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# Deploying OPF tools for future clean energy sources dominated electric grids

Valentin Ilea

05.11.2025

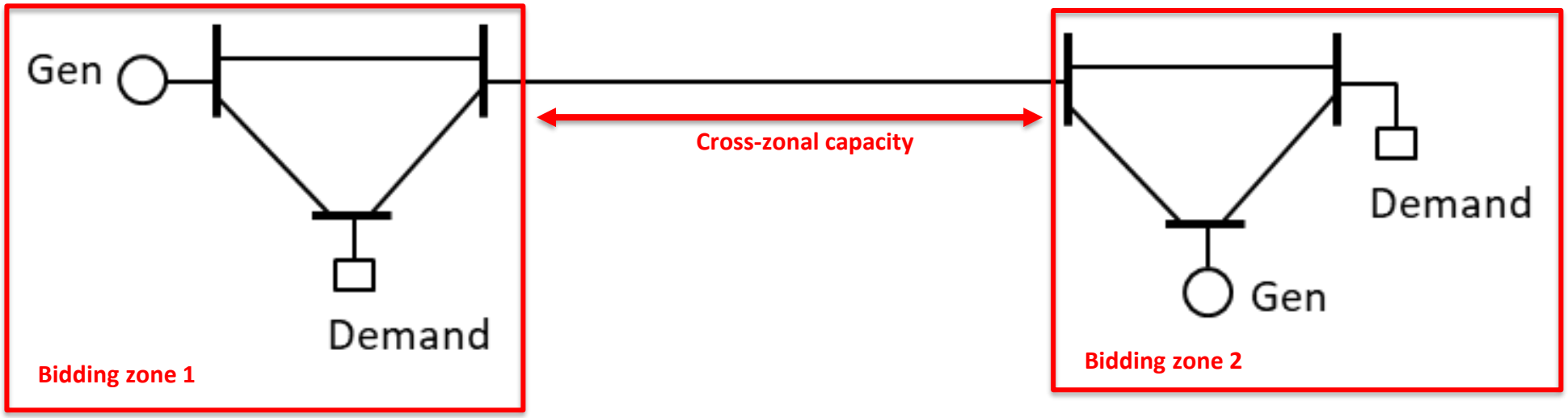
Department of Energy

# About me

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Associate Professor in Electric Power Systems
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Italy

- The Day-ahead Energy Market in Europe is a ***zonal market***: the *European Power System* is divided into **bidding zones** between which the power exchanged is limited by the available **cross-zonal capacity**




- The solution of the market strongly depends on the congestion of the equivalent connections representing the cross-zonal capacity

# 01 - Model-based BZ Configurations - Background

- ***The market efficiency is continuously monitored at EU level***: every 3 years, Entso-E publishes a technical report containing the congestions registered in the last 3 years and the related costs

- ***A European Bidding Zone Review Process has been formally launched by the recent Clean Energy Package, Regulation (EU) 2019/943*** and the identification of alternative Bidding Zones configurations is a crucial task in this framework

- There are mainly ***two approaches*** to define alternative bidding zones **(BZ)** configurations:
  - ***expert-based***, that relies on the experience and knowledge of the TSO
  - ***model-based***, that relies on mathematic models

- The ***Italian National Regulatory Authority asked the Italian TSO to investigate model-based approaches to adopt in future national BZ Review processes***

Terna Rete Italia
TERNA GROUP

Italian TSO
- 72000 km of HV lines
- over 10 BILLION € of investments into developing transmission infrastructure over next years (2030, 2035, and beyond)

ensiel
ENERGIA E SISTEMI ELETTRICI

Politecnico di Torino
Dipartimento Energia "G.Ferraris"

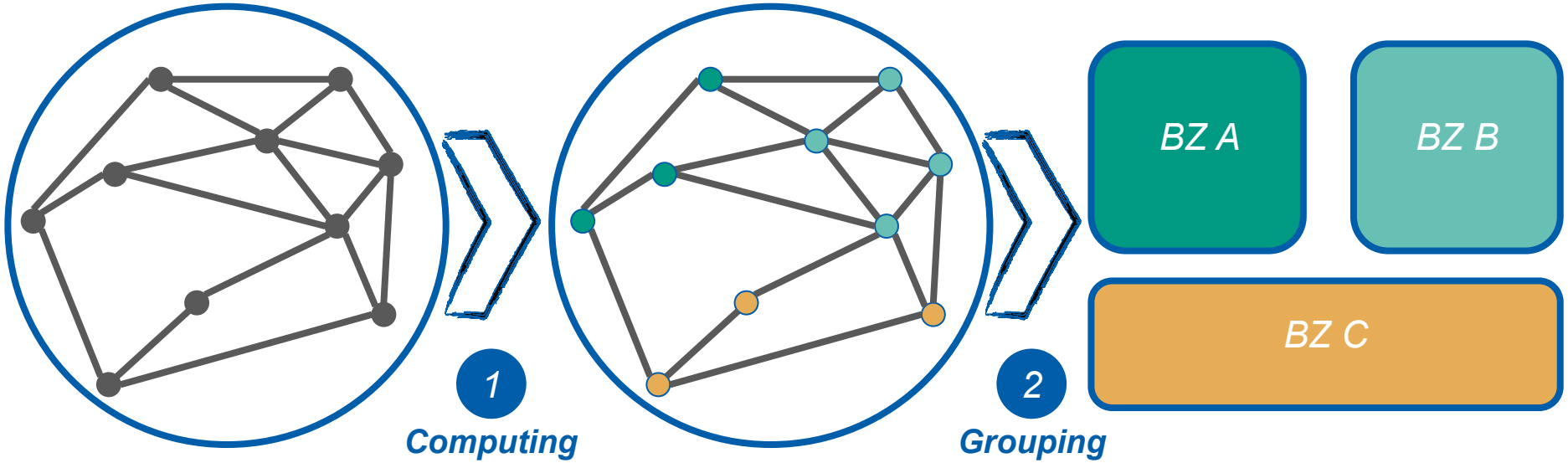
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UNIVERSITÀ DI PAVIA

"Energy and Electric Power Systems"national inter-University Consortium:
- 21 Italian universities
- recognized by the Italian Government
- 3 Ensiel Units involved in the project (Politecnico di Milano, Politecnico di Torino, Università di Pavia)

# 01 - Model-based BZ Configurations - Main steps

**From a nodal world…** **…to a zonal prospective**




**LMPs**
***Locational Marginal/Nodal Prices***

*The price at each node represents the locational value of energy i.e. cost of supplying extra 1MW of energy to node.*

**PTDFs**
***Power Transfer Distribution Factors***

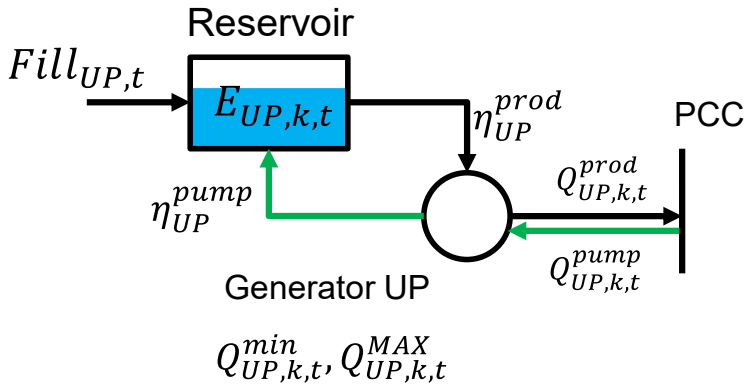
*For a (node;CBCO) pair, nodal PTDF represents how much power flow on the CBCO changes, after increasing by 1MW the injection at the given node.*

