CONFIDENTIAL
LIMITED USE

Francesco Rizzo
Lusaka, Sep. 5th 2018

Tools and best practices for operation in system with non-dispatchable renewable sources

Shaping a Better Energy Future

Measures for a smoother VRES integration and operation

TECHNOLOGIES

- Improved forecasting
- Improved monitoring
- Optimisation of operating reserve
- Greater flexibility of conventional generation
- Expansion of local transmission and distribution grids
- Cross-border interconnections
- Energy storage systems
- Demand response

MARKET DESIGN

- Frequent scheduling of the electricity market
- Negative market prices
- Nodal pricing
- Larger balancing areas
- Ancillary Services

REGULATORY POLICIES

- Connection rules and requirements for VRES
- TSOs/DSOs coordination rules

Main TSO actions face VRES Integration and operation

Network reinforcements

- **Network development** (e.g. in areas affected by congestions) through construction of new lines/transformers or installation of **additional equipment** (e.g. SVC, STATCOM, SC)
- Installation of **Storage Systems** (energy/power intensive)

Scheduling, Monitoring and control

- **Forecasting** (tools, algorithms and data)
- **Dedicated tools** for monitoring, control and simulation of RES
- **RES console/control center** within the control room
- Data exchange and coordination **TSOs/DSOs**

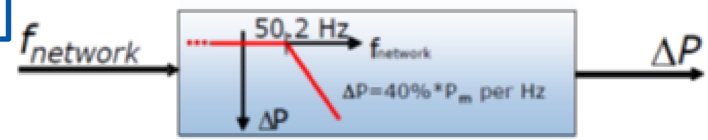
Requirements for RES (Grid Codes)

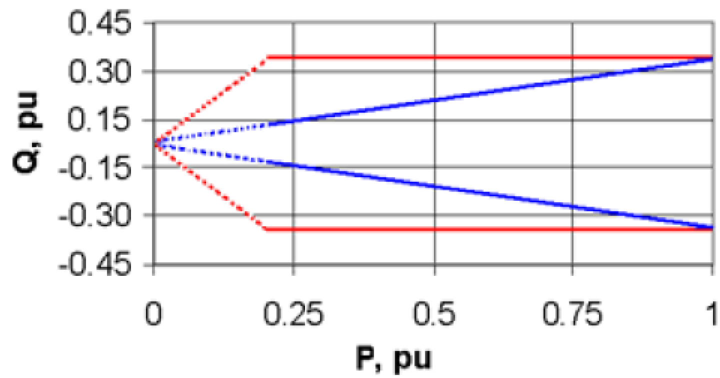
- **FVRT requirement** for RES including the required fault reactive current contribution
- **Voltage/Reactive Power** Control
- **Frequency** control (over-frequency)
- **Synthetic Inertia**
- **Protection settings**
- **Curtailments** (programmed or instantaneous)
- **Power quality** (e.g. flicker, harmonics)

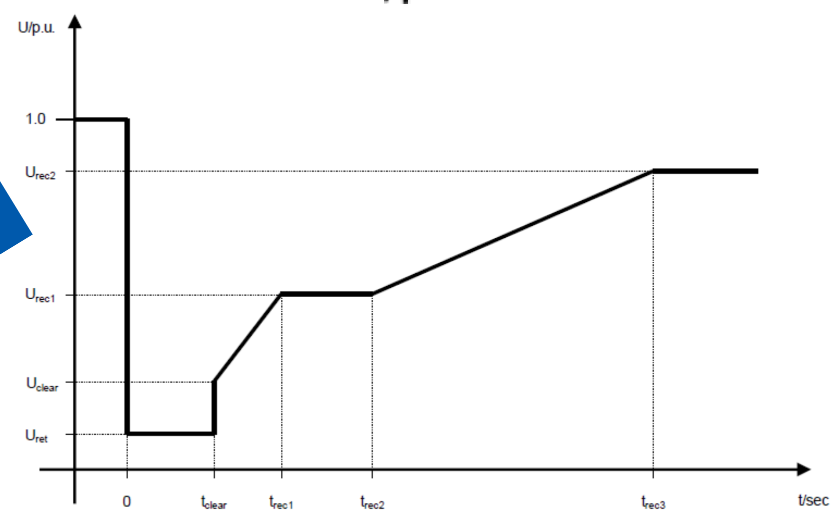
Grid Code development for Transmission network

Development of requirements and procedures for VRES according to the system characteristics

- Frequency regulation
- Inertia support
- Voltage control
- Protection settings
- Fault Voltage ride through
- Data Exchange between TSO and DSOs



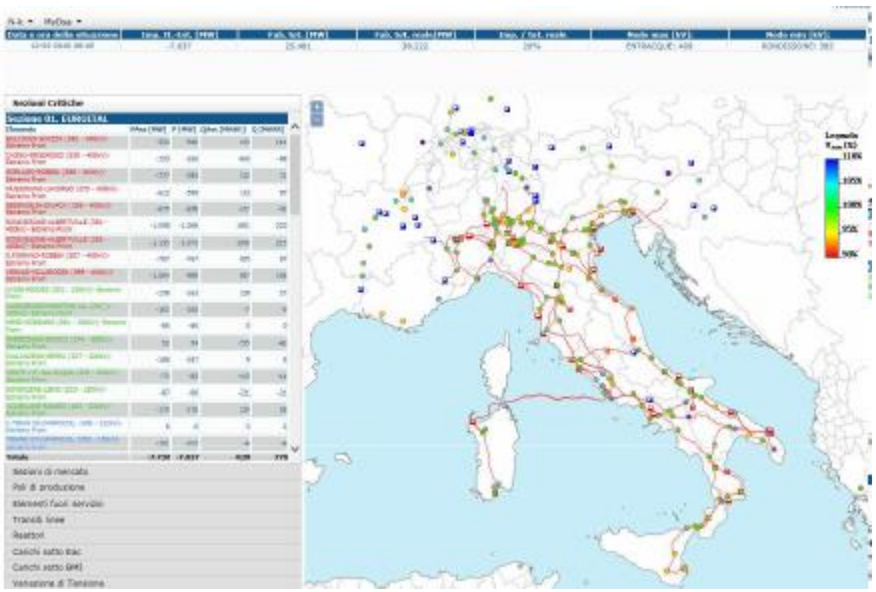


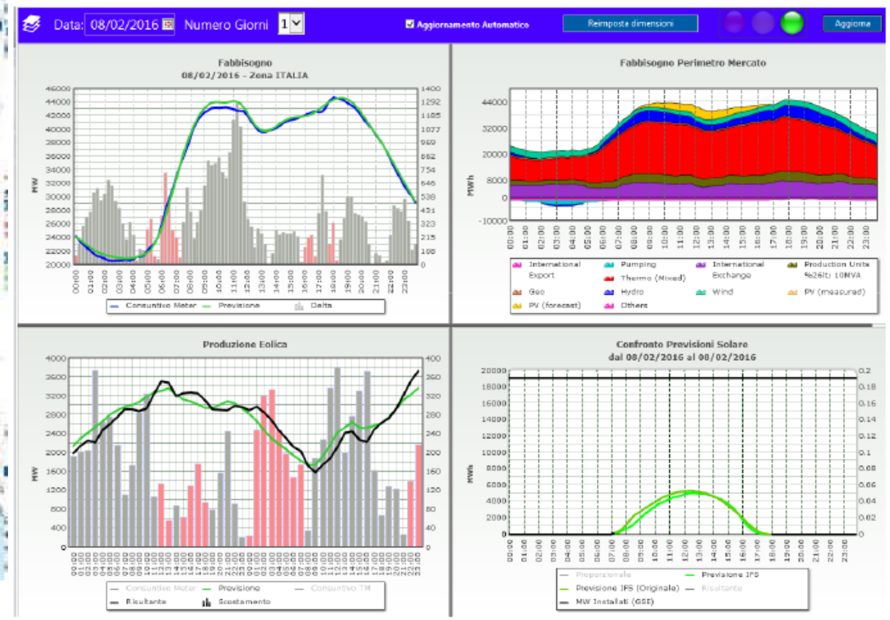


VRES Integration actions taken from the Italian TSO TERNA

Tools and solutions for real time operation

- **Forecasting tool** based on weather forecasts and neural networks model
- **Advance dispatching** - short time analysis of reserve adequacy
- **DSA** – Static and Dynamic security Assessment





CESI

Italian Transmission system operator storage pilot projects

The Italian TSO Terna has already installed more than 50MW of Battery EES systems to relieve constraints on the transmission grid

Power Intensive

Scope: Safe management of the grid

Total Capacity: **40 MW**

Number of Sites: (Phase I) : **2**

Phase I: 16 MW Storage Lab

Codrongianos
Installed Power: ≈ 8 MW
Status: 5.4 MW completed

Ciminna
Installed Power: ≈ 8 MW
Status: 3.2 MW completed

Technology evaluation

Phase II: 24 MW

Casuzze and Codrongianos: to be started

Energy Intensive

Scope: Solve Grid congestion / bottlenecks

Total Capacity: **35 MW**

Number of Sites: **3**

Ginestra
Installed Power: ≈ 12 MW
Status: completed

Flumeri
Installed Power: ≈ 12 MW
Status: 6.0 MW completed

Scampitella
Installed Power: ≈ 12 MW
Status: building in progress

Ginestra and Flumeri among the biggest installations in Europe

Index

- Evaluation of Reserve Margin in presence of variable renewable generation
- Dynamic Security Assessment
- WAMS – Wide Area Measurement Assessment
- Dynamic rating
- Synthetic Inertia

Additional Reserve and Balancing Capability

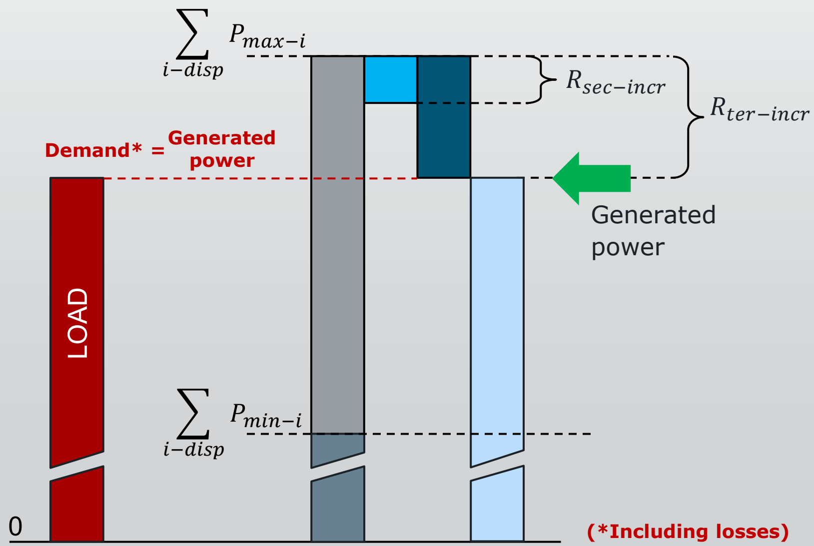
- Secondary reserve*
- Tertiary reserve*

$$R_{sec\,(daily)} = \sqrt{10 \cdot L_{max} + 150^2} - 150$$

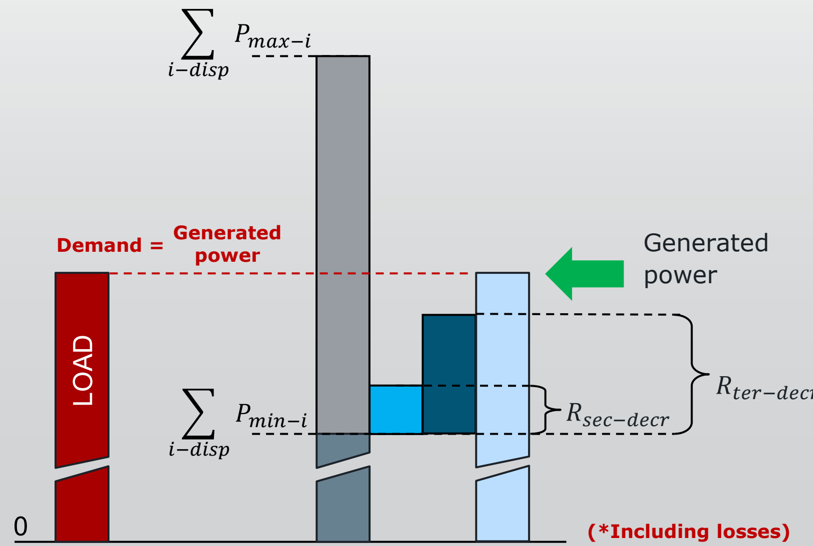
$$R_{ter-incr} = L_{max} \cdot 0.08$$

(Example of reserves according to ENTSO-E rules)*

➢ **In Peak Load condition these reserves define the maximum thermal generation**



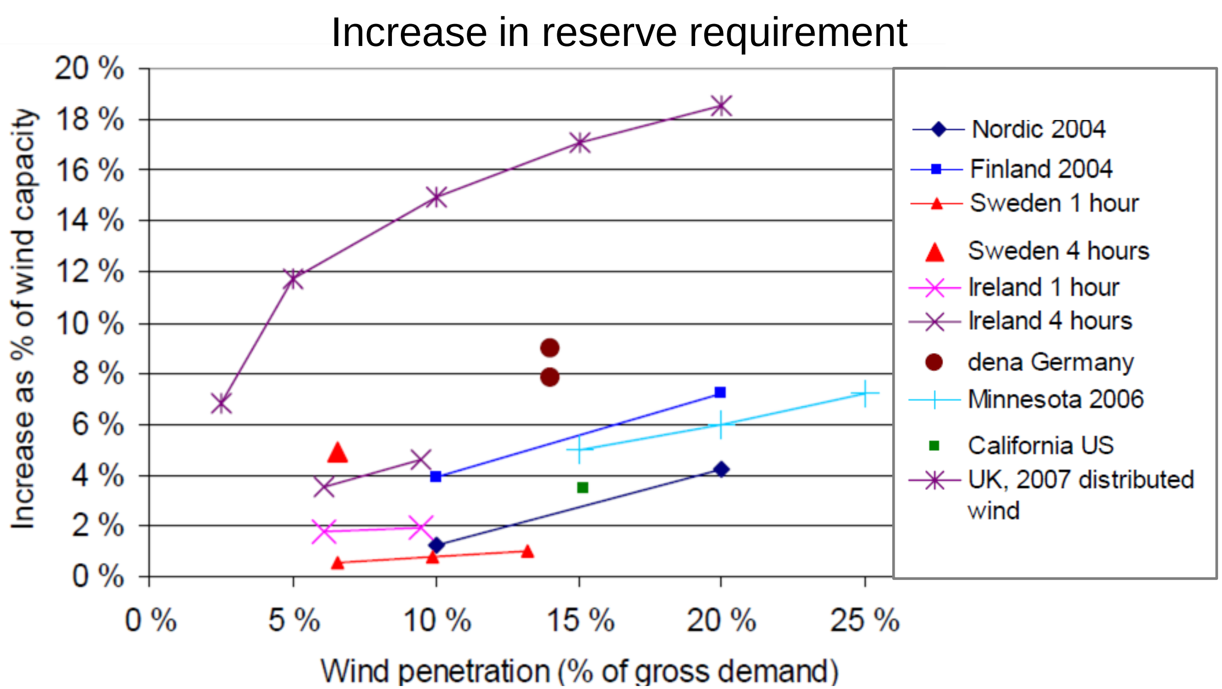
➢ **In Low Load condition these reserves define the minimum thermal generation**



