9 DynPOWER Rome, Italy 2025

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International Workshop on

Dynamic Stability Challenges of the Future Power Grids

INNOVATIVE APPROACH TO SECONDARY VOLTAGE REGULATION:

Data-driven MPC Application on the Italian Transmission Network

Presenters

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Tuesday, September 9th 2025, Rome, Italy

Agenda

- Introduction
- Paradigm shift in Secondary Voltage Regulation
- Secondary Voltage Regulation: data-driven MPC approach
- Testing
- Conclusions

Introduction

Introduction

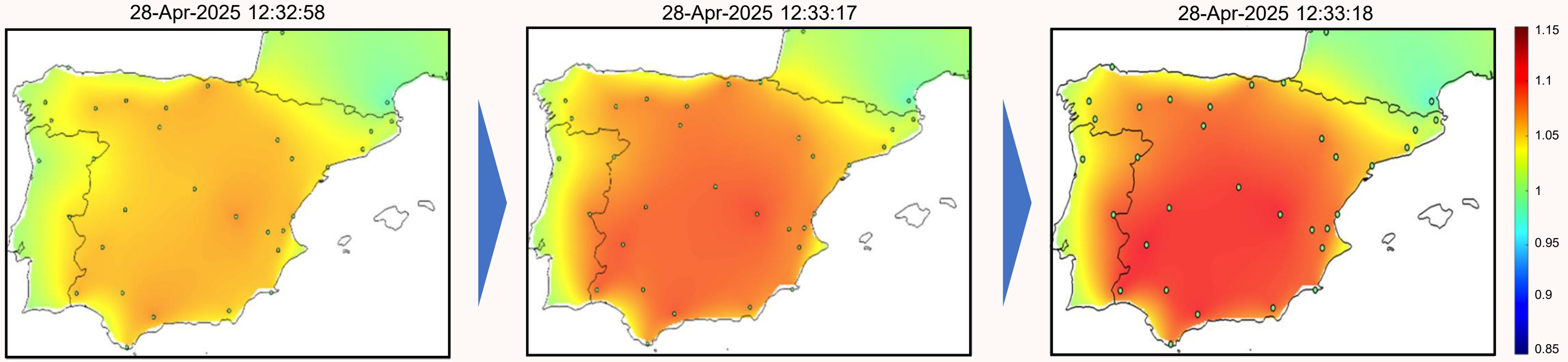
CONTEXT

Power systems are undergoing a profound transformation driven by the energy transition, characterized by the replacement of conventional synchronous generation with an **increasing share of renewable resources.**

RECENT EVENTS

As a result, the system is losing the essential resources for **maintaining regulated nodal voltage profiles**.

The most recent example of this challenge is represented by the 28th April 2025 blackout in Spain.
A voltage instability phenomenon triggered a cascade of generation losses that caused the frequency of the Spanish and Portuguese power systems to drop.



Source: ENTSO-E 28th April 2025 Blackout Report
https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/

Introduction

CHALLENGES

Reduction of conventional resources → Impacts on **system stability**

Increase in the number of RES to be controlled → Difficulty in **diffuse reactive power control**

Bidirectional active power flows → **Higher voltage profile variability at nodes**

Integration of Inverter-Based resources → Need for **system adaptivity** (topology, technology, voltage at connection point,…)

NEEDS

An **overall revision** of the entire **voltage regulation system** is needed from both:

CONTROL CENTRE PERSPECTIVE

- Integrating WAMS into the control system
- Reviewing regulation algorithms
- Reduction in the control cycle timing

FIELD PERSPECTIVE

- Field actuators review
- Interfacing of IBRs

EVOLVING REGV

Real-time measurements from the **Wide Area Measurement System** (WAMS) can play a key role in achieving a more accurate understanding of system dynamics, opening the way **for new control methodologies** based on **data-driven approaches.**

In this context, a new Secondary Voltage Regulator based on **data-driven Model Predictive Control** is proposed.

The approach has been validated on the Italian transmission grid, showing strong performance under various operating conditions.

Paradigm shift in Secondary Voltage Regulation

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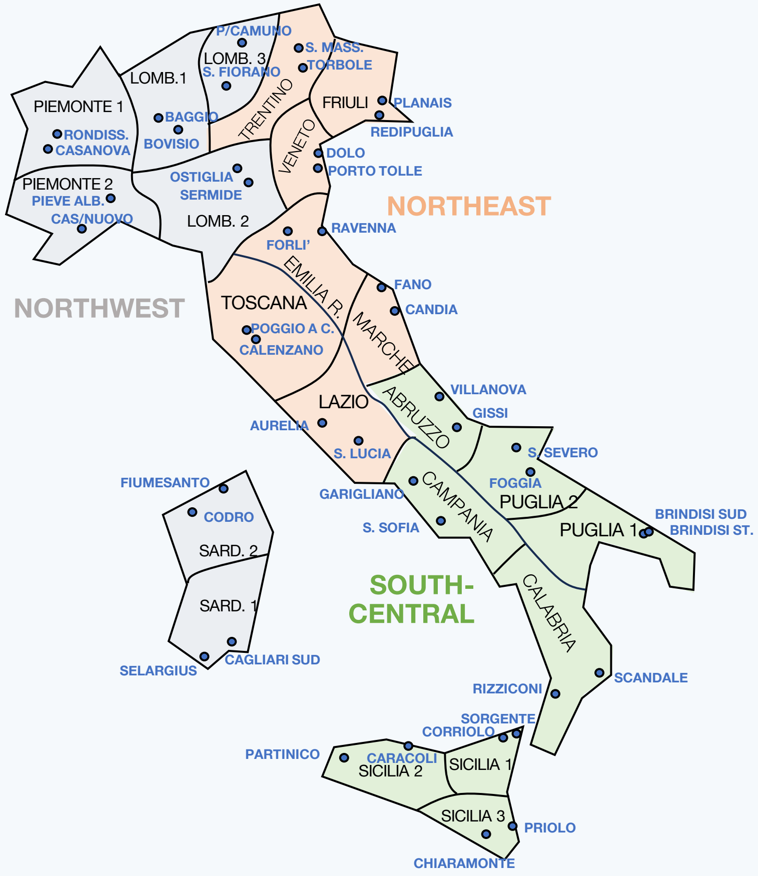
Paradigm shift in Secondary Voltage Regulation

