Estimation of aggregated bidding curves of flexibility resources connected to Active Distribution Networks

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In recent years, electricity generation from renewable sources (RES)

has increased significantly,

in particular Distributed Renewable Energy Sources (DRES),

i.e. small size generators (<10 MW) connected to Medium Voltage (MV)

and Low Voltage (LV) distribution networks

Stochasticity of wind speed and of solar irradiation

Non-programmability of production

⇒ Impact on the **power system stability**

Ancillary services (balancing, voltage management,…)

- are provided by conventional generators

  (coal, gas turbine and hydroplants) connected to transmission network

  by means of exchanges of active and reactive power

- are purchased by the TSO in real time on different markets (intraday, balancing…),

  where each resource offers a power variation (active or reactive),

  with respect to its scheduled commitment, at a given price.

Due to the high ratio of reactance to resistance (X/R ratio) of transmission lines,

active and reactive power can be decoupled in transmission networks:

- services aimed at restoring the **energy balancing** are based on **active power**
- **voltage control** is based on **reactive power**.

$\Rightarrow$ For transmission network resources **capabilities in the reactive/active plane**

(i.e. the active and reactive limits of the power exchange)

can be considered (at least in first approximation) as being **rectangular**

In recent years the **share of production** from conventional units is reducing

(thermal units from 80% to 48%)

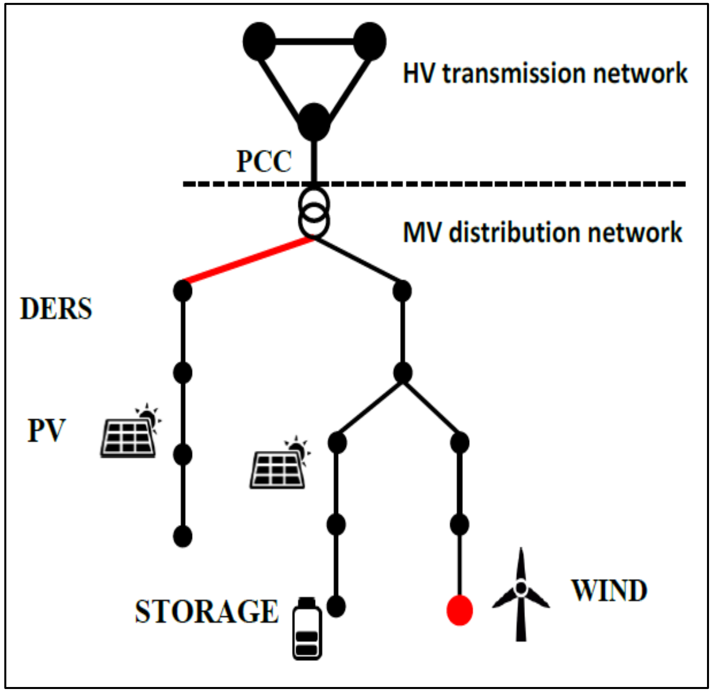
⇒ both **DRES** and **loads** will be allowed to participate

⇒ to the operation of the power system

European Commission - *Establishing a guideline on electricity balancing*

Delibera 300/Rel/2017

MV network (managed by a Distribution System Operator - DSO)



- designed for connection of loads
  (have a radial structure)

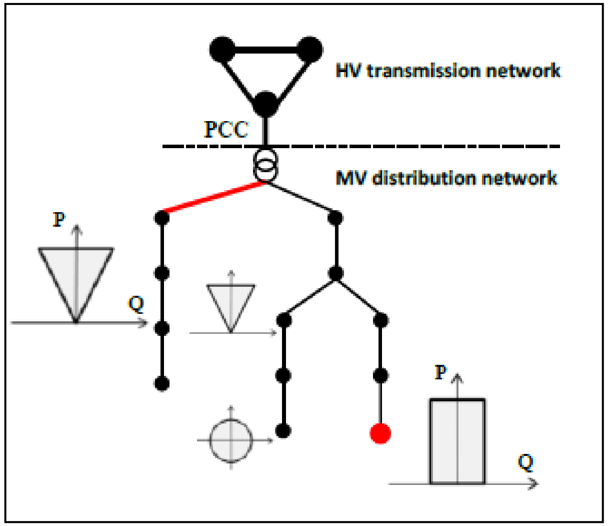
- not designed for high penetration
  of distributed generations:
  DRES may cause voltage congestions (red dot)
  and current congestions (red line).

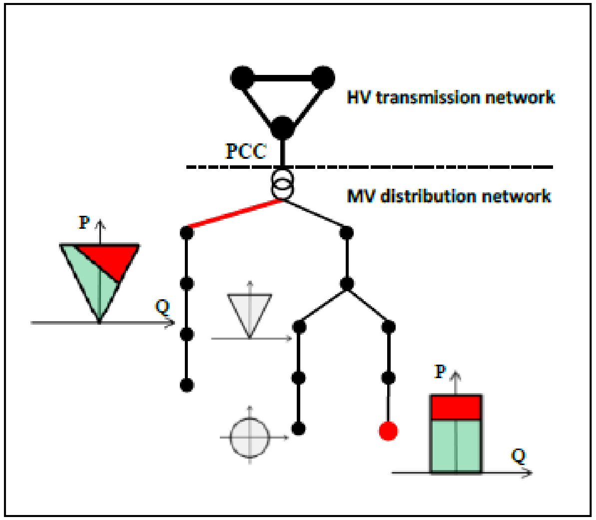
- not designed for participation of distributed generators
  to the management of the transmission network:
  voltage and current congestions in MV networks
  limit the power exchange of distributed resources

- due to the low X/R ratio, active power and reactive power cannot be decoupled

- For DRES the band of feasible reactive power variations depends on the active power :
    - **circular** capabilities
    - **triangular** capabilities

- **Voltage and current congestions in MV networks may limit the power exchange of DRES**





- Load flexibilities are characterized by a fixed power factor (ratio P/A, active/apparent)

  $\Rightarrow$ an active power variation determines a reactive power variation.

- In distribution networks **active power losses** (due to impedance and admittance) may have a substantial effect.

