Robust, distributed and optimal control of smart grids

Jacquelien Scherpen

If I report about my work, it is joint work with Michele Cucuzzella, Sebastian Trip, Krishna Kosaraju, Xiaodong Cheng, Yu Kawano, Amirreza Silani, Matin Jafarian, Gunn Larsen, Desti Alkano, Bao Nguyen, Shuai Feng, Juan Machado,.......

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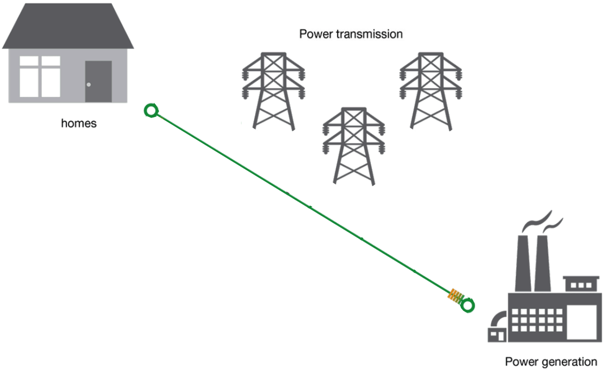
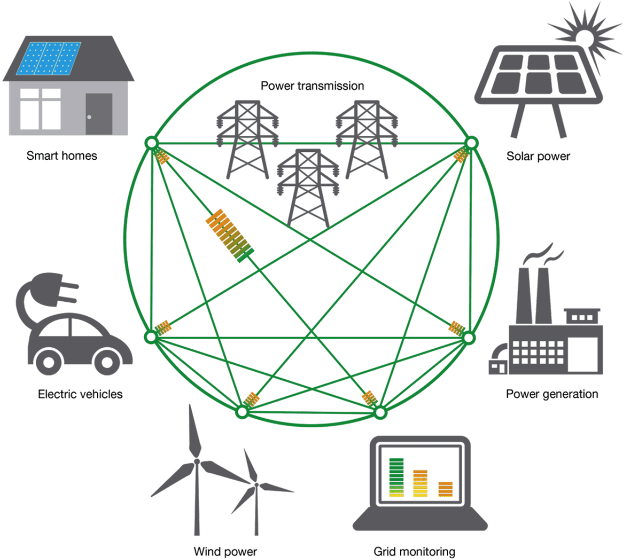
21 July 2021, Online seminar EPS-SIF Energy School

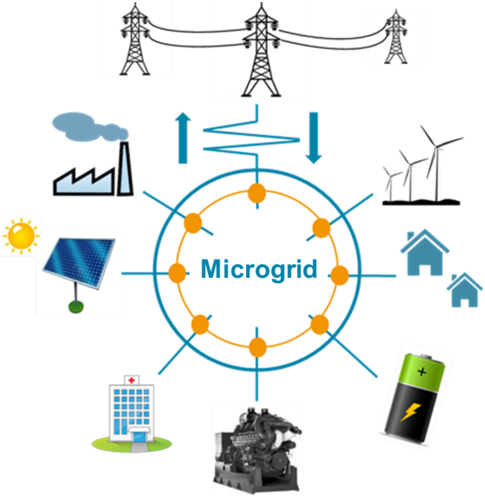
Traditional electricity network



The developing electricity network



Microgrid



Physics and markets, time scales

Traditional grid:

- Power plants: synchronous generators, reaction is slow, inertia in the system. Grid is AC, frequency deviation measure of imbalance, capacity and congestion checks rather predictable
- Market: day ahead, intraday, real time (15 minutes) plus capacity and congestion checks

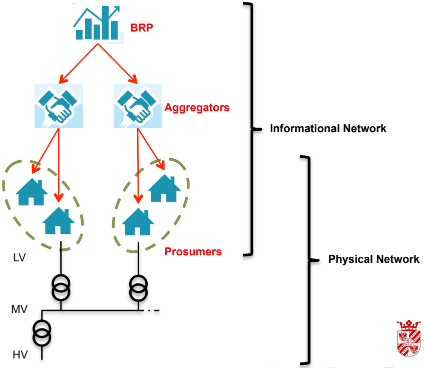
New grids:

- In addition: embedding of power converters, no inertia, very fast changes, fast time scale (seconds), voltage stability issue with many PV's in a region
- Many more market players, aggregators with an additional layer, flexibility trading, demand response

Two layers and perspectives

- Physics layer, dynamics of the physics first brought to steady state, then "welfare" optmization is performed.
- Economic/market layer, optimization criterion is defined, physics in the form of constraints of the optimization problem.

Clearly layers are coupled!



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Overview

- Control of the physics of the (traditional) AC power grid, physics layer
- Control of DC microgrids, physics layer
- Distributed optimal control solutions, market layer
- Energy System Integration, market layer

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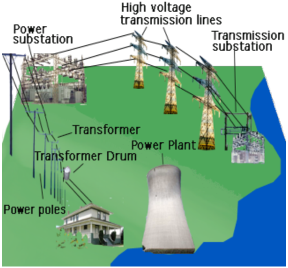
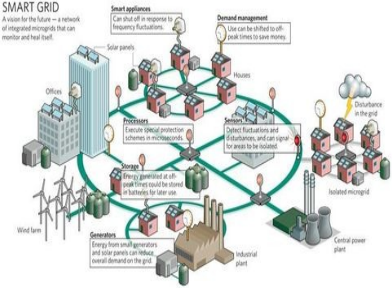
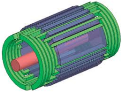
The grid and the synchronous machine







Future power grid,
EJC special issue
paper 2013.

