Flexibility services in the electrical system

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Outline

The European electrical system

Flexibility in electrical system

Flexibility in
  the day-ahead energy market
  the reserve market
  the distribution network

Flexibility from
  heat pumps
  a price signal in the distribution network

Conclusion
Producers, consumers and the market

Electricity is a commodity which main roles are:

Producers → Market operator → Consumers

The most common market is the day-ahead energy market.
Electricity retailers

Small consumers do not buy their electricity individually but make use of the services of intermediation provided by retailers 🛒.
The network

Once traded, electricity needs to be conveyed. The physical link is called the network.

The network is divided into 2 layers:

- The **distribution** network operated by the Distribution System Operator (DSO).
  
  Low-voltage < 1kV & medium-voltage < 36kV

- The **transmission** network operated by the Transmission System Operator (TSO).
  
  High-voltage > 36kV
Imbalance

One of the most important task of the TSO is to maintain the balance at every moment between production and consumption.

This equilibrium is first ensured on the trades with the obligation for each participant to submit a planning of production and consumption called baseline.

The baselines are provided by Balancing Responsible Parties (BRP) which may regroup multiple actors.

To access to the network, every user of the network needs a BRP.

Figure: Example of baseline and realization.
Balancing responsibilities

In real-time, realizations may deviate from baselines. The TSO is responsible to compensate the overall imbalance.

Due to the unbundling of the electrical system, the TSO does not own production or consumption assets and must contract and activates balancing services according to the needs of the system.

Imbalance of the system: +1MW
Imbalance price

The most expensive activated service defines the imbalance price which serves as a basis for the payment or compensation of BRPs in imbalance.

Figure: Imbalance prices on June 1, 2015 of Elia, the Belgian TSO.
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**Definition of the flexibility**

*Flexibility* in electrical system is the *modification* of the production or consumption *in reaction* to an activation *signal* to provide a *service*. e.g. a gas unit producing 25MW asked to produce 1MW more.

The actor providing flexibility is called in this work a *Flexibility Service Provider (FSP)*.

The needs for flexibility can be triggered by:

- the loss of a production unit,
- an unexpected over-production of a wind turbine,
- a congestion in a line of the network, etc.
Changes of the electrical system

The current electrical system is extremely reliable.

“Why looking at flexibility since everything is already working?”

The electrical system is changing from its traditional conception.

- Renewable energies
  - Production in distribution
    - Congestions and voltage issues
      - Investments or flexibility
  - Flexible thermal units
    - Control on the production
      - Flexibility of the consumption

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Renewable energy curtailment

Production units may change their output to provide flexibility.

<table>
<thead>
<tr>
<th>Flexibility</th>
<th>Thermal unit</th>
<th>Wind turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>↑ modulation</td>
<td>↑ fuel</td>
<td>-</td>
</tr>
<tr>
<td>↓ modulation</td>
<td>↓ fuel</td>
<td>□ blades pitch</td>
</tr>
</tbody>
</table>

To provide an upward modulation, a production unit runs below its maximum power.

Figure: Wind turbine production plan with reserved capacity.

Reserving capacity on a wind turbine is equivalent to throwing away this free energy.
Flexibility of the consumption

A large part of the consumption can be controlled. 

* e.g. electrical heaters, air-conditioners, industrial consumption, etc.

The control of loads gives rise to new challenges:

- Developing solutions which considers the constraints of all processes behind the electrical consumption.
  
  * e.g. getting flexibility from heat pumps.

- Integrating the payback effect coming from the modulation of energy consumption into flexibility services.

  If the consumption of a fridge decreases for 1h, the temperature inside the fridge rises. In the 2nd hour, the fridge consumes more to restore the temperature.

- Determining the cost to provide the flexibility.
Flexibility in distribution networks

The DSO may resort to different options to obtain flexibility:

- Using **flexibility services** in the distribution network.

![Diagram showing the interactions between Producer/Consumer, FSP, DSO, and TSO]

- Changing the **distribution network tariffs** to shift consumption.

![Graph illustrating peak solar energy usage]
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Retailers and day-ahead energy market

We study the system ...

... using game theory, in particular congestion games.

Each retailer with flexible consumption can choose its consumption in each hour to minimize the cost of buying its energy.
Shifting demand according to energy prices

Changing the consumption profile...

... affects the energy prices.
Congestion game

An example of congestion game is the car trip Liège-Bruxelles. The more care there is on the road, the more time it takes. At 7 am, the time taken is identical for the two paths. This situation is a Nash equilibrium.

Schematically we have
Retailers-market system as a congestion game

The mapping of the retailers-market system as a congestion game is:
Results

We define and work on a particular regime of the game: the laminar flow, valid if retailers are “big enough”.

Contributions
If the Nash equilibrium is laminar, we obtain

- a bound on the ratio maximum/minimum market price,
- a bound on the ratio of the total system cost at the Nash equilibrium and the optimal one,
- the price of flexibility, i.e. the cost of shifting energy away from a given hour.
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Impact of load flexibility on the reserve market

What is the impact of a retailer controlling flexible consumption on the day-ahead energy market and on the secondary reserve market?
Agent-based modeling

Each actor is modeled individually in an agent-based system.

Input → Agent → Output

The behavior of the actors are given by optimization problems.

Maximize revenues / minimize costs
subject to
agent’s constraints.

