Two contributions for optimisation of the electric system with high share of renewable production

R. Girard

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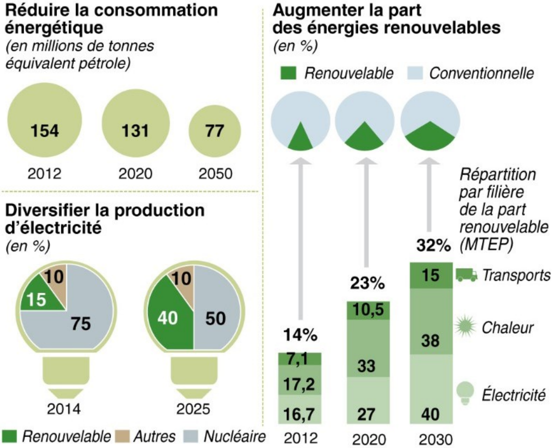
Content

Context : energy transition

- Energy transition law



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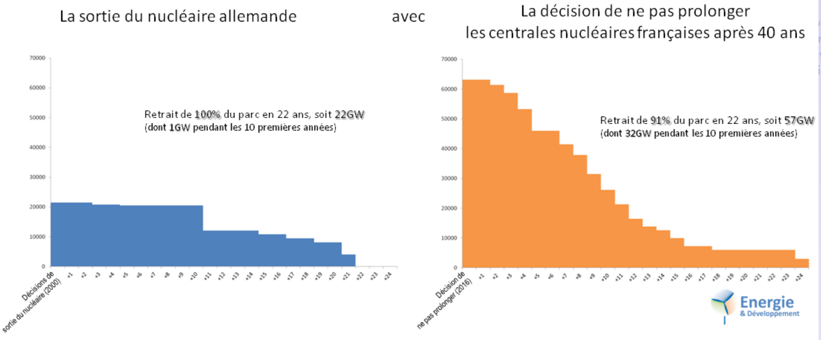
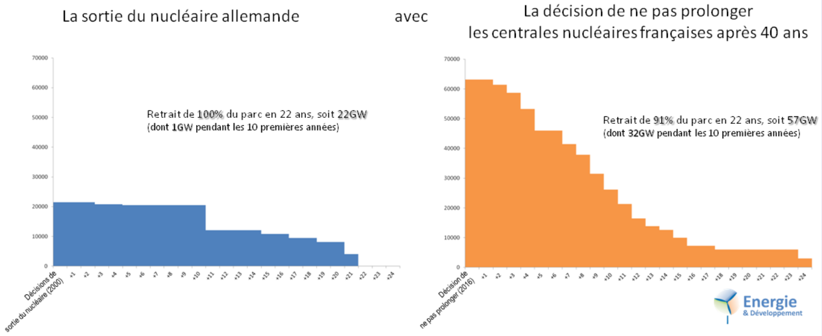


Context : energy transition

- Energy transition law
- The Nuclear french parc is getting old and was all built in a short period (15 years).
- New nuclear is an option that is economically a huge risk (e.g. Hinkley point : 22 billion euros, 3300 MW, 110 euros/MWh). Renewable is much cheaper (wind 80 euros/MWh, PV around 60 euros/MWh).



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- We have shown that it is possible to have 100% renewable in 2050 (ADEME study) with a cost equivalent to 40% Renewable.

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- We have shown that it is possible to have 100% renewable in 2050 (ADEME study) with a cost equivalent to 40% Renewable.
- Some aspect still need to be studied in more detail.
  - Distribution network
  - Primary reserve
  - European scale optimisation
  - ...

