GLOBAL PST CONSORTIUM

Learning from System Events

XM Forum 2026

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Photo by Werner Slocum, NREL 69180

Blackouts are becoming multi-factor events

Several layers can interact:

- Infrastructure
- Protection
- Control systems
- Generation behavior
- Network topology
- Operator decisions
- Market/dispatch conditions
- Communications
- Weather

Why look at blackouts again?

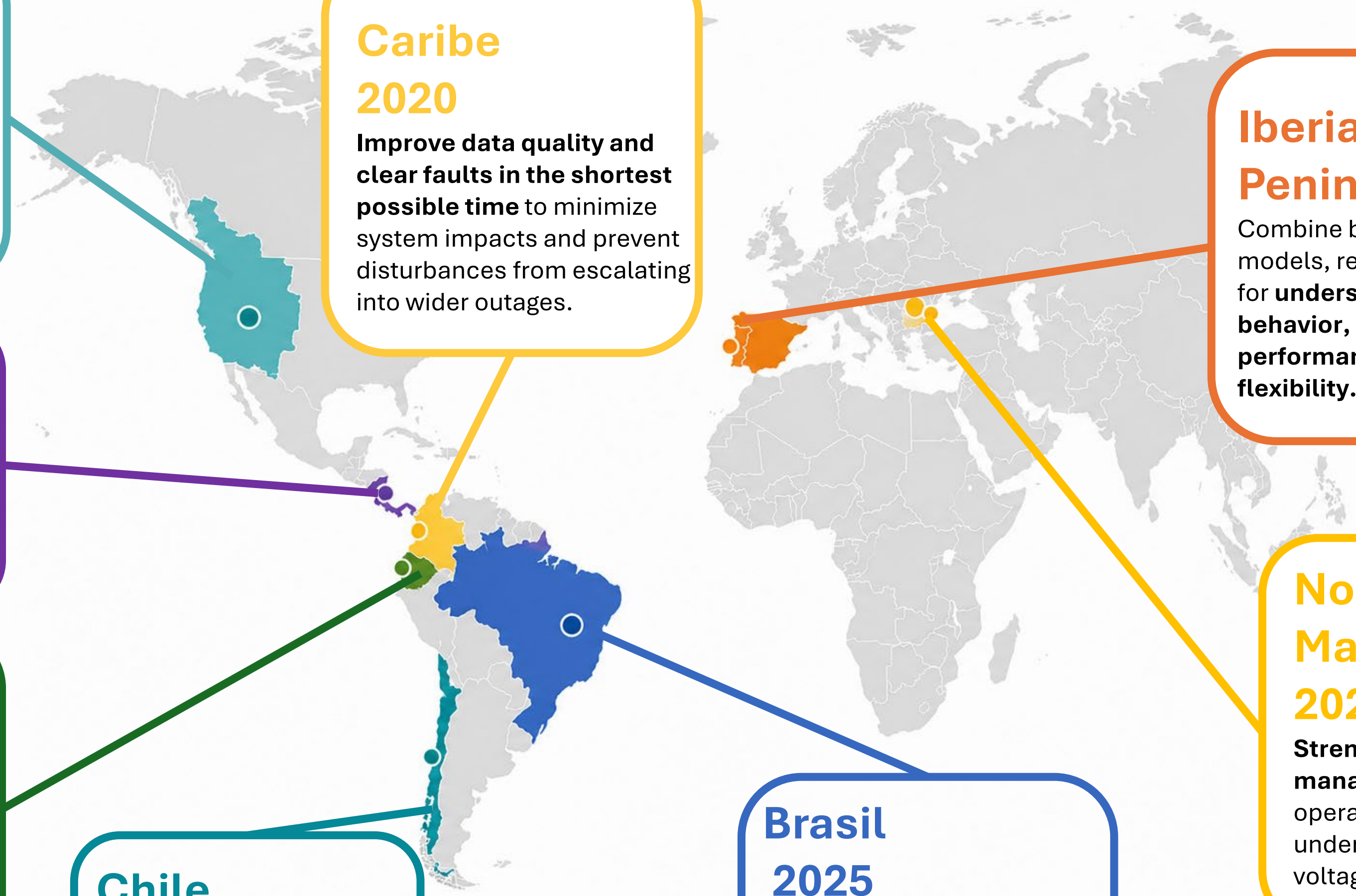
- Power systems are changing faster than operational practices
- Increasing IBR penetration
- Lower synchronous generation in some operating conditions
- More complex protection and control interactions
- Extreme weather and infrastructure risks
- Greater dependence on digital systems
- Increasing consequences of loss of supply

What has changed?

Lessons Learned from Power System Events Around the World

Recent events show that the challenge is no longer only "N-1 security."

System operators must manage fast dynamics, low system strength, voltage stability issues, oscillations, limited observability, extreme weather, protection/control interactions, and restoration as an integrated problem.



WECC 2024

Four events in 2024 were related to IBRs. Most of the events were tied to poor coordination between relay settings. Need for better coordination and grid code enhancement.

Colombia Caribe 2020

Improve data quality and clear faults in the shortest possible time to minimize system impacts and prevent disturbances from escalating into wider outages.

Iberian Peninsula 2025

Combine better dynamic models, real-time assessment for **understanding dynamic behavior, voltage/frequency performance, and system flexibility.**

Panamá 2025

Strengthen resilience and system preparedness, under contingency.

Ecuador 2024

Improve planning and infrastructure investment to ensure sufficient flexibility and system security.

Chile 2025

Strengthen system-wide protection and coordination

Brasil 2025

Improve system models to better represent the evolving power system and support accurate dynamic security assessment, planning, and operation

North Macedonia 2025

Strengthen voltage management and operational coordination under low-load and high-voltage conditions.

Lessons Learned from Power System Events Around the World

- Planning cannot cover 100% of the risk or anticipate every possible scenario.
- Recent blackout events show that a combination of factors can push the system beyond its expected operating conditions and ultimately lead to a blackout.
- Several challenges must be managed in real time.
- **Equipping system operators with better data, models, situational awareness, and decision-support tools is therefore critical to identify emerging risks earlier, respond faster, and reduce the likelihood and impact of major disturbances.**

Dimension	Brazil	Ecuador	Colombia	WECC	Chile	Iberia	North Macedonia	Panama
Transmission vulnerability	●	●	●	–	●	●	●	●
Protection/ control	●	–	●	●	●●	●	●	●●
IBR behavior	●	–	–	●●	●	●●	–	–
Voltage stability	●	●	●	●	●	●●	●●	●
Frequency stability	●	●	–	●	●	●	●	●
Situational awareness	●	●	●	●	●	●●	●	●
Extreme conditions	–	●●	–	–	–	–	–	–

Brazilian Interconnected Power System and August 15th 2023 Event

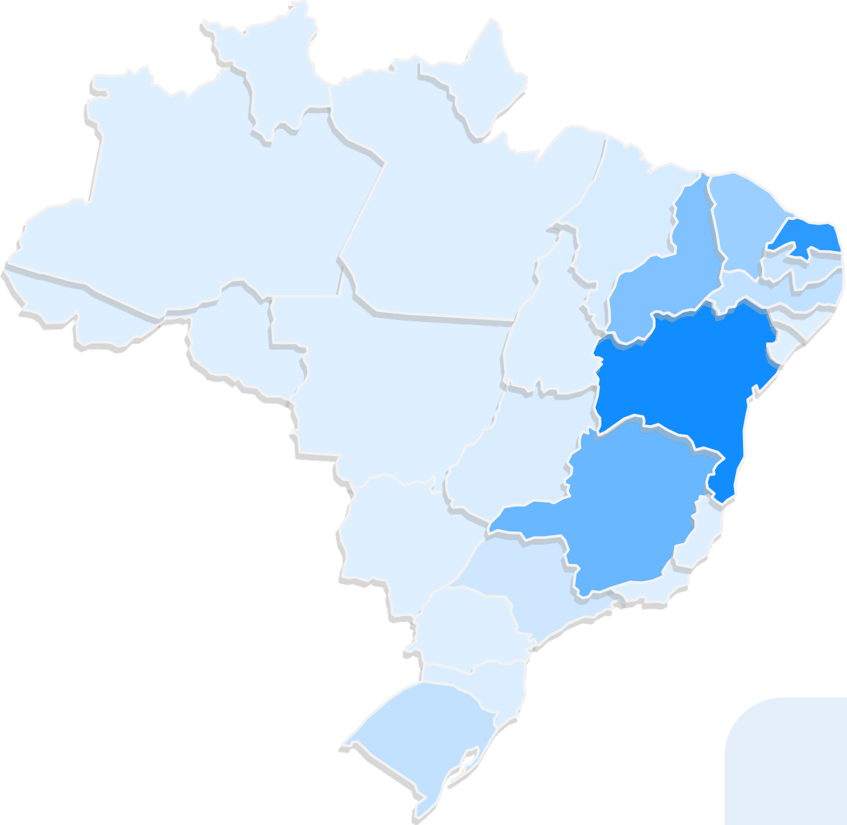
Operador Nacional do Sistema Elétrico – ONS