This kind of models allows to

- model individually each actor and observe their reaction in the complete modeled system,
- to highlight and understand unpredicted behaviors of the actors.
General view of the simulated system

1) Prices forecast
   \[ \text{Imbalance tariffs} \]

2) Actors optimize their position
   \[ \text{Bids to the energy market} \]

3) Clearing of the energy market

4) Actors optimize their position
   \[ \text{Energy prices} \]

5) Clearing of the reserve market

6) Actors optimize their position
   \[ \text{Reserve acquisition} \]

7) Imbalance settlement
   \[ \text{Imbalance of the actors} \]
Results

Drastic reduction of the reserve procurement costs even though the total cost increases above 4% of flexible consumption.

Reserve services provided by the consumption are less efficient due to the payback effect.
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Active distribution network management

Flexibility in the distribution network is mostly unused up to now and could solve local congestion problems.

There is a need of a framework detailing the interactions needed to exchange flexibility.
Timeline of the interaction between the agents

Figure: To each arrow corresponds an exchange of information whose source is given by the dot and the destination by the arrow head.
DSIMA: an open-source testbed

The testbed to evaluate interaction models is available as an open source code at the address

http://www.montefiore.ulg.ac.be/~dsima

Figure: Screenshot of the user interface.
Interaction models

DSIMA allows comparing quantitatively different interaction models. In the thesis, six interaction models are studied.

These interaction models are differentiated by

1. their type of access contract to the distribution network,
2. their financial compensation of flexibility services.

Table: Summary of the parameters of 4 of the studied interaction models.

<table>
<thead>
<tr>
<th>Interaction model</th>
<th>Access type</th>
<th>Financial compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>unrestricted</td>
<td>–</td>
</tr>
<tr>
<td>Model 2</td>
<td>restricted</td>
<td>–</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 5</td>
<td>unrestricted</td>
<td>bids &amp; imbalance</td>
</tr>
<tr>
<td>Model 6</td>
<td>dynamic</td>
<td>–</td>
</tr>
</tbody>
</table>
Results obtained on a 75 bus network for a representative 2025 year.

![Figure: Quantitative comparison of four interaction models.](image)

Protection costs reflect the cost of shedding of production or consumption due to problems in the management of the system.
Coordination problem

Assume that the DSO predicts that the power flow will exceed the capacity of the line 3 by 1MW. To solve this issue, the DSO curtails a wind turbine by 1MW.

At the same time, assume that the TSO asks a storage unit to inject 0.4MW. These activations lead to a remaining congestion of 0.4MW.
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Flexibility from heat pumps

This **electrical energy** consumed by the heat pump is converted into **heat** which is **stored** by the **building** and, depending on its thermal inertia, allows consumption to be shifted.
A flexibility service considering payback

This flexibility service consists in a modulation in one quarter followed by a well defined and limited energy payback in the following hour.

(a) Modulation signal

(b) Modulation added to the baseline
Optimization of the baseline

Minimize energy cost

subject to
- thermal state transition model,
- state constraints,
- power limitations,
- heat pump constraints.

using an accurate thermal model of the building and the heat pump.
Optimization of the modulation

To obtain the maximum flexibility in quarter $t$, solve

Maximize flexibility available in quarter $t$

subject to

- thermal state transition model,
- state constraints,
- power limitations,
- heat pump constraints,
- payback limited on $k$ quarters.

Accurately defining this payback is the key element that allows flexibility to be used in one quarter without risking creating other issues afterwards.
Results

A modulation of 2.5 kW with a payback of 1 hour provided by space heating from a 4.3 kW heat pump. Domestic hot water counterbalances space heating to limit deviations during payback.
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Price signal in the distribution network

The DSO may use the tariff of distribution as a price signal to shift the consumption and alleviate problems in its network.

This solution has the major advantage that the infrastructure is already in place with the system of off-peak and on-peak tariffs.

In Belgium, there are night-only meters that switch on electric boilers and heaters only during off-peak periods.
Problem statement

Find the best off-peak hours pattern by solving

Minimize energy costs
and photovoltaic curtailment costs

subject to

- distribution network model and constraints,
- automatic tripping of solar panels,
- a fixed number of off-peak hours, etc.

Examples of off-peak patterns
Results

The test case is a sunny summer day on a 108 buses medium-voltage network with 5040 houses. 5.7% of houses are equipped with night-only meters and 30% with PV panels of 6 kW.

This is therefore a good short-term solution to increase the amount of renewable energy produced in the distribution network.
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Summary

This thesis assesses impacts of exchanging flexibility in the electrical system and analyzes the resulting complex interactions.

The modeling techniques used to carry the analysis are
- game theory,
- agent-based modeling,
- optimization.

The impacts on different parts of the electrical system are presented:
- the day-ahead energy market,
- the secondary reserve,
- the distribution system.

Methods to obtain flexibility from the consumption are broached:
- direct control of a portfolio of heat pumps,
- dynamic pricing to control electric heaters and boilers.
Discussion

This thesis strengthens the state of the art by formalizing the interactions needed to use flexibility in the European electrical system.

This work could be continued along two major lines:

- doing further academic researches:
  - more detailed models,
  - other modelization techniques,
  - compare investments in flexibility and in the network,
  - etc.

- going from theory to practice.
This work could be continued along two major lines:

- doing further academic researches:
- going from theory to practice. There already are
  - many applied projects on flexibility,
  - an increasing number of flexible consumption devices,
  - algorithms able to coordinate these flexible loads.

My opinion is that one important remaining step to perform is to complete the regulation of flexibility in the electrical system.

Fortunately, many regulators of various countries of the European electrical system are currently writing this legislation.
Conclusion

- TSO
- DSO
- FSP
- BRP
- Producer
- Big consumer
- Small consumer
- Market operator
- Retailer

Big consumer
Producer
Market operator
Retailer

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Further information

in the thesis:

S. Mathieu, “Flexibility services in the electrical system,”

and in the corresponding papers:


