# Optimal operation of medium-voltage AC networks with distributed generation and storage devices

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# Medium voltage (*MV*) power distribution networks

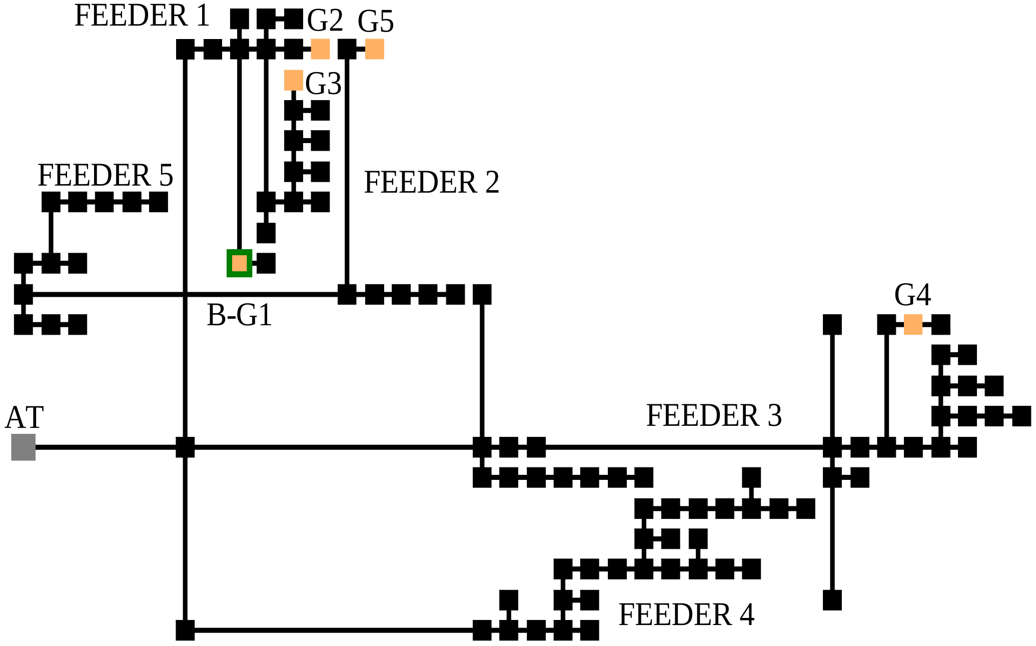
- *Traditional* use :

  deliver to consumers
  the power produced by large plants connected
  to the high voltage (*HV*) transmission network.

- Evolution:

  host *distributed generation,*
  both conventional and from Renewable Energy Sources.

# Example of medium-voltage network: the Atlantide network



AT: connection with HW network

Transformer (fixed ratio or OLTC)

102 nodes

101 lines

5 feeders:

Feeder 1: generators G1, G2, G3 (high RES generation - photovoltaic plants) and storage device

Feeder 2: generator G5

Feeder 3: generator G4

Feeders 4 and 5: no generation

# Operation of Distribution Networks

Technical conditions must be satisfied:

- constraints on current in lines (a security requirement)
- constraints on voltages at nodes (service quality)
- balance among load and generation at any time

DN will be operated by the Distribution System Operator (*DSO*)
with regulation resources of 2 kinds:

- internal (owned by *DSO*): on-load tap changers, storage devices
- external: modification of generation schedules
  (subject to payment to the power producers)

Production schedules are defined by **power producers** one-day ahead on the basis of

1. forecast of load and electricity prices, for *dispatchable* power plants (e.g. thermal)

2. weather forecast (wind speed, solar irradiation), for *non-dispatchable* power plants (wind, photovoltaic)

Because of partial unpredictability of non-dispatchable generation,
imbalance between load and generation may occur,
which must be solved while satisfying the technical constraints.

