International

Workshop

The Use of Synchrophasors in Power Systems

An Indispensable Infrastructure in the 21st Century

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The Swedish Foundation for International Cooperation in Research and Higher Education

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The MedFasee Project

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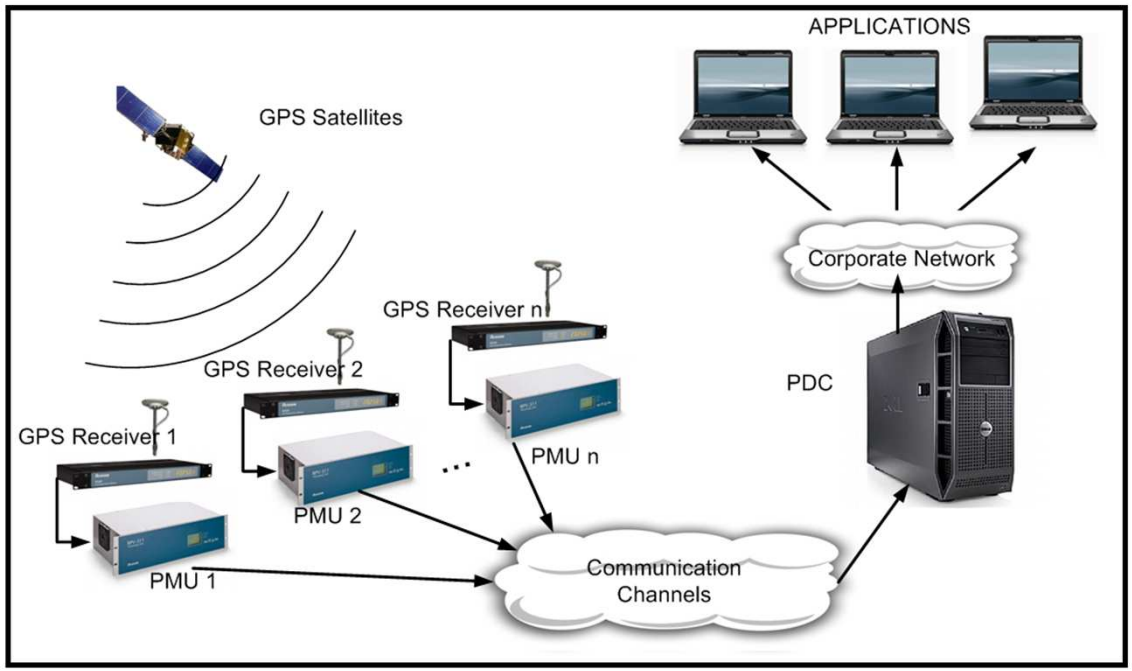
UFSC

Outline of the Presentation

- Wide Area Monitoring System (WAMS)
- MedFasee: the Brazilian Low-Voltage WAMS
  - Development
  - Selected Applications
- The MedFasee CTEEP Project
- Conclusions
- References

Wide Area Monitoring System (WAMS)

- Simultaneous signals measurements at remote geographic locations using PMUs (Phasor Measurement Units)
- Time synchronized measurements using satellite signals (GPS)
- Data acquisition and handling in remote sites (PDC)
- Upgrade rate (scanning) >> SCADA
- Allows dynamic monitoring and control of electric systems
- New paradigm for the system operation



MedFasee: the Brazilian Low-Voltage WAMS
Historical Review

- Project started in 2003
- The main goals were:
  - ✓ Development of a Synchronized Phasor Measurement System (SPMS) prototype
  - ✓ Aplications for power system monitoring and analysis
- All hardware and software components for the SPMS prototype were developed by the MedFasee team
- Project sponsored by:
  - ✓ Brazilian Government (Finep/CT-Energ)
  - ✓ Reason Tecnologia S.A. (www.reason-international.com)

MedFasee: the Brazilian Low-Voltage WAMS

First Prototype: Structure and Geographical Location

- Three PMUs installed in laboratories of three universities in Southern Brazil

- PMUs:
  - ✓ Measurement of the instantaneous three-phase low voltage (outlet)
  - ✓ Network interface connected through the Internet to send synchrophasors to the PDC

