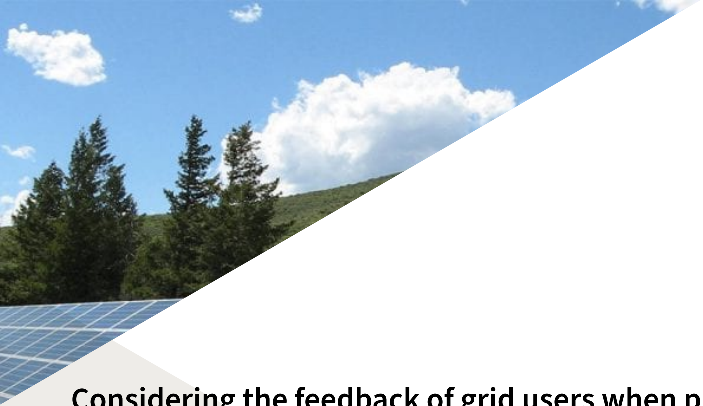

LIÈGE université
Sciences Appliquées

Considering the feedback of grid users when planning distribution networks

HEXAGON workshop on power network optimization

Bertrand Cornélusse, University of Liège, Belgium

Bergamo, June 2024

Overview

1. Introduction
2. Distribution network development planning
3. Grid user's optimization problem
4. Coupling the problems
5. Results and future work

Introduction

About the "Smart Microgrids Team" at ULiège

- Around 10 researchers applying optimization, machine learning, and control to power systems (and power electronics)
- working on (from real-time to long-term)
  - Hardware-in-the-loop (HiL) for the design and simulation of inverter-based resources
- Real-time optimization in distribution networks (using HiL)
- Microgrids and energy communities operation and sizing
- **Distribution network planning**
- Senegal’s electrical infrastructure planning

About me

- PhD thesis (2010): apply ML to approximate unit commitment for fast intraday reaction (with EDF)
- European Market coupling algorithm (Euphemia) at N-SIDE (until 2016)

Savelli, I., Cornélusse, B., Giannitrapani, A., Paoletti, S., & Vicino, A. (2018). A new approach to electricity market clearing with uniform purchase price and curtailable block orders. Applied energy, 226, 618-630.

- Since then: various projects on distribution networks and energy communities.
- **Looking for collaboration, industrial and academic, on "distribution network planning"**

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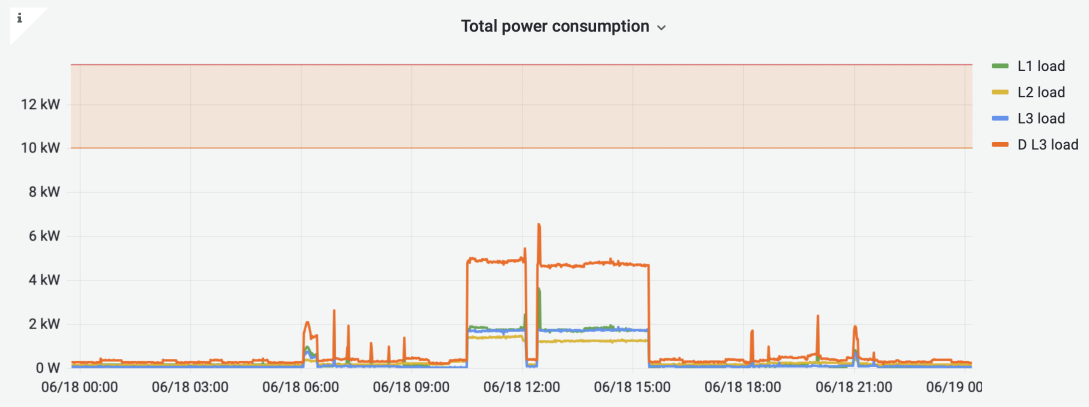
Context I