# 01 - Model-based BZ Configurations - OPF nodal market formulation

- An accurate representation (at nodal level) of the transmission network is necessary => a **DC power flow (PF) based optimization model**, has been adopted

- Constraints are adopted that model:
  - The ***Italian market rules*** to obtain the power production of generators
  - The ***N security conditions***: DC PF equations, power flow branches constraints, generation capability constraints etc.
  - The ***N-1 corrective security conditions*** using first-order sensitivities to calculate the branch power flows following outages and the effect of corrective actions; both branch and generator outages are considered
  - ***Maximum flow constraints*** on network interfaces for weakly meshed parts of the grid to assess potential voltage issues

- ***Hydro Reservoir*** constraints for managing hydroelectric and Pumped-Storage Hydroelectric Power Plants

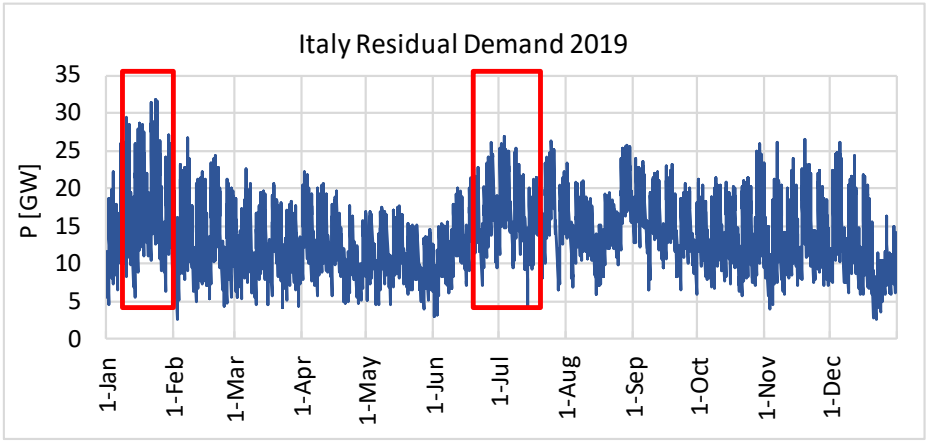


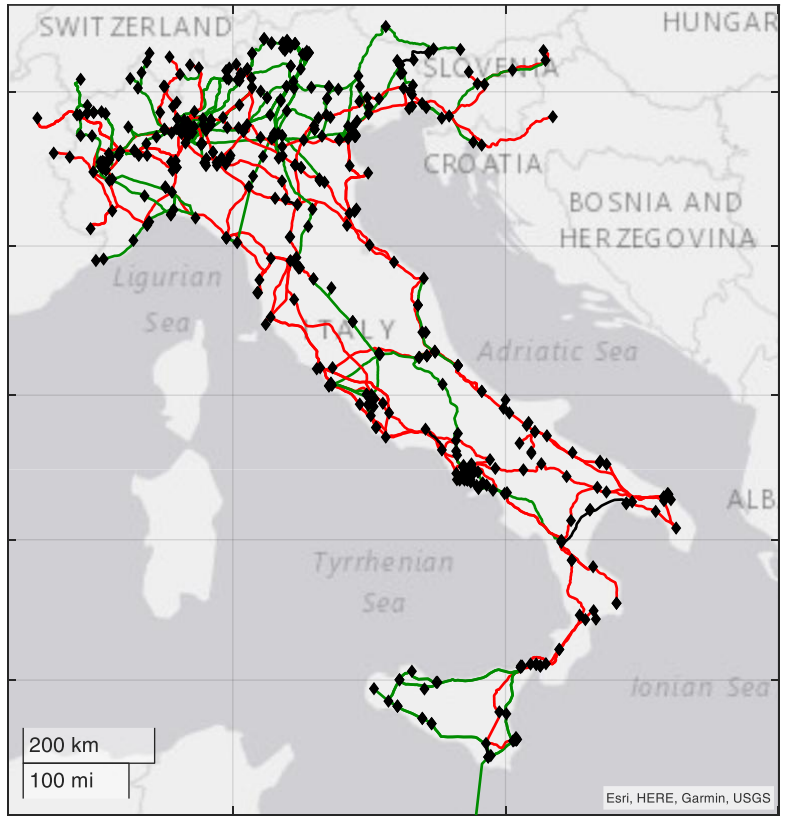

- ***Tertiary Reserve*** constraints to provide a minimum level of generation reserve at area level as capability to keep the network frequency at nominal value

- the ***LMPs*** are given by the Lagrangian multipliers of the DC PF equations, while the PTDFs are calculated for the congested branches at optimal solution

# 01 - Model-based BZ Configurations - Application to Italian TN - Data

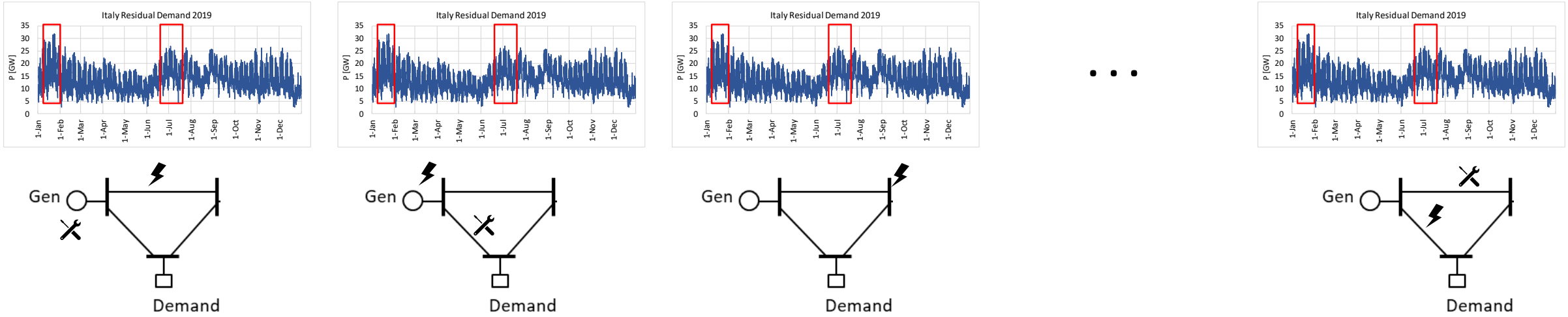
- The power system considered is the *Italian High Voltage* (HV) transmission
- The *Sardinia Island* is *not* included as its connection with continental Italy is in HVDC
- To determine the *operating scenarios*, the year 2019 is considered and, for simplification, each day is reduced to six significant hours, namely 4:00, 8:00, 12:00, 16:00, 18:00 and 22:00
- *Net demand* (total minus imports) of the Italian TN is shown bellow. *Two periods* with peak demand are identified: beginning of the year (winter), and middle of summer



