A progressive method to solve large-scale AC Optimal Power Flow with discrete variables and control of the feasibility

Manuel Ruiz, Jean Maeght, Alexandre Marié,
Patrick Panciatici and Arnaud Renaud
manuel.ruiz@artelys.com

MOTIVATIONS

The iTesla project

- Pan-European R&D project :
  - Security assessment on large scale power networks by means of security rules
  - Coordinated by RTE (Réseau de Transport d'Electricité)
  - Includes 6 European TSOs, 13 R&D companies and academic partners
  - Official website: http://www.itesla-project.eu/

Offline platform

- Sampling of network states
- Infeasible states detected through steady-state optimization
- Unstable states detected through dynamic optimization
- Data mining on the results

Every week

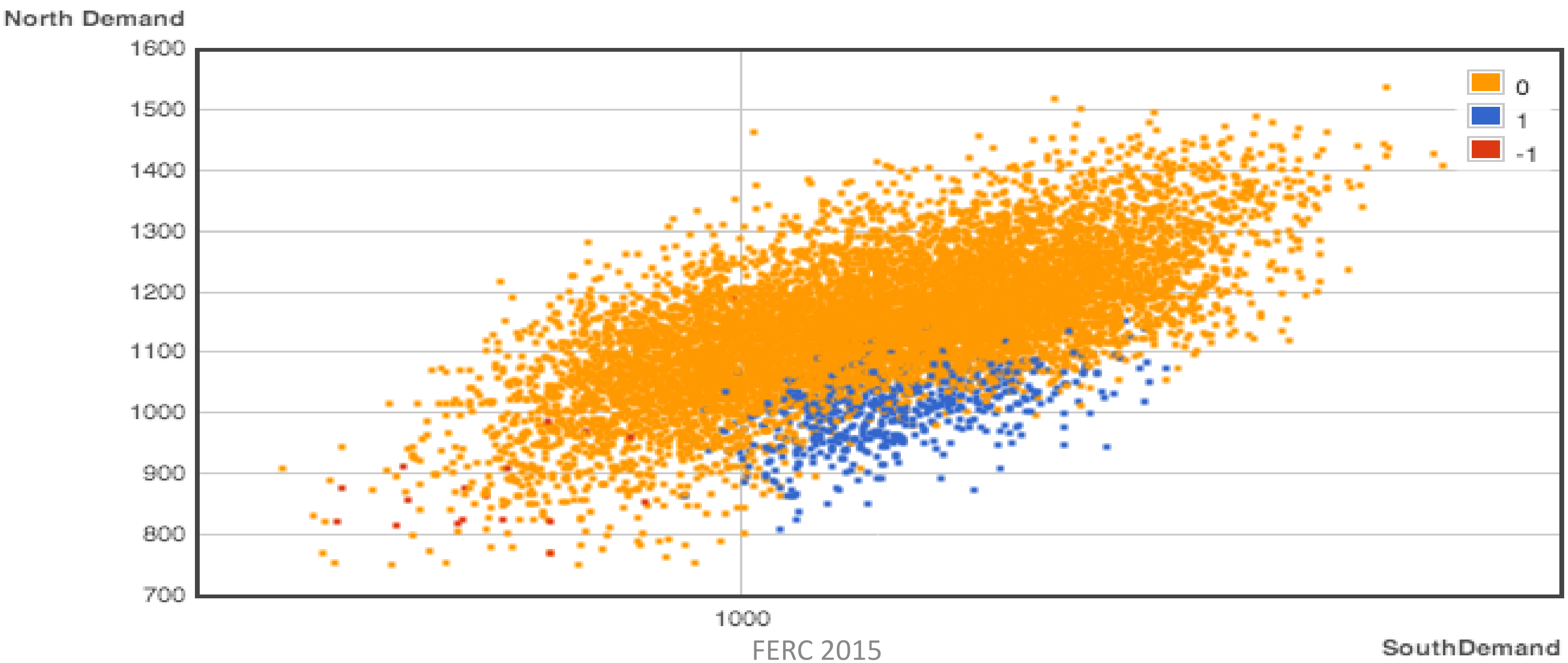
Online platform

- Data acquisition from European TSOs (24 hour forecasts)
- Data merging
- Security assessment
- Recommendation for the operators