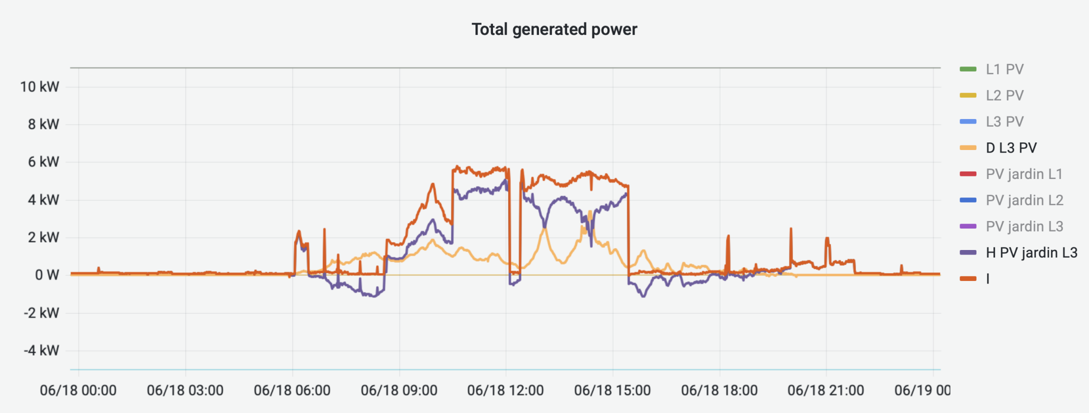
Energy transition

- Large increase in distributed generation
- Shift to electricity consumption for mobility, heating and cooling
- Battery storage

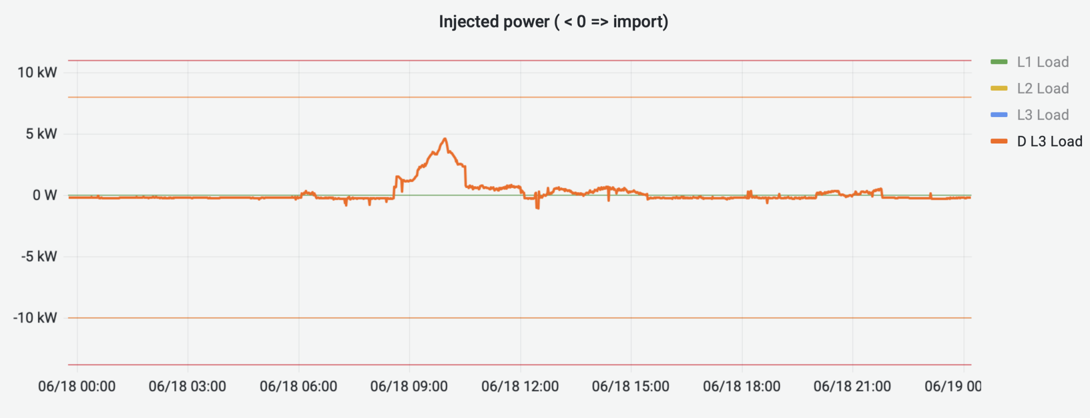
Context II


Total power consumption
12 kW
10 kW
8 kW
6 kW
4 kW
2 kW
0 W
06/18 00:00
06/18 03:00
06/18 06:00
06/18 09:00
06/18 12:00
06/18 15:00
06/18 18:00
06/18 21:00
06/19 00
L1 load
L2 load
L3 load
D L3 load

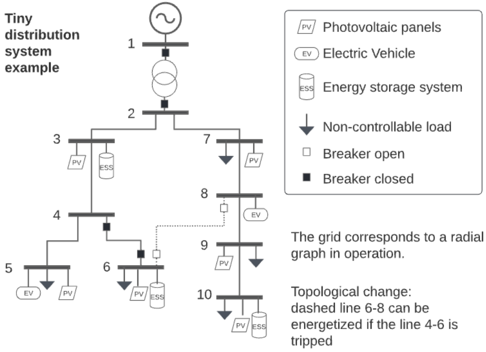
Context III


Total generated power
10 kW
8 kW
6 kW
4 kW
2 kW
0 W
-2 kW
-4 kW
06/18 00:00
06/18 03:00
06/18 06:00
06/18 09:00
06/18 12:00
06/18 15:00
06/18 18:00
06/18 21:00
06/19 00
L1 PV
L2 PV
L3 PV
D L3 PV
PV jardin L1
PV jardin L2
PV jardin L3
H PV jardin L3
I

Context IV


Injected power (< 0 => import)
10 kW
5 kW
0 W
-5 kW
-10 kW
06/18 00:00
06/18 03:00
06/18 06:00
06/18 09:00
06/18 12:00
06/18 15:00
06/18 18:00
06/18 21:00
06/19 00
L1 Load
L2 Load
L3 Load
D L3 Load

Context V



Tiny distribution system example

The grid corresponds to a radial graph in operation.