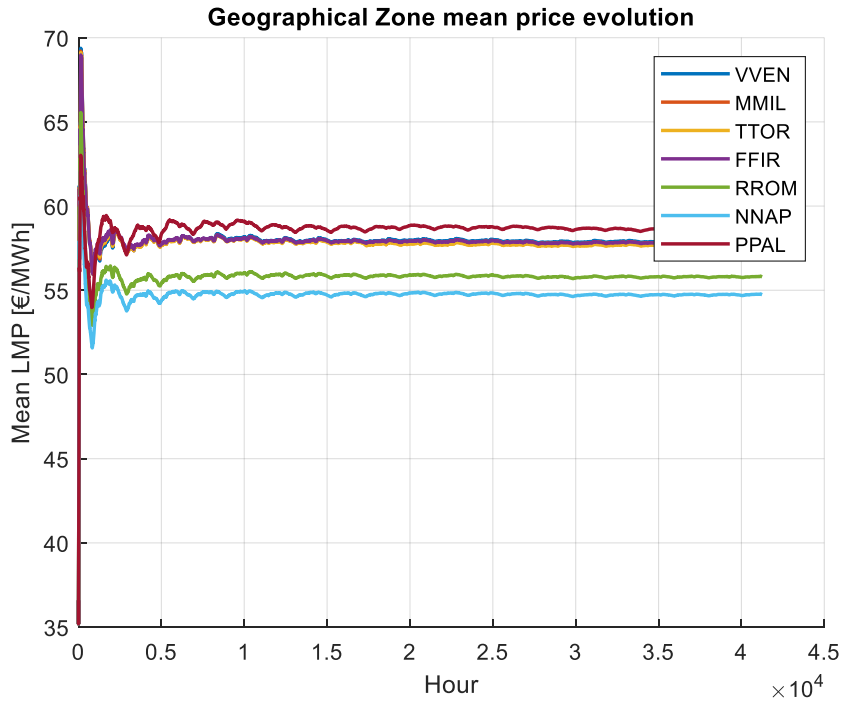
# 01 - Model-based BZ Configurations - Application to Italian TN - Data

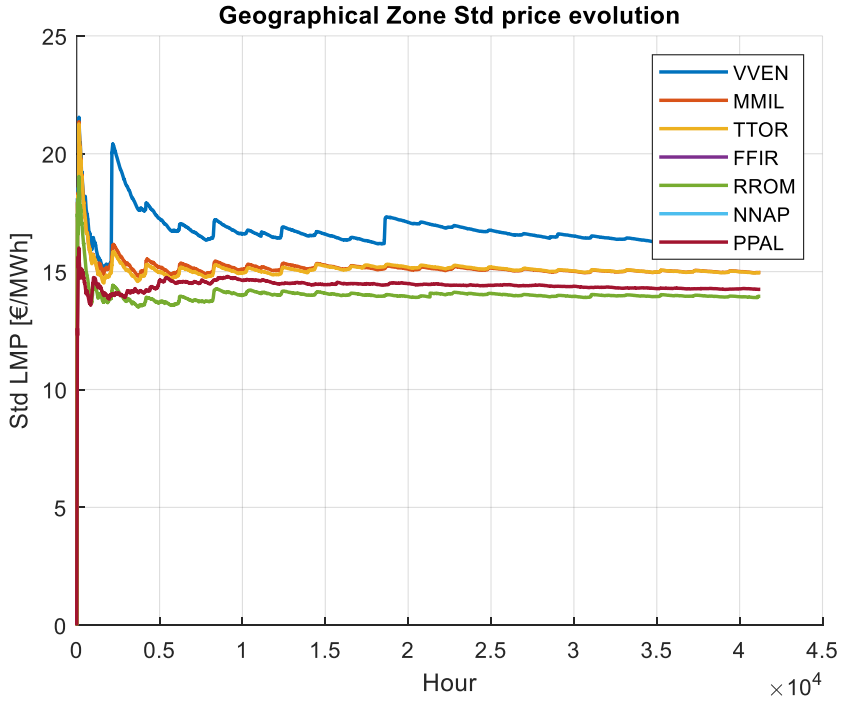
- The data set is extended under a *Monte Carlo approach* by replicating the year many times and considering unprogrammed faults (UF) and scheduled maintenances (SM) of the electric branches and UPs



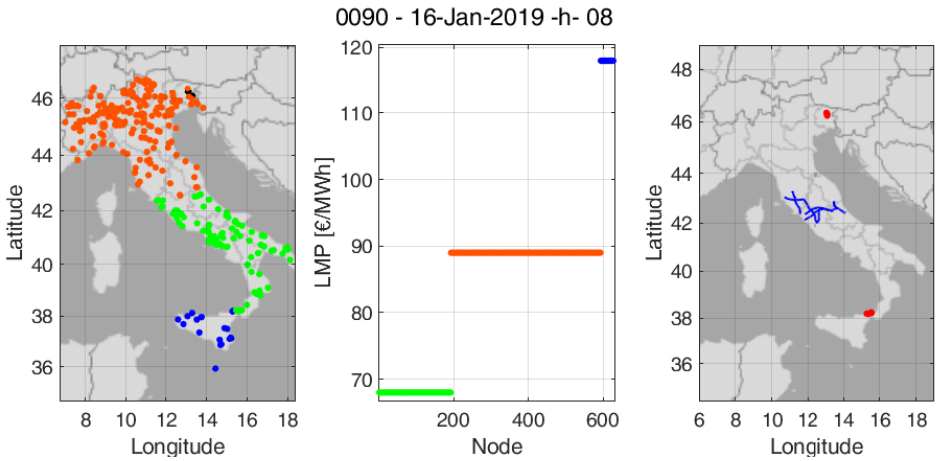

- the *number of UF and SM* in the considered period is randomly generated using the *Poisson distribution* and the mean number of UF/SM per year ($\mu_P$) as parameter. The *duration of the UF/SM event* is randomly generated using the *Gamma distribution* and the mean and standard deviation of the event duration ($\mu_G$ and $\sigma_G$) as parameters.

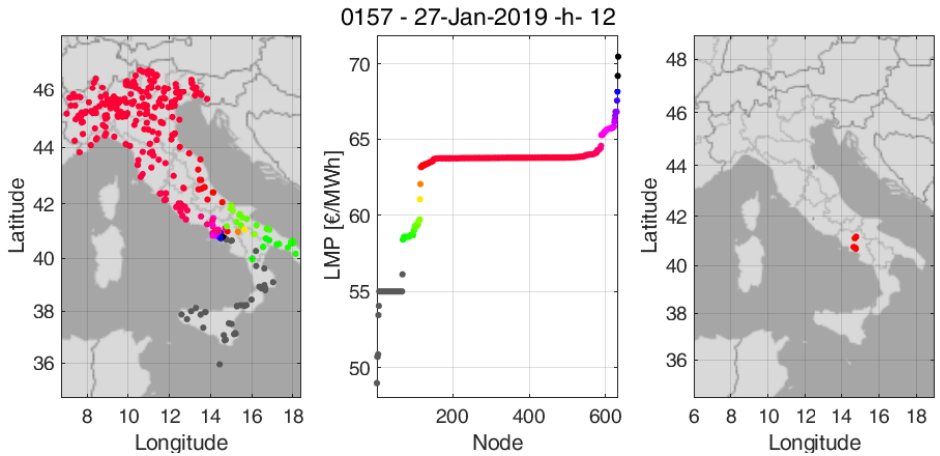
# 01 - Model-based BZ Configurations - Application to Italian TN - Results