Júlio César Cândido Vieira
(julio.vieira@ons.org.br)

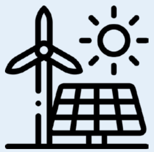
August 19, 2026

Distribution of Renewable Generation (Wind and Solar)

Installed Capacity (GW)



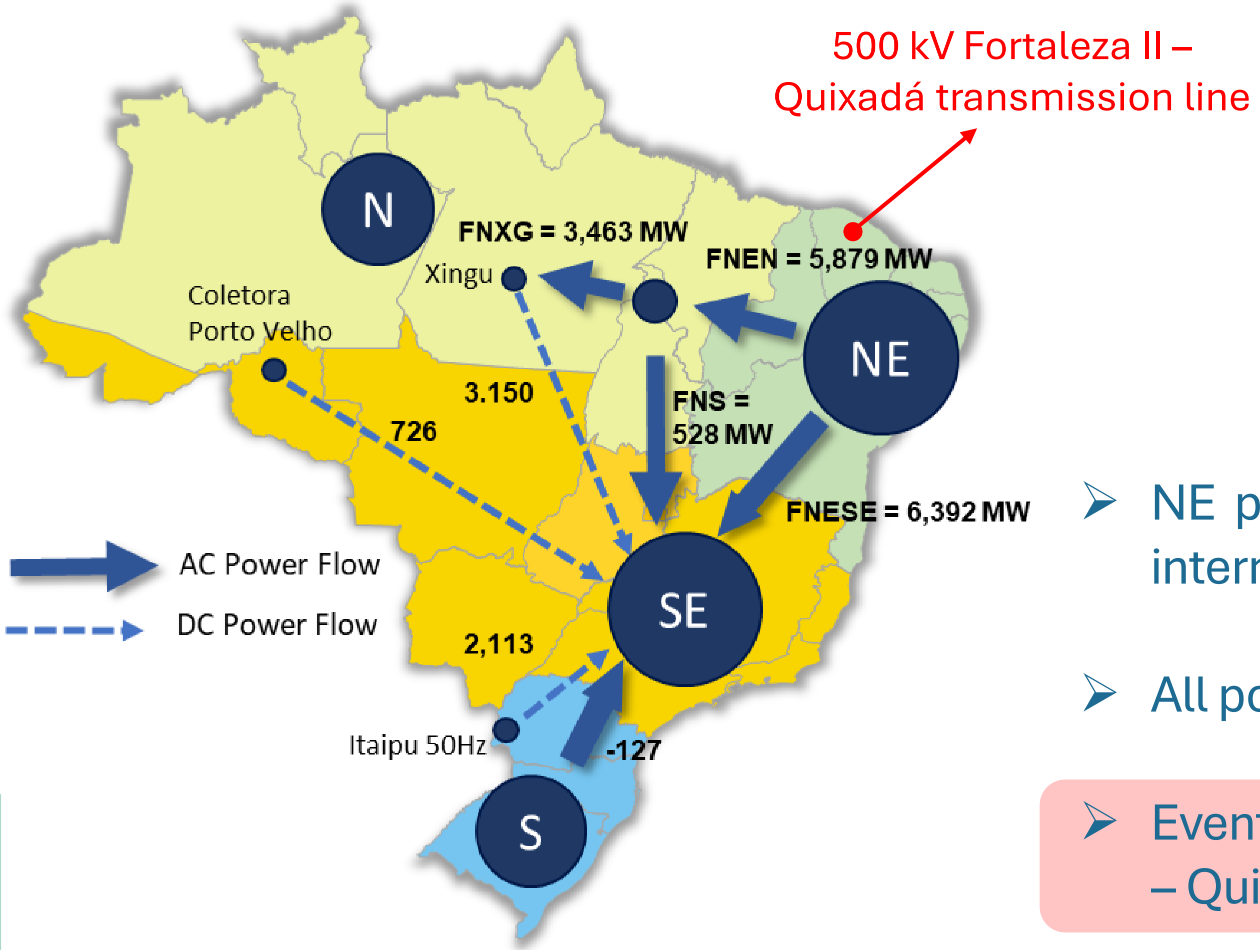
- **High concentration of Inverter-Based-Resources (IBRs) in Northeast** (NE) of Brazil;
- On the other hand, **there is a scarcity of synchronous sources** → Low short circuit ratio (SCR) and inertia;
- There is a **high variability of power flow** between the NE and the rest of Brazilian Interconnected Power System (BIPS);
- **Voltage control of this area is heavily dependent on the reactive power response of IBR.**



Brazil | Northeast
54.9 GW | 42.8 GW (≈ 78%)

Updated on 07.31.2026

Pre-event Power System Condition

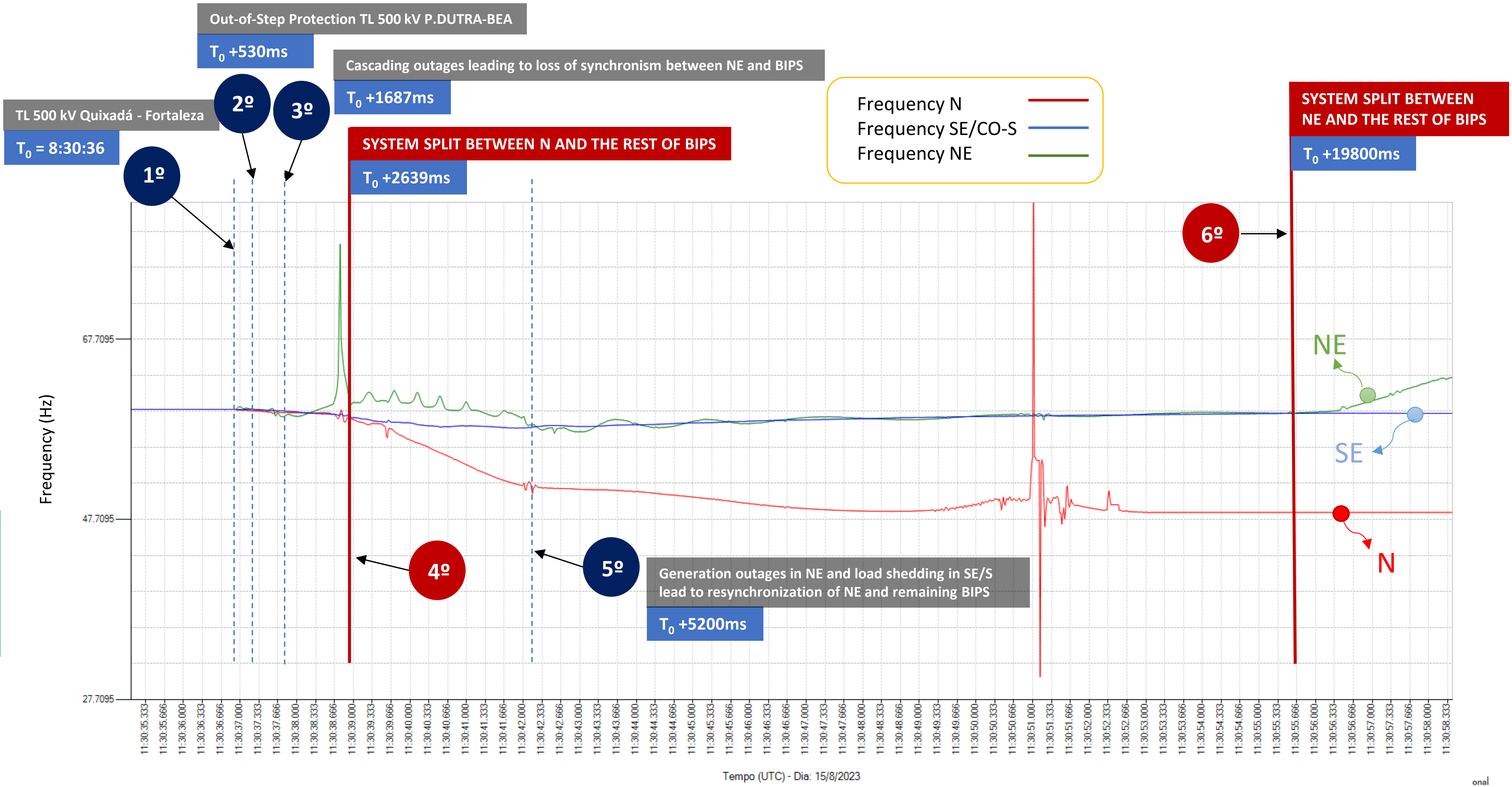


Northeast (NE)	
Synchronous Generation	2,926 MW
Wind Generation	16,317 MW
Solar Generation	3,211 MW
Total Generation	**22,454 MW**
Total Load	**10,151 MW**

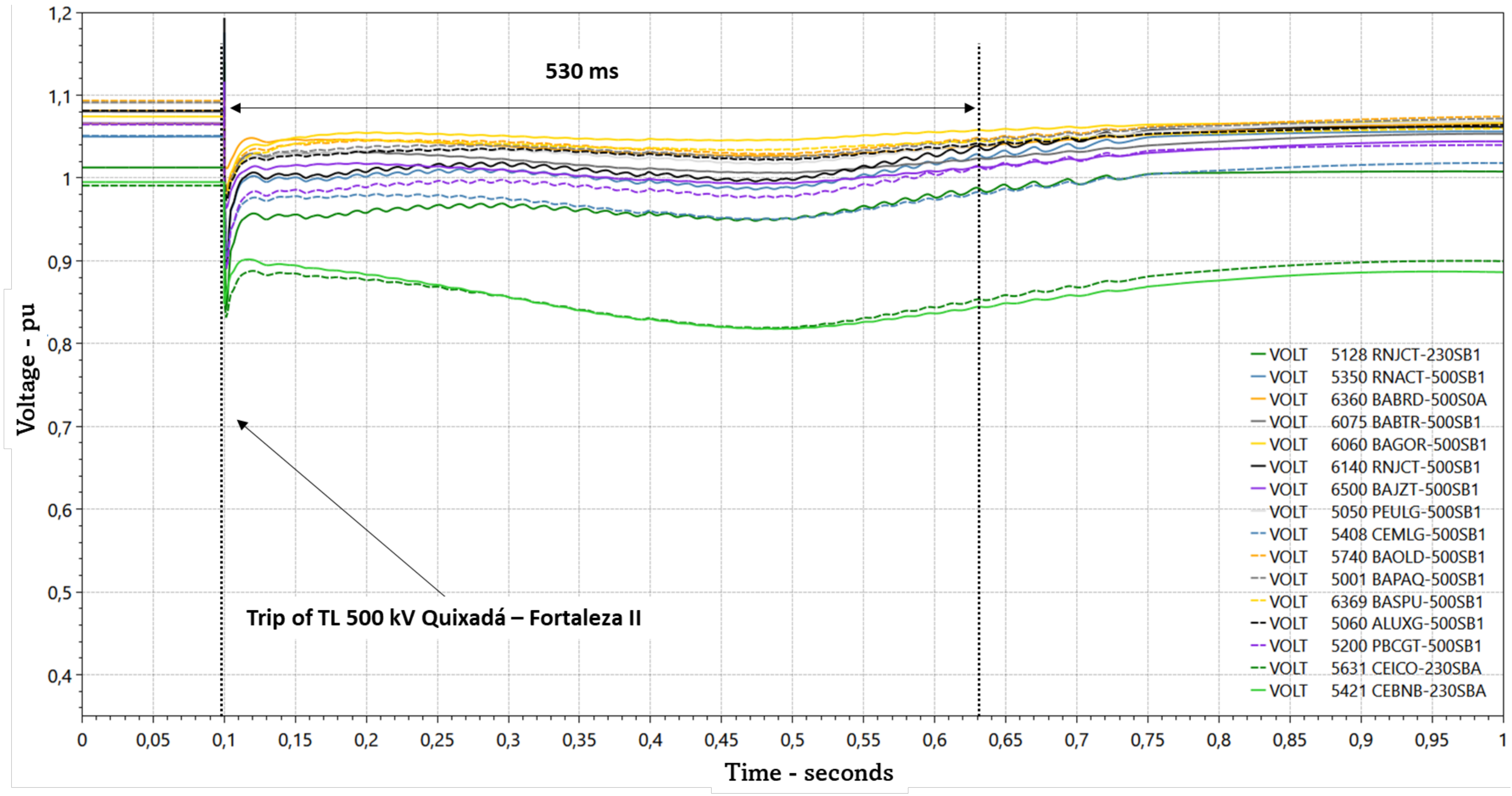
- NE power exporting around 12 GW with 90% IBR internal generation;
- All power flows within stability limits;
- Event started with the outage of 500 kV Fortaleza II – Quixadá transmission line.

The system is planned to endure any single outage.
So why did this outage result in a partial blackout?