Every day

A sampling example

- Power System network with 2 loads (NORTH and SOUTH)
- Generated from historical data, sampled cases are to be analyzed
  - Sampled data are loads or fixed injections (including renewable generation)
  - Steady state, Unstable state or Unknown
- Screening rules describing the boundary between stable and unstable are then extracted from the analysis of the sampled cases



Topic of the talk

- Monte Carlo simulations provide us with thousands of samples (partial network situations)

- Our aim is to build up the complete state for each sample:
  - To assess feasibility
  - To identify the sample parameters that cause infeasibilities
  - While having a realistic and detailed representation of the network

- Specificity of the mathematical problem
  - Non linear
  - Without any guarantee of feasibility (due to sampling)
  - With discrete aspects (rigorous description of the power system network)
  - Large scale network (target is European network)

MATHEMATICAL FORMULATION EXTENDED OPTIMAL POWER FLOW

Common Optimal Power Flow

- The power system network is described using buses and branches:
  - Loads and production units are set up on buses.
- AC formulation using voltage and production levels:
  - Induces active and reactive non linear power balances,
  - Allows computation of active power losses.
- Security constraints:
  - Bounds on voltage magnitude,
  - Upper bounds on currents (thermal limits).

Lines with PST

- Phase-Shifting Transformers are used to adjust the voltage ratio and the difference in the phase angle.

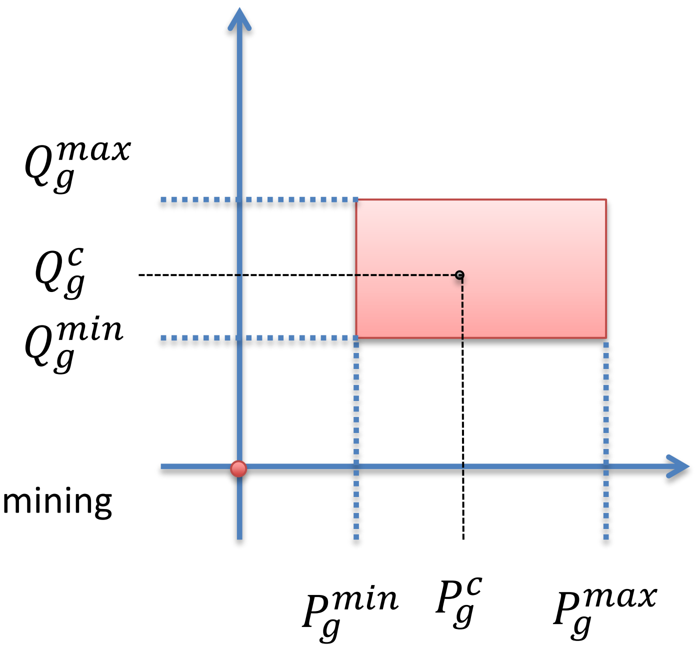
- Operating points of PST are to be chosen in a set of discrete configurations defining:
  - Reactance,
  - Voltage ratio and the difference in the phase angle.

- Using the admittance matrix Y_j of operating point j, the model simply reads:
  - $Y = \sum_{\mathrm{j}} \lambda_j Y_j$,
  - $\sum_{\mathrm{j}} \lambda_{\mathrm{j}} = 1,\ \lambda_{\mathrm{j}} \in \{0; 1\}$.

Production units

- Commitment of production unit
  - Active and reactive power injection are bounded when the unit is switched on
  - Given set production levels are to be reached

- Commitment constraints for unit g
  - p_g, q_g: active and reactive injections
  - $is\_on_g \in \{0; 1\}$
  - $is\_on_g \begin{bmatrix} P_g^{min} \\ Q_g^{min} \end{bmatrix} \leq \begin{bmatrix} p_g \\ q_g \end{bmatrix} \leq is\_on_g \begin{bmatrix} P_g^{max} \\ Q_g^{max} \end{bmatrix}$



- Definition of the over active injection level:
  - P_g^c: set value of active injection computed using data mining
  - p_g^{add}: active over injection defined by
  - $p_g \leq P_g^c + p_g^{add}$ pour chaque groupe g