Content

General version of the problem

$$\min_{x\in\mathbb{R}^n} \quad \sum_{i=1}^n C_i(x_i) \qquad (1)$$

$$s.t. \quad \left\{ \begin{array}{cc} lb_i \leq x_i \leq ub_i & i=1,..,n \\ lbC_i \leq \sum_{j=1}^i x_j \leq ubC_i & i=1,..,n \end{array} \right.$$

where lbC,$ulbC$, lb and ub vectors of $\mathbb{R}^n$, and C_i $(i=1\dots,n)$ cost functions

General version of the problem

$$\min_{x \in \mathbb{R}^n} \sum_{i=1}^{n} C_i(x_i) \tag{1}$$

$$s.t. \quad \begin{cases} lb_i \leq x_i \leq ub_i & i = 1, .., n \\ lbC_i \leq \sum_{j=1}^{i} x_j \leq ubC_i & i = 1, .., n \end{cases}$$

where lbC,$ulbC$, lb and ub vectors of $\mathbb{R}^n$, and C_i $(i = 1 \ldots, n)$ cost functions

Result : If C_i are convex piecewise linear functions this can be solved

- in quasi linear time in n
- without approximation
- Package implemented in the R sofware, freely available CRAN.

Recurrence equation of Bellman type and Algorithm

Let us define $D_k(z)$, for $k \in \mathbb{N}_n^*$:

$$D_k(z) = \min\left(\sum_{i=1}^{k} C_i(x_i)\right) \quad (2)$$

$$s.t. \begin{cases} x_i \in [lbP_i; ubP_i] & i = 1,..,k \\ \sum_{j=1}^{i} x_j \in [lbC_i; ubC_i] & i = 1,..,k-1 \\ \sum_{j=1}^{k} x_j = z \end{cases}$$

- **Interpretation** : z storage level at time step k
- easy reccurence equation on D_k
- **Algorithm** :
  - **Step 1** for $k = 1..K$ compute D_k with the reccurence equation
  - **Step 2** for $k = K..1$ compute z_k^* the optimal state of storage at time k

Reccurence equation with elementary operations

Equations of the algorithm :

$$D_i(z) = (D_{i-1}[lbC_i, ubC_i]) \Box (C_i[lbP_i, ubP_i])$$

$$f = \oslash \left[D_i[lbC_i, ubC_i], z^*_{i+1}\right] + C_{i+1}[lbP_{i+1}, ubP_{i+1}]$$

$$z^*_i = \text{Argmin} f$$

Elementary operations :

$$InfConv \quad : \quad (f \Box g)(x) = \min_{y \in \mathbb{R}} \{f(x-y) + g(y)\}$$

$$Squeeze \quad : \quad f[a,b](x) = \begin{cases} f(x) & \text{if} \quad x \in [a,b] \\ +\infty & \text{otherwise} \end{cases}$$

$$SWAP \quad : \quad (\oslash[f,y])(x) = f(y-x)$$

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Introduction

Contribution to the temporal problem

Optimisation problem and Bellman Equation

Tricks toward the algorithm

Contribution to the optimisation for active distribution network (ADN) simulation

The case of convex piecewise linear functions

- Set of convex piecewise linear function is stable by these operations. An element of this set is described by :
  - a vector of slopes (or increase between consecutive slopes)
  - a vector of breakpoints

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- Set of convex piecewise linear function is stable by these operations. An element of this set is described by :
  - a vector of slopes (or increase between consecutive slopes)
  - a vector of breakpoints
- All these operations can be done with low computational cost
  - SWAP : change offset and read the slopes/Breakpoints vectors in reverse.
  - Sum(n, m), insertion of m points in an ordered chain of n points.
  - Squeeze, two insertions in an ordered chain ofn points.
  - InfConv, $f \square g = (f^* + g^*)^*$ legendre transform "$*$" is juste an inversion of Breakpoints and Slopes !

The case of convex piecewise linear functions

- Set of convex piecewise linear function is stable by these operations. An element of this set is described by :
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Package implemented in R/Cpp ConConPiWiFun available on CRAN

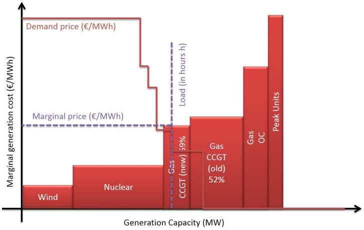
Empirical comparison with CPLEX :

n	100	1000	5000	10^4	10^5	10^6
dyn.prog. [ms]	0.34	3.06	28.8	61.5	649.2	6285
CPLEX [ms]	4.31	724	63579	NC	NC	NC

Robin Girard, Vincent Barbesant, Fiona Foucault, and Georges Kariniotakis. Fast dynamic programming with application to storage planning. In IEEE PES T & D Conference and Exposition, 2014.