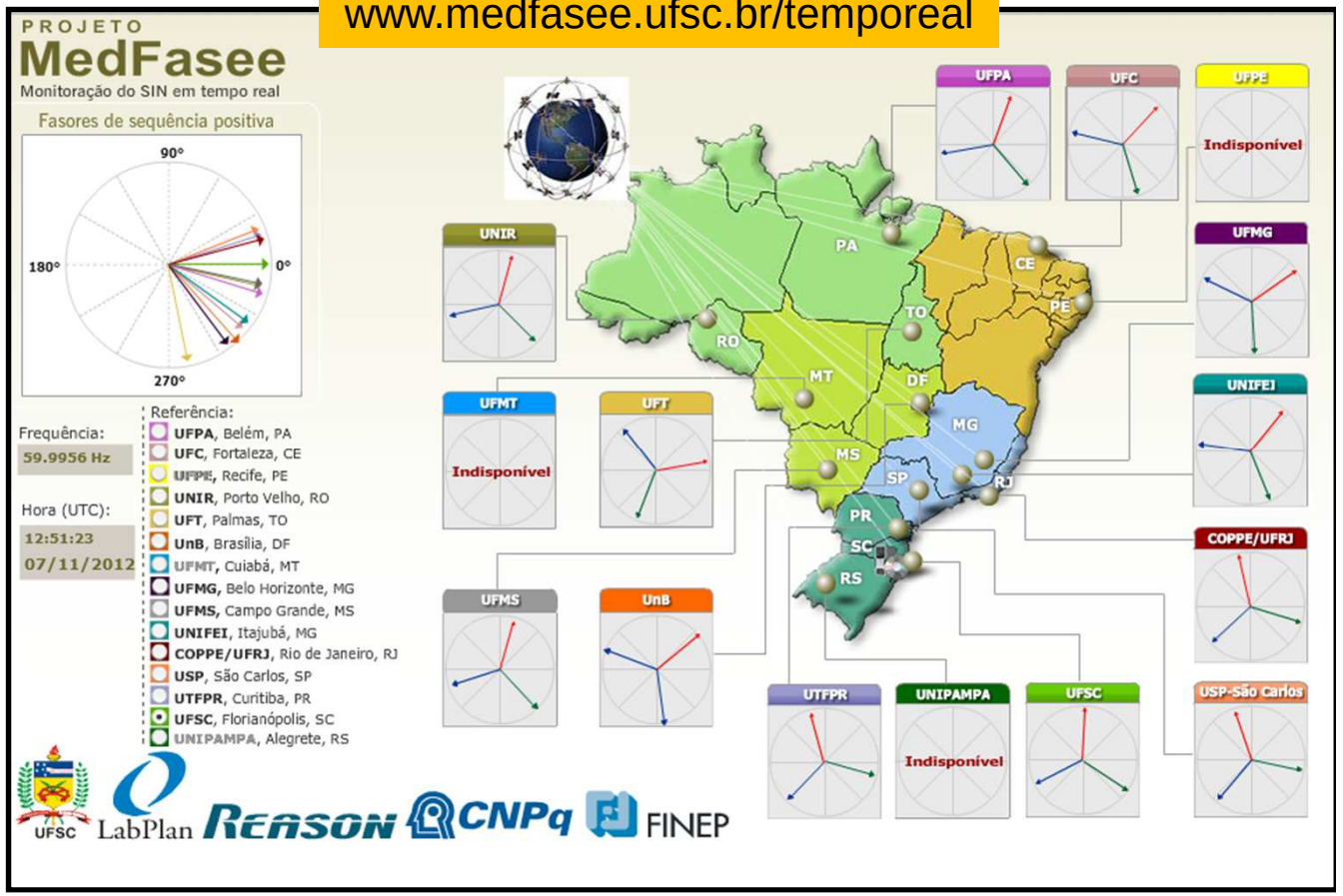
- PDC:
  - ✓ Located in the Electrical System Planning Research Laboratory (LabPlan) at UFSC

MedFasee: the Brazilian Low-Voltage WAMS

Current Configuration: Characteristics

- **Project scope:**
  - ✓ 15 universities participate in the project, covering the 5 geographical regions of the country
- **Main objective:**
  - ✓ Development, dissemination and educational use of the SPMS technology

www.medfasee.ufsc.br/temporeal



- **Aditional benefits:**
  - ✓ 2011 – Beginning of an oficial partnership between UFSC and the National Operator of the Brazilian Power System (ONS) to access the data base of the MedFasee Project

MedFasee: the Brazilian Low-Voltage WAMS

Developed Applications

- ✓ **Basic Applications:**
  - Acquisition and treatment of phasor data (PDC)
  - Visualization of the dynamic behavior in real time and from data records
  - Synchronized record and analysis of perturbation data
- ✓ **Monitoring Applications:**
  - Off-line and real time analysis of electromechanical oscillations
- ✓ **Special Applications:**
  - Hybrid dynamic simulation
  - Simulation models validation
  - Line parameters estimation
  - Fault location
- ✓ **Protection and Control Applications:**
  - Control for damping critical oscillations