- The criterion is defined as $\sum_{g \in Units}(p_g + p_g^{add})$

Other aspects

- Compensation units with similar attributes can be activated at some nodes
  - $-V_n^2 \cdot nb_n^{shunt} \cdot B_n^{shunt}$: reactive injection in power balance
  - nb_n^{shunt}: number of activated devices
  - B_n^{shunt}: value of the attribute for one unit

- The main objective is to build a realistic feasible solution to be able to launch dynamic simulation
  - Reduce active power losses
  - Reduce the deviation to set production levels

- The network topology is given as an input
  - Ongoing work to optimize the topology

SOLVING APPROACH
CUSTOM DECOMPOSITION STRATEGY

Diagnosis of feasibility

- Sampling may have produced infeasible situations in terms of loads and fixed injections:
  - Fixed injection or loads too high on a node,
  - Current intensity level too low on a line.

- Optimal power flows:
  - Slack variables in power balances or constraints related to thermal limits
  - Continuous relaxations of discrete aspects using $x \in \{0; 1\} \Longrightarrow x \in [0,1]$:

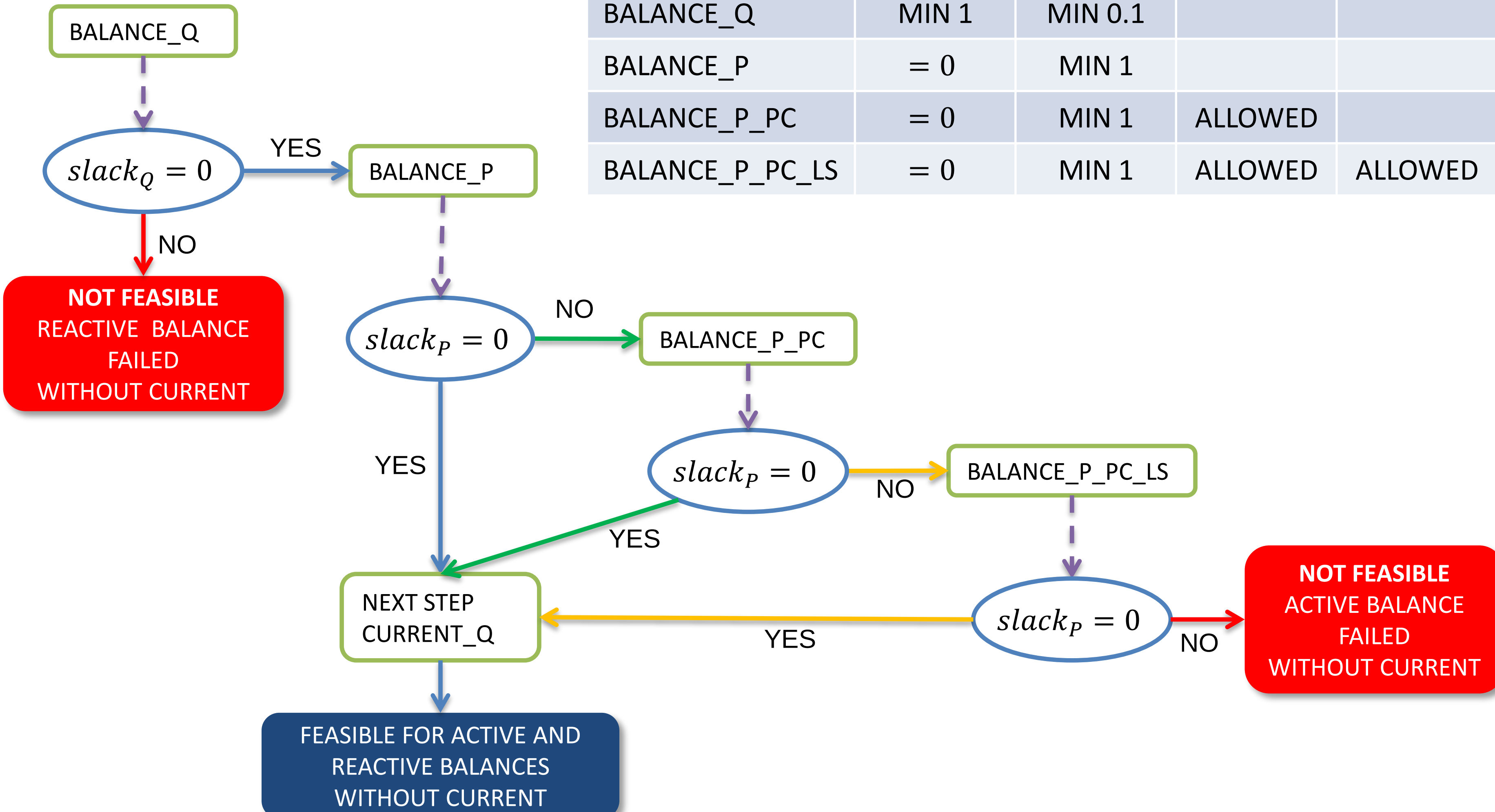
- The resulting NLP are solved with KNITRO using an interior point method for non linear programming.