Event Summary Timeline

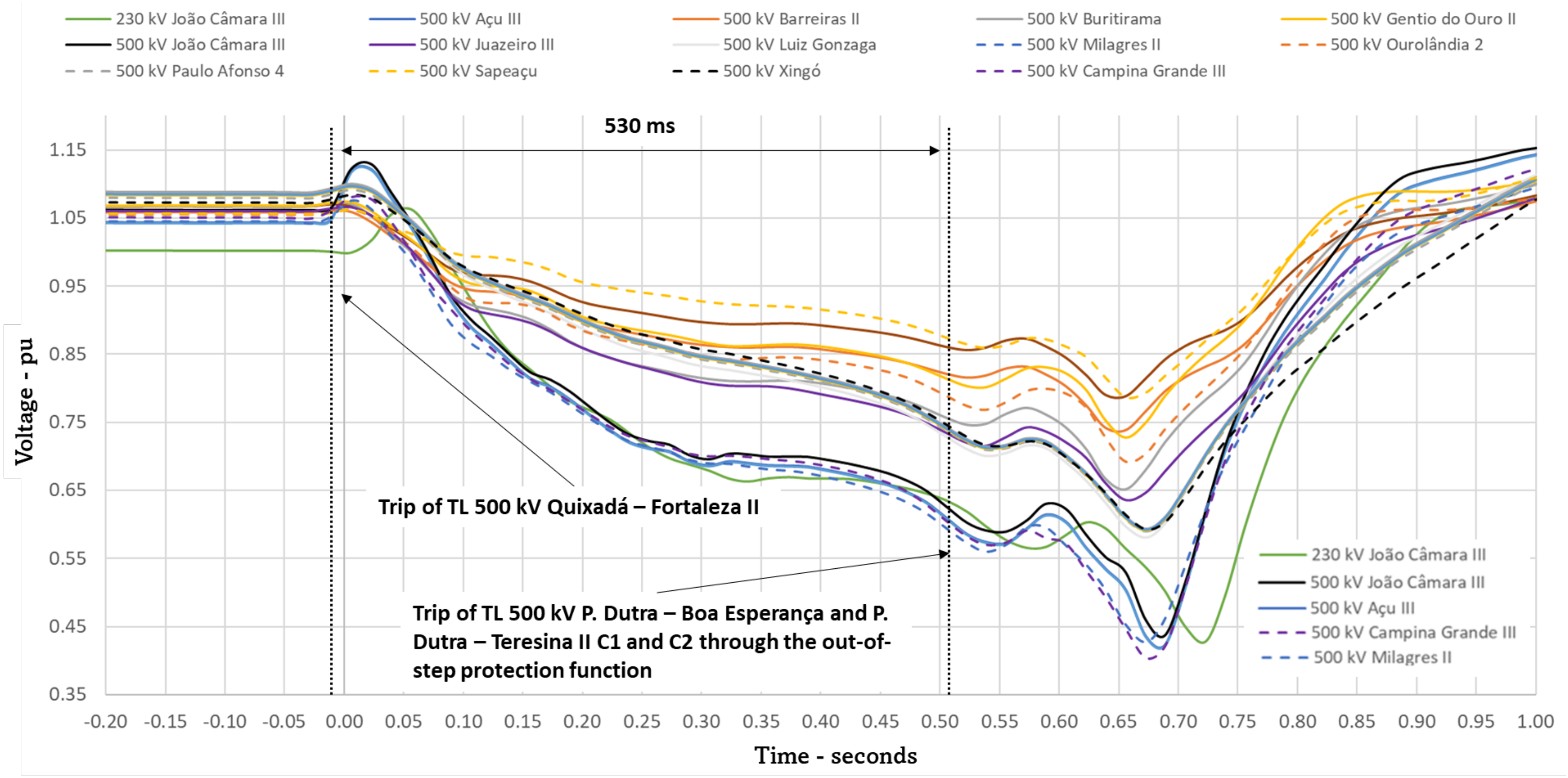


Expected System Response – Transient Stability Simulation



ONS Operador Nacional do Sistema Elétrico

Observed System Response – PMU Measurements



Voltage Collapse

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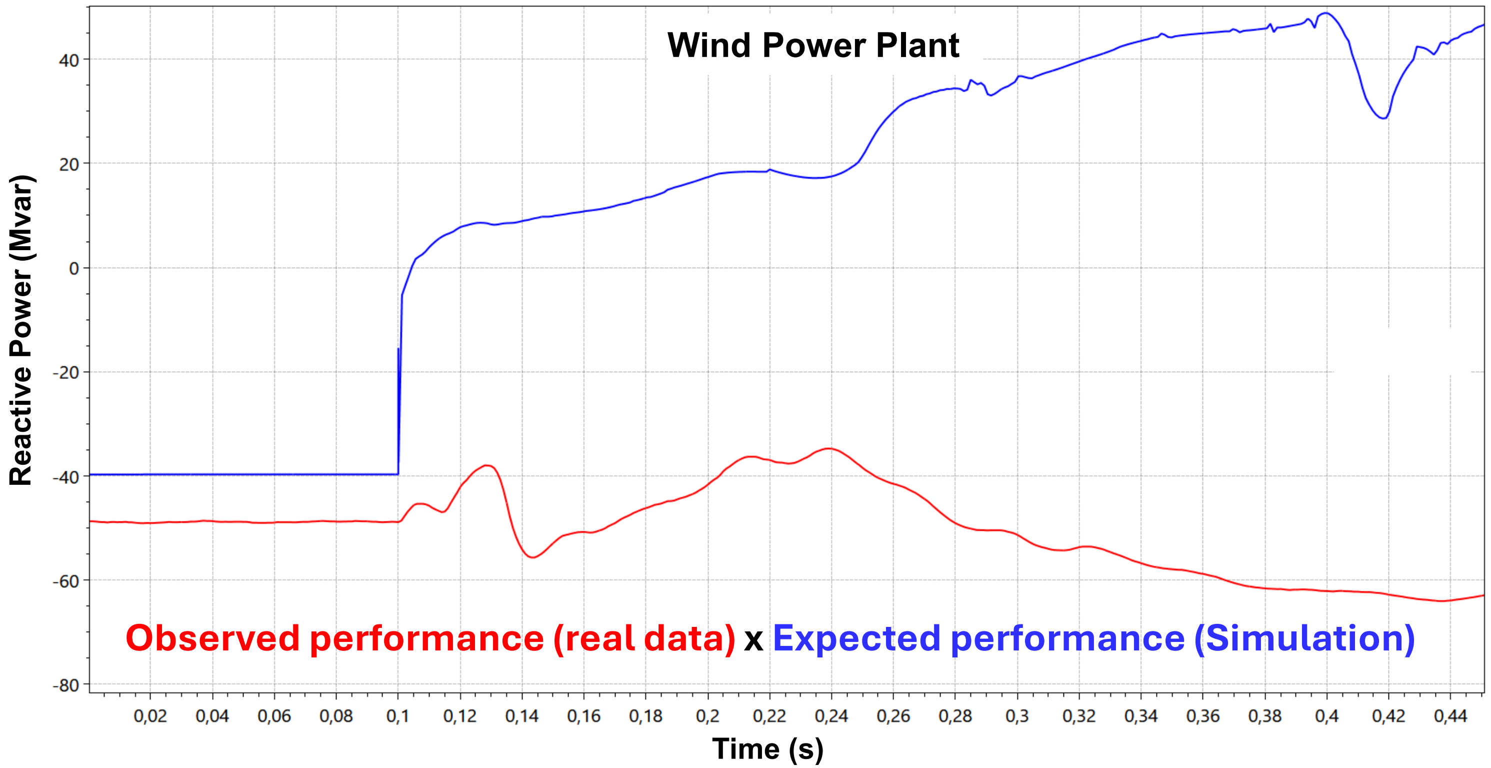
What explains the difference between the responses?

Simulations *x* Observed performance

- By analyzing the system disturbance files provided by the asset owners at the time of the event, the main **difference between the simulation and the observed response arises from discrepancies in the IBR response**.

- More specifically, the main differences involved the performance of the **PPC voltage control and the reactive current injection during faults control**.



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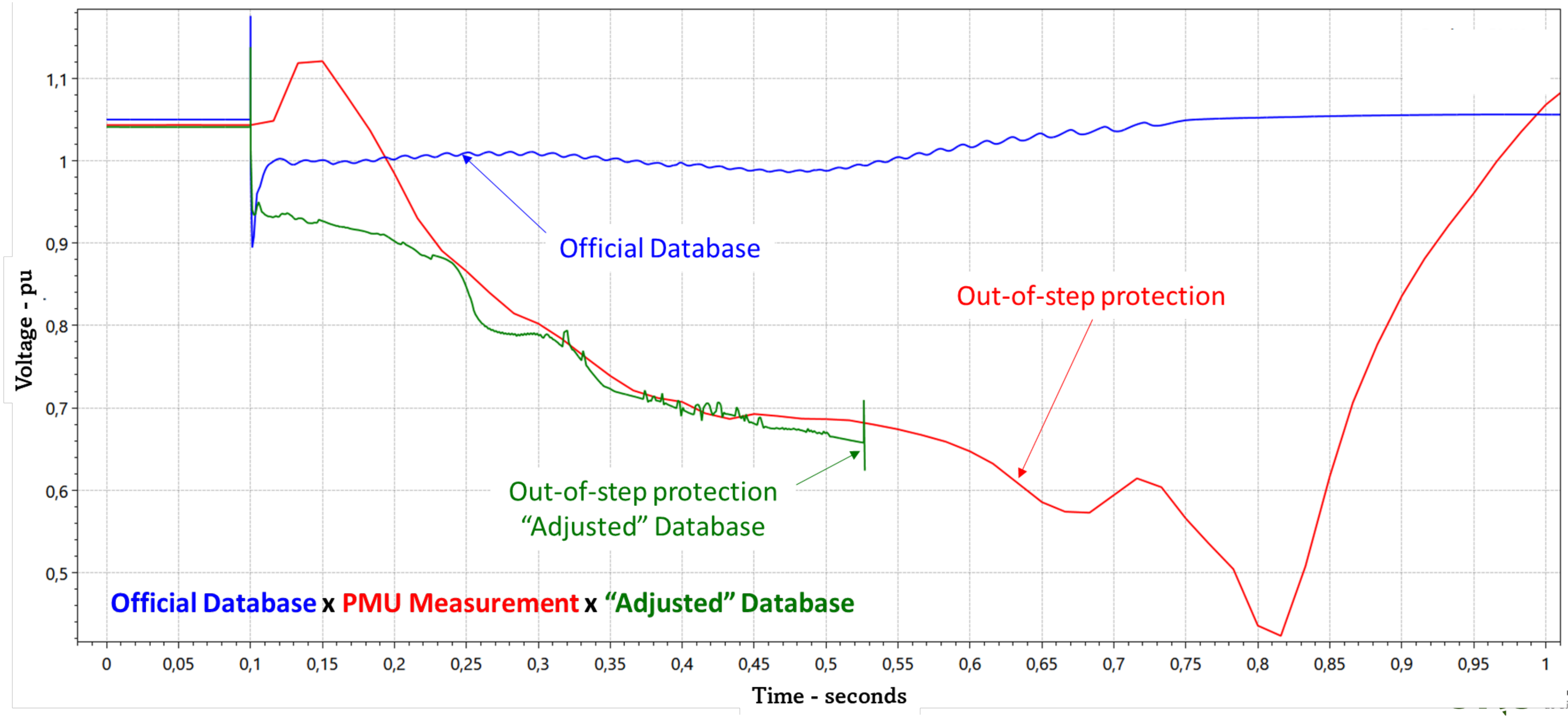
Transient Stability Database Simulations

Modifications in "Adjusted" Database

- Faster PPC voltage control and reactive current injection during faults in the RMS models than in the actual field response. Therefore, **the PPC voltage control and the fault current injection logic were disabled in the models**.



