Optimization needs and challenges from operational planning to operation of large transmission systems
an European TSO perspective

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Optimization issues for large European electricity networks: from D-2 to Real time

- European power system
  - RTE overview
- Context & Needs
- Challenges
- Possible solutions
- Conclusions
European power system

34 interconnected countries
- Security of the European power system
- Economical optimization

4 synchronous areas
- Installed capacity ~ 880 GW
- Annual consumption ~ 3200 TWh
- Annual exchanges ~ 380 TWh
- 300 000 km of lines
- ~ 530 millions inhabitants

41 Transmission System Operators

Fast and continuous increases of cross-boarder exchanges and interconnection capacities
RTE is the French Transmission System Operator.

**RTE owns and operates** the largest electricity grid in Europe:

- 100 000 km of EHV and HV lines
- French peak load served > 100 GW (60+ million inhabitants)
- 41 interconnection power lines
  - Balance: 44,2TWh export (2012) ≈ 12 GW.year
- 8500 staff

**Financial figures**

- Turnover: 4 529 million € (2012)
- Annual Investment: 1 357 million € (2012)
Growth of renewable generation installed capacity all over EU: Less predictable, less controllable, less observable

Wind energy
- DE: 29 GW, ES: 22 GW (2011)
- France: 7.4 GW installed capacity
- French target: 25 GW in 2020 (6 GW offshore)

PV-solar energy
- DE: 32 GW, IT: 16.5 GW (2011)
- France: 3.5 GW installed capacity
- French target: 5.4 GW in 2020
**Growth of electricity demand peaks**: French electrical heating!

- New usages of electricity: EV, Electrical Heating using heat pump could continue to increase electrical consumption peaks
- Demand Response and storage could help but will require a rethinking of current operating practices.

![Daily load curve before and during cold wave](image1)

![Differences between annual max. and min. power](image2)
Increasing difficulties for the development of network infrastructures (Overhead power lines)

• NIMBY $\rightarrow$ transmission infrastructure no longer seen as positive, and highly resisted by locals

• NOCEBO $\rightarrow$ despite all evidence, fear that long term exposure to low frequency EMF could generate health trouble is on the rise

• A multi-layer administrative and regulatory framework (power devolution to region and counties, etc.) $\rightarrow$ permits increasingly difficult to obtain

<table>
<thead>
<tr>
<th>Country</th>
<th>Mean duration to build new lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>3</td>
</tr>
<tr>
<td>Belgium</td>
<td>5</td>
</tr>
<tr>
<td>Danmark</td>
<td>2,5</td>
</tr>
<tr>
<td>Finland</td>
<td>5</td>
</tr>
<tr>
<td>France</td>
<td>6,5</td>
</tr>
<tr>
<td>Germany</td>
<td>10</td>
</tr>
<tr>
<td>Greece</td>
<td>6</td>
</tr>
<tr>
<td>Poland</td>
<td>4</td>
</tr>
<tr>
<td>Portugal</td>
<td>2</td>
</tr>
<tr>
<td>Sweden</td>
<td>7</td>
</tr>
</tbody>
</table>

Up to 7 years of consultation before having a chance to get necessary permits (and then build...
Developing grids: need for new answers, more complex and expensive

- Most new circuits from 50 to 225 kV underground
- Use of long AC 225 kV underground even far from urban areas (e.g. new project for securing supplies in the French Riviera)
- HVDC underground (and tunnels) as an alternative to 400 kV overhead lines (France-Spain, France-Italy ...), even for distances as short as 60 km
- Upgrade use of existing corridors of overhead 400 kV with high temperature conductors (HTLS...), Phase-Shifter Transf., FACTS
- Advanced measurement, monitoring and controls
  - PMUs, DLR, Post-fault actions (SPS, ...
In the past:

**European power system:**

- was optimised at the national scale
- Transmission grid was designed together with domestic generation by vertically-integrated monopolies

Cross-border interconnection lines mainly to allow mutual support between countries
A paradigm shift:

European power system is
- progressively optimised at the European scale to benefit from complementarities in generation mixes
- allowing competition in a deregulated generation business
- contributing to the Security of Supply both in the short and long term at the EU level

Cross-border interconnection lines main purpose enable system optimisation through competition
- Optimization which maximizes the use of grid assets, pushing the system to its limits.
TSO DECISION MAKING PROCESSES

New simulation/optimization problems

A complex multi stage decision making process: Sliding window, from 2 days ahead to real time

- Minimizing costly strategic and preventive decisions taking into account uncertainties and corrective actions for a large system (large number of contingencies).
New tools are required to help the operators to make decisions in all stages on this complex process:

- Large size system: Pan European, all probable contingencies
- Dynamic behavior: Possible unstable phenomena (less margin)
- More accurate modeling of all system’s components: *discrete behavior*
- Corrective actions associated with constraint violations
- Taking into account uncertainties *(and their correlations)*

Ideally, all together ....
Challenge: System Size

*Electrical phenomena don’t stop at administrative borders*

Some figures about the problem size

**Continental European Synchronous EHV network** (above 100 kV). Aggregated generations and loads

- 10000 Buses
- 15000 Power lines
- 2500 Transformers (80 PSTs)
- 3000 Generators
- 5000 Loads (with capacitor banks)
- 10 HVDC Links

**Optimization problem: for one state**

- State variables : 20000
- Constraints : 64500
- Continuous controls : 6000
- Discrete controls : 10500 (subset)
- “N-1” power lines $\Rightarrow$ **15001 states** $\approx$ 300 $10^6$ variables
Challenge: System dynamic behavior

- Corrective actions: post-fault steady state depends on the trajectory

- Possible unstable phenomena (less margin)

✓ Time domain simulation of the Pan-European model: a tough mathematical problem
  - Very large system (around 125,000 state variables)
  - Non-linear, stiff, oscillating, poorly damped, discontinuous…

✓ Poorly damped inter-area power oscillations can occur in large synchronous power system
  - Impossible to predict using only a local vision
Challenge: Modeling of discrete behavior of equipments

• The problem
  – A large share of equipments have a discrete behavior
    - Breakers (open/close)
    - Tap of transformers (PST)
    - Status of generators (on/off)
    - Switching of capacitor banks
  – Realistic modeling of equipment is required to make robust decisions
  – Over simplified modeling could lead to unrealistic states

This is an intractable problem for a such large size system
Challenge: Post-Fault actions

Corrective actions

• From preventive to corrective controls: full preventive mode not anymore possible or too costly. Priority of corrective actions.

• Installation of controls or modification of operating rules to act just after a contingency,

• Example: PST control in case of overloaded line

  Each 10 seconds
  \[
  \text{If } (I > I_{\text{max}}) \text{ then change one tap of the PST}
  \]

• Corrective actions are conditional: associated with constraint violations and not trigged unconditionally after a fault
Uncertainties (and their correlations)

• Risk based optimization could be the ultimate solution
  ✓ Very complex
  ✓ Operators are a bit reluctant to make decisions based on probabilistic approaches, they prefer a binary answer: secure or unsecure

• First step: “worst-case” approach useful to anticipate possible unsecure states of the system. A screening method by contingency.
  ✓ All stochastic inputs: uncontrollable generations (wind power, PV) and loads (uncontrollable ones) are considered,
  ✓ Check the existence of at least one initial state (among all possible ones, uncertain injections)
    ▪ for which the post-contingency, post-fault & corrective state is outside acceptable limits for the considered contingency
    ▪ by maximizing the violations of these limits

Challenge:
Possible solutions:

**Mixed Integer Non Linear Programming (MINLP)**

**Worst case approach** (Screening method)
Initially, all integer restrictions are relaxed and the resulting NLP relaxation is solved.