Topological change: dashed line 6-8 can be energetized if the line 4-6 is tripped

Distribution networks require upgrades, but other possibilities

- Active network management (ANM) schemes
- Home energy management systems
- Energy communities

The current entering a network and the voltage along a feeder fluctuate more and more

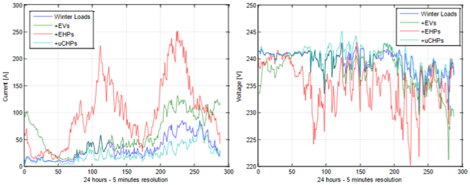


Figure 34: Current and voltage comparison for all the winter cases

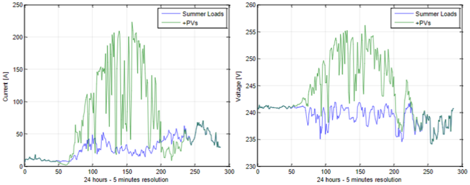


Figure 35: Current and voltage comparison for all the summer cases

Source: Randles, D., By, P., Navarro Espinosa, A., & Ochoa, L. (2015). Low voltage Network Models and Low Carbon Technology Profiles. www.enwl.co.uk/lvns.

Long-term anticipation is hard.

Instead of relying (only) on forecasts (open loop), **let’s account for user feedback on network planning and regulatory decisions.**

Research questions

1. How should networks be reinforced?
2. How should (or will) users invest?
3. How do network investment policies and regulations impact the equilibrium between the network and users?
4. What are good policies for the energy transition, good for everyone?
5. Can ANM or energy communities allow to reduce hardware investment?

Methodology to answer these questions

Use optimization to represent the **”game”** between the distribution system operator (DSO) and network users

- DSO develops the networks based on patterns of users’ withdrawals and injections, and available budget
- Network users minimize their bill using all available options (grid connection, local generation, storage, etc.)

Solve this game for a representative set of cases (grid topologies, characteristics of users, etc.) and several scenarios

- Network tariffs
- Energy prices
- Costs of storage, renewable generation

Challenges

- How to model the game?
- Generate a representative set of cases (get data, LV, MV)
- Model uncertainty (available technologies and associated costs, energy costs, etc.)
- Model the behavior of users (are they always perfectly rational?)
- Handle the long-term and multi-stage nature of the problem (computational burden)
- Handle unbalanced low-voltage networks
- Evaluate or constrain CO_2 emissions and/or other limits

Distribution network development planning

Distribution network development planning (DNDP)

Given

- an area with demand and injection nodes (users that may be connected to the distribution grid)
- substations locations (connection to the existing higher-level grid)
- possible routes between substations and grid users where to put cables
- costs for cable categories, substations, losses, etc.
- an estimate of withdrawal/injection for grid users (time-series)
- some pre-existing substations and cables (and their lifetime)
- operational limits
- (a budget)

Determine

- which substations to build or reinforce
- where to put new cables and reinforce existing ones

DNDP as a mixed-integer non-linear program I

Solve the following (deterministic single-stage) mathematical program over a sufficiently long time horizon:

$$
\begin{aligned}
\min \quad & \mathit{TLCC}(\mathit{GRID\_CAPEX}, \mathit{losses}) & & \text{(1a)}\\
\text{s.t.} \quad & \text{nodal power balance equations} & \forall t \in \mathcal{T} \quad & \text{(1b)}\\
& \text{power flow equations} & \forall t \in \mathcal{T} \quad & \text{(1c)}\\
& \text{operational limits} & \forall t \in \mathcal{T} \quad & \text{(1d)}\\
& \text{radial operation} & \forall t \in \mathcal{T} \quad & \text{(1e)}
\end{aligned}
$$

It is a MINLP.

