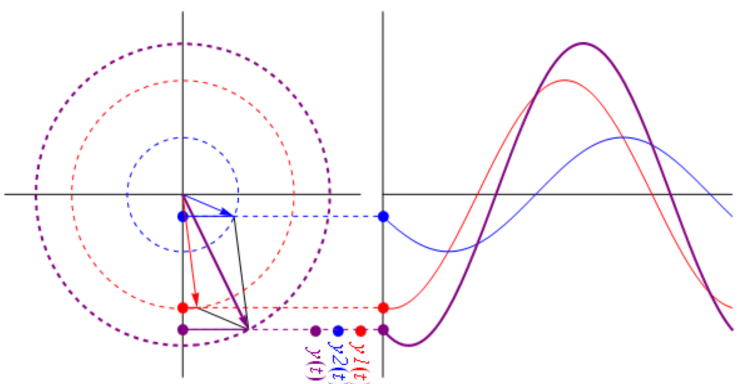
IV International Workshop on Synchrophasor Applications

The Ecuadorian Wide Area Monitoring, Protection and Control System - WAMPAC



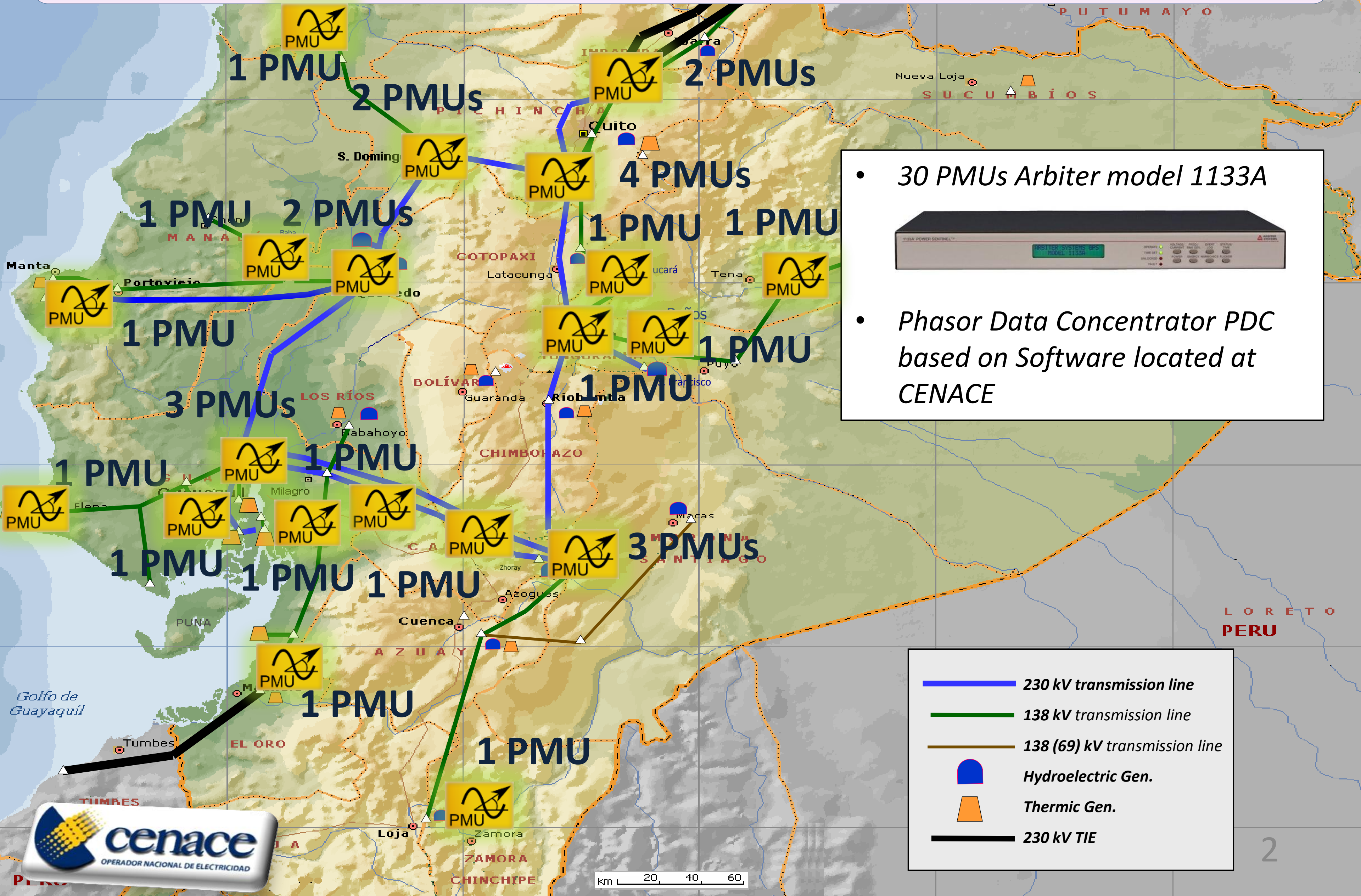
Dr.-Ing. Jaime Cepeda

cepedajaime@ieee.org

jcepeda@cenace.org.ec

November 29, 2016

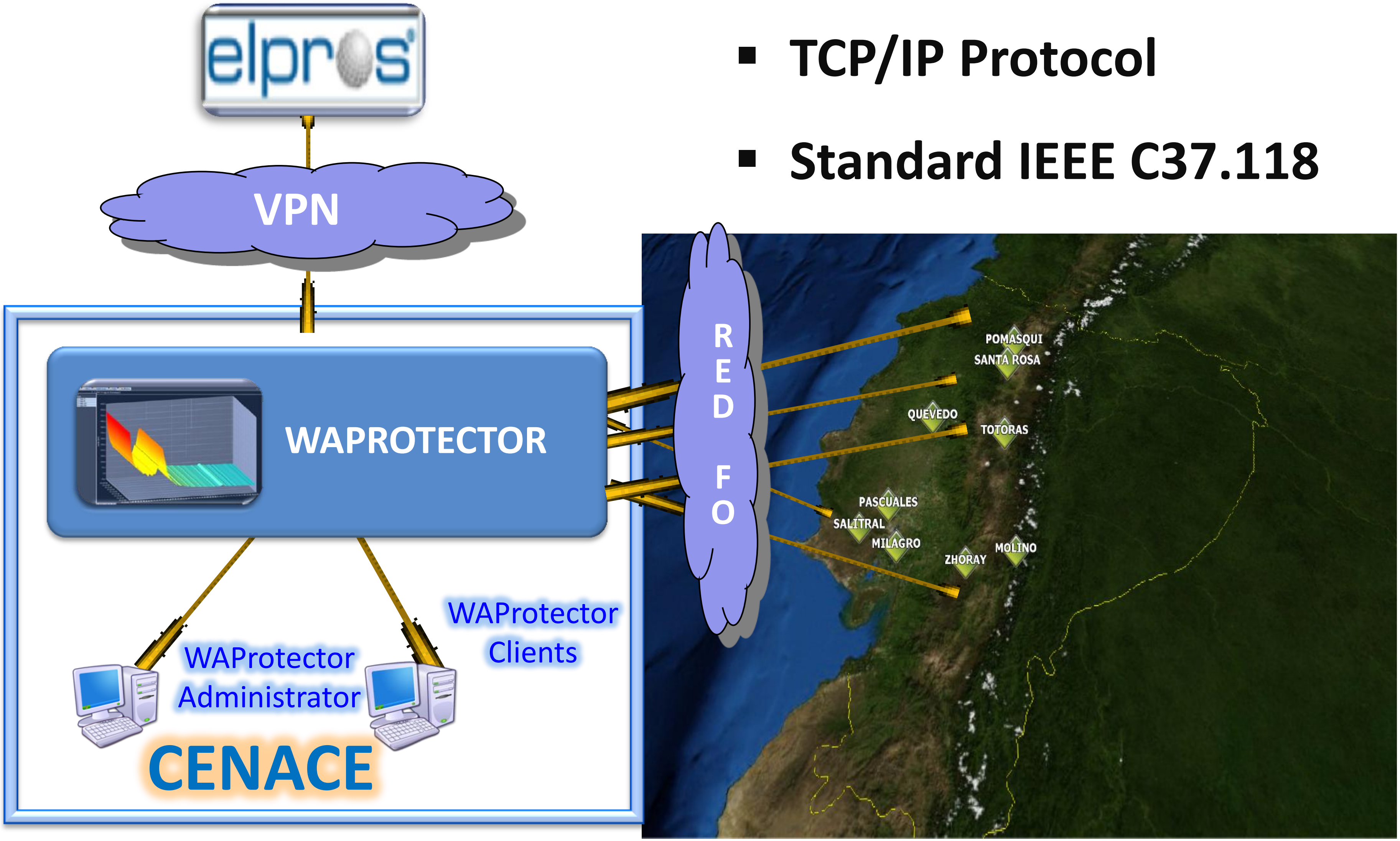
PMUs installed at Sistema Nacional Interconectado



- *30 PMUs Arbiter model 1133A*
- *Phasor Data Concentrator PDC based on Software located at CENACE*

WAMS Platform - WAProtector

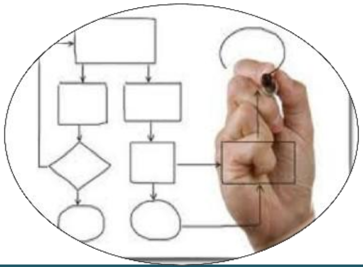
- TCP/IP Protocol
- Standard IEEE C37.118

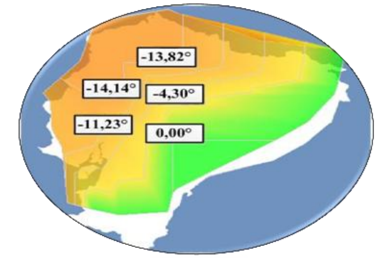


Independent System Operator - ISO

cenace
OPERADOR NACIONAL DE ELECTRICIDAD

Synchronized Phasor Measurement Applications - ISO





PLANNING

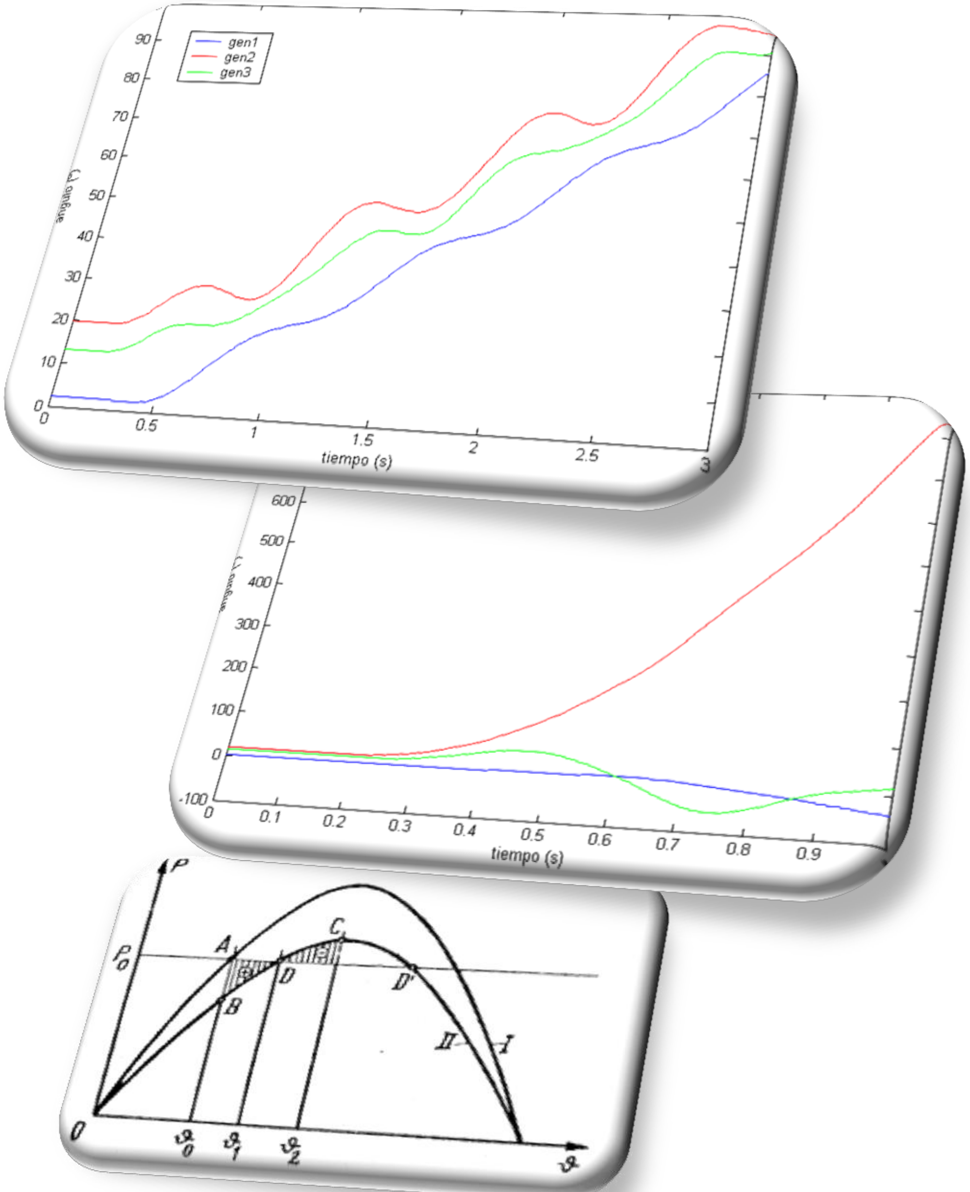
- PMU location
- Parametrization of WAMS Applications
- Dispatch based on security constraints
- PSS tuning
- Design of wide area protection and control schemes
- Model parameter identification

REAL TIME OPERATION

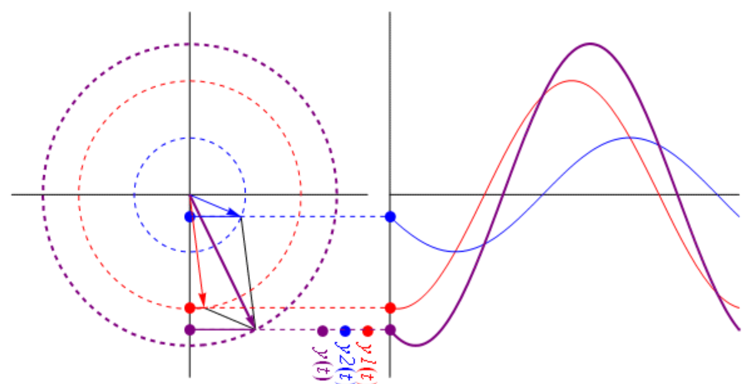
- Static and dynamic security state Monitoring
- Early warning
- Situational awareness
- Control
- Protection
- Operators’ Training

POST-OPERATIVE ANALYSIS

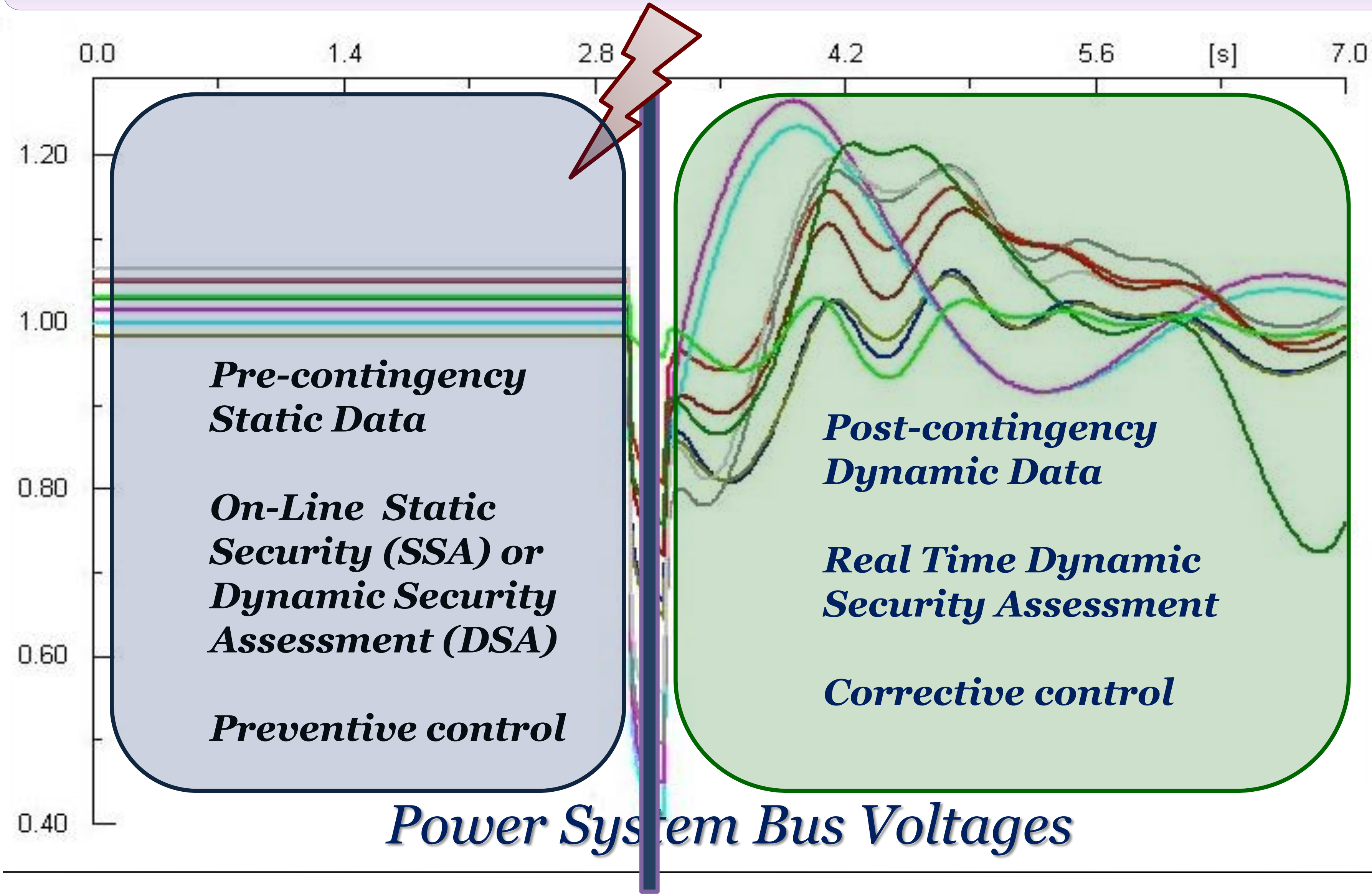
- Post-Mortem Analysis
- Static security statistics
- Dynamic security statistics
- Vulnerability status patterns identification
- Power Quality analysis



Real Time Operation



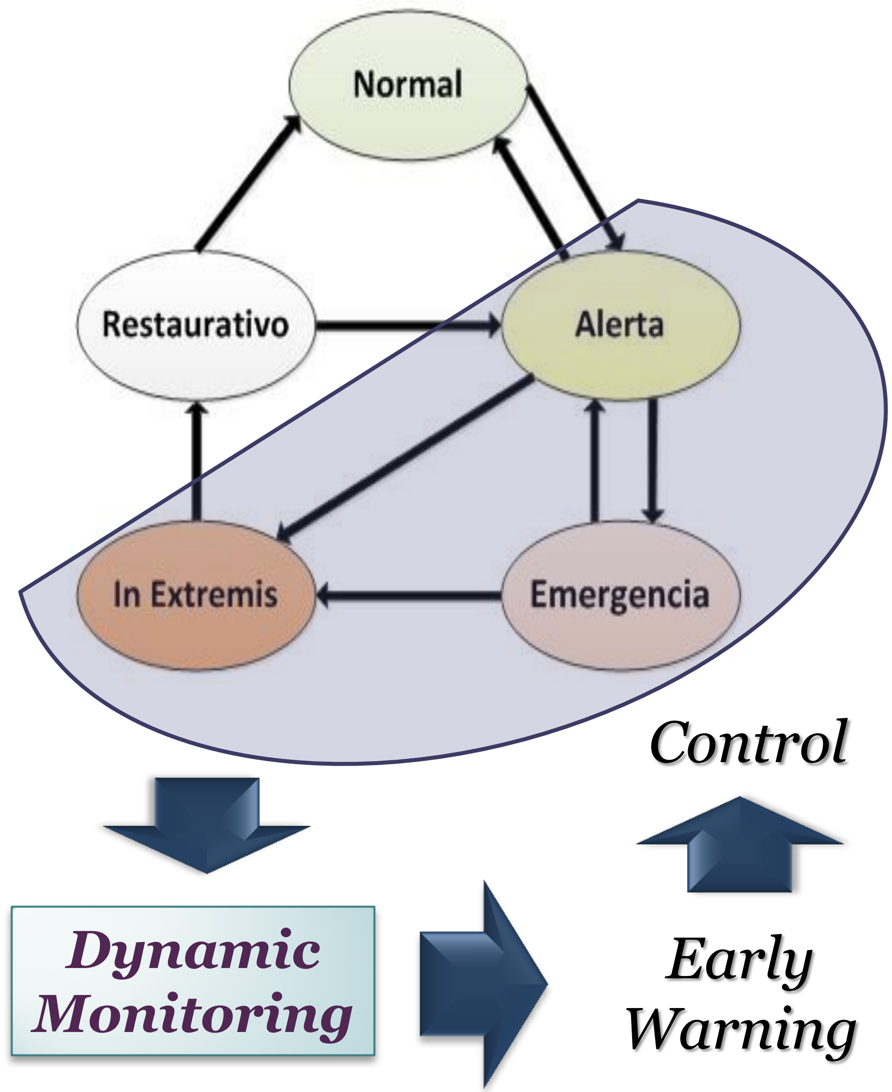
PMUs – Assessment and Types of Control Actions



