International Workshop on

Dynamic Stability Challenges of the Future Power Grids

Digital Intelligence for Modern Power Systems: Experiences in Monitoring, Modeling, Analytics, and Control of the Ecuadorian Power Grid

Jaime C. Cepeda
Escuela Politécnica Nacional, Ecuador
jaime.cepeda@epn.edu.ec

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From synchrophasor data to secure system operation

- Ecuadorian power system context
- WAMS infrastructure and operational applications
- Dynamic operational challenges in the Ecuadorian power system
- Oscillatory stability and PSS tuning
- Model Validation
- Real-time simulation and Digital Twins
- Predictive analytics for real-time operation
- Conclusions: Operational impact and lessons learned

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FIEE

Ecuadorian Power System: A hydro-dominant grid operates through a critical regional interconnection

7,788.99 MW 2025 effective installed capacity

73.61% 2025 hydro generation

5,634.31 MW
July 15, 2026 historical domestic peak

97.81% 2025 electricity access

Ecuador SNI

Hydroelectric generation centers 230 / 500 kV backbone

Four 230 kV lines

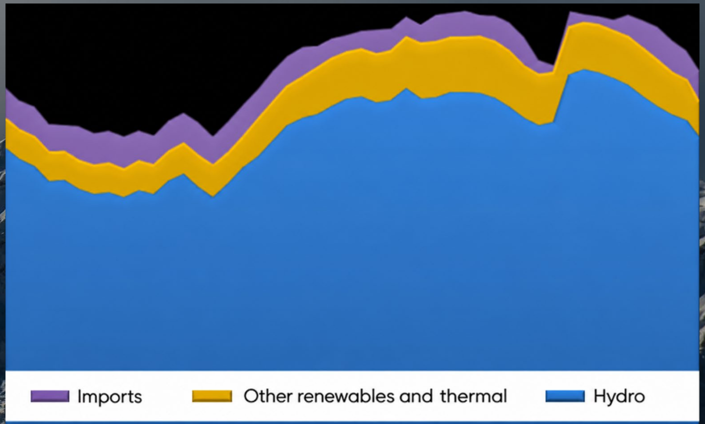
Colombia

Larger (~3 times) synchronous power system

Operating implication

Excitation of a persistent 0.3–0.4 Hz inter-area mode.

Congested transmission corridors



Since 2010, CENACE has built an end-to-end synchrophasor platform

01

More than 60 PMUs

Strategic buses and generator terminals

02

Optical-fiber network

Synchronized, low-latency data transport

03

PDC - WAProtector

IEEE C37.118 acquisition, archive and analytics

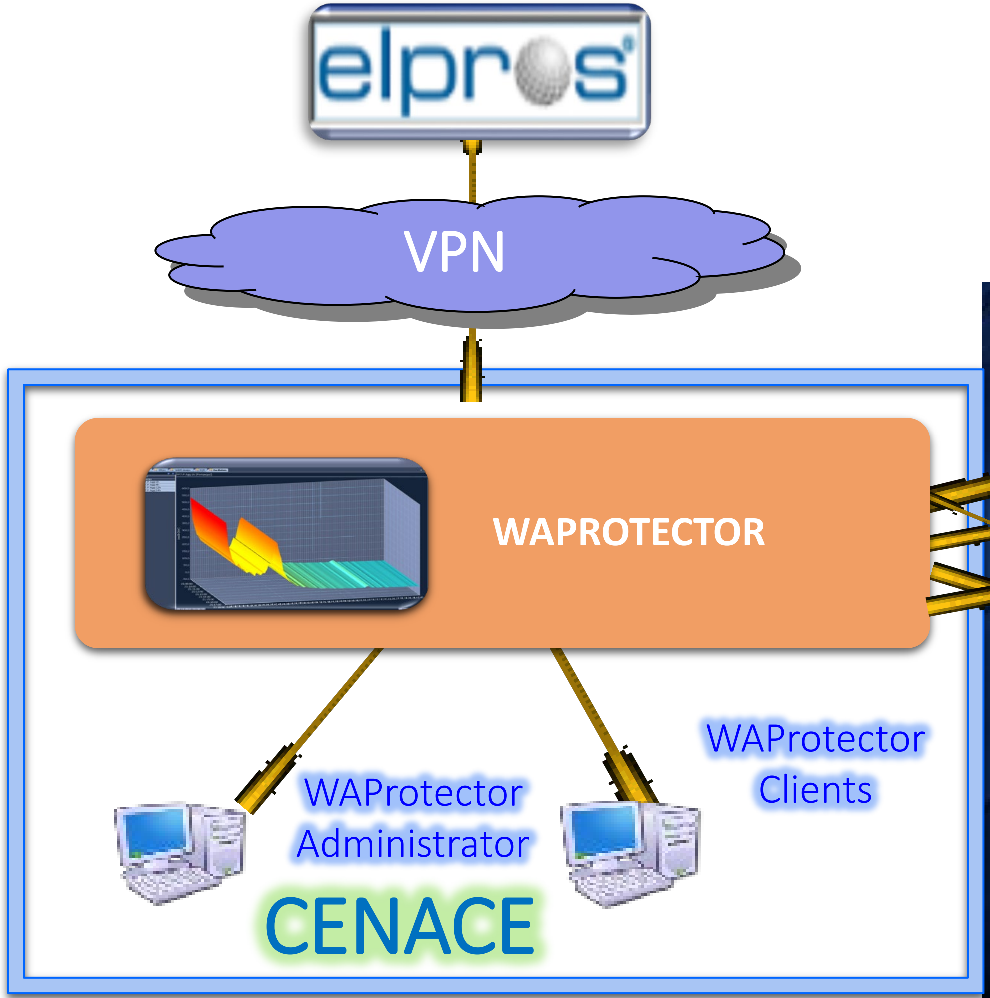
04

Security applications

Angle, voltage, oscillations, events and harmonics

A single operational data backbone supports planning studies, real-time situational awareness and post-event analysis.

Ecuadorian WAMS



- TCP/IP Protocol
- Standard IEEE C37.118

Ecuadorian necessity of dynamic visibility beyond conventional SCADA

SYSTEM CHALLENGE

High hydro power plants far from main load centers, and a synchronous tie with Colombia create:
- Poorly-damped Low-frequency oscillations;
- Congested corridors.

WAMS RESPONSE

Time-synchronized PMU measurements reveal:
- phase angle,
- voltage,
- frequency,
- modal behavior in quasi-real time.

OPERATIONAL VALUE

Ecuadorian ISO (CENACE) can perform:
- model validation,
- controllers' tuning
- early warning analysis
- post-operative analysis

Post-operative learning informs planning; planning defines real-time limits and actions.

WAMS value compounds through a closed learning loop

POST-OPERATIVE

Fault reconstruction
Dynamic-security statistics
Oscillation patterns
Power-quality assessment

PLANNING

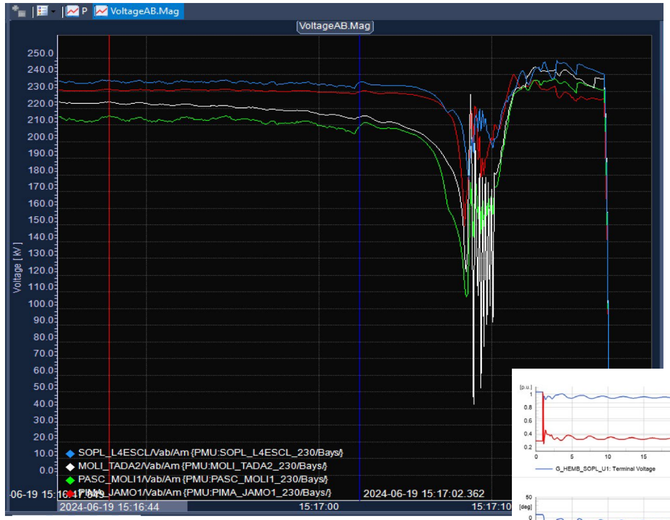
PMU placement
Application thresholds
Model identification
Controller tuning
Special Protection schemes

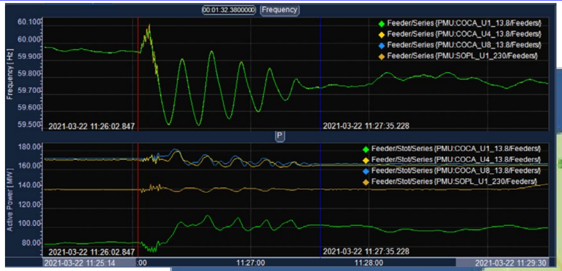
REAL-TIME

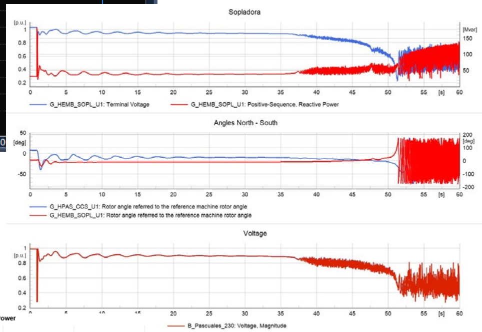
Security-state monitoring
Early warning
Situational awareness
Control and protection
Operator training

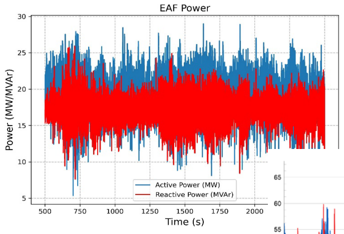
Measured behavior → validated knowledge → operating limits and actions → new records

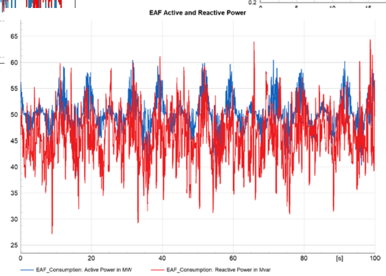
Dynamic operational challenges in the Ecuadorian power system