Perspective market structures

Different market schemes have been recently proposed

to foster the participation of distributed resources

to the operation of transmission network

These architectures are based on the interactions between four main actors:

1. **Transmission System Operator (TSO)**
2. **Distribution System Operator (DSO)**
3. **Balance Service Provider (BSP)**
4. **Distribution flexible resources (DFR)**

1. **TSO**: to avoid voltage and current congestions in the transmission network

   TSO needs detailed information regarding the power exchange of each node

   and the available band of regulation

2. **DSO**: needs to know the maximum power that can be generated/absorbed by the local

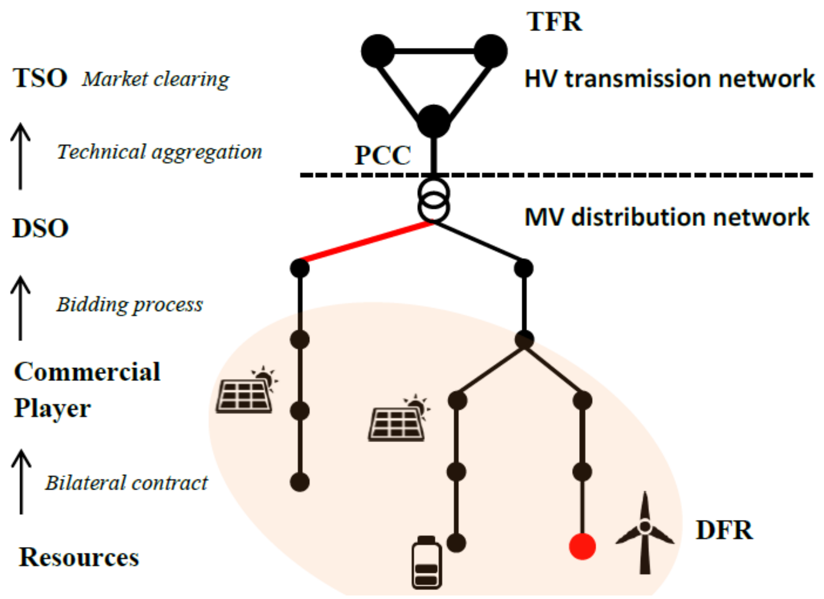
   resources without endangering the reliable operation of its network

3. **BSP - Balance Service Provider**:

   sells the flexibility of a single energy resource

   or of an aggregation of energy resources

   by presenting bids



4. **DFR - Distribution flexible resources** :

   are the providers of ancillary services that operate at distribution level

   they interface with the market by means of BSP

Validation of bids proposed by BSFs

As **modulation of active or reactive power**,

according to orders set by the TSO in real time,

may cause voltage or current violations in the distribution network,

the DFRs are subject to limitations different from those pertaining to TFRs

and the bids proposed by BSFs need to be validated by the DSO

before being sent to the market.

Coordination schemes

A. The distribution network has been assessed to be robust enough to accept any power variation

$\Rightarrow$ no validation is needed

$\Rightarrow$ all bids from local resources are ordered according to bid prices

B. participation of distributed resources to the market can determine local congestions

i. prequalification of submitted bids

DSO establishes the limits of the resources that guarantee the network operation in all conditions over a give time horizon (e.g. seasonally)

⇒ This approach **underestimates the total power** that local resources can provide as the imposed operational margins do not take into account the actual network state

This scheme is <u>most likely to be implemented in the short term</u>

ii. **DSO makes a technical aggregation of the resources offered by the BSPs** taking into account the actual state of the network and the network constraints

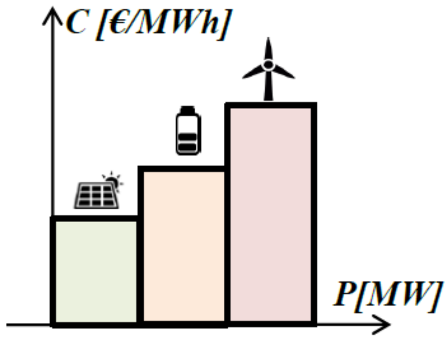
- this scheme allows exploiting the available flexibilities in an optimal way (e.g. enabling the participation of resources located in weak areas of the network, which usually would be excluded by more conservative schemes, in order to avoid congestions)

- resources with higher marginal costs have an increased possibility to participate to the market (they might be needed to enable other resources)

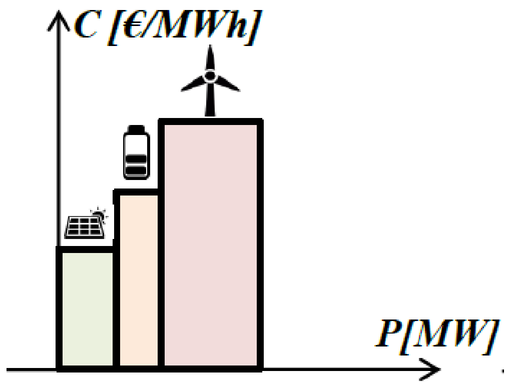
- the DSO may also use his own assets (capacitors, compensators, etc.) in the aggregation.

Result of the technical aggregation by DSO

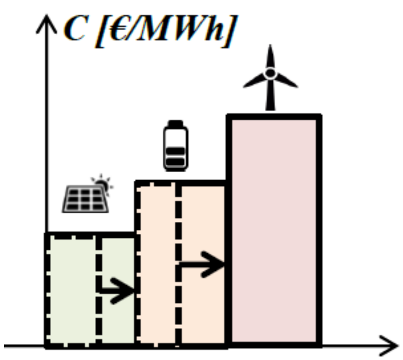
Without network congestions the resources can exchange the maximum amount of power.



However, network congestion can limit the availability of the resources.



In order to try and restore the maximum capability, the DSO can operate the network in a smarter way, by coordinating the use of the resources and its own asset.



We have developed a software tool to determine

the optimal operation of the distribution network, consisting of

- a detailed mathematical model of the distribution network,
    - Generators,
    - Nodes
    - Lines/transformers (fixed ratio, OLTC)
    - Storage devices

- a fast solver to compute the solution that minimizes the total cost of variations

The mathematical model

The optimal dispatch of the resources in the distribution network is determined by a **nonlinear optimization model** that computes

- variations of active power (ΔP_g^+, ΔP_g^-) and reactive power ($\Delta Q_{g,}^+$, ΔQ_g^-) with respect to the scheduled productions (P_g^0, Q_g^0) for every resource g
- the usage of storage devices, taking into account active power losses in charge and discharge operations
- voltage (V_i) and phase angle (θ_i) for every node i
- active power flow ($TA_{i,j}$), reactive power flow ($TR_{i,j}$) and current ($TI_{i,j}$) for every link (i, j) (lines/transformers)
- transformation ratio for every On Load Tap Changer (voltage $TC_{i,j}$ or $TC_{j,i}$, depending on which node the tap changer is located)

Objective function

Minimize the total cost of

- active and reactive power modulations of distributed resources
- charge and discharge of storage devices (modelled as generators)

$$\min \sum_{g \in \mathcal{G}} \left(c_g^{\Delta P^+} \Delta P_g^+ + c_g^{\Delta P^-} \Delta P_g^- + c_g^{\Delta Q^+} \Delta Q_g^+ + c_g^{\Delta Q^-} \Delta Q_g^- \right)$$

➢ The unitary costs of variations ($c_g^{\Delta P^+}, c_g^{\Delta P^-}, c_g^{\Delta Q^+}, c_g^{\Delta Q^-}$) are defined by the Balance Service Providers

Generators: lower and upper bounds to active power output

For every generator g

$$\underline{P}_g \le \underbrace{P_g^0 + \Delta P_g^+ - \Delta P_g^-}_{\boxed{\begin{array}{c}\text{updated active power output}\\ =\\ \text{scheduled} + \text{variation}\end{array}}} \le \overline{P}_g$$

$\Delta P_g^+ \geq 0$ and $\Delta P_g^- \geq 0$, but not both positive in the optimal solution,

since in the objective function the cost term

$$c_g^+ \ \Delta P_g^+ + c_g^- \ \Delta P_g^-$$

has positive cost coefficients $c_g^+ > 0$ and $c_g^- > 0$.