CONFIDENTIAL – LIMITED USE

Additional Reserve and Balancing Capability

- Need for Additional Reserve to cope with the intermittency of non-programmable RES generation
  - Additional reserve [%]: percentage of wind generation
  - Penetration: wind production [MW] / demand

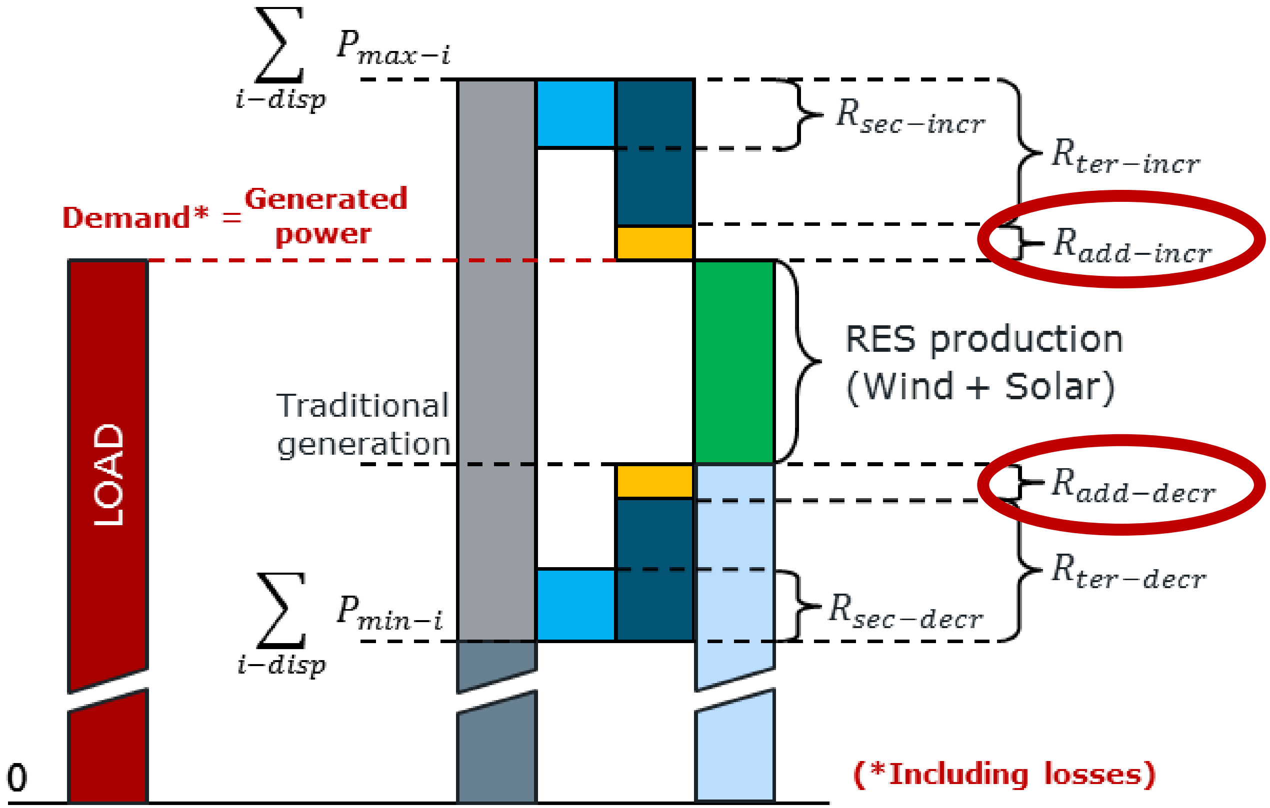


Source: IEA-Wind

CONFIDENTIAL – LIMITED USE

Additional Reserve and Balancing Capability

- **Maximization of RES penetration considering also additional reserve**



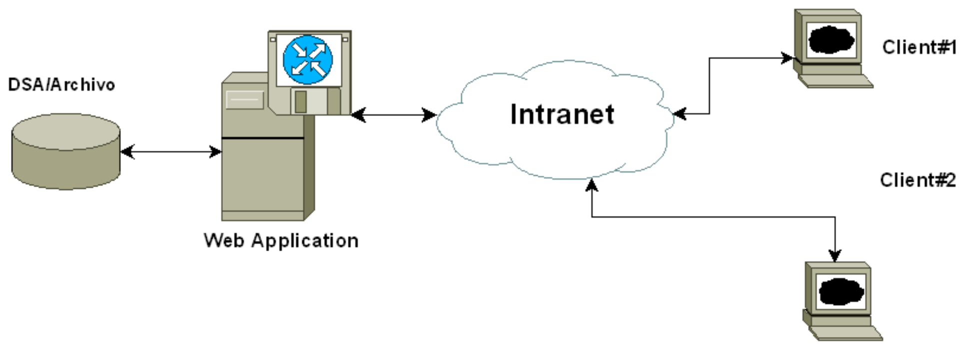
CONFIDENTIAL – LIMITED USE

CESI

Index

- ❑ Evaluation of Reserve Margin in presence of variable renewable generation
- ❑ **Dynamic Security Assessment**
- ❑ WAMS – Wide Area Measurement Assessment
- ❑ Dynamic rating
- ❑ Synthetic Inertia

DSA – Generality



- Static Security Assessment (SSA)
- Dynamic Security Assessment (DSA)
- Evaluation of performances of UFLS strategies and SPS
- Voltage Stability Assessment

MMI Example

Date and Time

Power Exchange

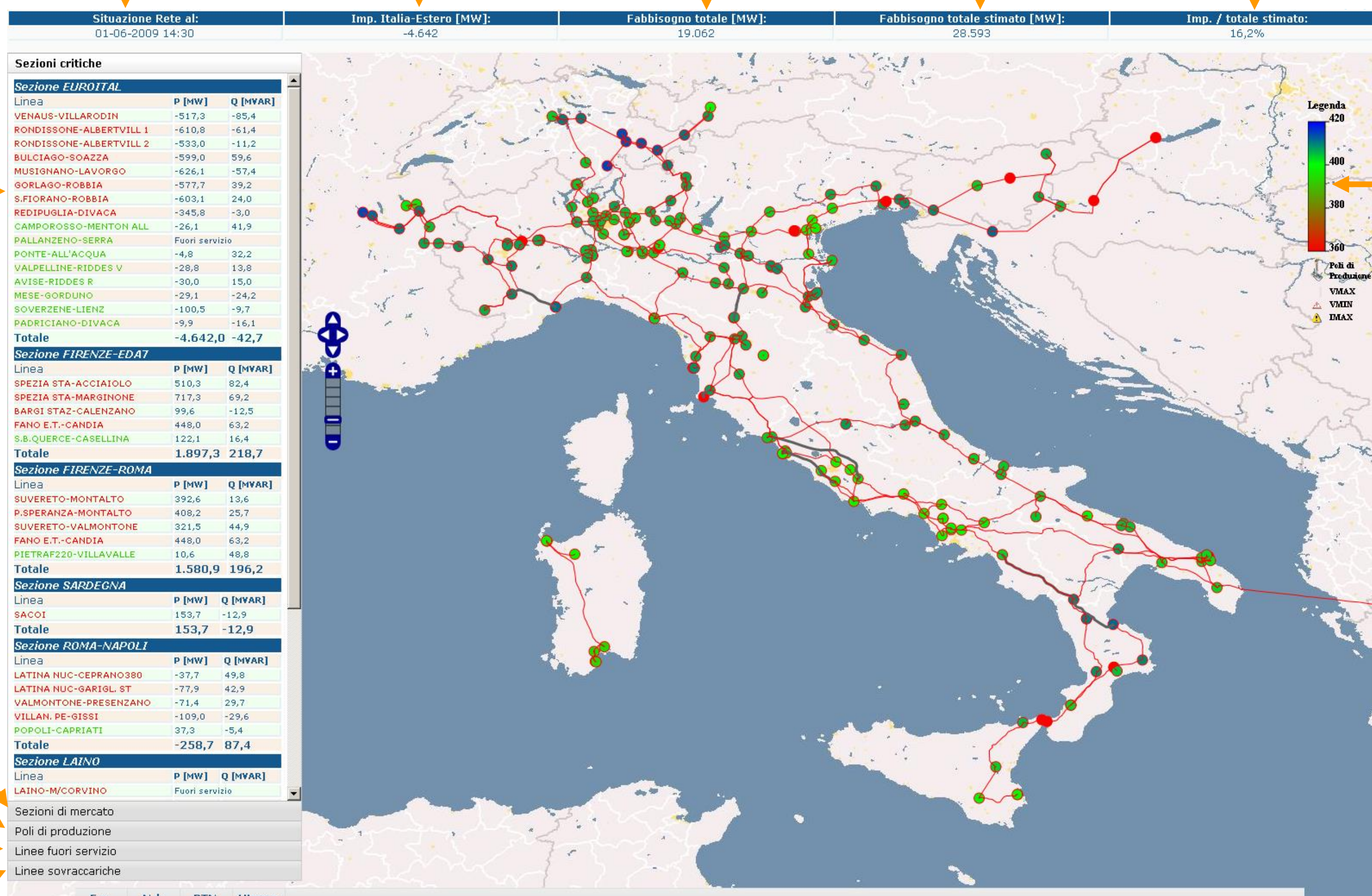
Load Demand (400-220 kV)

Load Demand (real balance)

Power Exchange (%)