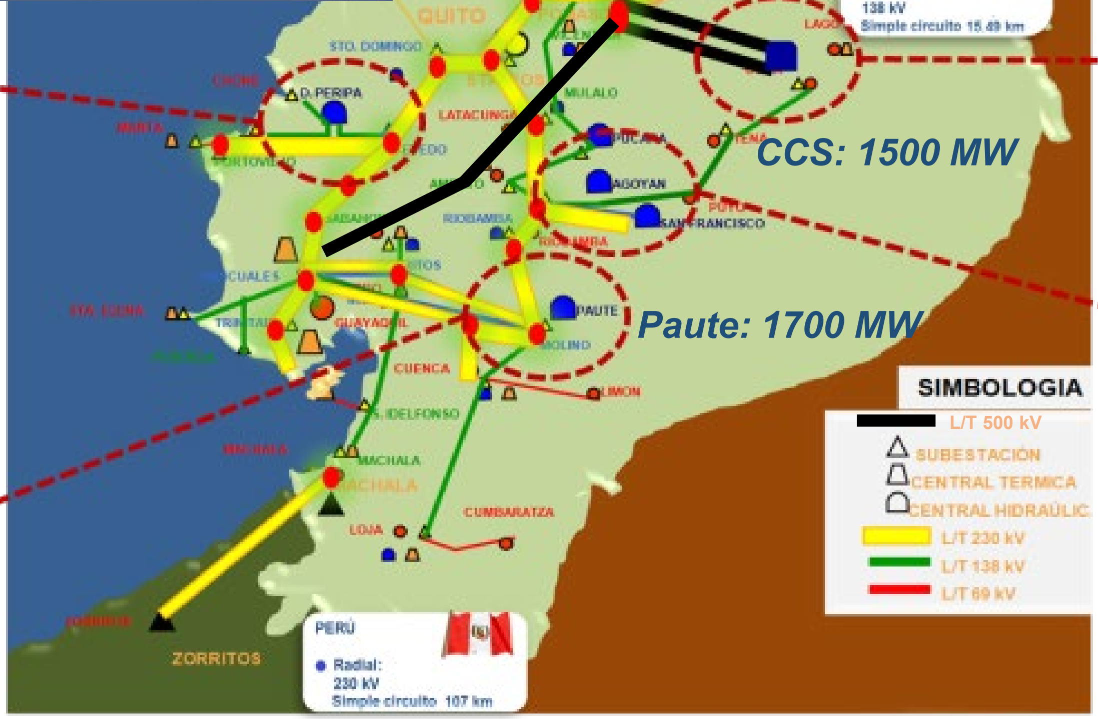






1.0 - 1.8 Hz
Local

0.4 - 0.5 Hz
Inter-area
COLOMBIA



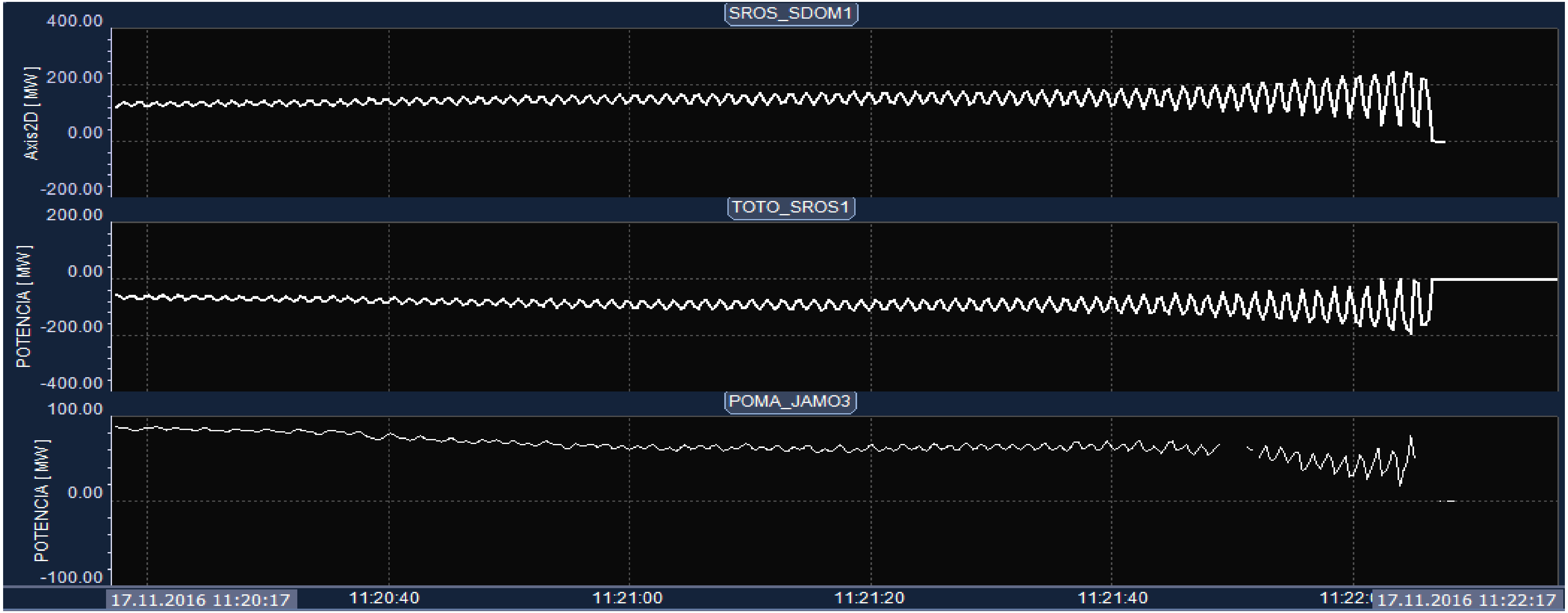
0.4 - 0.5 Hz
Inter-area
COLOMBIA

0.7 - 1.2 Hz
Local

0.8 - 1.1 Hz
Local

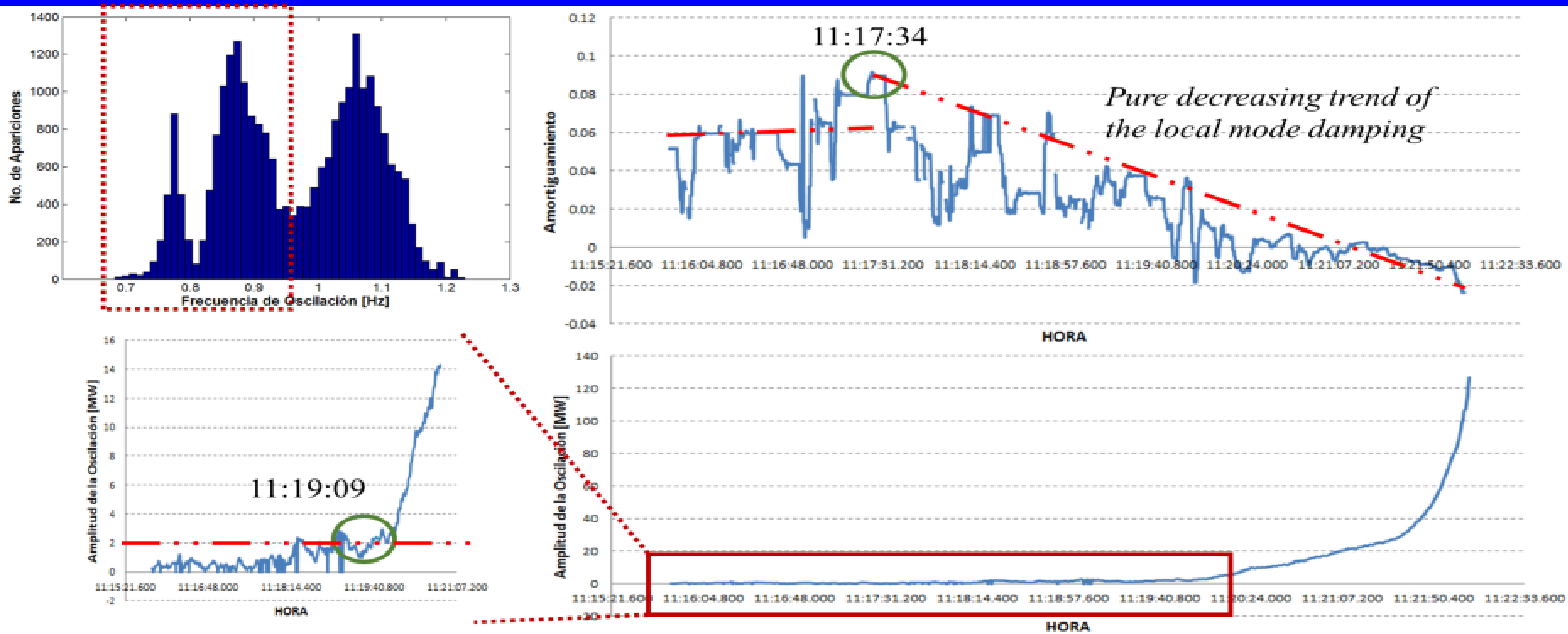
Congested transmission corridors

Power Flow: T/L Sta. Rosa – Sto. Domingo, T/L Totoras – Sta. Rosa and T/L Pomasqui – Jamondino

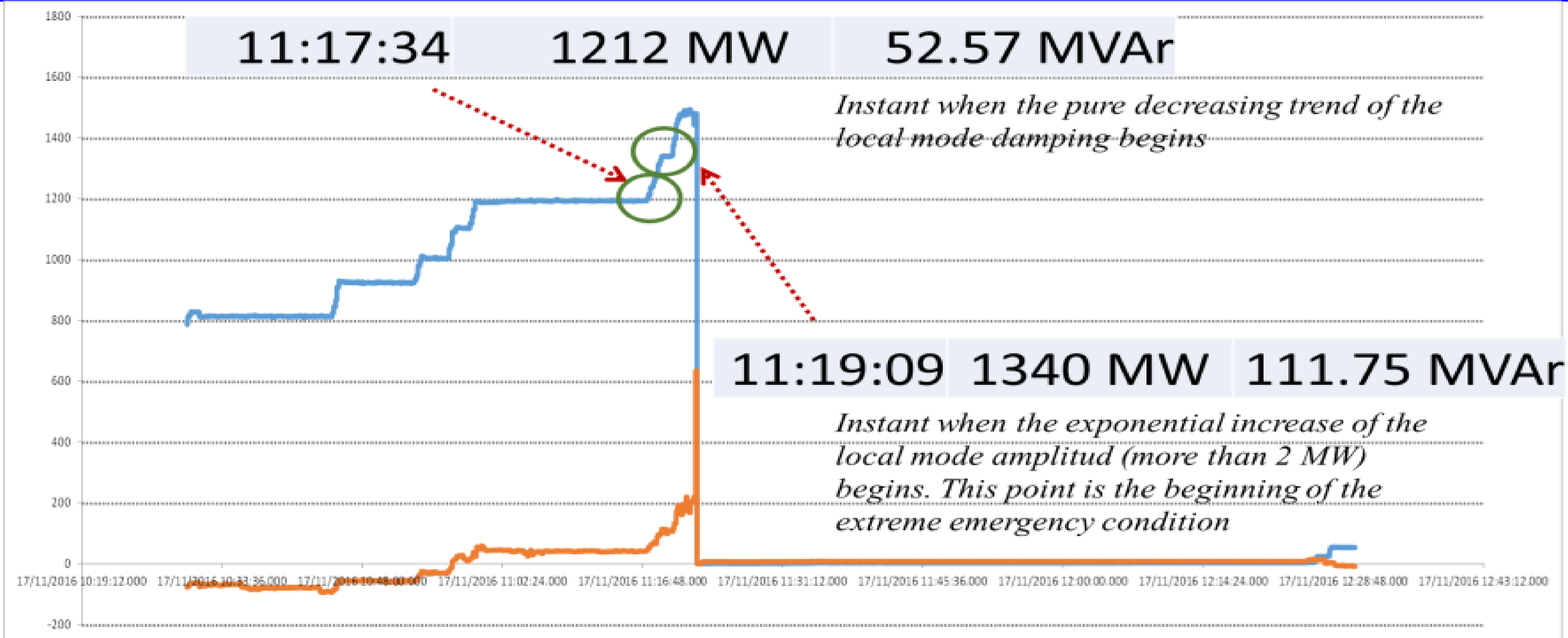


Local Oscillation mode at CCS: 0.75 Hz with negative damping

Oscillatory Local Modes: T/L Santa Rosa – Santo Domingo



Active and Reactive injection power of Coca Codo Sinclair



Local mode Oscillatory Stability Condition

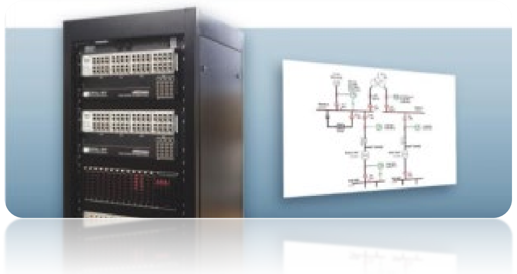
The causes of the excitation of the local oscillatory mode with negative damping were:

Highly congested branches: This congestion is produced by the 230 kV system, which must withstand the high power flow from the north.