MedFasee: the Brazilian Low-Voltage WAMS

PMUs and PDC Characteristics

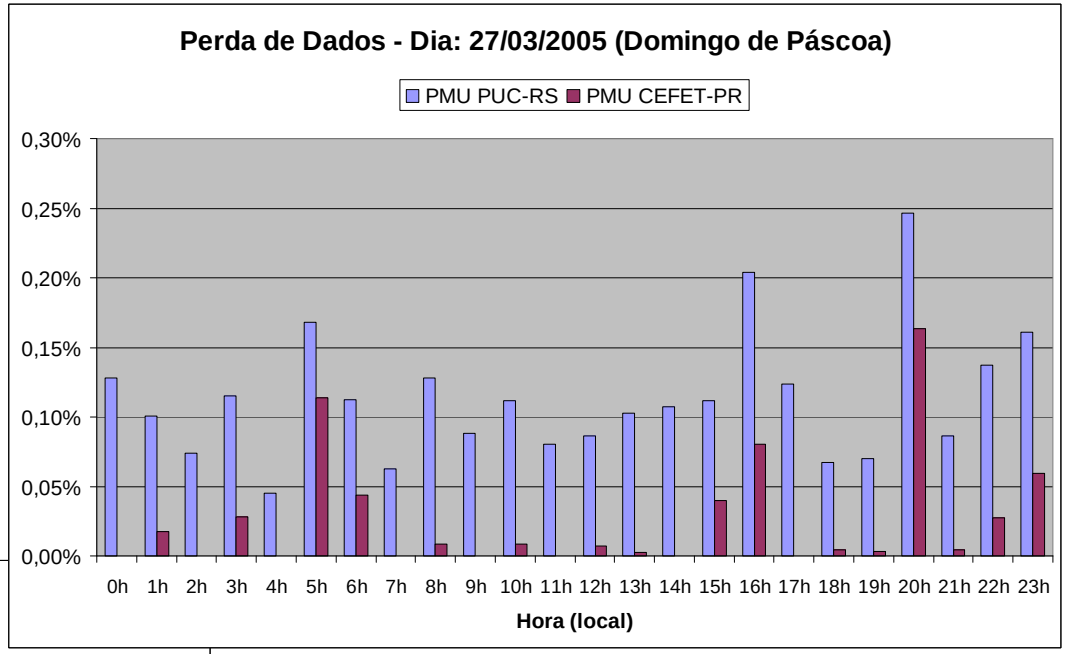
- **PMUs:**
  - ✓ Sampling process synchronized by GPS
  - ✓ 8 analog channels
  - ✓ Complex voltages obtained from DFT (Discrete Fourier Transform)
  - ✓ Continuous transmission of PMUs data to PDC:
    - Rate of 60 synchrophasors per second
    - Ethernet link and UDP/IP protocol
- **PDC:**
  - ✓ GNU-Linux environment (free software)
  - ✓ Object Oriented Modeling
  - ✓ Programmed in C/C++
  - ✓ RTAI (Real Time Application Interface) system for Linux
  - ✓ Use of MySQL database