The physics of the grid

From a power systems perspective:

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- Models of the power systems (synchronous generators), interconnected via transmission lines (often approximated by pi models, a resistor, inductor and two grounded capacitors).
- Classical models used by power systems engineers not always suitable to study the embedding of renewables.
- Renewables embedding are known to cause large fluctuations, sometimes causing large, and not always predictable power outages.
    - Difference in time-scales, "inertia" of synchronous generators is lacking with embedding of renewables

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The physics of the traditional grid

- Most control system studies use swing equations. Swing equations limited due to missing transient response of electrical part. Still, so far best we can do.

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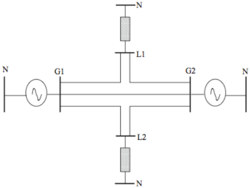
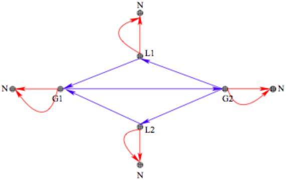
- Also, literature relates frequency deviations to pricing mechanisms and stability for the swing equations.

"Full" synchronous generator model in the grid

Example network:



Corresponding graph:



The incidence matrix and the Kirchhof laws, together with the 8th order models of the synchronous generators provide a port-Hamiltonian model of the overall system.

A port-Hamiltonian model of the grid

A port-Hamiltonian model is based on the internal energy (Hamiltonian) in combination with the (power) ports of the system, system theoretic concept of **passivity**.

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- 3 phase rotor and stator flux linkages (6 in total) ψ_r, ψ_s.
- the momentum p.
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Inputs:

- Electrical field E_f.
- Mechanical torque T_m.

Together with the incidence matrix, a pH model is obtained.

Equilibrium points and stability analysis

For a pH model, the derivative of the Hamiltonian (change in energy) equals the supplied power. The Hamiltonian usually can be used for stability analysis. However,

- No equilibrium points, i.e., angle constantly changes for a fixed frequency.
- Angle difference between generators.
- Stability analysis not straightforward from Hamiltonian.
- Possible for synchronous machine connected to an infinite bus (SMIB).

Lyapunov function

$$V(x) = H(x) - \left(\frac{E_f \psi_f}{r_f} + T_m \tan^{-1} \left(\frac{\psi_q}{\psi_d} \right) \right)$$

with ψ_q, ψ_d, ψ_f transformed fluxes.

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In power systems literature these models are not used, many simplifications based on physical intuition are made, and from a control systems perspective often not useful. Still in the traditional grid these models are useful. Problems pop up due to increased interconnections and embedding of renewables.

Utility optimization

Model is rather complex.

- To consider utility optimization, in literature, a PH model is also made of the swing equations, only taking the mechanical structure into account. Inverters (for e.g. the coupling of solar panels to the AC grid) and load models can be added as well.

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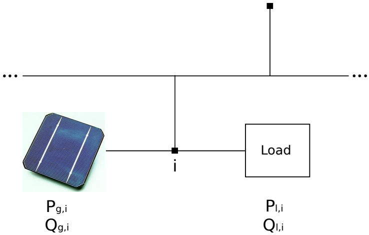
Also, so far focus on frequency. However, for embedding renewables the voltage in the distribution grid important! How to approach this?

Problem statement voltage regulation

Consider a network of n nodes (busbars) and m edges (lines)



described by power flow equations with P active, and Q reactive power

$$P_i = \sum_{j \in \mathcal{N}_i} G_{i,j} V_i^2 - G_{i,j} V_i V_j \cos(\theta_{i,j}) - B_{i,j} V_i V_j \sin(\theta_{i,j}),$$

$$Q_i = \sum_{j \in \mathcal{N}_i} -B_{i,j} V_i^2 + B_{i,j} V_i V_j \cos(\theta_{i,j}) - G_{i,j} V_i V_j \sin(\theta_{i,j}),$$

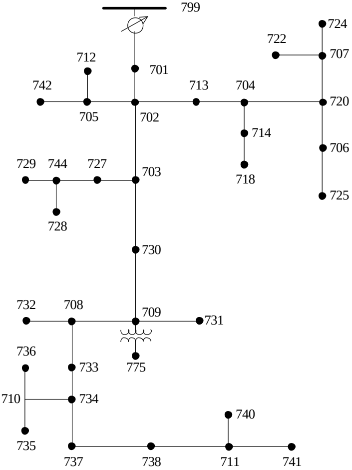
where $P_i = P_{g,i} - P_{l,i}$, $Q_i = Q_{g,i} - Q_{l,i}$ with indexes 'g' and 'l' representing the generation and load respectively.

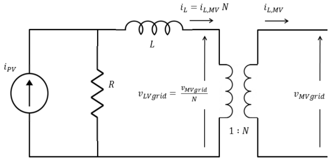
Goals

1. Power loss minimization (improving the utilization of the grid)
2. Voltage regulation: maintaining the voltage at each busbar within its desired bounds through regulating active and reactive power
3. Dealing with the capacity limitations of the grid
4. Maximizing the social welfare
5. Fair sharing of energy

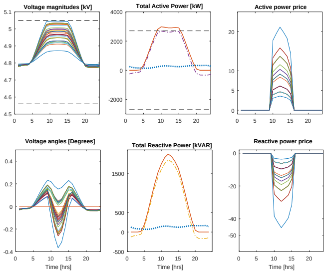
Primal-dual problem formulation helps to find the optimal solution. Dual decomposition helps to formulate the problem in a distributed manner.