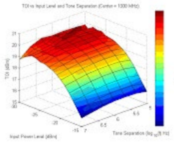
High power injections from CCS: CCS power plant is a source that injects a large amount of power (up to 1500 MW) into the Ecuadorian system, via a radial 500 kV corridor that is then connected to the 230 kV system that becomes congested.

Dynamic of power plant elements: Dynamic parameters of each one of the 8 units, and the controllers' behavior (AVR and PSS with prior parameters) also contributed to lack of damping torque.

PSS Tuning Methodology



python



MATLAB SIMULINK

Installation of monitoring devices in the Generation power Plant: PMUs

Modeling of key system elements: generator, AVR and simplified network.

Model validation through field tests and real-time records (WAProtector)

Probabilistic Oscillatory analysis:

Modal Analysis

Frequency response

Time domain Simulation

Multiple scenarios (Monte Carlo)

PSS Tuning.- Robust Methodology:

- Multiple scenarios (Monte Carlo)
- Heuristic optimization algorithm
- Frequency response (constraints)
- TestBed for PSS Tuning → *Digital Twin*

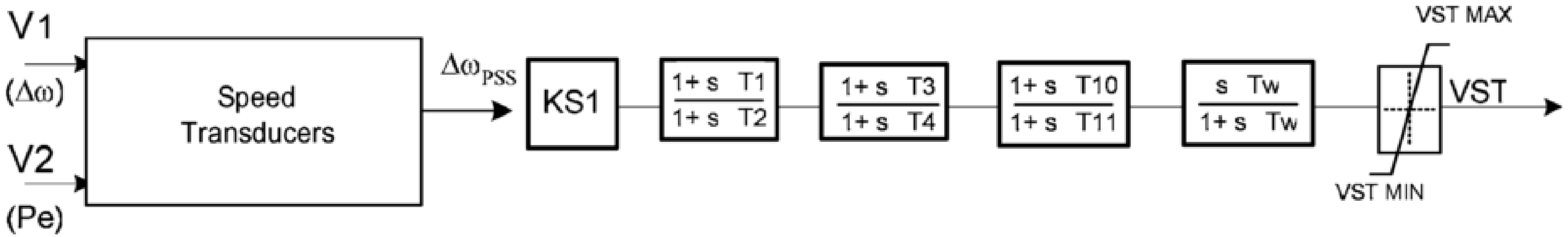
eMEGAsim

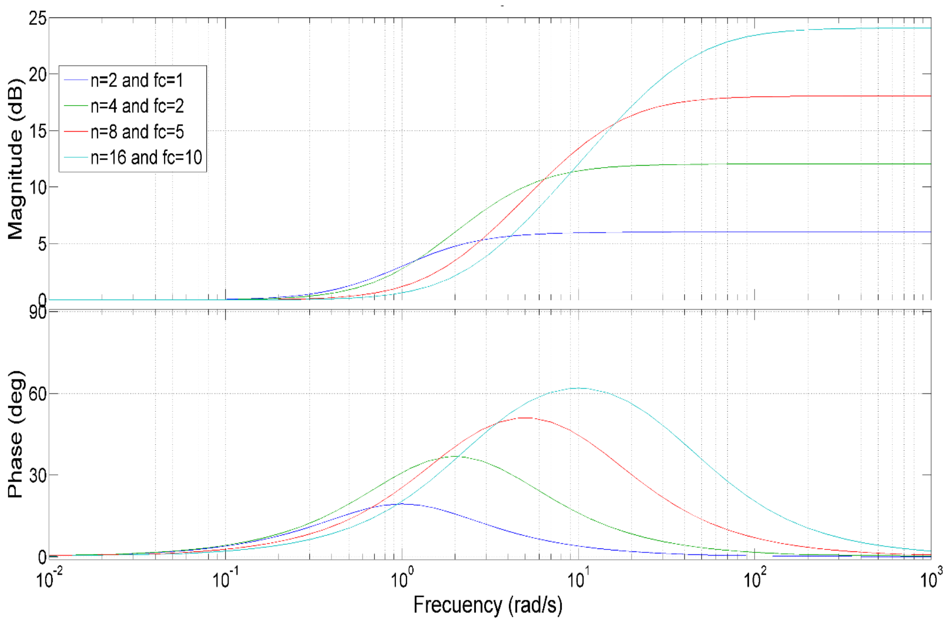
Field PSS tuning

Tuning validation tests

(WAProtector)

PSS Tuning Methodology



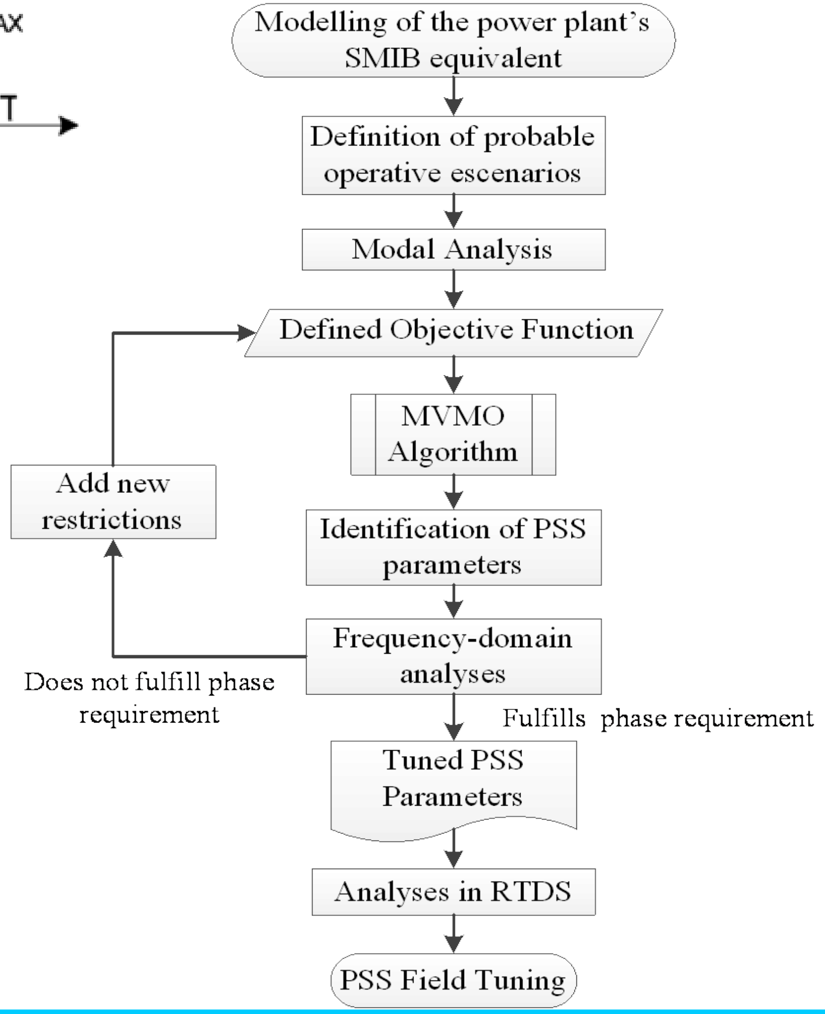


$$\min OF = \left|\xi_{th} - \xi_{sys}\right|$$

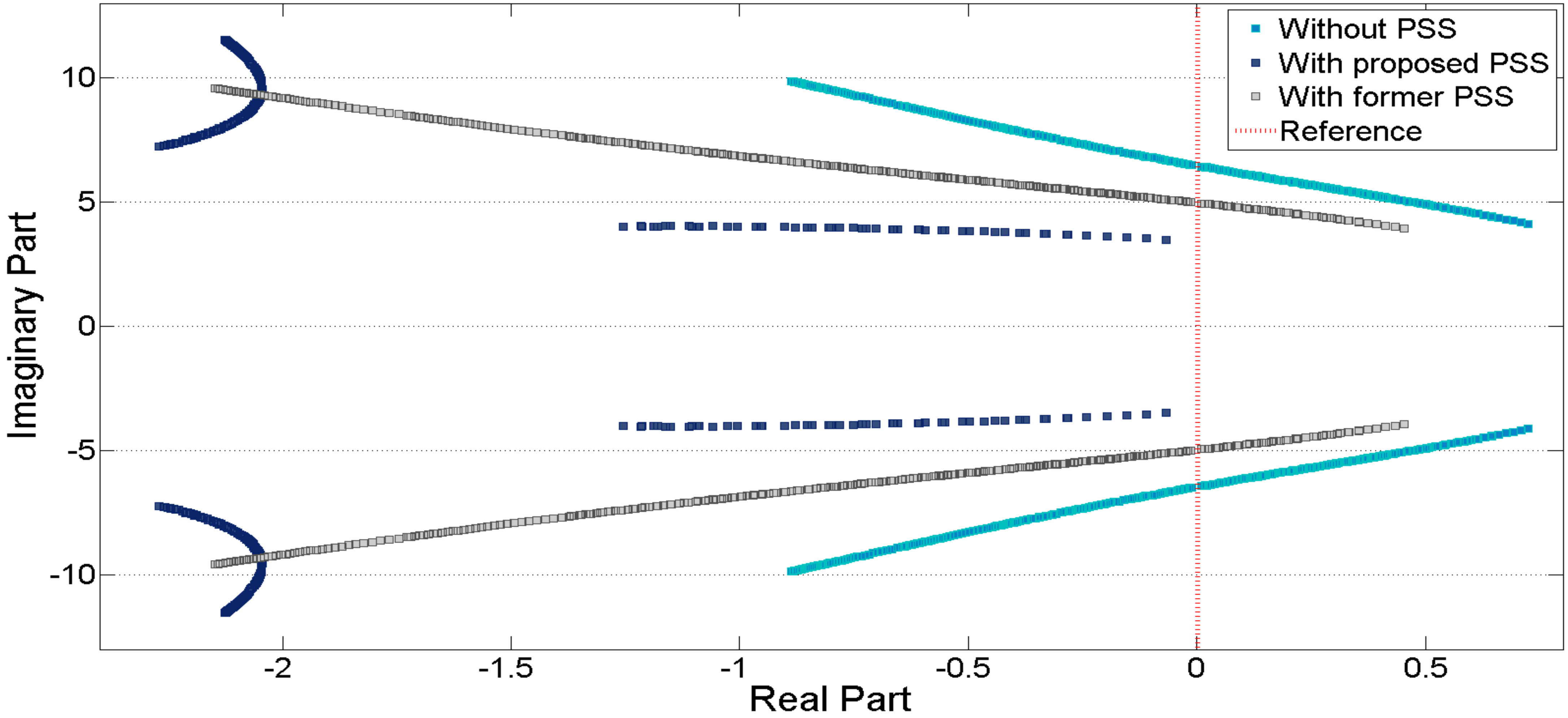
$$\xi_{sys} = \min_{p=1\ldots nm}\left(\xi_p\right)$$