Critical Corridors Exchanges

Voltage Levels



Market Corridors

Main Power Plants

Lines Out of Service

Overloads

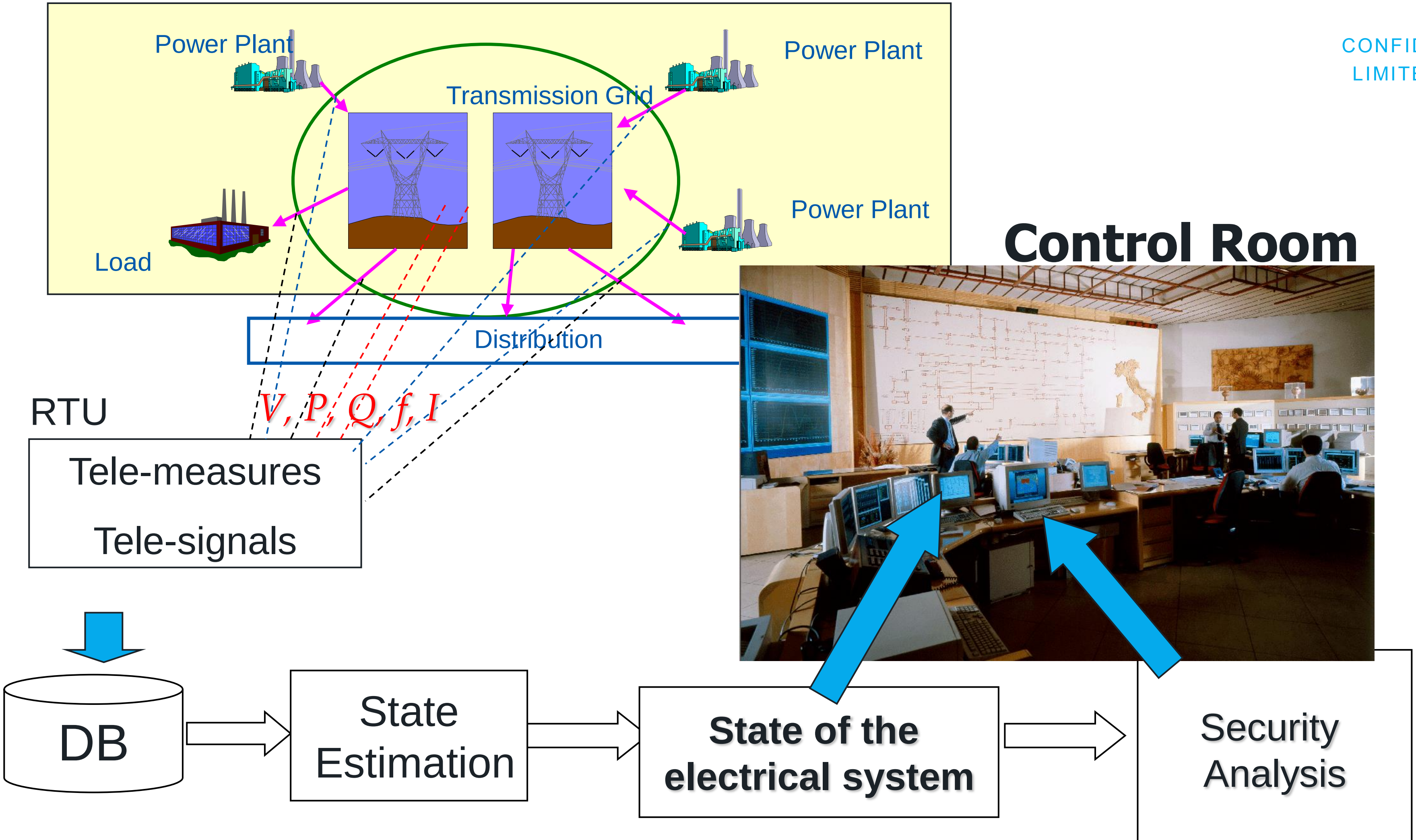
UFLS

N-K

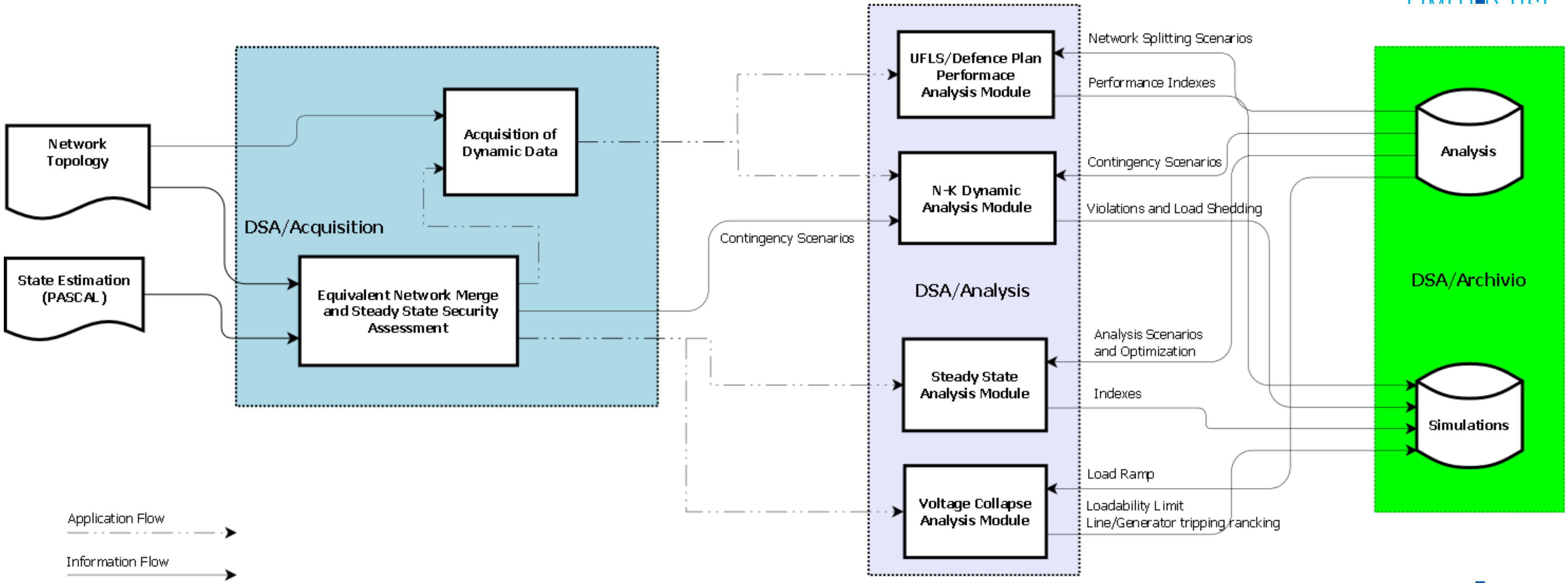
Layers

Access control

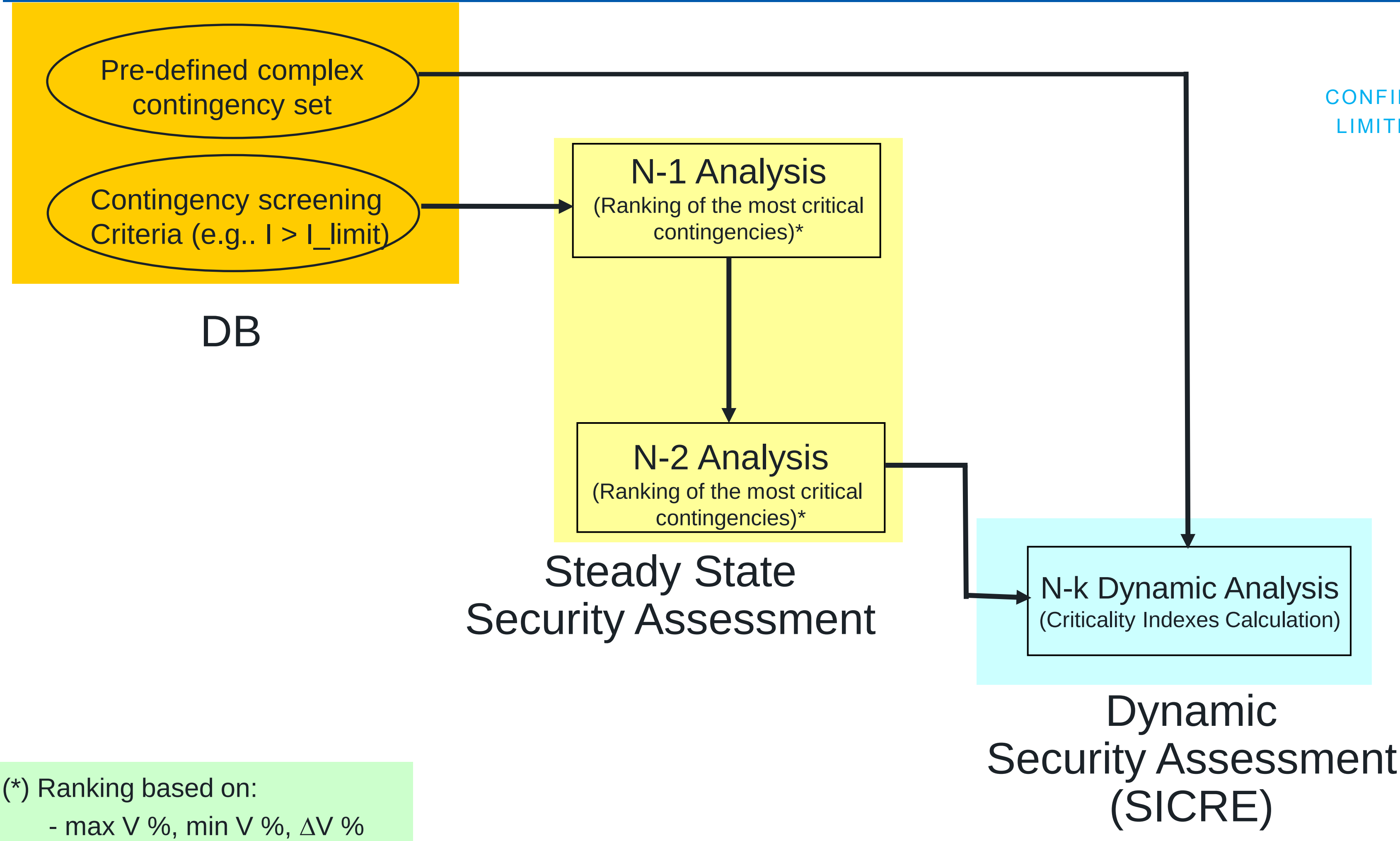
SCADA and EMS



System Architecture



N-K Dynamic Analysis Module



(*) Ranking based on:
- max V %, min V %, ΔV %
- Overload %

SSA: N-2 Security Assessment Report

CONFIDENTIAL
LIMITED USE

Cascading per la situazione del 2009-10-23 delle ore 16:30

Legenda tipologia elementi	
i	Elemento di rete iniettore (trasformatore, gruppo)
d	Linea in doppia terna
b	Linea

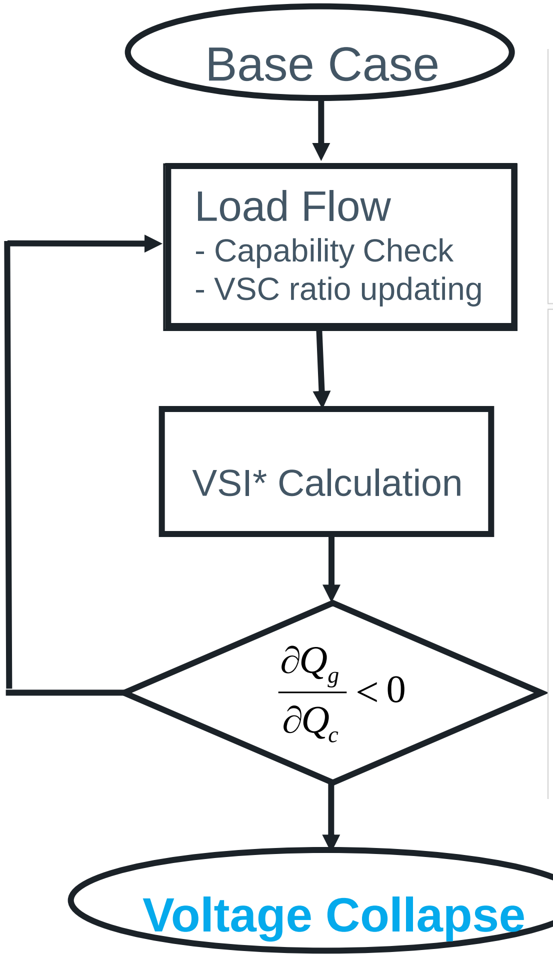
Risultati analisi N-1

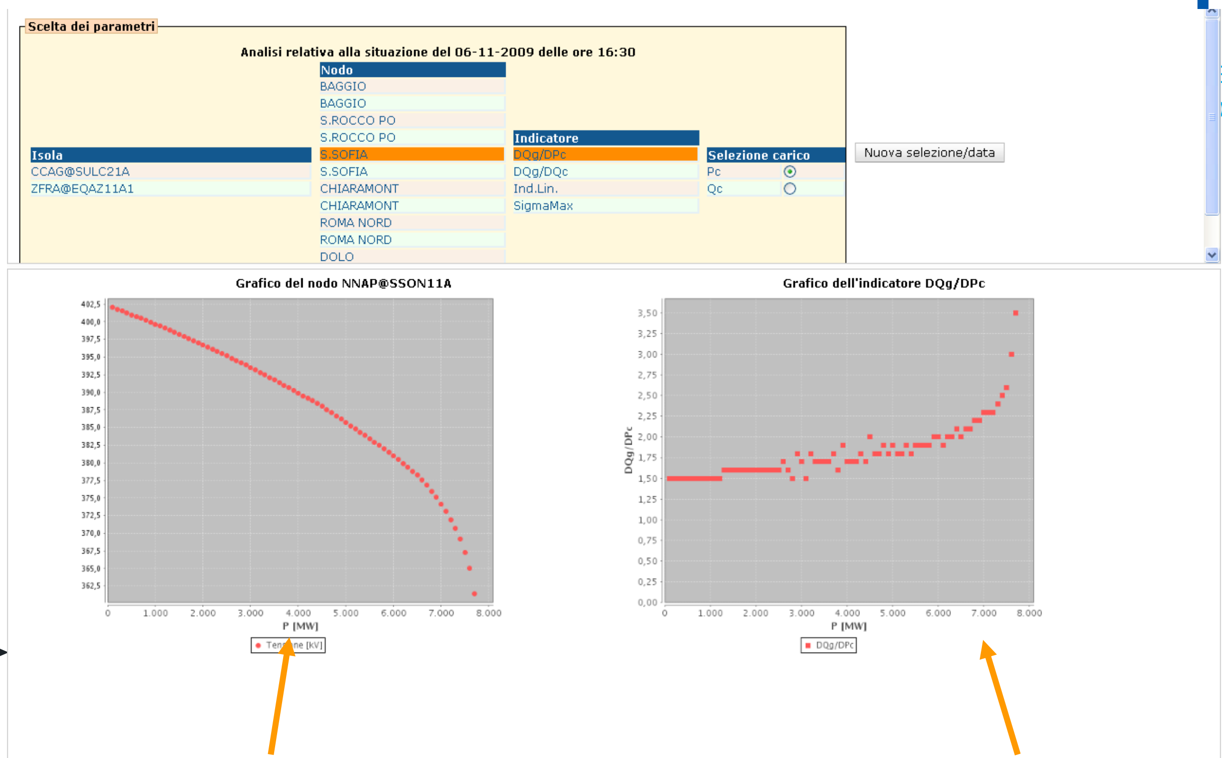
Elemento 1	Tipo elemento 1	Livello elemento 1	Carico iniziale elemento 1 [MW]	Numero violazioni corrente	Numero violazioni tensione	Ranking N-1
PLANAIS-REDIPUGLIA	b	400 kV	-869.5	9	0	100,00 %
REDIPUGLIA-DIVACA	b	400 kV	-913.7	9	0	99,86 %
VILLAN. PE-GISSI	b	400 kV	-1230.6	1	4	22,14 %
GISSI-LARINO	b	400 kV	-833.8	0	2	10,03 %
ROSARA-TERAMO	b	400 kV	-839.3	1	0	2,47 %

Cascading

Elemento 1	Livello elemento 1	Elemento 2	Tipo elemento 2	Livello elemento 2	Carico iniziale elemento 2 [MW]	Numero violazioni corrente	Numero violazioni tensione	Ranking N-2
PLANAIS-REDIPUGLIA	400 kV	BUIA-UDINE NE	b	220 kV	-176.9	0	0	Cascading
REDIPUGLIA-DIVACA	400 kV	PADRICIANO-DIVACA	b	220 kV	-158.7	0	0	Cascading
REDIPUGLIA-DIVACA	400 kV	PDRVAP	b	220 kV	---	0	0	Cascading
PLANAIS-REDIPUGLIA	400 kV	PADRICIANO-DIVACA	b	220 kV	-158.7	0	0	Cascading
PLANAIS-REDIPUGLIA	400 kV	SAFAU AL-UDINE NE	b	220 kV	170.2	0	0	Cascading
REDIPUGLIA-DIVACA	400 kV	SAFAU AL-UDINE NE	b	220 kV	170.2	0	0	Cascading
REDIPUGLIA-DIVACA	400 kV	BUIA-UDINE NE	b	220 kV	-176.9	0	0	Cascading

Voltage Collapse Analysis Module





PV-QV Curves

Carpentier Index

(*) VSI: Voltage Stability Indexes

UFLS/Defence Plan Performance Analysis Module

Scheduling:

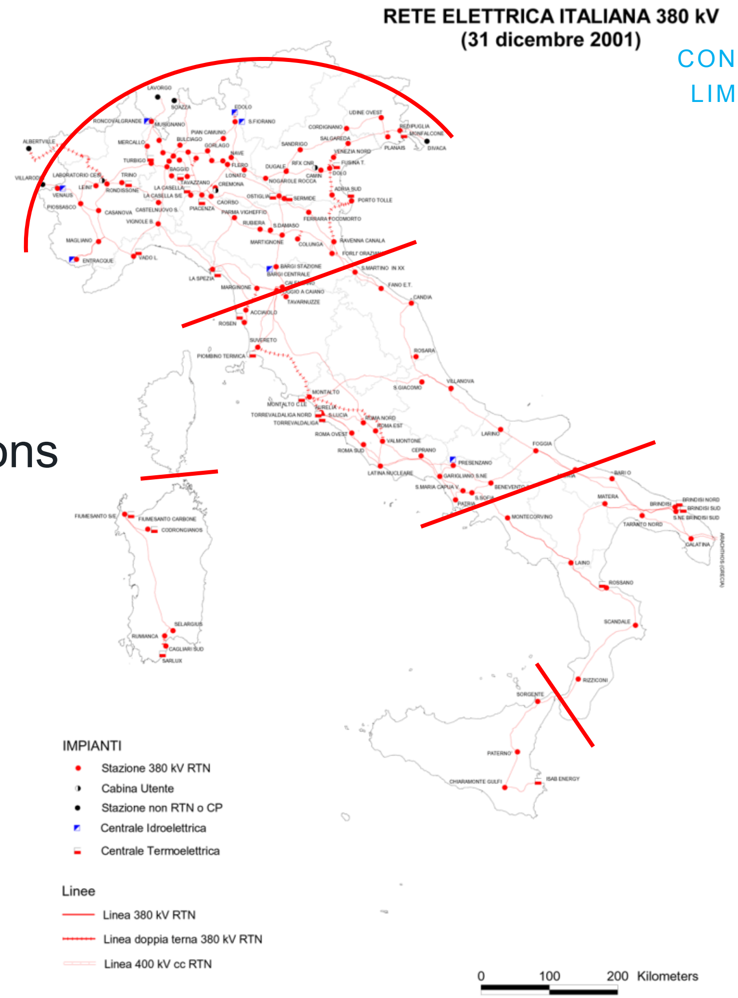
- Configurable scheduling of the analyses
- Many contingency scenarios