## Research project on *DN* networks: ENEL - Siemens - RSE - UniBg

Project aims:

1. build and test a prototype network, with

   distributed generation (conventional + RES), storage devices, on-load tap changers

2. develop a *software* tool for the *on-line* optimal operation of the prototype-*DN*

   for determining *how to use* the *regulation resources*

   so as to minimize the total cost of the *DSO*'s control action,

   while satisfying technical constraints

- **INDUSTRIAL USE ⇒ develop a licence-free software**
- **15 minutes TIME DISCRETIZATION ⇒ compute solution in few minutes**

# Contribution by UniBg + RSE

Development of the software tool to be used by *DSO* :

- for the on-line network control
- as a simulation tool
  - to find efficient network configurations (e.g. positions of storage units)
  - to analyze the impact of alternative sets of regulation resources

# *NLP* model

- For every generator $g$ and every period $h$ compute

  variations of active ($\Delta P^{+}_{g,h}, \Delta P^{-}_{g,h}$) and reactive ($\Delta Q^{+}_{g,h}, \Delta Q^{-}_{g,h}$) power outputs

  with respect to scheduled productions ($Pi_{g,h}$, $Qi_{g,h}$)

- satisfying security requirements (current in lines)
- ensuring service quality (voltages at nodes)

Optimal Power Flow
in Alternating Current

- aiming at minimizing total cost of variations + value of active power losses

# Generators: variations of active power production

Active power output of generator $g$ in period $h$ is expressed as forecast + variation

$$Pi_{g,h} + \mathit{\Delta} P^{+}_{g,h} - \mathit{\Delta} P^{-}_{g,h}$$

with $\mathit{\Delta} P^{+}_{g,h} \geq 0$ and $\mathit{\Delta} P^{-}_{g,h} \geq 0$.

Decision variables $\mathit{\Delta} P^{+}_{g,h}$ and $\mathit{\Delta} P^{-}_{g,h}$ may not be both positive, since the cost term

$$c^{+}_{g,h}\ \ \mathit{\Delta} P^{+}_{g,h} + c^{-}_{g,h}\ \ \mathit{\Delta} P^{-}_{g,h}$$

in the objective function has positive cost coefficients $c^{+}_{g,h} > 0$ and $c^{-}_{g,h} > 0$.

Updated active power output must be between minimum and maximum active power output

$$\underline{P}_{g,h} \leq Pi_{g,h} + \mathit{\Delta} P^{+}_{g,h} - \mathit{\Delta} P^{-}_{g,h} \leq \overline{P}_{g,h}$$

# Generators: variations of reactive power production

Analogously, for reactive power output of generator $g$ in period $h$

$$\underline{Q}_{g,h} \leq Qi_{g,h} + \Delta Q^{+}_{g,h} - \Delta Q^{-}_{g,h} \leq \overline{Q}_{g,h}$$

with $\Delta Q^{+}_{g,h} \geq 0$ and $\Delta Q^{-}_{g,h} \geq 0$,

and the cost term in the objective function

$$ct^{+}_{g,h}\ \Delta Q^{+}_{g,h} + ct^{-}_{g,h}\ \Delta Q^{-}_{g,h}$$

has positive cost coefficients $ct^{+}_{g,h} \geq 0$ and $ct^{-}_{g,h} \geq 0$.

# Nodes: active power balance

In every period $h \in \mathcal{H}$

$$\overbrace{\sum_{g\in\mathcal{G}_i}\left(Pi_{g,h}+\Delta P^{+}_{g,h}-\Delta P^{-}_{g,h}\right)}^{\boxed{\substack{\text{sum of active power output of}\\ \text{all generators located at node } i}}} = \underset{\substack{\uparrow\\ \text{active}\\ \text{load}}}{C_{i,h}} + \overset{\substack{\text{shunt}\\ \text{conductance}\\ \downarrow}}{G_{i,h}}\, V^{2}_{i,h} + \underbrace{\sum_{(i,j)\in\mathcal{L}} TA_{i,j,h}}_{\boxed{\substack{\text{sum of active power flows}\\ \text{from node } i}}}$$

Voltage $V_{i,h}$ must be between minimum and maximum : $\underline{V}_{i,h} \le V_{i,h} \le \overline{V}_{i,h}$.