PREVIOUS STRUCTURE

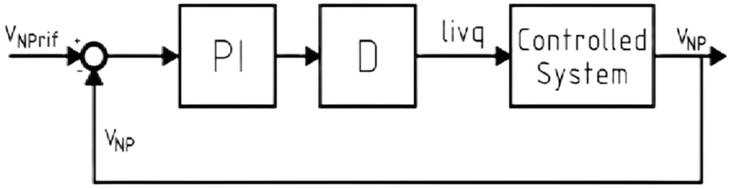
3 Regional Voltage Regulators

22 Control Areas

60 Resources managed



Control law: $liv_q = (v_{PN_{rif}} - v_{PN}) * (K_P + \frac{K_I}{s}) * D$



MAIN LIMITATION:

Control: Unable to control numerous and heterogeneous resources;

Setpoints: Unable to send indipendent setpoints to each resource

Control Cycle times: 70-80 secs. Unable to take advantage of the potential offered by IBRs

Where:

$V_{PN,rif}$ Voltage reference for the pilot node (from R3V)

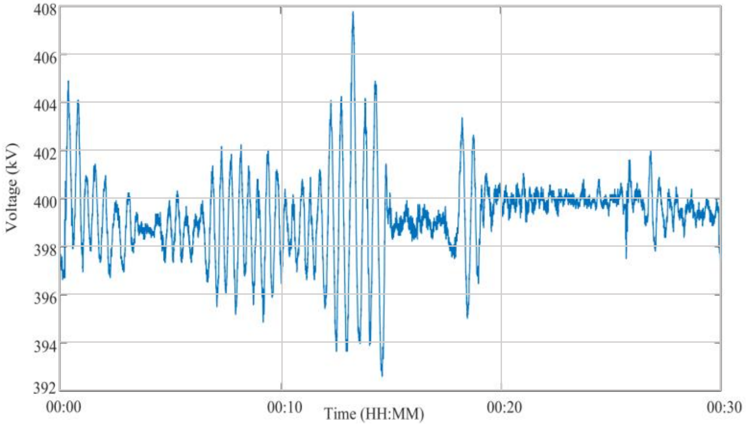
V_{PN} Pilot node voltage measurement

D Coupling matrix between nodes and resources

OSCILLATIONS EVENT

Voltage oscillation phenomenon in a pilot node.

- Pilot node voltage shows a slow oscillatory phenomenon around the reference;
- The oscillation is driven by the time constant of the conventional SVR;
- Oscillations occurred due to dynamic interaction between two conventional resources, triggering a reactive power oscillation.