Application for market price simulation with storage constraint

- Several other applications in the paper.
- Here simulation of market prices, taking into account a stock.
- temporal constraint on one of the production mean



$$\min \sum_{i=1}^{n} \pi_{it} P_{it} + P_t^s$$

$$\sum_i P_{it} = NC_t$$
$$0 \geq \sum_i P_t^s + \epsilon_t \leq C$$
$$\forall i, \quad 0 \leq P_{it} \leq P_{it}^{\max}$$

Content

Examples of questions asked today in the industry

- Dimensioning the PV connection with a power lower than P_{peak}.
  - Intensity constraints : Pmax, curtailment, demand side management, storage, . . .
  - Voltage constraints : reactive power injection, on load tap changer, ...
- Storage : centralized Vs de-centralized
- Operation : centralized Vs de-centralized, coordination between DSO/TSO
- Distance between mathematical optimum and the optimum in a liberalized system.

2 kinds of approaches to answer these questions

- Load flow in different cases (limited)
- Optimal power flow

Formulation simple OPF

$$\min \sum_{i=1}^{N^{Nodes,j}} \left|P_{i,t}^{IP,MP,j} - P_{i,t}^{IP,j}\right| + \left|P_{i,t}^{ST,MP,j} - P_{i,t}^{ST,j}\right| + \sum_{i=1}^{N^{Nodes,j}} r_i^j l_{i,t}^j$$

Objective function

- Max revenu on a market
- Min the distance to a set point (i.e. sent by the centralized system, auto-consumption, . . .)
- loss minimization

Formulation simple OPF

$$\min \sum_{i=1}^{N^{Nodes,j}} \left|P_{i,t}^{IP,MP,j} - P_{i,t}^{IP,j}\right| + \left|P_{i,t}^{ST,MP,j} - P_{i,t}^{ST,j}\right| + \sum_{i=1}^{N^{Nodes,j}} r_i^j l_{i,t}^j$$

$$P_{i,t}^j - r_i^j l_{i,t}^j - \sum_{k \in c(i)} P_{i,t}^j - P_{i,t}^{Load,j} + P_{i,t}^{ST,j} + P_{i,t}^{IP,j} = 0$$

$$Q_{i,t}^j - x_i^j l_{i,t}^j - \sum_{k \in c(i)} Q_{i,t}^j - Q_{i,t}^{Load,j} + Q_{i,t}^{ST,j} + Q_{i,t}^{IP,j} = 0$$

$$U_{f(i),t}^j - U_{i,t}^j - 2\left(r_i^j P_{i,t}^j + x_i^j Q_{i,t}^j\right) + {z_i^j}^2 l_{i,t}^j = 0$$

Power flow constraints for radial network

- Active/reactive power of storage, prod, demand, market import/export,. . .)
- On load tap changer

Formulation simple OPF

$$\min \sum_{i=1}^{N^{Nodes,j}} \left|P_{i,t}^{IP,MP,j} - P_{i,t}^{IP,j}\right| + \left|P_{i,t}^{ST,MP,j} - P_{i,t}^{ST,j}\right| + \sum_{i=1}^{N^{Nodes,j}} r_i^j I_{i,t}^j$$

$$P_{i,t}^j - r_i^j I_{i,t}^j - \sum_{k \in c(i)} P_{i,t}^j - P_{i,t}^{Load,j} + P_{i,t}^{ST,j} + P_{i,t}^{IP,j} = 0$$

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$$I_{i,t}^j \leq I_i^{max,j}$$

$$V_j^{min} \leq V_{i,t}^j \leq V_j^{max}$$

Network constraints (Intensity/Voltage)