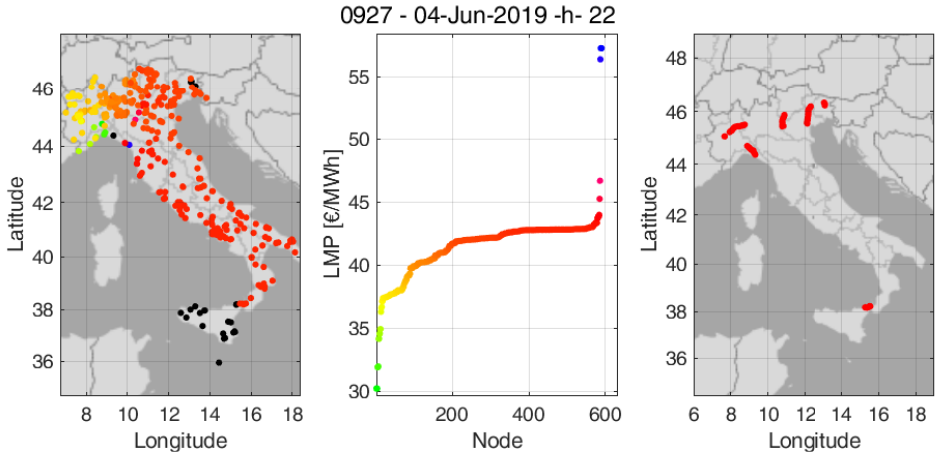


# 01 - Model-based BZ Configurations - Application to Italian TN - Results

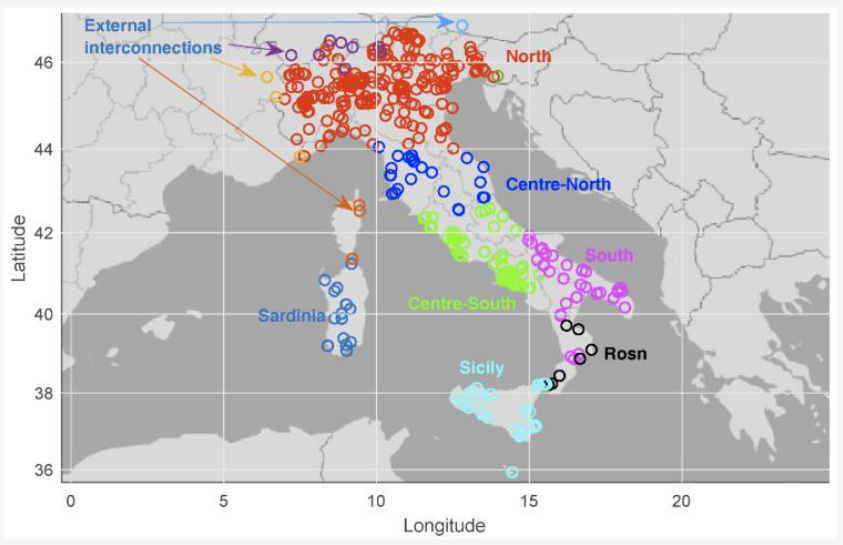


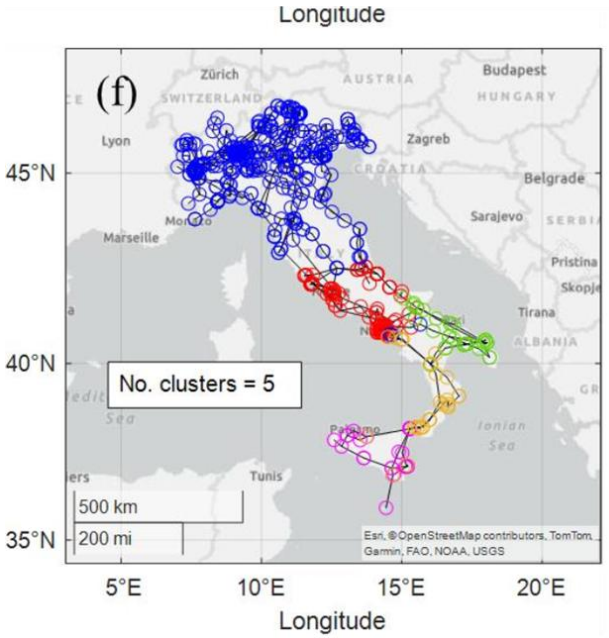



# 01 - Model-based BZ Configurations - Application to Italian TN - Results

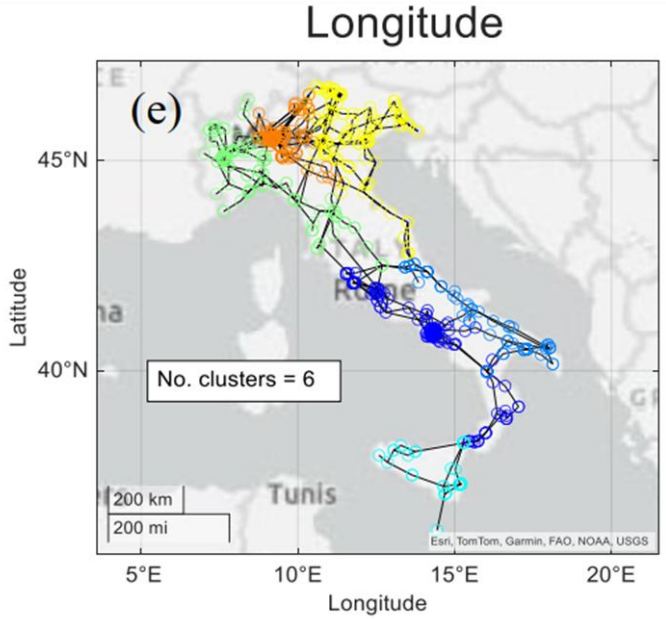
## Existing Real-Life Configuration

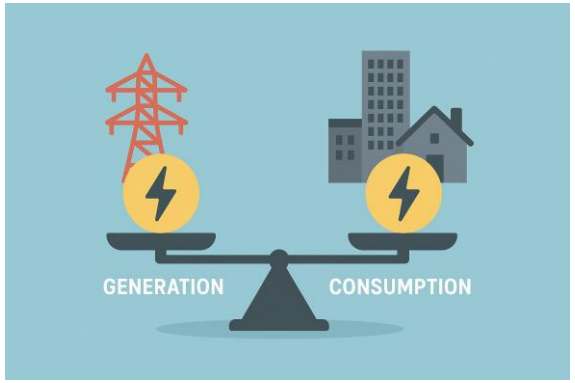


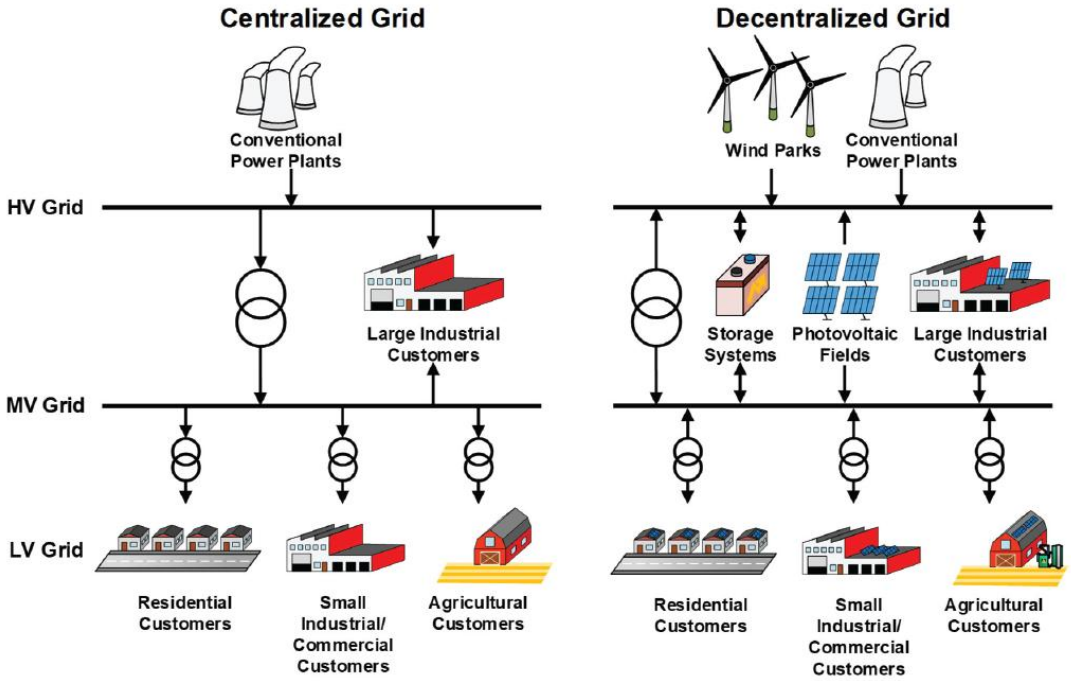

## Clustering Algorithm A




## Clustering Algorithm B






- Transition from managing a few centralized plants to coordinating a multitude of small-scale DERs.
- Low observability (still), especially at LV level.

- Need for new tools enable the communication of grid status
- and aggregated flexibility capabilities without exposing sensitive system information.
- Need for real-time measurement infrastructure.

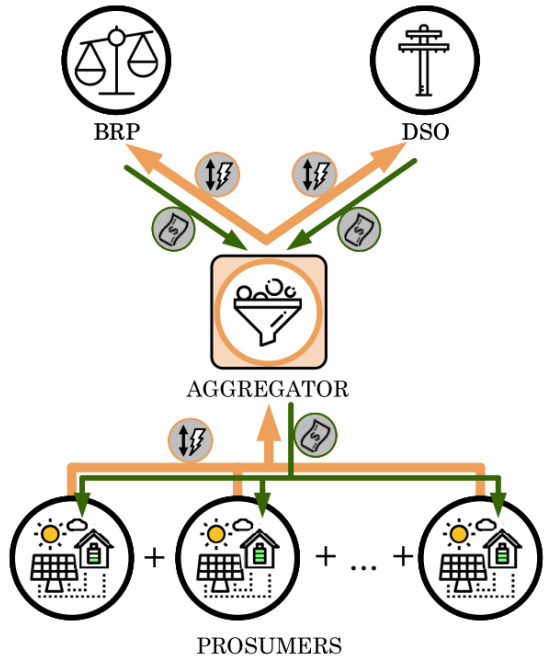