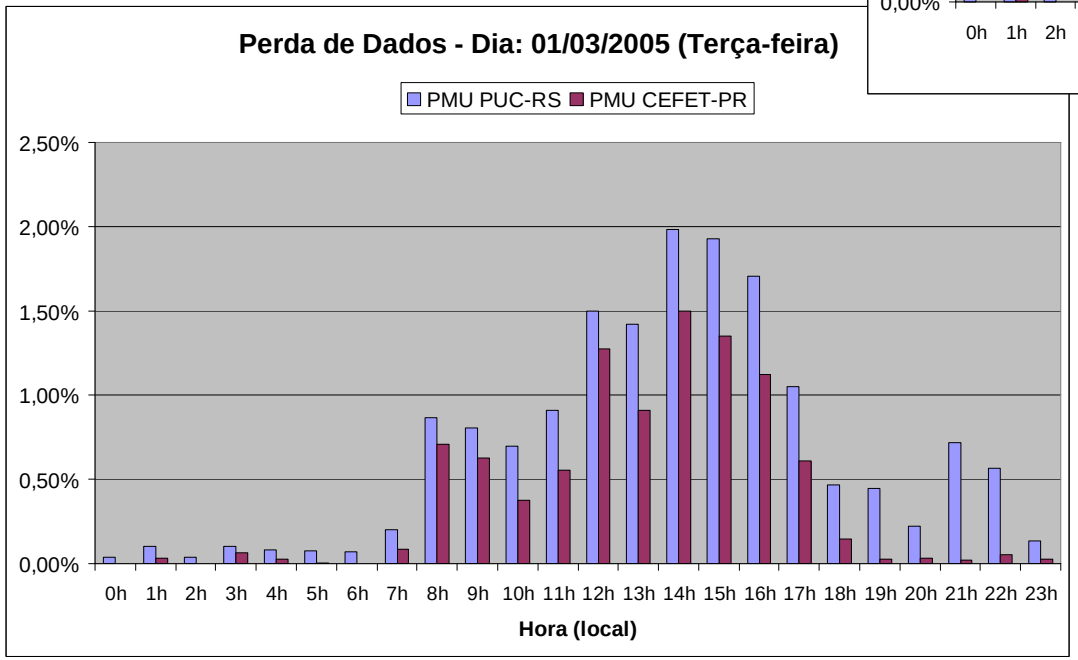
PMU

PDC

MedFasee: the Brazilian Low-Voltage WAMS
Communication System Assessment

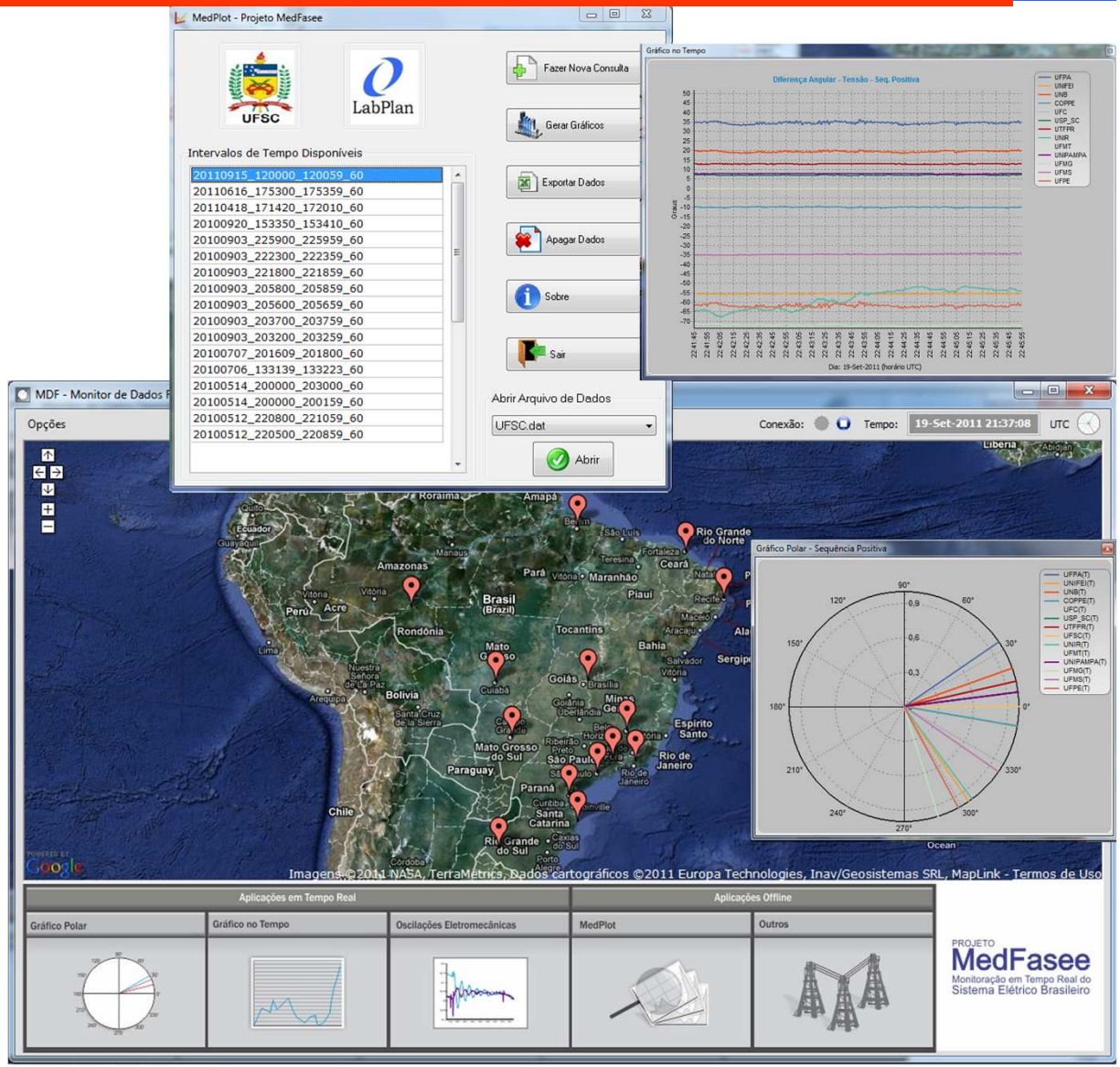
- **Performance of the communication links:**
  - ✓ **Internet public network**