Key Findings

- The voltage collapse observed after the 500 kV Quixadá - Fortaleza II line trip **could not be replicated in simulations using the official transient stability database**.

- The Digital Fault Recorders (DFR) files received indicated that the **IBRs near the area of interest did not perform as expected regarding reactive power response**.

- ONS successfully replicated the disturbance by **modifying the transient stability database**, adjusting the main differences between the behavior of in field deployed equipment controls and the performance of simulation models provided to ONS by the asset owners.

- **ONS is taking extensive actions to ensure that the simulation models' response is consistent with the real equipment performance**, to prevent such an event from happening again in the future.

Post-Disturbance Actions

1. **Information Requested**
    - Data and validated models of wind and solar plants, including detailed information on the equipment.
    - Detailed three-phase EMT model (PSCAD), developed from the source code of the real equipment, and validation of transient stability model against field test results or PSCAD model.
2. **Improved Observability**
    - PMU installation on every wind/solar power plant.
3. **Changes in the IBR integration process**
    - PSCAD model and PSCAD x Field (type test) validation of the equipment as a necessary input for pre-operational studies. The transient stability model provided at this stage needs to be validated against the PSCAD model, with typical parametrization.
    - Validation report of the transient stability model against field tests of the real plant with final parametrization as a requirement for commercial operation.

ONS Operador Nacional do Sistema Elétrico

20 años
Hechos por Colombia

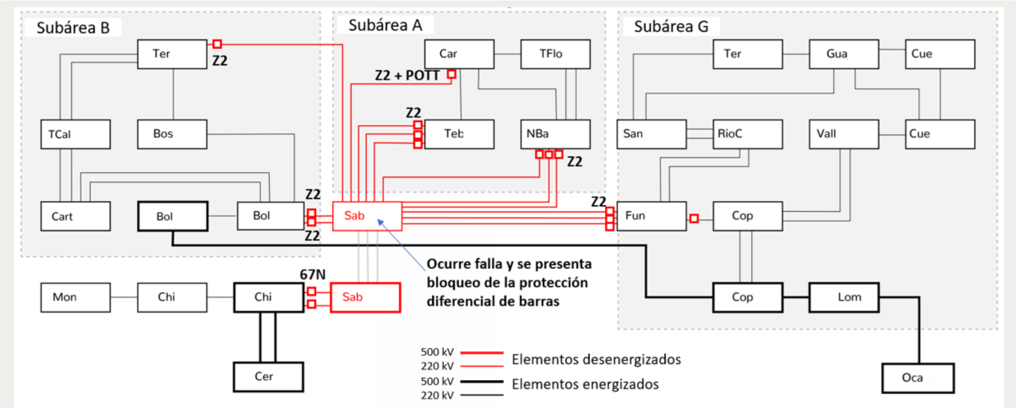
Acciones Tomadas derivadas de Apagones y Riesgos Emergentes

Juan Fernando Piñeros

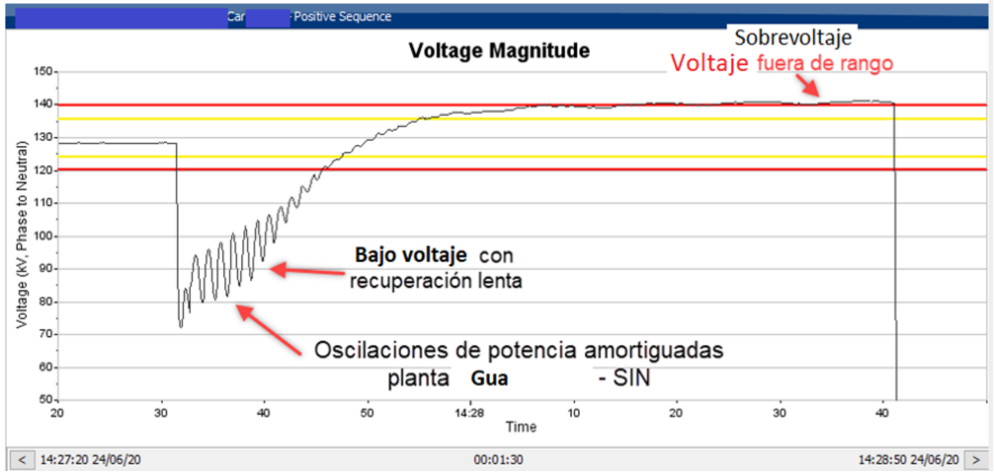
Evento Caribe 2020

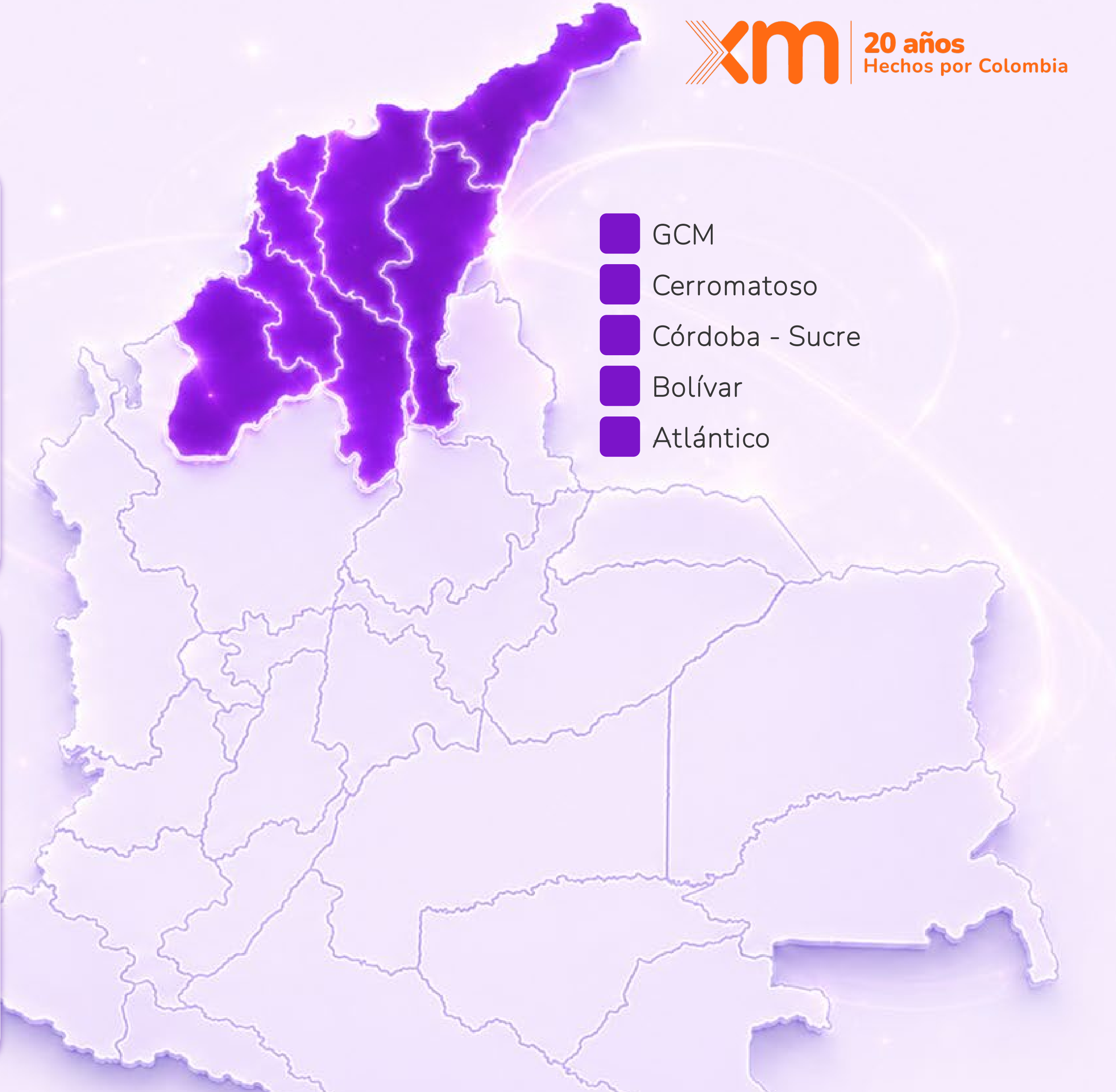
20 años
Hechos por Colombia

24 junio - 1900MW, 21% demanda del SIN



Recuperación Lenta Inducida de Tensión (FIDVR)





20 años
Hechos por Colombia

Evento Caribe 2020

Acciones:

- Optimización de la Coordinación de Protecciones de Respaldo.
- Gestión sobre la necesidad de REDUNDANCIA en protecciones diferenciales de barras.
- Revisión y cambio de criterios ajustes de Sobretensiones.
- Nuevo Acuerdo CNO 2139 de 2026 de pruebas arranque autónomo.
- Restablecimiento ágil: actualización y socialización de guías, revisión puntos sincronismo. Simulacro Seguridad operacional (FF-HH).

