
Part II: Implementation

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Outline

- Introduction
- Resource agents
  - energy storage
  - PV
  - loads
  - synchronous machine
- Grid agent
  - Aim
  - Safe state of the grid
  - Optimal control
  - Aggregation
- Simulations
  - Case study
  - Results
- Conclusions
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Introduction

What are we going to show in this second part?

1. computation of the $PQt$ profiles, belief function and virtual costs for generic network resources (i.e., dispatchable and stochastic generation systems, storage units, loads);

2. how the grid agent can compute the setpoint of its internal resources and aggregate $PQt$ profiles, cost functions and beliefs in order to abstract its state to an external agent;

3. a case study containing a minimum set of elements allowing to show the applicability and the potentials of the proposed control method.
Introduction

To fix the ideas, let make reference to the following example

CIGRE LV microgrid benchmark TF C6.04.02

uncontrolled load (MV)

MV battery

0.5 MVA

ESS

15 km

(MV1)

UL

0.5 MVA

8 km

(MV1)

200 kVA

0.4 kV

uncontrolled load (LV)

15 kVA

UL1

10 kV

30 kW

30 kWh

water boilers

solar PVs

water boilers

hydro

Ess1

LV battery

10 kW

PV1

10 kW

PV2

10 kW

PV3

μHA

IEEE PES

Power & Energy Society®

IEEE
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Resource agents – *Energy storage systems*

The case of a battery

**PQₜ profile**

- **requirement**: compute the internal limits that the battery must respect for the next time step.

- **HP**: the state of charge \( \text{SoC} \) is **fixed between two setpoints implementations** (correct if \( \Delta t \) is small enough) → battery model is **extremely simple**

\[
R_t = \frac{\Delta V^{dc}}{\Delta I^{dc}} = \frac{V_t^{dc} - V_{t-\Delta t}^{dc}}{I_t^{dc} - I_{t-\Delta t}^{dc}}
\]

\[
E_t = V_t^{dc} + R_t I_t^{dc}
\]
Resource agents – *Energy storage systems*

The case of a battery

**$PQt$ profile**

- **limits on DC**: $V_{dc}$ and $I_{dc}$ need to respect specific battery constraints $V_{\text{min}} \leq V_{dc} \leq V_{\text{max}}$ and $I_{\text{min}} \leq I_{dc} \leq I_{\text{max}}$.

Therefore, the DC limits in power are:

$$P_{\text{dc}}^{\text{min}} = \max \left\{ \frac{V_{\text{max}}(E_t - V_{\text{max}})}{R_t}, (E_t - R_t I_{\text{min}})I_{\text{min}} \right\}, P_{\text{dc}}^{\text{max}} = \min \left( P_{\text{dc}}^{V_{\text{dc}}}, P_{\text{dc}}^{I_{\text{dc}}} \right)$$

With:

$$P_{\text{dc}}^{V_{\text{dc}}} = \begin{cases} 
\frac{E_t^2}{4R_t}, & \text{if } \left( \frac{E_t}{2} \right) > V_{\text{min}} \\
V_{\text{min}} \left( \frac{E_t - V_{\text{min}}}{R_t} \right), & \text{otherwise} 
\end{cases}$$

$$P_{\text{dc}}^{I_{dc}} = \begin{cases} 
\frac{E_t^2}{4R_t}, & \text{if } \left( \frac{E_t}{2R_t} \right) > I_{\text{max}} \\
(E_t - R_t I_{\text{max}})I_{\text{max}}, & \text{otherwise} 
\end{cases}$$
Resource agents – *Energy storage systems*

The case of a battery

**PQt profile**

- **limits on AC:** the battery is interfaced with a power converter of **rated power** $S_r$ and **efficiency** $\eta$, therefore

\[
\begin{align*}
P_{ac}^{\min} &= \eta P_{dc}^{\min} \\
P_{ac}^{\max} &= \eta P_{dc}^{\max} \\
\text{if } P_{dc} \geq 0 \\

P_{ac}^{\min} &= \frac{P_{dc}^{\min}}{\eta} \\
P_{ac}^{\max} &= \frac{P_{dc}^{\max}}{\eta} \\
\text{if } P_{dc} < 0
\end{align*}
\]

\[
\sqrt{(P_t^{ac})^2 + (Q_t^{ac})^2} \leq S_r
\]
Resource agents – *Energy storage systems*

The case of a battery

**Belief function**

- As storage devices are highly controllable, we assume an ideal belief.

\[
BF_{b}(u_b) = \{u_b\}
\]
Resource agents – *Energy storage systems*

The case of a battery

**Virtual cost**

- If $SoC_t > SoC_{target}$ → the battery prefers to be discharged → the agent advertises a negative cost for discharging ($P>0$) and positive cost for charging ($P<0$).