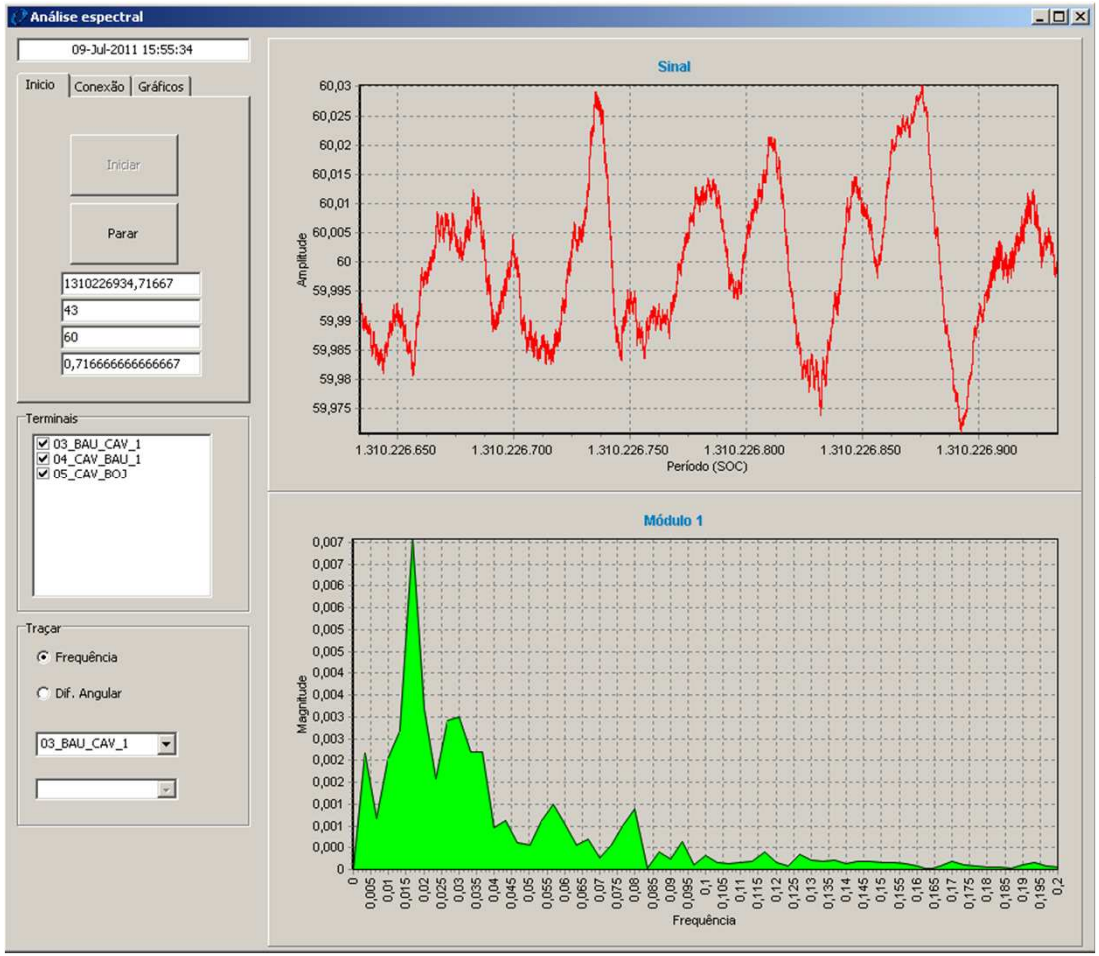
MedFasee: the Brazilian Low-Voltage WAMS Monitoring Environment

- ✓ **Integrated Environment:**
  - Monitoring applications
- ✓ **Geographic Visualization of PMUs:**
  - Main screen of the application
  - Terminals configuration
- ✓ **Off-line Module:**
  - Disturbance analysis