# Nodes: reactive power balance

In every period $h \in \mathcal{H}$

$$\overbrace{\sum_{g\in\mathcal{G}_i}\left(Qi_{g,h}+\Delta Q^{+}_{g,h}-\Delta Q^{-}_{g,h}\right)}^{\boxed{\text{sum of reactive power output of all generators located at node } i}} = \underset{\substack{\uparrow\\ \text{reactive}\\ \text{load}}}{D_{i,h}} + \overset{\substack{\text{shunt}\\ \text{susceptance}\\ \downarrow}}{B_{i,h}}\ V^{2}_{i,h} + \underbrace{\sum_{(i,j)\in\mathcal{L}} TR_{i,j,h}}_{\boxed{\text{sum of reactive power flows from node } i}}$$

# Lines: active power flow

In every period $h \in \mathcal{H}$

loss angle of series
impedance of line $(i, j)$
↓

phase angle
of node $i$
↓

$$TA_{i,j,h} = \left(\frac{\cos\delta_{i,j,h}}{z_{i,j,h}} + x_{i,j,h}\right) V_{i,h}^2 - \frac{\cos\left(\delta_{i,j,h} + \theta_{i,h} - \theta_{j,h}\right)}{z_{i,j,h}} V_{i,h}\, V_{j,h}$$

↑
active power flow
on line $(i, j)$

↑
series
impedance

↑
transversal
conductance
of node $i$

- ➢ Phase angle $\theta_{i,h}$ must be between minimum and maximum

$$\underline{\theta}_{i,h} \leq \theta_{i,h} \leq \overline{\theta}_{i,h}$$

- ➢ Phase angle at slack node in period 1 is set to 0 : $\theta_{i_1,1} = 0$

# Lines: reactive power flow

In every period $h \in \mathcal{H}$

loss angle of series
impedance of line $(i, j)$
↓

phase angle
of node $i$
↓

$$TR_{i,j,h} = \left(\frac{\operatorname{sen}\delta_{i,j,h}}{z_{i,j,h}} - y_{i,j,h}\right) V_{i,h}^{2} - \frac{\operatorname{sen}\left(\delta_{i,j,h} + \theta_{i,h} - \theta_{j,h}\right)}{z_{i,j,h}} V_{i,h} \; V_{j,h}$$

↑
reactive power flow
on line $(i, j)$

↑
series
impedance

↑
transversal
susceptance
of node $i$

# Transformers: active power flow

- Fixed ratio transformers :

rated power
of transformer
↓

$$TA_{i,j,h} = \left( \frac{Sn_{i,j,h}\ \cos\delta_{i,j,h}}{Z_{i,j,h}\ Vn^2_{i,j,h}} + x_{i,j,h} \right) V^2_{i,h} - \frac{Sn_{i,j,h} \cos\left(\delta_{i,j,h} + \theta_{i,h} - \theta_{j,h}\right)}{Z_{i,j,h}\, Vn_{i,j,h}\, Vn_{j,i,h}} V_{i,h}\, V_{j,h}$$

↑ ↑

series impedance
of transformer

$Vn_{i,j,h}$
rated voltage at node $i$
of transformer

- On load tap changers (OLTC) with tap changer on node $i$ :

$$TA_{i,j,h} = \left( \frac{Sn_{i,j,h}\ \cos\delta_{i,j,h}}{Z_{i,j,h}\ TC^2_{i,j,h}} + x_{i,j,h} \frac{Vn^2_{i,j,h}}{TC^2_{i,j,h}} \right) V^2_{i,h} - \frac{Sn_{i,j,h} \cos\left(\delta_{i,j,h} + \theta_{i,h} - \theta_{j,h}\right)}{Z_{i,j,h}\, TC_{i,j,h}\, Vn_{j,i,h}} V_{i,h}\, V_{j,h}$$

↑

$TC_{i,j,h}$ voltage at node $i$
of tap changer $(i,j) \in \mathcal{L}_1^{\mathcal{TC}}$

$$Vn_{i,j,h}\left(1-d_{i,j,h}\right) \le TC_{i,j,h} \le Vn_{i,j,h}\left(1+u_{i,j,h}\right)$$