Case study: A modified IEEE 37 bus with storage and PV





PV model



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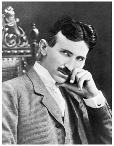
AC vs DC networks



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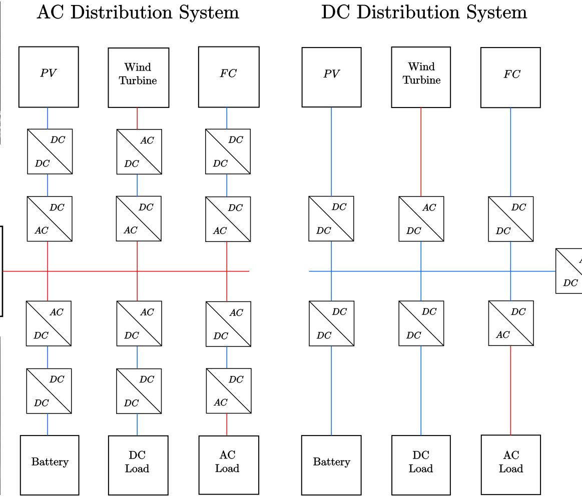

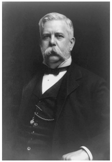

Westinghouse

Edison

AC-DC converters:	8	2 (3)
DC-DC converters:	4	4

Advantages of DC microgrids

- DC microgrids are more efficient
- Lossy DC-AC and AC-DC conversion stages are reduced
- No reactive power to control
- Frequency synchronization is overcome
- Skin effect and harmonics (power quality) are not present

Examples

Background

- Lots of work on design and control of DC-DC converters, also in the Power Electronics and Power Systems literature.
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- Specific usage of passivity in relation to old work of Brayton and Moser (1964), used for control by us in early/mid 00's.

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Our results: novel passivity approaches, using Brayton-Moser perspectives. There are mainly two types of DC/DC converters:

- **Buck** converters
  step-down the input voltage

- **Boost** converters
  step-up the input voltage

Node and Edge model

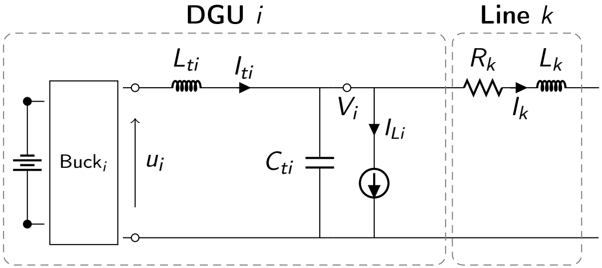

Figure: Electrical scheme of DGU i and line k.

DGU i:

$$L_{ti}\dot{I}_{ti} = -V_i + u_i$$

$$C_{ti}\dot{V}_i = I_{ti} - I_{Li} - \sum_{k\in\mathcal{E}_i} I_k,$$

Line k:

$$L_k\dot{I}_k = (V_i - V_j) - R_k I_k.$$

$\mathcal{E}_i$: set of lines incident to DGU i. Furthermore, here constant current load.

DC network model (Physical system)

Connected and undirected graph:
$\mathcal{G} = (\mathcal{V}, \mathcal{E})$, $\mathcal{V} = \{1, ..., n\}$, $\mathcal{E} = \{1, ..., m\}$.

Network model:

$$
\begin{aligned}
L_t \dot{I}_t &= -V + u \\
C_t \dot{V} &= I_t + \mathcal{B} I - I_L - (G_L V + P_L [V]^{-1}) \\
L \dot{I} &= -\mathcal{B}^T V - R I,
\end{aligned}
$$

$\mathcal{B} \in \mathbb{R}^{n \times m}$: incidence matrix. R, L_t, L, C_t and I_L (G_L, P_L) are unknown.

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current balance: $\mathbb{1}^T \overline{I}_t = \mathbb{1}^T I_L$.

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There is flexibility in distributing the total required generation of current among the nodes!

Control Objectives

- **Current sharing**

$$\lim_{t\to\infty} I_t(t) = \bar{I}_t = W^{-1}\mathbb{1}\, i_t^*,$$

$i_t^* = \mathbb{1}^T I_L / (\mathbb{1}^T W^{-1}\mathbb{1}) \in \mathbb{R}$,

$W = \mathrm{diag}(w_1, \ldots, w_n), w_i > 0, i \in \mathcal{V}$.

- **Average voltage regulation**

$$\lim_{t\to\infty} \mathbb{1}^T W^{-1} V(t) = \mathbb{1}^T W^{-1} V^\star,$$

$V^\star \in \mathbb{R}^n$: desired voltages.

Results

Buck networks, distributed solutions:

- Using shifted passivity for unknown constant current (I) loads
- Using shifted passivity, Brayton-Moser control method, for unknown constant impedance (Z) loads
- Using Krasovskii passivity, for unknown ZI loads

Buck networks, decentralized solutions:

- Using Brayton-Moser framework for new passive output, unknown ZIP loads (P represents constant power loads).

Boost networks, decentralized solution:

- Using Krasovskii passivity, for unknown ZIP loads

Buck: distributed, constant current load

S. Trip, M. Cucuzzella, X. Cheng, J.M.A. Scherpen, 'Distributed averaging control for voltage regulation and current sharing in DC microgrids', IEEE Control Systems Letters, Jan. 2019.