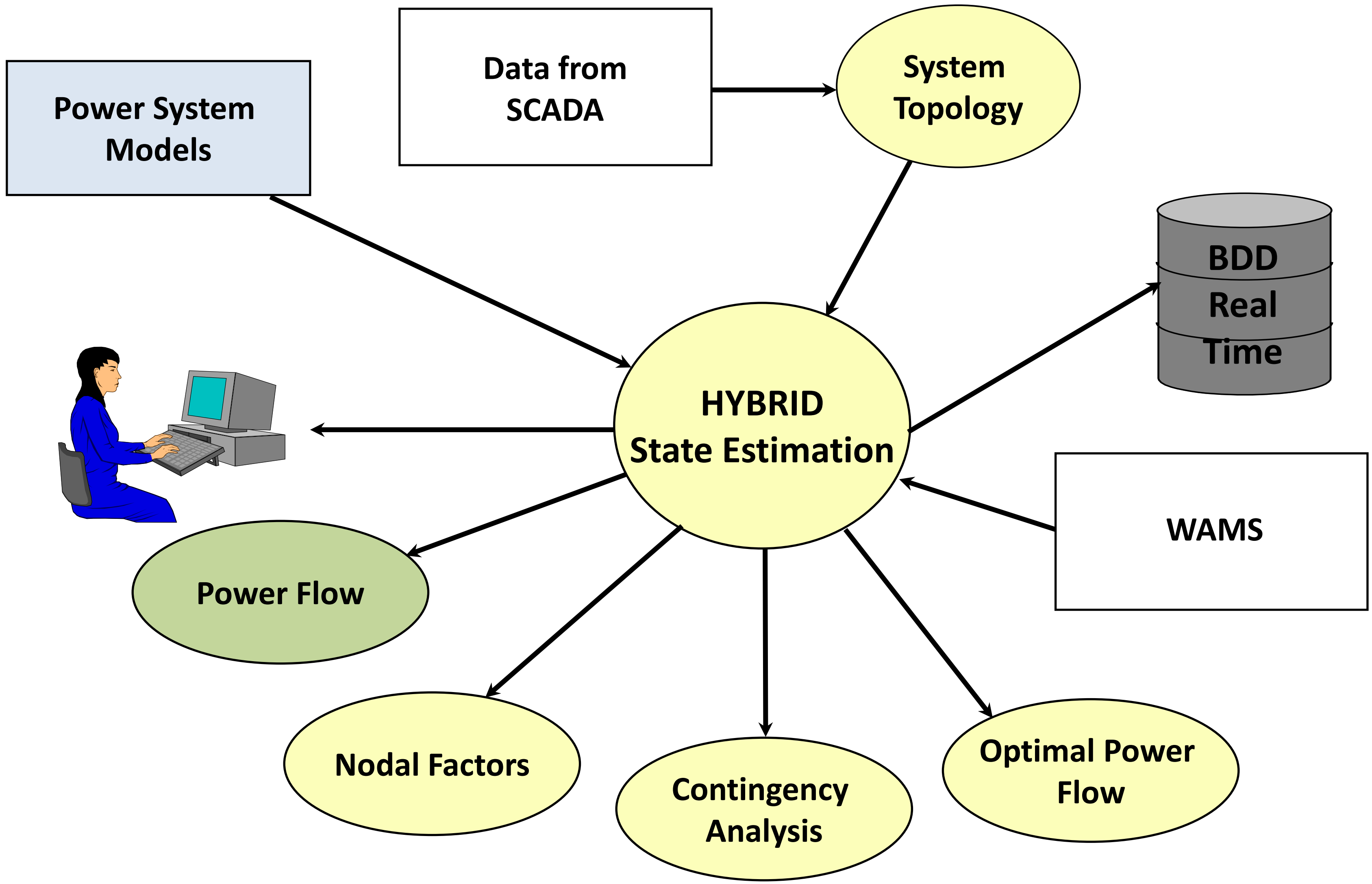
Assessment and Enhancement of Power System Security

WAMPAC System:

- Static and Dynamic Monitoring
- Power System Vulnerability Status
- Preventive and Corrective Control
- Special Protection Schemes' Trigger



Steady-state Monitoring - SCADA/EMS - WAMS



Static Security Assessment – Contingency Analysis

- ✓ To assess the degree of security facing the loss of power system elements (contingency) ⇒ "***What if" Analysis.***

- ✓ ***Contingency Types:***
- ❑ Simple contingency (N-1 criterion)
- ❑ Souble contingency (N-2 criterion)
- ❑ Multiple contingency (N-x criterion)

- ✓ It involves performing a **complete power flow** for each of the selected contingencies, to evaluate the state of the system after each contingency.

Dynamic Security Assessment

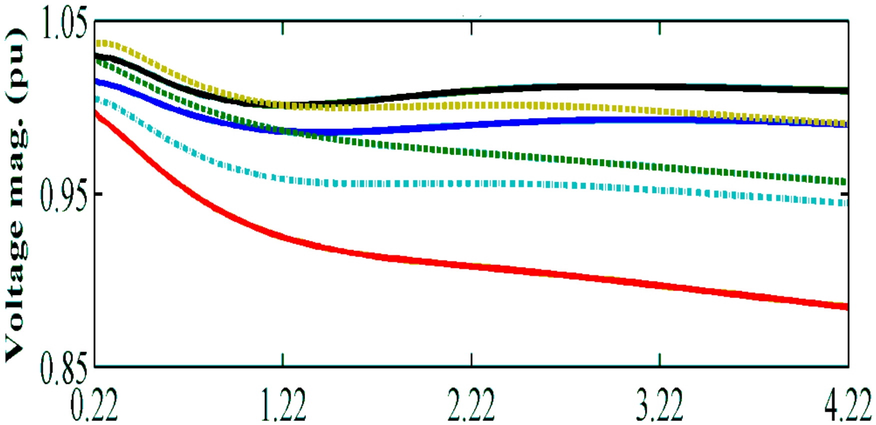
- Power System Stability
  - Voltage Stability
  - Angle Stability
  - Frequency Stability

Voltage Stability

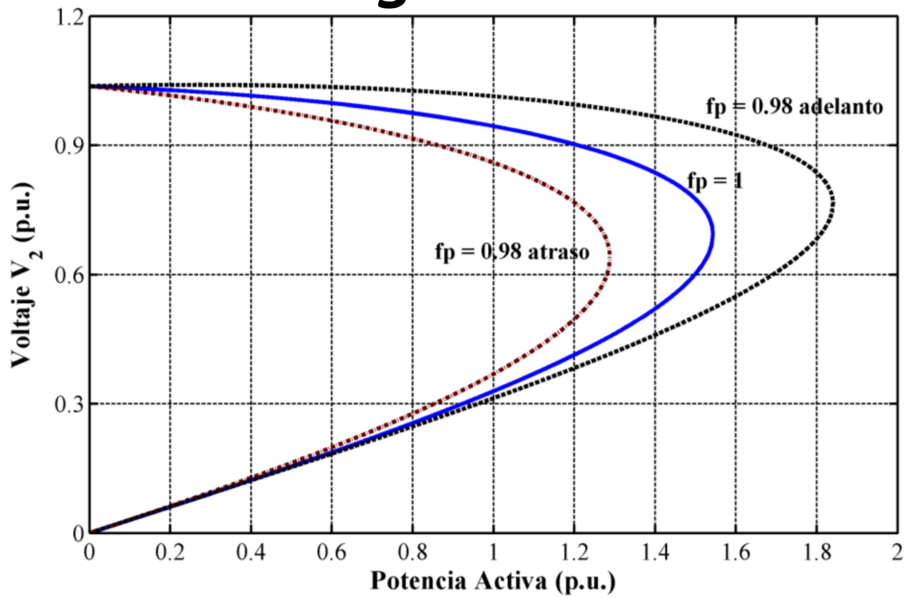
Ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance.

Lack of reactive power resources in the grid.

Short - Term



Long - Term



Voltage Stability Assessment

OFF-LINE

Dynamic Analysis

Sensitivity analysis

Modal Analysis

Distance to Instability (CPF: P-V curves)

ON-LINE

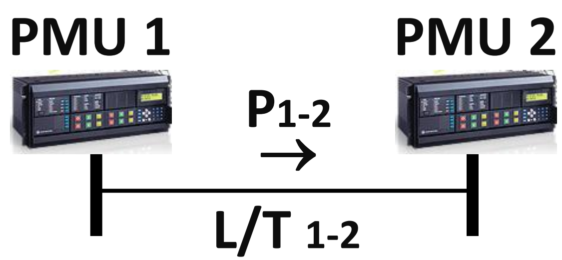
Artificial Intelligence Systems: to estimate the power system cargability margin.

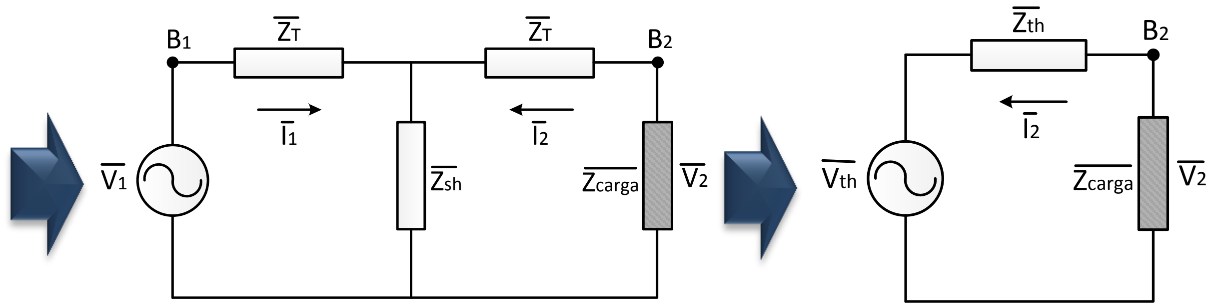
- Artificial Neural Network (ANN)
- adaptive neuro-fuzzy inference system (ANFIS)

Thevenin Equivalent:
Real time determination of Power – Voltage (P-V) in real time

Voltage Stability of Corridors

- Voltage Stability of Corridors ⇒ **Thevenin Equivalent ⇒ Transmission Line Transfer Capacity**



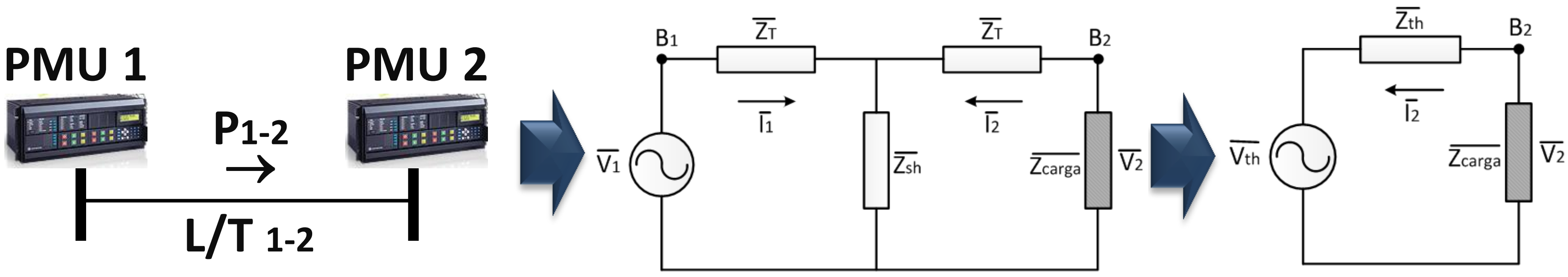


$$\bar{Z}_T = \frac{\bar{V}_1 - \bar{V}_2}{\bar{I}_1 - \bar{I}_2} \qquad \bar{Z}_{sh} = \frac{\bar{I}_1\bar{V}_2 - \bar{I}_2\bar{V}_1}{\bar{I}_1\bar{I}_1 - \bar{I}_2\bar{I}_2} \qquad \bar{Z}_{th} = \frac{\bar{Z}_T + \bar{Z}_{sh}}{\bar{Z}_T \cdot \bar{Z}_{sh}} + \bar{Z}_T \qquad \bar{V}_{th} = \frac{\bar{Z}_{sh}}{\bar{Z}_{sh} + \bar{Z}_T}\bar{V}_1$$

$$\bar{S}_c = \bar{V}_2 \cdot \left(-\bar{I}_2\right)^* = \bar{V}_2 \cdot \left(\frac{\bar{V}_{th} - \bar{V}_2}{\bar{Z}_{th}}\right)^* = \bar{V}_2 \cdot \left(\frac{\bar{V}_{th} - \bar{V}_2}{R_{th} + jX_{th}}\right)^*$$

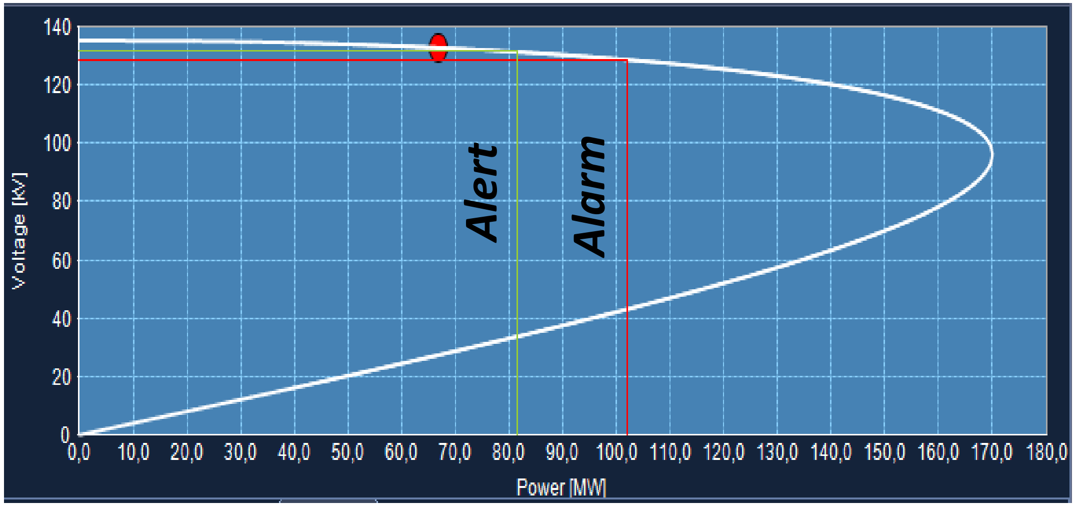
$$\boxed{V_2 = \sqrt{\frac{V_{th}^2}{2} - (QX_{th} + PR_{th}) \pm \sqrt{\frac{V_{th}^4}{4} - V_{th}^2(QX_{th} + PR_{th}) - (PX_{th} - QR_{th})^2}}}$$

Voltage Stability of Corridors

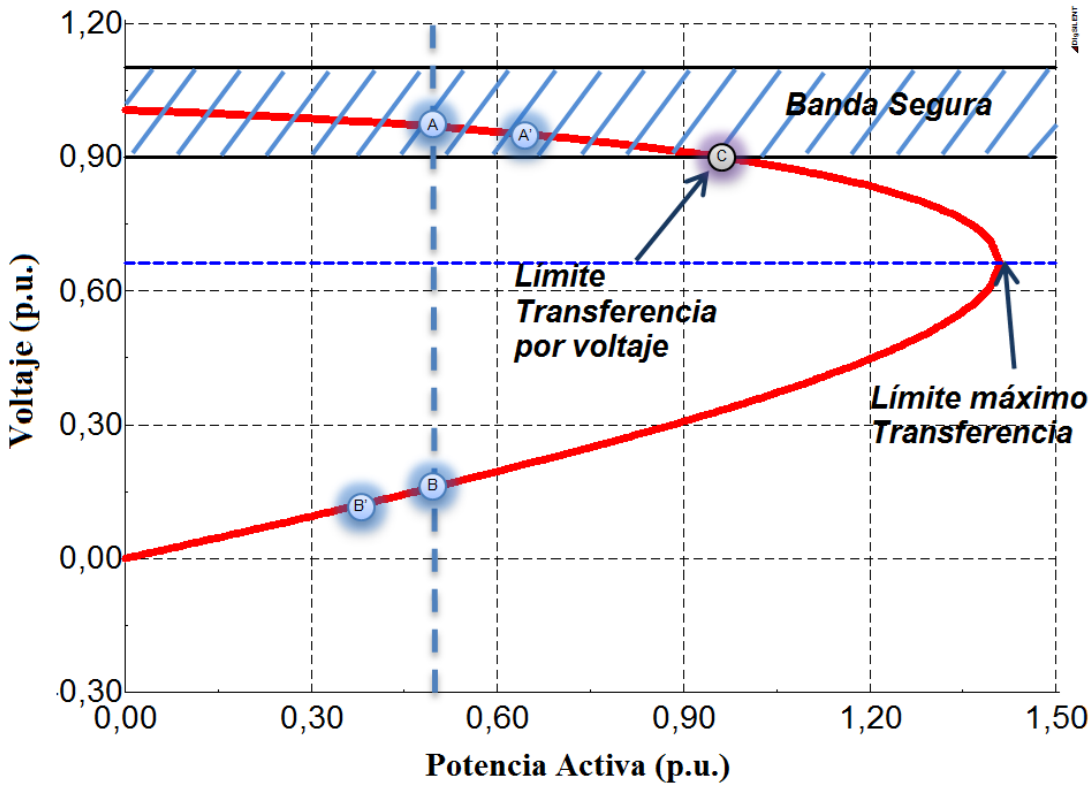


$$V_2 = \sqrt{\frac{V_{th}^2}{2} - (QX_{th} + PR_{th}) \pm \sqrt{\frac{V_{th}^4}{4} - V_{th}^2(QX_{th} + PR_{th}) - (PX_{th} - QR_{th})^2}}$$

Monitoring of the operating point of the corridor regarding pre defined limits ⇒ Congestion Alert

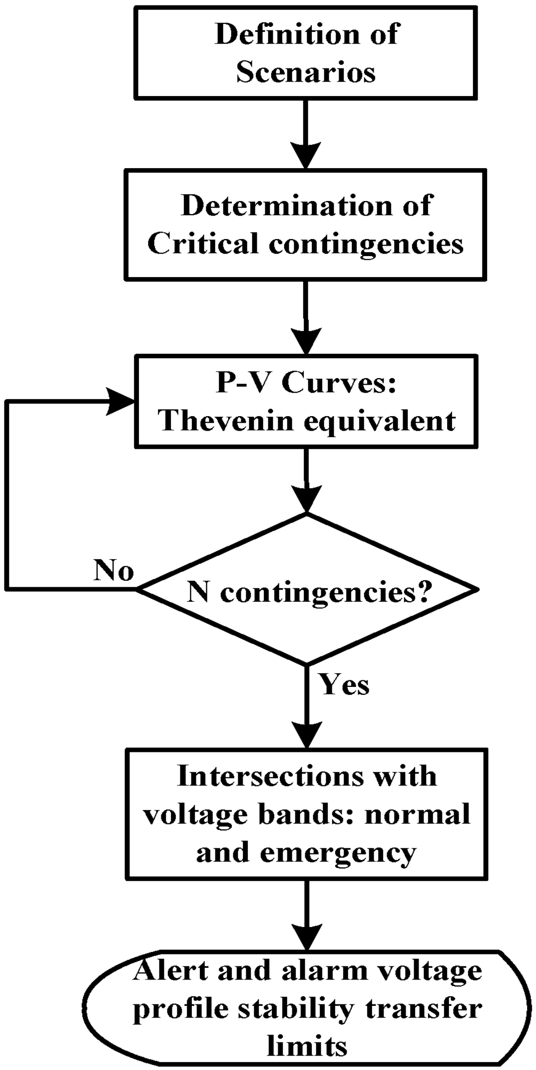


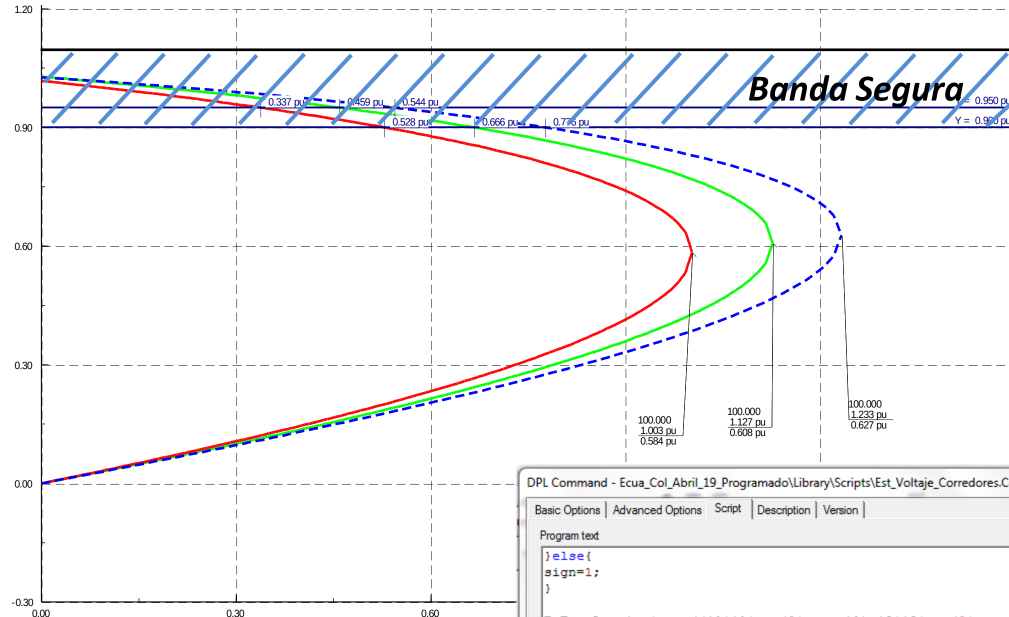
Voltage Stability of Corridors



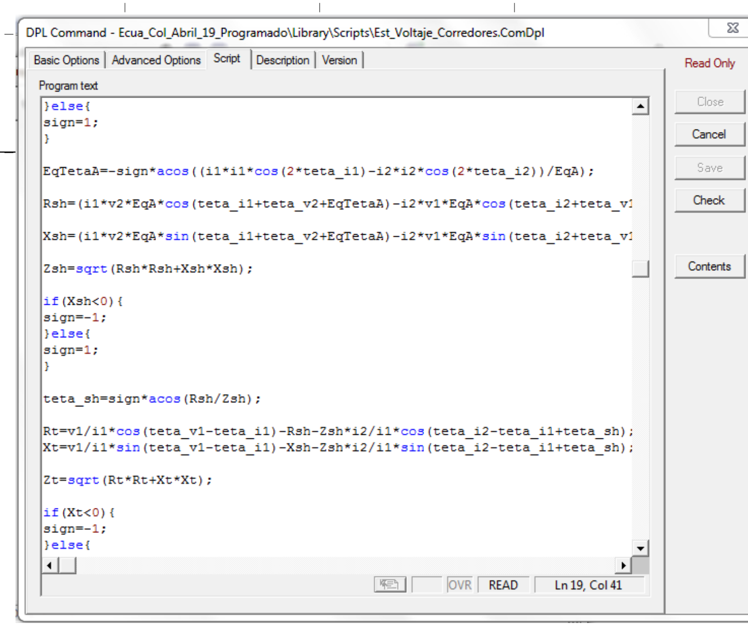
Voltaje de Barras	Inferior		Superior	
	Normal	*Emergencia*	*Normal*	*Emergencia*
230 kV	-5%	-10%	5%	6%
138 kV	-5%	-10%	5%	6%
69, 46, 34.5 kV	-3%	-5%	5%	6%