Generators: lower and upper bounds to reactive power output

For every generator g

$$\underline{Q}_g \leq \underbrace{Q_g^0 + \Delta Q_g^+ - \Delta Q_g^-}_{} \leq \overline{Q}_g$$

$$\boxed{\begin{array}{c}\text{updated reactive power output} \\ = \\ \text{scheduled} + \text{variation}\end{array}}$$

$\Delta Q_g^+ \geq 0$ and $\Delta Q_g^- \geq 0$, but not both positive in the optimal solution,

since the cost term

$$ct_{g,h}^+ \ \Delta Q_g^+ + ct_g^- \ \Delta Q_g^-$$

in the objective function has positive cost coefficients $ct_g^+ \geq 0$ and $ct_g^- \geq 0$.

Triangular capability constraints

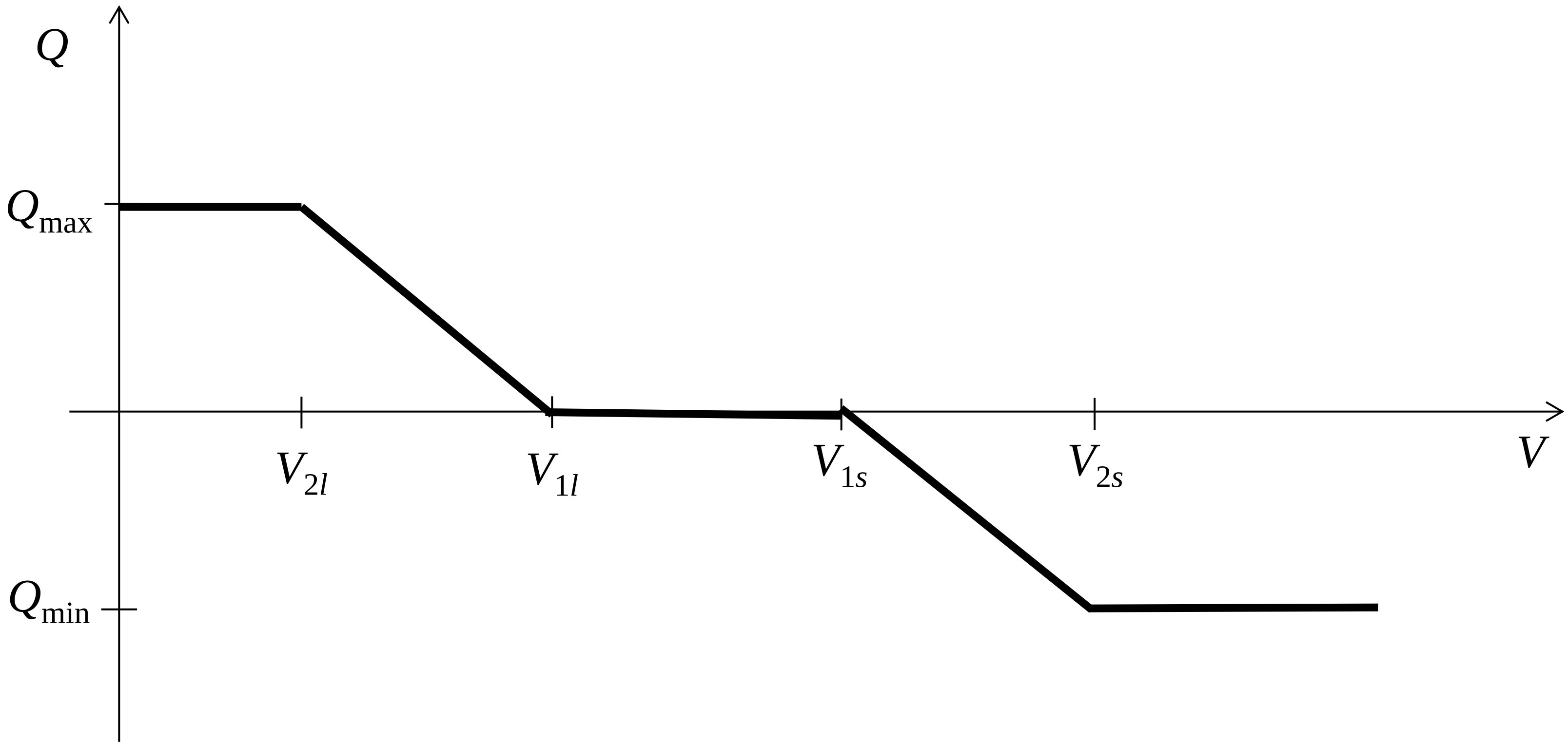
$$\underline{tg}_g \leq \frac{Q_g^0 + \Delta Q_g^+ - \Delta Q_g^-}{P_g^0 + \Delta P_g^+ - \Delta P_g^-} \leq \overline{tg}_g$$

Circular capability constraints

$$\sqrt{P_g^2 + Q_g^2} \leq \overline{|S|}_g$$

Droop curve $Q = f(V)$ for generators subject to local control

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



Approximated by a spline function to get rid of *discontinuity of first derivatives*, since a **Newton-type solver** is used.

Nodes: active power balance

$$\overbrace{\sum_{g\in\mathcal{G}_i}\left(P_g^0+\Delta P_g^+-\Delta P_g^-\right)}^{\text{sum of active power output of all generators located at node } i} = \underset{\substack{\uparrow \\ \text{active load}}}{C_i} + \overset{\substack{\text{shunt conductance} \\ \downarrow}}{G_i}\, V_i^2 + \underbrace{\sum_{(i,j)\in\mathcal{L}} TA_{i,j}}_{\text{sum of active power flows from node } i}$$

Lower and upper bounds on voltage: $\underline{V_i} \le V_i \le \overline{V}_i$.

Nodes: reactive power balance

$$\overbrace{\sum_{g \in \mathcal{G}_i} \left(Q_g^0 + \Delta Q_g^+ - \Delta Q_g^- \right)}^{\text{sum of reactive power output of all generators located at node } i} = \underbrace{D_i}_{\substack{\uparrow \\ \text{reactive load}}} + \overset{\substack{\text{shunt susceptance} \\ \downarrow}}{B_i} V_i^2 + \underbrace{\sum_{(i,j) \in \mathcal{L}} TR_{i,j}}_{\text{sum of reactive power flows from node } i}$$

Lines: active and reactive power flows

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

phase angle of node *i*

$$TA_{i,j} = \left(\frac{\cos \delta_{i,j}}{z_{i,j}} + x_{i,j}\right) V_i^2 - \frac{\cos\left(\delta_{i,j} + \theta_i - \theta_j\right)}{z_{i,j}} V_i \, V_j$$

active power flow on line (i, j)

series impedance

transversal conductance of node *i*

$$TR_{i,j} = \left(\frac{\text{sen}\, \delta_{i,j}}{z_{i,j}} - y_{i,j}\right) V_i^2 - \frac{\text{sen}\left(\delta_{i,j} + \theta_i - \theta_j\right)}{z_{i,j}} V_i \; V_j$$

reactive power flow on line (i, j)

transversal susceptance of node *i*

Lower and upper bounds on phase angle: $\underline{\theta}_i \leq \theta_i \leq \overline{\theta}_i$