DNDP as a mixed-integer non-linear program II

Variables:

- Design: **which route to select, which cable** (integer), **substations capacities** (continuous)
- operation (indexed by time): voltages, currents, active and reactive powers

Objective (Greek variables are parameters):

$$min \underbrace{\left(C^{cond} + C^{sub}\right)}_{GRID\_CAPEX} + \underbrace{\alpha \sum_{t \in \mathcal{T}} \left(C_t^{loss} + \omega^l s_t^l\right)}_{OPEX}$$

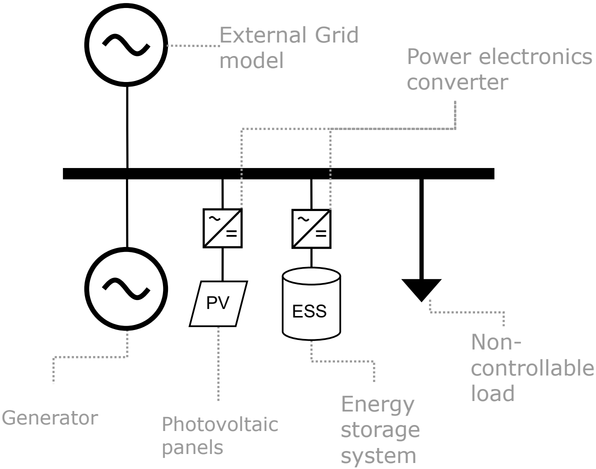
DNDP as a mixed-integer non-linear program III

Constraints:

- Non-linear: power flow equations
- Combinatorial: choice of routes and cables, radiality constraints

Grid user’s optimization problem

Grid users as microgrids



Grid users' optimization problem

Given

- a demand (e.g. a time series of inflexible demand, an electric vehicle to charge with some flexibility, etc.)
- available area for installing renewable generation (PV)
- costs for PV panels, inverters, storage, energy from the grid, etc.
- some pre-existing devices (and their lifetime)
- (a budget)

Determine

- which grid connection to buy, which devices to install
- the operation policy of the devices (storage, generator, EV, etc.)

Grid users' microgrid sizing I

Solve a linear program over a sufficiently long time horizon $\mathcal{T}$

$$
\begin{aligned}
\min \quad & \mathit{TLCC}(\mathit{USER\_CAPEX}, \mathit{USER\_OPEX}) & & \qquad (2a) \\
\text{s.t.} \quad & \text{nodal user's power balance} & \forall t \in \mathcal{T} & \qquad (2b) \\
& \text{bound device power by its capacity} & \forall t \in \mathcal{T} & \qquad (2c) \\
& \text{state update rules} & \forall t \in \mathcal{T} & \qquad (2d) \\
& \text{device capability diagrams} & \forall t \in \mathcal{T} & \qquad (2e)
\end{aligned}
$$

Kept linear for computational reasons (anticipating on the sequel).

Grid users' microgrid sizing II

Continuous variables: PV (inverter and panels) capacity, storage (inverter and energy) capacity, grid connection capacity (s_i^{grid}), device active and reactive powers.

Objective of user *i*:

$$\min \underbrace{c_i^{PV} + c_i^{st} + c_i^{grid}}_{USER\_CAPEX} + \underbrace{\alpha \sum_{t \in \mathcal{T}} \Delta t \left(p_{i,t}^{imp} (\pi^{EI} + \Pi^{EI}) + p_{i,t}^{exp} (-\pi^{EE} + \Pi^{EE}) \right)}_{USER\_OPEX}$$

Greek letters are parameters.

Coupling the problems

Connections between the two problems

DNDP and microgrid seem to be decoupled problems.

However, they are tightly linked, for instance:

- The ability for a user i to withdraw from / inject into the grid (s_i [kVA]) is a function
  - of the network "strength"
  - of other users s_j , $\forall j \neq i$
- The DSO's investment must be funded by the grid tariffs × grid users' power and energy usage (over an investment period)

The bilevel model I

$$
\begin{aligned}
\text{min} \quad & \text{TLCC(GRID\_CAPEX, losses) (upper-Level)} \\
\text{s.t. :} \quad & \text{DSO Constraints} \\
& \text{DSO budget balance constraint} \\
& \text{Grid users' optimality (lower level) :} \\
& (p^{imp}, p^{exp}, q^{imp}, q^{exp}, s^{grid}) \\
& \qquad \in \text{argmin} \left\{ \sum_i TLCC_i(USER\_CAPEX, USER\_OPEX) \middle| \text{ s.t.: grid users' constraints} \right\}
\end{aligned}
$$