Voltage Stability of Corridors – Determinarion of Limits

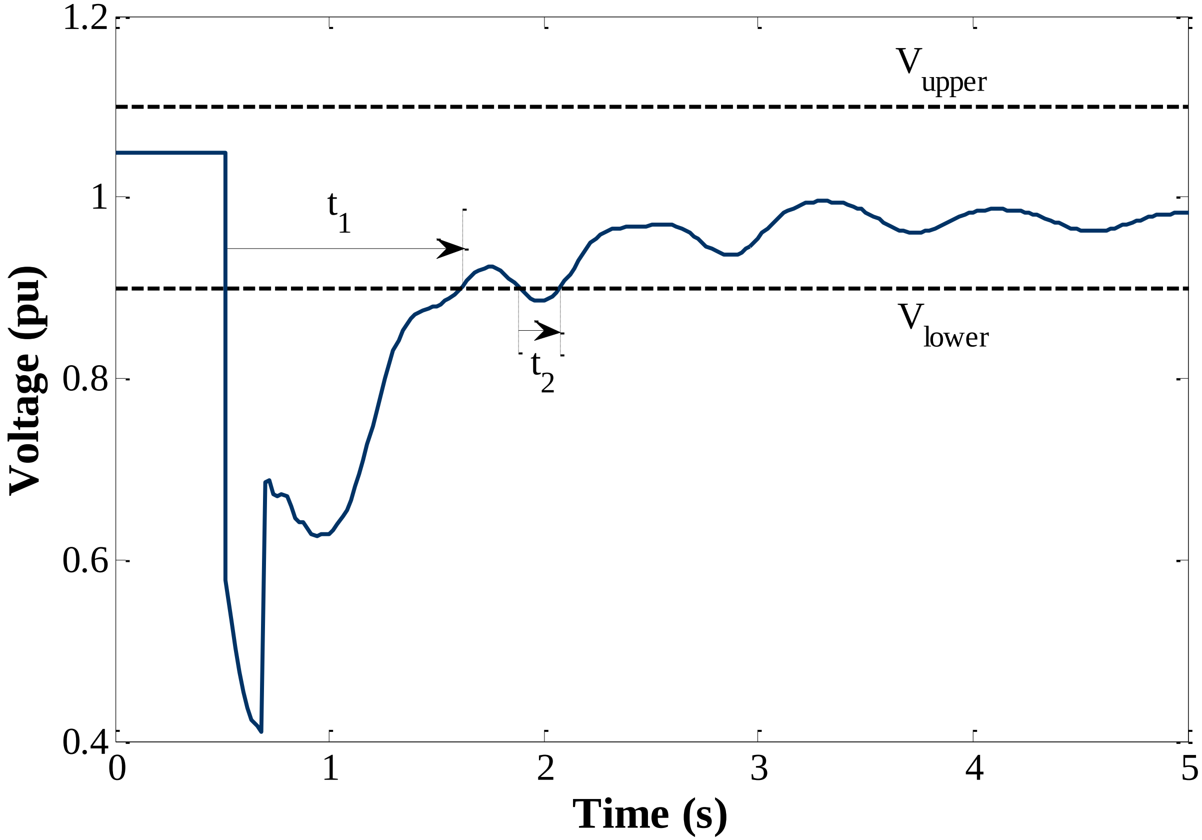




Script en DPL
(DIgSILENT Programming Language)



Short-term Voltage Stability



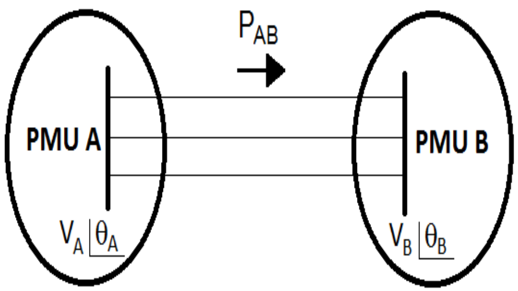
$$\mathrm{VDI_i} = \begin{cases} 0 & \text{if } \mathrm{V_{lower}} \le V \le \mathrm{V_{upper}} \\ \min\left\{1, \dfrac{t_{\mathrm{n}}}{\mathrm{tv_{max}}}\right\} & \text{if } V < \mathrm{V_{lower}} \vee V > \mathrm{V_{upper}} \end{cases}$$

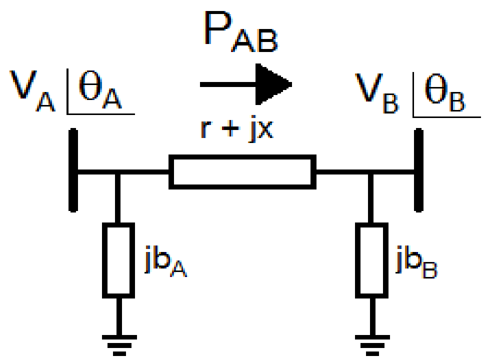
Steady-state Angle Stability

- **Angular difference between the nodes of the power system ⇒ Direct measurement of the transmission capacity between the nodes**

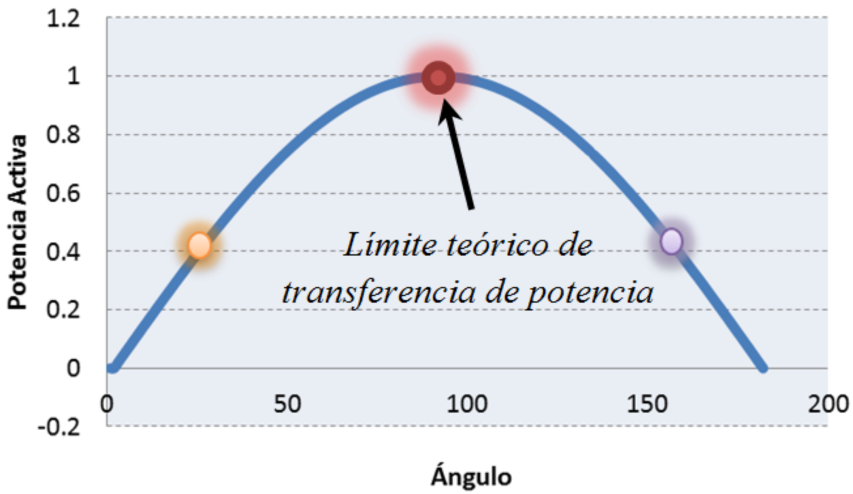
- **Maximum limit of angular difference between nodes A and B ⇒ power transfer limit.**

- **⇒ Angular Difference Monitoring ⇒ power system congestion alert**



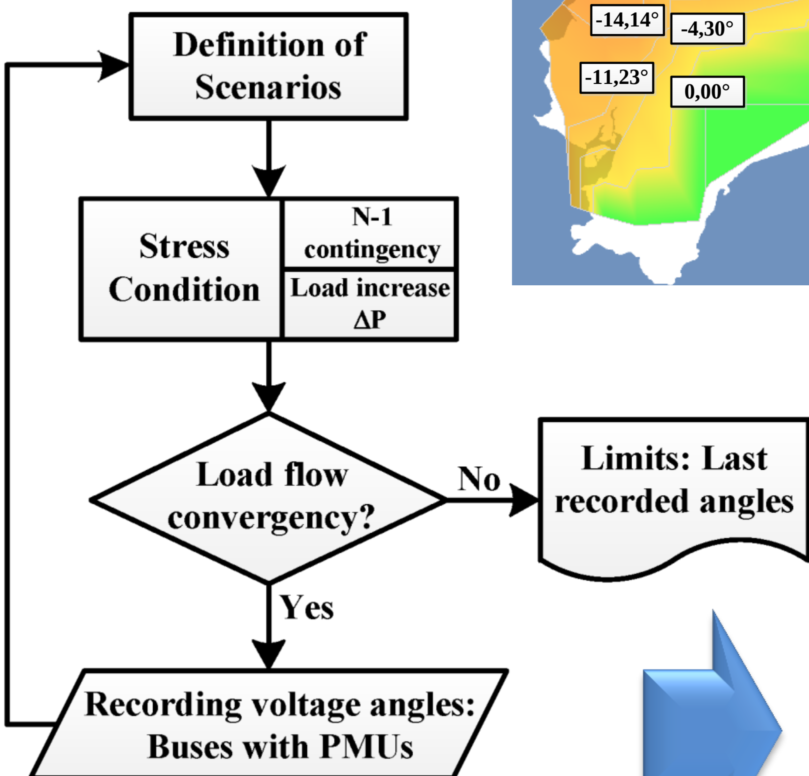


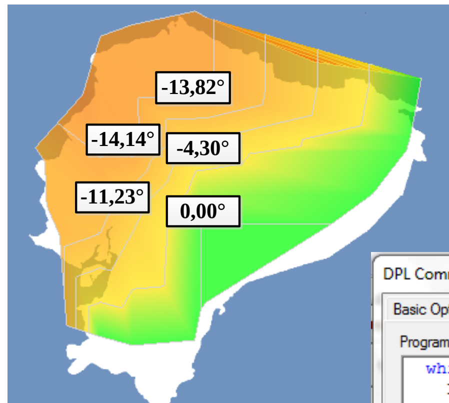
$$P_{AB} \cong \frac{V_A V_B \sin(\theta_A - \theta_B)}{x}$$



$$P_{AB} \approx \frac{V_A V_B(\theta_A - \theta_B)}{x} \Rightarrow P_{AB} \propto (\theta_A - \theta_B)$$

Steady-State Angle Stability – Determinarion of Limits





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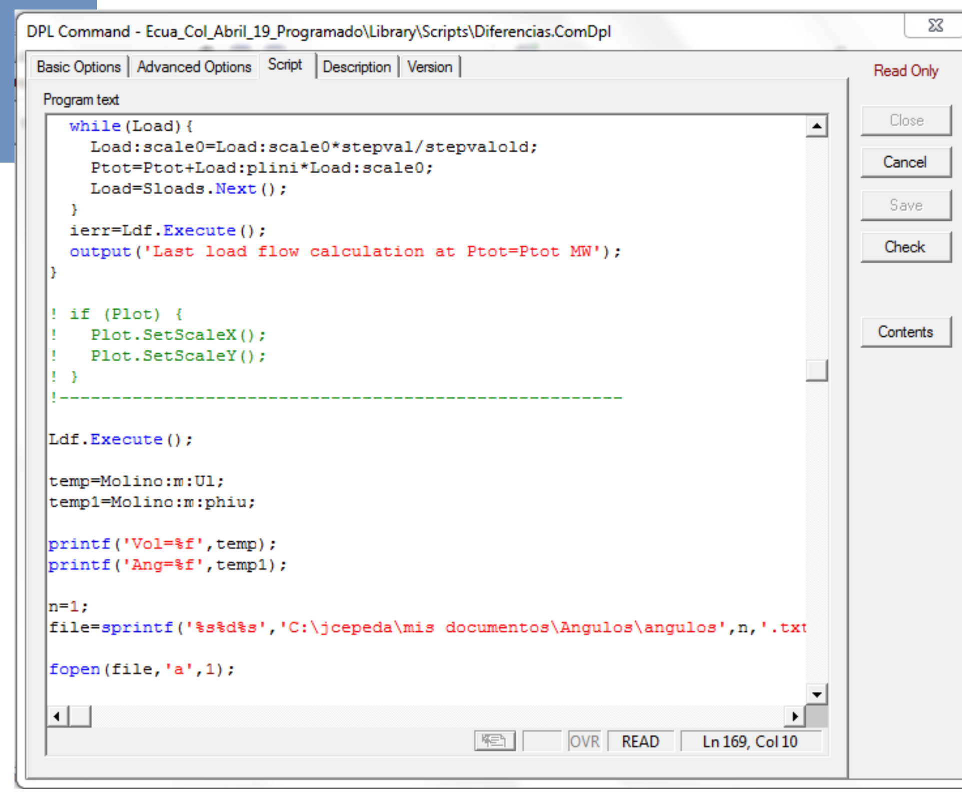


Oscillatory Stability

- **Load or generation variations ⇒ Generators try to find new equilibrium (stable) points ⇒** power and frequency oscillations caused by electric energy interchanges between machines

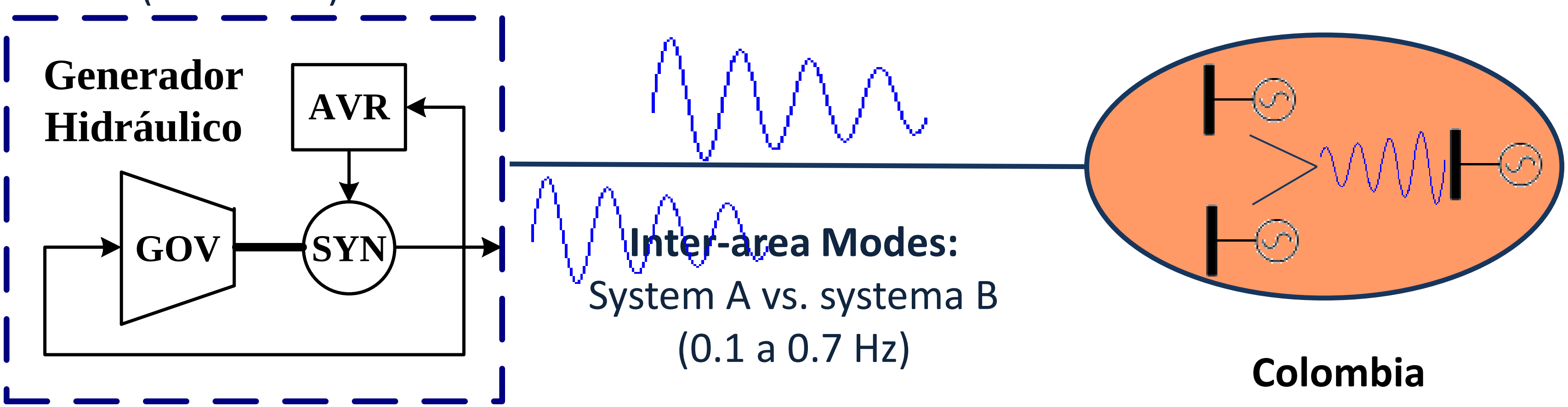
- ***Oscillatory Modes***

$$f_i = \frac{\omega_i}{2\pi} \qquad \zeta_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}}$$

Control Modes:
(0.01 a 0.1 Hz)

Local Modes:
Generator vs. System
(0.7 a 2 Hz)

Inter-area Modes:
System A vs. systema B
(0.1 a 0.7 Hz)



Oscillatory Stability Assessment

- **Based on Simulations**

  Time Domain Simulations
  - Non-linear interactions
  - Mode excitation facing large perturbations

  Modal Analysis
  - Linearized system model
  - Mode excitation facing small perturbations (***small signal stability***)

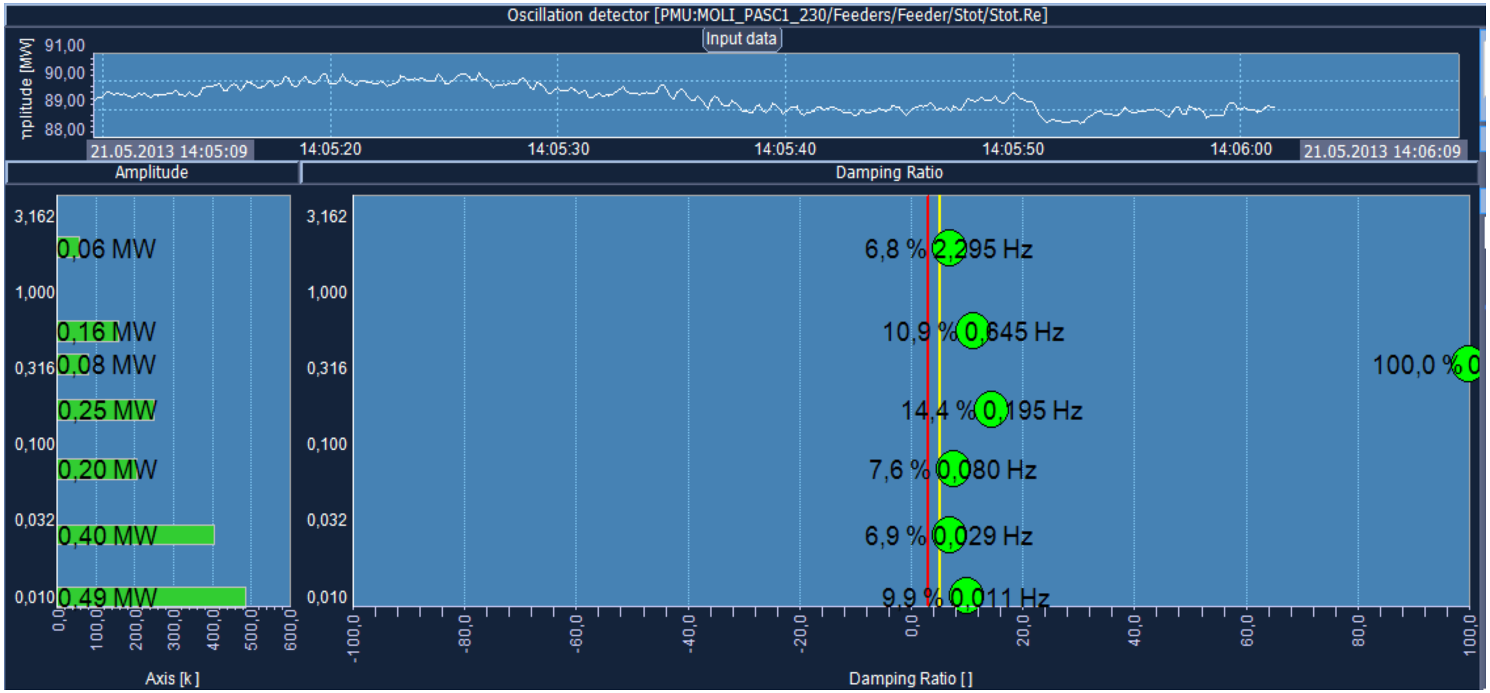
- ***Based on Signals***

  Modal Identification Algorithms
  - Electric signals are decomposed in their oscillatory modes
  - Fourier Analysis, Prony Analysis, Hilbert-Huang Transform, Kalman Filter, Wavelet Transform, WAProtector Algorithm