Fixed ratio transformers: active and reactive power flows

rated power
of transformer
$\downarrow$

$$TA_{i,j} = \left(\frac{Sn_{i,j} \ \cos \delta_{i,j}}{Vn_{i,j}^2 \quad Z_{i,j}} + x_{i,j} \right) V_i^2 - \frac{Sn_{i,j} \cos\left(\delta_{i,j} + \theta_i - \theta_j\right)}{Vn_{i,j}\, Vn_{j,i} \ Z_{i,j}} V_i \, V_j$$

$\uparrow$ $\uparrow$

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

series impedance
of transformer

$$TR_{i,j} = \left(\frac{Sn_{i,j} \ \mathrm{sen}\, \delta_{i,j}}{Z_{i,j} \, Vn_{i,j}^2} - y_{i,j} \right) V_i^2 - \frac{Sn_{i,j} \ \mathrm{sen}\left(\delta_{i,j} + \theta_i - \theta_j\right)}{Z_{i,j} \, Vn_{i,j} \, Vn_{j,i}} V_i \, V_j$$

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

$$TA_{i,j} = \left(\frac{Sn_{i,j}\ \cos\delta_{i,j}}{Z_{i,j}\, Vn_{i,j}^2} + x_{i,j}\right) V_i^2 - \frac{Sn_{i,j}\cos\left(\delta_{i,j} + \theta_i - \theta_j\right)}{Z_{i,j}\, Vn_{i,j}\, \boldsymbol{TC_{j,i}}} V_i\, V_j$$

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

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

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

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

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

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

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

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

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

Determine

Pb_b : active power exchange between storage and network in period h

E_b : electricity stored at the end of period h

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

Qb_b : reactive power exchange between storage and network in period h

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

Storage devices: active power

$$E_b = E_{b,0} + Pb_b \, \Delta h$$

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

Pb_b : active power exchange between storage and network

Δh : period length (1 hour or fraction)

$$\underline{E}_b \leq E_b \leq \overline{E}_b$$

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

$$\underline{Pb}_b \leq Pb_b \leq \overline{Pb}_b$$

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

Storage devices: active power charge and discharge – losses

$$Pb_b = \Delta Pb_b^+ - \Delta Pb_b^-$$

$\Delta Pb_b^+ > 0$: active power discharge

$\Delta Pb_b^- > 0$: active power charge

(cost term in objective function $cb_b^+ \, \Delta Pb_b^+ + cb_b^- \, \Delta Pb_b^-$ with $cb_b^+, cb_b^- \geq 0$)

$$TA_{i,j} = \eta_b^+ \, \Delta Pb_b^+ - \eta_b^- \, \Delta Pb_b^-$$

$0 \leq \eta_b^+ \leq 1$: discharge loss coefficient

$0 \leq \eta_b^- \leq 1$: charge loss coefficient

Storage devices: reactive power

$$\underline{Qb}_b \leq Qb_b \leq \overline{Qb}_b$$

Qb_b : reactive power exchange between storage and network

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

$$Qb_b = \Delta Qb_b^+ - \Delta Qb_b^-$$

(cost term in objective function $ctb_b^+ \, \Delta Qb_b^+ + ctb_b^- \, \Delta Qb_b^-$ with $ctb_b^+, ctb_b^- \geq 0$)

$$TR_{i,j} = Qb_b^+$$

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

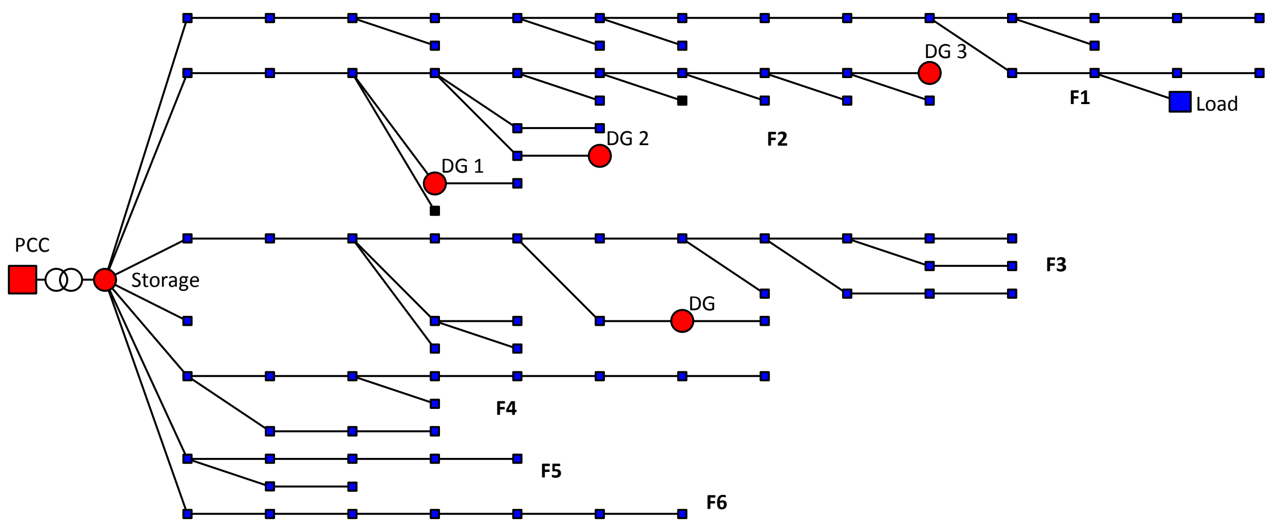
<u>Same solution</u> computed by the 2 codes, but with different computational times :

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

Numerical example

Distribution network developed in the Atlantide project with

- 4 controllable generators (DG1, DG2, DG3, DG4)
- 1 storage device
- 1 controllable load



Possible current congestions in feeder 2 and voltage congestions in feeders 1 and 2.