Modelling:

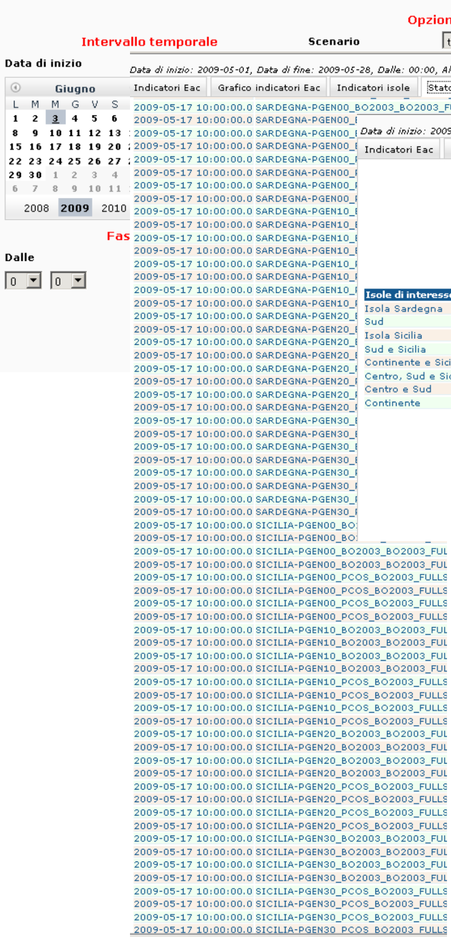
- Different UFLS strategy
- Different models of controls and protections
- SPS

Performance evaluation:

- Performance Indexes Calculation
- Statistical Analysis
- Detailed analysis of simulations



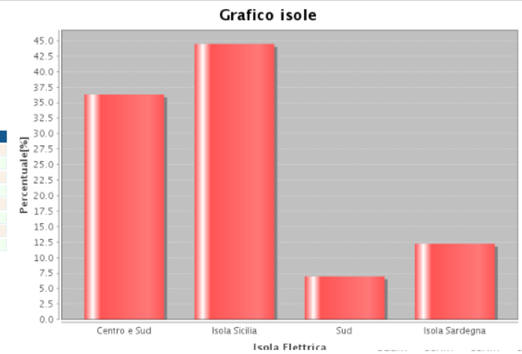
Indexes and statistical analysis (1)



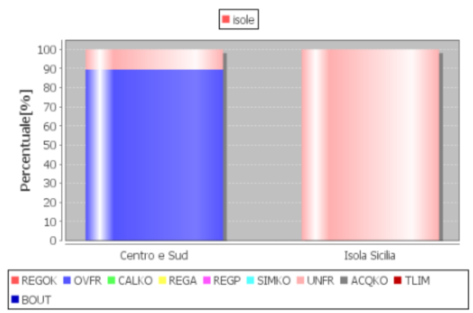
Parametri della ricerca:
Data di inizio: 2009-05-01, Data di fine: 2009-05-28, Dalle: 00:00, Alle: 23:45, Scenario: tutti, Isola elettrica: tutti, AVR: tutti, Alleggerimento: tutti, Protezioni: tutti, Gruppi: tutti, Risultato Analisi: tutti

Indicatori Eac | Grafico indicatori Eac | Indicatori isole | Stato isole a termine simulazione

Isole di interesse	Occorrenze	%
Isola Sardegna	701	12,24%
Sud	399	6,97%
Isola Sicilia	2546	44,47%
Sud e Sicilia	0	0.00%
Continente e Sicilia	0	0.00%
Centro, Sud e Sicilia	0	0.00%
Centro e Sud	2079	36,31%
Continente	0	0.00%



Isole di interesse	REGOK	OVFR	CALKO	REGA	REGP	SIMKO	UNFR	ACQKO	TLIM	BOUT
Isola Sardegna	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Sud	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Isola Sicilia	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,00%	0,00%
Sud e Sicilia	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Continente e Sicilia	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Centro, Sud e Sicilia	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Centro e Sud	0,00%	89,47%	0,00%	0,00%	0,00%	0,00%	10,53%	0,00%	0,00%	0,00%
Continente	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%



Legenda	
REGOK	Il sitema e' dichiarato a regime (derive variabili elettromecciche tarscurabili)
---	Non comparsa
OVFR	Sovrafrequenza non controllata
REGP	Frequenza a regime dopo il tempo finale di simulazione
REGA	Frequenza a regime entro il tempo finale di simulazione
UNFR	Collasso di frequenza
ACQKO	Errore durante l'acquisizione del modello dinamico
TLIM	La simulazione ha raggiunto il tempo limite
SIMKO	Errore durante la simulazione dinamica
CALKO	Errore durante il calcolo degli indicatori di sintesi
BOUT	Isola in emergenza estrema

Transients Diagramming

Nuova selezione/data

Situazione:	2009-03-10 18:00:00
Esito:	
Descrizione:	TEST N-k
Protezioni:	0
Scenario:	GG23122008
Tipologia analisi:	
Controllo:	LIV2
Telescatti:	0

Elenco contingenze
FUNSIM STD
SHORT LIN RROM@RR1354 RROM@VLLR11 0.3 50.000 0.000 0.000
SIMTO 4.000
OPEN NNAP@NN1330 NNAP@BN2N11
OPEN NNAP@NN1330 NNAP@BN2N11

Grafico simulazione | Dati transitorio simulazione | Elenco eventi in uscita | Elenco violazioni

Tempo minimo: **0,000** Tempo massimo: **30,303** Ottieni grafico

Selezione variabili registrate: s

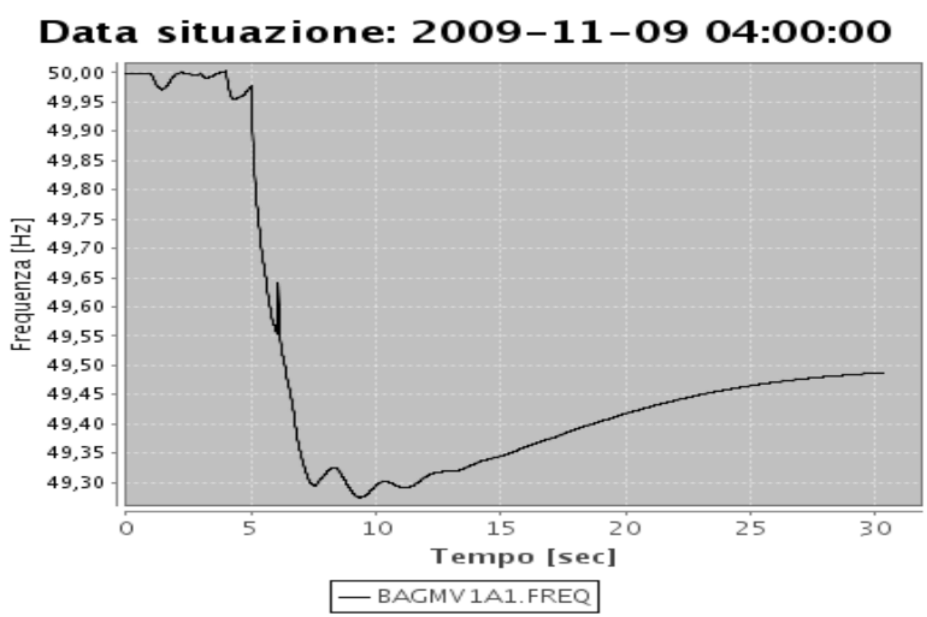
FSACV1A1.FREQ	FSACV1A1.TETA	FSACV1A1.V
SELCV1A1.TETA	SELCV1A1.V	MRTFV1A1.dFRE
MRTFV1A1.V	BAGMV1A1.dFREQ	BAGMV1A1.FRE
MCONV1A1.dFREQ	MCONV1A1.FREQ	MCONV1A1.TET
SCDNV1A1.FREQ	SCDNV1A1.TETA	SCDNV1A1.V
SSONV1A1.TETA	SSONV1A1.V	CHGPV1A1.dFR
CHGPV1A1.V	SRGPV1A1.dFREQ	SRGPV1A1.FRE
MOSRV1A1.dFREQ	MOSRV1A1.FREQ	MOSRV1A1.TET
RMNRV1A1.FREQ	RMNRV1A1.TETA	RMNRV1A1.V
CSNTV1A1.TETA	CSNTV1A1.V	DOLVV1A1.dFR
DOLVV1A1.V		

Range tempo

0%

Tempo minimo: **0,000**

Ottier



CONFIDENTIAL
LIMITED USE

CESI

DSA: Benefits for TSO

Control Room Operators:

- Online detection of criticalities on the network
- Online execution of operators defined simulations (work in progress)

Operational Study Department:

- Online testing of new UFLS and SPS
- Possibility to configure the views for the operators
- Statistical analyses of the security level of the network

Index

- ❑ Evaluation of Reserve Margin in presence of variable renewable generation
- ❑ Dynamic Security Assessment
- ❑ **WAMS – Wide Area Measurement Assessment**
- ❑ Dynamic rating
- ❑ Synthetic Inertia

Introduction

Needs for advanced measurement systems

- High system complexity
- Large geographical extension of transmission networks
- Inter-area dynamic phenomena
- Increasing concern of system's dynamic security

SCADA system and/or dynamic simulation no longer able to describe such complex phenomena

→

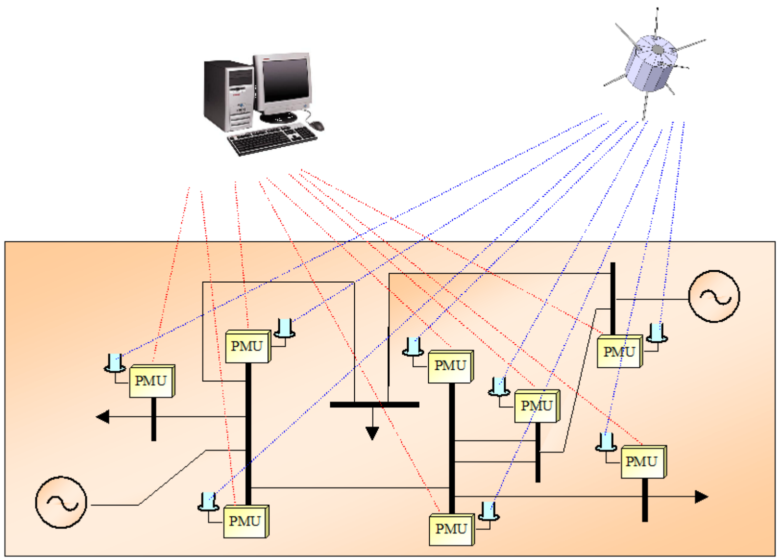
WAMS can collect from PMUs accurate and synchronized measure over large (interconnected) power systems

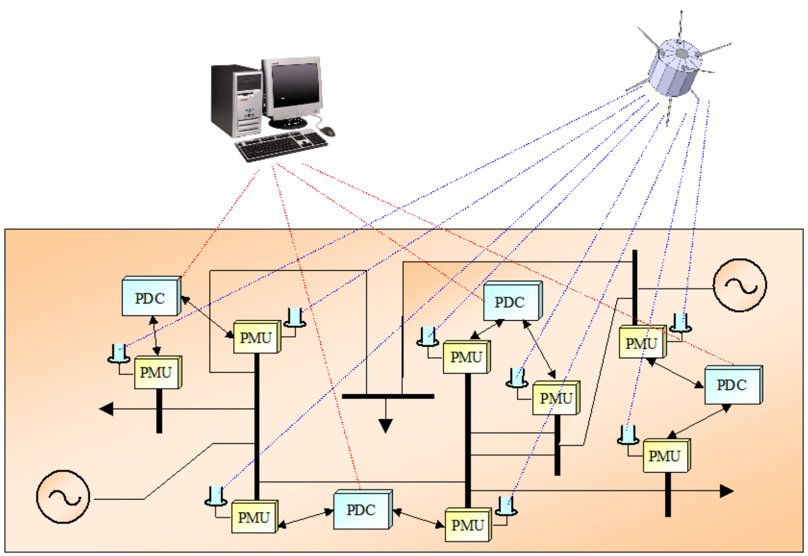
PMU technology main features

- GPS time synchronisation (according IEEE 1344 till 2005 then IEEE C37.118)
- High sampling rate (50-60 Hz)
- High speed telecommunication connection
- Calculation of module and angle of voltages and currents

PMU positioning strategy

- Complete system **observability** may be impossible to achieve
- Focus on **network critical portions** subject to:
  - Specific events (e.g. line trip with possible cascading)
  - Dangerous phenomena (e.g. voltage collapse, oscillations)

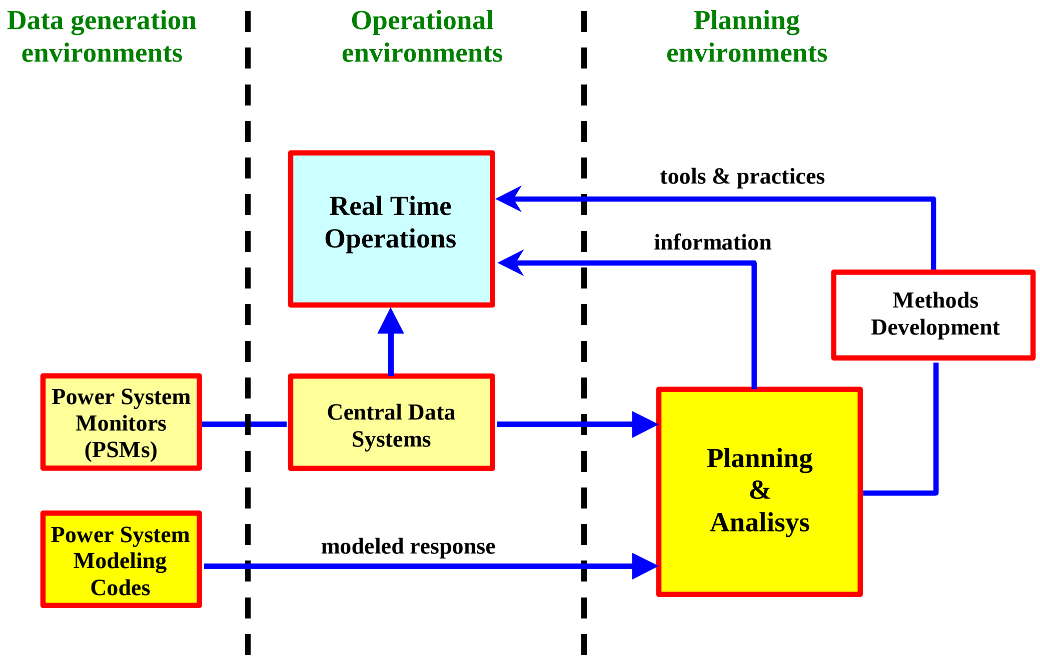




RECOMMENDATION:

Use **both <u>heuristic</u> and analytical criteria** to maximize the added value of measurements

Synchronized measures main applications



Result Analysis

- Machine's performances check (i.e. regulations' performances)
- Machine outages recognition
- Parameter identification
- Model validation

Data Acquisition and Operation

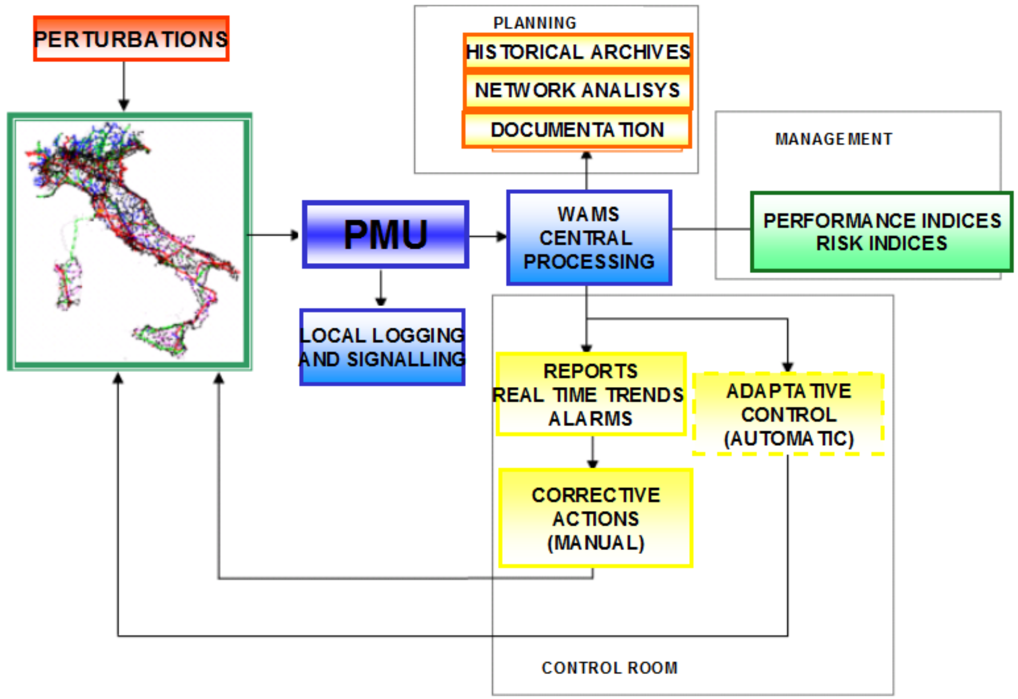
- State estimation "with angles"
- Stability margins
- Transfer capacity evaluation
- Inter-area oscillations monitoring
- Congestion clearing
- Restoration support

Post-Event Analysis

- Contingency recognition
- Oscillations analysis
- Event reconstruction

Italian WAMS - System characteristics

- Planned to improve system security after **2003 blackout.**
- Aimed to provide the control room operators with **advanced monitoring tools** and, in perspective, **automatic corrective controls**, both phenomenon and event-based, linked with a SPS.
- In service **since 2005**.
- Up to **100 PMU devices**, their number is in continuous growing.
- PMU locations have been selected in order to **maximise the added value of the measurements**.



- **Connection with the neighbouring countries** for comprehensive control of the interconnected power network and in-depth monitoring of the power import towards the Italian system.

CONFIDENTIAL – LIMITED USE

CESI

CESI experience - Electromechanic phenomena monitoring

Detailed **monitoring of system behavior**, thus improving knowledge of the system dynamic.

Processing methods aimed at **stability monitoring**.

Identify **weakly damped oscillatory behaviors**, mainly inter-area, with great care to the time at which these dynamics took place and their trend.

PMU systems provide thorough measurements of network sizes and **include angles estimated** in respect to an **absolute time reference**.

Methods Classes

Non-parametric methods

- Frequency modes estimation techniques
- Measure energy content in each frequency interval without seeking models for signal generation

Sub-space methods

- Frequency modes estimation techniques based on eigenvalue analysis of the autocorrelation matrix
- Assign information to either a signal subspace or a noise subspace

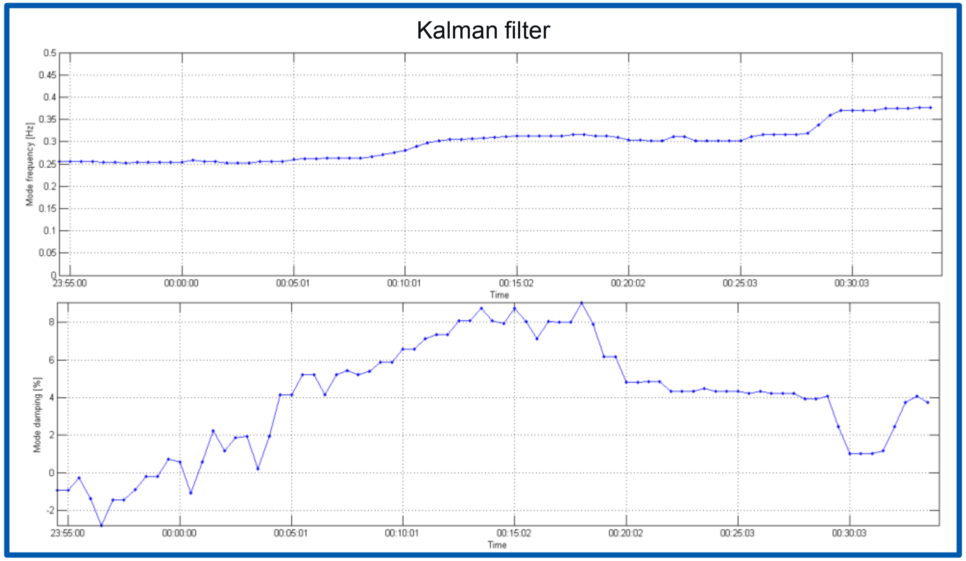
Parametric methods

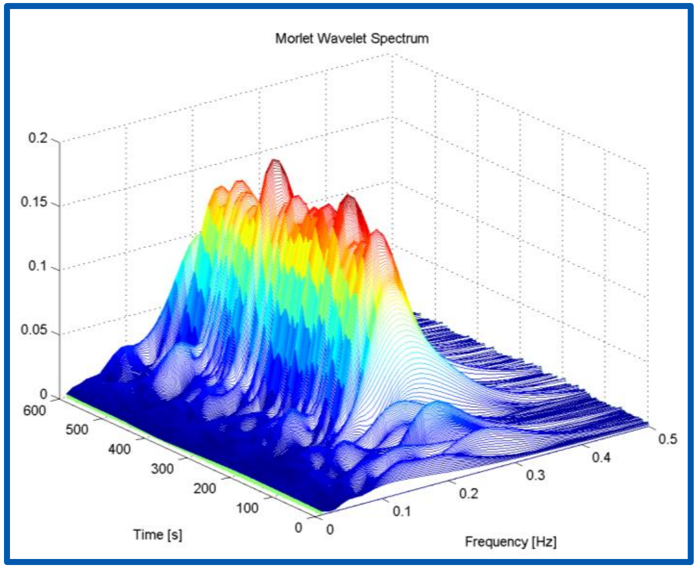
- Analyze its spectral content choosing a signal generation model and so setting the model parameters
- Estimate both frequency and damping of the oscillations

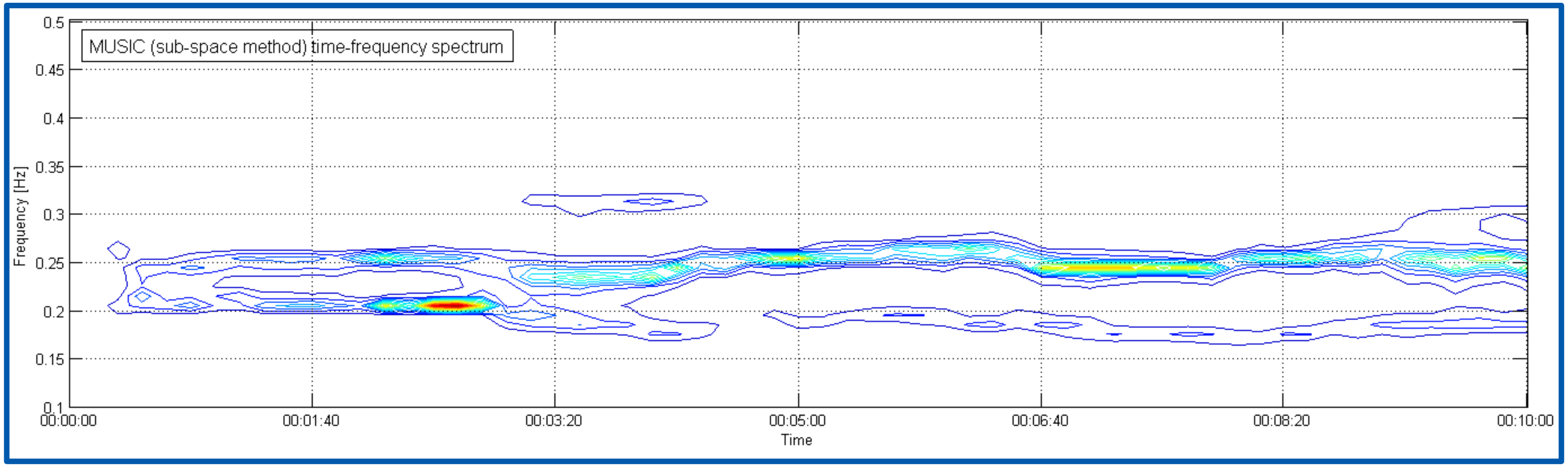
Direct methods

- Analyze the signals without making any other assumption regarding models for signal generation
- Estimate frequency, damping and amplitude of the oscillations

Methods Examples





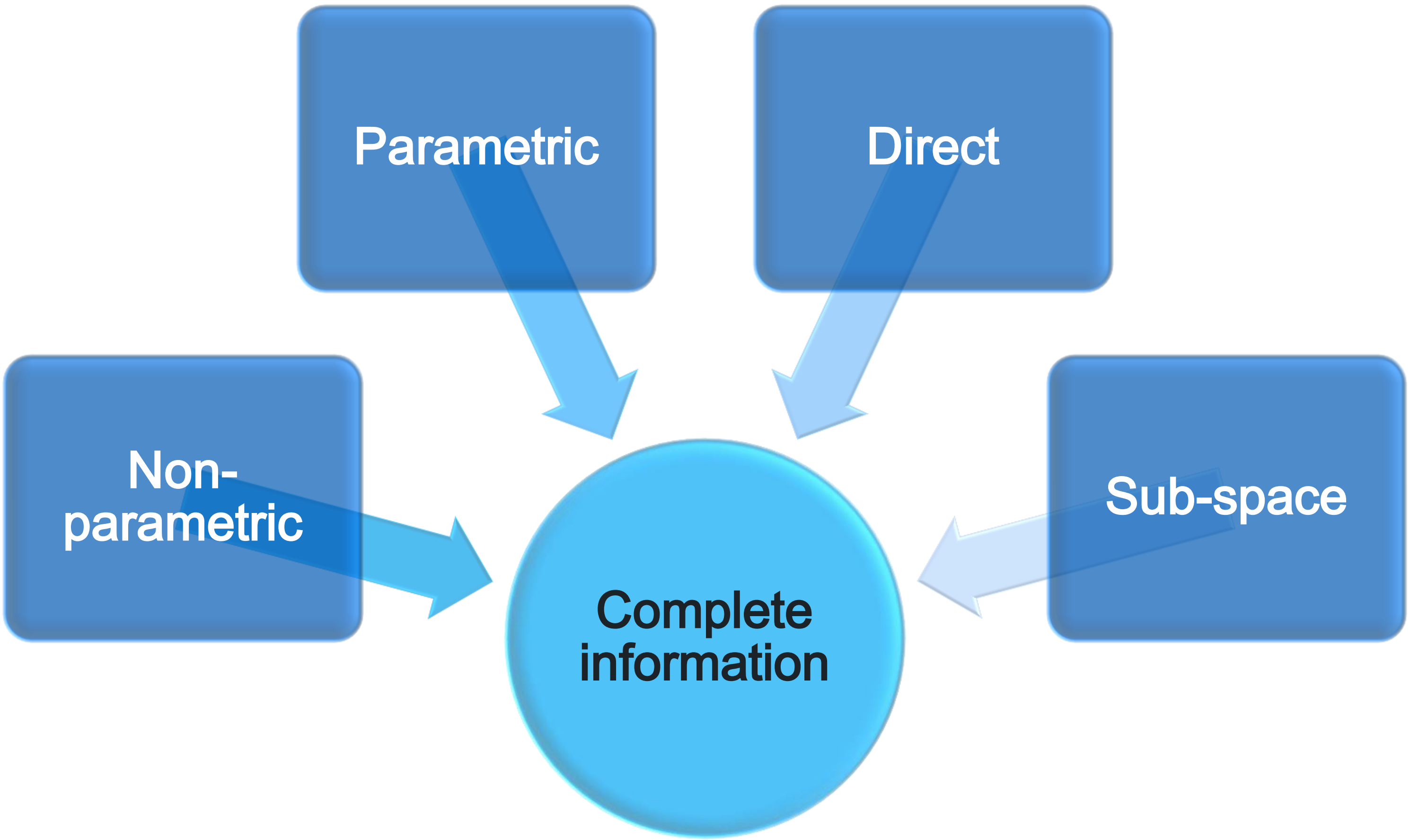


CONFIDENTIAL – LIMITED USE

CESI

Processing of analyses' results

- These techniques have been implemented in on-line applications, currently working at the National Control Centre (Rome), which has made possible a real-time monitoring of the network.