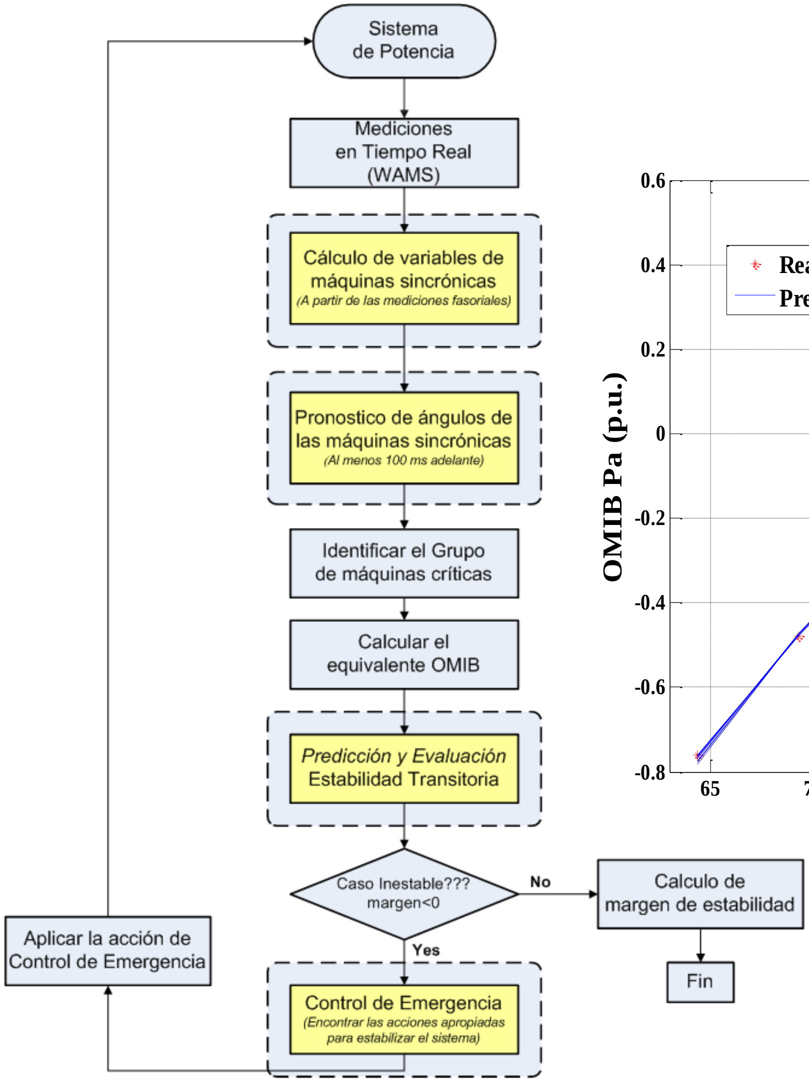
Modal identification algorithms

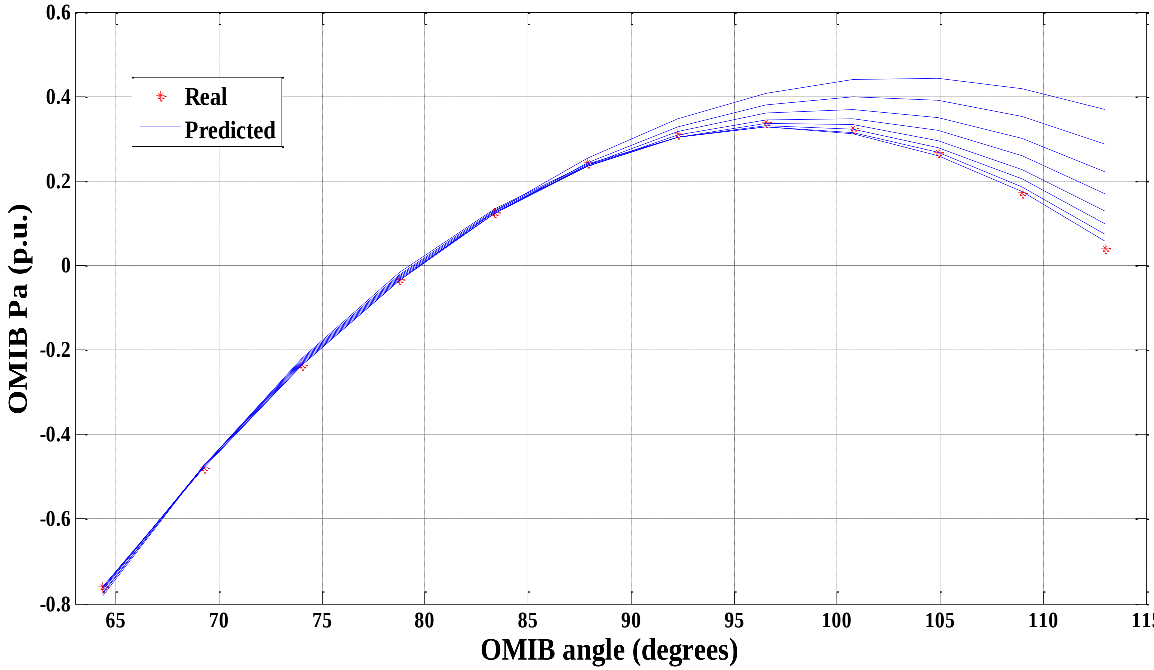
- These algorithms allow estimating the frequency, damping, amplitude and relative phase of modal components present in a given oscillatory signal which can be theoretically represented by the summation of the modes immersed in this signal.

$$\hat{y}(t) = \sum_{i=1}^{n} A_i e^{\sigma_i t} \cos(\omega_i t + \phi_i)$$

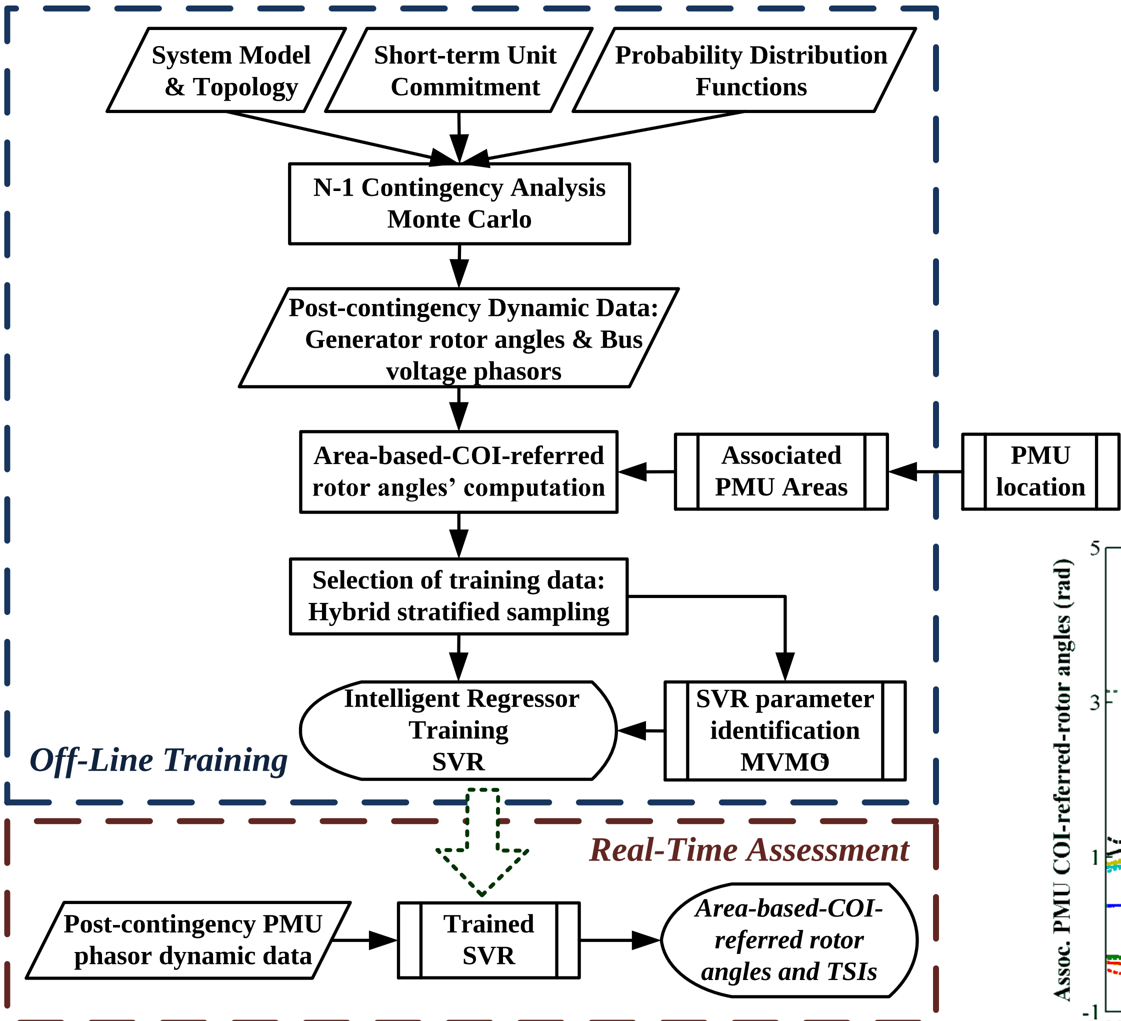


Real Time Transient Stability Assessment: E-SIME





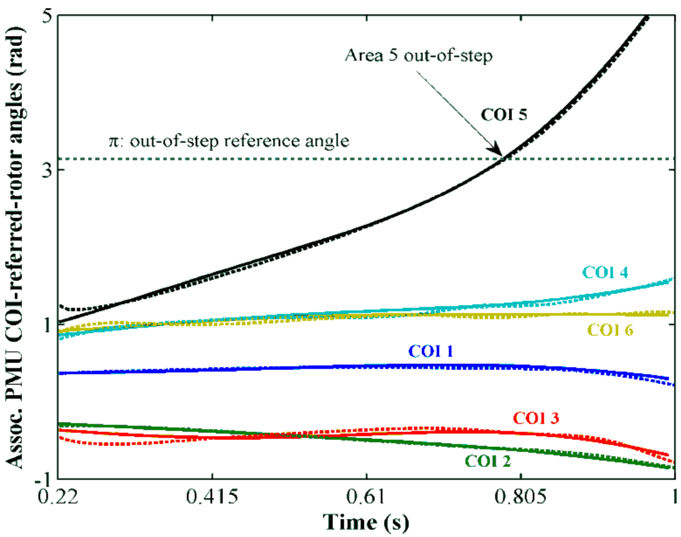
Real Time Transient Stability Assessment - COI estimation



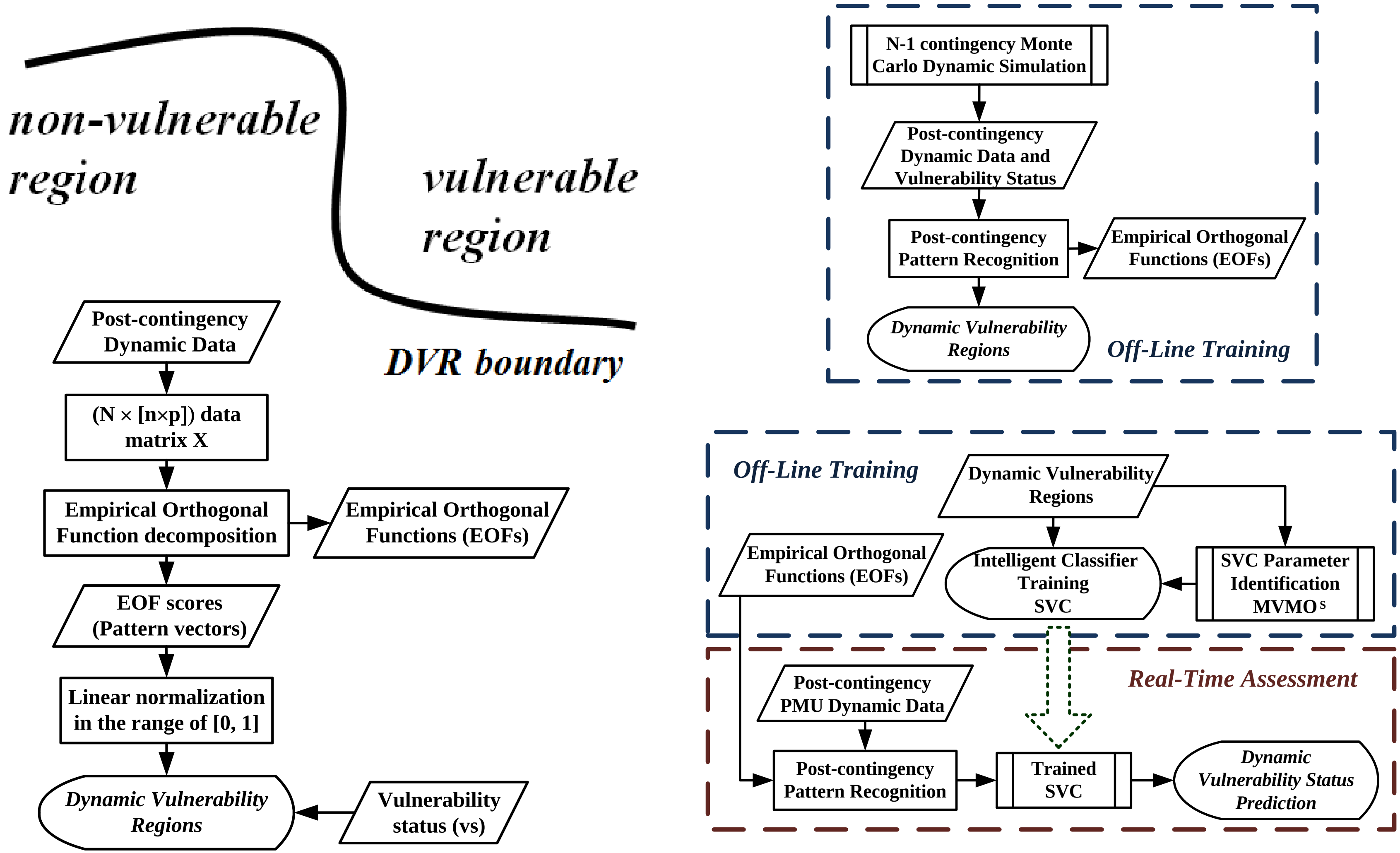
$$\delta_{COI_j} = \frac{1}{M_j} \sum_{i=1}^{N_j} M_i \delta_i$$

$$M_j = \sum_{i=1}^{N} M_i$$

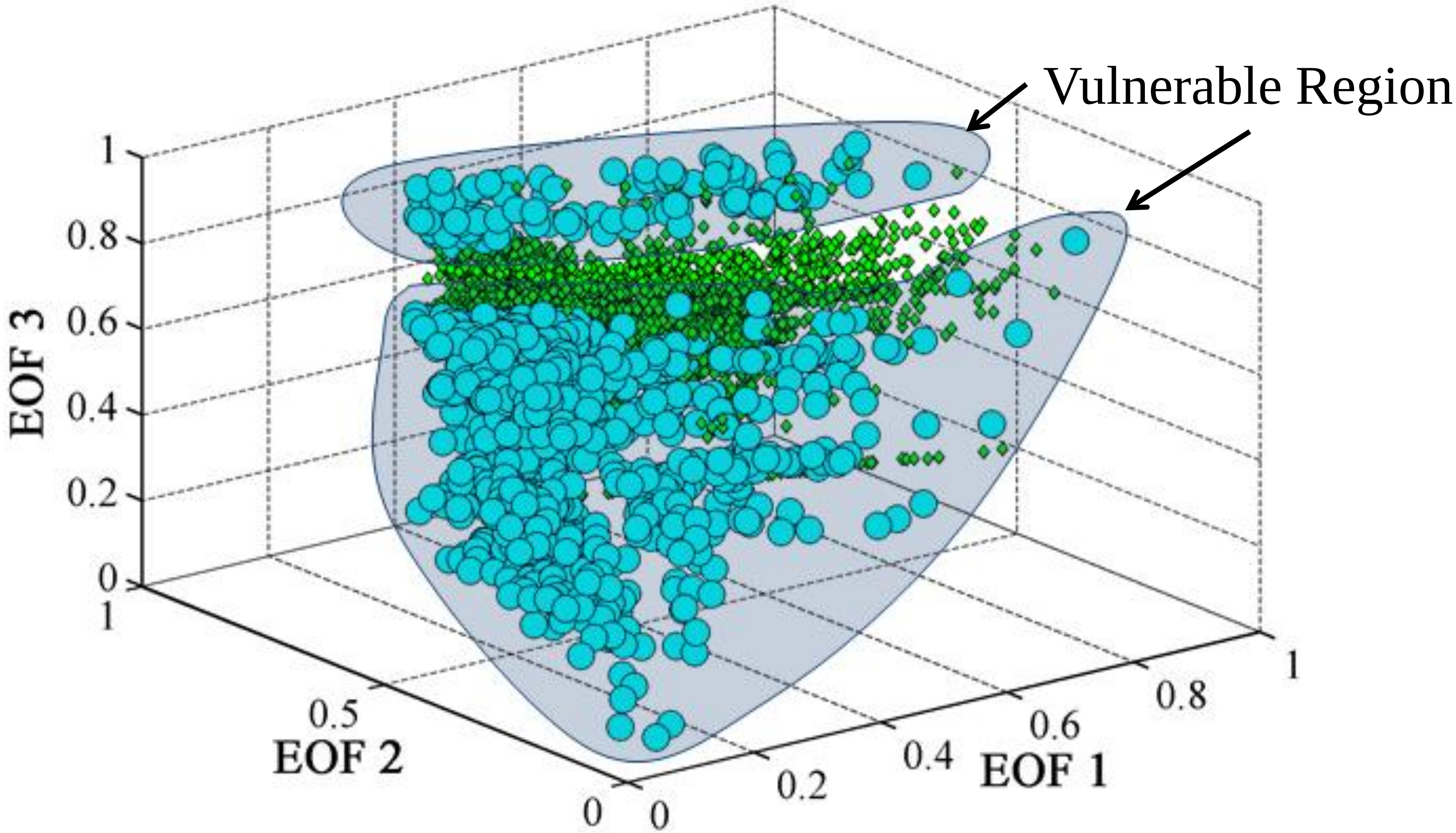
$$\delta_j^{COI_{System}} = \delta_{COI_j} - \delta_{COI_{System}}$$



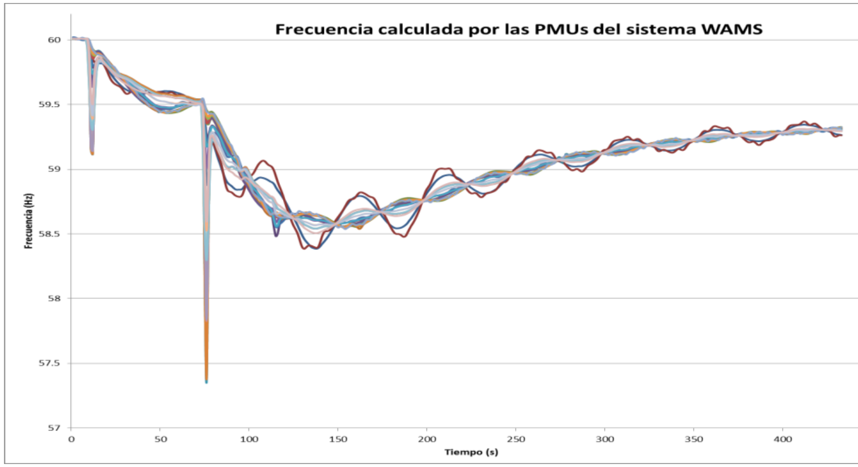
Real Time Transient Stability Assessment – Stability Status Prediction

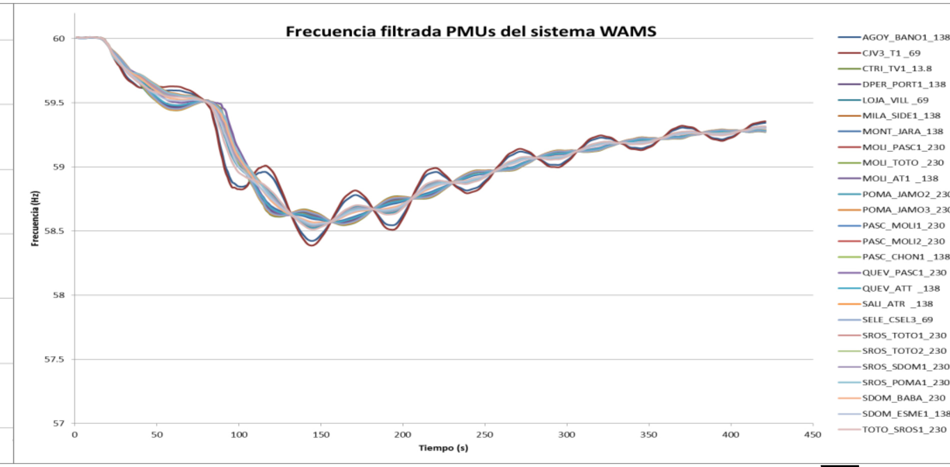


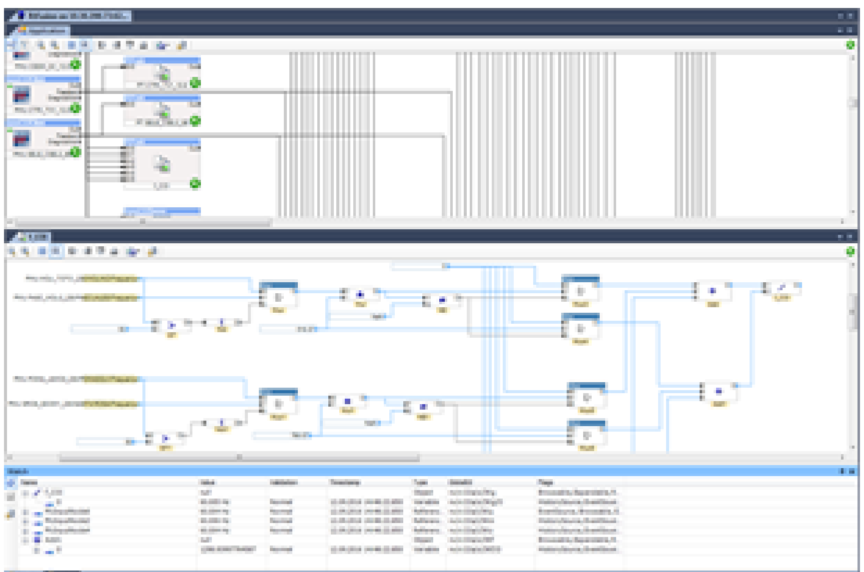
Real Time Transient Stability Assessment – Stability Status Prediction