Distributed flexibility resourse: capabilities and costs of power variations

resource (g)	capability shape	$\overline{\lvert S \rvert}_g$	Q_g^0	$\underline{Q}_g$	$\overline{Q}_g$	P_g^0	$\underline{P}_g$	$\overline{P}_g$	$c_g^{\Delta P^+}$	$c_g^{\Delta P^-}$
Storage	circular	1.1	0	–1	1	0	–1	1	50	0
DG 4	circular	2	0	–1	1	1	1	2	100	80
DG 1	triangular ($pf = 0.9$)	2	0	–0.5	0.5	1	0	1	120	100
DG 2	triangular ($pf = 0.9$)	1	0	–0.5	0.5	0.5	0	0.5	120	100
DG 3	triangular ($pf = 0.9$)	2	0	–0.5	0.5	0	0	1	120	100
Load	constant ($pf = 0.9$)	2	–0.4	–0.4	0	–0.8	–0.8	0	220	––

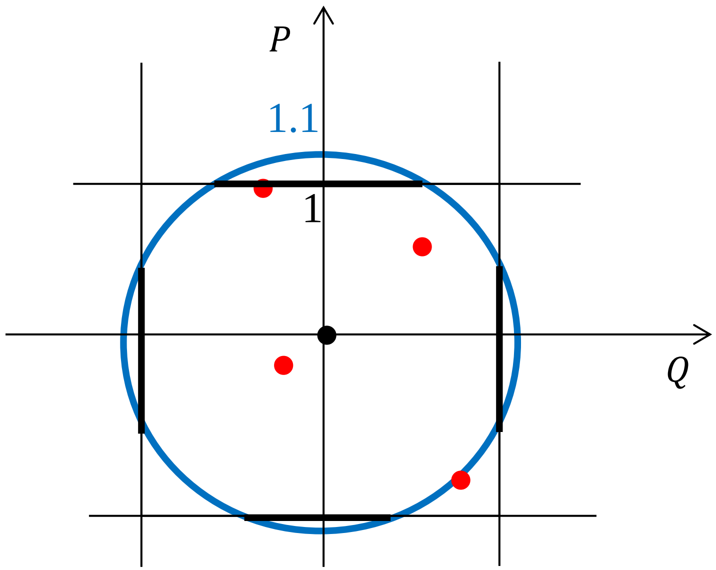
resource	up	down
STORAGE	**50**	**0**
DG 4	**100**	
DG 1		**100**
DG 2		**100**
DG 3	**120**	
LOAD	**220**	

Distributed resource: storage device

Capability: circular ($\overline{|S|}_{STO} = 1.1\ MVA$)

$\cap$ rectangular

	$[MW]$	$[€/MW]$
$\overline{P}_{STO}$	1	$c_{STO}^{\Delta P^+} = 50$
$\boldsymbol{P_{STO}^0}$	**0**	
$\underline{P}_{STO}$	-1	$c_{STO}^{\Delta P^-} = 0$



	$\underline{Q}_{STO}$	$\boldsymbol{Q_{STO}^0}$	$\overline{Q}_{STO}$
$[MVAr]$	-1	**0**	1
$[€/MVAr]$	$c_{STO}^{\Delta Q^-} = 0$		$c_{STO}^{\Delta Q^+} = 0$

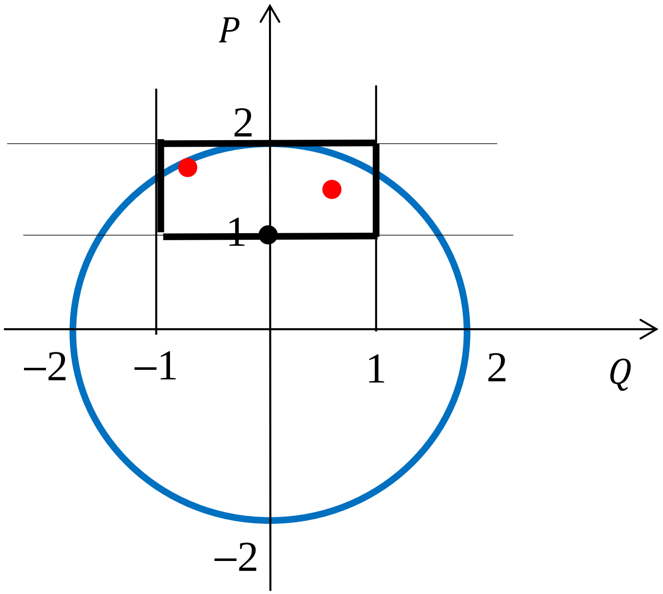
$$COST_{STO} = 50 \cdot \Delta P_{STO}^{+}$$

Distributed resource : DG4

Capability: circular ($\overline{|S|}_{DG4} = 2\ MVA$)

∩ rectangular

	$[MW]$	$[€/MW]$
$\overline{P}_{DG4}$	2	$c_{DG4}^{\Delta P^+} = 100$
$\boldsymbol{P_{DG4}^0}$	**1**	
$\underline{P}_{DG4}$	1	$c_{DG4}^{\Delta P^-} = 80$



	$\underline{Q}_{DG4}$	$\boldsymbol{Q_{DG4}^0}$	$\overline{Q}_{DG4}$
$[MVAr]$	−1	**0**	1
$[€/MVAr]$	$c_{DG4}^{\Delta Q^-} = 0$		$c_{DG4}^{\Delta Q^+} = 0$

$$COST_{DG4} = 80 \cdot \Delta P_{DG4}^{-} + 100 \cdot \Delta P_{DG4}^{+}$$

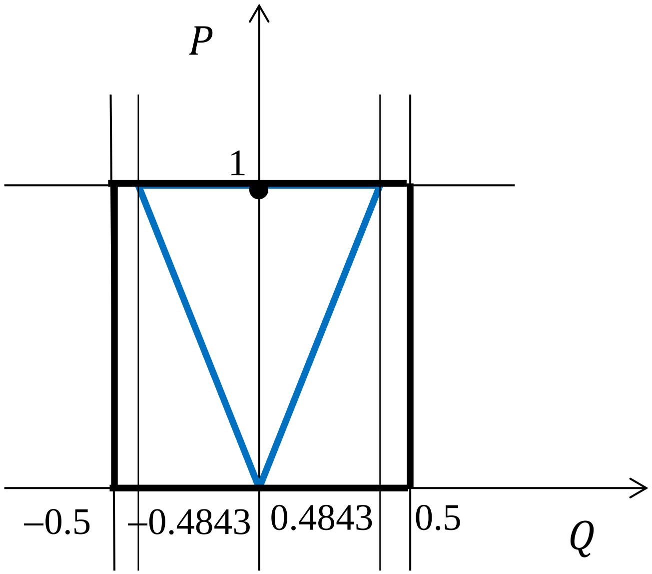
Distributed resource: DG1

Capability: triangular ($\cos\varphi = 0.9$)

$\cap$ circular ($\overline{|S|}_{DG1} = 2\ MVA$) (ridondante)

$\cap$ rectangular

	$[MW]$	$[€/MW]$
$\overline{P}_{DG1}$	1	$c_{DG1}^{\Delta P^+} = 120$
$\boldsymbol{P_{DG1}^0}$	**1**	
$\underline{P}_{DG1}$	0	$c_{DG1}^{\Delta P^-} = 100$



	$\underline{Q}_{DG1}$	$\boldsymbol{Q_{DG1}^0}$	$\overline{Q}_{DG1}$
$[MVAr]$	–0.5	**0**	0.5
$[€/MVAr]$	$c_{DG1}^{\Delta Q^-} = 0$		$c_{DG1}^{\Delta Q^+} = 0$