Formulation simple OPF

$$\min \sum_{i=1}^{N^{Nodes,j}} \left|P_{i,t}^{IP,MP,j} - P_{i,t}^{IP,j}\right| + \left|P_{i,t}^{ST,MP,j} - P_{i,t}^{ST,j}\right| + \sum_{i=1}^{N^{Nodes,j}} r_i^j I_{i,t}^j$$

$$P_{i,t}^j - r_i^j I_{i,t}^j - \sum_{k \in c(i)} P_{i,t}^j - P_{i,t}^{Load,j} + P_{i,t}^{ST,j} + P_{i,t}^{IP,j} = 0$$

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$$I_{i,t}^j \leq I_i^{max,j}$$

$$V_j^{min} \leq V_{i,t}^j \leq V_j^{max}$$

$${P_{i,t}^{ST,j}}^2 + {Q_{i,t}^{ST,j}}^2 \leq {S_i^{max,ST,j}}^2$$

$${P_{i,t}^{IP,j}}^2 + {Q_{i,t}^{IP,j}}^2 \leq {S_i^{max,IP,j}}^2$$

Inverter apparent power

Formulation simple OPF

$$\min \sum_{i=1}^{N^{Nodes,j}} \left|P_{i,t}^{IP,MP,j} - P_{i,t}^{IP,j}\right| + \left|P_{i,t}^{ST,MP,j} - P_{i,t}^{ST,j}\right| + \sum_{i=1}^{N^{Nodes,j}} r_i^j l_{i,t}^j$$

$$P_{i,t}^j - r_i^j l_{i,t}^j - \sum_{k \in c(i)} P_{i,t}^j - P_{i,t}^{Load,j} + P_{i,t}^{ST,j} + P_{i,t}^{IP,j} = 0$$

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$$U_{f(i),t}^j - U_{i,t}^j - 2\left(r_i^j P_{i,t}^j + x_i^j Q_{i,t}^j\right) + z_i^{j\,2} l_{i,t}^j = 0$$

$$l_{i,t}^j \leq l_i^{max,j}$$

$$V_j^{min} \leq V_{i,t}^j \leq V_j^{max}$$

$$P_{i,t}^{ST,j\,2} + Q_{i,t}^{ST,j\,2} \leq S_i^{max,ST,j\,2}$$

$$P_{i,t}^{IP,j\,2} + Q_{i,t}^{IP,j\,2} \leq S_i^{max,IP,j\,2}$$

$$l_{i,t}^j = \frac{P_{i,t}^{j\;2} + Q_{i,t}^{j\;2}}{U_{f(i),t}^j}$$

Variable change

Formulation simple OPF

$$\min \sum_{i=1}^{N^{Nodes,j}} \left|P_{i,t}^{IP,MP,j} - P_{i,t}^{IP,j}\right| + \left|P_{i,t}^{ST,MP,j} - P_{i,t}^{ST,j}\right| + \sum_{i=1}^{N^{Nodes,j}} r_i^j l_{i,t}^j$$

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$$l_{i,t}^j = \frac{{P_{i,t}^j}^2 + {Q_{i,t}^j}^2}{U_{f(i),t}^j}$$

Non convexity

Convex relaxation

Non-convexity :

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No algorithm exists with global convergence guarantee

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Relaxation :

$$l_{f(j),j} U_{f(j)} \geq {P_{f(j),j}}^{2} + {Q_{f(j),j}}^{2}$$

Convex relaxation

Non-convexity :

$$I_{i,t}^{j} = \frac{{P_{i,t}^{j}}^{2} + {Q_{i,t}^{j}}^{2}}{U_{f(i),t}^{j}}$$

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$$I_{f(j),j} U_{f(j)} \geq {P_{f(j),j}}^{2} + {Q_{f(j),j}}^{2}$$