$$\mathbf{x}_{j-\min} \le \mathbf{x}_j \le \mathbf{x}_{j-\max}$$

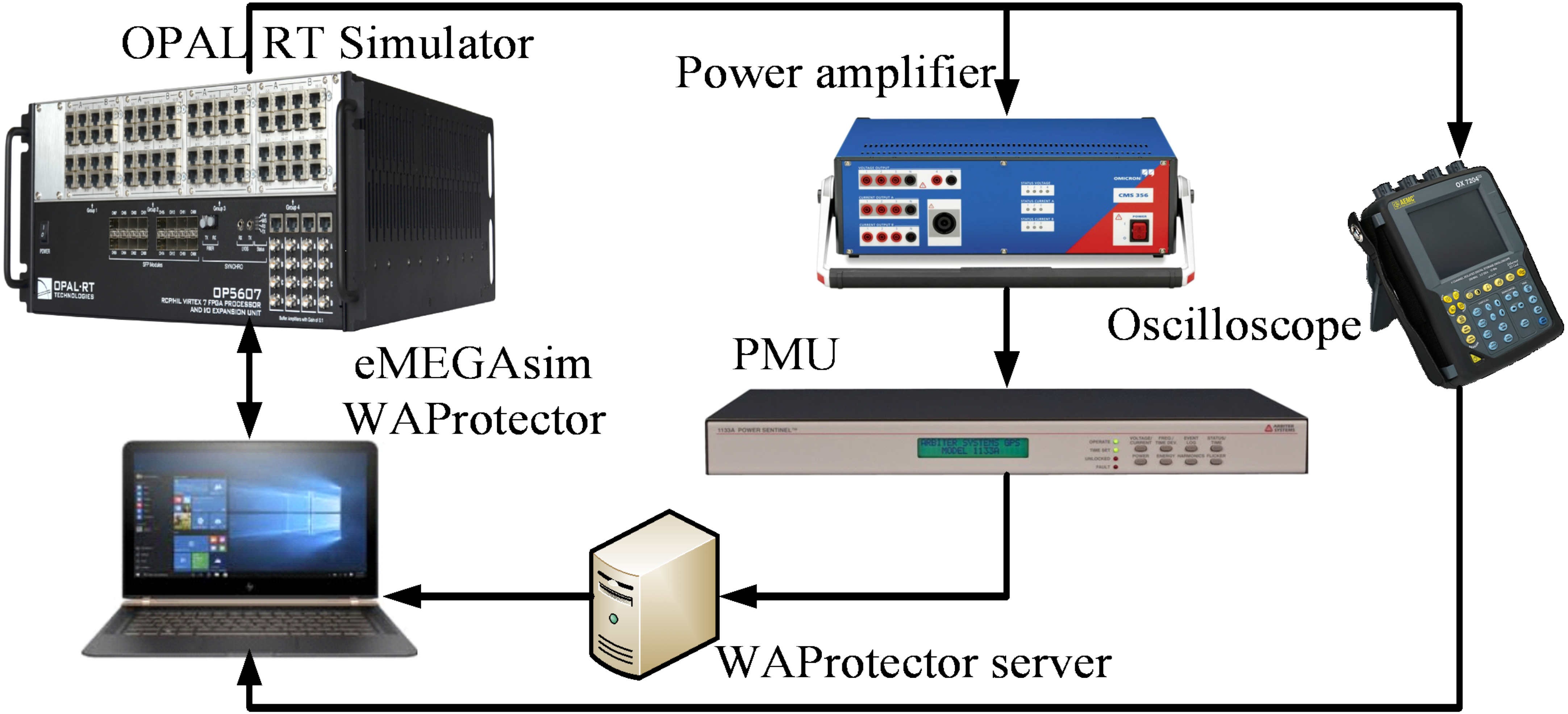
$$fc = \frac{1}{2\pi}\frac{1}{\sqrt{T_1 T_2}} \qquad n = \frac{T_1}{T_2}$$



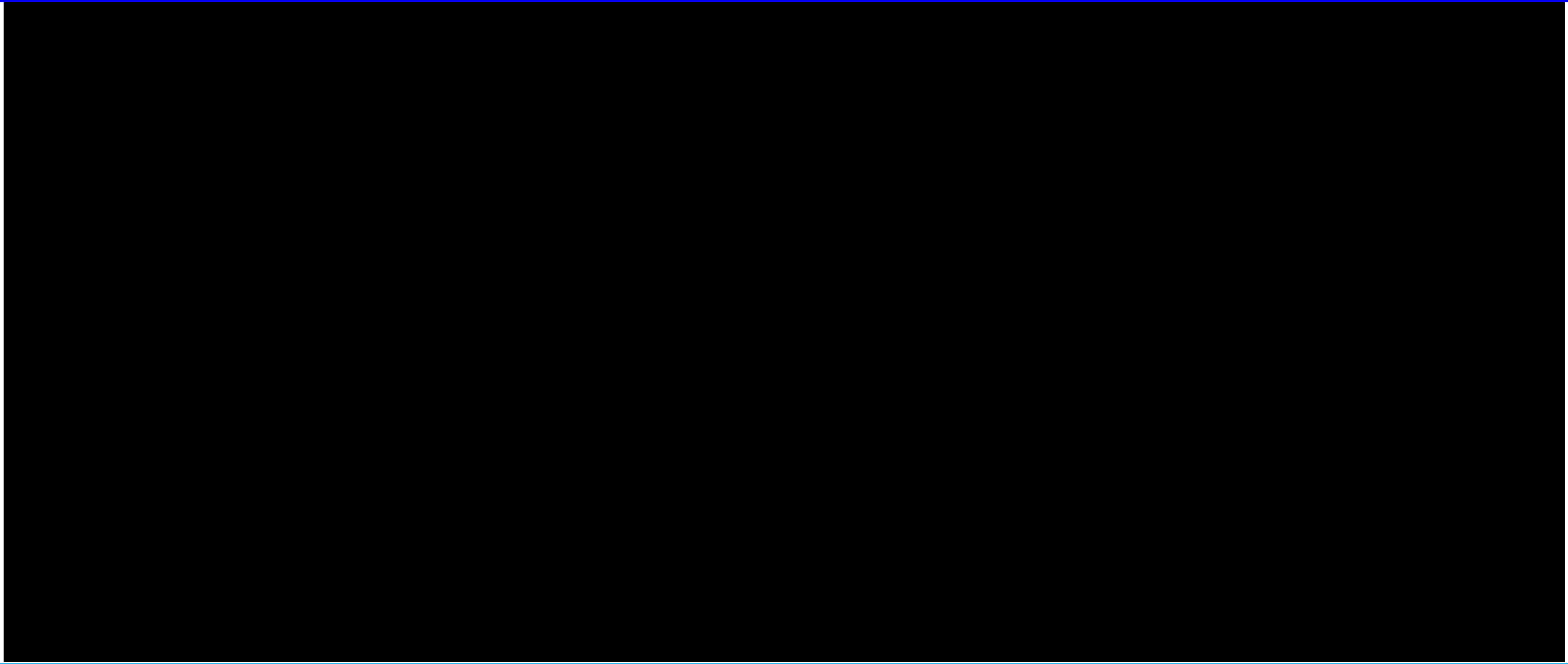
Root locus plot: different PSS and different scenarios (Monte Carlo)



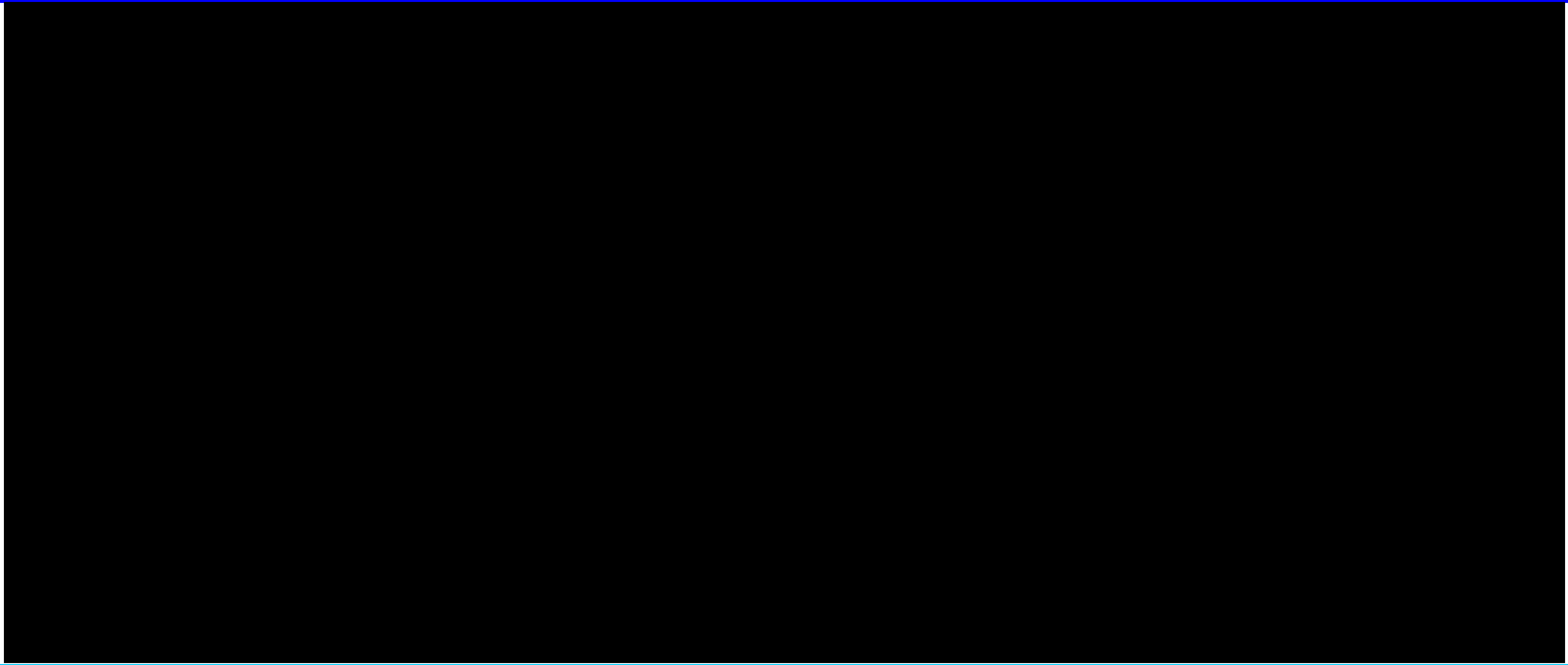
Local mode Oscillatory Stability Condition