El mayor riesgo,

patrón común que conduce al apagón total.

Desconexión anticipada de plantas durante eventos.

20 años
Hechos por Colombia

¿Qué desconecta los generadores de forma anticipada ?

Sobre / baja tensión

Se debe dar margen al sistema para que actúen los controles.

Afectó enormemente el apagón en Chile y España-Portugal.

ANSI 59 en un Transformador BT 220kV
1.1 p.u   0 sec
→ 355MW

Sobre / baja Frecuencia

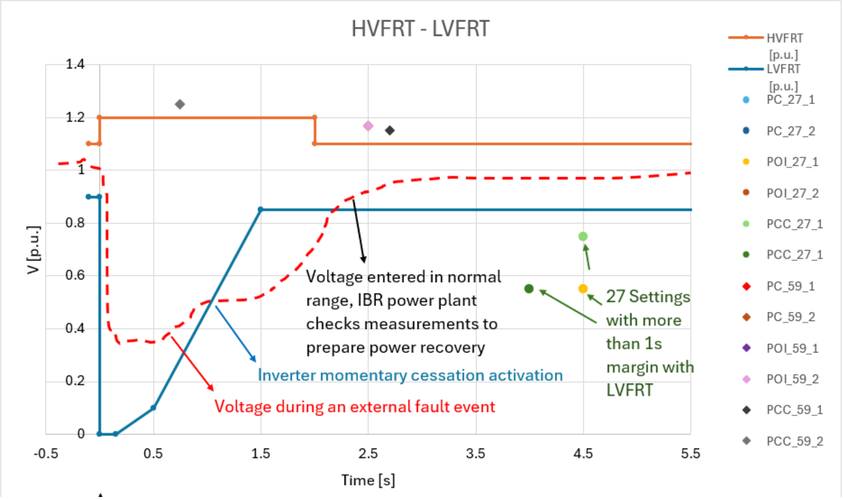
Se debe dar margen al sistema, considerar las operaciones de esquemas de deslastre de carga.

La generación es el soporte incluyendo la generación distribuida.

FRT

En plantas basadas en Inversores hay que maximizar la permanencia y el aporte robusto a la estabilidad, minimizar oscilaciones de potencia.

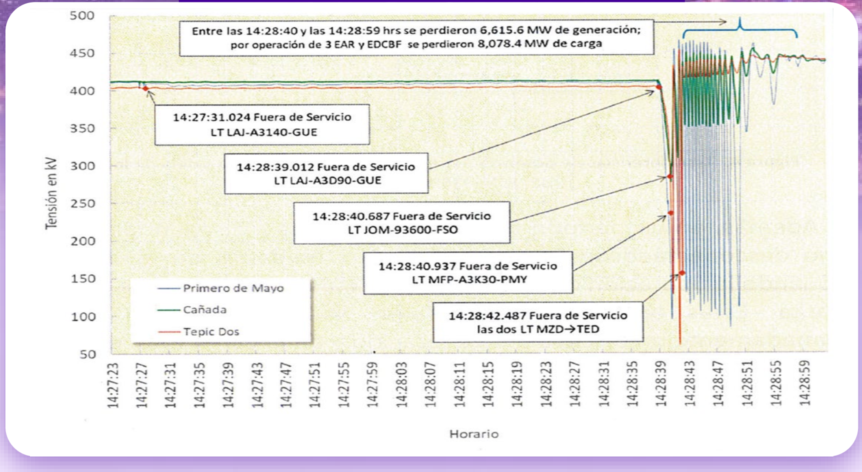
Coordinar con el Sistema



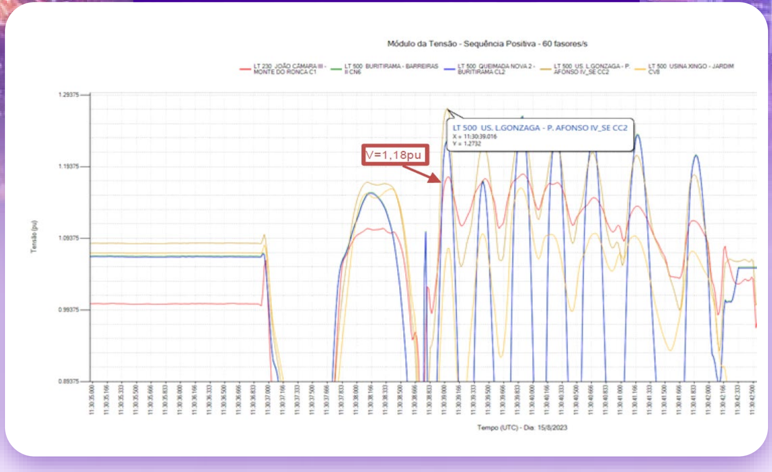
20 años
Hechos por Colombia

¡El voltaje hoy es más sensible!

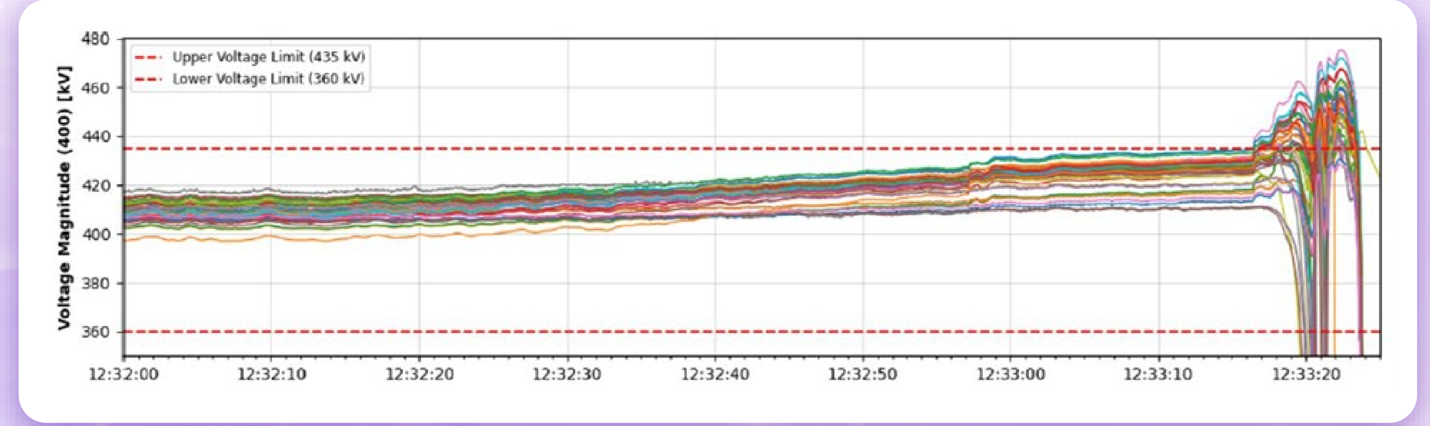
México 2020



Brasil 2023



España 2025



Chile 2025

20 años
Hechos por Colombia

¡Lo mejor: evitar que el voltaje y por ende la potencia se comiencen a mover bruscamente!

Redundancia
+
Redundancia
+
Redundancia

Hay que despejar las fallas y condiciones anormales en el menor tiempo posible.