Solvable in polynomial time

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Non-convexity :

$$I^j_{i,t} = \frac{{P^j_{i,t}}^2 + {Q^j_{i,t}}^2}{U^j_{f(i),t}}$$

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Relaxation :

$$I_{f(j),j} U_{f(j)} \geq {P_{f(j),j}}^2 + {Q_{f(j),j}}^2$$

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Relaxation may be inexact :

$$I_{f(j),j} U_{f(j)} > {P_{f(j),j}}^2 + {Q_{f(j),j}}^2$$

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Power flows obtained may not be physically meaningful

Illustration of Inexact Relaxation

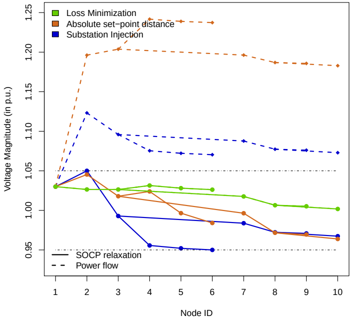


Illustration of Inexact Relaxation

- SOCP voltages : voltages obtained as a result of the relaxed problem

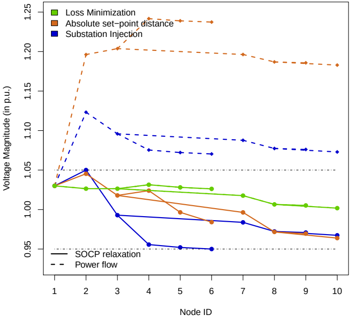
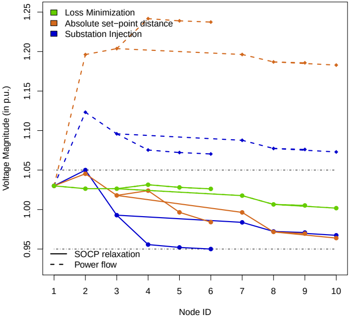
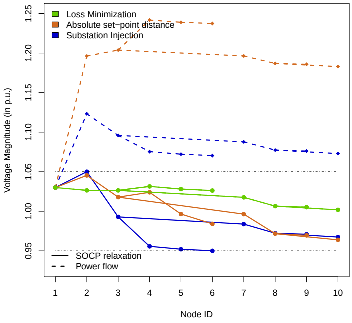


Illustration of Inexact Relaxation

- SOCP voltages : voltages obtained as a result of the relaxed problem
- Real power flow voltages : injections obtained from the relaxation are passed to BFS power flow solver

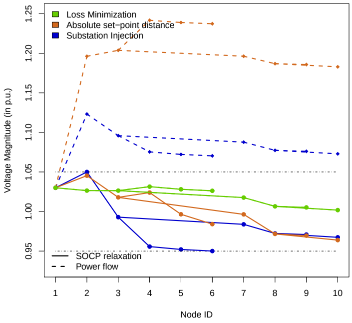


Existing Approaches



Existing Approaches

- Focus on finding conditions ensuring exactitude *a priori*



"Optimal power flow in distribution networks", Gan, 2013
"Geometry of feasible injection region of power networks", Zhang, 2011
"Optimal inverter VAR control in distribution systems with high PV penetration", Farivar, 2012
"Geometry of power flows and optimization in distribution networks", Lavaei, 2014

Existing Approaches

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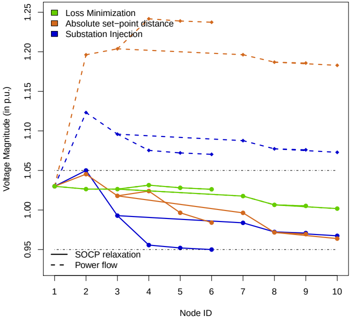

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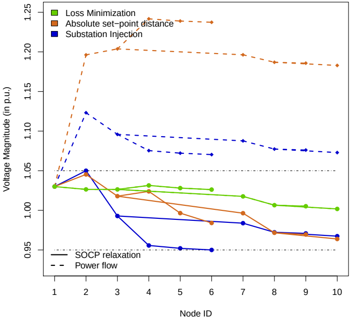