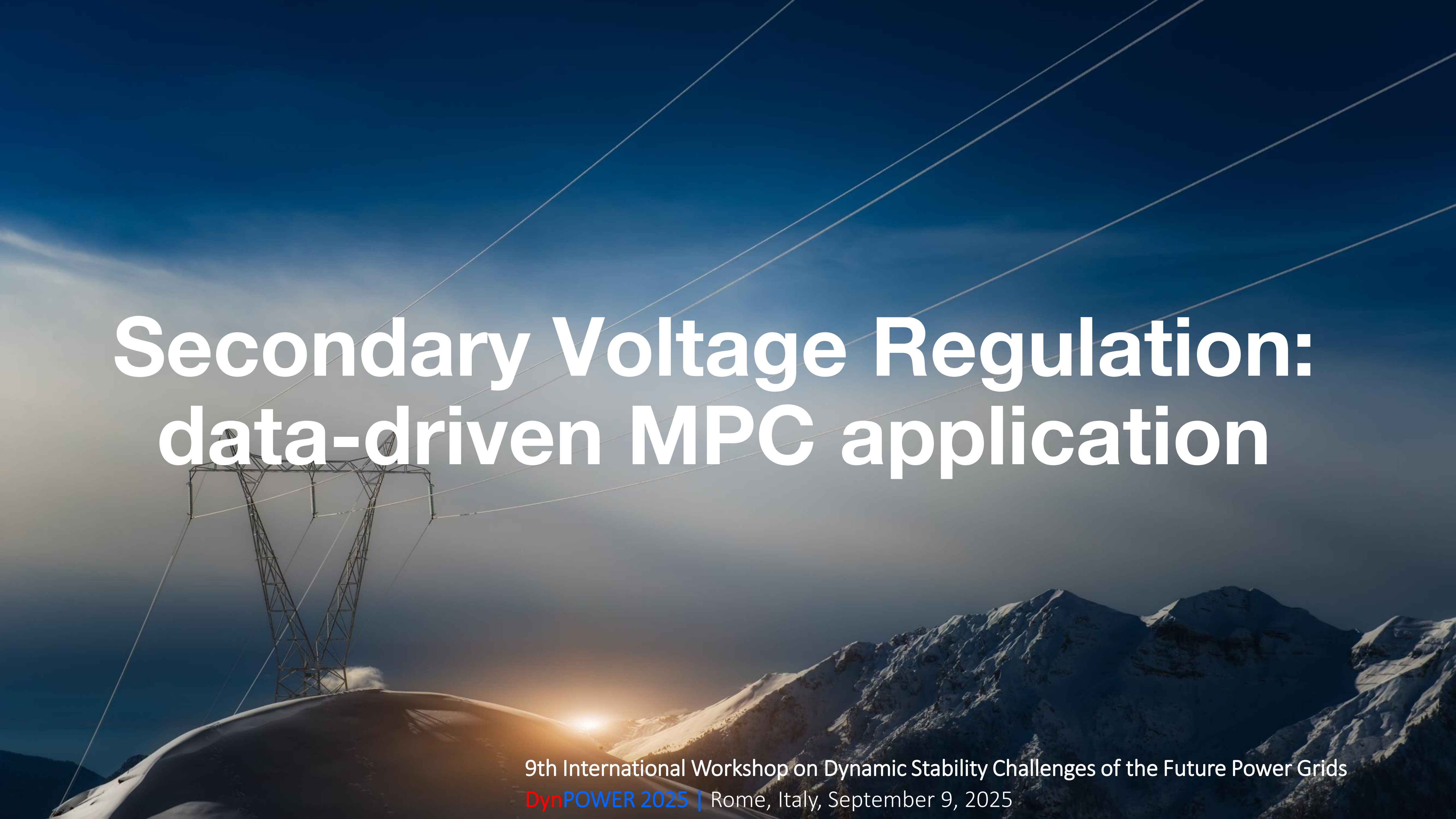
Paradigm shift in Secondary Voltage Regulation

PREVIOUS SVR		ACTUAL SVR
Focused only on **traditional resources**, due to the higher time constant and measures received every 4 sec	RESOURCES	Extension to **IBRs**, with faster response times enabled by **WAMS measurements**
Reactive power level sent at **area level**, due to the controller's limitation in handling many resources.	SETPOINTS	Each resource receives an **individual set-point.**
Each area includes **two nodes** (pilot and vicarious), regulating **one at a time**	NODES	All **controlled nodes** are treated with **equal priority**, and **simultaneous regulation** on multiple node is enabled
Fixed SVR configuration, based on static coupling and grid sensitivity	STRUCTURE	**Dynamic areas clustering** based on grid conditions, aiming **at minimizing dynamic coupling** among regulating resources

Paradigm shift in Secondary Voltage Regulation

RESOURCES AVAILABLE FOR SVR

Resources	Regulator Previous	Regulator Actual	
Traditional Power Plants	✓	✓	**Previous architecture:** up to 60 traditional resources
Synchronous Condensers	✓	✓	**24** synchronous condensers
STATCOMs	✓	✓	**5** STATCOMs. The previous regulator allows the use of STATCOMs only in slow regulation mode.
PV	✗	✓	Actual regulator doesn't allow to take advantage of the potential of inverter-based resources, which include **several thousand units** across various types
Wind Farm	✗	✓	
BESS	✗	✓	
Discrete resources (tap-changers, reactors etc.)	✗	✓	Approximately **200 resources**.
DSO perimeter's resources	✗	✓	Approximately **20** resources planned



Secondary Voltage Regulation: data-driven MPC application

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SVR: Data-driven MPC approach