Frequency Stability

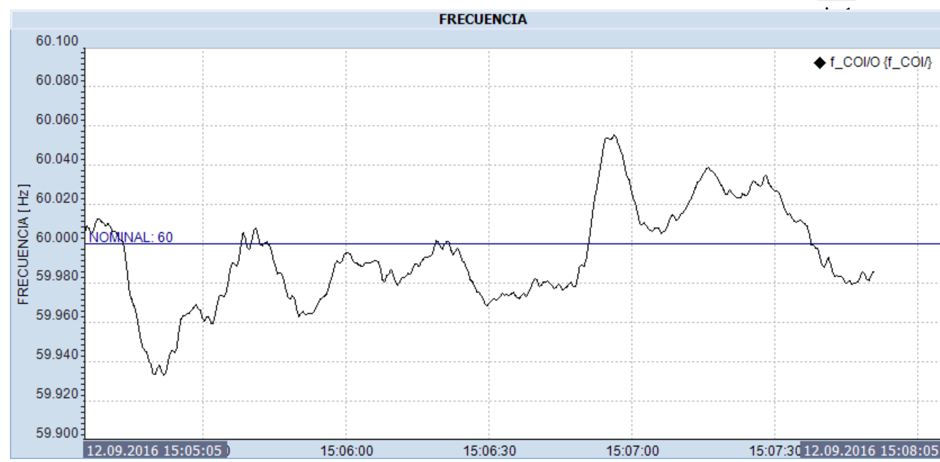


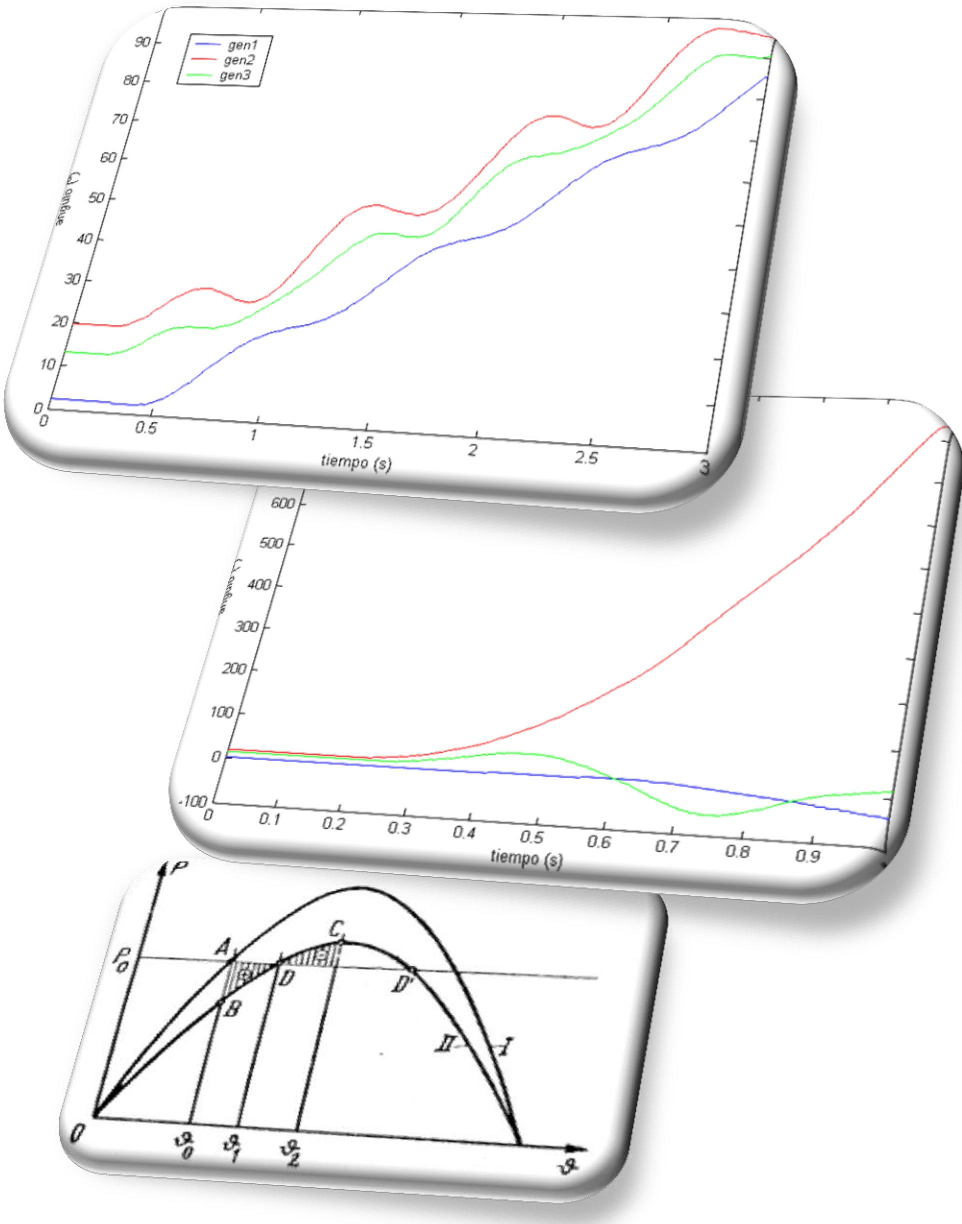




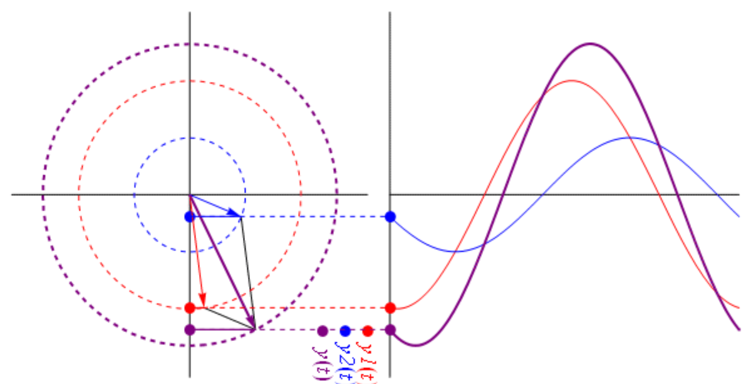
$$\mathbf{f}_{\mathrm{k}} = \lambda_1^{1/2} u_{\mathrm{k}1} \mathbf{v}_1 + \lambda_2^{1/2} u_{\mathrm{k}2} \mathbf{v}_2 + \ldots + \lambda_{\mathrm{p}}^{1/2} u_{\mathrm{kp}} \mathbf{v}_{\mathrm{p}}$$

$$f_{COI} = \frac{\sum_{i=1}^{N} H_i f_i}{\sum_{i=1}^{N} H_i}$$

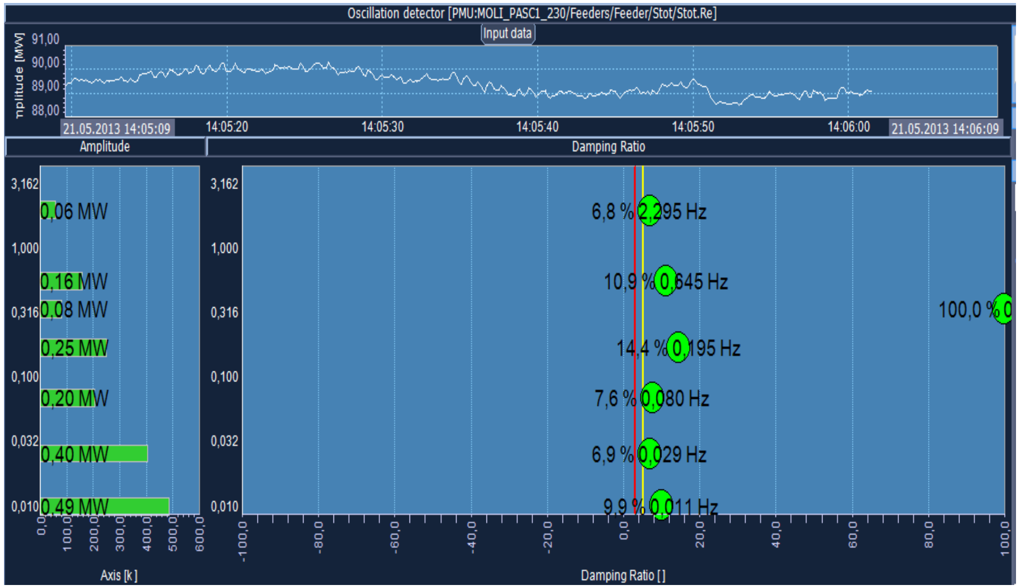




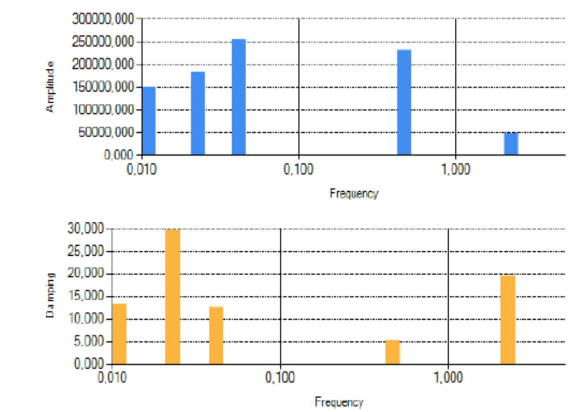
Post-Operative Analysis



Oscillatory Stability WAMS Data



Oscillatory Modes Identified for each update period (1 ciclo)



Dominant modes

f	f +/-	A	A stat	D	D +/-	D stat
0,011 Hz	0,002 Hz	0,15 MW	Normal	13,36 %	21,21 %	Normal
0,023 Hz	0,006 Hz	0,18 MW	Normal	29,53 %	38,21 %	Normal
0,042 Hz	0,070 Hz	0,26 MW	Normal	12,66 %	16,61 %	Normal
0,471 Hz	0,275 Hz	0,23 MW	Normal	5,05 %	13,77 %	Normal
2,278 Hz	0,554 Hz	0,05 MW	Normal	19,52 %	29,59 %	Normal

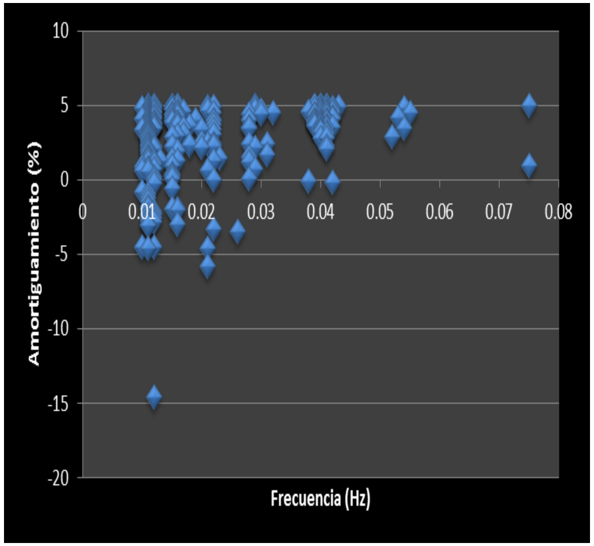
Damping limits: Warning = 5,0 % Alarm = 3,0 %

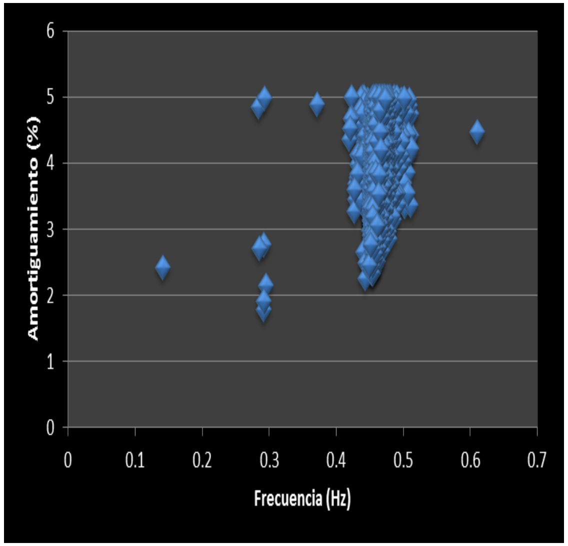
f: Average natural frequency of the oscillation mode
f +/-: Standard deviation of the natural frequency by the normal distribution. (+/-34.1 %)
A: average amplitude of the oscillation mode
A stat: status of the amplitude regarding the limits
D: average damping of the oscillation mode
D +/-: Standard deviation of the damping by the normal distribution. (+/-34.1 %)
D stat: status of the damping regarding the damping limit

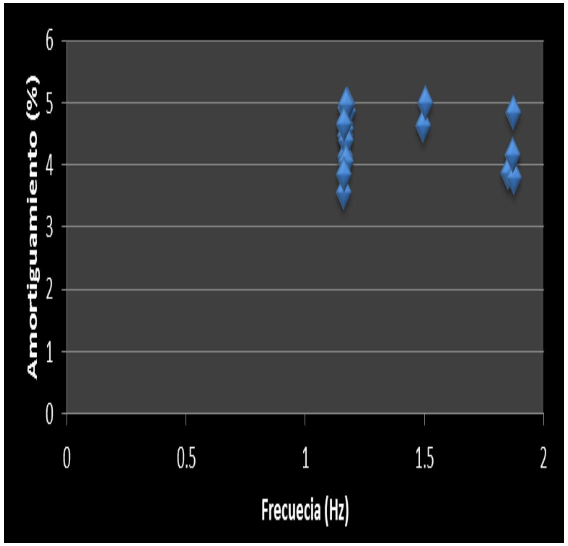
Average information of Oscillatory Modes per Hour

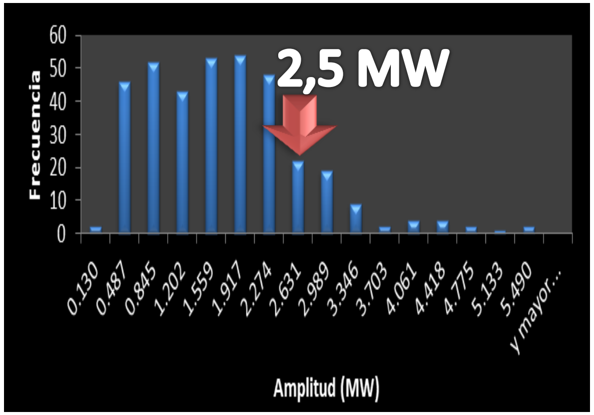
Oscillatory stability Post-operative Analysis

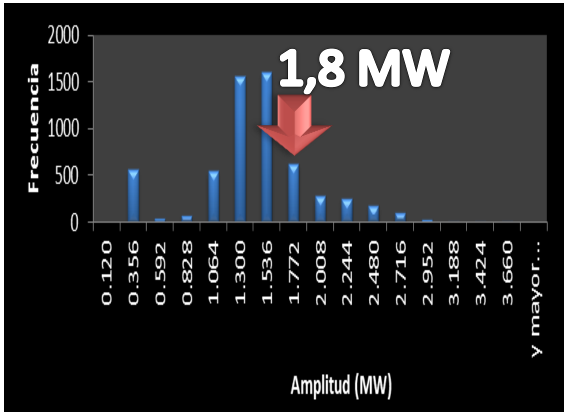
Control Modes	Inter-area Modes	Local Modes

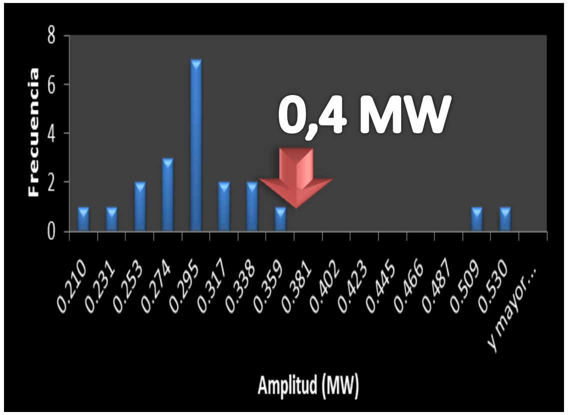




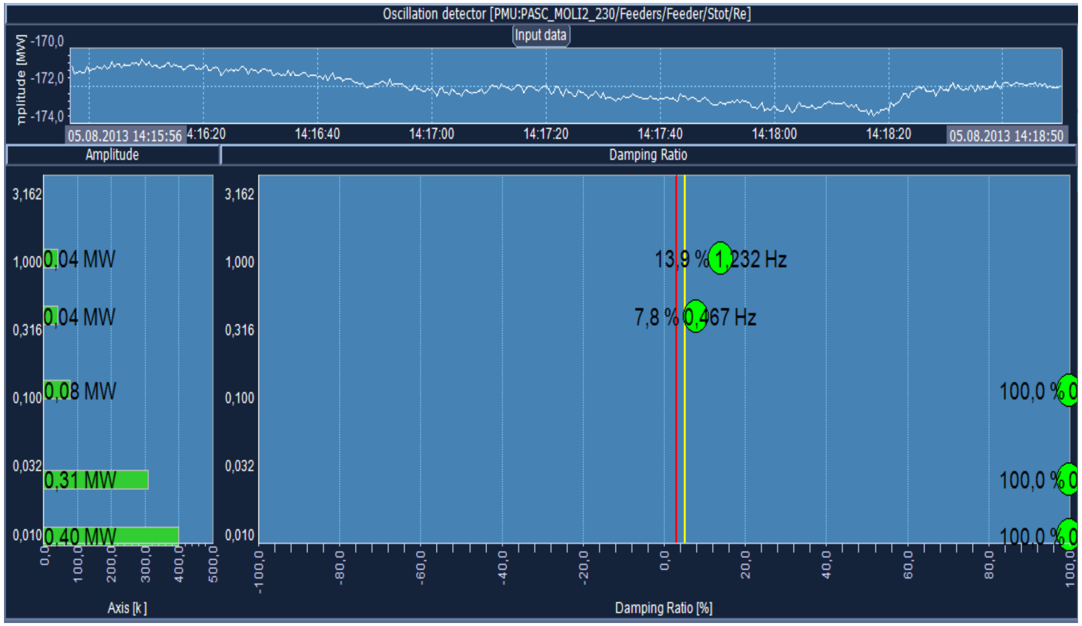








Oscillatory Stability – Determination of Limits



Damping:
Alarm: 3%
Alert: 5%

Amplitude:

Límites	*CONTROL*	*INTER-AREA*	*LOCALES*
Alerta (MW)	2.5	1.8	0.4
Alarma (MW)	3.5	2.4	0.6

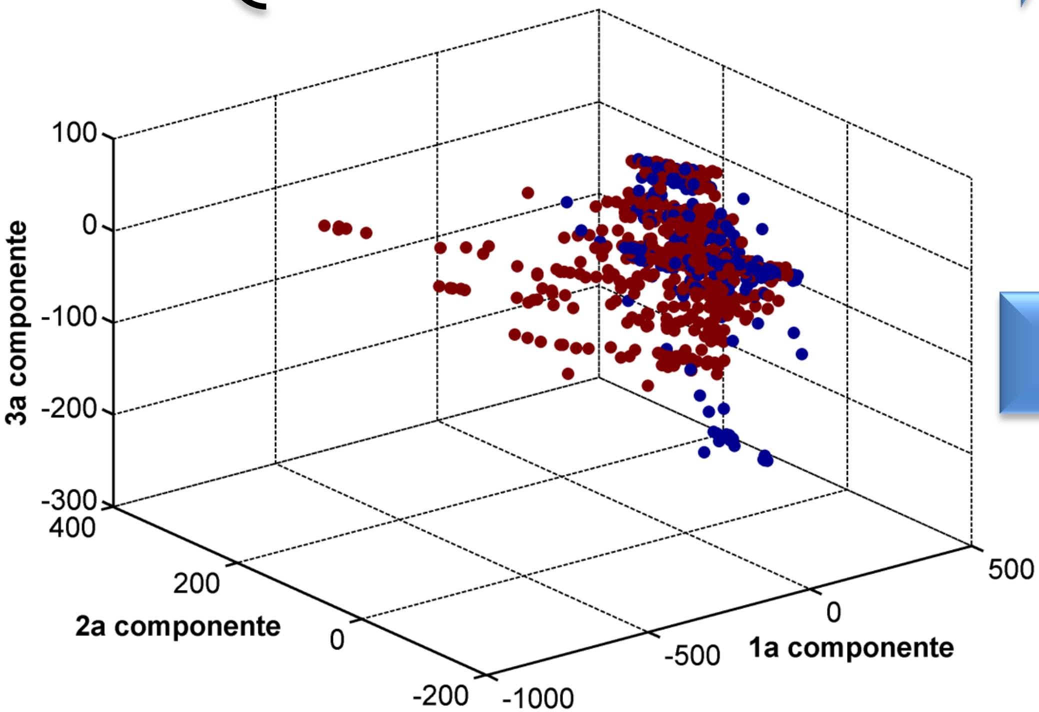
Analytics – Statistics of Oscillatory Stability

Data Analytics

Key Tasks

- ***Outliers Detection***
- ***Data Preparation***
- ***Data Mining***
- ***Data Recognition***

System Security Regions

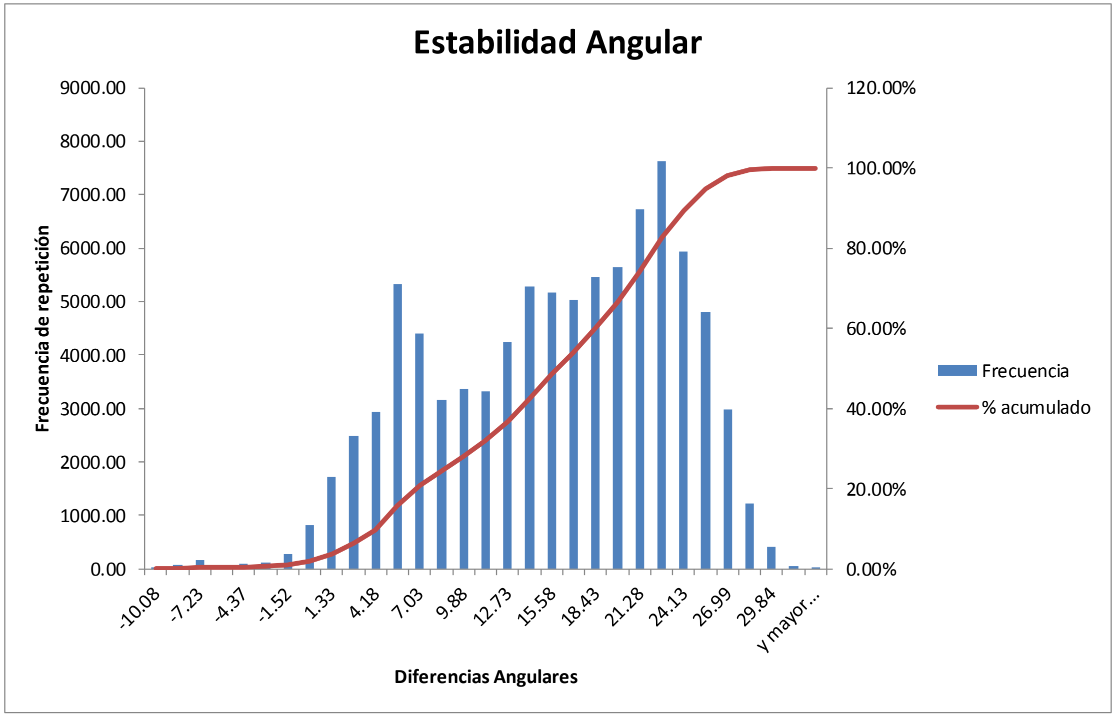


Characterization of operation states $\Rightarrow$ ***correlation*** *with poorly-damped modes*