Learning from System Events

A select overview

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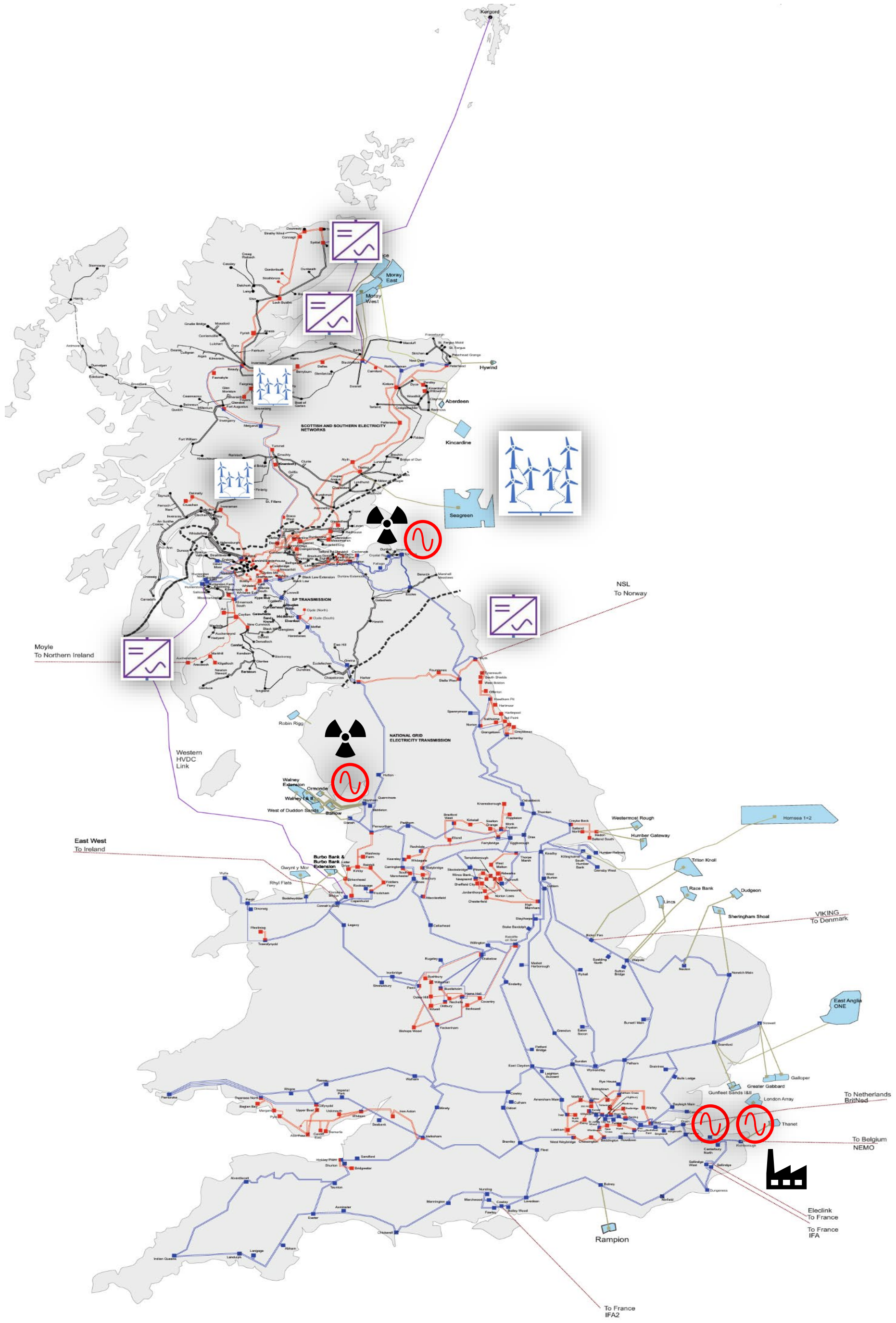
8th XM Forum
August 19th, 2026
Cartagena, Colombia

Oscillations in GB

- August 2021
  - Converter driven instability
  - Very high amplitude oscillations 80 kV pk-pk @400kV level
  - Widespread disconnection of IBR, nuclear reactor close to tripping
- June – July 2023
  - Converter driven instability
  - No electrical/physical fault
  - Nuclear reactor and HVDC link trip, widespread disconnection IBR
- January 2025
  - Converter driven instability
  - No electrical/physical fault
  - Nuclear reactor and CCGT units trip



Oscillations in GB

12-13 Hz SSO event introduced by HVDC interconnector

Weak grid conditions at remote end converter

Oscillations induced through HVDC controls

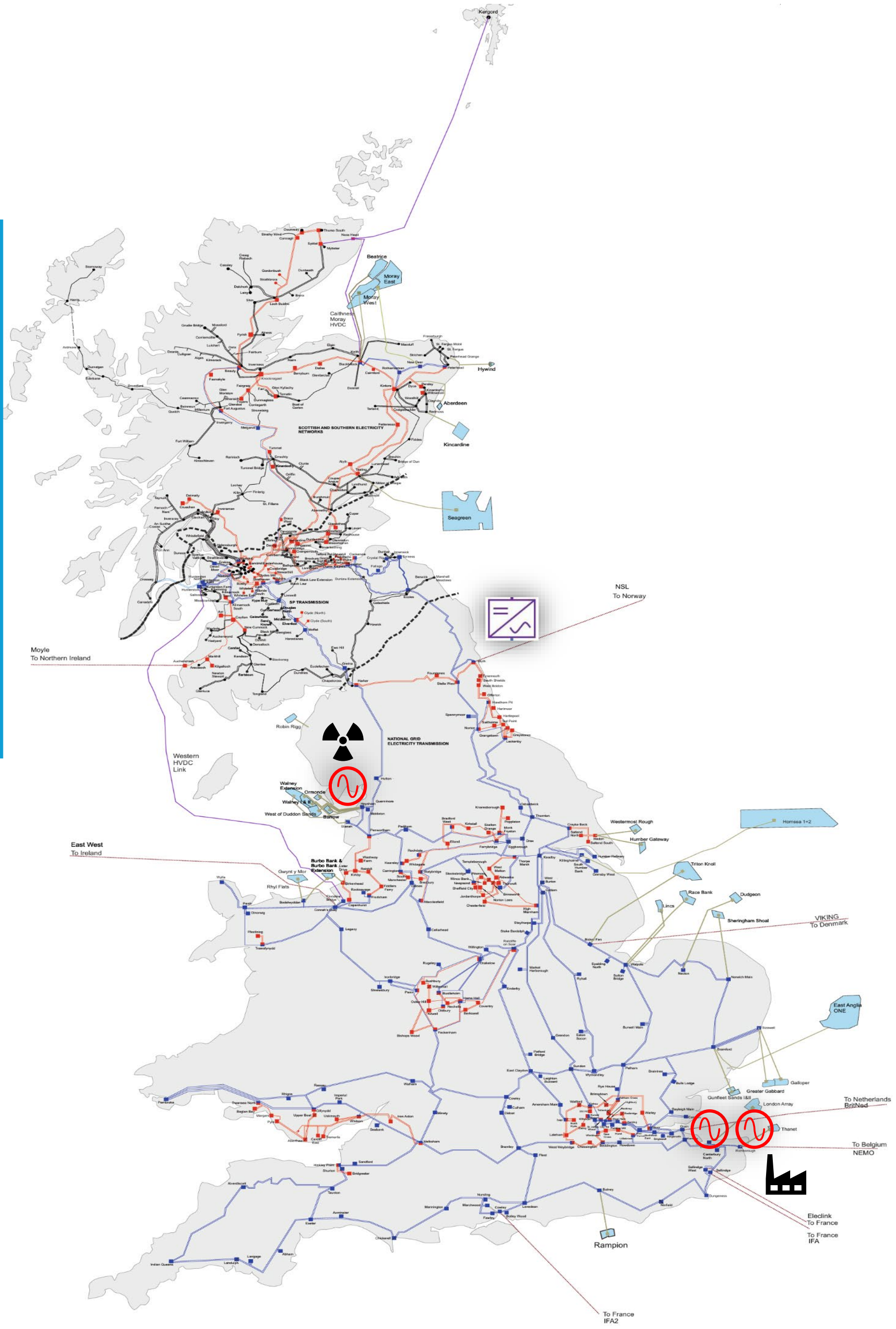
Frequency of oscillations aligned with natural frequency of turbine

Turbine protection detected four acceleration events in ten seconds

Turbine governor valves close steam admission briefly to prevent overspeed

The hydraulic oil system not designed to sustain repeated operation in rapid succession

- January 2025
  - Converter driven instability
  - No electrical/physical fault
  - Nuclear reactor and CCGT units trip



Oscillations in Iberia, 2025

Multiple voltage control circuits returned to service

Overnight gens switched out (mostly CCGT)

HVDC mode change

IBR output curtailed to reduce power flows to FR and PT flows reduced

period before the incident. Oscillatory behaviour was noted in the morning, but no significant oscillations with amplitudes above 20 mHz were detected until 12:03.