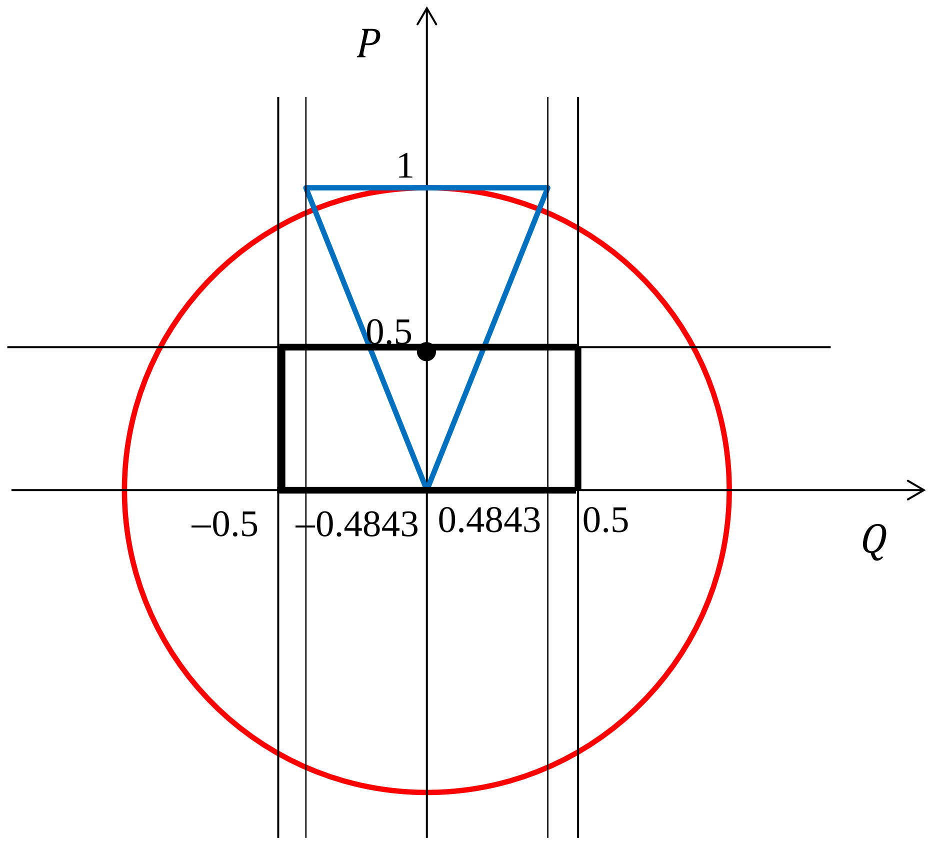
$$COST_{DG1} = 100 \cdot \Delta P_{DG1}^- + 120 \cdot \Delta P_{DG1}^+$$

Distributed resource : DG2

Capability: triangolare ($\cos\varphi = 0.9$)

$\cap$ circular ($\overline{|S|}_{DG2} = 1\ MVA$)

$\cap$ rectangular



	$[MW]$	$[€/MW]$
$\overline{P}_{DG2}$	0.5	$c_{DG2}^{\Delta P^+} = 120$
$\boldsymbol{P_{DG2}^{0}}$	**0.5**	
$\underline{P}_{DG2}$	0	$c_{DG2}^{\Delta P^-} = 100$

	$\underline{Q}_{DG2}$	$\boldsymbol{Q_{DG2}^{0}}$	$\overline{Q}_{DG2}$
$[MVAr]$	−0.5	**0**	0.5
$[€/MVAr]$	$c_{DG2}^{\Delta Q^-} = 0$		$c_{DG2}^{\Delta Q^+} = 0$

$$COST_{DG2} = 100 \cdot \Delta P_{DG2}^{-} + 120 \cdot \Delta P_{DG2}^{+}$$

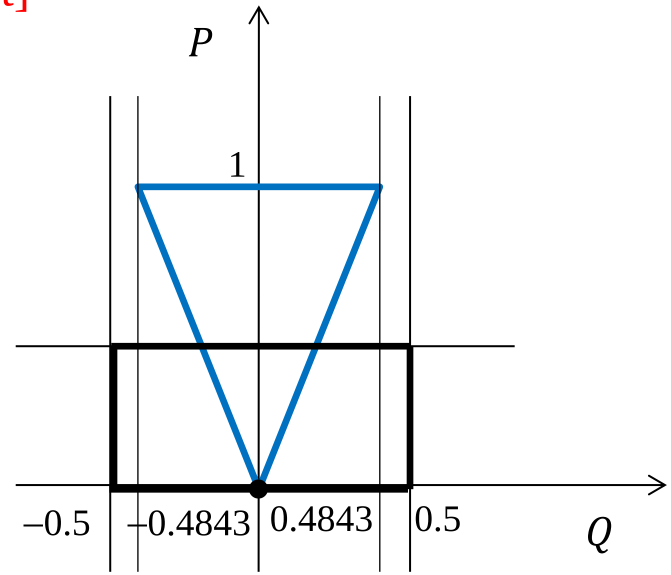
Distributed resource : DG3

Capability: triangular ($\cos\varphi = 0.9$)

$\cap$ circular ($\overline{|S|}_{DG3} = 2\ MVA$) [ridundant]

$\cap$ rectangular

	$[MW]$	$[€/MW]$
$\overline{P}_{DG3}$	1	$c_{DG3}^{\Delta P^+} = 120$
$\boldsymbol{P_{DG3}^0}$	**0**	
$\underline{P}_{DG3}$	0	$c_{DG3}^{\Delta P^-} = 100$



	$\underline{Q}_{DG3}$	$\boldsymbol{Q_{DG3}^0}$	$\overline{Q}_{DG3}$
$[MVAr]$	–0.5	**0**	0.5
$[€/MVAr]$	$c_{DG3}^{\Delta Q^-} = 0$		$c_{DG3}^{\Delta Q^+} = 0$

$$COST_{DG3} = 100 \cdot \Delta P_{DG3}^{-} + 120 \cdot \Delta P_{DG3}^{+}$$

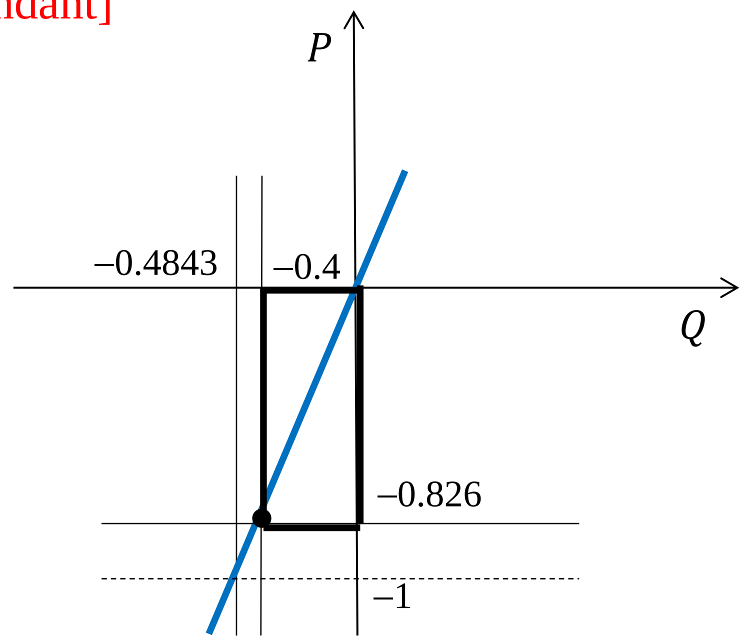
Distributed resource : load

Capability: constant power factor ($\cos\varphi = 0.9$) [straight line through (0, 0) and (–0.4843, – 1)]