CONFIDENTIAL – LIMITED USE

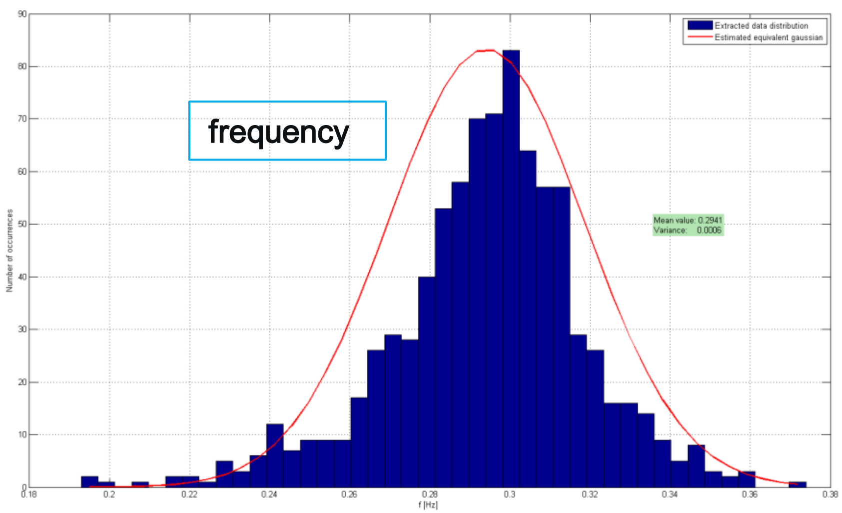
CESI

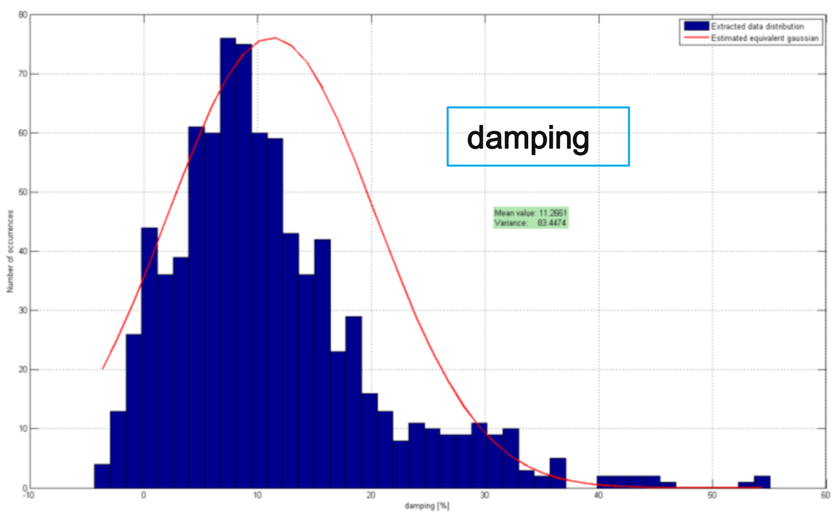
Statistical analysis and correlation with external factors

- On-line application has been provided a lot of analysis results obtained on long registrations (10-15 days) on which it will be possible to conduct statistical analysis.

- Analyzing distribution of frequency and damping could be very useful to characterize typical oscillatory modes crossing the different parts of the electrical network.

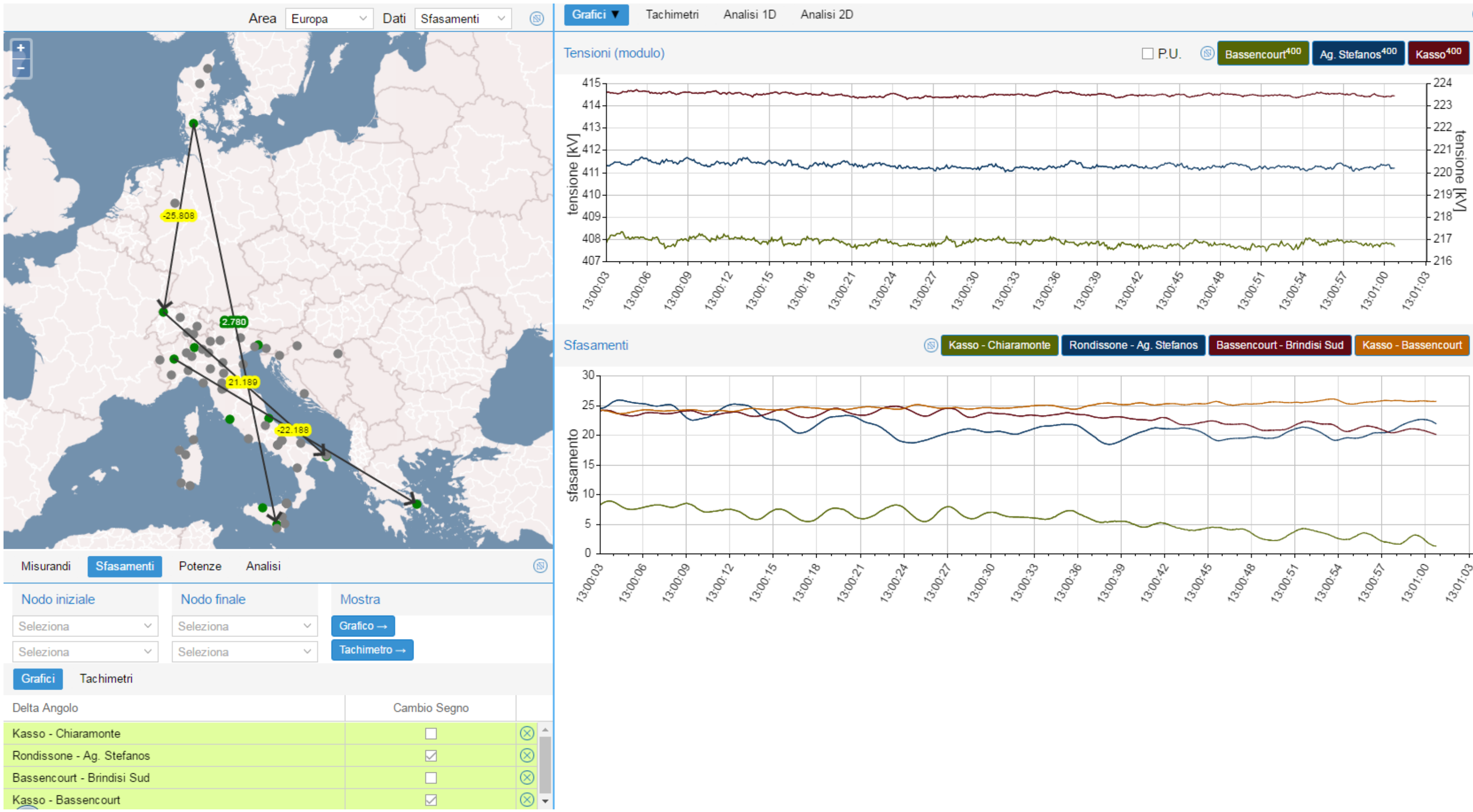
- It is very important to investigate how their damping depends on moment of the day, load situation, network mesh condition, amount of renewable production, quantity of power exchanged with foreign countries.