# 02 – Optimal management of DNs – Local flexibility markets (LFMs)

- A platform that facilitates the exchange of flexibility services between resource providers (typically aggregators, prosumers, or other distributed asset owners) and buyers, mainly DSOs and, in some cases, BRPs.
- They enable DSOs to procure flexibility services while addressing local grid constraints.
- DERs can be activated for specific, localized purposes that contribute to the secure and economical operation of the grid.

📜 **Aligned with EU Clean Energy Package (CEP):**
- Supports *market-based* procurement of flexibility
- Engages *aggregators, prosumers, energy communities.*

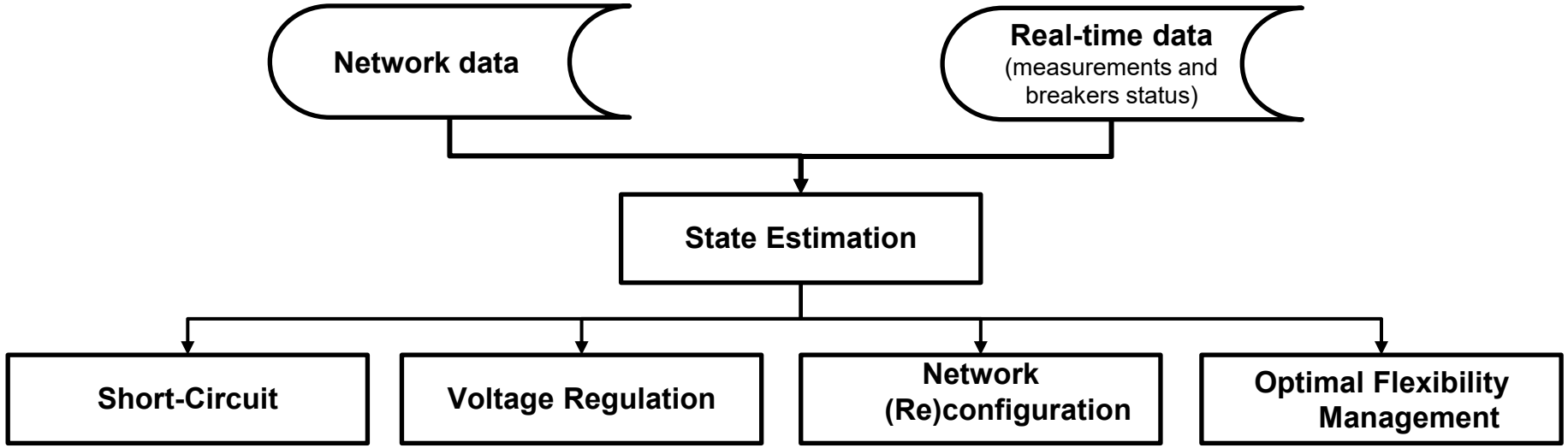
🏛️ **Guidance from ENTSO-E:**
- Enable DERs to provide services *where most needed and valued.*

🤝 **Encouraged for DSOs:**
- Use *transparent* and *competitive* processes.