- Opposite if $SoC_t < SoC_{target}$

- $SoC_t = SoC_{target}$ → the cost is zero
Resource agents – *Photovoltaic*

**PQt profile**

- *limits on AC active power:* by combining a forecasting tool, and the capability curve of the DC/AC converter, the PV agent computes the maximum power production $P_{pv,f}^p$ that can be maintained in $t \in [t_0, t_0 + T]$.

- *Reactive power:* constraint given by a minimum power factor.
Resource agents – *Photovoltaic*

**Belief function**

- **Active power:** advertise the **uncertainty of the solar resource** we consider that the active power production may decrease from the requested setpoint, $u_{pv}$, with a **predicted maximum variation** provided $\Delta P_{pv,f,\text{max}}$ by the forecasting tool.
Resource agents – *Photovoltaic*

**Belief function**

- **Reactive power**: controlled by the converter → the belief of $Q$ is restricted only by its relation with $P$

Hence, $BF_{pv}(u_{pv})$ → line from $u_{pv}$ to $u'_{pv}$

$$u'_{pv} = \left( P - \Delta P_{\text{max}}^{pv,f}, Q' \right)$$

$$Q' = \begin{cases} 
\max \left\{ -P' \sqrt{1 - \cos^2_{\text{min}}(\phi)}, Q \right\}, & \text{if } Q < 0 \Delta P_{\text{max}}^{pv,f} \\
\min \left\{ P' \sqrt{1 - \cos^2_{\text{min}}(\phi)}, Q \right\}, & \text{otherwise} 
\end{cases}$$

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$PQt$ profile slice

belief

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$S_r$

$u_{pv}$

$u'_{pv}$

$P_{pv}(t)$

$\cos_{\text{min}}(\phi) = 0.8$
Resource agents – *Photovoltaic*

**Virtual cost**

> **assumption**: We can assume that the PV agent wishes to **maximize the active power production** and **minimize the reactive power**. Therefore, an example of the advertised virtual cost function is

\[
C_{pv}(P,Q) = -a_{pv}P + b_{pv}Q^2
\]

*with*

\[
a_{pv}, b_{pv} > 0
\]
Resource agents – *Controllable loads*

The case of a water boilers

**PQt profile**

- **HP**: internal controller of the WB is capable of any active power in \([0, P_{\text{max}}^{wb}]\). We also assume that the thermal state of the boiler is represented by the total energy stored in it at time \(t\), given by

\[
\varepsilon(t) = \int_{\tau=0}^{t} \left( P_{\text{in}}(\tau) - P_{\text{out}}(\tau) \right) d\tau
\]
Resource agents – *Controllable loads*
The case of a water boilers

**PQt profile**

*Principle*: the WB agent commands the internal controller to maintain $P_{in}(t) = -P$ as close as possible. Whenever $\varepsilon(t) < \varepsilon_{\text{min}}$, it switches the setpoint to the maximal heating power ($P_{in}(t) = P_{\text{max}}^{\text{wb}}$), until $\varepsilon(t) \geq \varepsilon_{\text{margin min}}$.
Resource agents – *Controllable loads*

The case of a water boilers

**Belief function**

- **Principle**: the WB load can be highly uncertain. To account for this, we assume that the WBA has a forecasting tool to predict the load profile.

\[
BF_{wb}(P; t) \text{ is then given by either } [P, 0], [-P_{\text{max}}^{wb}, P], \text{ or } [-P_{\text{max}}^{wb}, 0] \text{ depending on whether }
\]

\[
\hat{\varepsilon}_{\text{min}}(t'), \hat{\varepsilon}_{\text{max}}(t') \text{ are the worst estimated energy.}
\]

\[
P_{\text{wb}}(\varepsilon^{\text{min}}) \quad \text{belief} = \{P\}
\]

\[
-P_{\text{wb}}^{\text{max}} \quad P_{\text{wb}}(\varepsilon^{\text{max}})
\]

\[
\hat{\varepsilon}_{\text{max}}(t') \geq \varepsilon_{\text{max}} \text{ or } \hat{\varepsilon}_{\text{min}}(t') < \varepsilon_{\text{min}}
\]
Resource agents – *Controllable loads*

The case of a water boilers

*Virtual cost*

- *Principle*: similar to the one of a battery but centered around the forecasted value of the demand.
Resource agents – *Controllable loads*

The case of space heating (example)
Resource agents – *Controllable loads*

The case of space heating (example)
Resource agents – *Uncontrollable load*

**PQt profile**

- **Principle:** simplest case, for each time step, the *PQt* profile is defined by a single point given by a demand forecasting tool.