$u_{i,j,h}$ : maximal increase with respect to rated voltage at node $i$

$d_{i,j,h}$ : maximal decrease with respect to rated voltage at node $i$

# Transformers: reactive power flow

- Fixed ratio transformers :

rated power
of transformer
↓

$$TR_{i,j,h} = \left( \frac{Sn_{i,j,h}\,\mathrm{sen}\,\delta_{i,j,h}}{Z_{i,j,h}\,Vn_{i,j,h}^2} - y_{i,j,h} \right) V_{i,h}^2 - \frac{Sn_{i,j,h}\,\mathrm{sen}\left(\delta_{i,j,h} + \theta_{i,h} - \theta_{j,h}\right)}{Z_{i,j,h}\,Vn_{i,j,h}\,Vn_{j,i,h}} V_{i,h}\,V_{j,h}$$

↑ ↑

series impedance
of transformer

$Vn_{i,j,h}$
rated voltage at node *i*
of transformer

- On load tap changers (OLTC) with tap changer on node *i* :

$$TR_{i,j,h} = \left( \frac{Sn_{i,j,h}\,\mathrm{sen}\,\delta_{i,j,h}}{Z_{i,j,h}\,TC_{i,j,h}^2} - y_{i,j,h}\,\frac{Vn_{i,j,h}^2}{TC_{i,j,h}^2} \right) V_{i,h}^2 - \frac{Sn_{i,j,h}\,\mathrm{sen}\left(\delta_{i,j,h} + \theta_{i,h} - \theta_{j,h}\right)}{Z_{i,j,h}\,TC_{i,j,h}\,Vn_{j,i,h}} V_{i,h}\,V_{j,h}$$

↑

$TC_{i,j,h}$ voltage at node *i*
of tap changer $(i,j) \in \mathcal{L}_1^{\mathcal{TC}}$

Transformer $(i,j)$ with tap changer **on node *j***

$$TA_{i,j,h} = \left(\frac{Sn_{i,j,h}\ \cos\delta_{i,j,h}}{Z_{i,j,h}Vn_{i,j,h}^{2}} + x_{i,j,h}\right)V_{i,h}^{2} - \frac{Sn_{i,j,h}\cos\left(\delta_{i,j,h} + \theta_{i,h} - \theta_{j,h}\right)}{Z_{i,j,h}\,Vn_{i,j,h}\,\boldsymbol{TC_{j,i,h}}}V_{i,h}\,V_{j,h}$$

$$TR_{i,j,h} = \left(\frac{Sn_{i,j,h}\ \mathrm{sen}\,\delta_{i,j,h}}{Z_{i,j,h}Vn_{i,j,h}^{2}} - y_{i,j,h}\right)V_{i,h}^{2} - \frac{Sn_{i,j,h}\ \mathrm{sen}\left(\delta_{i,j,h} + \theta_{i,h} - \theta_{j,h}\right)}{Z_{i,j,h}\,Vn_{i,j,h}\,\boldsymbol{TC_{j,i,h}}}V_{i,h}\,V_{j,h}$$

$$Vn_{j,i,h}\left(1 - d_{j,i,h}\right) \leq TC_{j,i,h} \leq Vn_{j,i,h}\left(1 + u_{j,i,h}\right)$$

# Current transits

Current transit $TI_{i,j,h}$ in line/transformer

$$TI_{i,j,h} = \frac{1}{\sqrt{3}\ V_{i,h}} \sqrt{TA_{i,j,h}^2 + TR_{i,j,h}^2}$$

is bounded above by the maximum value $\overline{TI}_{i,j,h}$

$$TI_{i,j,h} \leq \overline{TI}_{i,j,h}$$

# Storage devices: active and reactive power (if inverter is installed)

Determine

$Pb_{b,h}$ : active power exchange between storage and network in period $h$

$E_{b,h}$ : electricity stored at the end of period $h$

$TA_{i,j,h}$ : active power flow from/to network

$Qb_{b,h}$ : reactive power exchange between storage and network in period $h$

$TR_{i,j,h}$ : reactive power flow from/to network

# Storage devices: active power

$$E_{b,h} = E_{b,h-1} + Pb_{b,h}\,\Delta h$$

$E_{b,0}$ : electricity stored in storage device $b$ at the beginning of period 1