Testbed for PSS Tuning - CCS behaviour prior PSS Tuning



Testbed for PSS Tuning - CCS behaviour after PSS Tuning



PSS tuning improved damping and expanded secure export capability

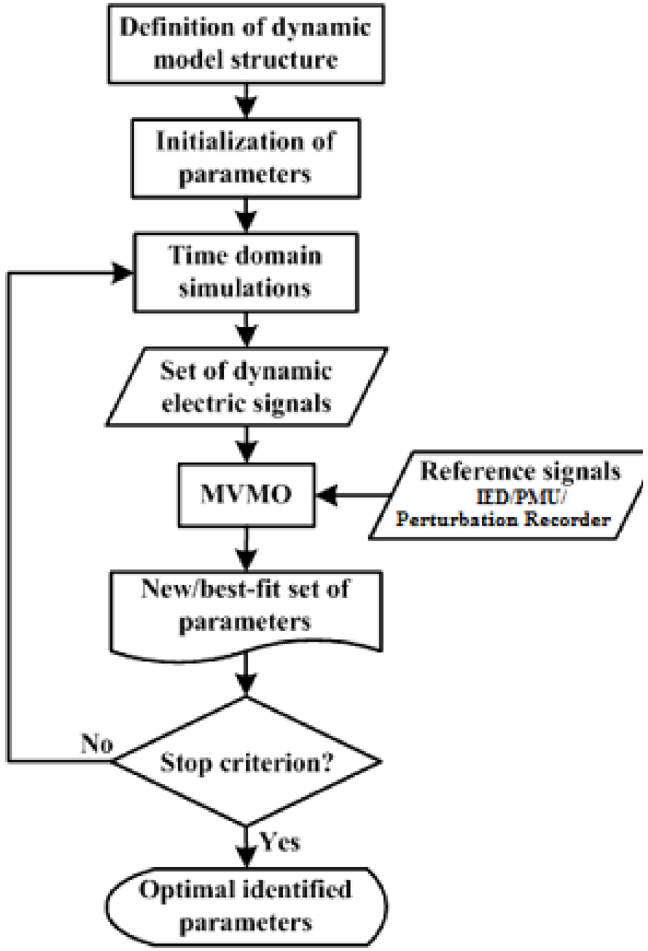
BEFORE CCS PSS TUNING		AFTER CCS PSS TUNING
300 MW	**+150 MW** →	**450 MW**
MW export ceiling		MW export capability

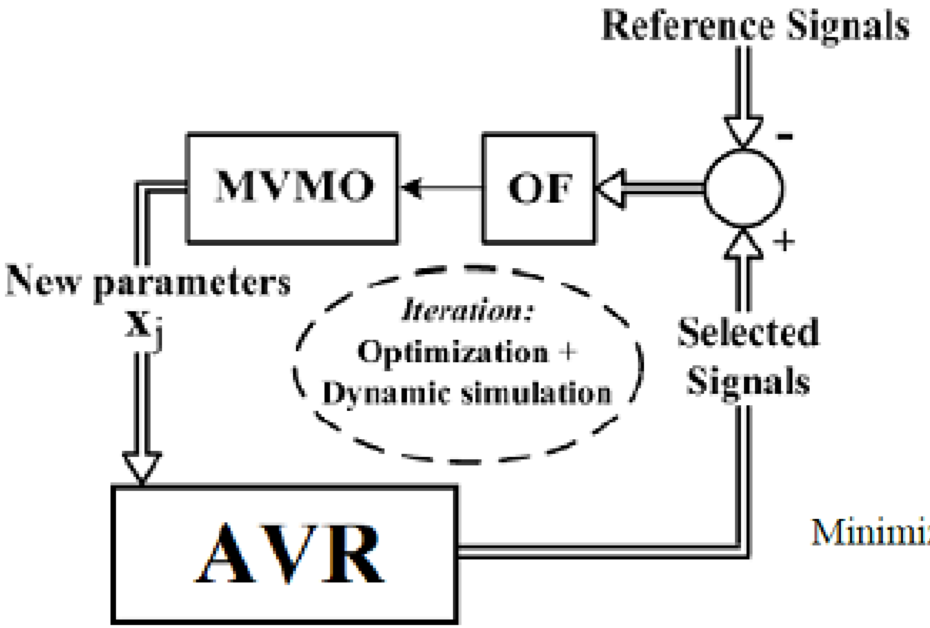
0.3–0.4 Hz
persistent inter-area mode monitored by WAMS

320 MW released constraints
hydro generation had been constrained under instability risk

CIER 2021
Second Prize — Digitalization Innovation Award

Model Validation based on MVMO





Minimize:

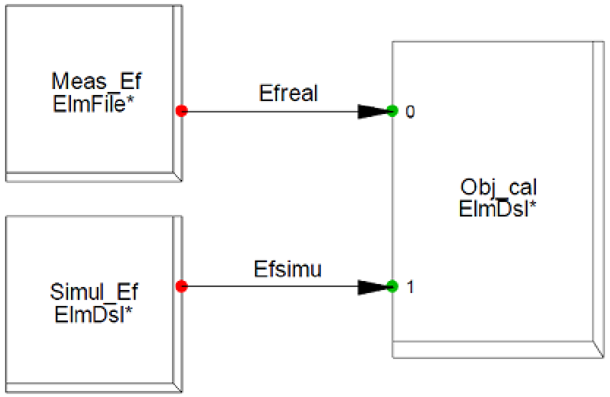
$$OF = \sum_{np=1}^{p} \alpha_{np} \int_{0}^{\tau} g(t)\,dt$$

$$g(t) = w_1\left[y_1(t) - y_{1_{ref}}(t)\right]^2 + \ldots + w_n\left[y_n(t) - y_{n_{ref}}(t)\right]^2$$

Subject to:

$$\mathbf{x}_{j-\min} \le \mathbf{x}_j \le \mathbf{x}_{j-\max}$$

DSL Modeling

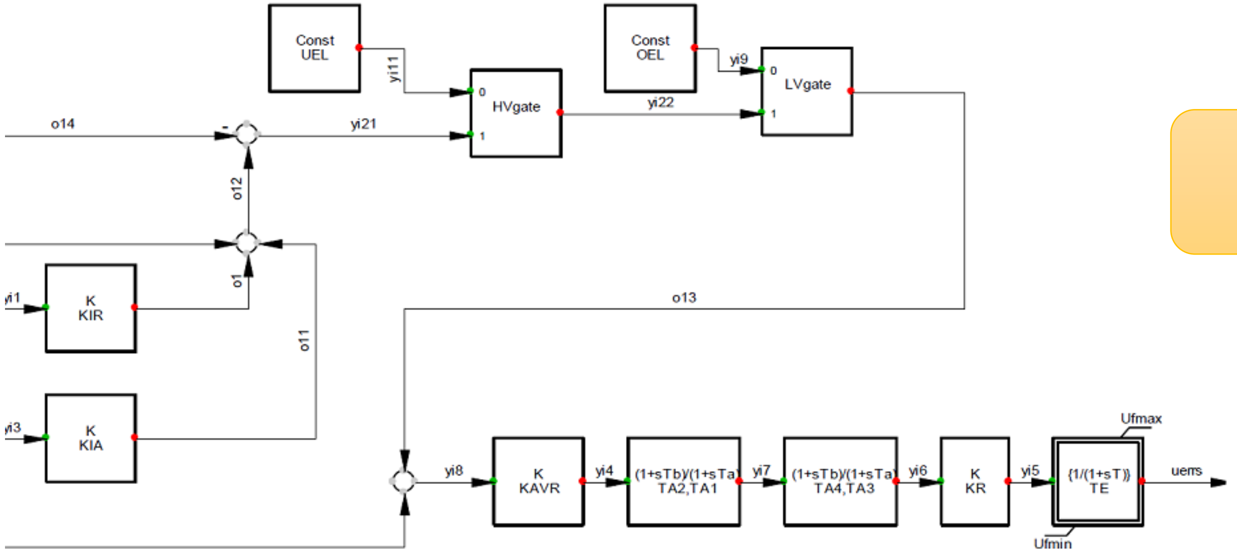


DSL

DPL

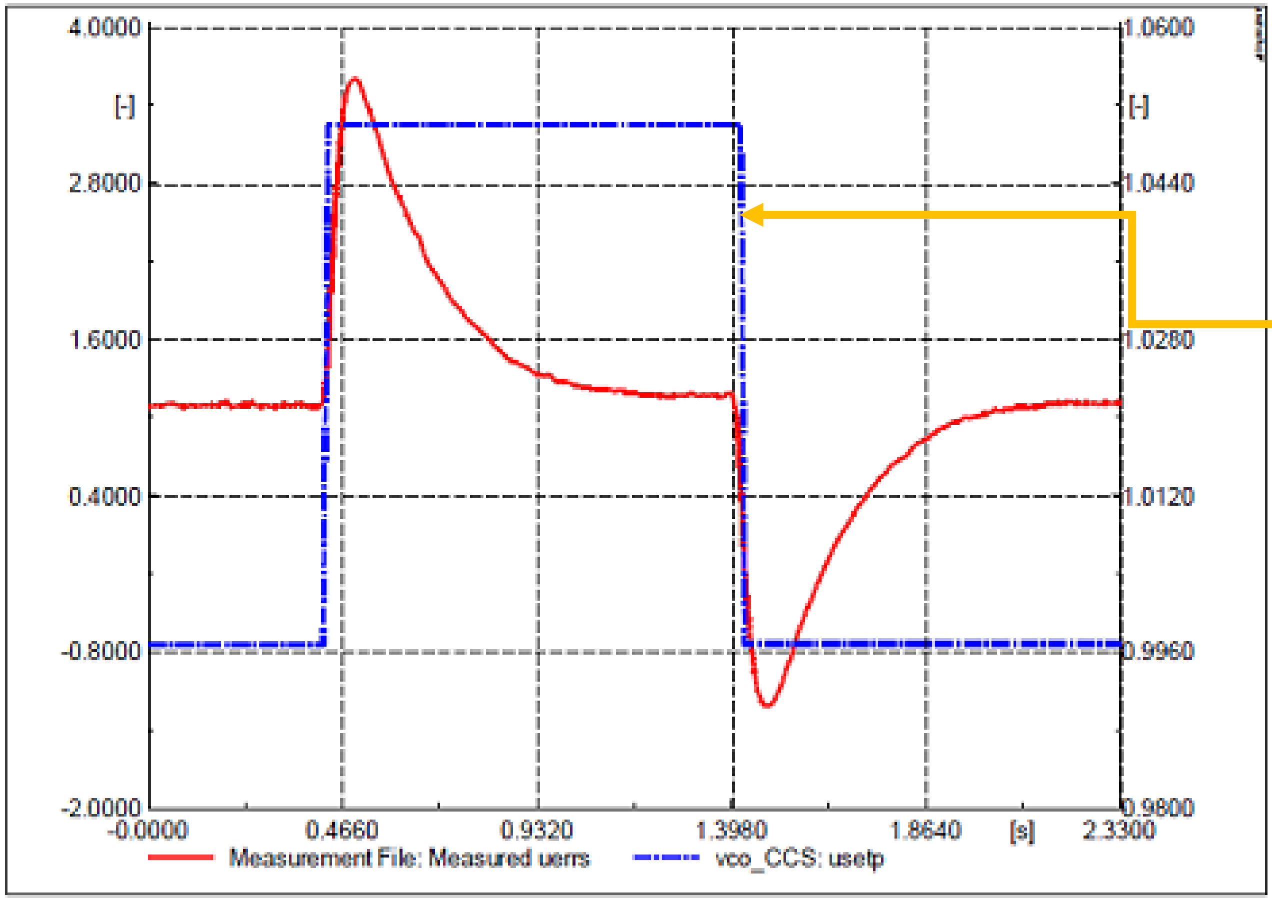
$$g(t) = w\left[Ef_{simu}(t) - Ef_{real}(t)\right]^2$$