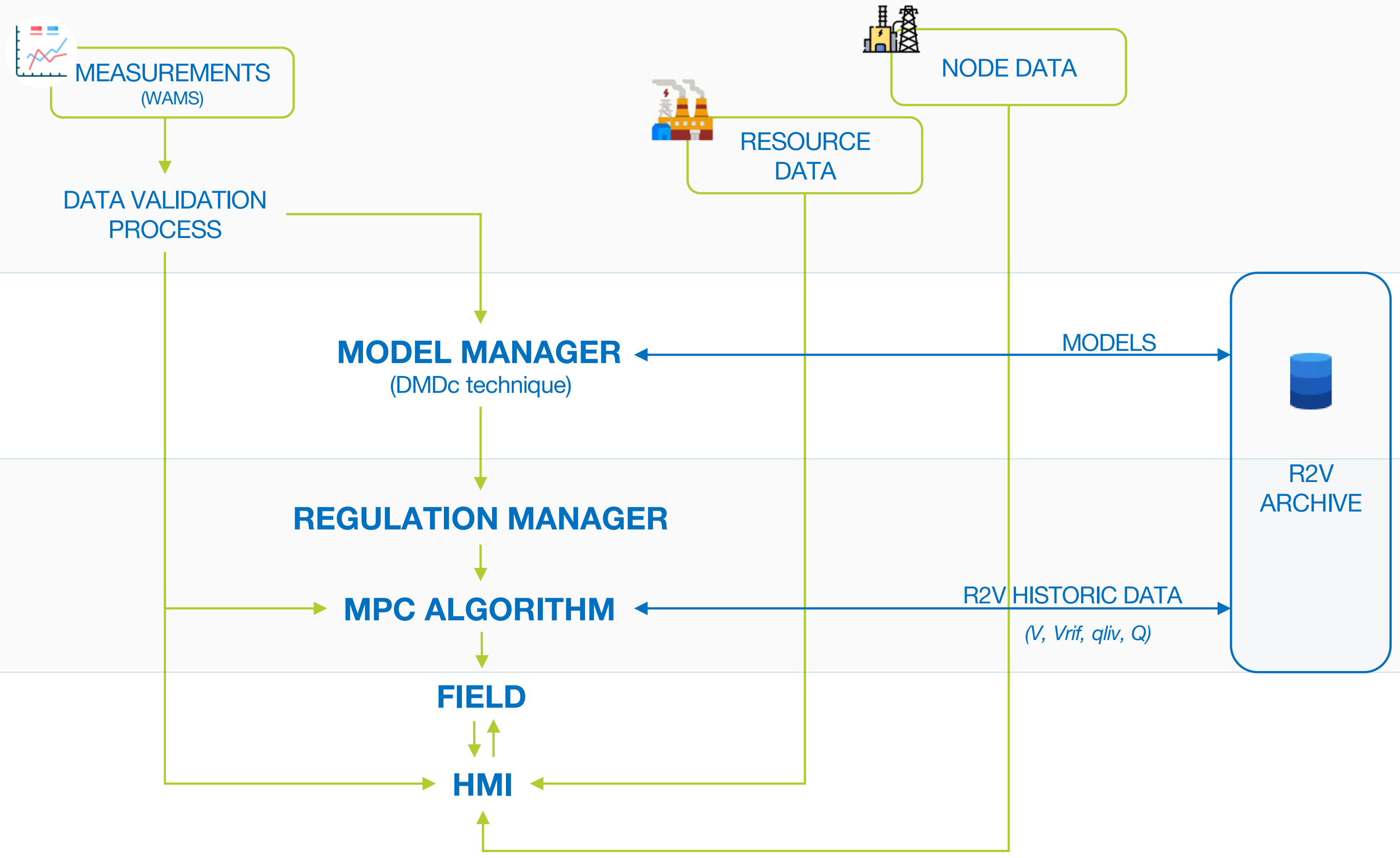
ARCHITECTURE

1 DATA MANAGING

2 MODELS

3 REGULATION

4 VISUALIZATION



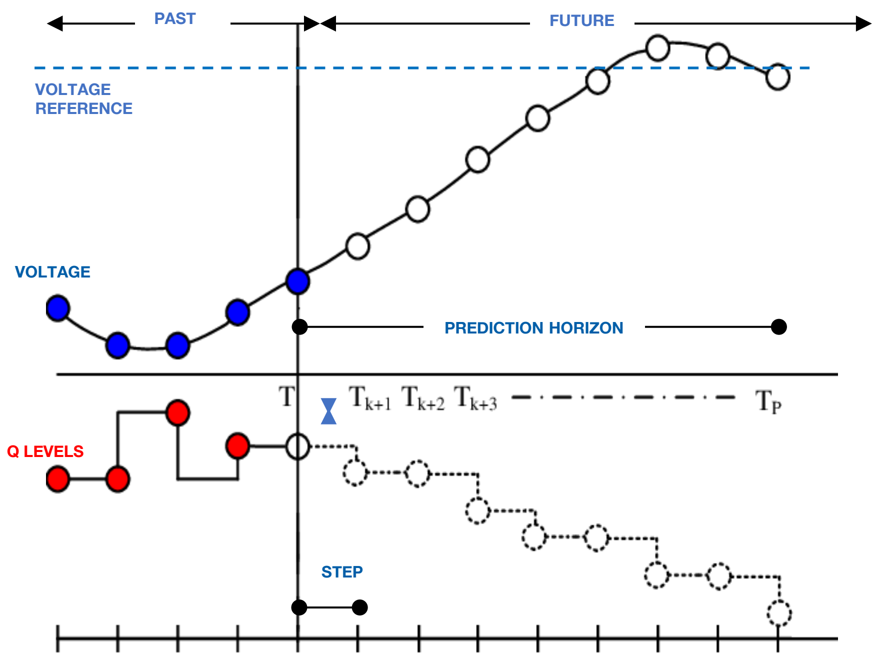
SVR: Data-driven MPC approach

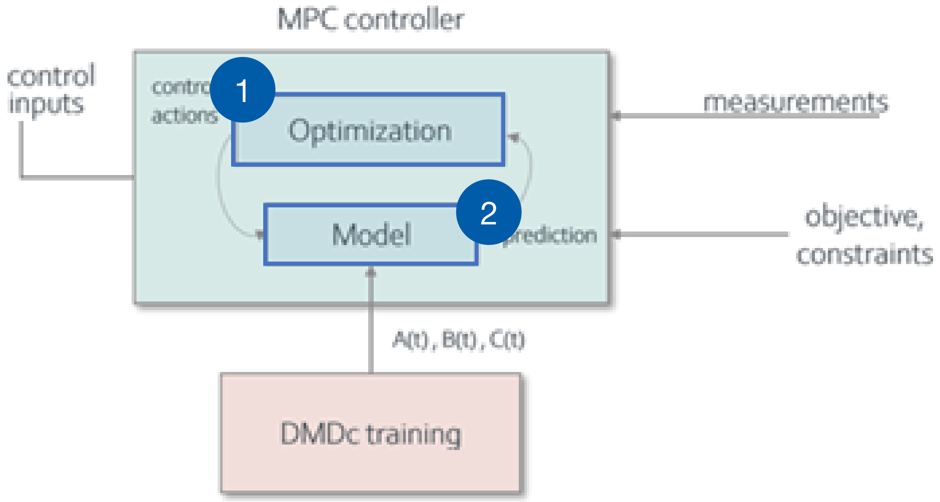
MPC CONTROLLER

1. OPTIMITAZION

What does it do? Compute optimal reactive power set points in order to reach desired voltage values at controlled nodes.