The bilevel model II

Budget balance constraint

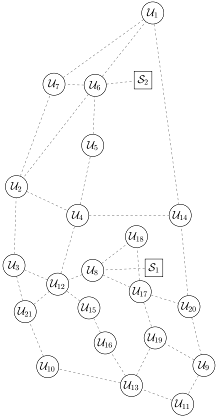
$$\underbrace{(1+\tau)^{\Gamma}\left(C^{sub}+C^{cond}\right)+\Gamma\alpha\sum_{t\in\mathcal{T}}C_t^{loss}}_{\text{DSO costs + margin}}\leq\underbrace{\Gamma\sum_{i\in\mathcal{B}_u}\left(c_i^{grid}+\alpha\sum_{t\in\mathcal{T}}c_{i\,t}^{grid}\right)}_{\text{Users' grid costs}}$$

where τ is an "interest rate for the DSO" and with

$$c_{i,t}^{grid}=\Delta t\left(p_{i,t}^{imp}\Pi^{EI}+p_{i,t}^{exp}\Pi^{EE}\right)$$

Results and future work

We consider a 23-nodes medium voltage network



MPV: Maximum PV capacity per bus (MVA), STO: add storage capability, EIP: energy import price (k€/MWh), EV: add electric vehicles' consumption, HP: add heat pumps' consumption. False (F), true (T).

Case	MPV	STO	EIP	EV	HP
BASE 0	0	F	0.3	F	F
1	**0.4**	F	0.3	F	F
2	**0.4**	**T**	0.3	F	F
3	**0.4**	**T**	**0.6**	F	F
4	0	F	0.3	**T**	**T**
5	**0.4**	F	0.3	**T**	**T**
6	**0.4**	**T**	0.3	**T**	**T**
7	**0.4**	**T**	**0.6**	**T**	**T**

Results

Table 1: Results obtained with the bilevel model

DNO: DNO's total annual amortized cost (M€/y), Users: Users' total annual amortized cost(M€/y), UPVC: Users' PV annual amortized cost of investments (M€/y), UStoC: Users' storage annual amortized cost of investments (M€/y), UGCC: Users' annual grid connection cost (M€/y), USS: Users' average self-sufficiency (%), USC: Users' average self-consumption (%).

Case	**DNO** M€/y	**Users** M€/y	**UPVC** M€/y	**UStoC** M€/y	**UGCC** M€/y	**USS** %	**USC** %
BASE 0	1.05	7.28	0.00	0.00	2.35	0	-
1	1.09	5.82	0.24	0.00	1.95	25	32
2	0.90	5.07	0.25	0.96	1.20	46	60
3	0.89	7.70	0.25	1.03	1.18	47	61
4	2.40	23.30	0.00	0.00	7.38	0	-
5	2.40	21.70	0.25	0.00	6.97	9	37
6	1.64	20.20	0.32	2.15	5.24	22	93
7	1.62	32.70	0.32	2.26	5.20	23	95

CO_2 analysis

Table 2: CO_2 data

Transformer	600	ton/MVA
Aluminum	16	ton/ton Al
Al density	2.7	ton/m^3
PV	1700	ton/MWp
Storage	200	ton/MWh
Energy from grid	0.128	ton/MWh

Table 3: CO_2 results

Substations	62.7	T/year
Lines	0.3	T/year
Losses	1.7	T/year
PV	571.0	T/year
Storage	16.7	T/year
Net grid consumption	555.0	T/year
PV	47	kg/MWh
Grid	128	kg/MWh

Conclusion and future work I

I think this is a rich framework but much still has to be done.

- Dynamic / capacity tariffs → change input scenarios
- Limited budget for grid users → add a (linear) budget constraint
- Bounded rationality → a subset of users will act optimally, a subset will act close to optimal, others will not do anything
- Active network management (e.g. curtailment, impact of using reactive power of inverters, fixed cos phi, P(u) curve, Q(u) curve) → relax bounds on variables, additional constraints
- Dynamic network reconfiguration → split topology variable per time step

Conclusion and future work II

- Compare myopic to perfect foresight policy e.g. model more realistic storage operation (force charge and discharge based on current state while staying in SoC range)
- Use flexibility of batteries and EVs (V2G) → Consider EVs as storage systems with extra availability constraints

Acknowledgments

Active contributors on this work

- Manon Cornet
- Geoffrey Bailly
- Mevludin Glavic

Thanks to ORES and RESA (Belgian DSOs) for discussions and input.

Link to the working paper

Bailly, G. , Cornet, M. , Glavic, M., & Cornélusse, B. (2024). A Bilevel Programming Approach for Distribution Network Development Planning. ORBi-University of Liège. `https://orbi.uliege.be/handle/2268/319836`