Small and short-lived 0.2 Hz oscillations

4 $kV_{pk\text{-}pk}$ (1%)
0.2 Hz

7 $kV_{pk\text{-}pk}$ (2%)
0.2 Hz
6m

6 $kV_{pk\text{-}pk}$ (1.5%)
0.2 Hz
2m

32 $kV_{pk\text{-}pk}$ (8%)
0.6 Hz 4m42s
V_{min} of 0.94pu

23 $kV_{pk\text{-}pk}$ (4%)
0.2 Hz
3m20s
V_{min} of 0.94pu

Figure 2-12: Total load in Spain on 24 and 28 April between 9:00 and 12:32

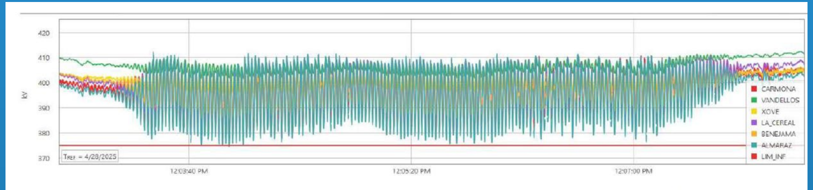


Gráfico 9 Tensiones en los nudos de 400 kV durante la primera oscilación (12:03). Fuente: REE

Multiple shunt reactors switched

https://www.naspi.org/sites/default/files/2020-11/02_wsu_mani_interarea_oscillations_20201105.pdf

5:49 8:52 10:30 11:06 11:23 12:03 12:19

April 28th, 2025 – impact on NPP in F

Several thousand MW oscillations across ES – FR interconnection

NPP#1 SW France 2x 1300 MW – one unit online

NPP#2 SW France 4x 900 MW – three units online

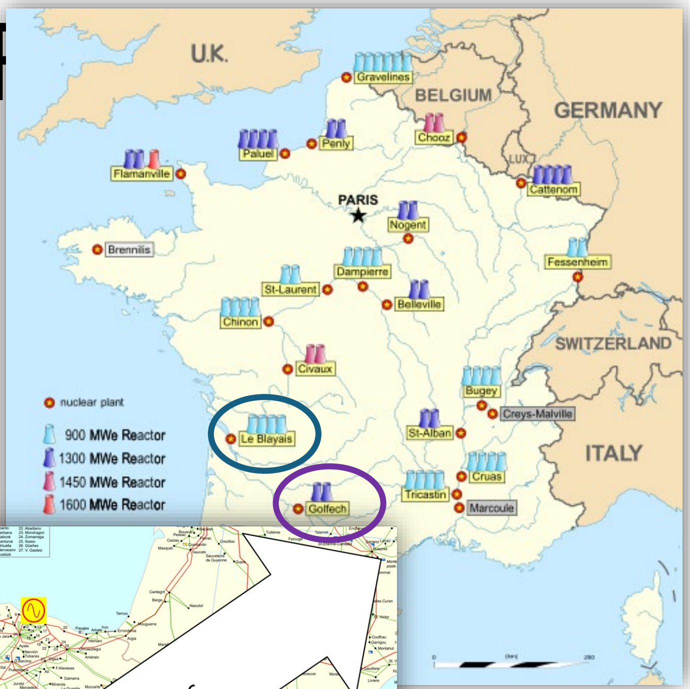
NPP#1

- experienced rapid fluctuations in V, f and P
- steam valves closing twice in one second
- overspeed protection activation
- rods insertion to balance power
- significant reduction in neutron flux
- automatic shutdown

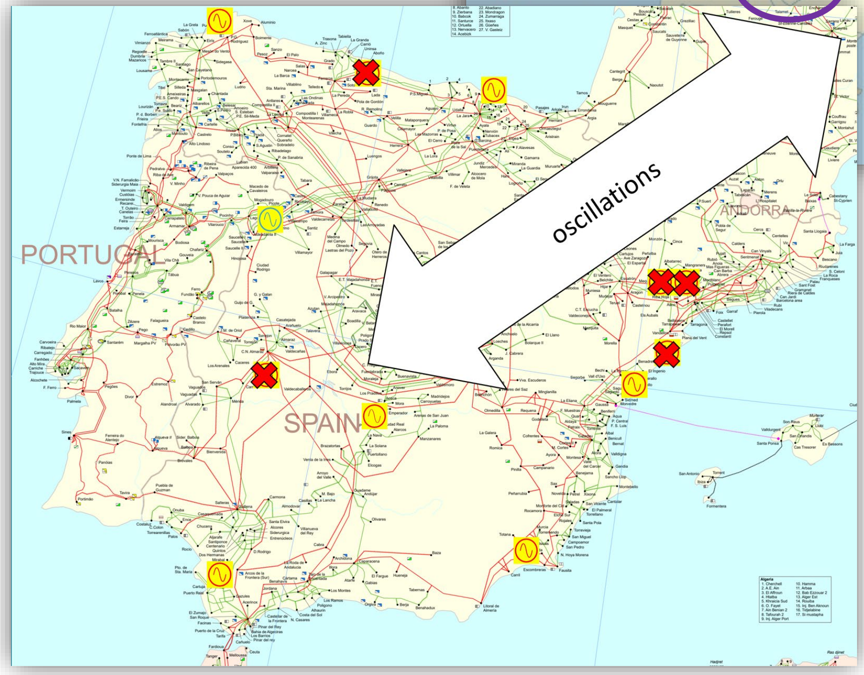
NPP#2

- steam valves closing more slowly
- reduction in power less significant
- protection against excessive variations in neutron flux not triggered

ENTSO-E frequency response defined by loss of 2x 1500 MW N4 units already fully committed at that stage …



Source: Wikipedia



Source: ENTSO-E

Real-Time System Operation - The Times They Are a-Changin'

- Changes in system dynamics → Seasoned operators operating at novice level
  - Mental models formed operating power systems dominated by synchronous machines

Human operator pushed out of the loop?

- Limited time to assess the situation (gather info to inform decision-making),
- Inadequate decision-making support tools
- Inadequate training
- Limited predetermined remedial actions provided for converter-driven instability,
- Limited previous experience to allow 'engineering judgement' approach

Existing **DTS solutions not suitable** for operator training against oscillations scenarios

Consequences manifest in real-time, but issues inherited from decisions at system design and planning timescales

RADAR

MODERNIZING GRID RESILIENCE

Rapid Adaptation of Grid Defense, Analytics and Resilience

Objective

Address the critical challenges of maintaining reliability and resilience amid rapid change in electric grids and emerging vulnerabilities.

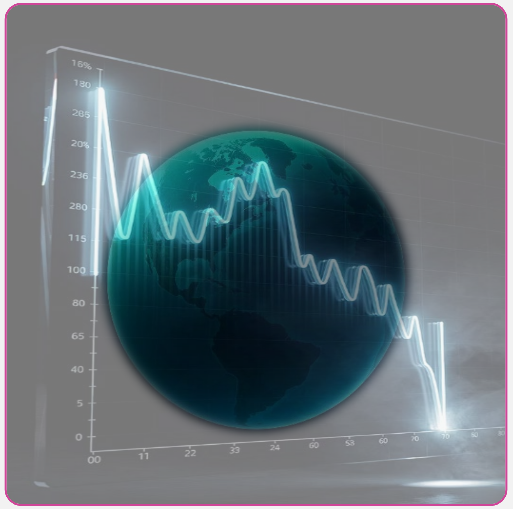
How

- Grid Vulnerability and Risk Framework
- Rapid Transition Model for Transmission
- Advanced Tools for High IBR Operations and Planning
- Advanced Training for Grid Operations

Highlights

- 3.5 Yr Duration
- 1st Deliverables in Year 1
- Regional Risk Framework Studies
- Advanced Data Tools To Support Event Analysis
- Training to Address Complex Topics

EPRI – Notable Power System Events webpage



An online repository for information related to power system events.

This application is a repository for information related to major power system events that have occurred in recent years. It contains information from the key reports on the events that may be of interest to EPRI members.

https://neinfo.epri.com/

For Access, contact: Mobolaji Bello, mbello@epri.com

GLOBAL PST CONSORTIUM

Photo by Werner Slocum, NREL 69160

"We can learn from past events and continuously improve, but we cannot eliminate 100% of the risk.

We can, however, detect risks earlier, respond faster, and make the grid more flexible and resilient—with better data, better tools, and better decisions in real time."

Thank you!