1. At each instant, optimizer solves an optimal problem over a **prediction horizon**, minimizing an objective function under physical constraints.
2. Only the first output (Q-Levels) is applied. When new measures are available, optimization is repeated at the next step.





2. MODEL

What does it do? Makes a future prediction of the evolution of the state of the network based on the estimate of the current state x(t).

State Space Linear Model, identified through DMDc

$$\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k$$
$$\mathbf{y}_k = \mathbf{C}\mathbf{x}_k$$

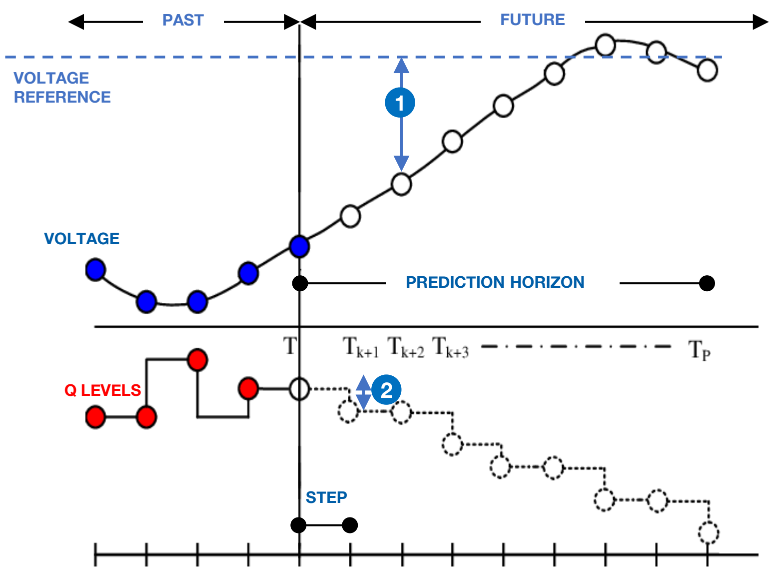
SVR: Data-driven MPC approach

OBJECTIVE FUNCTION

1 2 3

$$\min_{\mathbf{Q}_{\text{liv}}(\mathbf{k})} \sum_{j=1}^{N_p} \|\mathbf{W}^{\mathbf{p}}(\hat{\mathbf{V}}_{\mathbf{p}}(k+j)-\mathbf{r})\|^2 + \delta_c \sum_{j=1}^{N_c-1} \|\mathbf{W}^{\mathbf{c}}\boldsymbol{\Delta}\mathbf{Q}_{\text{liv}}(k+j)\|^2 + \delta_r\delta_o \sum_{j=1}^{N_c-1} \|\mathbf{W}^{\mathbf{r}}(\mathbf{Q}_{\text{liv}}(k+j)-\mathbf{q}_{\text{ref}})\|^2$$

$$\begin{aligned} \text{s.t.} \quad & \hat{\mathbf{V}}_{\mathbf{p}}(k+j|k) = f(\hat{\mathbf{x}}(k+j-1|k), \boldsymbol{\Delta}\mathbf{Q}_{\text{liv}}(k+j-1|k)) \\ & \mathbf{V}_{\mathbf{p},\text{min}} \leq \hat{\mathbf{V}}_{\mathbf{p}}(k+j|k) \leq \mathbf{V}_{\mathbf{p},\text{max}} \\ & \mathbf{Q}_{\text{liv},\text{min}} \leq \hat{\mathbf{Q}}_{\text{liv}}(k+j|k) \leq \mathbf{Q}_{\text{liv},\text{max}} \\ & \boldsymbol{\Delta}\mathbf{Q}_{\text{liv},\text{min}} \leq \boldsymbol{\Delta}\hat{\mathbf{Q}}_{\text{liv}}(k+j|k) \leq \boldsymbol{\Delta}\mathbf{Q}_{\text{liv},\text{max}} \end{aligned}$$



1. The first term minimize errors between the predicted voltage output and the set-point (setpoints carried out from the R3V ORPF);

2. The second term reflects the energy released by the control signal used to keep the trajectory of the system as close as possible to the desired trajectory, giving stability.

3. The reactive power reference Qref is carried out from an R3V ORPF. Setting the Qref to zero, the reactive power reserve available in the actuators is maximized.

SVR: Data-driven MPC approach

MODEL MANAGER

Model Manager is a module for identifying models that represent **dynamic interactions between nodes and resources**, using the **Dynamic Mode Decomposition with Control** technique.