Contribution:

- line impedance taken into account
- distributed, only local current measurements and current information through communication network (design is independent from physics) needed, and no information about parameters of the model is needed
- existence of steady state solution and global convergence is proven

Cyber system

Communication network: connected and undirected $\mathcal{G}^c = (\mathcal{V}, \mathcal{E}^c)$, $\mathcal{E}^c = \{1, ..., m_c\}$ may be different from $\mathcal{E}$.

$\mathcal{B}^c \in \mathbb{R}^{n \times m_c}$: incidence matrix.

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Consensus dynamics:

$$T_{\theta i}\dot{\theta}_i = -\sum_{j \in \mathcal{N}_i^c} \gamma_{ij}(w_i I_{ti} - w_j I_{tj}),$$

$T_{\theta i} > 0$, $\gamma_{ij} > 0$.

$\mathcal{L}^c = \mathcal{B}^c \Gamma (\mathcal{B}^c)^T$: (weighted) Laplacian matrix, $\Gamma \in \mathbb{R}^{m_c \times m_c}$.

Control scheme

We have control schemes only using the communication scheme. Provably correct, i.e., current sharing and average voltage regulation goal is achieved, i.e.,

The solutions to the closed-loop system converge exponentially to a steady steady achieving current sharing and average voltage regulation.

Case study

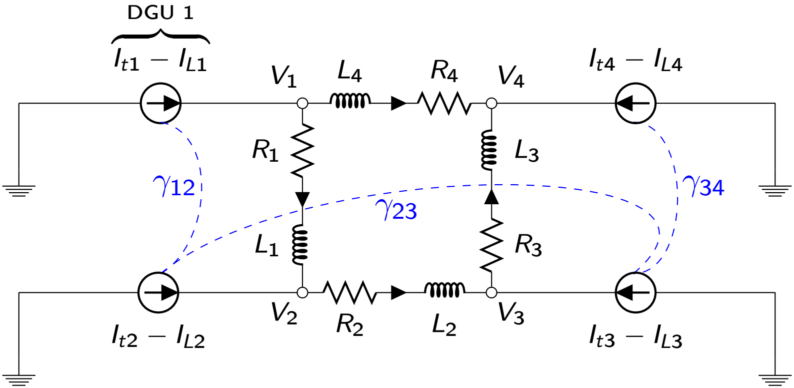


Figure: Scheme of the considered (Kron reduced) microgrid with 4 power converters. The dashed lines represent the communication network.

Voltages and Currents

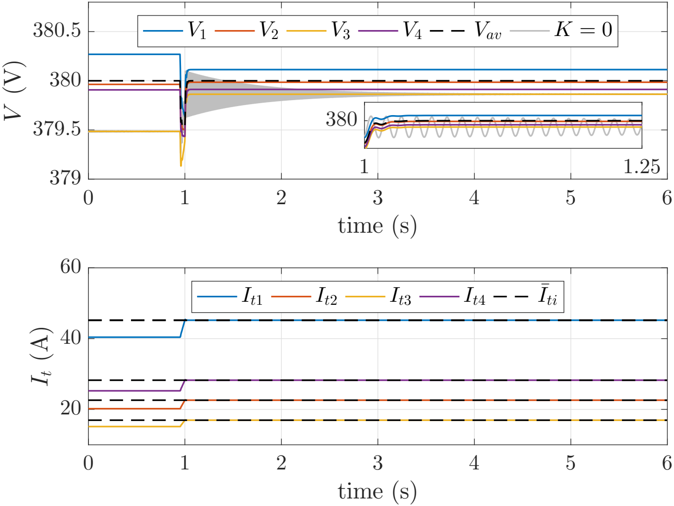
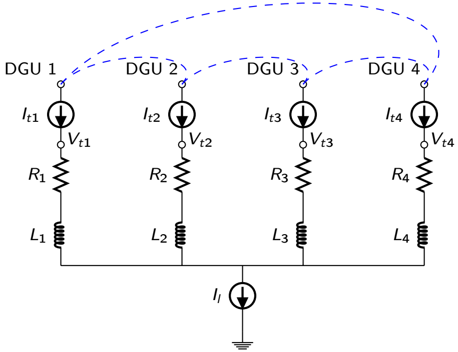
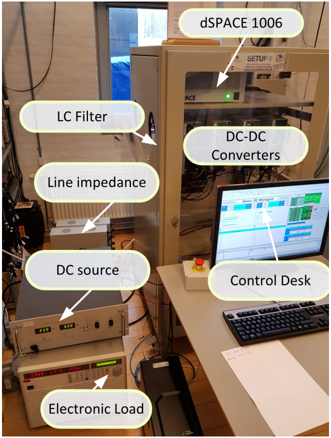


Figure: Voltage at each node and weighted average value of the network voltages, generated currents and corresponding values that achieve current sharing.

Experiments

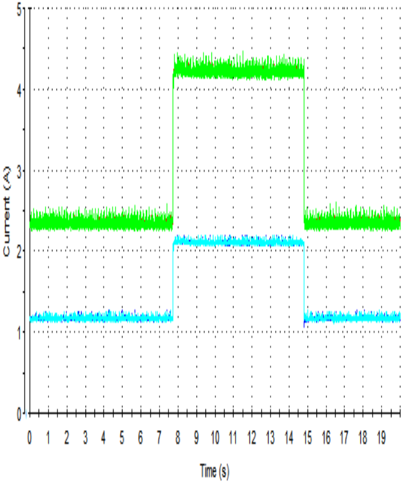
Intelligent Microgrid Laboratory (Aalborg University) with ZIP loads.