Steady-state angle stability Post-operative Analysis

Deviations in the limits established for the angular difference between **Santa Rosa and Molino** (reference), for August 2015 (scenario considered as high hydrology)

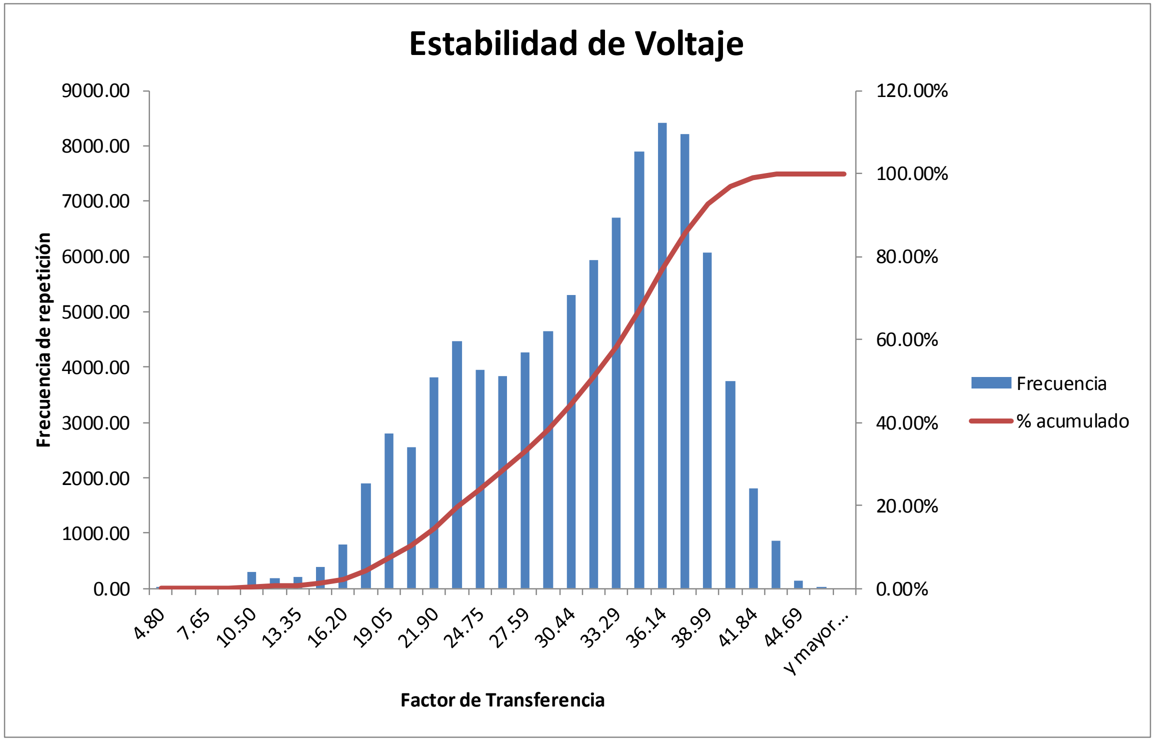
MOLINO - SANTA ROSA				LIMITES ALTA H		DESVIOS	LIMITES BAJA H		DESVIOS
Max. (°)	31.26	**PROMEDIO**	14.98	**Alerta (°)**	23.26	10.6%	**Alerta (°)**	15.56	51.6%
Min. (°)	-10.08	**DSTANDARD**	7.66	**Alarma (°)**	35.04	0.0%	**Alarma (°)**	29.42	0.0%



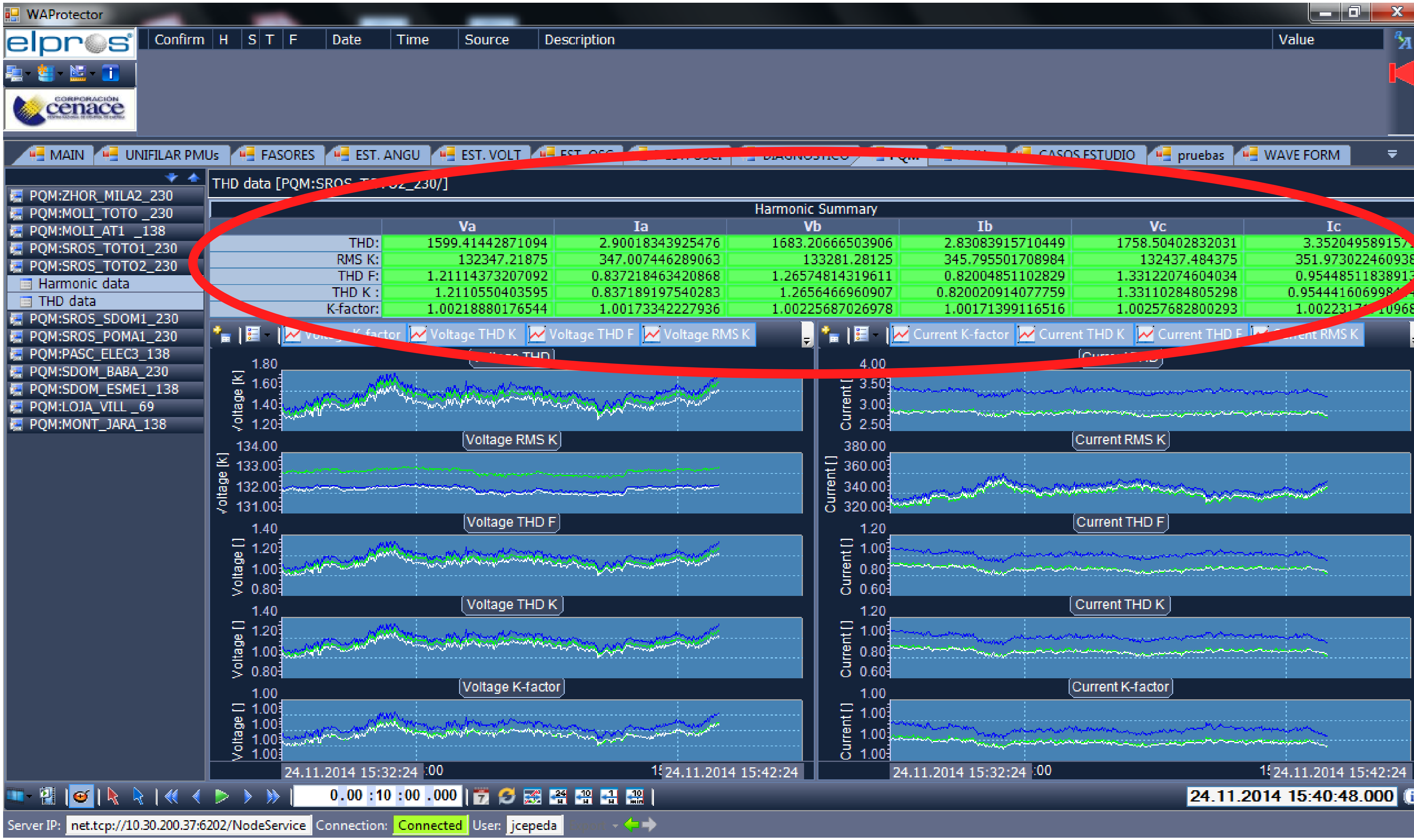
Voltage stability Post-operative Analysis

Deviations in the limits established for voltage stability of **corridor Santa Rosa - Totoras**, for August 2015 (scenario considered as high hydrology)

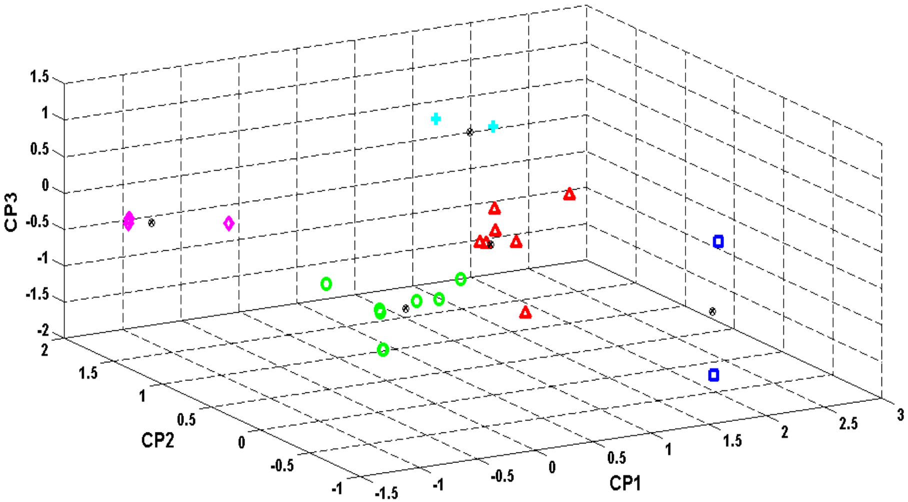
SANTA ROSA - TOTORAS				LIMITES ALTA H		DESVIOS	LIMITES BAJA H		DESVIOS
Max. (LF-P)	46.11	PROMEDIO	30.36	Alerta (LF-P)	55.00	0.0%	Alerta (LF-P)	42.00	0.2%
Min. (LF-P)	4.80	DSTANDARD	6.91	Alarma (LF-P)	73.00	0.0%	Alarma (LF-P)	59.00	0.0%



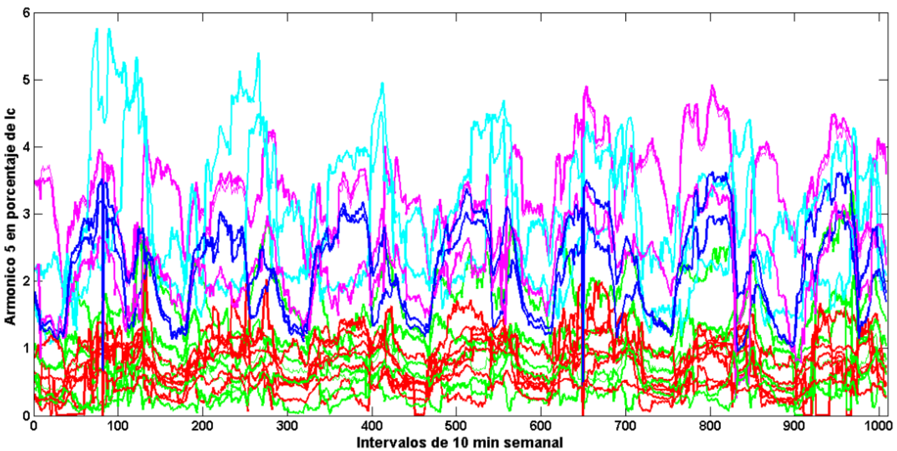
Power Quality

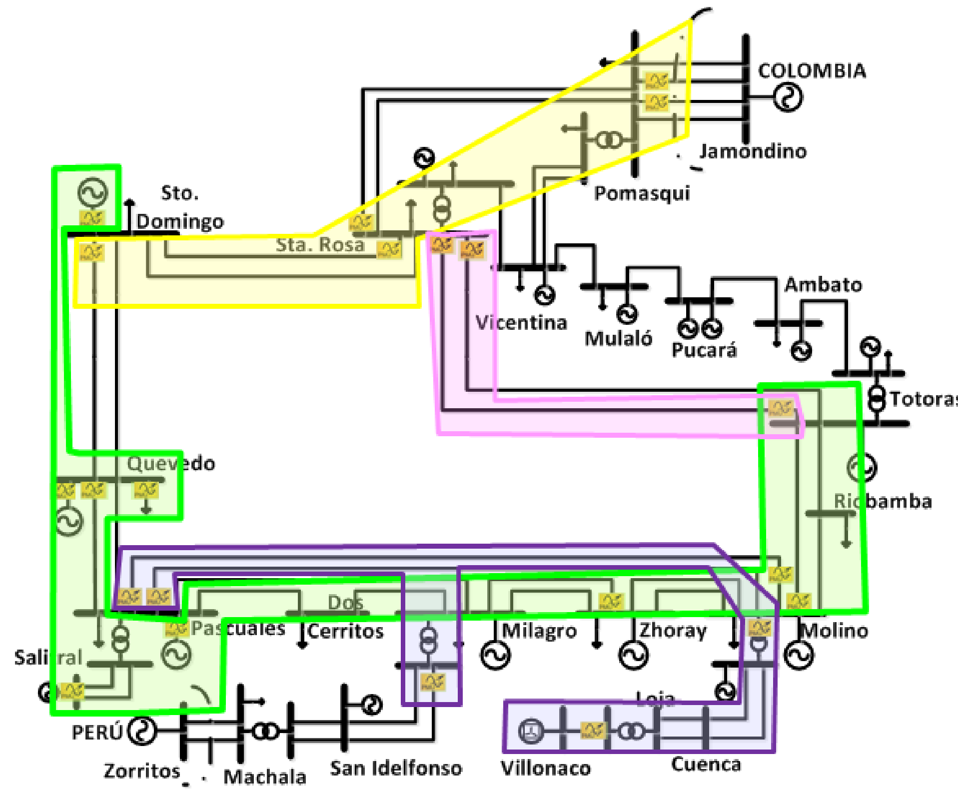


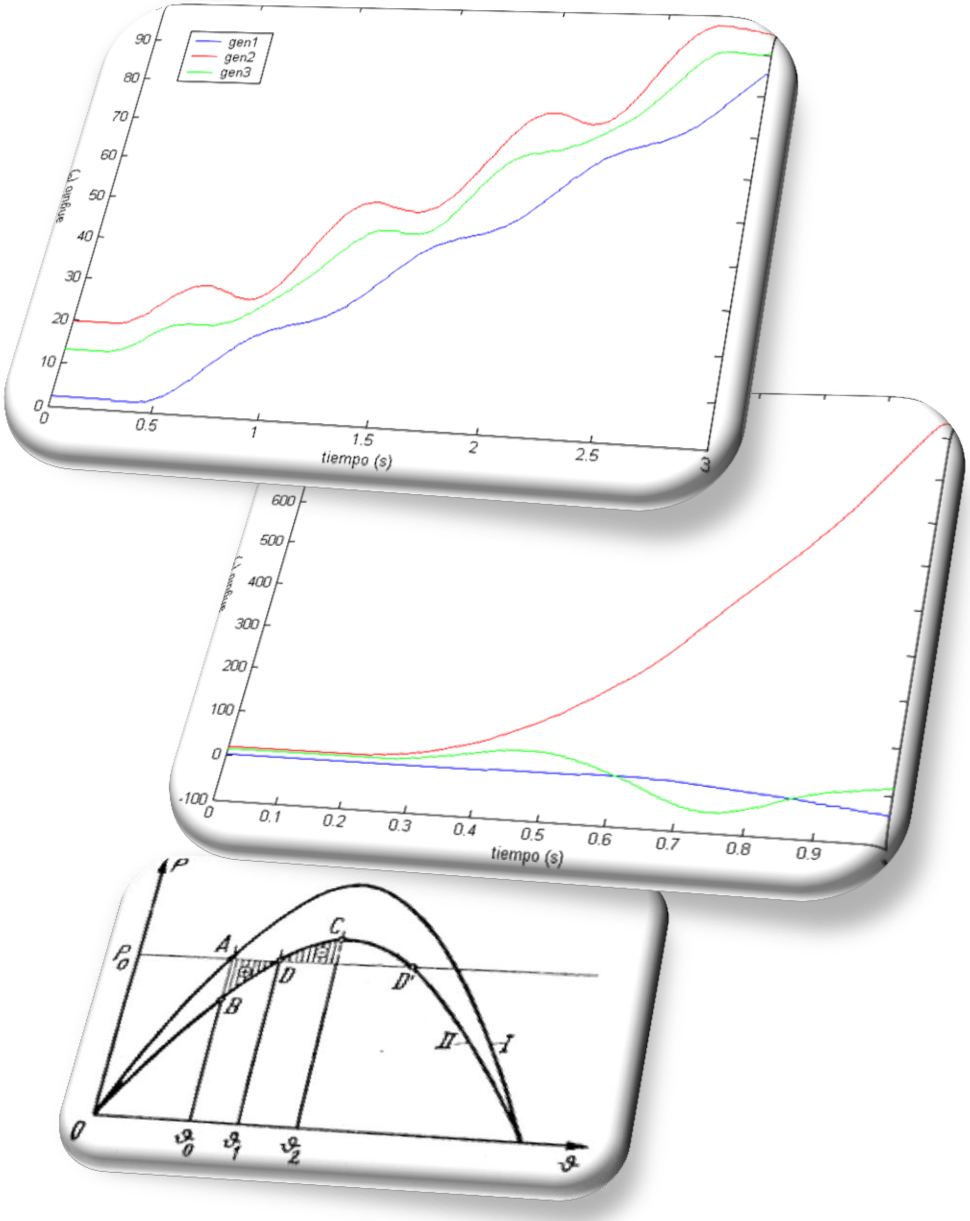
Geographic Characterization of Harmonics



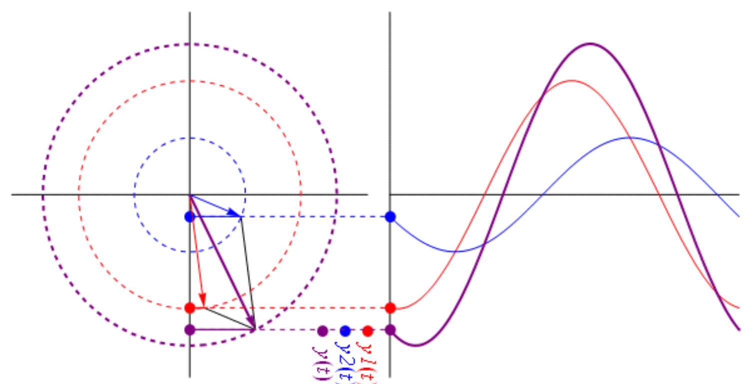
Geographic Clusters – Current Harmonics



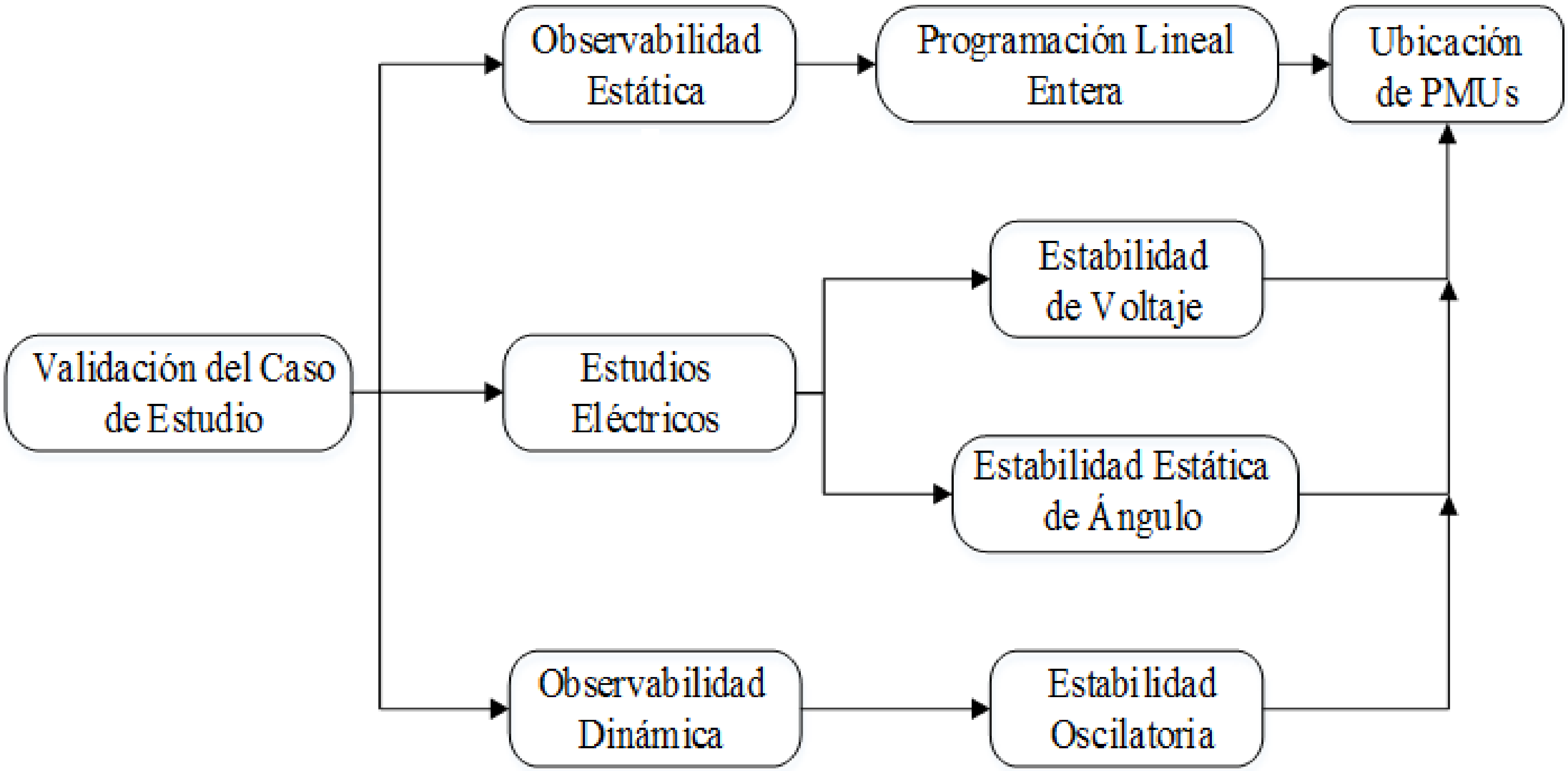



gen1
gen2
gen3
tiempo (s)
tiempo (s)
A
B
C
D
D'
P_0
P
O
II
I
ϑ_0
ϑ_1
ϑ_2
ϑ

Planning


$y_1(t)$
$y_2(t)$
$y(t)$

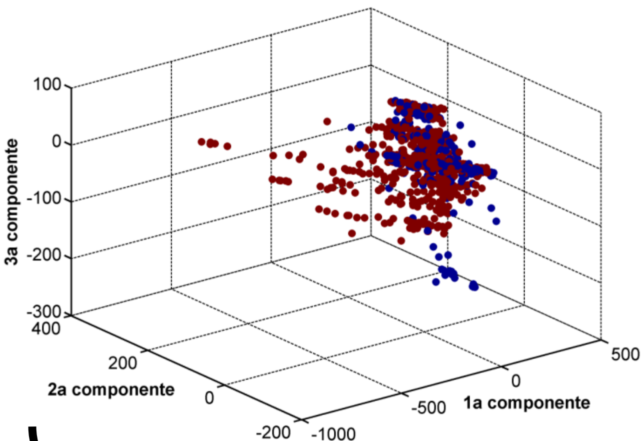
PMU Location



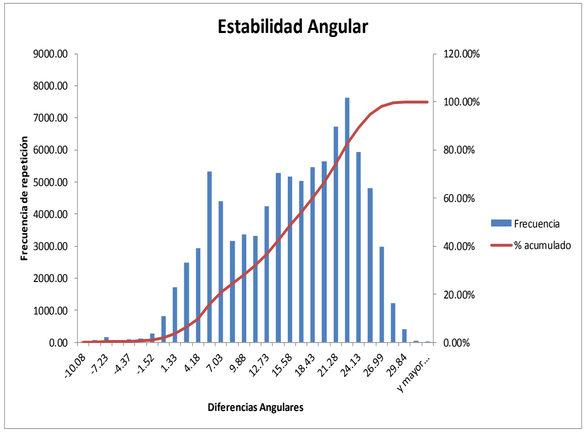
Requerimientos para la supervisión y control en tiempo real del Sistema Nacional Interconectado (REGULACIÓN No. ARCONEL- 003/16)