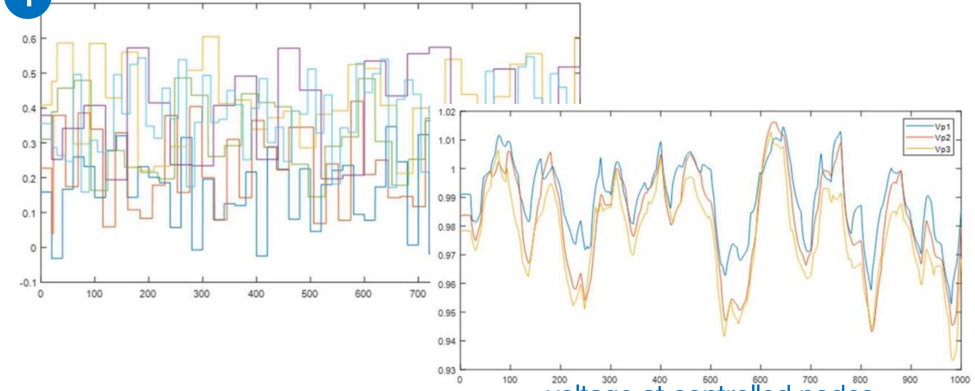
Advantage: avoids the need for complex mathematical – fully data-driven approach.

WORKING PRINCIPLE

1. The system is described by spatial-temporal data collected at different times. These data are grouped into "snapshots.“
2. Using the snapshots, the DMDc method finds the main dynamic modes of the system, including the effect of control actions.
3. The output of DMDc is the A, B, and C matrices of the state-space linear model. Finally, the model replaces the previous one.

1

Iivq sent to the resources



voltage at controlled nodes

2 **DMD with Control (DMDc)**

Find the dynamic properties of $\mathbf{A}$ and $\mathbf{B}$

$$\mathbf{X}' = \mathbf{A}\mathbf{X} + \mathbf{B}\boldsymbol{\Upsilon}$$

i. Construct the input data matrix

$$\boldsymbol{\Omega} = \begin{bmatrix} \mathbf{X} \\ \boldsymbol{\Upsilon} \end{bmatrix}$$

ii. Find the truncated SVD of input matrix $\boldsymbol{\Omega}$

$$\boldsymbol{\Omega} \approx \tilde{\mathbf{U}}\tilde{\boldsymbol{\Sigma}}\tilde{\mathbf{V}}^* = \begin{bmatrix} \tilde{\mathbf{U}}_1 \\ \tilde{\mathbf{U}}_2 \end{bmatrix} \tilde{\boldsymbol{\Sigma}}\tilde{\mathbf{V}}^*$$

iii. Find the truncated SVD of output matrix $\mathbf{X}'$

$$\mathbf{X}' \approx \hat{\mathbf{U}}\hat{\boldsymbol{\Sigma}}\hat{\mathbf{V}}^*$$

iv. Compute reduced-order approximation of $\mathbf{A}$

$$\tilde{\mathbf{A}} = \hat{\mathbf{U}}^*\mathbf{X}'\tilde{\mathbf{V}}\tilde{\boldsymbol{\Sigma}}^{-1}\tilde{\mathbf{U}}_1^*\hat{\mathbf{U}}$$

v. Investigate the dynamic properties of

$$\tilde{\mathbf{A}}\mathbf{W} = \mathbf{W}\boldsymbol{\Lambda}$$

vi. Solve for the dynamic modes of

$$\boldsymbol{\Phi} = \mathbf{X}'\mathbf{V}\boldsymbol{\Sigma}^{-1}\tilde{\mathbf{U}}_1^*\hat{\mathbf{U}}\mathbf{W}$$

UPDATED EVERY 5 MIN

3

$$\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k$$
$$\mathbf{y}_k = \mathbf{C}\mathbf{x}_k$$

Proctor, Joshua L., Steven L. Brunton, and J. Nathan Kutz. "Dynamic mode decompositionwith control." SIAM Journal on Applied Dynamical Systems 15.1 (2016): 142-161.