$$\int_a^b f(x)dx \approx (b-a)\left[\frac{f(a)+f(b)}{2}\right]$$

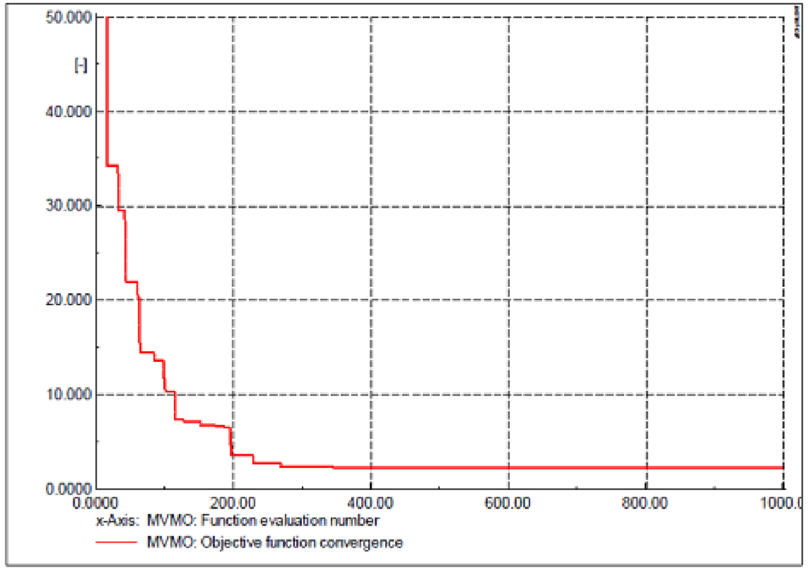


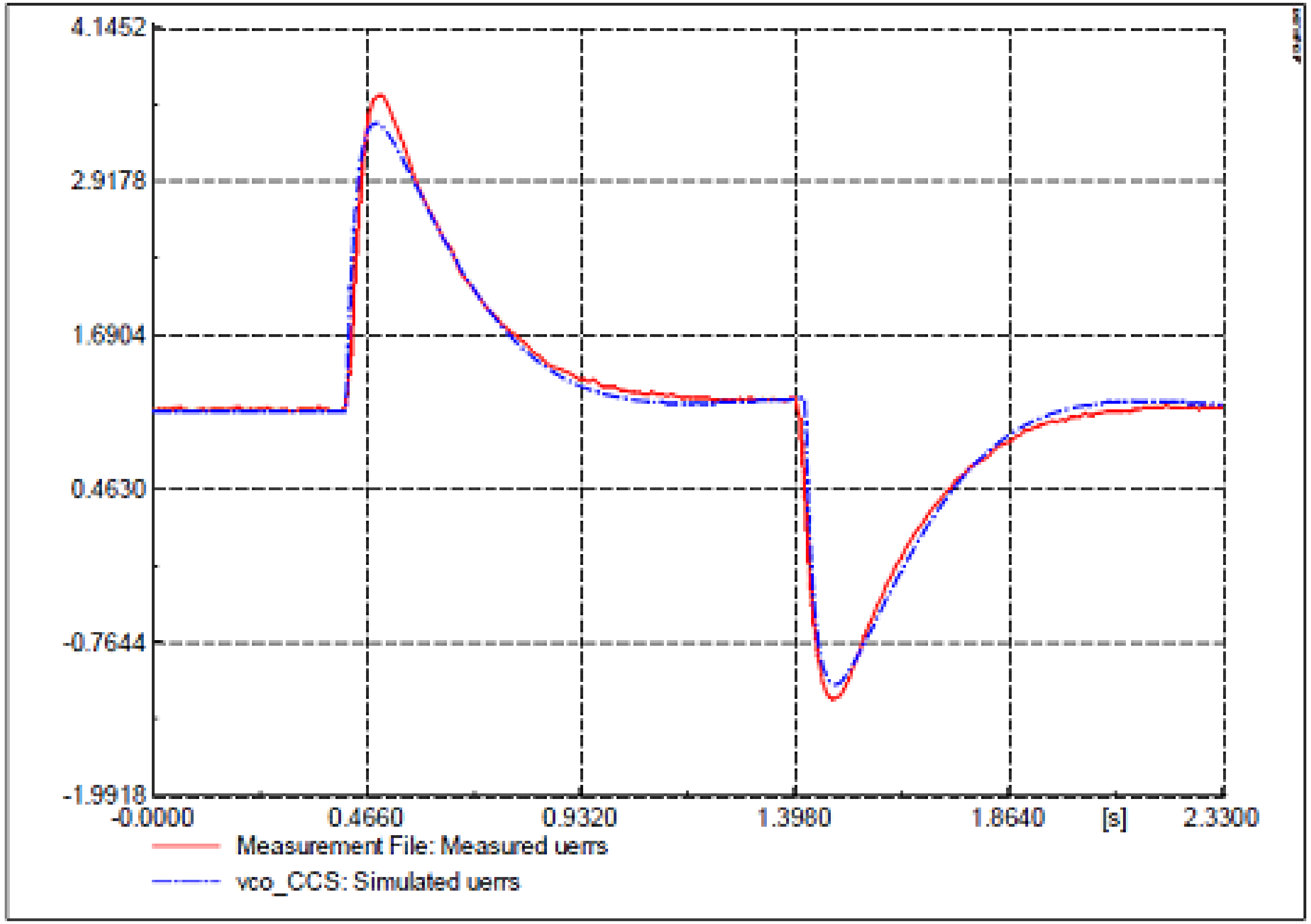
AVR

Parameter estimation

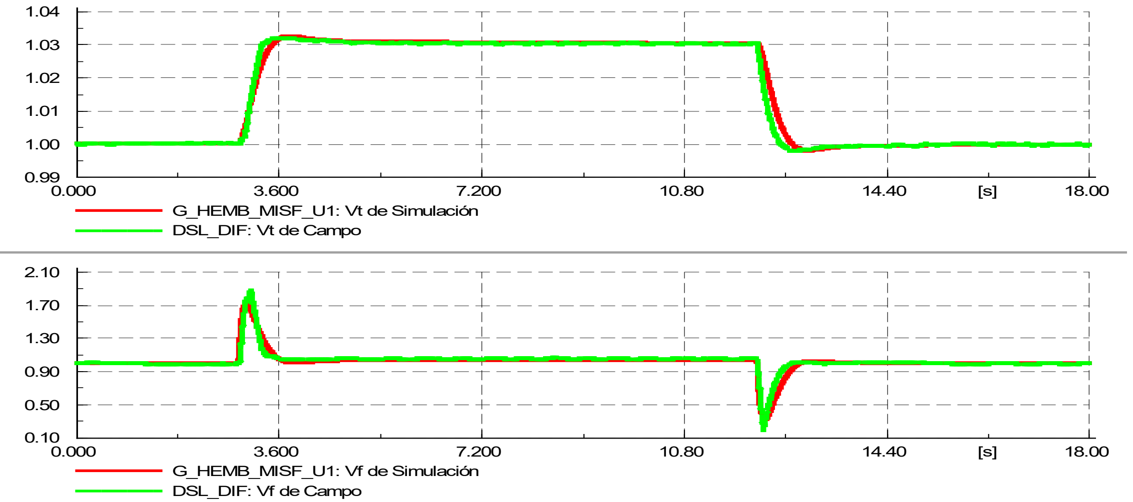


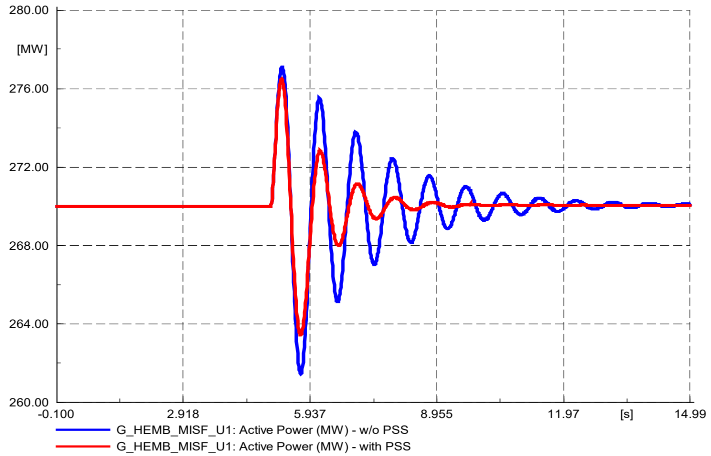
Parameter estimation

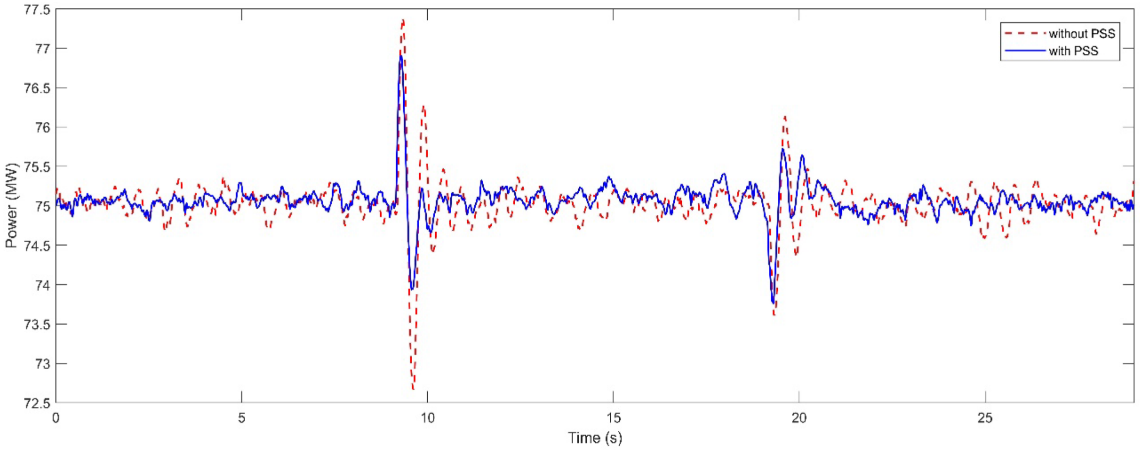


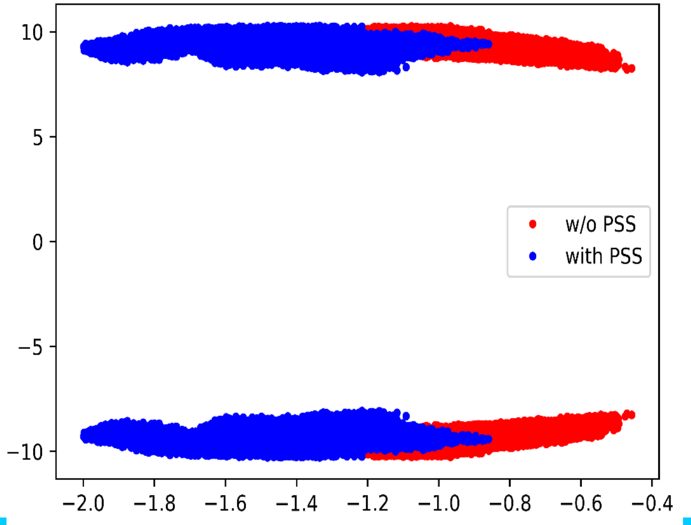


Ensuring the success of stability studies and other dynamic analysis









Real-time applications convert stability indicators into operator action

ANGLE

Phase-angle difference

VOLTAGE

Transmission-corridor margin

OSCILLATIONS

Mode frequency and damping

EARLY WARNING

Recognize stress
select control action
protect system integrity

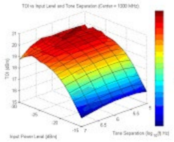
DIGITAL-TWIN TRAINING

PowerFactory static model → **OpenModelica FMUs + ePHASORsim** → **Virtual PMUs → WAProtector HMI**

Operators rehearse realistic dynamic scenarios using the same monitoring interface used in the control room.