CONFIDENTIAL – LIMITED USE

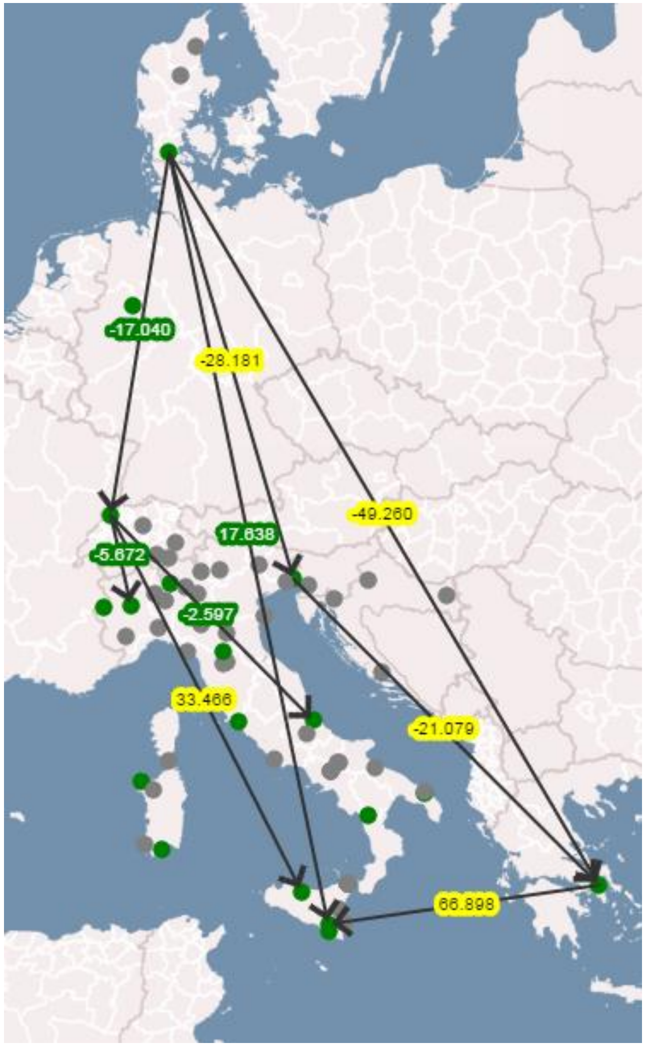
WebWAMS – Home page



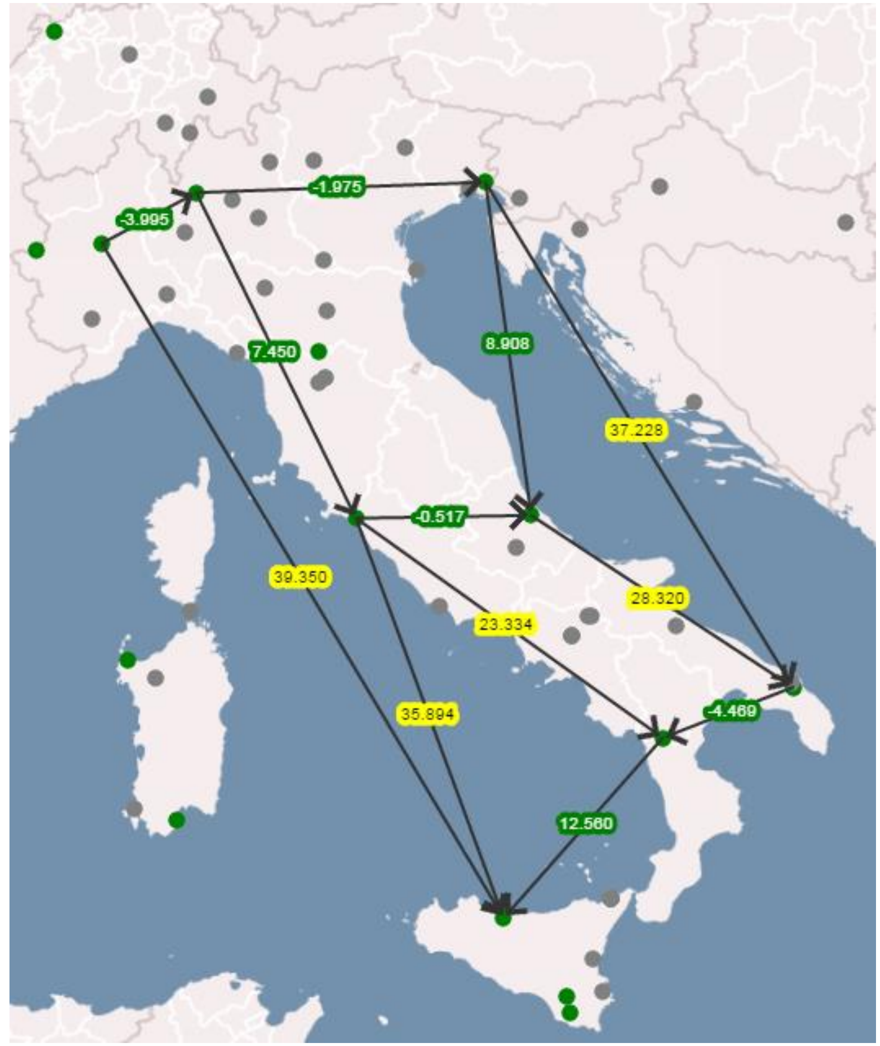
CONFIDENTIAL – LIMITED USE

WebWAMS – Angle Differences

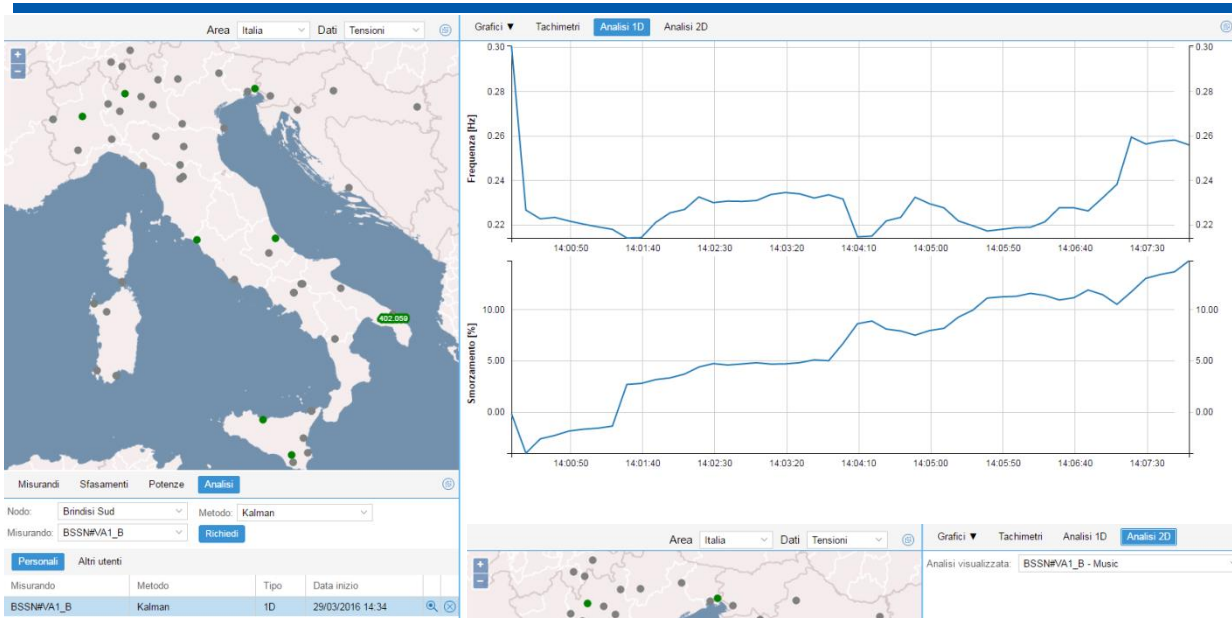
European Angle Differences



Italian Angle Differences

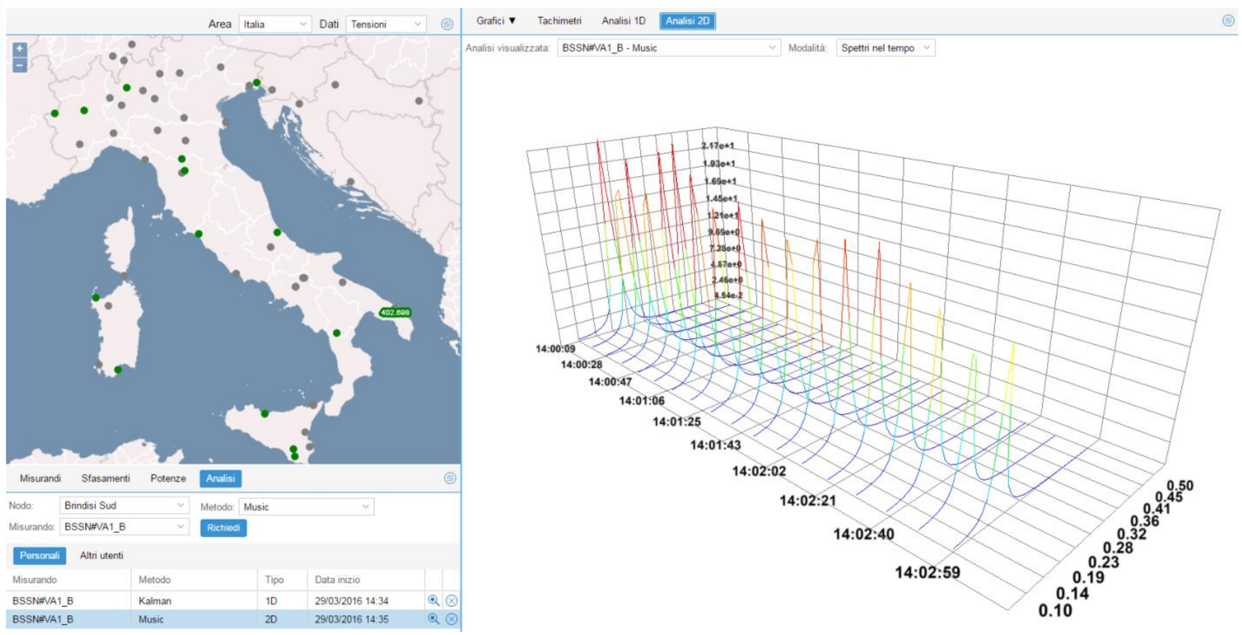


WebWAMS – Oscillation Analysis



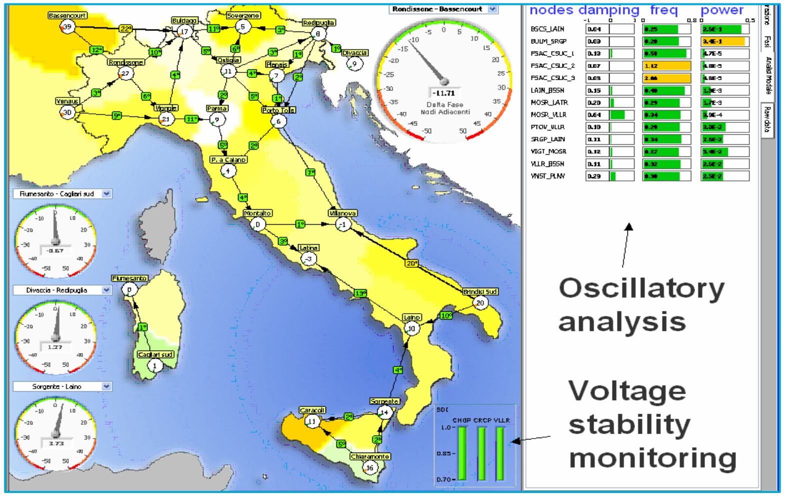
1D Analysis

2D Analysis

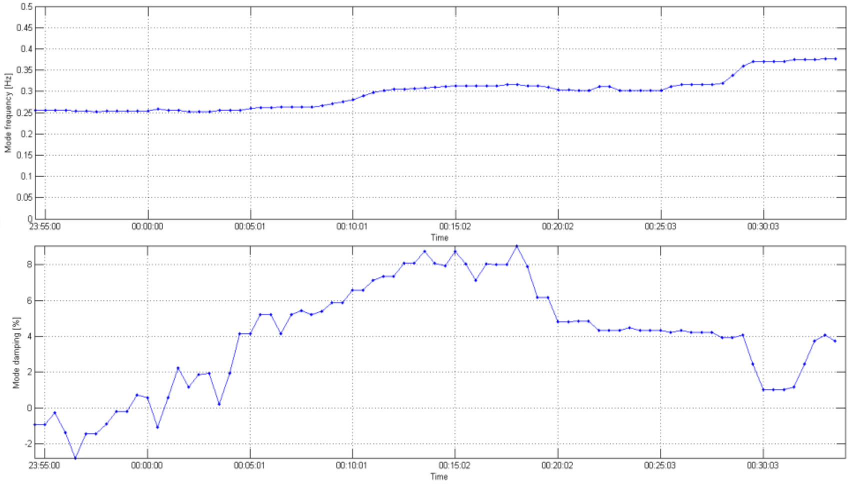


EUROPE - Italian WAMS experience – “Main Features”

- **Basic On-Line Monitoring Features:**
  - Voltages and Current Trends
  - Active and Reactive Power Flows and Directions
  - Frequency Trends
  - Angle Values and Differences Representation



- **Advanced Off-Line and On-Line Monitoring Features:**
  - Voltage stability assessment
  - Oscillations’ stability assessment
  - Statistical analysis on main inter-area oscillation modes
  - Event Detection
  - Frequency Stability and Islanding
  - Dynamic Thermal Line Rating
  - PMU State Estimation linked with TM/TS State Estimation
  - Restoration tests support



Frequency and damping estimation with model identification performed with Kalman filter

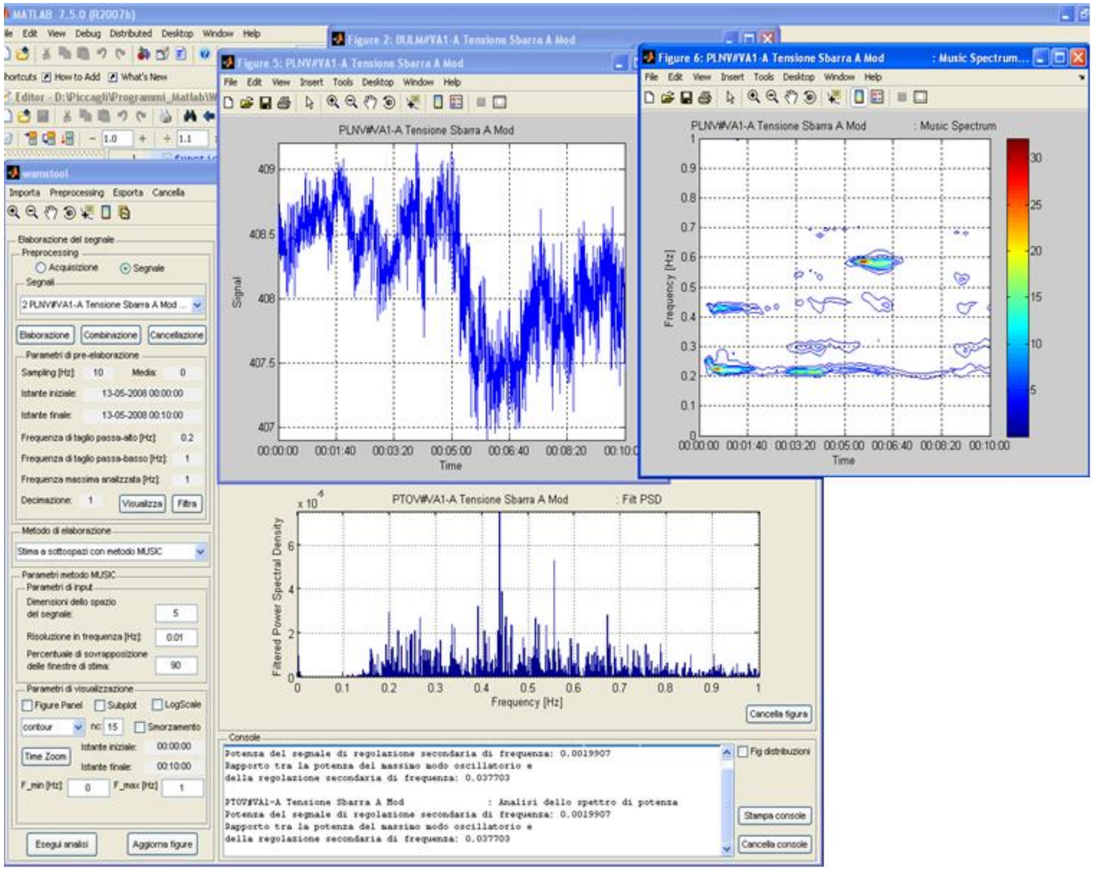
CESI

WAMSTOOL

MATLAB library and GUI for off-line processing and visualization of wide-area signals

Features:

- Power Spectrums
- Digital Filtering
- Frequency-Damping Estimation:
  - ARMA Identification
  - Kalman Filter
  - Prony Analysis
  - Maximum Likelihood Estimation
- Subspaces Methods
- Wavelet Transform
- Time, Frequency, Time-Frequency plots



CONFIDENTIAL – LIMITED USE

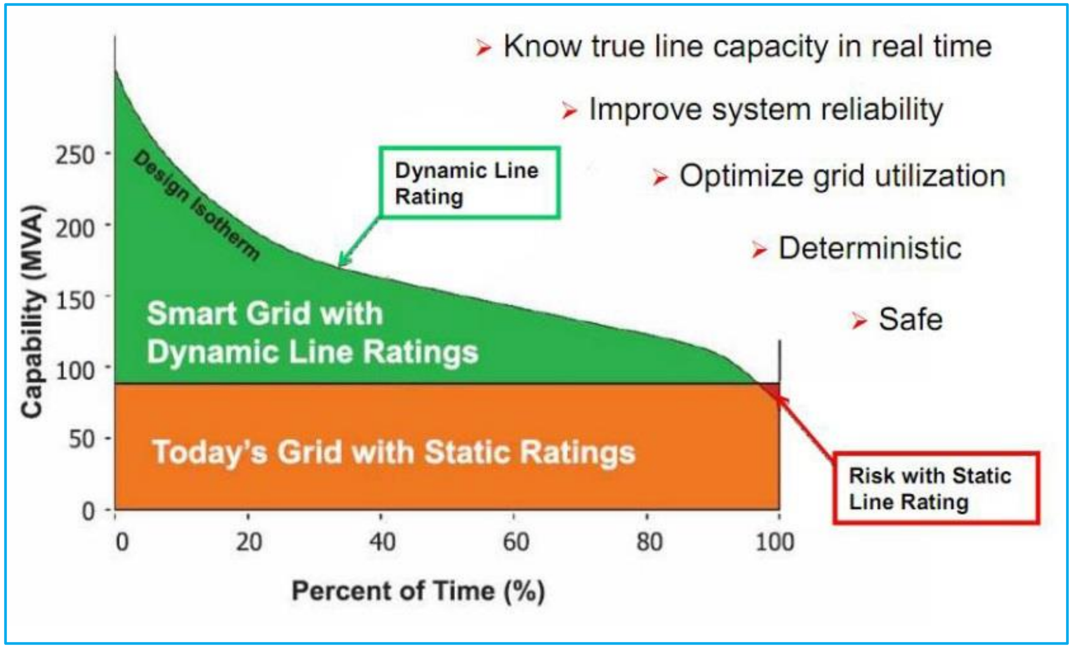
CESI

Index

- ❑ Evaluation of Reserve Margin in presence of variable renewable generation
- ❑ Dynamic Security Assessment
- ❑ WAMS – Wide Area Measurement Assessment
- ❑ **Dynamic rating**
- ❑ Synthetic Inertia

Introduction to Dynamic Line Rating

- Dynamic Line Rating (DLR) permits to take into account the real thermal stresses on lines and equipment, making dynamic the characterization of networks limits.
- Traditional static line ratings are expressed as the Ampere limits calculated in project phase assuming average boundary conditions (e.g. weather conditions), but they are usually based on the thermal limits of the conductors.
- DLR allows to know at every time the actual loading of the line and how much it can be further loaded without incurring in premature aging of the conductors.
- DLR methods are based on the real-time line's temperature estimation and the following calculation of the residual loading margin.



Dynamic Line Rating using WAMS

- Knowing the present temperature of the conductor is possible not only to calculate the static Ampere limit of the line, **but also** to estimate how much the line may be overloaded at a specific overcurrent prior the reaching of the thermal limit of the conductor.

- This passes through the further estimation of **the average current and of the thermal time constant of the line**.

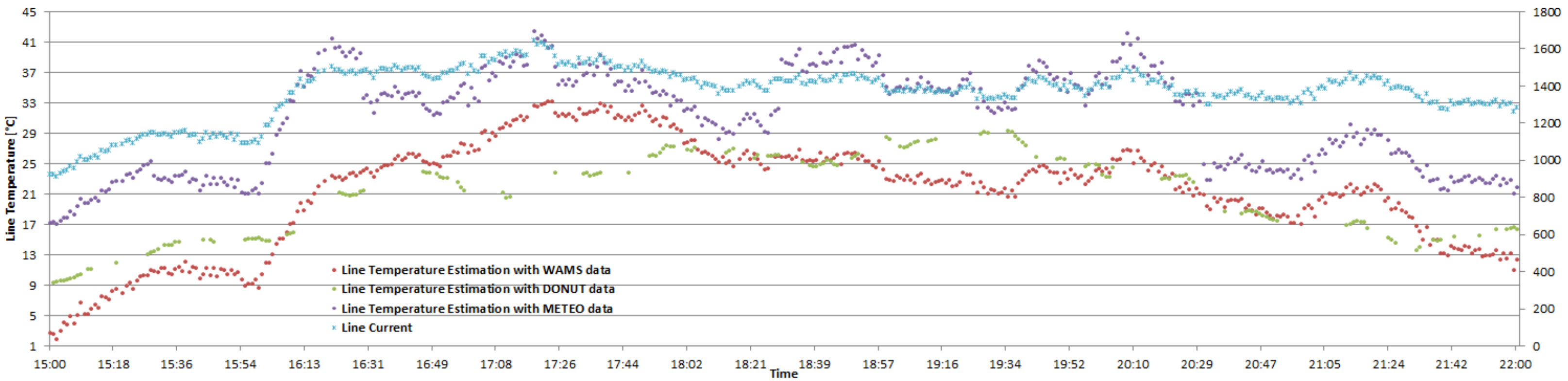
- WAMS DLR technique consists in the real-time reconstruction of the electrical parameters of the line based on the elaboration of the WAMS measurements.

- Comparing the real-time values with the standard values is possible to estimate with a good accuracy the current temperature of the line thus consider a mean value along the whole length.

- Where the dynamic limits calculated will be higher than static ones currently available, it will be possible to relax some of the optimization procedure constraints and define a better dispatching strategy, exploiting the actual line load margins.

Dynamic Line Rating results

- The algorithm for real time estimation of the line rating has been integrated in an on-line software application presently operating at the National Control Center where it is profitably used to inspect the real time rating of the lines but also to analyze the past days data.