- Binary variables => Continuous variables // $x = 0 \text{ or } 1 \Rightarrow 0 \leq x \leq 1$
- Minimum found is lower than the one considering integer restrictions

Selection of an integer variable (Heuristic): variables that “changes the problem the most”

Branching on is achieved by creating two new NLP problems with a fixed value for the selected integer variable (0 and 1)
Non convexity of optimization problems in power systems

Convex set

Non Convex set

Equality constraints => non convexity

in each bus: $\sum I(V) = 0$

Solutions live on the boundary: Obviously a non convex set
MINLP: Handling of discrete variables:
non linear **non convex** optimization / Strong branching fails

When the objective or the constraints are **not** convex functions then standard algorithms to solve NLP are able to guarantee convergence only to a **local minimum**.

Thus the solution of the relaxations does **not provide a lower bound** for the characterization of dominated nodes.

In case of large non convex problems, the CPU time spent to diagnostic infeasibility becomes prohibitive and generally leads to the failure of branch an bound solvers (see Prof. P. Bonami’s recommendations, BONMIN author)
Possible Relaxation:
Mathematical Programming with Equilibrium Constraints: MPEC

→ Idea: \((x-v_1)(x-v_2) = 0 \iff x=v_1\text{ or } x=v_2\)

- A more general class of optimization problems (larger than MINLP)

\[
\begin{align*}
\text{minimize} & \quad f(x) \\
\text{subject to} & \quad c(x) \geq 0 \\
& \quad 0 \leq x_1 \perp x_2 \geq 0
\end{align*}
\]

\[
\begin{align*}
\text{minimize} & \quad f(x) \\
\text{subject to} & \quad c(x) \geq 0 \\
& \quad x_1, x_2 \geq 0, X_1x_2 \leq 0
\end{align*}
\]

where \( x = ( x_0, x_1, x_2 ) \) and \( \perp \) is the \text{complementary operator} which requires that either a component \( x_{1i} = 0 \) or the corresponding component \( x_{2i} = 0 \)

\[
\begin{align*}
\text{minimize} & \quad f(x) \\
\text{subject to} & \quad c(x) \geq 0 \\
& \quad x_1, x_2 \geq 0, X_1x_2 \leq 0
\end{align*}
\]

where \( X_1 = \text{diag}(x1) \)

Unfortunately, it has been shown that \text{the domain } x_1, x_2 \geq 0, X_1x_2 \leq 0 \text{ has no interior but adaptations of Interior Point Methods often works } \ldots
POSSIBLE SOLUTIONS for MINLP

Conclusions for large systems

- Existing MINLP solvers can’t reliably solve non convex problems. NLP relaxed sub problems don’t provide a lower bound of the solution of the original problem.

- In our experiments, we found that MPEC constitute the only “practical” alternative for very large scale MINLP problems:
  - Sub-optimal solutions for non convex MINLP problems.
  - But at least, the feasibility of the solution is ensured

- Any new idea about convex relaxations could be very useful
Online security assessment: Illustration of the “worst case” approach

As a screening method
Contingency ranking with respect to overloads in very large power systems taking into account uncertainty, preventive and corrective actions (TPWRS paper)

• The proposed approach
  – Using a DC approximation: a sequence of very large Mixed Integer Linear Programming problems
  – Ranking of contingencies severity into 4 clusters whatever the uncertainties
    1. Contingencies which don’t require preventive or corrective actions
    2. Contingencies which require only corrective actions
    3. Contingencies which require corrective and preventive actions
    4. Contingencies for which the security of the system can’t be ensured using the defined preventive and corrective control schemes
  – Operators have to pay attention in priority to contingencies in cluster 4, then in 3 and 2
Conclusions

• Power systems are complex systems (System of Systems).
• This complexity is increasing and will continue to increase:
  ✓ Distributed intelligence (smartgrid?). TSO: at substation level
  ✓ Data/measurement based methods (pattern recognition vs. electrical physical models) to cope with partial information, complex behavior ...
  ✓ Operator mission: “man in the loop”
    ▪ From pilot to navigator: setting of automatic pilots
  ✓ Taking advantage of HPC and advanced telecommunication solutions
THANKS FOR YOUR ATTENTION!

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