SNI Digital Twin

DSA



MATLAB SIMULINK

ePHASORsim
Real-Time Transient Stability Solver

HYPERSIM

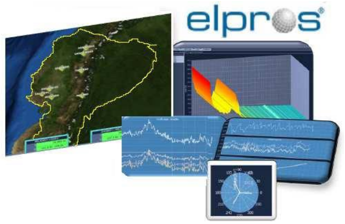
- WAMS' APPLICATIONS
- - Angular Difference
- - Oscillatory Stability
- - Voltage Stability of Transmission
- Corridors
- - Frequency Monitoring

Real-Time Digital Simulator

Virtual PMU

C37.118

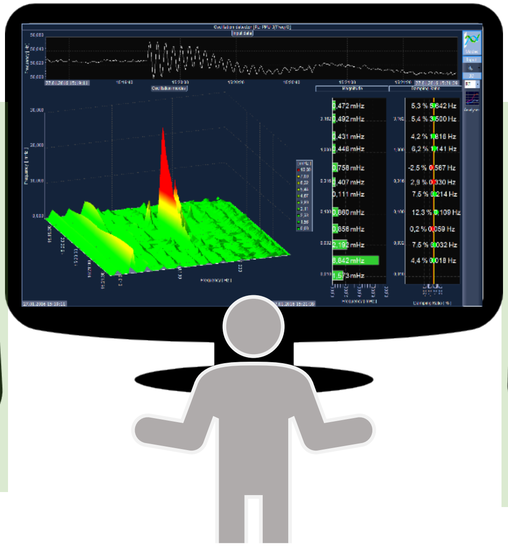
elpros



Wide Area Monitoring System

- Dynamic Simulation (Operation Commands)

- Load Flow Simulation



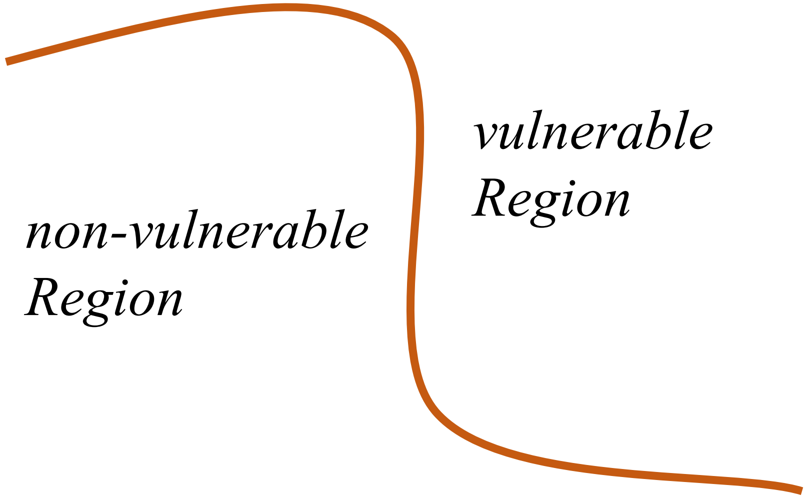
- Study Cases

- Generation and Demand

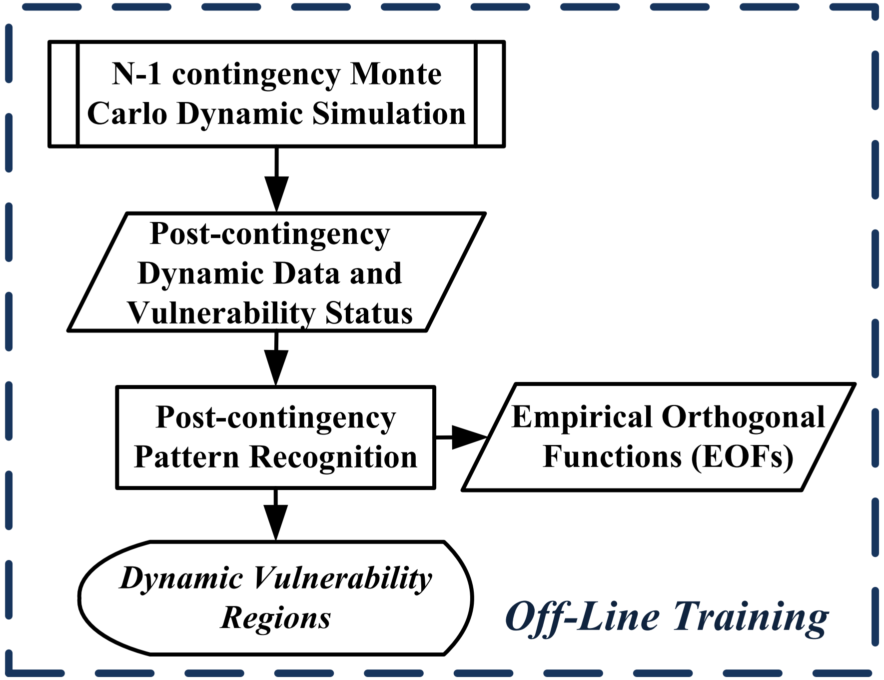
Training Environment

Machine learning improves early warning of SNI

Post-contingency Dynamic Vulnerability Region (DVR) ⇒ DVA ⇒ "Determine if the post-contingency dynamic state is within a "vulnerable" or "non-vulnerable" region



DVR Recognition

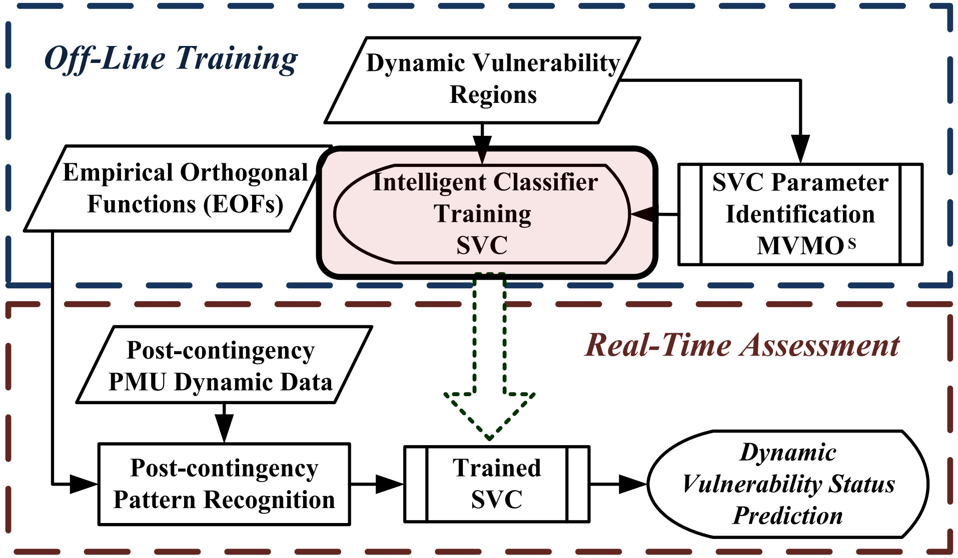


$$\mathbf{f}_k = \lambda_1^{1/2} u_{k1} \mathbf{v}_1 + \lambda_2^{1/2} u_{k2} \mathbf{v}_2 + \ldots + \lambda_p^{1/2} u_{kp} \mathbf{v}_p$$

$$EV_i = \frac{\lambda_i}{\sum_{i=1}^{p} \lambda_i} \times 100$$

Machine learning improves early warning of SNI

Real-Time Status Prediction



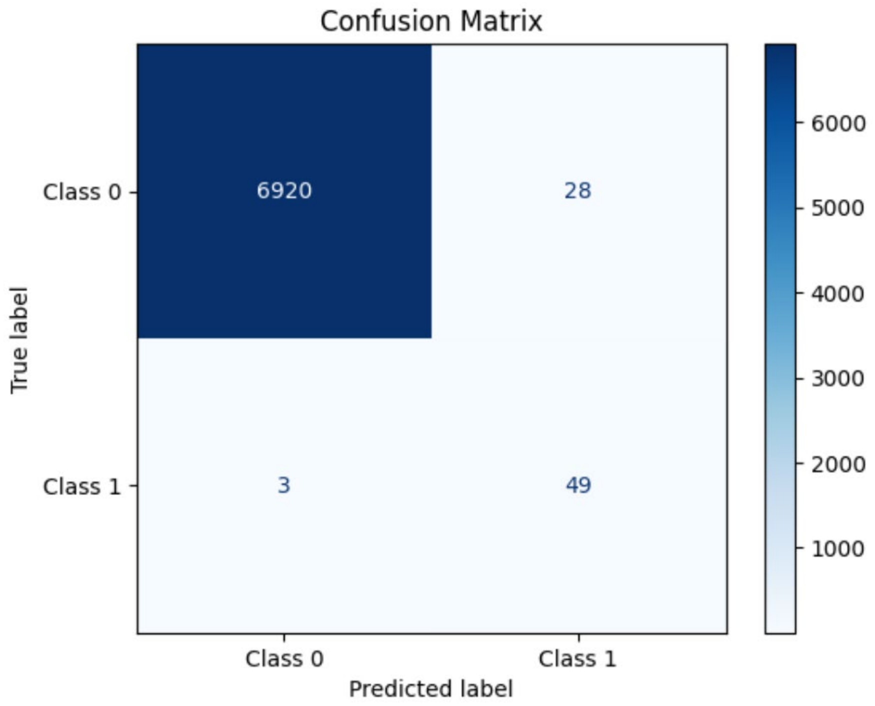
$$\min_{\mathbf{w},b,\xi} \quad \frac{1}{2}\mathbf{w}^{T}\mathbf{w} + C\sum_{i=1}^{l}\xi_i$$

$$\text{subject to} \quad y_i\left(\mathbf{w}^{T}\phi(\mathbf{x}_i)+b\right) \geq 1-\xi_i, \quad \xi_i \geq 0$$

$$K(\mathbf{x}_i,\mathbf{x}_j) \equiv \phi(\mathbf{x}_i)^{T}\phi(\mathbf{x}_j)$$

$$K(\mathbf{x}_i,\mathbf{x}_j) = e^{-\gamma\left\|\mathbf{x}_i-\mathbf{x}_j\right\|^{2}}, \gamma > 0$$