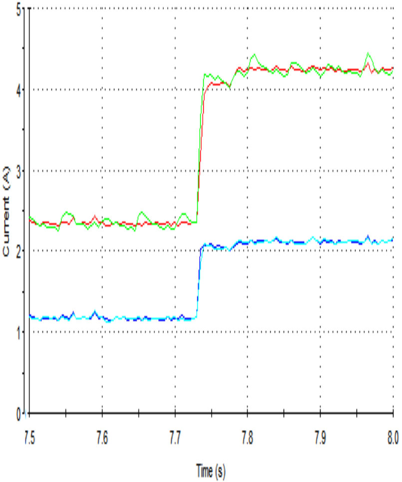




S. Trip, R. Han, M. Cucuzzella, X. Cheng, J.M.A. Scherpen, J. Guerrero, 2018

Currents (piecewise constant impedance load, full and zoom)





A similar control scheme for AC microgrids

- Make physical models, with node and edge dynamics
- apply Park's transformation, and give formulas for active and reactive power
- design q component such that $V_q = 0$ in finite time (e.g., sliding mode)
- design d component similar to DC case

M. Cucuzzella, S. Trip, A. Ferrara, J.M.A. Scherpen, 2018.

Our results, summary DC networks

- Crucial is the usage of variations on the passivity properties.
- Distributed solutions obtained with a communications layer.
- Constant and time-varying ZIP loads.
- Various publications.

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An example project: The Flexines Project, start 2008

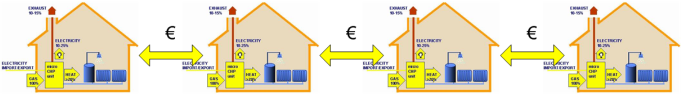
Flexines

Gas important in Groningen area, micro-CHP of interest for distributed generation.

- **Business case**: Estimation that in 2020 1 million μCHP units in the Netherlands, in 2030 4 million.

Naast de provincie en de gemeente Groningen, wordt dit project medegefinancierd door het Ministerie van EZ en het Europees fonds voor regionale ontwikkeling

Another alternative: Distributed control



Current experiments: no predictions included.

- Distributed control $\rightarrow$ Local price communication between neighbors.

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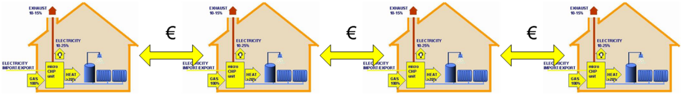
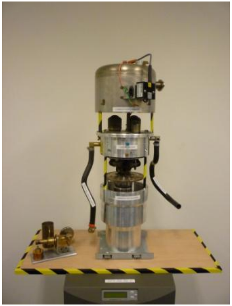


Current experiments: no predictions included.

- Distributed control → Local price communication between neighbors.
- The micro Combined Heat Power (μCHP) system is an option for local production (e.g., Houwing et al. 2011).
  - Overall efficiency of the μCHP can be as high as 90%.
  - Electrical output is typical 1kWh.



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Network control issues

- Imbalance zero.
- Avoid peaks $\rightarrow$ may allow more connections on one transformer.
- Lower transmission losses $\rightarrow$ local delivery.
- Delivery certainty.
- Local optimization versus global optimization.

Problem formulation

Minimize imbalance and costs of production given the imbalance equations per household, i.e., $\min_u \Sigma x^T x + u^T u$.

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$x_i[k]$ is imbalance *information* household i at time k. Then

$$x_i(k+1) = A_{ii} x_i(k) + \sum A_{ij} x_j(k) + u(k) + w_i(k)$$

x_i imbalance information, w_i change in demand (white noise), u_i change in production. NB: real imbalance $\tilde{x}_i$: $A_{ij} = 0$, $A_{ii} = 1$.

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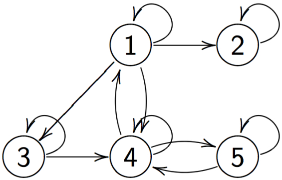

$$A = \begin{bmatrix} * & 0 & 0 & * & 0 \\ * & * & 0 & 0 & 0 \\ * & 0 & * & 0 & 0 \\ * & 0 & * & * & * \\ 0 & 0 & 0 & * & * \end{bmatrix}$$

Dual-decomposition and sub-gradient iterations

- Game theoretic interpretation from economics literature, dual decomposition in optimization treated in litearuature
- Based on price mechanisms in linear quadratic team theory and dynamic dual decomposition for distributed control, in literature.
- Recently applied to production side control with micro CHP's and heat pumps, (Larsen, van Foreest, Scherpen, 2013, 2014).

From a centralized MPC to a distributed MPC

- In principle, a centralized optimization method fulfilling the constraints exists, and is very successful in e.g., chemical process industry, called **Model Predictive Control**.
- Adaption of method to only communication between "neighbors" via dual decomposition, and using gradient iterations in the computations makes the method completely distributed, i.e., local computations, achieve a global goal!

Networks of households with μCHP and heat pumps

- Heat demand is leading, i.e., it is a constraint that the heat demand has to be met with local devices.
- Constraints on production side, i.e., μCHP, and heat pump (off-time, not on for very small demand, maximum production level, etc.), of which some are non-convex.
- Information exchange with neighbors.