$Pb_{b,h}$ : active power exchange between storage and network

$\Delta h$ : period length (1 hour or fraction)

$$\underline{E}_{b,h} \leq E_{b,h} \leq \overline{E}_{b,h}$$

$\underline{E}_{b,h}$ , $\overline{E}_{b,h}$ : minimum and maximum electricity that can be stored

$$\underline{Pb}_{b,h} \leq Pb_{b,h} \leq \overline{Pb}_{b,h}$$

$\underline{Pb}_{b,h}$, $\overline{Pb}_{b,h}$: minimum and maximum active power exchange between storage and network

# Storage devices: active power charge and discharge – losses

$$Pb_{b,h} = \Delta Pb^{+}_{b,h} - \Delta Pb^{-}_{b,h}$$

$\Delta Pb^{+}_{b,h} > 0$ : active power discharge in period $h$

$\Delta Pb^{-}_{b,h} > 0$ : active power charge in period $h$

(cost term in objective function $cb^{+}_{b,h}\ \Delta Pb^{+}_{b,h} + cb^{-}_{b,h}\ \Delta Pb^{-}_{b,h}$ with $cb^{+}_{b,h}, cb^{-}_{b,h} \geq 0$)

$$TA_{i,j,h} = \eta^{+}_{b,h}\ \Delta Pb^{+}_{b,h} - \eta^{-}_{b,h}\ \Delta Pb^{-}_{b,h}$$

$0 \leq \eta^{+}_{b,h} \leq 1$ : discharge loss coefficient

$0 \leq \eta^{-}_{b,h} \leq 1$ : charge loss coefficient

# Storage devices: reactive power

$$\underline{Qb}_{b,h} \leq Qb_{b,h} \leq \overline{Qb}_{b,h}$$

$Qb_{b,h}$ : reactive power exchange between storage and network in period $h$

$\underline{Qb}_{b,h}, \overline{Qb}_{b,h}$: minimum and maximum reactive power exchange between storage and network

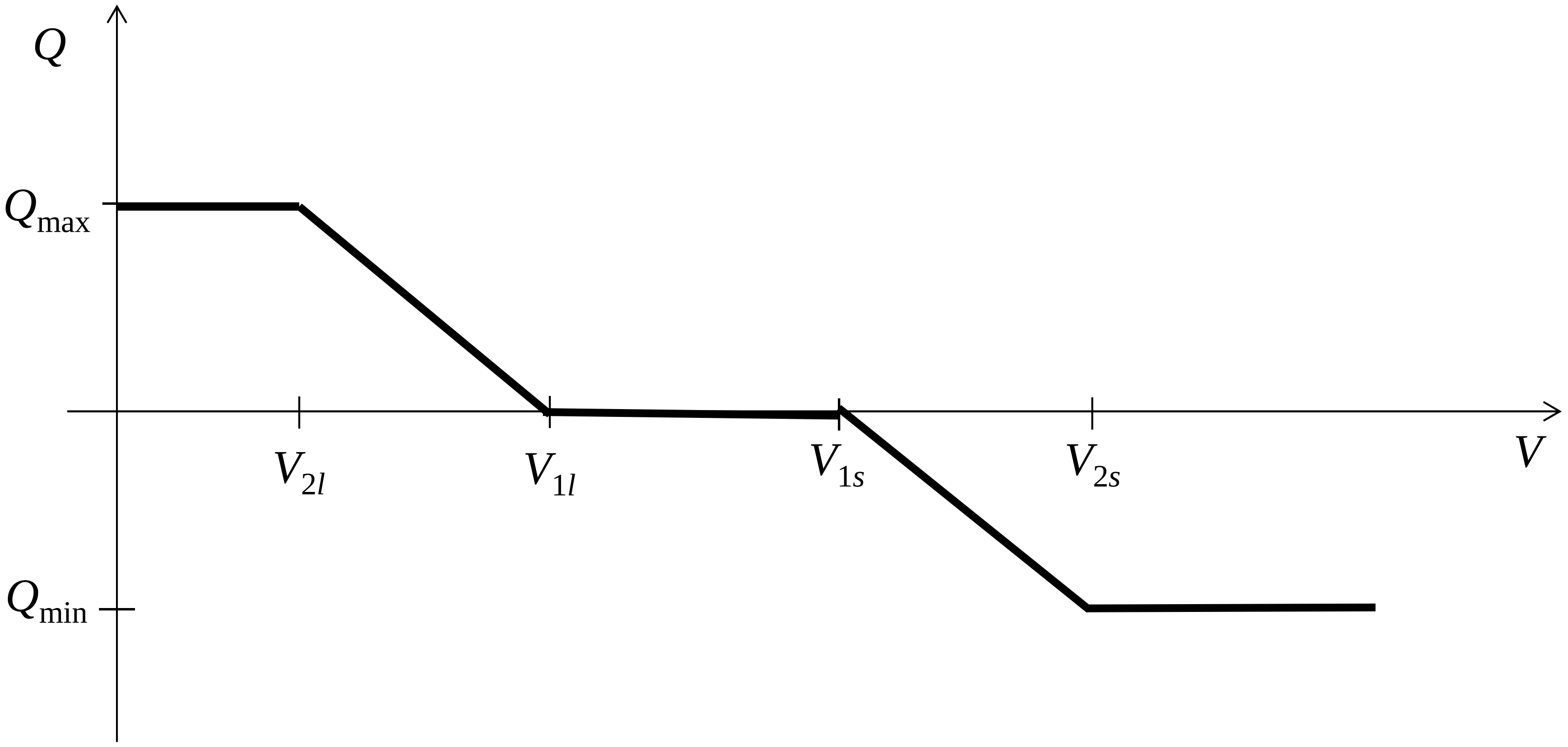
$$Qb_{b,h} = \Delta Qb^{+}_{b,h} - \Delta Qb^{-}_{b,h}$$