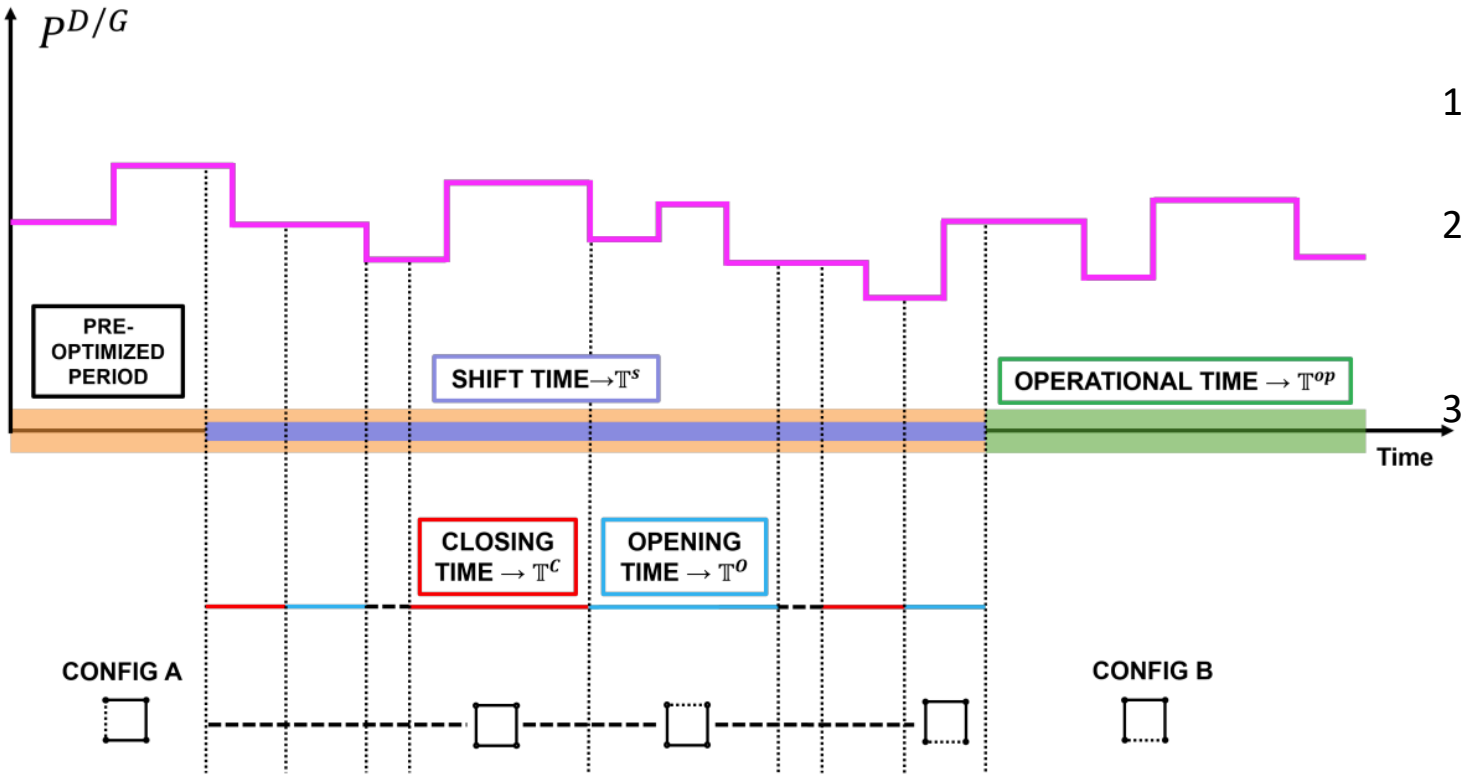


SIEMENS **Grid Software Business Unit, Siemens SpA, Milano, Italy**

POLITECNICO MILANO 1863 DIPARTIMENTO DI ENERGIA **Electrical Division - Department of Energy**

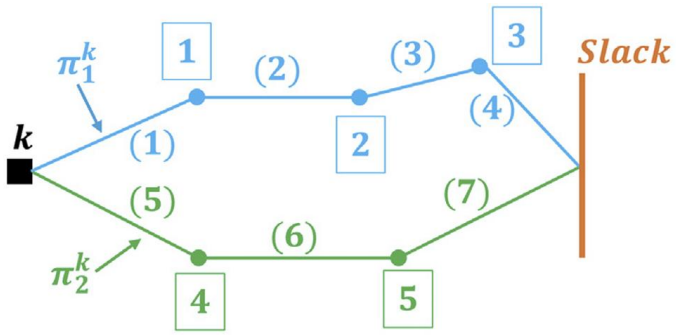


# 02 – Optimal Network Reconfiguration - Overview




**Assumption: perfect knowledge of demand and generation power profiles.**

1. CONFIG A
2. Define CONFIG B (based on an objective function) and the optimal sequence of maneuvers
3. Compliance with technical constraints during SHIFT and OPERATIONAL TIME; maximum current, maximum and minimum voltage, Rapid Voltage Change-RVC (a rapid lowering of the RMS value of the nodal voltage during switching maneuvers*).




$$\mathbb{P}^k = \{\pi_1^k, \pi_2^k, \ldots, \pi_p^k, \ldots, \pi_{np}^k\}$$

$$W_{p,t}^k = \begin{cases} 1 & \text{if } \pi_p^k \text{ is the active path for bus } k \text{ at time } t \\ 0 & \text{otherwise} \end{cases}$$

$$\sigma_{j,t} = \begin{cases} 1 & \text{if branch } j \text{ is connected at time } t \\ 0 & \text{otherwise} \end{cases}$$

A candidate sub-network is both connected and radial if the following constraints are satisfied during $\mathbb{T}^o$ time intervals:

- each node has one active path only:

$$\sum_{p \in \mathbb{P}^k} W_{p,t}^k = 1, \ \forall\, k \in \mathbb{N}^\nabla \ \& \ \forall\, t \in \mathbb{T}^o$$

- if a path is active, all the branches belonging to the path must be connected:

$$\tilde{N}_p^k W_{p,t}^k \leq \sum_{j \in \beta_{\pi_p^k}} \sigma_{j,t}, \ \forall\, k \in \mathbb{N}^\nabla \ \& \ \forall\, t \in \mathbb{T}^o$$

- if a path is not active, at least one branch within the path must be opened:

$$(\tilde{N}_p^k - 1)(1 - W_{p,t}^k) \geq \sum_{j \in \beta_{\pi_p^k}} \sigma_{j,t}, \ \forall\, k \in \mathbb{N}^\nabla \ \& \ \forall\, t \in \mathbb{T}^o$$

E. Ramos, A. Exposito, J. Santos, and F. Iborra, “Path-based distribution network modeling: application to reconfiguration for loss reduction,” IEEE Trans. on Power Systems, vol. 20, no. 2, 2005.

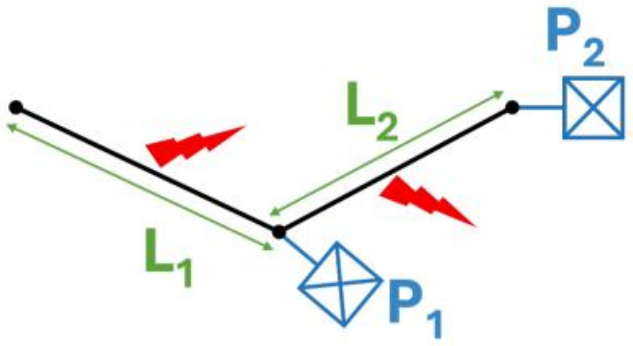
# 02 – Optimal Network Reconfiguration - Security of supply maximization

- A fault can occur anywhere along the feeder length with the same probability
- Longer line → higher probability that a failure will occur to it

$$Pr(\Lambda_{\hat{j}}) = \frac{L_{\hat{j}}}{\sum_{j \in \mathbb{B}} L_j} = \tilde{\rho}_{\hat{j}}$$

✅ **No need for fault probability information**

- Greater number of users connected to a line → greater damage caused by the line possible disconnection

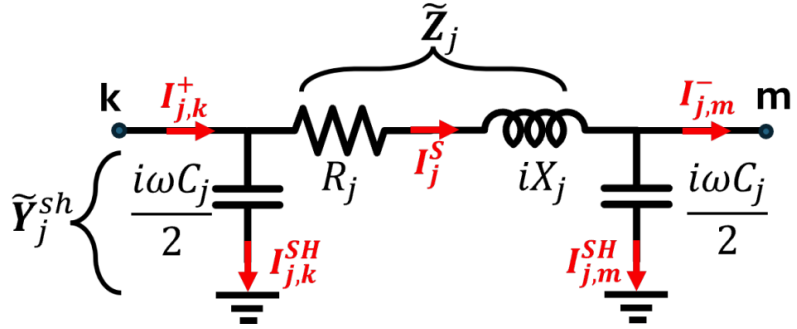



$$\Xi = \tilde{\rho}_1(P_1 + P_2) + \tilde{\rho}_2 P_2 = \tilde{\rho}_1 P_1 + (\tilde{\rho}_1 + \tilde{\rho}_2) P_2$$

$$OF = \min \Xi$$

$$\Xi = \sum_{\substack{k \in \mathbb{N}^{\nabla} \\ p \in \mathbb{P}^{\mathbb{N}} \\ t \in \mathbb{T}^{op}}} [W_{p,t}^{k} \sum_{j \in \beta_{\pi_p^k}} \tilde{\rho}_j \sum_{k \in \eta_{\pi_p^k}} \eta_{\pi_p^k} (\tilde{P}_{k,t}^{D} + \sum_{g \in \eta^{\mathbb{G}}} \tilde{P}_{g,t}^{G})]$$