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- Information exchange with neighbors.
- Via game theory and dual decomposition price mechanism interpretation.
- Control of the imbalance can be done fully distributed at each household with only information of the neighbors.
- Implementation feasible, imposing constraints.

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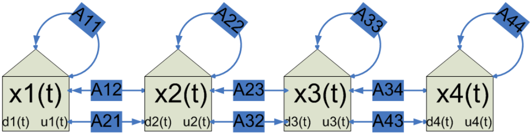
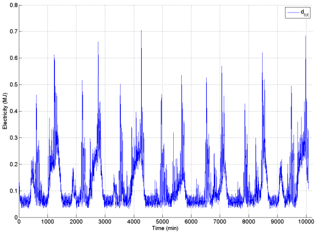
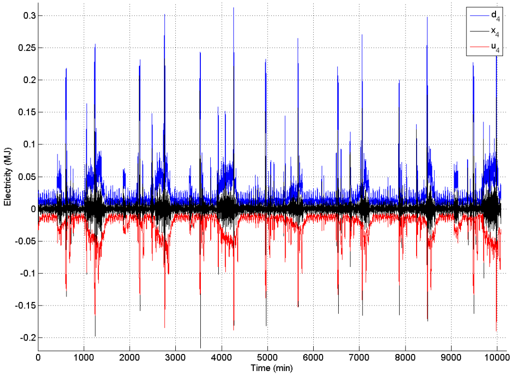
Realistic electrical demand obtained from field tests





Optimal control $u(k)$



Summary of production side

- By embedding the electrical power grid in the dual decomposition framework distributed suboptimal control of decentralized power generation can be achieved.
- Method can also capture current network structure.
- Information from physical far away neighbours set to zero. This is promising with respect to computational complexity, and reduces transportation costs.

Summary of production side

- By embedding the electrical power grid in the dual decomposition framework distributed suboptimal control of decentralized power generation can be achieved.
- Method can also capture current network structure.
- Information from physical far away neighbours set to zero. This is promising with respect to computational complexity, and reduces transportation costs.
- Propose that the structure of the network in the future may change when there is a high share of controllable decentralized generation present.

Demand side control in similar fashion feasible

- Study towards embedding of washing machines done.
- Mixed integer optimization problem.
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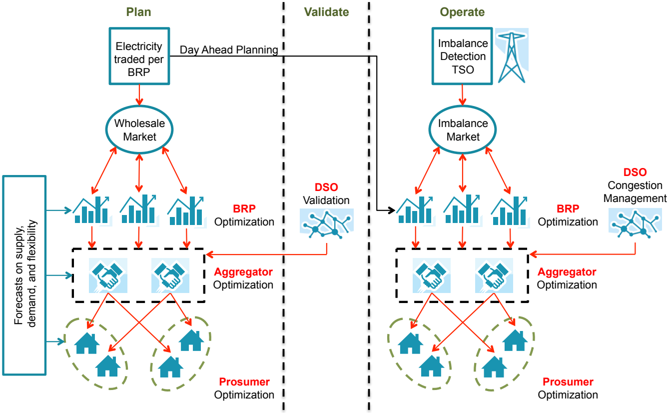
- Multiple types of devices can be included.
- Connect to local production of power as presented before.
- Scalability of simulations, so far simulations up to 10.000 households via parallel implementation goes well.
- Combination of hierarchical scheduling methods with distributed control, embedding in market structure $\rightarrow$ fit in Universal Smart Energy Framework.

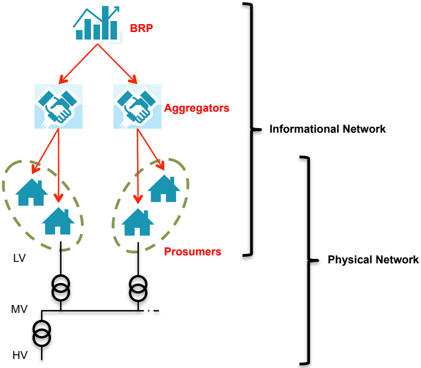
Market embedding

- Market in the Netherlands an EU deregulated, separate price for network transport and energy delivery.
- Transport can partly be accounted for by choices in A matrix, i.e., low weight corresponds to expensive transport.
- However, supplier market is deregulated, physical neighbors may have different suppliers $\rightarrow$ how to embed distributed control algorithms?

Market embedding

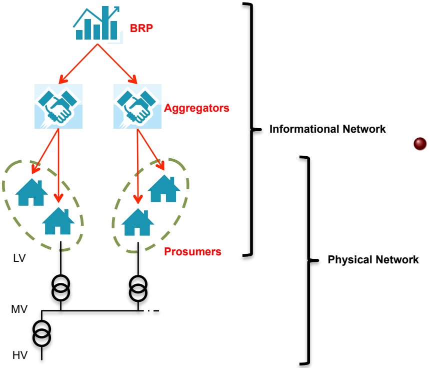
Embed distributed algorithms in market. $\rightarrow$ Collaboration within a consortium.





- Extra aggregator layer. Distributed control per layer, combined distributed and hierarchical control, how to guarantee performance?