(cost term in objective function $ctb^{+}_{b,h}\ \Delta Qb^{+}_{b,h} + ctb^{-}_{b,h}\ \Delta Qb^{-}_{b,h}$ with $ctb^{+}_{b,h}, ctb^{-}_{b,h} \geq 0$)

$$TR_{i,j,h} = Qb^{+}_{b,h}$$

# Local controllers

At each node, the relation between reactive power $Q$ and voltage $V$ must be enforced that is represented by the following **piece-wise** linear function



Get rid of *discontinuity of first derivatives*, since **Newton-type solvers** are used.

Therefore we have introduced the following **spline approximation** of the curve $Q = f(V)$

$$Q = \begin{cases} f_1(V) = Q_{\max} & V \le V_{2l} - \varepsilon \\ f_2(V) = \dfrac{Q_{\max}}{4(V_{1l} - V_{2l})\varepsilon}\left[-V^2 + 2(V_{2l} - \varepsilon)V - (V_{2l} + \varepsilon)^2 + 4V_{1l}\varepsilon\right] & V_{2l} - \varepsilon < V < V_{2l} + \varepsilon \\ f_3(V) = -\dfrac{Q_{\max}}{V_{1l} - V_{2l}}(V - V_{1l}) & V_{2l} + \varepsilon \le V \le V_{1l} - \varepsilon \\ f_4(V) = \dfrac{Q_{\max}}{4(V_{1l} - V_{2l})\varepsilon}\left[V^2 - 2(V_{1l} + \varepsilon)V + (V_{1l} + \varepsilon)^2\right] & V_{1l} - \varepsilon < V < V_{1l} + \varepsilon \\ f_5(V) = 0 & V_{1l} + \varepsilon \le V \le V_{1s} - \varepsilon \\ f_6(V) = \dfrac{Q_{\min}}{4(V_{1s} - V_{2s})\varepsilon}\left[-V^2 + 2(V_{1s} - \varepsilon)V - (V_{1s} - \varepsilon)^2\right] & V_{1s} - \varepsilon < V < V_{1s} + \varepsilon \\ f_7(V) = -\dfrac{Q_{\min}}{V_{1s} - V_{2s}}(V - V_{1s}) & V_{1s} + \varepsilon \le V \le V_{2s} - \varepsilon \\ f_8(V) = \dfrac{Q_{\min}}{4(V_{1s} - V_{2s})\varepsilon}\left[V^2 - 2(V_{2s} + \varepsilon)V + (V_{2s} - \varepsilon)^2 + 4V_{1s}\varepsilon\right] & V_{2s} - \varepsilon < V < V_{2s} + \varepsilon \\ f_9(V) = Q_{\min} & V_{2s} + \varepsilon \le V \end{cases}$$