# 02 – Optimal Network Reconfiguration – Power flow constraints model




$$\sum_{g\in\eta^{\mathbb{G}}} \boldsymbol{I}^G_{g,t} - \boldsymbol{I}^D_{k,t} = \sum_{j\in\mathbb{B}^+_k} \boldsymbol{I}^+_{j,t} - \sum_{j\in\mathbb{B}^-_k} \boldsymbol{I}^-_{j,t},\ \forall\, k\in\mathbb{N}$$

$$\boldsymbol{V}_{k,t} - \boldsymbol{V}_{m,t} = \tilde{\boldsymbol{Z}}_j \boldsymbol{I}^S_{j,t} + \Delta\boldsymbol{V}^S_{j,t},\ \forall\, j\in\mathbb{B}\backslash\mathbb{B}^{Z_0}$$

$$\boldsymbol{I}^{SH}_{j,k,t} = \tilde{\boldsymbol{Y}}^{SH}_j \boldsymbol{V}_{k,t} + \Delta\boldsymbol{V}^{SH}_{j,t},\ \forall\, j\in\mathbb{B}\backslash\mathbb{B}^{Z_0}$$

$$-\tilde{M}(1-\sigma_{j,t}) \le \Delta\boldsymbol{V}^S_{j,t} \le \tilde{M}(1-\sigma_{j,t}),\ \forall\, j\in\mathbb{B}\backslash\mathbb{B}^{Z_0}$$

$$-\tilde{M}(1-\sigma_{j,t}) \le \Delta\boldsymbol{V}^{SH}_{j,t} \le \tilde{M}(1-\sigma_{j,t}),\ \forall\, j\in\mathbb{B}\backslash\mathbb{B}^{Z_0}$$

$$\boldsymbol{I}^+_{j,k,t} = \boldsymbol{I}^S_{j,t} + \boldsymbol{I}^{SH}_{j,k,t},\ \forall\, j\in\mathbb{B}$$

$$\boldsymbol{I}^-_{j,m,t} = \boldsymbol{I}^S_{j,t} - \boldsymbol{I}^{SH}_{j,m,t},\ \forall\, j\in\mathbb{B}$$

$$\boldsymbol{V}_{k,t} = \tilde{\boldsymbol{V}}^{PS},\ \forall\, k\in\mathbb{N}\backslash\mathbb{N}^{\nabla}$$

$$\tilde{\boldsymbol{S}}^D_{k,t} = \boldsymbol{V}_{k,t}\boldsymbol{I}^{D^*}_{k,t},\ \forall\, k\in\mathbb{N}$$

$$\tilde{\boldsymbol{S}}^G_{g,t} = \boldsymbol{V}_{k,t}\boldsymbol{I}^{G^*}_{g,t},\ \forall\, k\in\mathbb{N}$$

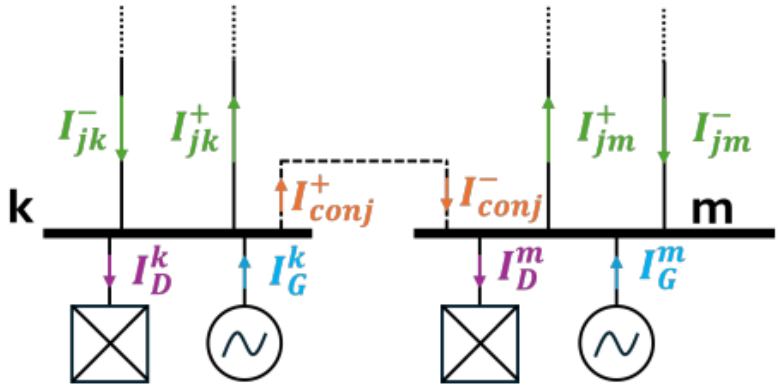
$$|\boldsymbol{I}^+_{j,t}| \le \tilde{I}^{MAX}_j \sigma_{j,t},\ \forall\, j\in\mathbb{B}$$

$$\tilde{V}^{min}_k \le |\boldsymbol{V}_{k,t}| \le \tilde{V}^{MAX}_k,\ \forall\, k\in\mathbb{N}^{\nabla}$$

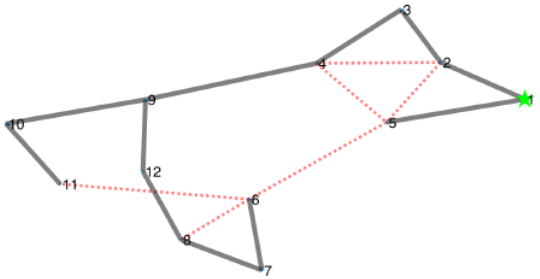
A. Borghetti, "A Mixed-Integer Linear Programming Approach for the Computation of the Minimum-Losses Radial Configuration of Electrical Distribution Networks," in *IEEE Transactions on Power Systems*, vol. 27, no. 3, pp. 1264-1273, Aug. 2012, doi: 10.1109/TPWRS.2012.2184306.

$$-\tilde{M}(1-\sigma_{j,t}) \leq \boldsymbol{V}_{k,t} - \boldsymbol{V}_{m,t} \leq \tilde{M}(1-\sigma_{j,t}),\ \forall\ j \in \mathbb{B}^{Z_0}$$

$$\boldsymbol{I}^{+}_{conj,t} = \boldsymbol{I}^{-}_{conj,t},\ \forall\ j \in \mathbb{B}^{Z_0}$$



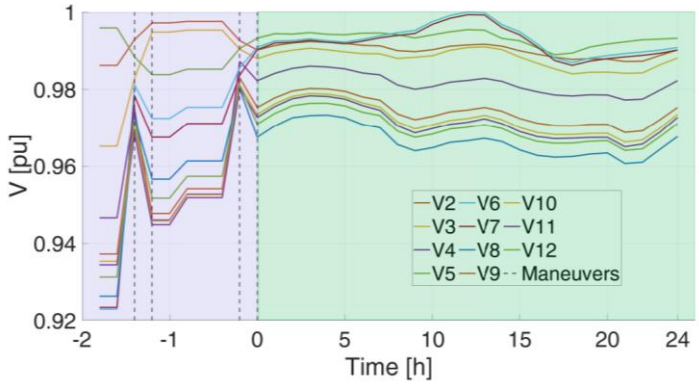
# 02 – Optimal Network Reconfiguration – Results