52 of the 7000 Monte Carlo scenarios were transient unstable related to CCS



classification recall coefficient can be calculated of 0.996 for class 0 (stable) and 0.9423 for class 1 (unstable)

Streaming analytics with deep learning adds seconds-ahead prediction to the WAMS learning cycle

PMU streams

Synchrophasor records

→

Cassandra

Time-series storage

→

Python + RNN

Modal prediction

→

Operator's decision

Predictive stability alert

Predictive assessment

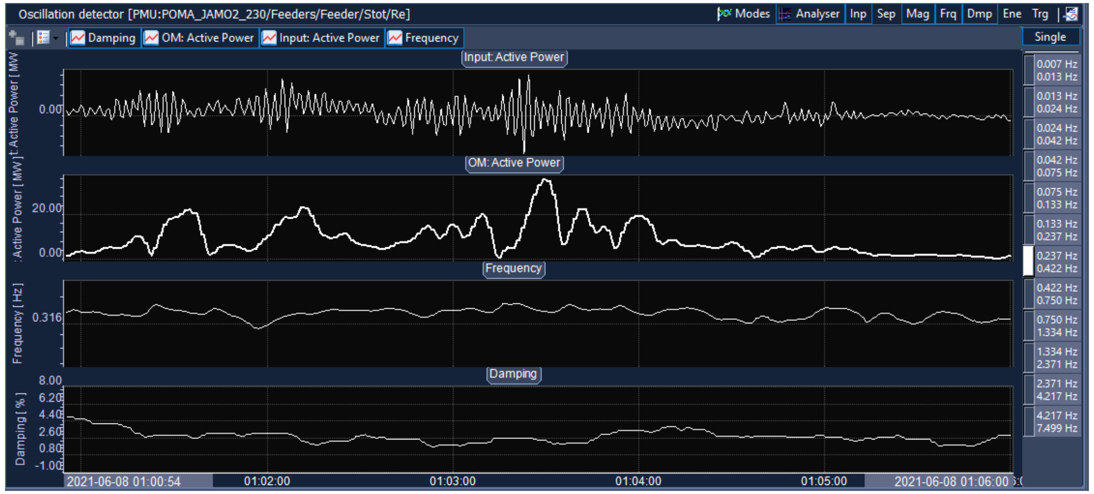
Short-term forecasts of modal behavior help operators anticipate deteriorating damping before limits are crossed.

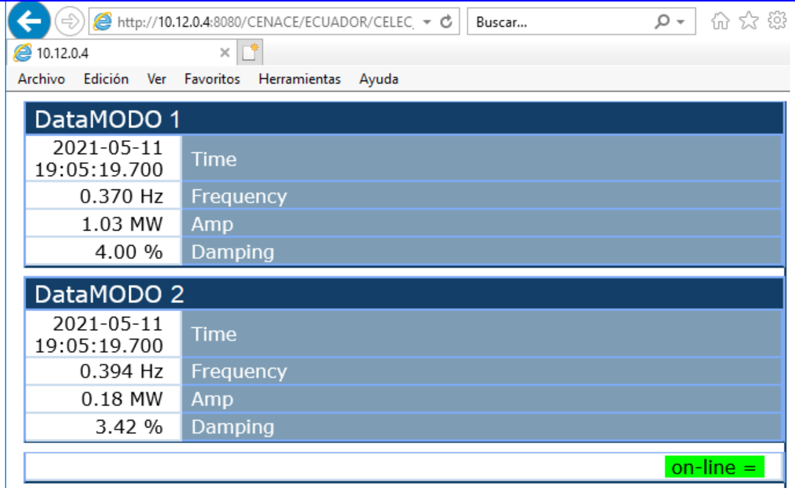
Post-operative learning

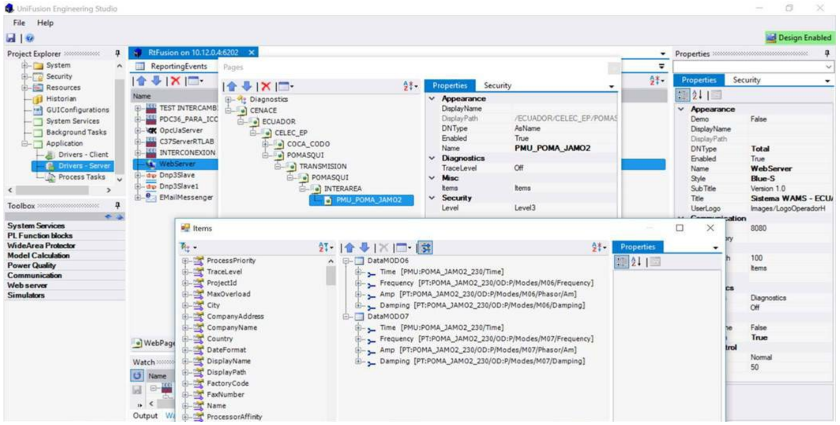
Fault analysis, daily/weekly/monthly statistics and mode-pattern characterization feed the next planning cycle.

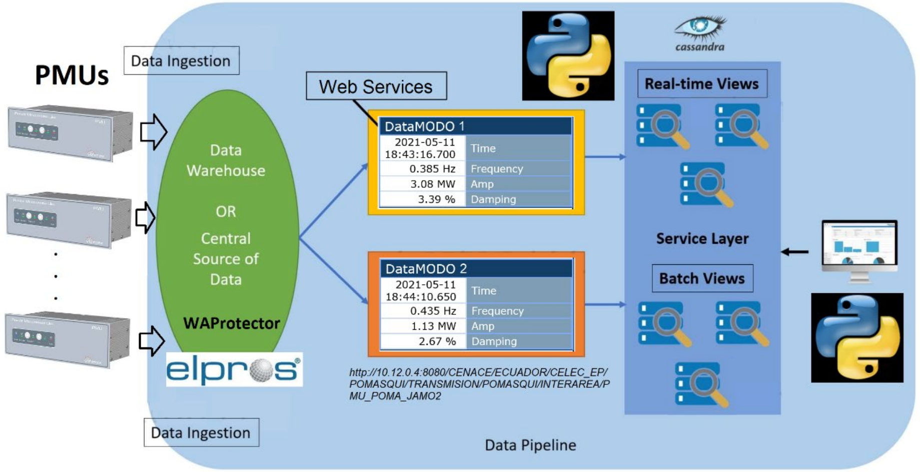
Data → prediction → action → recorded outcome → improved thresholds and models

Early Warning – Oscillatory Stability: Deep Learning for Time Series Prediction - LSTM

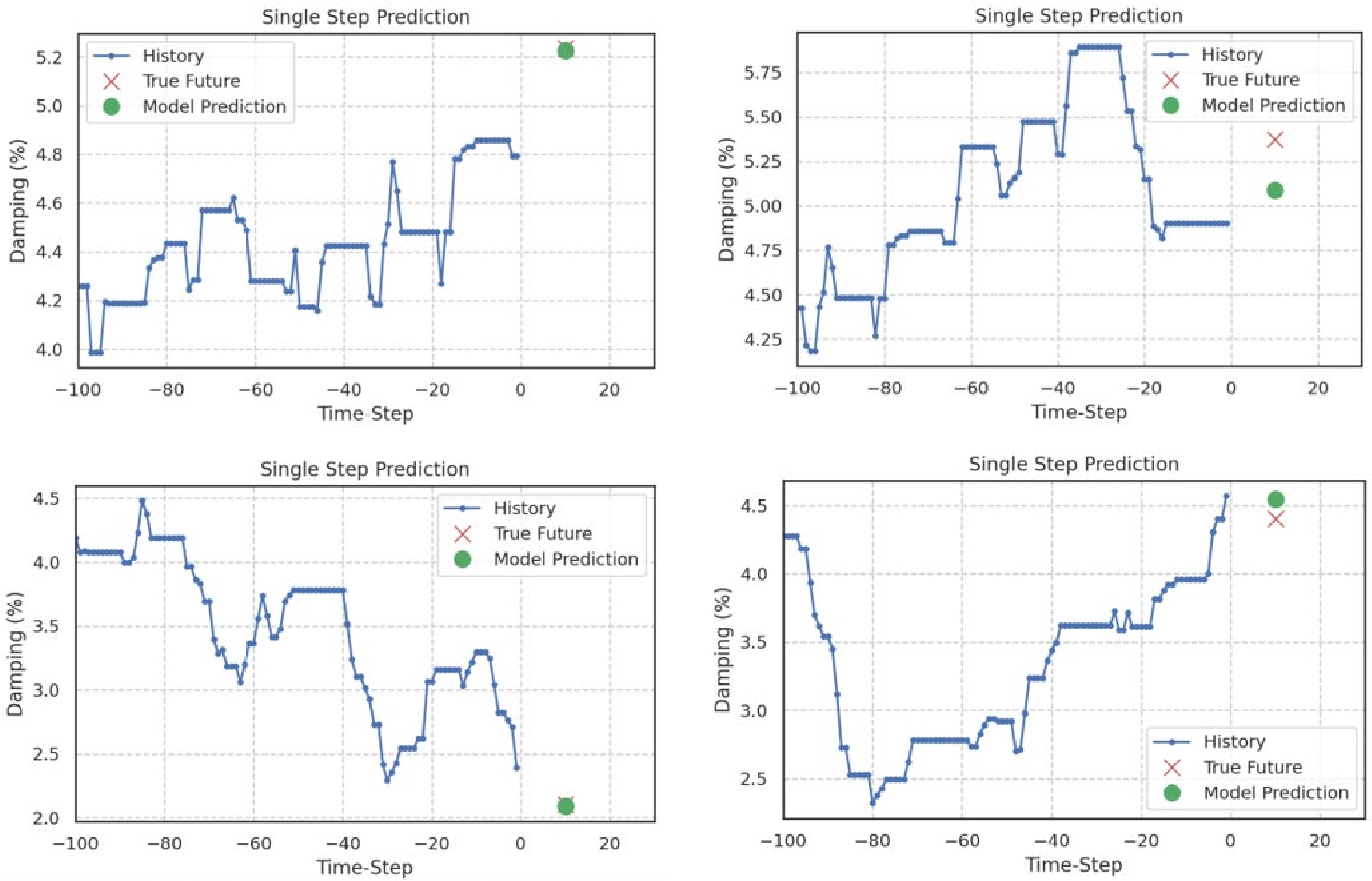








Early Warning – Oscillatory Stability: Deep Learning for Time Series Prediction - LSTM



python™

Conclusions: Operational impact and lessons learned

Dynamic observability enables secure operation
PMUs reveal stability phenomena that conventional monitoring cannot capture.

Measurements must lead improvement of power system operations
WAMS supports model validation, controller tuning, early warning and operating-limit definition.

Validated models allows simulation to deliver a real operational value → Controllers' tunning
Based on validated models, PSS retuning improved damping and increased secure Ecuador–Colombia export capability by 150 MW.

GRID CODE

Digital twins enable a realistic dynamic security assessment
Real-time simulation and virtual PMUs connect engineering studies with operator training, field challenges and operational decision-making.

What is next? → From monitoring to prediction
The future operating paradigm is a continuous loop: **measure → validate → predict → act → learn**.

Jaime C. Cepeda
Escuela Politécnica Nacional,
Ecuador
jaime.cepeda@epn.edu.ec

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