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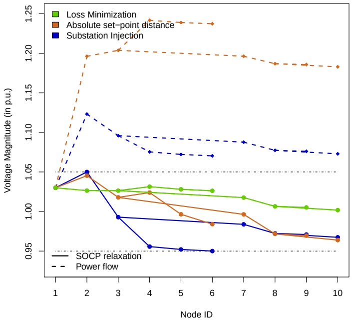
- Objective function increasing in the injections OR no upper voltage binding constraints
- Not compatible with ADN operation (e.g. PV generator aiming to minimize curtailing while avoiding over-voltage)

We focus on obtaining a solution when relaxation is inexact



Compressed Formulation

Definitions :

$$dV(\mathbf{x}) = \sum_{j\in[1,J]} |P_j^{pv,sp} - P_j^{pv}| + |P_j^{st,sp} - P_j^{st}|$$

$$rl(\mathbf{x}) = \sum_{j\in[1,J]} r_{f(j),j} l_j$$

$$rL(\mathbf{x}) = \sum_{j\in[1,J]} r_{f(j),j} \frac{{P_j}^2 + {Q_j}^2}{U_{f(j)}}$$

$$rGap(\mathbf{x}) = rl(\mathbf{x}) - rL(\mathbf{x})$$

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$$rGap(\mathbf{x}) = rl(\mathbf{x}) - rL(\mathbf{x})$$

Solution of the original problem :

$$\dot{\mathbf{x}} = \text{Argmin}_{\mathbf{x}\in S}\, dV(\mathbf{x}) + \, rl(\mathbf{x})$$

Principle of Cutting Planes

- Iterative procedure
- Add linear cut(s) at each step. Solution after cut k :

$$\tilde{\mathbf{x}}_k = \text{Argmin}_{\mathbf{x}\in\tilde{S}_k}\, dV(\mathbf{x}) + rl(\mathbf{x})$$

- A cut is valid if it excludes the previous solution and keeps the original solution
- Validity of de cut relies on 3 inequalities
  - $rl(\dot{\mathbf{x}}) < rl(\tilde{\mathbf{x}}_{k-1})$
  - $dV(\dot{\mathbf{x}}) - dV(\tilde{\mathbf{x}}_{k-1}) \geq 0$
  - $rl(\dot{\mathbf{x}}) < rL(\tilde{\mathbf{x}}_{k-1})$
- Proof by induction