MedFasee: the Brazilian Low-Voltage WAMS Monitoring Environment

- **Real Time Module:**
  - ✓ **Electromechanical oscillations analysis:**
    - Identification and tracking of low frequency oscillations
    - Methodology:
      - Fast Fourier Transform (FFT)
    - Available variables:
      - Angle differences
      - Frequencies
    - Adjustable refresh rate



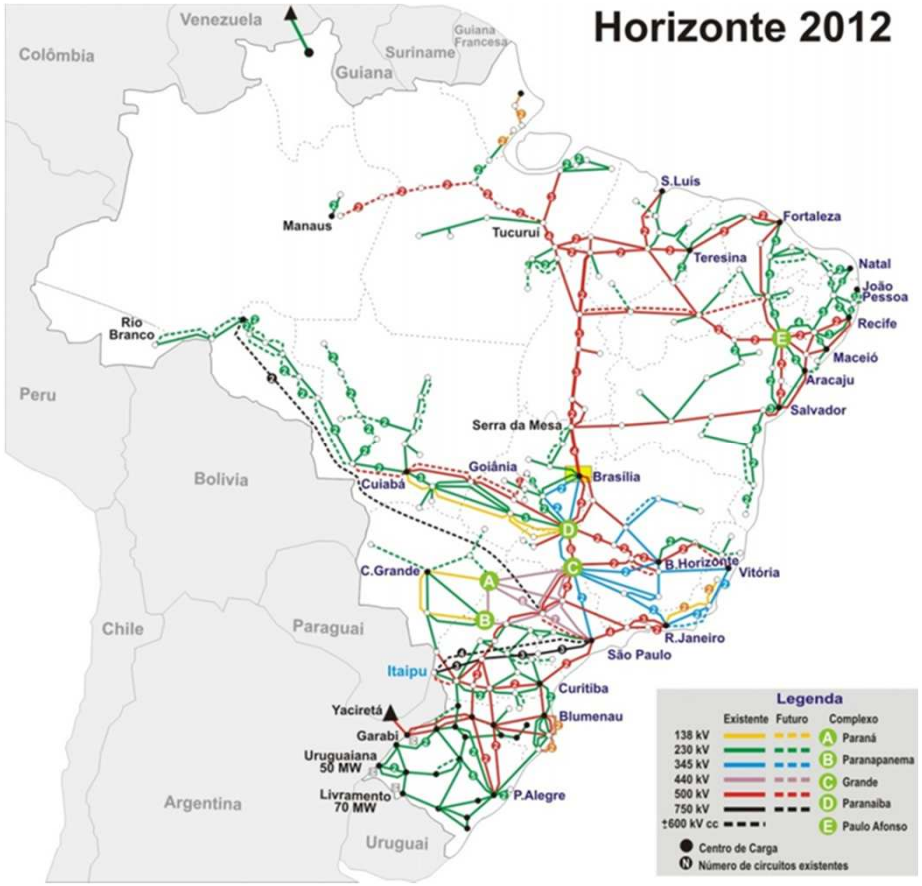
MedFasee: the Brazilian Low-Voltage WAMS

Selected Applications:

- System Wide Model Validation
- Monitoring of Electromechanical Oscillations
- Evaluation of Special Protection Schemes

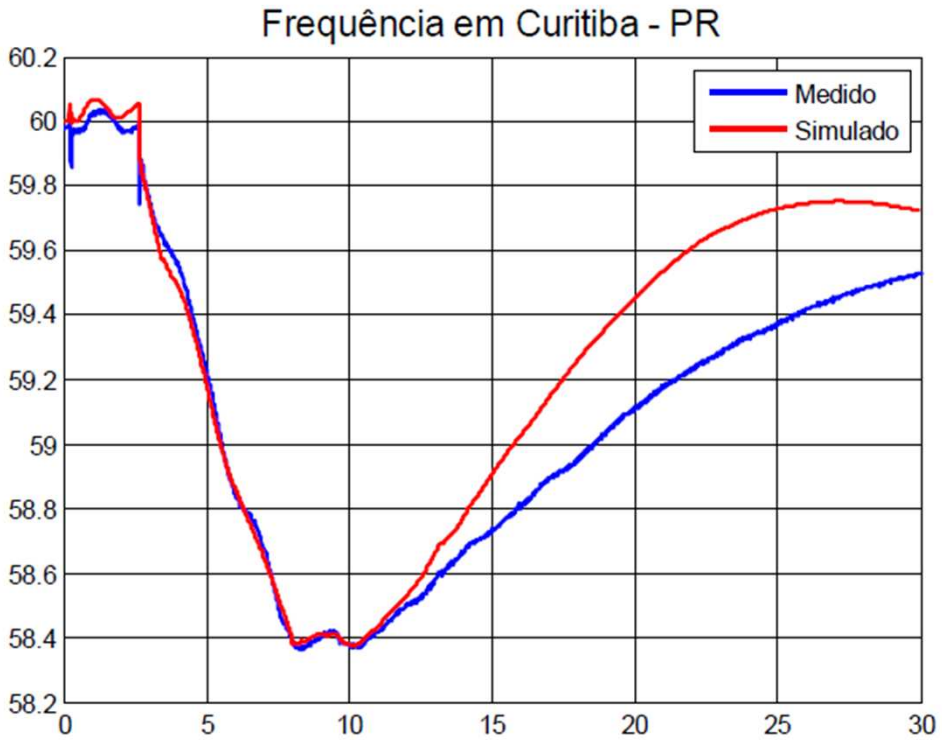
Selected Applications
System Wide Model Validation