**Belief function**

- **Principle:** any admissible value at any moment. The belief is the complete area of operation of the UL agent. The consumption of the UL is always inside the semi-circle defined by its max apparent power.

**Virtual cost** it is always zero.
Resource agents – *Synchronous machine*

**PQt profile**

- **HP**: we consider a *cylindrical-rotor machine* coupled with a *generic micro-turbine*.
- The SG agent computes the *capability curves* of the generator using the *measurement of the voltage in the connection bus* with the grid ($V_{sg}$).
- The bounds of this resource are dependent on $V_{sg}$ that depends on external variables $\rightarrow$ the prediction of the limits for any $t \in [t_0, t_0 + T]$ is a complex task. Then, the SG agent advertises as admissible set of setpoints the largest set of all the possible values of $V_{sg}$: $C^l_{sg}$
Resource agents – *Synchronous machine*

**Belief function**

- Changes of $V_{sg}$ boundaries of the capability curves may vary → the nearest to the bounds might be shifted to the smallest set of all the possible values of $V_{sg}$: $C_{sg}^s$

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$C_{sg}^s$  $C_{sg}^l$

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**Diagram:**

- $V_{sg}I_{l_{max}}$
- $P_{max}$
- $P$
- $I_{f_{max}}$
- $BF_{sg}(u''_{sg})$
- $BF_{sg}(u'_{sg})$
- $BF_{sg}(u_{sg})$
- $u''_{sg}$
- $u_{sg}$
- $u_{sg}$
- $P_{min}$
- $Q$
- $\frac{V_{sg}^2}{X_d + X_t}$
Resource agents – *Synchronous machine*

**Virtual cost**

- **assumption**: we consider that the SG agent prefers to operate the resource to **maximize the overall efficiency of the machine including the primary mover.**
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The grid agent – **Aims**

- **Observe** and estimate the state of the grid;
- Compute the **safe state of the grid**;
- Compute **optimal setpoints** to be forwarded to the **resource agents** to steer the electrical state of the grid to:
  - Minimize the cost of the followers
  - Satisfy the leader’s request as much as possible
  - Maintain the grid in a safe state of operation
The grid agent – *Safe state of the grid*

We define formally the **power flow equations that govern a grid**. We consider a system with *n* **buses**, and the non-linear load-flow constraints represented in a vector form using a function

\[ G : \mathbb{R}^{4n} \rightarrow \mathbb{R}^{2n} \]

\[ G(z) = 0 \]

Here, \( z \in \mathbb{R}^{4n} \) is a vector that includes all the system variables, namely the **power injections** \( \{ P_i, Q_i \}_{i=0}^{n-1} \) and the **voltage angles and magnitudes** \( \{ \delta_i, V_i \}_{i=0}^{n-1} \)
The grid agent – **Safe state of the grid**

We assume that GA is **capable to determine the safe state of the grid**, by knowing:

- the current grid state $y$;
- the requested setpoint from its leader, $P_0, Q_0$
- the requested setpoints to the followers, $x$.

Such that

\[
V_i \in [V_{\text{min}}, V_{\text{max}}], \forall i = 1, \ldots, n \quad \text{(nodes)}
\]

\[
I_{\ell} \leq I_{\ell}^{\text{max}}, \forall \ell = 1, \ldots, m \quad \text{(lines)}
\]
The grid agent – *Optimal control*

\[ \begin{align*}
F & \quad \text{\(PQt\) profiles, Virtual Costs, Beliefs} \\
| & \downarrow \quad | \\
\quad P_0, Q_0 & \quad F & \quad \text{Followers (}A_i\text{)} & \quad \hat{x}_i & \quad \text{Grid} \\
| & \downarrow \quad | \\
\quad P_i, Q_i & \quad \hat{x}_i \\
| & \downarrow \quad | \\
\quad z & \quad \text{State Estimation}
\end{align*} \]
The grid agent – *Optimal control*

