

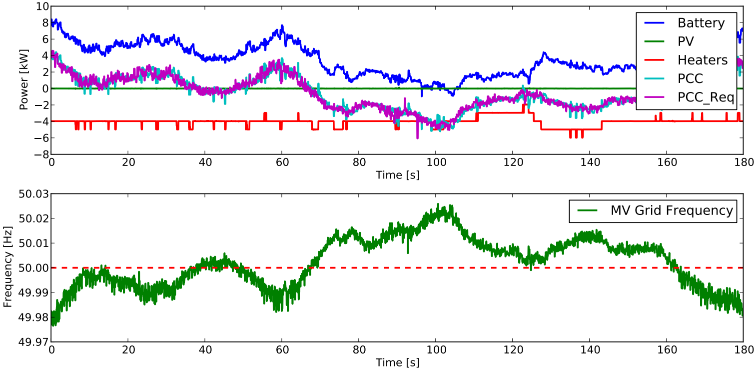


Commelec in EPFL's Microgrid Lab: Experiments

Provide primary frequency support to MV grid

Two-step approach

1. Determine baseline power flow at PCC, P_{baseline}
2. Set PCC target power as: $P_{\text{target}} = P_{\text{baseline}} + c\,\Delta f$
   where c is the (inverse) frequency droop parameter [W/Hz]



EPFL's Microgrid Lab: In Progress

- Islanding maneuvers with Commelec (using supercapacitors)
- Hydrogen Fuel Cell + Electrolyzer
- Façade PV plant (thin-film technology)
- Fully controllable and low latency (< 100ms) inverters for PV plants
- EV charging station

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Other Aspects

- Novel load-flow algorithms and certificates of convergence
- Commelec's Message Format and Transport Protocol
- Reliability: packet delivery, fault tolerance
    - IP parallel redundancy protocol (iPRP)
- Network security
- ...

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Thank you!

Team

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