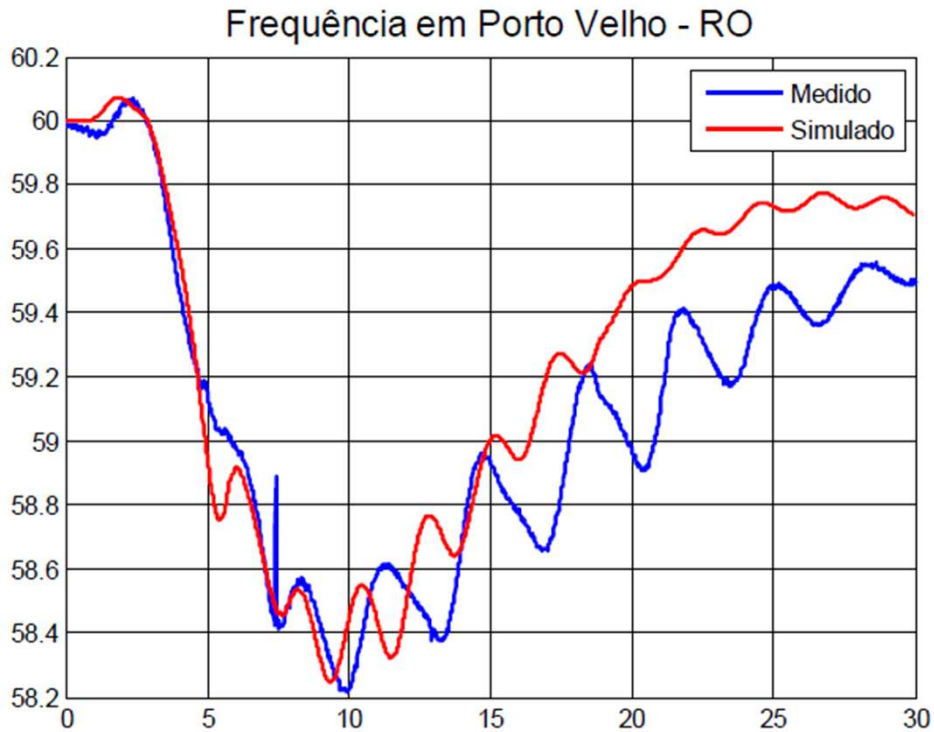
- **General Purpose:**
  - ✓ To evaluate the model adequacy to represent the behavior of the real system
- **Criteria to increase confidence in the models:**
  - ✓ **Qualitative:**
    - Similarity of the relevant variables (measured and simulated)
    - The models must predict:
      - o System stability or instability
      - o Oscillatory behaviour
      - o Maximums and minimums should occur in near instants
  - ✓ **Quantitative:**
    - Correct estimation of the frequency and damping of the dominant oscillation modes
    - If the simulation and the data measurement have close values then confidence increases



Selected Applications
System Wide Model Validation

- **System Wide Model Validation following an event**
  - ✓ Event: Disconnection of the Itaipu Hydro Plant in 02/09/2011
    - Frequency: Curitiba – PR and Porto Velho – RO