Operation phase



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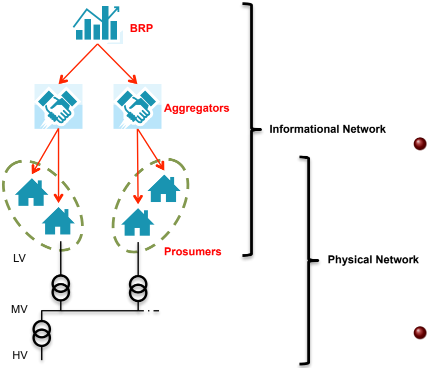

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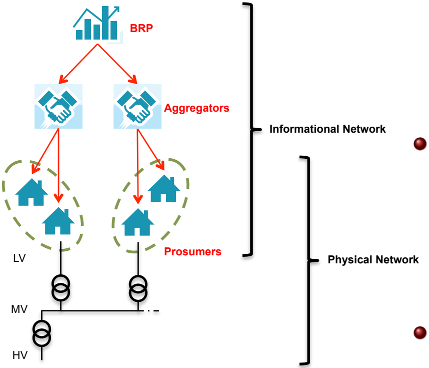

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- Collaboration between market parties?

Overview

- Control of the physics of the (traditional) AC power grid, physics layer
- Control of DC microgrids, physics layer
- Distributed optimal control solutions, market layer
- Energy System Integration, market layer

Energy System Integration

Hot topic in current energy world.

- Coupling of the different grids, from power, gas, heat to industrial grids.

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- Coupling of gas and power grids very natural through e.g.,
    - Combined Heat Power (CHP) Systems, running on gas,
    - Power-to-Gas facilities and fuel cells.
    - Different storage and transportation options.

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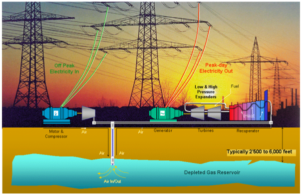
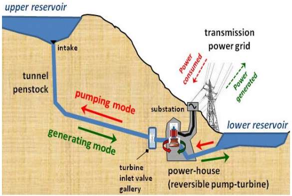
- Coupling of gas and power grids very natural through e.g.,
  - Combined Heat Power (CHP) Systems, running on gas,
  - Power-to-Gas facilities and fuel cells.
  - Different storage and transportation options.
- Recently started the control of a district heating project.

Storage options

- Renewables:
  weather dependence hence severe for grid stability
- Energy storage options:
  compressed air energy storage & pumped hydro storage
- Batteries and power-to-gas





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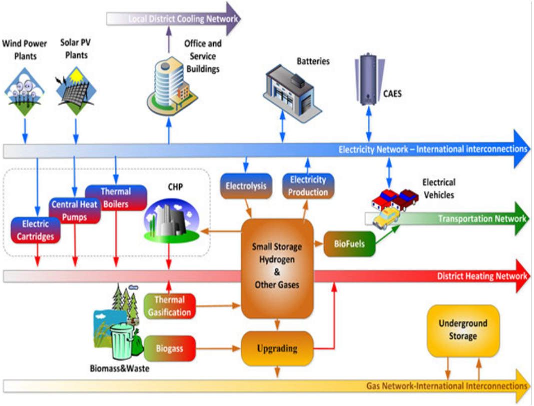
Energy System Integration and storage in PtG



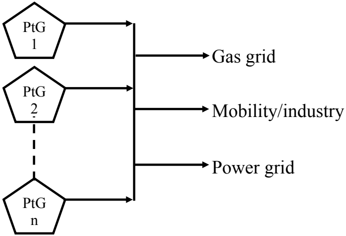
- H_2 production depends on the excess power, power-to-gas (PtG)
- Local storage device
- Time-varying price and demand patterns on energy grids

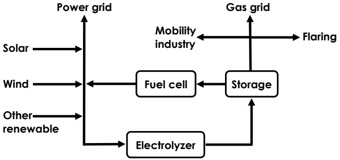
Supply coordination of agents in a grid

Congestion control in networks developed further

- Wireless networks, many static results.
- Congestion for energy systems, dynamic systems.
- Multiple grid extension motivated by PtG application.

Managing PtGs facilities



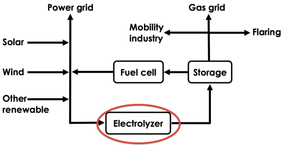


Goal Maximizing profit, while ensuring the availability of the supply

Mean Coordination towards PtG facilities' decision

Result Optimization of decision, while preventing overloading grids

PtG model, electrolyzer and fuel cell simple model



- $2H_2O + \mathrm{e} \rightarrow 0_2 + 2H_2$.
- Proton Exchange Membrane (PEM) water electrolyzer, 70% efficiency.
- Basically $p_i(k) \in 0 \cup [p_i^{min}, p_i^{max}]$ with p_i amount of hydrogen depending on intermittent excess power.

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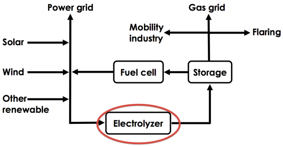

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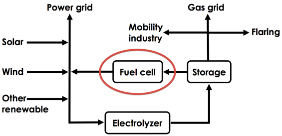

- Power generator.
- PEM fuel cell, $40 - 60\%$ efficiency.
- Amount of hydrogen to satisfy electricity demand $P(k)$: $E(k) = \frac{1}{\epsilon} P(k)$ with efficiency ϵ.