- When necessary, fixed injections can be modified:
  - Production curtailment of fatal production unit (PC)
  - Load shedding (LS)

- Whenever LS is used the instance is considered as not feasible
  - In such a case, results analysis can be used to correct the sampling (high loads or renewable productions)

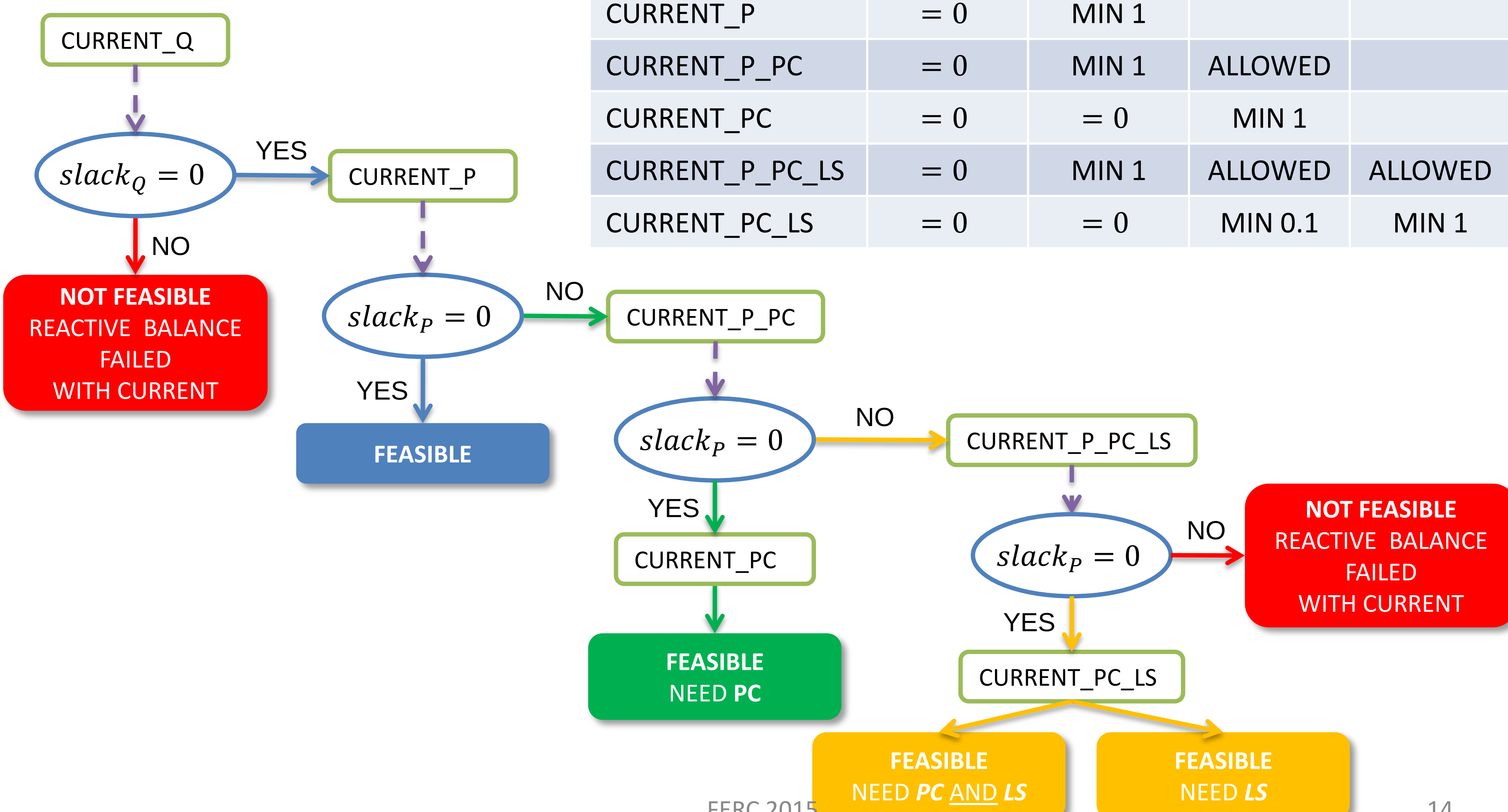
WITHOUT LIMIT

STEP	$slack_Q$	$slack_P$	*PC*	*LS*
BALANCE_Q	MIN 1	MIN 0.1		
BALANCE_P	$= 0$	MIN 1		
BALANCE_P_PC	$= 0$	MIN 1	ALLOWED	
BALANCE_P_PC_LS	$= 0$	MIN 1	ALLOWED	ALLOWED



WITH LIMIT

STEP	$slack_Q$	$slack_P$	*PC*	*LS*
CURRENT_Q	MIN 1	MIN 0.1		
CURRENT_P	$= 0$	MIN 1		
CURRENT_P_PC	$= 0$	MIN 1	ALLOWED	
CURRENT_PC	$= 0$	$= 0$	MIN 1	
CURRENT_P_PC_LS	$= 0$	MIN 1	ALLOWED	ALLOWED
CURRENT_PC_LS	$= 0$	$= 0$	MIN 0.1	MIN 1



Building up a feasible solution

- Discrete aspects are handled separately.
- Resolution of MINLP is based on a MPEC reformulation that can be directly handled by KNITRO.
  - $x \in \{0; 1\} \Leftrightarrow x = 0 \; or \; 1 - x = 0 \Leftrightarrow 0 \leq x \; \perp 1 - x \geq 0$
- KNITRO then treats MPEC as a NLP.
  - Defining the constraint $x \geq 0$ and $1 - x \geq 0$
  - Adding a penalty term $\Pi \cdot x(1 - x)$ in the objective
  - Iteratively updating the penalty weight Π to converge to a locally optimal solution.

Decomposition strategy

Discrete aspects
- MPEC reformulation
- Continuous relaxation
- Fixed

Feasibility phase
- PST configuration
- Unit commitment
- Shunt commitment

- Detection of infeasibilities using slack variables

PST setting
- PST setting
- Unit commitment
- Shunt commitment

- Starting from the solution of the feasibility phase

Unit commitment
- PST setting
- Unit commitment
- Shunt commitment

- Starting from the solution of the PST phase

Shunt commitment
- PST setting
- Unit commitment
- Shunt commitment

- Starting from the solution of unit commitment

COMPUTATIONAL RESULTS

Dataset description (1)

- FR-THT: Very High Voltage (VHV) French transmission network.
- 1600 substations, 1900 buses, 2700 branches.
- On average 7000 variables and 7500 constraints after presolve. Jacobian size is over 43 000 non zero elements and the hessian matrix 15 000.
- MPEC reformulations consist in 83(PST step), 112(UNIT step) and 1384(SHUNT step) complementarities.
- Each problem is solved by KNITRO with less then 10s.

Dataset description (2)