- in a ball around every corner point, the function is approximated by a quadratic one
- $\varepsilon$ = 1 *Volt*, very small since in the problem the order of magnitude for voltage is *kV*
- first derivative is continuous, as required by the solver

# Objective function: minimize operation costs

Operation costs: sum of

1. cost of variations from scheduled active and reactive power production
2. cost of storage charge and discharge and of reactive power production
3. cost of active power losses

# Procedure coding : 2 versions

1) *NLP* model coded in GAMS and solved by MINOS

   (+) model development easy

   (–) licence is needed for use in industry

   (–) data are not efficiently managed

2) a FORTRAN code, based on an Interior Point method, which efficiently integrates

   - data management
   - representation of *NLP* model
   - optimization algorithm with sparsity fully exploited

# Comparison of computational times

<u>Same solution</u> computed by the 2 codes, but with different computational times :

| nodes | variables | constraints | GAMS+ MINOS [*sec*] | FORTRAN CODE [*sec*] |
|---|---|---|---|---|
| 15 | 92 | 36 | 0.33 | 0.02 |
| 162 | 351 | 324 | 0.49 | 0.03 |
| 162 | 4247 | 3912 | 57.99 | 0.59 |
| 5112 | 11776 | 10224 | 108.74 | 2.65 |
| 5112 | 11824 | 10272 | 121.40 | 3.32 |
| 20000 | 40005 | 40000 | 736.48 | 7.39 |

# Test on Atlantide network

**Aim of test: local vs. centralized control**

Objective : minimize active power losses

Time horizon: 1 hour

| 1 | **Base case** |
|---|---|
| no regulation resources | fixed transformation ratio: 20.5 *kV* |

| **network losses** | **V HV node** | **Vmax** | **Q HV node** | **Q G3** | **Q G4** | **Q storage** | **P storage** |
|---|---|---|---|---|---|---|---|
| [ *kW* ] | [ *kV* ] | [ *kV* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kW* ] |
| 135.27 | **20.5** | 21.34 | 1138.16 | - | - | - | - |

node voltages increase up to 21.34 *kV* (high local generation, OLTC fixed)

| 2 | **Local control (1)** |
|---|---|
| G3 and G4 - dead band 19.5-20.5 *kV* | fixed transformation ratio: 20.5 *kV* |

| **network losses** | **V HV node** | **Vmax** | **Q HV node** | **Q G3** | **Q G4** | **Q storage** | **P storage** |
|---|---|---|---|---|---|---|---|
| [ *kW* ] | [ *kV* ] | [ *kV* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kW* ] |
| 159.88 | **20.5** | 21.01 | 1898.87 | -724.47 | 0 | - | - |

↗ ↗

the increase is
absorbed in G3

local control of G3 and G4

→ in G3 reactive power absorption (-724.47 *kW*)

→ node voltages up to 21.01 *kV*

| 3 | **Local control (2)** |
|---|---|
| G3 and G4 - dead band 19.5-20.5 *kV* | fixed transformation ratio: 20 *kV* |

| **network losses** | **V HV node** | **Vmax** | **Q HV node** | **Q G3** | **Q G4** | **Q storage** | **P storage** |
|---|---|---|---|---|---|---|---|
| [ *kW* ] | [ *kV* ] | [ *kV* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kW* ] |
| 149.49 | **20** | 20.71 | 1516.96 | -309.48 | 0 | - | - |

All values reduced with respect to case 2:

→ losses (149.49 *kW*)

→ highest voltage (20.71 *kV*) in the network

→ Q at HV node (1516.96)

→ reactive power absorption (-309.48 *kVAr*) in G3

| 4 | **Local control (3)** |
|---|---|
| G3 and G4 - no dead band | fixed transformation ratio: 20.5 *kV* |

| **network losses** | **V HV node** | **Vmax** | **Q HV node** | **Q G3** | **Q G4** | **Q storage** | **P storage** |
|---|---|---|---|---|---|---|---|
| [ *kW* ] | [ *kV* ] | [ *kV* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kW* ] |
| 160.09 | **20.5** | 20.99 | 1987.49 | -718.63 | -91.45 | - | - |
| ↗↗ | | | ↗↗ | ↗↗ | ↗↗ | | |

remove dead band : highest values, among local control cases, of

→ active power losses (160.09 *kW*)

