Modeling and optimizing a distributed power network: A complex system approach of the prosumer management in the smart grid

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Outline

Scope and goals of the project

- **Modelization of the Prosumer Interactions**
  - How do smart grid's units (distributed generators (DR), batteries, loads...) agree on production/consumption contracts while maintaining stable operating conditions ?
  - Enable Microgrid to form coalitions in order to :
    - Relieve the main grid
    - Minimize power losses
  - Distributed operations
  - 'Plug-and-Play' philosophy
  - How can the information system deal with multi-scale units of control ?
- **Interplay between the power grid control and Machine To Machine communications issues:**
  - Communications pipeline (Socket+Queue+Retransmissions),
  - Communications Many-to-One, Many-to-Many, etc...
  - Services Discovery,
  - ZeroMQ, RabbitMQ, ActiveMQ
- Dealing with huge sets of noisy measurements from the power grid: i.e. Storage and management of huge amounts of data.
- Electrical Grid stability is not considered

Scope and goals of the project

1. Forming coalitions Microgrid in a distributed environment (Game Theory)
2. Studying the communication pattern needed to enable coalition formation/maintenance (Consensus)
3. Realistic model of the demand/consumption

What is a prosumer ?

Producer + Con**sumer**

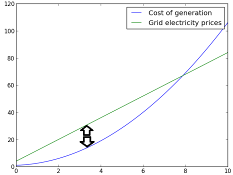
- Not only consumes, but produces, sells and stores energy
- Economically interested, prosumers expect retributions [4]

Interesting idea, but :

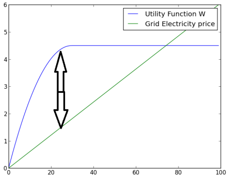
- How can a prosumer reach the grid's requirements (quality, stability, power...) to sell energy ?
- Whom to sell energy to ?
- How to reattribute prosumers ?
- How to deal with a huge amount of constantly changing buying/selling agents ?

Maximizing the exchange of energy with other Microgrid (reduce the dependance with the main grid), however a prosumer aims at maximizing a given utility function [7]

- **Producers**



- **Consumers** With $W_i(P)$ denoting a concave function representing how i values the energy it consumes.



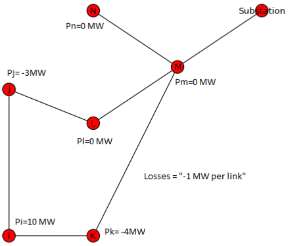
Modeling a coalition formation process

- Why forming coalitions ?
  - Economical objective : Every prosumer seeks to maximize its payoff
  - For the Grid: Minimizing the energy exchanged on the main grid
  - For a given prosumer, payoffs are higher in a coalition (Pareto order)
  - Visibility of DER (*Distributed Energy Resources*) units to the system operator
  - Local coalitions are favored as they reduce the amount of electricity transported over long distances
  - A first step towards complex objectives such as islanding in order to avoid cascades of failures (end parts of the network are more independant)
- Tools :
  - Game theory framework [6] [5]
  - Pareto order (Merge and Split algorithms)
  - Centralized/Decentralized algorithms

The timescale for the existence of coalitions is relatively large (several hours, day...). Different prediction tools can be used to predict production and consumption conditions for the next macro-period(s).

Very Simple (and unrealistic) Example

Network:



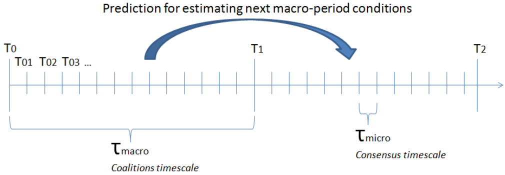
Coalitions values:

i's payoffs		
Coalition	payoff value	Ranking
(i)	0,0	7
(i,j)	11,4	3
(i,k)	14,4	2
(i,j,k)	19,4	1
(i,sub)	7,0	5
(i,j,sub)	11,0	4
(i,k,sub)	6,9	6
(i,j,k,sub)	impossible	impossib
j's payoffs		
Coalition	payoff value	Ranking
(j)		5
(i,j)	-13,4	1
(i,j,k)	-15,3	2
(i,j,sub)	-22,0	4
(j,sub)	-18,0	3
k's payoffs		
Coalition	payoff value	Ranking
(k)		5
(i,k)	-17,6	1
(i,j,k)	-19,3	2
(i,k,sub)	-27,9	4
(k,sub)	-24,0	3

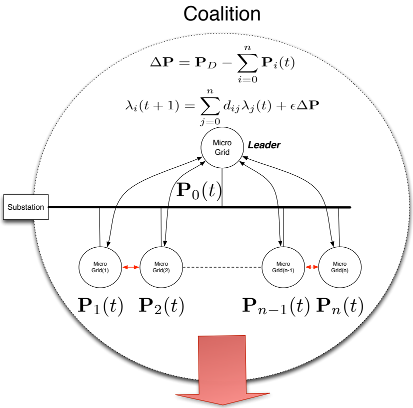
- I, J, and K have different preferences for the optimal coalition.
- How to find a consensus on the adopted coalition ?
- Network architecture that allows such formations ?