$\cap$ circular ($\overline{|S|}_{LOAD} = 2\ MVA$) [ridundant]

$\cap$ rectangular

	$[MW]$	$[€/MW]$
$\overline{P}_{LOAD}$	0	$c_{LOAD}^{\Delta P^+} = 220$
$\boldsymbol{P_{LOAD}^0}$	**– 0.826**	
$\underline{P}_{LOAD}$	– 0.826	---



$\underline{Q}_{LOAD}$	$\boldsymbol{Q_{LOAD}^0}$	$\overline{Q}_{LOAD}$
$[MVAr]$	$[MVAr]$	$[MVAr]$
–0.4	**–0.4**	0

$$COST_{LOAD} = 100 \cdot \Delta P_{LOAD}^{-} + 120 \cdot \Delta P_{LOAD}^{+}$$

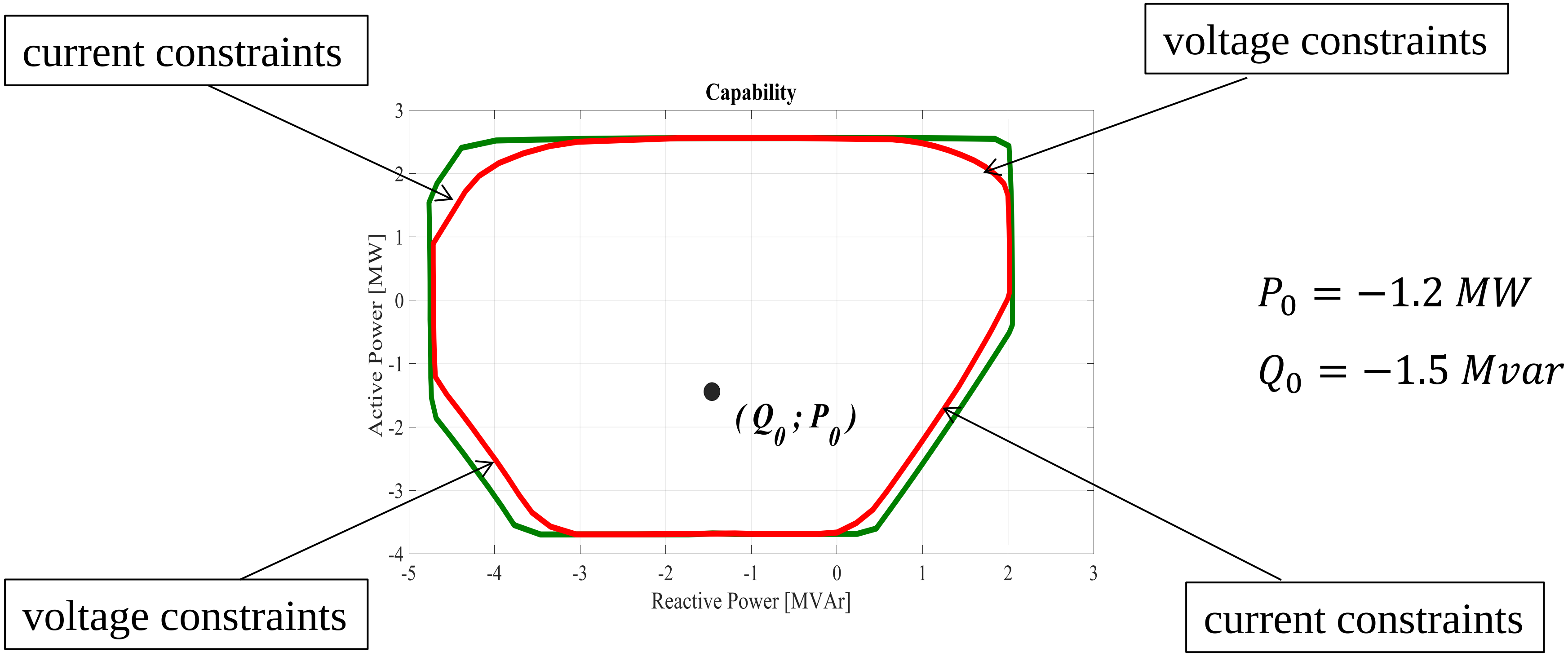
Computing the aggregated feasibility

Without network constraints:

Minkowsky sum of capabilities of single generators (green line)

With network constraints :

Voltage or current constraints become active (red line)



$$P_0 = -1.2\ MW$$

$$Q_0 = -1.5\ Mvar$$

Estimating costs in the capability area

Initialization:

Resources in *non decreasing cost* order

Iterative process:

at iteration k compute the maximum capability and the associated cost

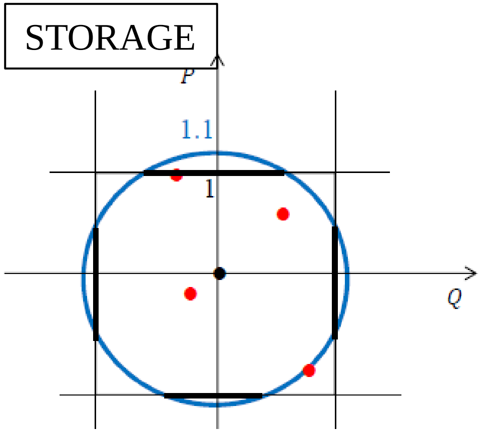
using the first k risources in this ordering

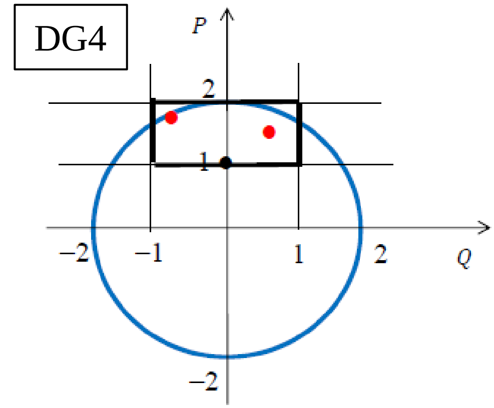
Good approximation in the interior of the capability region

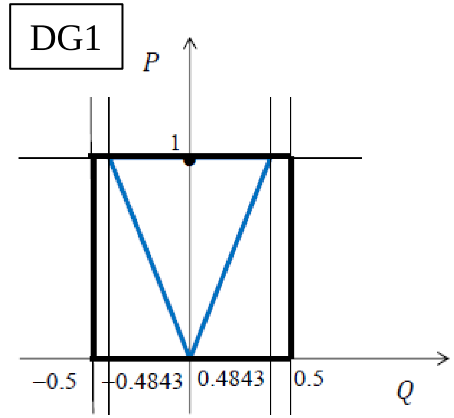
Near to the border voltage and current constraints become active