Dispatch with Security Constraints

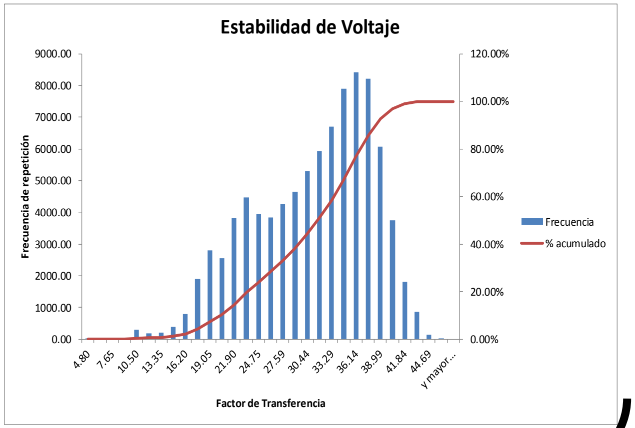
Oscillatory Stability Patterns



Steady-state Angle Stability Statistics



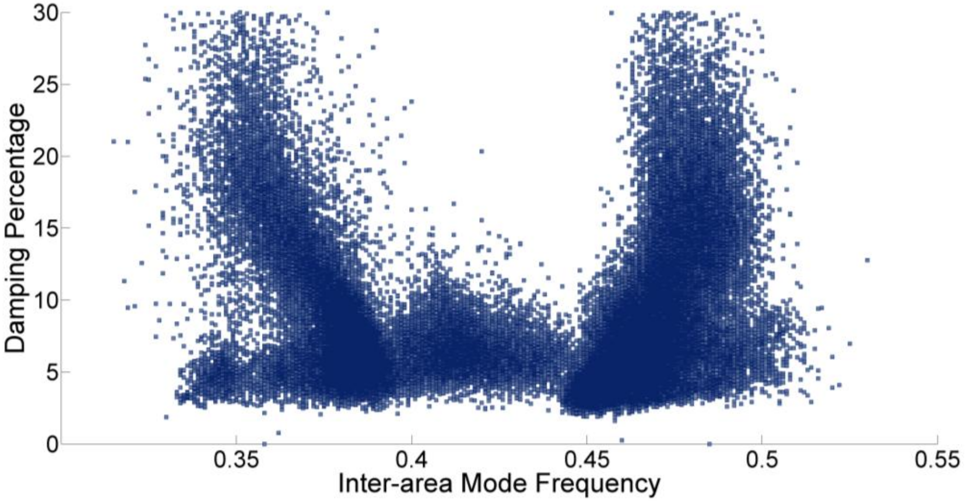
Voltage Stability Statistics

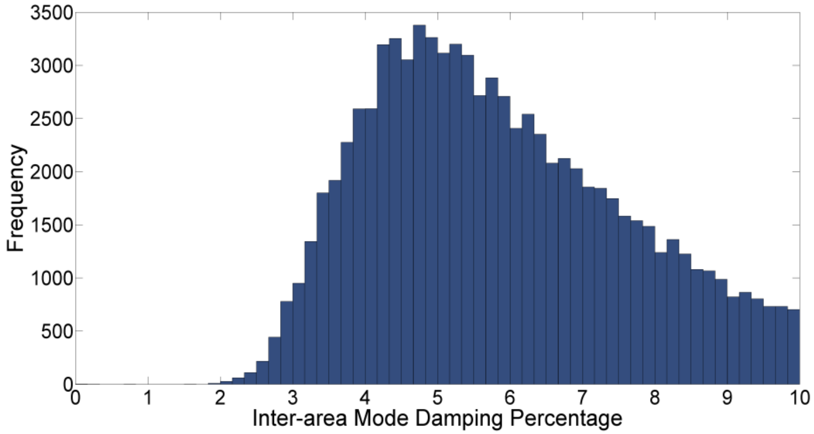


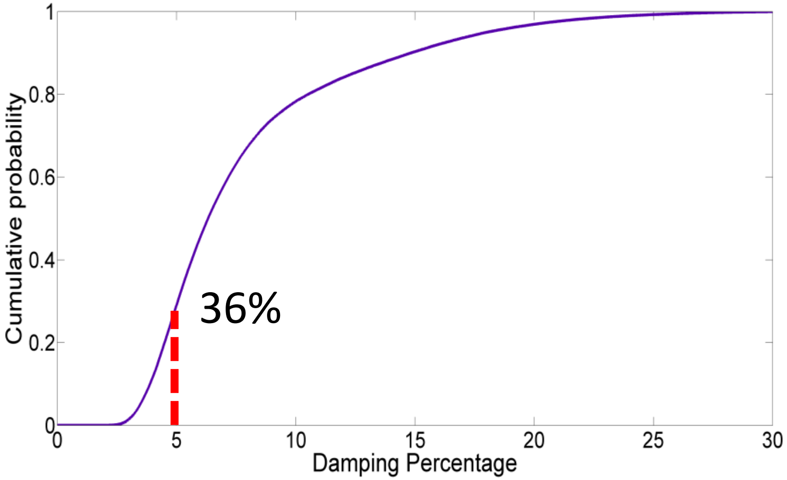
Correlations with Operation States

Seasonal Constraints based Dispatch

PSS Tuning


Damping Percentage
Inter-area Mode Frequency


Frequency
Inter-area Mode Damping Percentage


Cumulative probability
Damping Percentage
36%

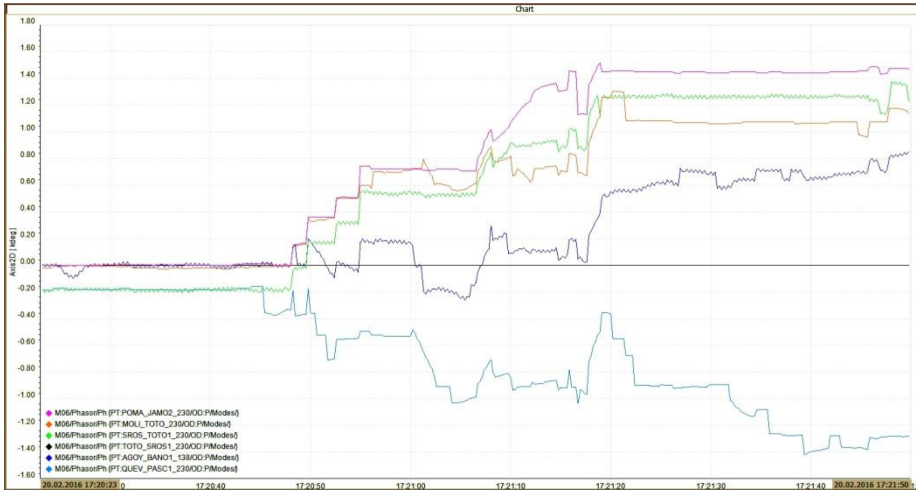
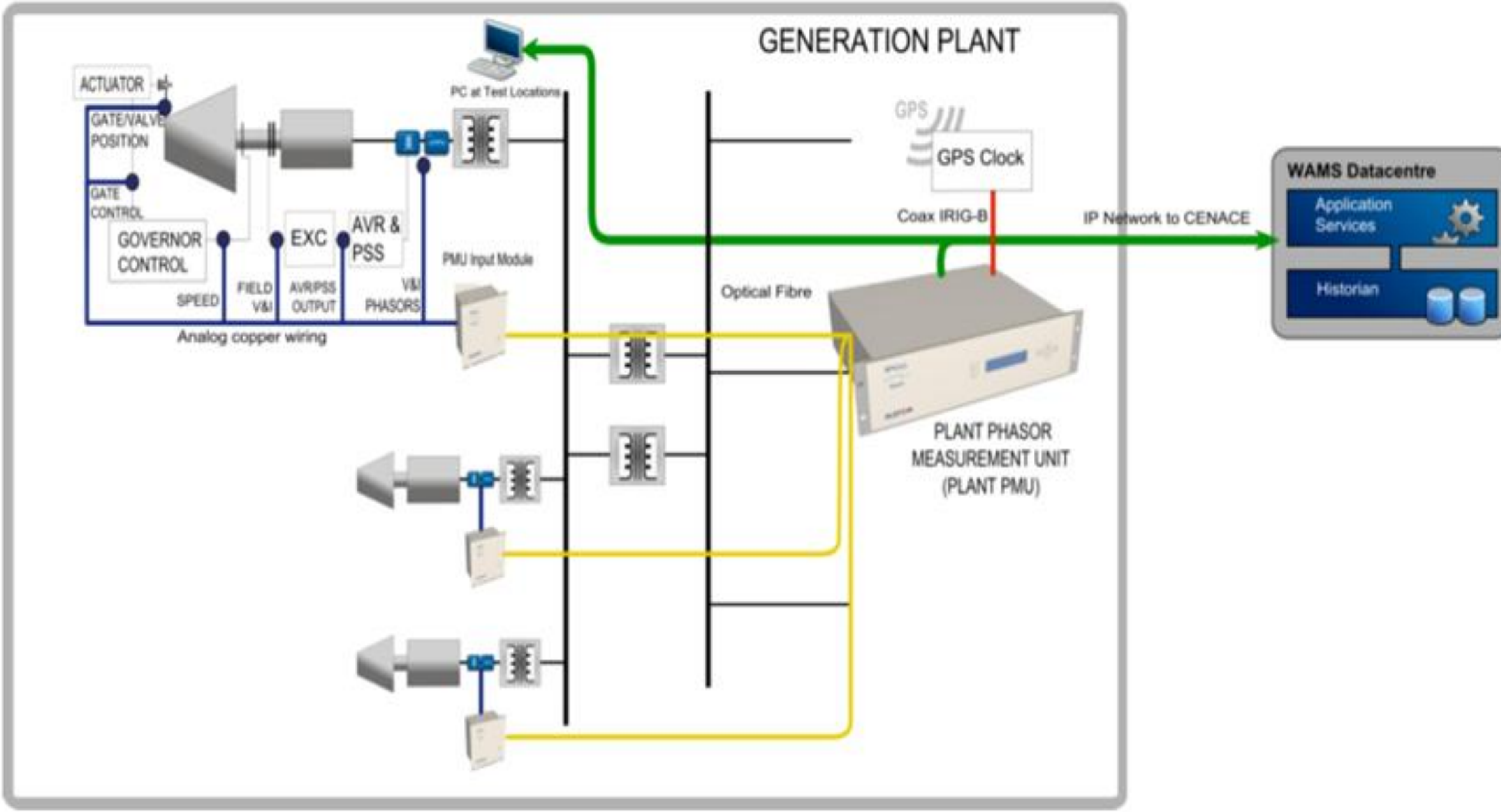


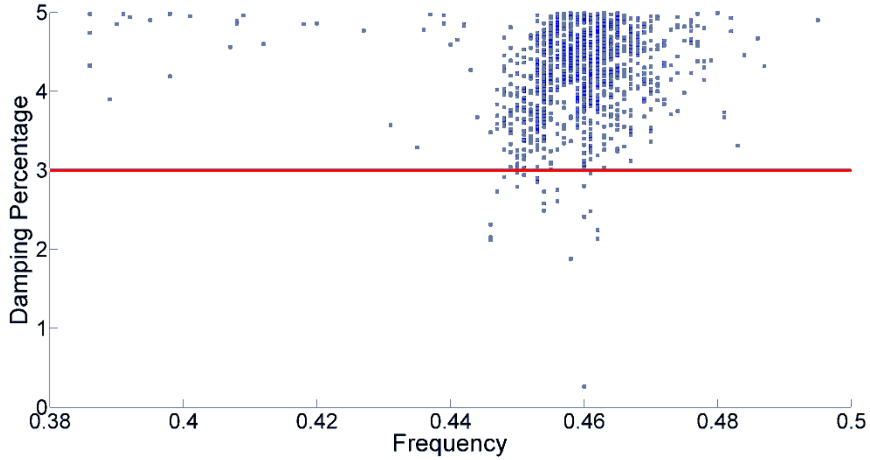
Chart
M06/Phasor/Ph {PT:POMA_JAMO2_230/OD:P/Modes/}
M06/Phasor/Ph {PT:MOLI_TOTO_230/OD:P/Modes/}
M06/Phasor/Ph {PT:SROS_TOTO1_230/OD:P/Modes/}
M06/Phasor/Ph {PT:TOTO_SROS1_230/OD:P/Modes/}
M06/Phasor/Ph {PT:AGOY_BANO1_138/OD:P/Modes/}
M06/Phasor/Ph {PT:QUEV_PASC1_230/OD:P/Modes/}
20.02.2016 17:20:23
20.02.2016 17:21:50

PSS Tuning

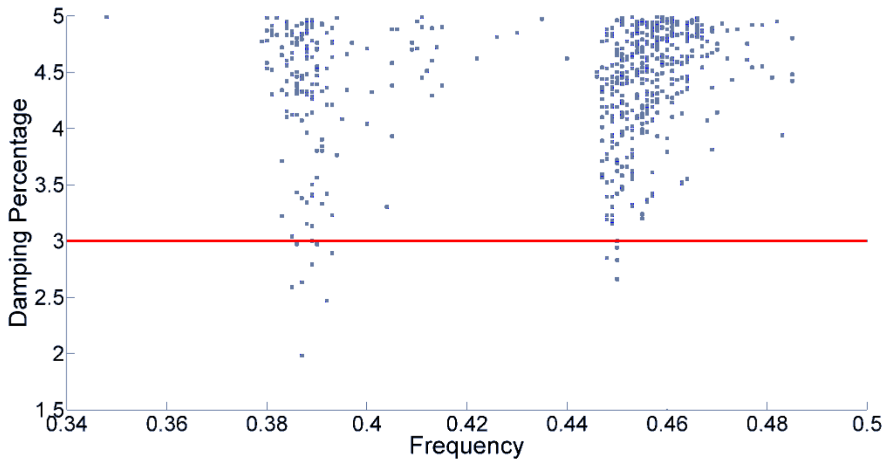


GENERATION PLANT
ACTUATOR
GATE/VALVE POSITION
GATE CONTROL
GOVERNOR CONTROL
SPEED
FIELD V&I
EXC
AVR & PSS
AVR/PSS OUTPUT
V&I PHASORS
Analog copper wiring
PC at Test Locations
PMU Input Module
GPS
GPS Clock
Coax IRIG-B
Optical Fibre
IP Network to CENACE
PLANT PHASOR MEASUREMENT UNIT (PLANT PMU)
WAMS Datacentre
Application Services
Historian

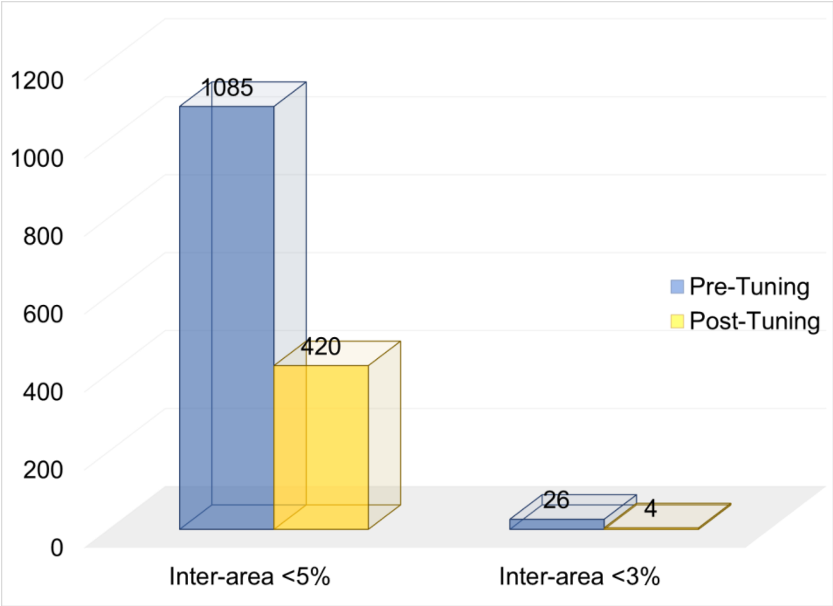
PSS Tuning



Two weeks before Tuning

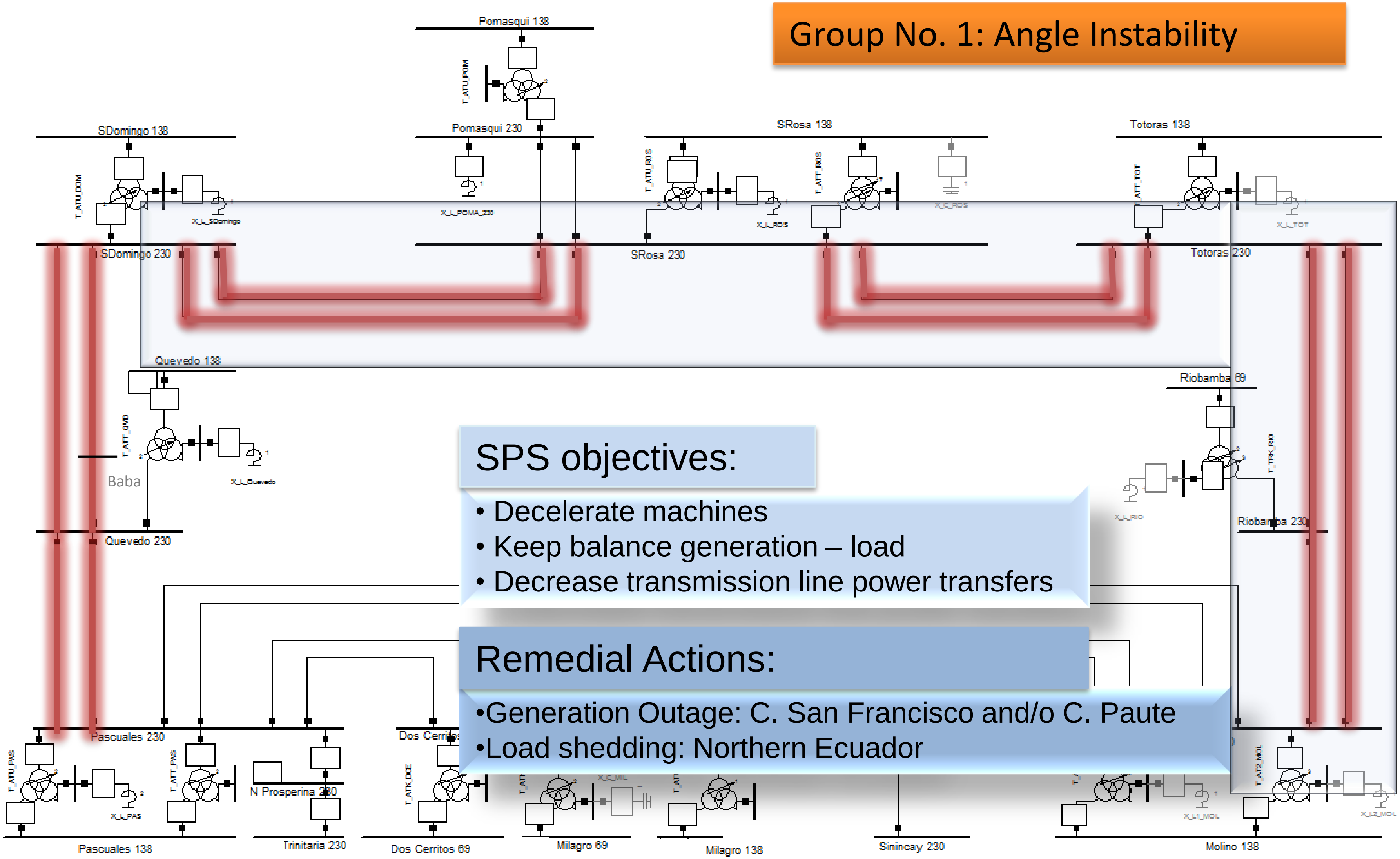


Two weeks after Tuning



Special Protection Scheme – SPS

Group No. 1: Angle Instability



SPS objectives:

- Decelerate machines
- Keep balance generation – load
- Decrease transmission line power transfers

Remedial Actions:

- Generation Outage: C. San Francisco and/o C. Paute
- Load shedding: Northern Ecuador

Special Protection Scheme – SPS

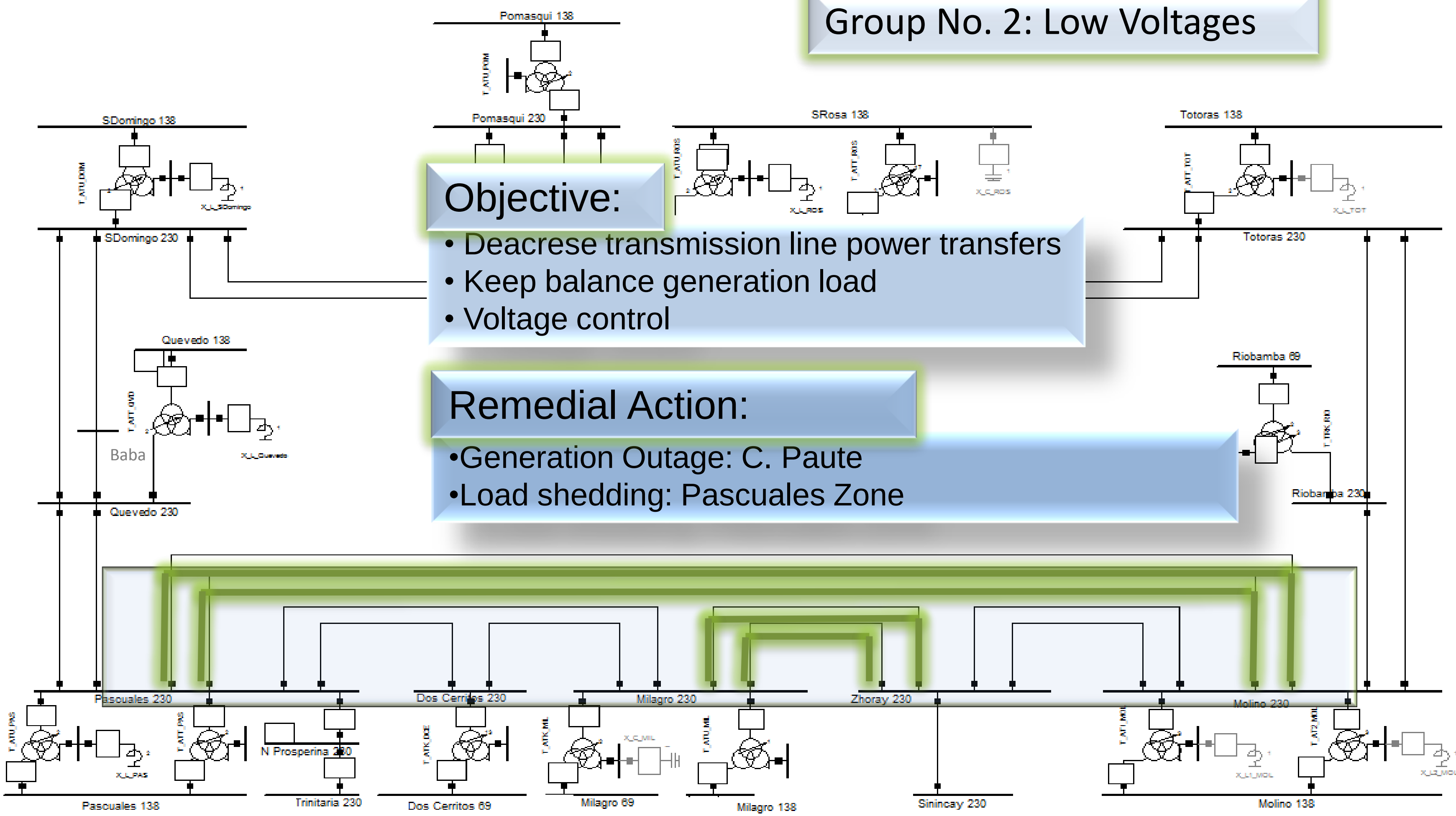
Group No. 2: Low Voltages

Objective:

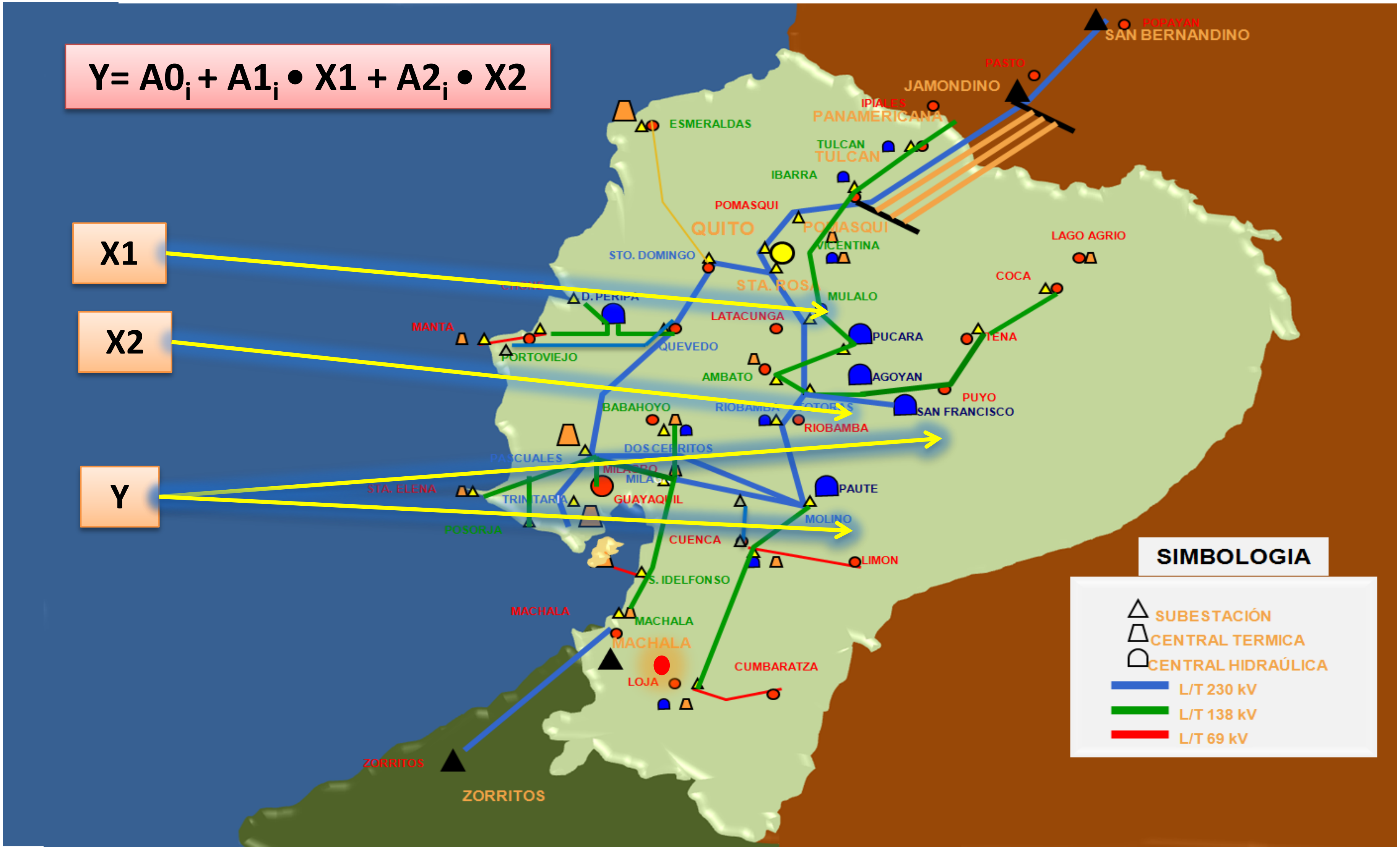
- Deacrese transmission line power transfers
- Keep balance generation load
- Voltage control

Remedial Action:

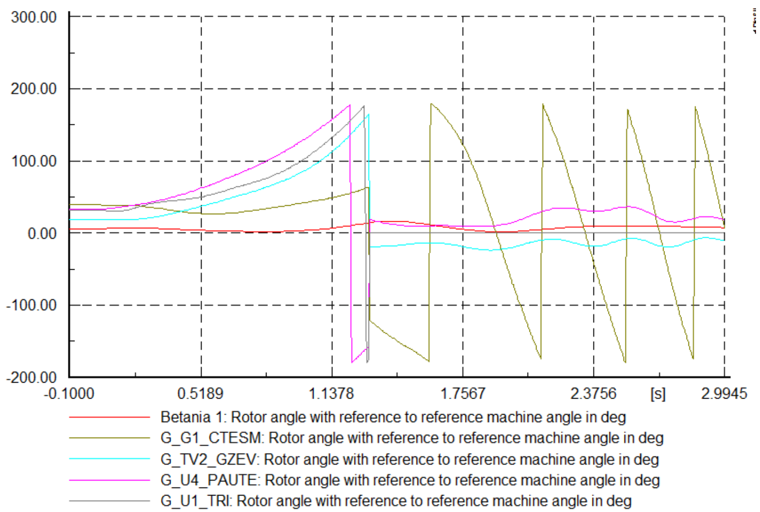
- Generation Outage: C. Paute
- Load shedding: Pascuales Zone

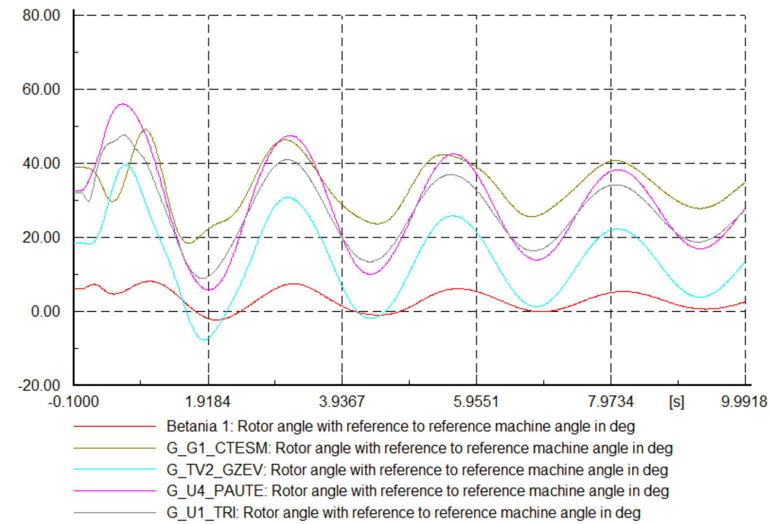


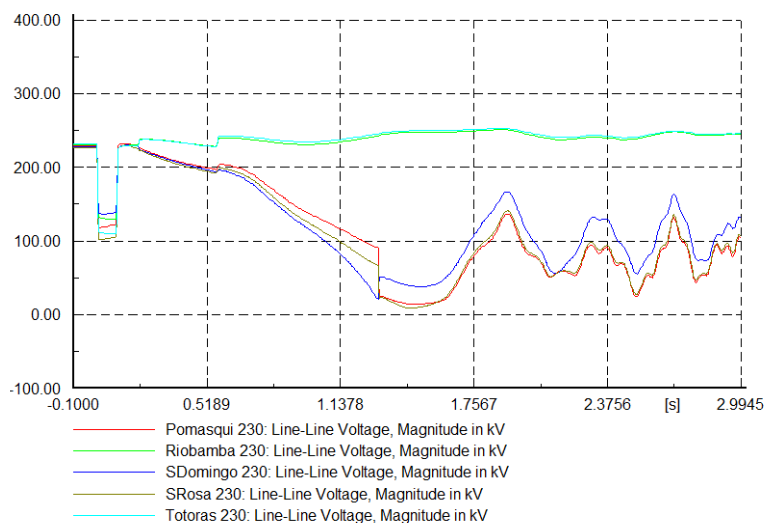
Intelligent Protection Scheme

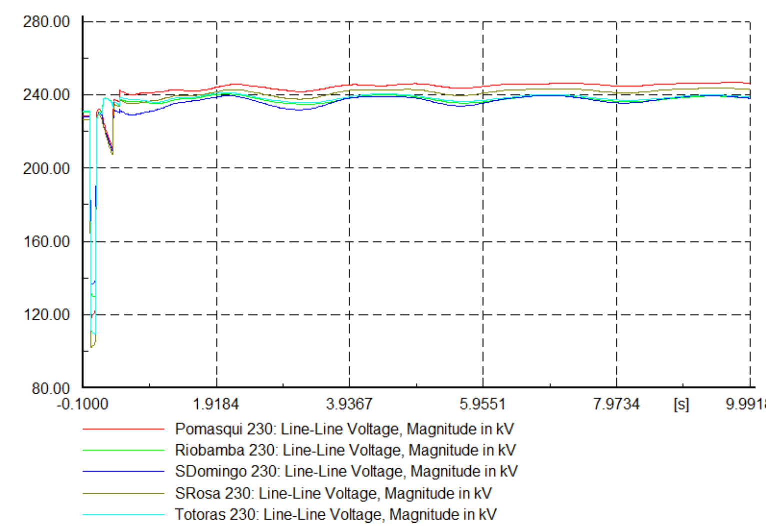


SPS Mitigation Effect

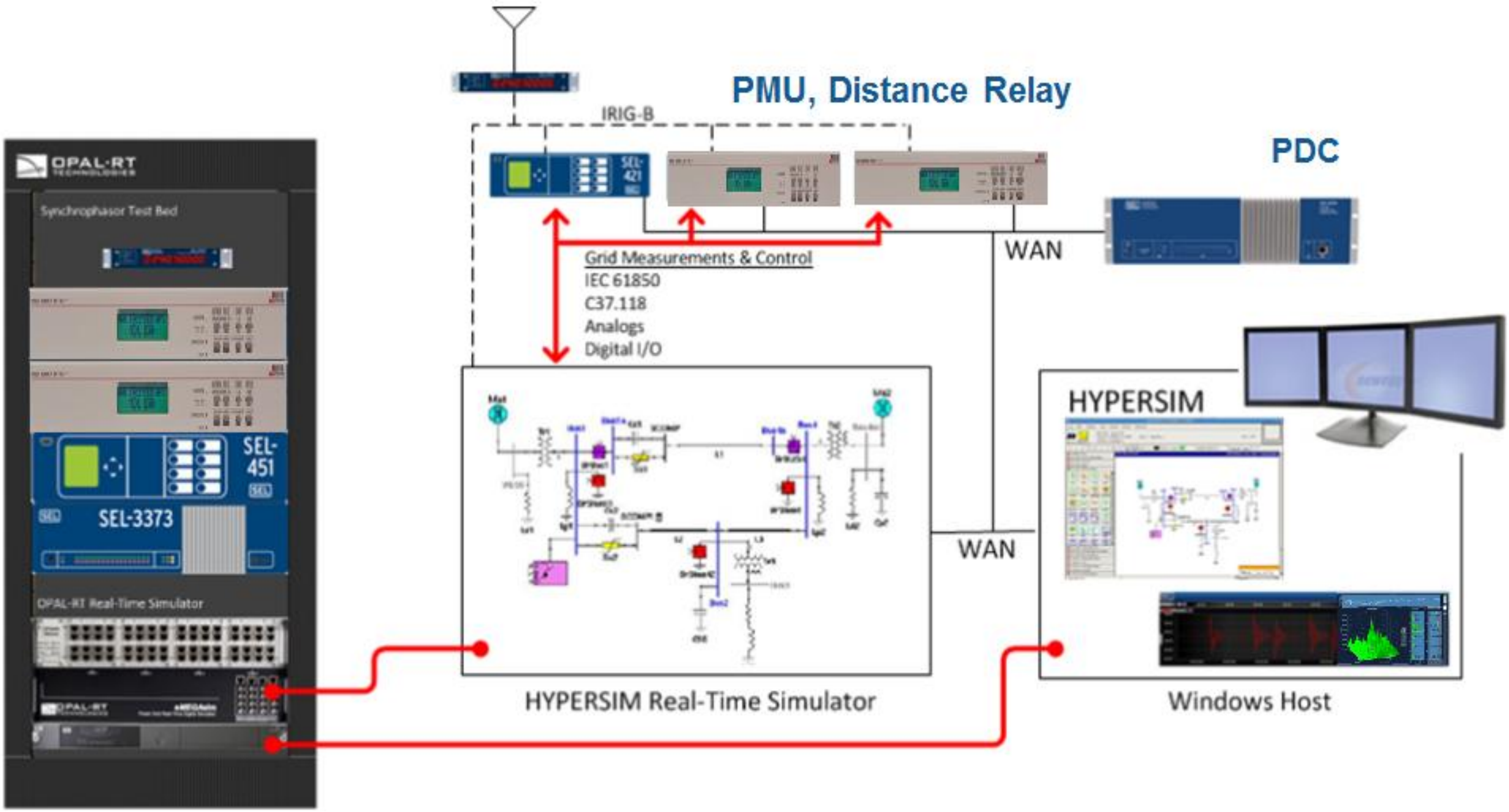




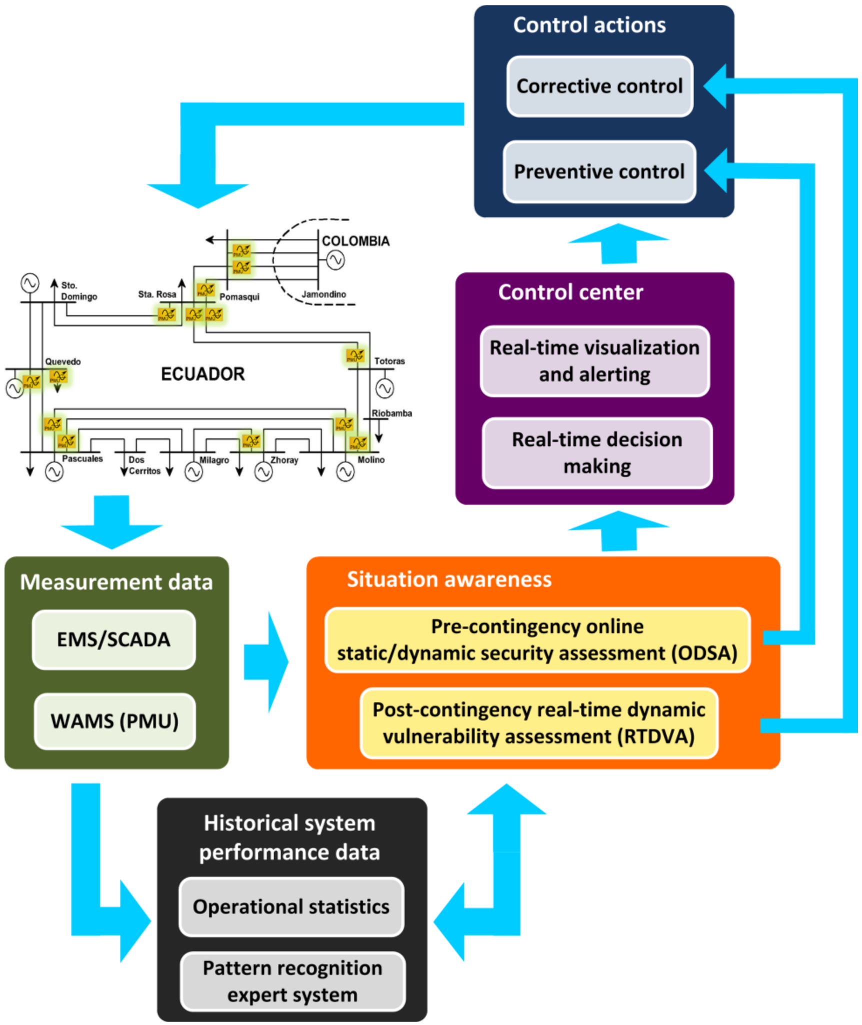




Parameter Identification - PMU Testbed - SPS Designed – Operators’ Training



Real Time Security Assessment and Enhancement



- Update of system behavior **knowledge database** (i.e. operational statistics) and execution of **pattern recognition** routines, which supports the dynamic security assessment (DSA) and real-time dynamic vulnerability assessment (DVA) tasks.
- **DSA** in normal operating states to determine whether or not the system security level is to be degraded in future time when considering a selected set of credible contingencies.
- **Real-time DVA** to determine the actual system security level as well as the tendency of changing its conditions to a critical state in post-disturbance immediate time.

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