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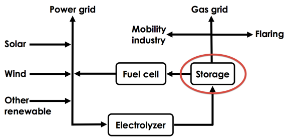
Dynamical storage model



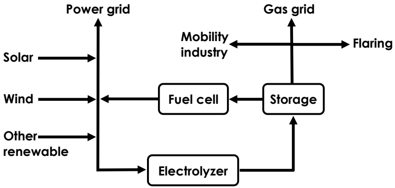
- Stored at normal temperature & pressure
- No leakage of stored gas

Charging routine $u_{s,i}(k)$, discharging routine $u_{t,i}(k)$, stored gas $z_i(k)$, maximum storage S_i:

$$z_i(k+1) = z_i(k) - u_{t,i}(k) + u_{s,i}(k)$$

$$0 \leq u_{s,i}(k) \leq S_i - z_i(k) \qquad \text{and} \qquad 0 \leq u_{t,i}(k) \leq z_i(k)$$

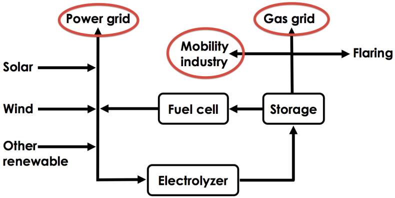
Constraint each PtG in the grids



$$g_i(k) + y_i(k) + e_i(k) + u_{s,i}(k) + f_i(k) = p_i(k) + u_{t,i}(k).$$

g_i, y_i, e_i is delivered to gas, industry and power grid, resp.
f_i is flared.
$u_{s,i}$ into storage
$u_{t,i}$ out of storage
p_i produced hydrogen

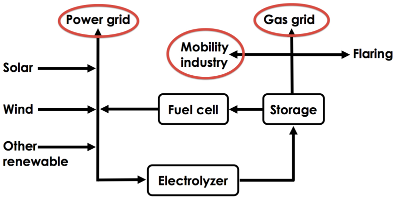
Cooperation towards coupling constraints



- Total demand and capacity constraints of the energy grids limit the supply of PtGs

$$\sum_{i=1}^{n} m_i(k) \leq M_m(k), \quad \forall m = g, y, e$$

Cooperation towards coupling constraints



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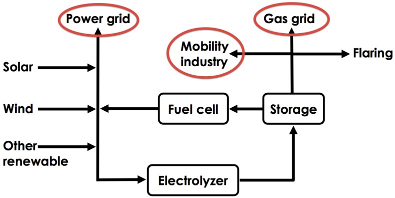

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$$\sum_{i=1}^{n} m_i(k) \leq M_m(k), \quad \forall m = g, y, e$$
- $M_m(k)$ depends nonlinearly on external signals (network distribution, congestion.
- Responsibility of Distributed System Operator (DSO) to avoid overloading grids.

Optimal control problem

Problem formulation

$$\max_{m_i(k)\in\mathcal{M},u_{t,i}\in\mathcal{U}_{t,i},u_{s,i}\in\mathcal{U}_{s,i}} \sum_{\tau=k}^{\infty}\sum_{i=1}^{n} U_i(\tau)$$

s.t.

$$\begin{aligned}
\sum_{i=1}^{n} m_i(\tau) &\leq M_m(\tau) \qquad \forall m = g, y, e \\
p_i(\tau) + u_{t,i}(k) &= \sum_{m=g,y,e} m_i(\tau) + u_{s,i}(\tau) + f_i(\tau)
\end{aligned}$$

and the static constraints of the fuel cell, and electrolyzer, as well as the dynamical model of the storage.

Optimal control problem

- Under conditions that
  - the profit function $U_i(k)$ is strongly concave, increasing, and twice differentiable and
  - all constraints are compact and convex,

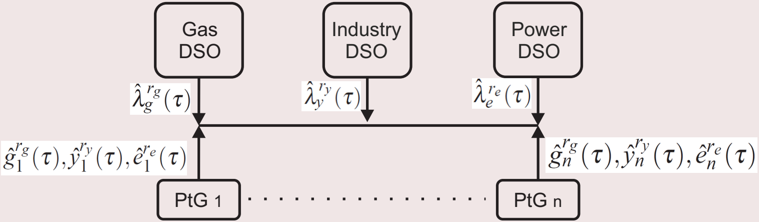
  the problem has one solution at most.
- A distributed controller can do the job.

Apply dual decomposition, then results in :

- A lower level problem, faced by each PtG
- A higher level problem, faced by each DSO

Distributed coordination

Distributed supply coordination



Iteration procedure to solve this problem. Information can be communicated asynchronously!

Profitable?

Current costs of PtG facilities make the investment not worthwhile yet. Future scenarios from 2017 [Energyacademy.org]:

- Hydrogen injection allowed on the gas grid increases to 0.5 % from 0.02%
- Demand on the industry grid increases with a factor of three
- PEM water electroctrolyzer cost decreases 60%

Table: Yearly profit of a PtG with future changes of price and demand levels.

Case	Electrolyzer cost	Gas demand	Industry demand	Annual profit(€)
1	Current	Future	Current	760k
2	Current	Future	Future	1,876k
3	Future	Future	Future	3,903k

Concluding remarks

- Control of the physics of the grid, versus market layer, different time scales, coupling takes place.

Many challenges and ongoing work:

- DC grid and coupling to the AC grid for smart parking lots and office buildings, vehicle-to-grid
- Energy System Integration: district heating networks included
- Coupling to changing regulations, economics, psychology, collaboration necessary to solve societal problem
- Time-varying loads
- Enough capacity, storage, optimal location of storage in order to prevent massive investments in infrastructure
- Many more ......