Maintaining the balance on smaller scales

- Typically, a coalition has to respect a "contract" towards the outside in order for the system to stay balanced
- Production and consumption conditions over time
- Necessity to adapt units behaviors inside the coalition for power generated and consume to stay within acceptable margins (defined in the contract)
- Load shedding, not an optimal policy
- Consensus algorithms are used to readjust some unit's production or consumption profiles [8] [3]
- "Penalize" the units for which the change is the least expensive (marginal cost, participation factors [3]
- Convergence of these consensus algorithms ?



Example of a microgrid supplying the main grid



Each micro grid update it power for the next time interval according to:

$$\mathbf{P}_i(t+1) = \mathcal{F}\left(\mathbf{P}_i(t), \sum_j \lambda_j d_{ij}\right)$$

- $\mathbf{P}_D$: Power level negotiated at the beginning of the contract
- $\mathbf{P}_i(t)$: Power produced by the microgrid i at time t
- $\lambda_i(t)$: Marginal cost of production during at time t

Example of consensus in a coalition

Fig2:

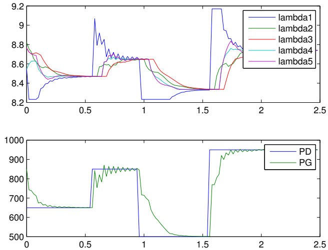
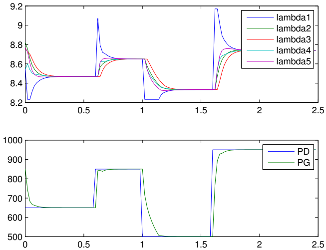


Fig 1:



Consensus in a 5 units coalition with (Fig 2) and without (Fig 1) time delays and under power demand variations. The first chart of each figure represents the evolution of the marginal costs while the second shows the evolution of power demanded and generated

Realistic Modeling

- In order to be insightful the model needs realistic input data
- Most publications that focus on topological questions use simplistic modeling assumptions *ex : The production of a wind turbine is a sequence of independent random variables from a given distribution...*
- Necessity to take into account the spacial and time correlations for both production and consumption profiles
- Necessity to study wind speed and solar intensity properties properly (non stationarity, autocorrelation... [1] [2]
- Use of Time Series to generate proper profiles (AR, ARIMA... models) [1] [2]
- Take into account human behaviors and movement patterns to predict future consumption regions and bottlenecks in the system ex : Electric vehicles recharge at different locations depending on the time of the day, on the day of the week, on the month of the year...

Example of wind data

Fig 1:

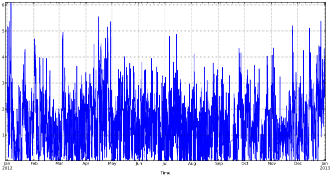


Fig2:

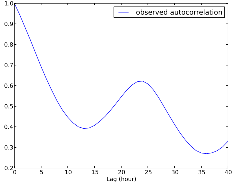


Fig 1 : Wind Speed in m/s in 2013 Fig 2 : Autocorrelation

Fig 1:

```
In [12]: ar_res.params
Out[12]:
array([ 4.64225190e-02,   9.36545529e-01,  -4.25345310e-02,
        4.54534481e-02,  -2.80967961e-02,  -2.32438085e-03,
       -3.05944207e-03,   3.24829274e-02,  -3.46334403e-02,
        3.17389716e-03,   1.70348438e-02,  -8.21700095e-03,
       -1.91462324e-02,  -1.16477481e-02,   4.50068693e-03,
        4.86837600e-03,   1.59398590e-02,  -2.19424421e-02,
        1.11120646e-02,  -5.09783957e-03,   2.05257232e-02,
        2.28682784e-02,   3.37823792e-02,   3.25650645e-02,
        4.58016862e-02,  -1.93634540e-02,  -2.20845484e-02,
       -1.81653609e-02,  -3.89473164e-02,   1.83009131e-03,
       -5.62356341e-03,  -1.33451311e-02,   6.91379002e-03,
        2.24182833e-04,  -2.92317158e-02,   1.61655992e-02,
        1.89621332e-02,   1.80597096e-03,  -1.06098597e-02,
       -2.07530347e-02,   5.34861932e-02])
```

Fig2:

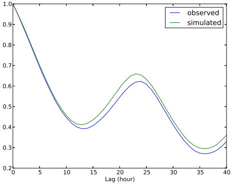


Fig 1 : AR parameters Fig 2 : Autocorrelations of simulated and observed data

Conclusion

The project revolves around :

- Studying various topologies enabling services discovery, decentralized communication in a 'plug-and-play' philosophy
- Designing appropriate mechanisms based on Game Theory for enabling coalition formations :
  - Increase local independence's towards the main grid
  - Allow DER to participate in transactions
  - Facilitate islanding processes in case of outages
  - Reduce power losses due to transportation
- Studying consensus algorithms inside coalitions (convergence, topologies...)
- Modeling properly unit's behaviors (input data...)
- How to deal with margins in the contracts ?
- Modeling the grid operator (accept/reject contracts, constraints on the network...)
- *Modeling and optimizing a distributed power network : A complex system approach of the prosumer management in the smart grid*, **Arxiv Id: 1305.4096**

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