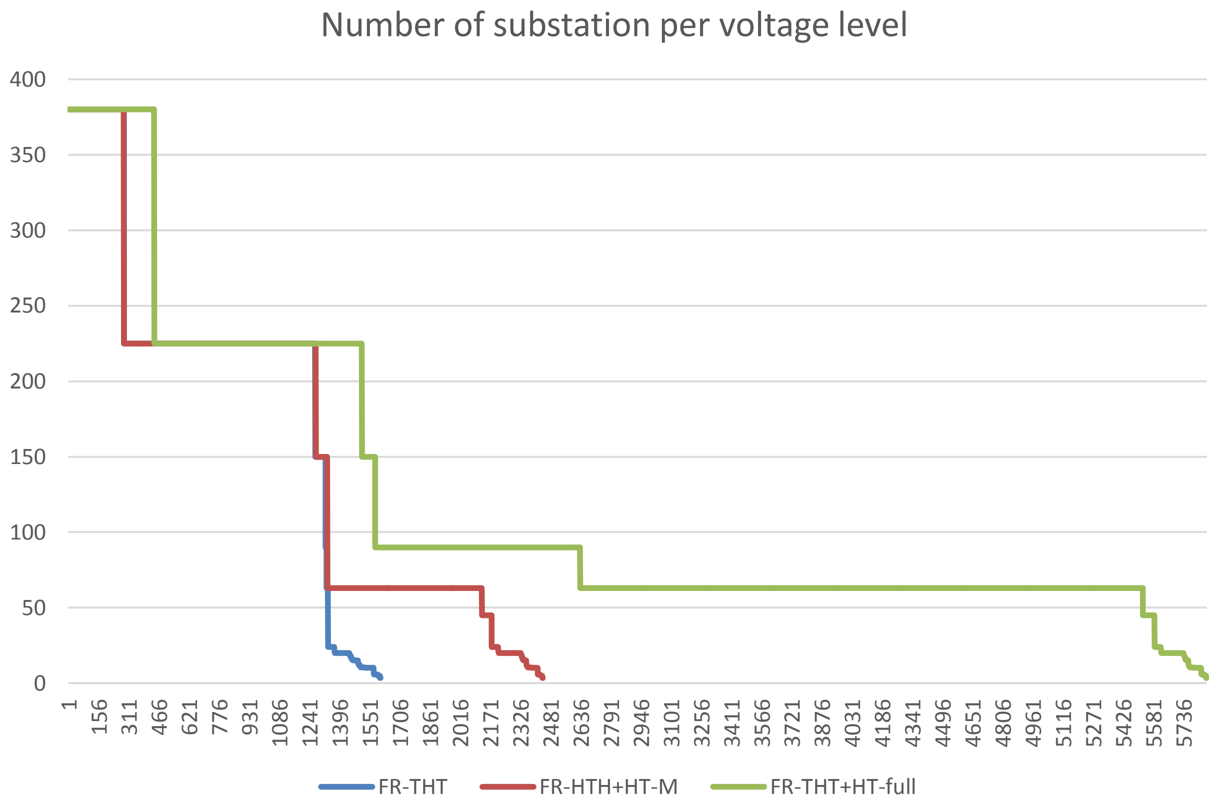
- FR-THT-HT-M: Very High Voltage French transmission network, High Voltage (HV) transmission area of Marseilles.
- 2400 substations, 2800 buses, 4060 branches.
- On average 13K variables and 12K constraints after presolve. Jacobian size is over 60 000 non zero elements and the hessian matrix 20 000.
- MPEC reformulations consist in 130(PST), 135(UNIT) and 6681(SHUNT) complementarities.
- During the feasibility phase each problem is solved by KNITRO with less then 10s. MPEC reformulation are solved within 1 or 2 minutes.

Dataset description (3)

- FR-THT-HT-full: Very High Voltage network and the whole High Voltage (HV) transmission network for France; a guard ring is added, with a few buses representing a simplified version of the neighborhood of France.
- 5857 substations, 6471 buses, 9831 branches.
- On average 36K variables and 30K constraints after presolve. Jacobian size is over 200K non zero elements and the hessian matrix 50K.
- MPEC reformulations consist in 355(PST), 174(UNIT) and 24018(SHUNT) complementarities.
- During the feasibility phase each problem is solved by KNITRO with less then 40s. MPEC reformulation are solved within less than 3 minutes.

Remarks on nominal voltage

- Each instance address a very different kind of power system with different voltage levels



Conclusion

- The problem of solving extended OPF with no guarantee on feasibility is addressed.
- A custom methodology is designed. It includes feasibility diagnosis and resolution of several OPF with discrete variables.
- The MPEC reformulation of MINLP is successfully applied and computational results obtained are promising.
- We are currently working on experimentations on European scale.

QUESTIONS ?