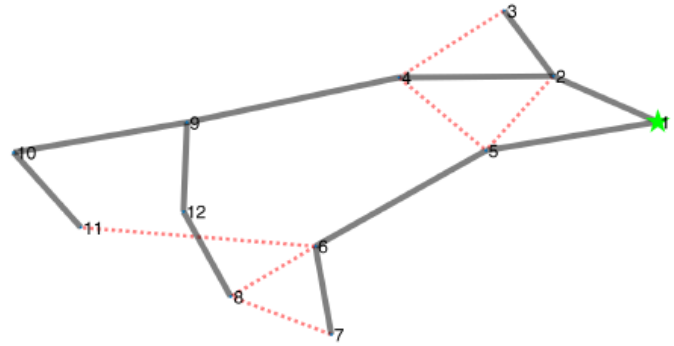



**(a)** *Initial configuration.*

$\mathbb{T}^s = 10\ steps$

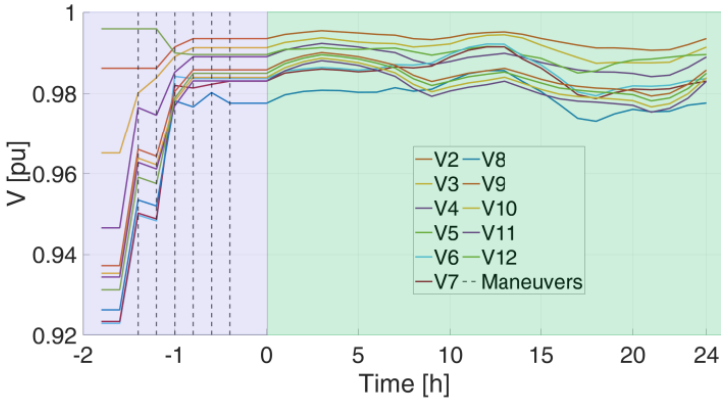
$V_k^{min} = 0.9\ pu$
$V_k^{MAX} = 1.1\ pu$
$\tilde{\epsilon}^{\Delta V} = 0.05\ pu$

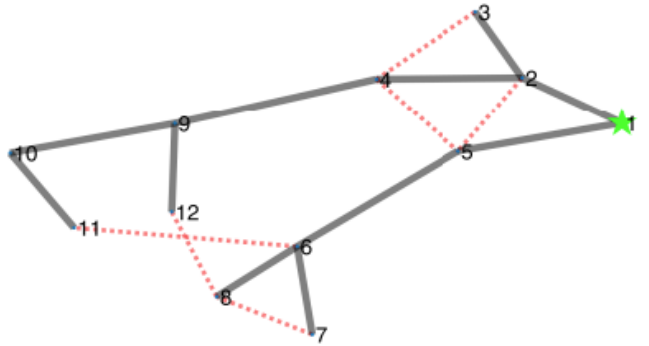


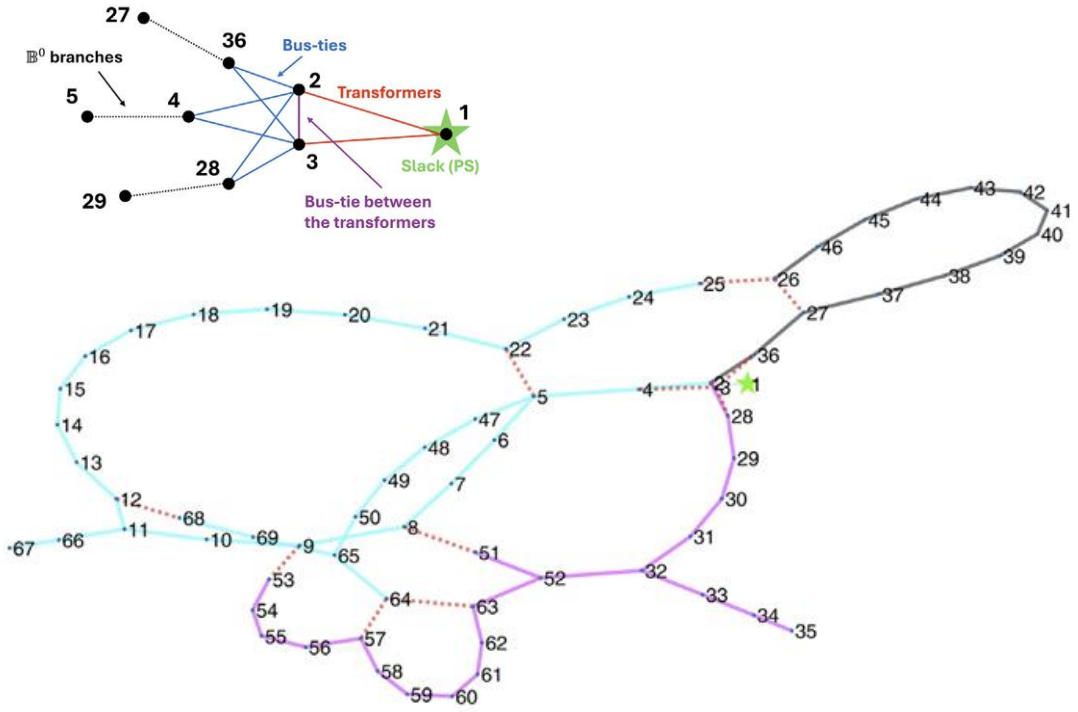

$\mathbb{T}^s = 10\ steps$

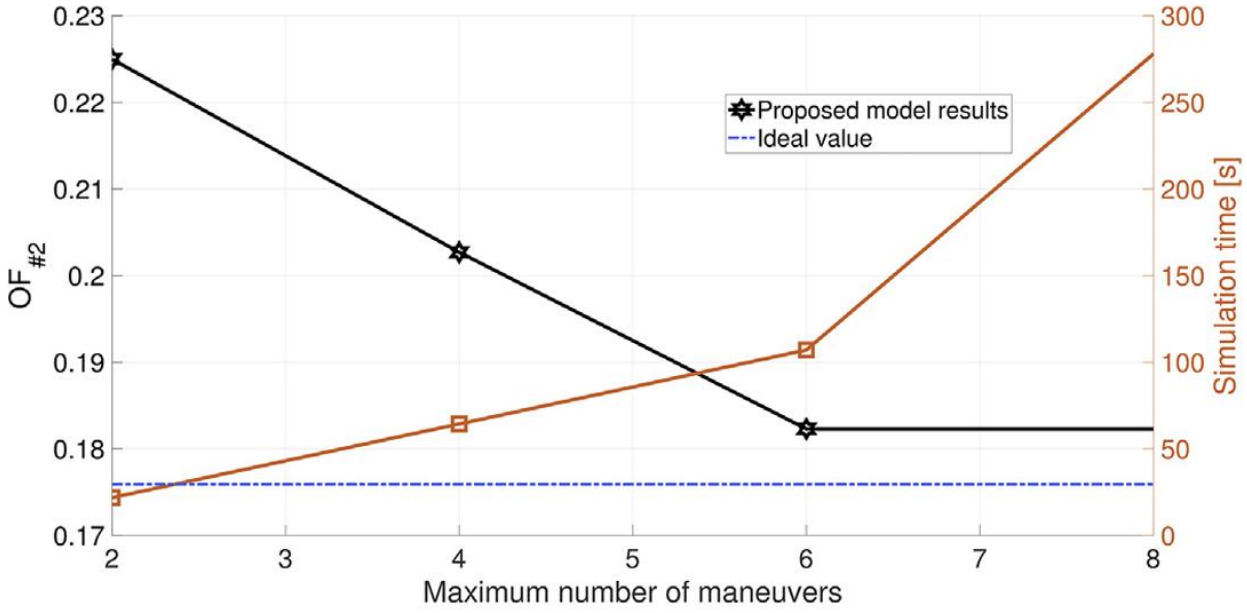
$V_k^{min} = 0.9\ pu$
$V_k^{MAX} = 1.1\ pu$
$\tilde{\boldsymbol{\epsilon}}^{\boldsymbol{\Delta V}} = \mathbf{0.01\ pu}$



# 02 – Optimal Network Reconfiguration – Results



# Thank You !!!