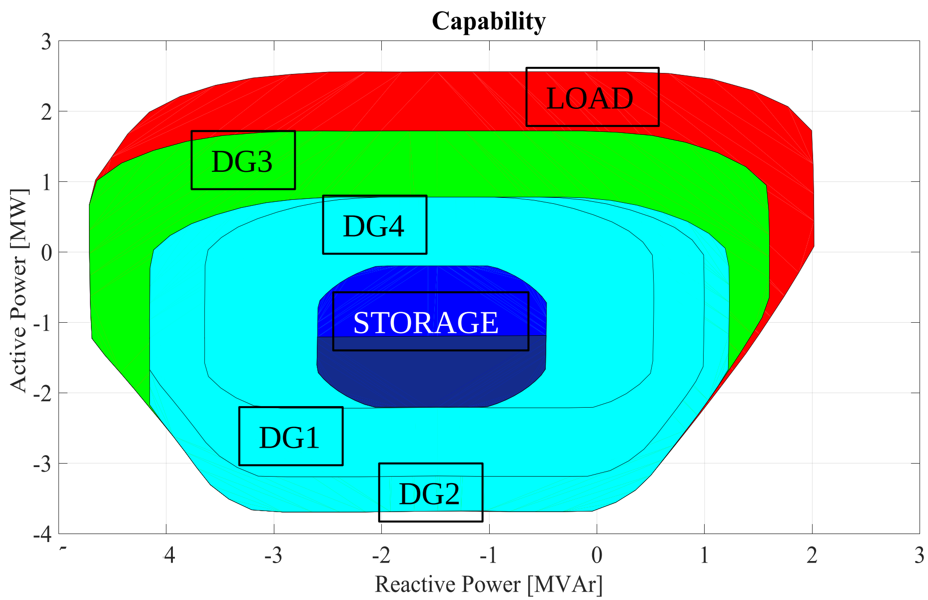
$\Rightarrow$ In order to avoid congestions, the resources must be coordinated in a

more complex way

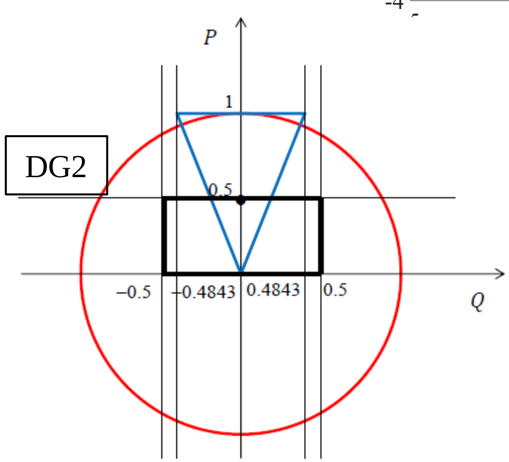


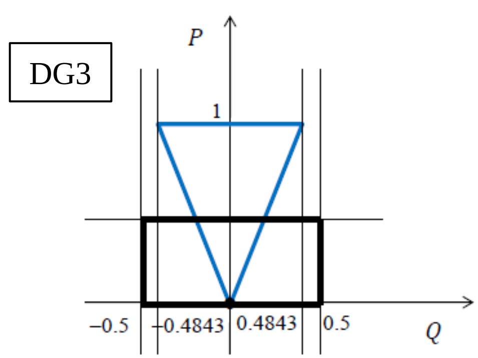


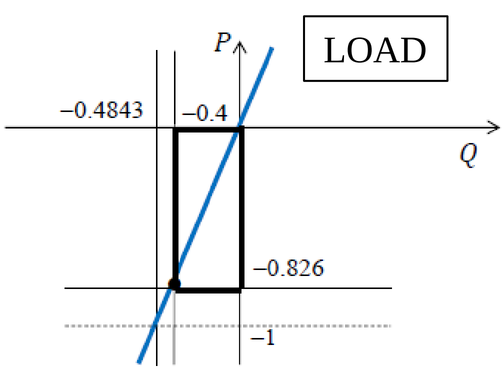




resource	up	down
STORAGE	**50**	**0**
DG 4	**100**	
DG 1		**100**
DG 2		**100**
DG 3	**120**	
LOAD	**220**	







Detemine the cost of the aggregated capability taking into account network constraints

Solve the optimization model for a grid of points in the capability area of (Q, P) plane

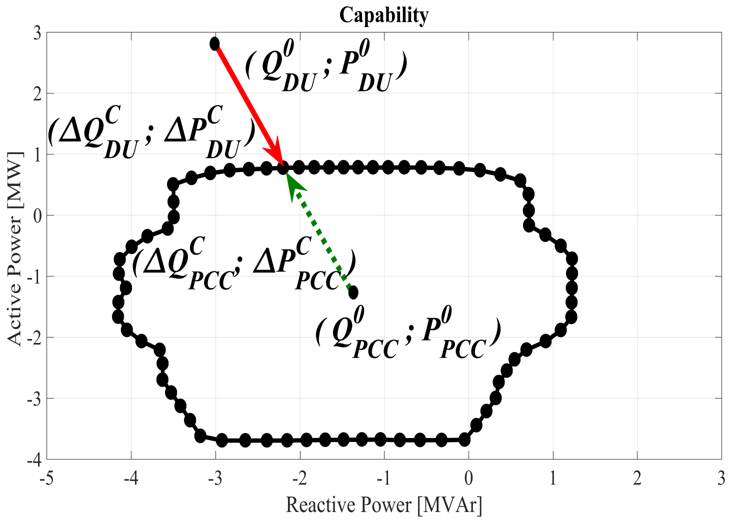
e.g.: $(\pm 5\ MW, \pm 5\ Mvar)$with precision 0.1 MW requires solving the NLP model 10 000 times

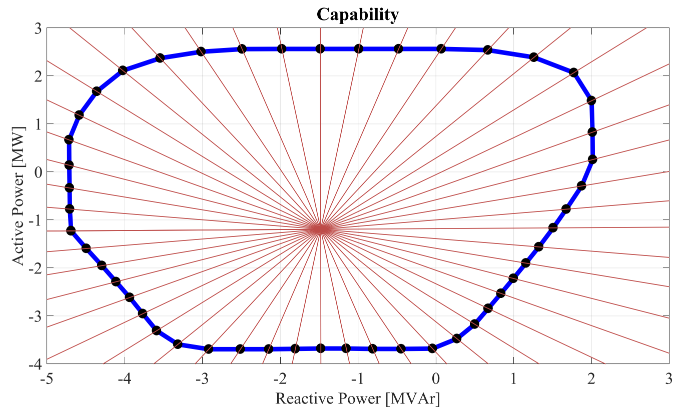
Faster methodologies have therefore been developed

1. **Radial reconstruction**
2. **Mesh reconstruction**

1. **Radial reconstruction** (consider a fixed power) is suitable

   for a market where the total apparent power variation is remunerated





2. **Mesh reconstruction** is suitable

   for a market that accepts separate bids for active and reactive power

   or

   when the market is resolved sequentially for active and reactive power

Conclusions

We propose a procedure that allows to

- maximize the participation of distributed resources to ancillary services
  (DSO may use his own assets: OLTC, capacitors, compensators,…)

- determine the bid price for the aggregated resources