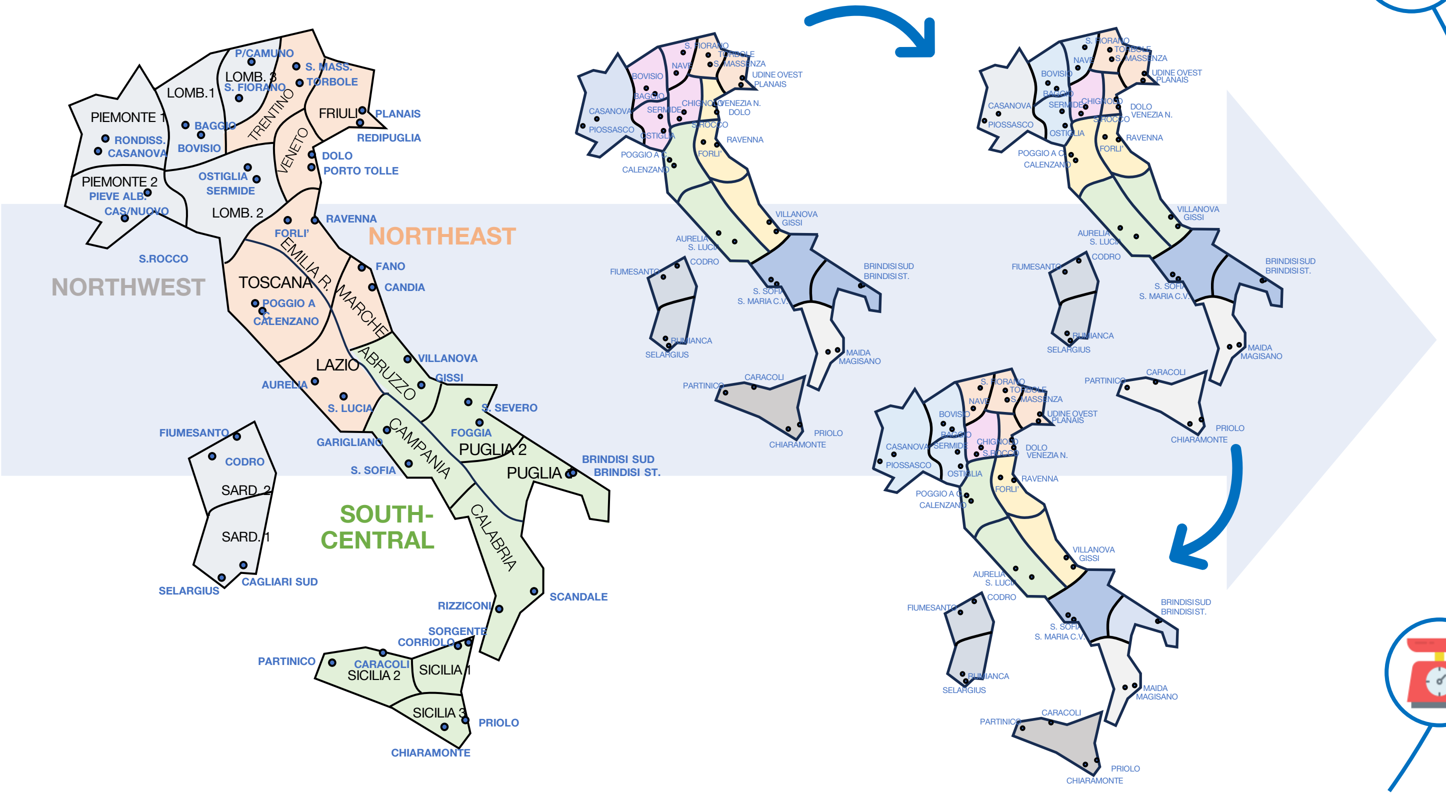
SVR: Data-driven MPC approach

REGULATION MANAGER

Regulation Manager is a module dedicated to the optimisation of the SVR structure. Its main functions are:

ACTUAL SVR
FIXED STRUCTURE

NEW SVR
DYNAMIC STRUCTURE



1) LOGICS FOR IDENTIFYING THE OPTIMAL CLUSTERING OF SVR

Clustering depends on the network topology, the short-circuit power at the nodes, and the in-service resources.
This allows to maximize the potential from each regulation resource while minimizing undesired dynamic interactions.

2) RANKING OF CONTROLLED NODES IN FUNCTION OF IN-SERVICE RESOURCES

Prioritization of controlled nodes as a function of the in-service resources, considering the impact each resource has on the voltage response.

3) OPTIMIZATION OF RESOURCE WEIGHTS FOR DIFFERENT REGULATION STRATEGIES

- **Strategy 1:** Once the desired voltage level at the nodes is reached, maximize the reactive power reserve on slow resources, increasing the operating margin.
- **Strategy 2:** Maximize the use of fast resources prioritizing responsiveness.

On-field testing

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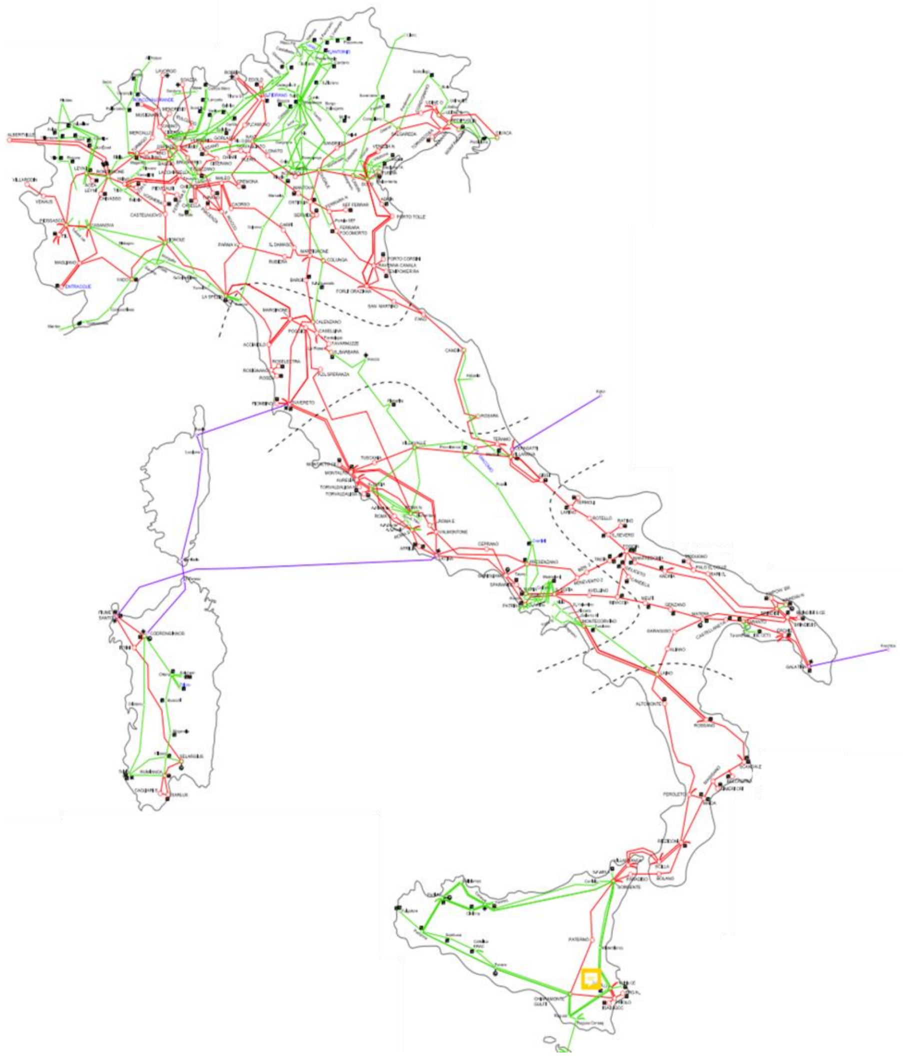
SVR: On-field testing