→ use of resources (Q-HV: 1987.49 *kVAr*, Q-G3: -718.63 *kVAr*, Q-G4: -91.45 *kVAr*)

| 5 | **Centralized control (1)** | |
|---|---|---|
| G3 and G4 | fixed transformation ratio: 20.5 *kV* | (no storage) |

| **network losses** | **V HV node** | **Vmax** | **Q HV node** | **Q G3** | **Q G4** | **Q storage** | **P storage** |
|---|---|---|---|---|---|---|---|
| [ *kW* ] | [ *kV* ] | [ *kV* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kW* ] |
| 159.73 | **20.5** | 21 | 1895.11 | -720.63 | 0 | - | - |

centralized control of G3 and G4

→ G3 absorbs reactive power to reduce voltage

(solution similar to case 2, since not enough resources are available)

| 6 | **Centralized control (2)** | |
|---|---|---|
| G3 and G4 | **OLTC** | (no storage) |

| **network losses** | **V HV node** | **Vmax** | **Q HV node** | **Q G3** | **Q G4** | **Q storage** | **P storage** |
|---|---|---|---|---|---|---|---|
| [ *kW* ] | [ *kV* ] | [ *kV* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kW* ] |
| 138.83 | **19.96** | 21 | 870.40 | 173.78 | 136.6 | - | - |

↘ ↘ injections of Q

add centralized control of OLTC

→ HV voltage (19.96 *kV*) is reduced

→ generators inject reactive power (Q-G3: 173.78 *kVAr*, Q-G4: 136.6 *kVAr*)

→ losses (138.83 *kW*) are reduced

| 7 | **Centralized control (3)** | |
|---|---|---|
| G3 and G4 | **OLTC** | **storage** |

| **network losses** | **V HV node** | **Vmax** | **Q HV node** | **Q G3** | **Q G4** | **Q storage** | **P storage** |
|---|---|---|---|---|---|---|---|
| [ *kW* ] | [ *kV* ] | [ *kV* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kW* ] |
| 104.60 | **20.18** | 21 | 721.90 | 42.45 | 133.88 | **241.2** | **-500** |

lower injections of Q

lowest value of
active losses

add storage device

→ improves network performance (losses)

→ exchange of power in the primary substation (721.90 *kVAr*) is reduced

# Combining local and centralized control

| | Local control | Centralized control | |
|---|---|---|---|
| 8 | G3 and G4 - dead band 19.5-20.5 *kV* | OLTC | - |
| 9 | G3 and G4 - dead band 19.5-20.5 *kV* | OLTC | storage |
| 10 | G3 and G4 - no dead band | OLTC | storage |

| | **network losses** | **V HV node** | **Vmax** | **Q HV node** | **Q G3** | **Q G4** | **Q storage** | **P storage** |
|---|---|---|---|---|---|---|---|---|
| | [ *kW* ] | [ *kV* ] | [ *kV* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kVAr* ] | [ *kW* ] |
| 8 | 148.95 | 19.49 | 20.37 | 1237.77 | 0 | 12.91 | - | - |
| 9 | 112.39 | 19.45 | 20.32 | 825.89 | 0 | 12.92 | 379.78 | -500 |
| 10 | 113.83 | 19.47 | 20.24 | 921.81 | -170.96 | 122.24 | 347.48 | -500 |

→ losses higher than in the centralized solution

→ **fast voltage variations with high frequency** (to be avoided as they can damage the final user)

OLTC position depends on variables and parameters not all strictly related to voltage modulation

# Conclusions from the tests

- integration of local droop within a centralized control requires an accurate **sensitivity analysis of the system behaviour** in the different conditions,
  as local control greatly affects the optimal power flow, in particular of the OLTC

- centralized solutions often better than solutions with local controls (voltage, losses)

- performance is related to the precision of the state estimator