- **Gradient-based approach**
- **Objective function is a weighted combination of**
  - followers costs
  - the cost of grid quality of service
  - the cost of deviation from the request (in our case study, LV grid agent only)
- **Given the current (measured/estimated) setpoint** \( \hat{x} = \left( \hat{P}_i, \hat{Q}_i \right) \)
  - the computed next setpoint is given by

\[
x = \text{Proj}\left( \hat{x} + \Delta x \right)
\]

Here:
- \( \Delta x \) is a vector in the direction opposed to the direction of the gradient of the overall objective function
- \( \text{Proj}\{} \) is the projection to safe setpoint.
The grid agent – **Aggregation**

To fix the ideas, the LV grid agent is viewed by the MV grid agent as a “regular” follower agent. The LV grid agent advertises its internal state by aggregating the $PQt$ profiles, costs, and belief functions of its followers

- **$PQt$ profile**: the set of $(P, Q)$ at the connection point that is feasible, given the $PQt$ profiles of followers;
- **Belief function**: similarly to $PQt$ profile, areas of possible $(P, Q)$ values at the connection point due to the uncertainty of the followers (given by their own beliefs);
- **Virtual Cost**: evaluation of the objective function of LV grid agent at a given request $(P, Q)$ at the connection point
The grid agent – *Aggregation*

- **non controlled load**
- **battery**
- **microhydro**
- **boiler**

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- **PV**
- **grid agent**
- **ESS**
- **SG**
- **LVGA**
- **Overhead line**
- **Twisted cable**
- **4x120 mm2 Al XLPE**
- **3x70 mm2 Al XLPE + 54.6 mm2 AAAC**
- **4x16 mm2 Cu**
- **4x25 mm2 Cu**
- **30 m**
- **3x50 mm2 Al + 35 mm2 Cu XLPE**
- **20 kV**
- **200 kVA**
- **0.4 kV**
- **0.5 MVA**
- **0.5 MWh**
- **15 km**
- **8 km**
- **10 km**
- **Pole-to-pole distance = 35 m**
The grid agent – **Aggregation**

Aggregated $PQ_t$ profile

safe approximation (subset of true aggregated $PQ_t$ profile)
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Simulations – *Case study*

CIGRE LV microgrid benchmark TF C6.04.02

Uncontrolled load (LV)

Uncontrolled load (MV)

0.5 MVA

15 km (MV1)

8 km (MV1)

200 kVA

0.4 kV

Feeder: (LV1)

(LV2)

(LV3)

(LV4)

(LV5)

(LV6)

0.5 MVA

0.5 MWh

Main grid

Uncontrolled load (MV)

MV battery

Wall boilers

Energy storage

Water boilers

Solar PVs

Hydro
Simulations – *Case study*

- **Sources of randomness**
  - solar irradiation
  - uncontrolled load
- **Storage**
  - batteries
  - water boilers
- **Data: traces collected at EPFL in Nov 2013**
- **Performance Metrics**
  - distance of node voltages to limits
  - state of charge
  - renewable curtailed
  - collapse/no collapse
Simulations – *Case study*

Comparison with classical droop controls

*Commelec*

*Primary droop control on frequency*

*Primary and secondary frequency controls*
Simulations – *Results*

ESS1 and ESS2 are driven to their midpoints
Simulations – *Results*

Boiler 2 charged only when feasible
Simulations – *Results*

Reduced Curtailment of Renewables
Simulations – Results
Reduced Curtailment of Renewables

Graphs showing the active power of PV systems over time.
Simulations – **Results**

Local power management

Boiler WB2 starts because WB1 stops at mid power due to line congestion

Boiler WB2 charges at full power because PV3 produces
Simulations – **Results**

Voltage and current profiles
Simulations – *Results*

Without manual intervention, droop control with secondary fills the MV battery (slack) until the collapse. Commelec automatically avoids the collapse.
Simulations – *Results*

Without manual intervention, droop control with secondary fills the MV battery (slack) until the collapse. Commelec automatically avoids the collapse.
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Conclusions
Conclusions

- 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 (simple, device specific) and grid agents (all identical)
  - a simple, unified protocol that hides specifics of resources
  - aggregation for scalability
Conclusions

- The translation of device-specific information in $PQt$ profile, cost and beliefs Implementation of Resource Agents is **simple**.

- Implementation on EPFL’ grid is underway
  - phase 1 (now) experimental microgrid
  - phase 2: campus feeders with automatic islanding and reconnection

- Implementation of Grid agent is more complex
  - we use the formal development framework (BIP)
  - automatic code generation
  - the same code is used in all grid agents (device independent)