Several validation tests have been carried out on the Italian transmission network;

- The Secondary Voltage Regulator is able to control multiple nodes and resources at the same time.
- Considering the electrical distance, SVR separate and coordinate the contribution of each resource according to grid sensitivity and dynamic behavior.
- This approach has shown strong performances in:
    1. Rapid convergence toward the reference
    2. Mitigating the impact of grid disturbances

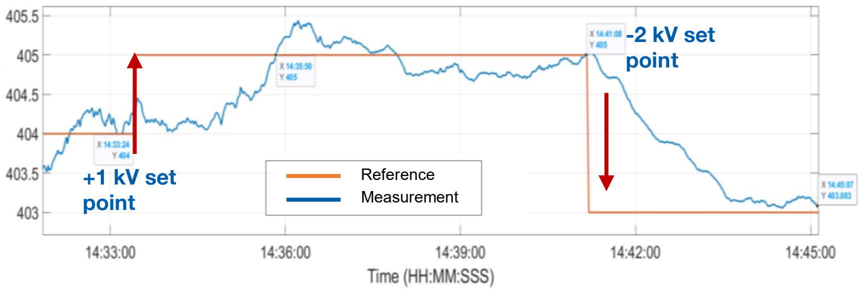


SVR: On-field testing

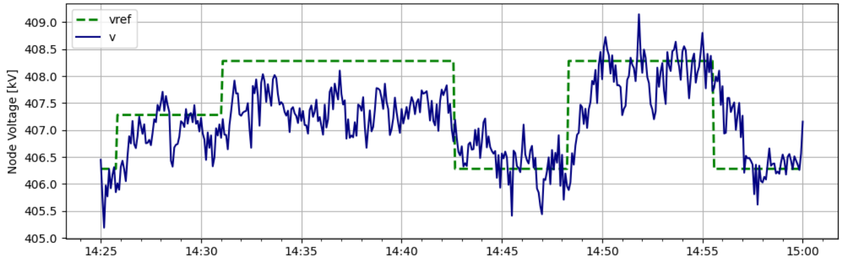
SENDING SET POINTS

Following a change in the voltage reference, the MPC controller accurately determines the appropriate level to be sent to the field to the power plant or STATCOM. The system stabilizes and reaches steady-state conditions within approximately three minutes.

POWER PLANT

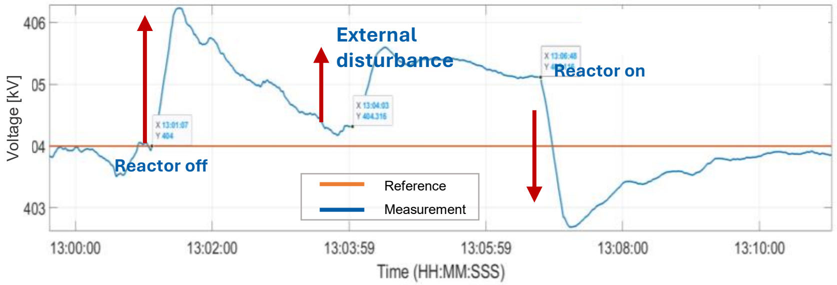


STATCOM



MANAGING GRID DISTURBANCES

The grid disturbance is emulated by switching off a reactor. Following the first transient, an external disturbance occurs. The controller promptly updates the reference set point, increasing the reactive power contribution to counteract the variation.



POWER PLANT

Conclusions

Conclusions

Medium/short-term scenarios characterized by high-RES production could lead to a lack of resources capable of regulating voltage at nodes.

Actual SVR is unable to take advantage of the potential of IBRs, limited by both the complexity of managing large numbers of units and by slow control dynamics.

Real-time data from the Wide Area Measurement System (WAMS) opens the way for new control methodologies based on data-driven approaches.

To address these challenges, a new Secondary Voltage Regulator based on Model Predictive Control (MPC) has been proposed. The MPC technique allows to continuously update model parameters in real time, enhancing the controller's adaptability and accuracy.

Field tests conducted on the Sicilian transmission network validate the effectiveness of the MPC-based controller under real-world conditions

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