Illustration of the convergence

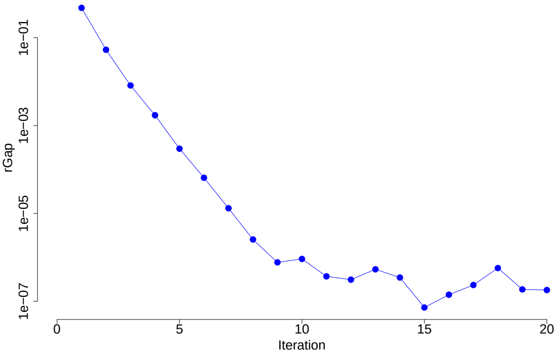


Figure – Value of Gap at Each Step, logarithmic scale

Illustration of the convergence

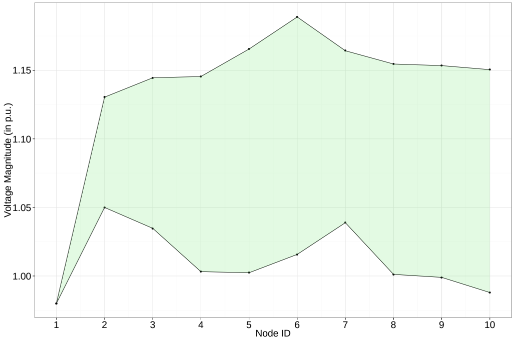


FIGURE – SOCP and Actual Voltages, Step 1

Illustration of the convergence

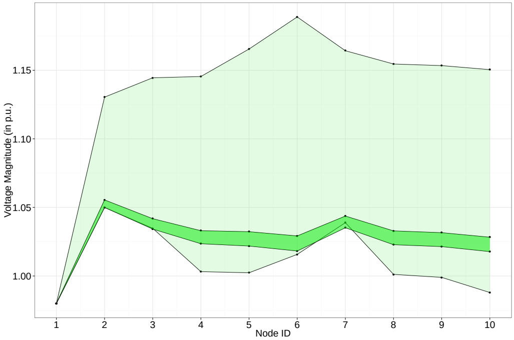


FIGURE – SOCP and Actual Voltages, Step 2

Illustration of the convergence

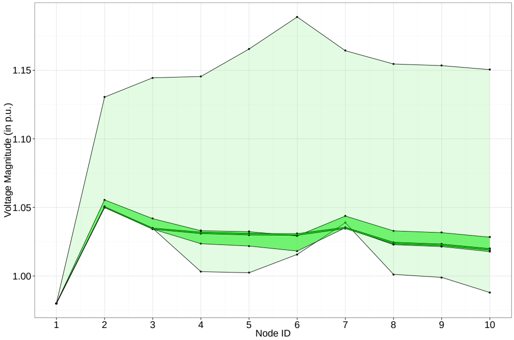


FIGURE – SOCP and Actual Voltages, Step 3

Coupling with the CPS

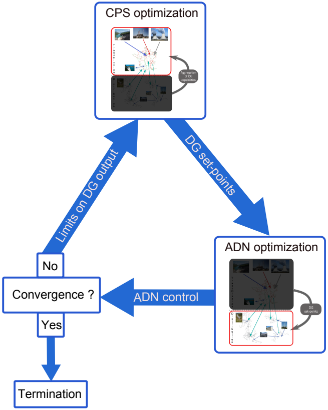
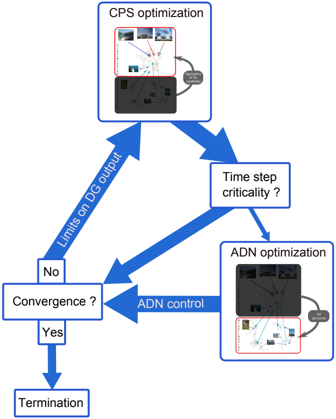


Figure – Chapter 2 of Y. Abdelouadoud PhD - 2014, coupling with the Centralized Power System

Coupling with the CPS

Addition of a criticaility criterion to reduce the computational time



Yassine Seddik Abdelouadoud, Robin Girard, François-Pascal Neirac, and Guiot Thierry. A criticality criterion to decrease the computational burden in multistage distribution system optimal power flow. In PowerTech, 2013.

Multi-temporal/Stochastic OPF

- Addition of the temporal dimension and stochastic dimension (e.g. for storage simulation)
- Multitemporal.

  Etta Grover-Silva, Robin Girard, and Georges Kariniotakis. Multitemporal Optimal Power Flow for Assessing the Renewable Generation Hosting Capacity of an Active Distribution System. In IEEE/PES Transmission and Distribution Conference and Exposition (T& D), 2016.
- Stocastic.

  Etta Grover-Silva, Xwégnon Ghislain Agoua, Robin Girard, and Georges Karinotakis. A stochastic multi-temporal optimal power flow approach for the management of grid connected storage. In CIRED (Congres International des Réseaux Electriques de Distribution), 2017
- Only a bit more than 2 days/10 scenarii possible. Further work on decomposition/parallel computing.
- Addition of constraints on building temperature (Submitted)

Storage dimensionning OPF

- Addition of an investment term in the cost function, a new variable : N_x number of hours of storage available (from which the capacity is deduced)
- investment cost is proportional to

$$\sum_x P_x^{max} N_x$$

- it is non linear and non convex. A solution : iterative linearization.
- Case study for storage dimensionning in the distribution network (paper submitted)

Conclusion, perspectives

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  - the other one on how to optimize an ADN using SDP.

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  - the other one on how to optimize an ADN using SDP.
- This domain is rich in applications and perspectives.

Thanks a lot for your attention !
Questions ?
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