- In the on-line application all the three methods for the conductor's temperature estimation are actually applied, then, a dedicated algorithm is implemented to select the final temperature, used for the estimation of the time constant of the line.

- The final temperature is identified selecting one of the three or a combination of them on the basis of the reliability calculated for each method, varying according with data characteristics.

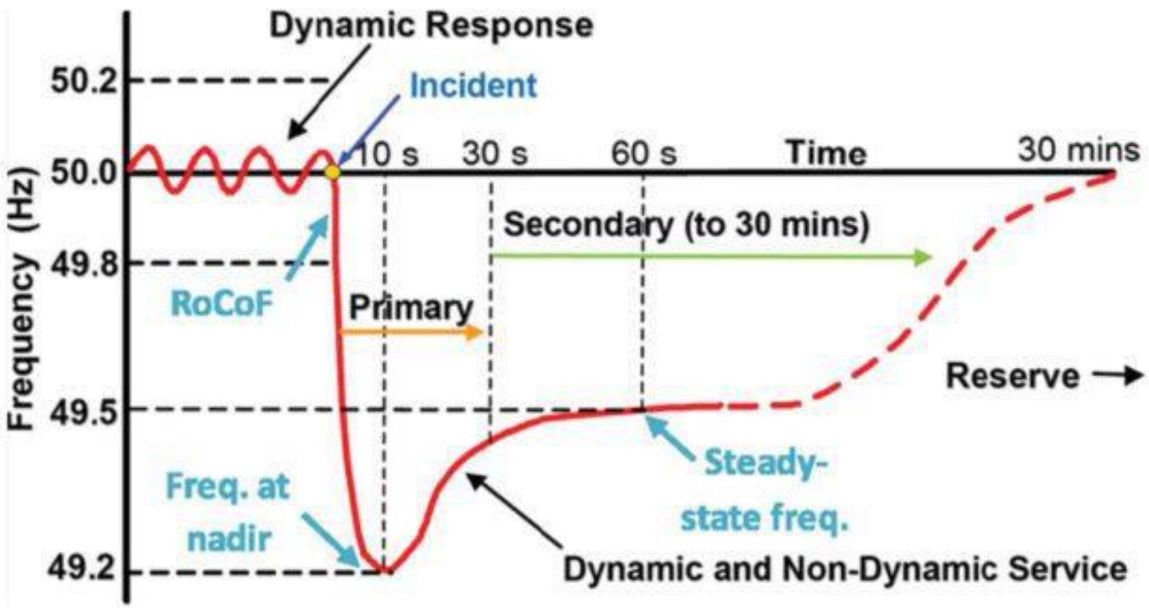
CONFIDENTIAL – LIMITED USE

CESI

Index

- ❑ Evaluation of Reserve Margin in presence of variable renewable generation
- ❑ Dynamic Security Assessment
- ❑ WAMS – Wide Area Measurement Assessment
- ❑ Dynamic rating
- ❑ Synthetic Inertia

Synthetic Inertia



Inertia is a property of the grid which limits frequency variations in the case of sudden load or generation changes. High penetrations of renewable energy reduce the inherent inertia of the grid. Synthetic inertia can be introduced using smart grid techniques to overcome this problem.

CONFIDENTIAL – LIMITED USE

Synthetic Inertia

The stability of the electric power system related to system frequency and rotor angle relies on the kinetic energy of rotating machines (motors and generators) that are connected to the power system. Equipment connected through power electronic converters does not contribute to the available kinetic energy from power system operational perspective.

$$J w_{nom} \frac{dw}{dt} = P_{mech} - P_{el}$$

- Wind power plants have a rotor that could accumulate energy: Studies have demonstrated that the Inertia Constant of a wind turbine is in the order of 2-6 s which is comparable to traditional generation.
- Solar systems haven't an inherent way of accumulating energy (e.g. batteries or flywheels are needed)

So, large amounts of wind power can have a negative impact on frequency stability.

CESI

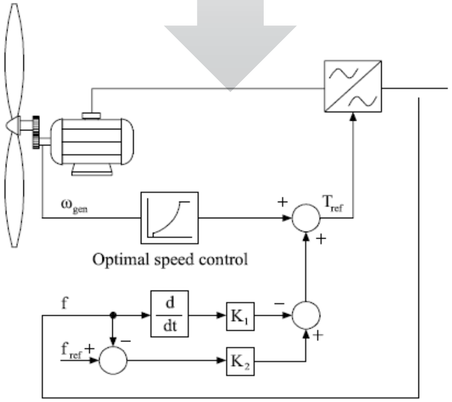
Synthetic Inertia

In addition, if system inertia is reduced due to the replacement of synchronous generators by wind power, this may also jeopardize rotor angle stability. Rotor angle stability is related to local unbalances in production and consumption and the resulting differences in frequency and rotor angle. Less inertia will also give faster changes in frequency and rotor angle and an increased probability of instability.

To mitigate these problems new techniques are available:

Using BESS

Using Advanced Control for Wind Turbina



CONFIDENTIAL – LIMITED USE

CESI

Synthetic Inertia

The power extracted from wind by a wind turbine is:

$$P = \frac{1}{2} \cdot \rho \cdot \pi \cdot v^3 \cdot r^2 \cdot C_p(\gamma)$$

with:

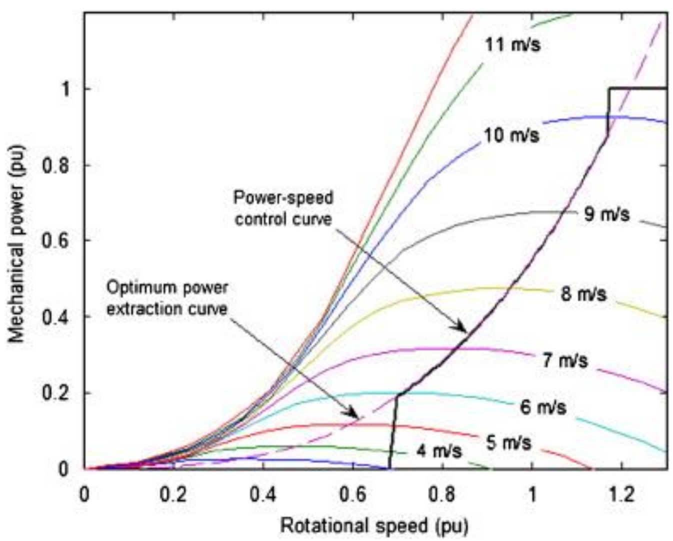
P: mechanical power

ρ: air density

γ: tip-speed ratio (the ratio of blade tip speed to wind speed)

v: wind speed

C_p: coefficient of efficiency



Synthetic Inertia

During a critical situation, thanks to a power control, it is possible to temporarily increase the electrical output power and so obtain a synthetic inertial response. The additional power has to be taken from the kinetic energy of the rotor because in general the wind production is already maximized thank to the optimal speed control.

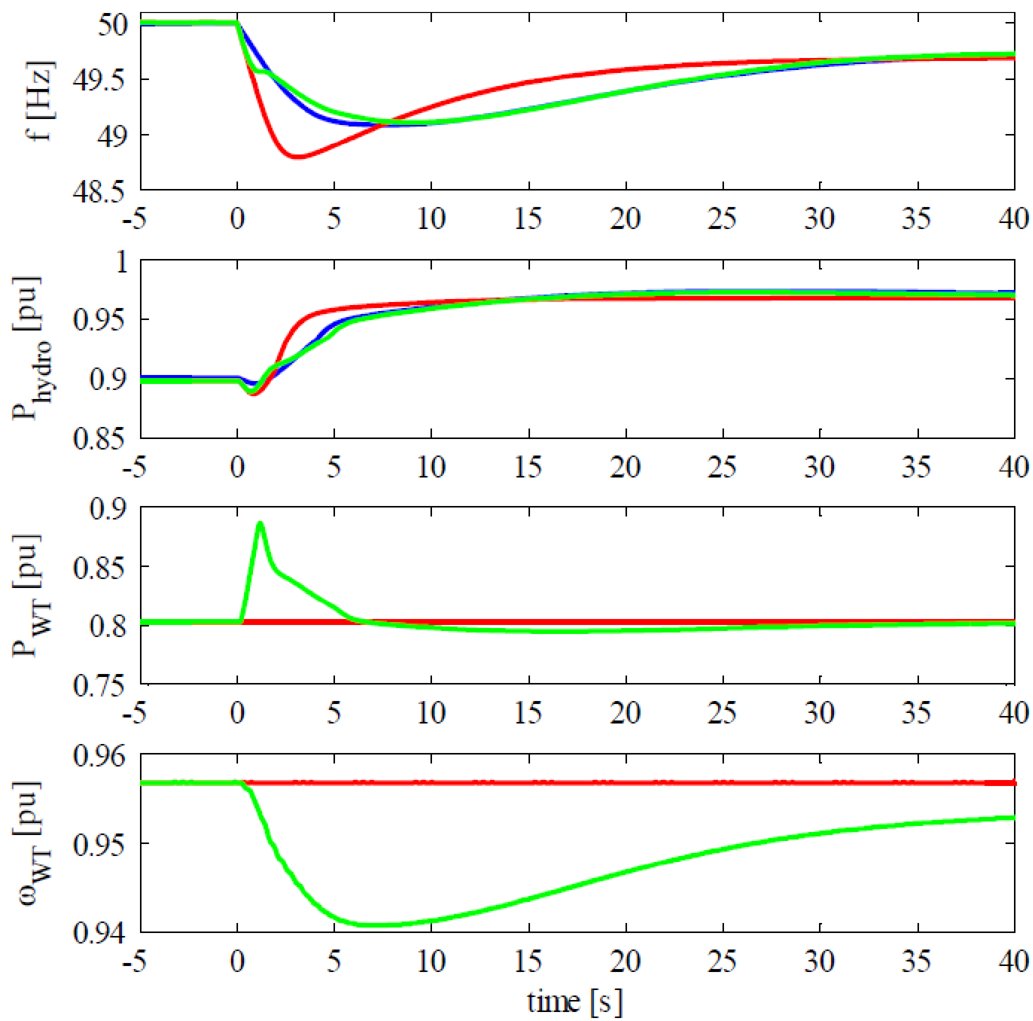
After a period of overproduction, the output power has to be reduced in order to accelerate and restore the turbine speed to a value determined by the optimal speed control. The maximum period of overproduction is limited by the fact that turbine must not stall, hence the minimum speed must not be reached. In order to mimic the natural inertia of a synchronous generator an extra torque proportional to df/dt is added:

$$\mathrm{T} = 2H\frac{df}{dt}$$ With H Inertia Constant

Power increase of 5-10% during a grid frequency drop in 5-8 seconds would be possible

CESI

Synthetic Inertia



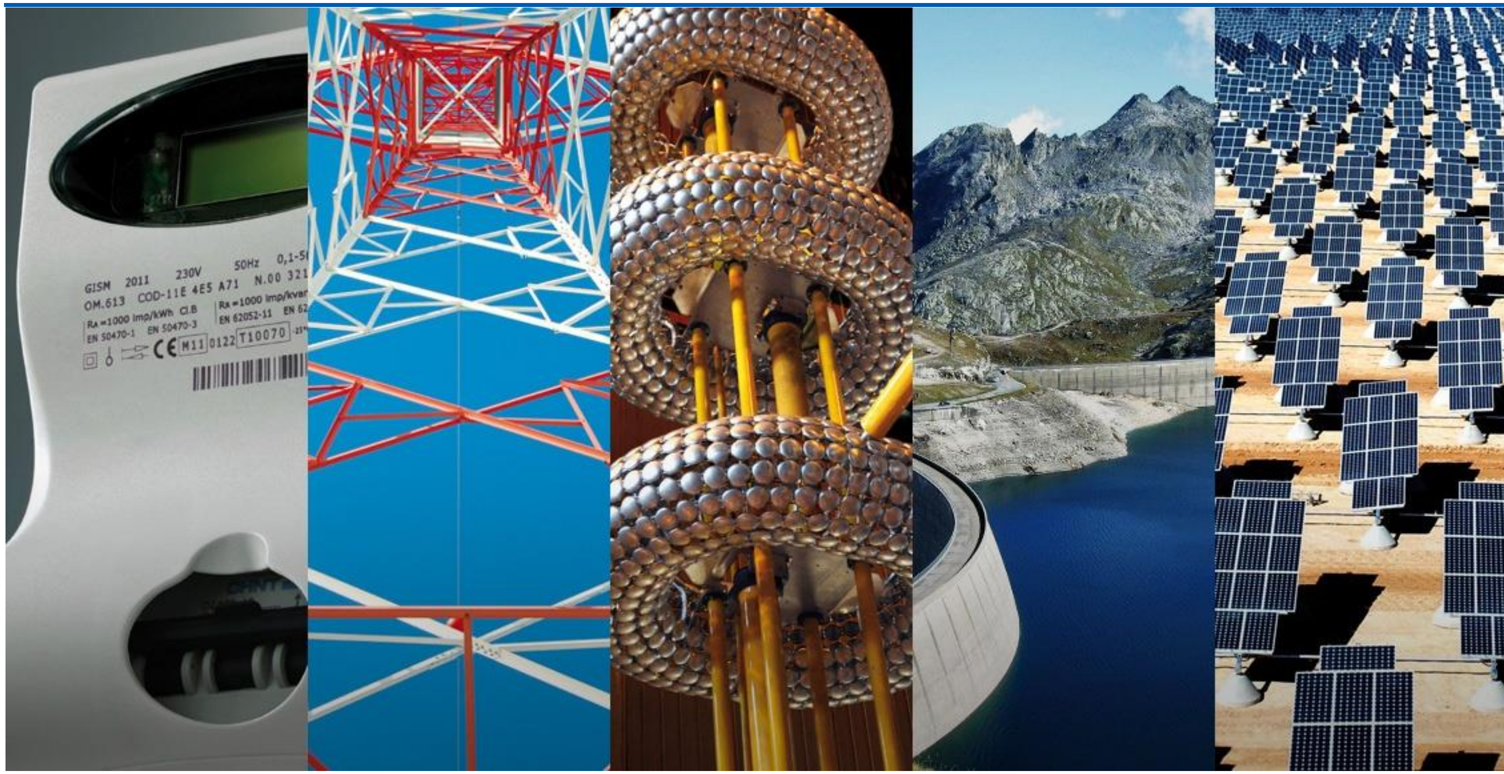
The test system modeled is characterized by a total load of 30000 MW. With blue line the demand is covered only with thermal and hydro plants; with the red line thermal power is replaced by 15000 MW of wind power (wind 10.5 m/s); with green line the wind power plants have the inertia control activated. The critical event is the loss of 1400 MW thermal production.

ISMES
IPH BERLIN
FGH
ISTEDIL

CESI

www.cesi.it

Testing • Consulting • Engineering • Environment



Milan • Berlin • Mannheim • Dubai • Abu Dhabi • Rio de Janeiro • Washington DC