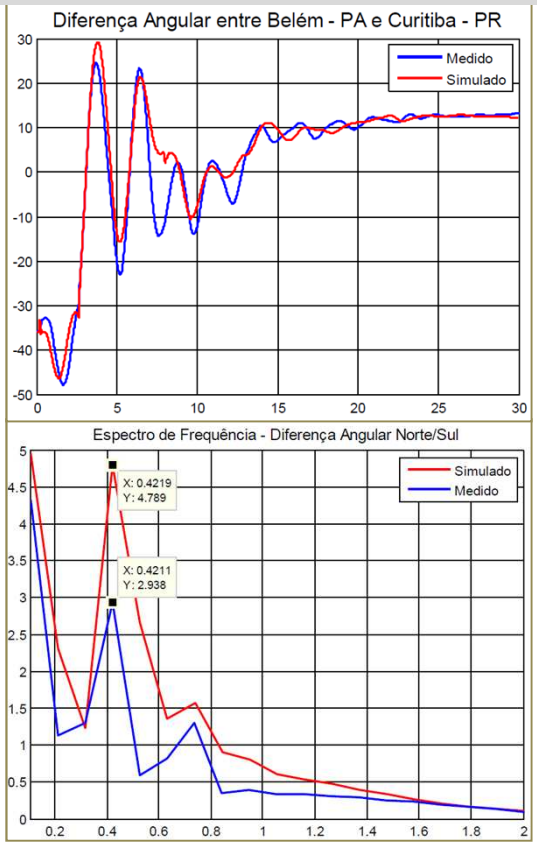


Selected Applications

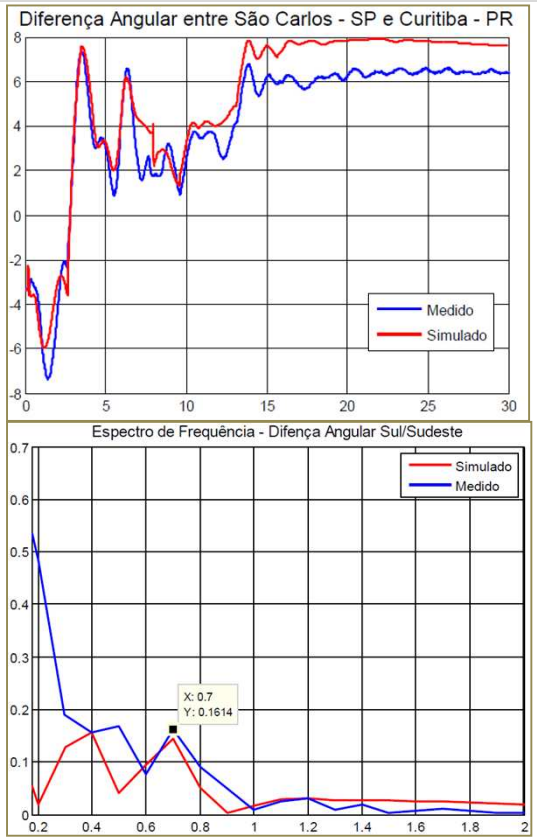
System Wide Model Validation

- **Qualitative and Quantitative Evaluation:**

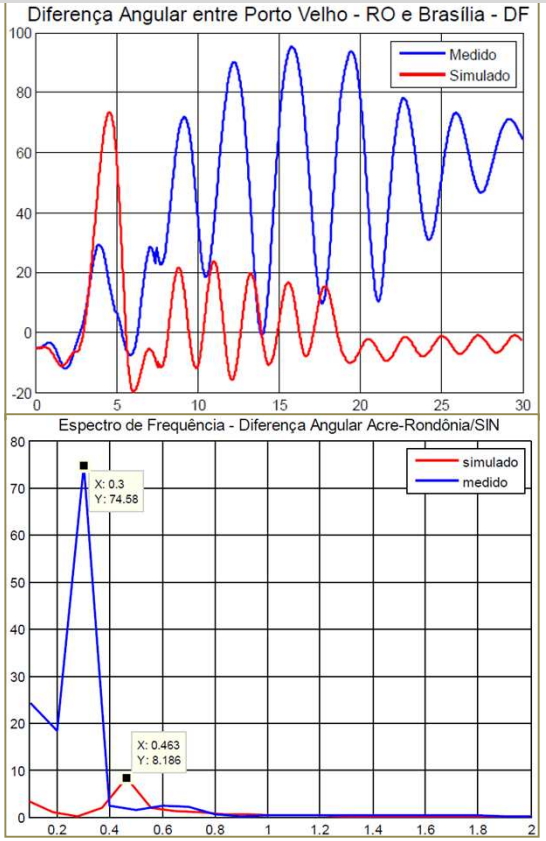
Belém-PA – Curitiba-PR



São Carlos-SP – Curitiba-PR



Porto Velho-RO – Brasília-DF



Angle Difference

DFT

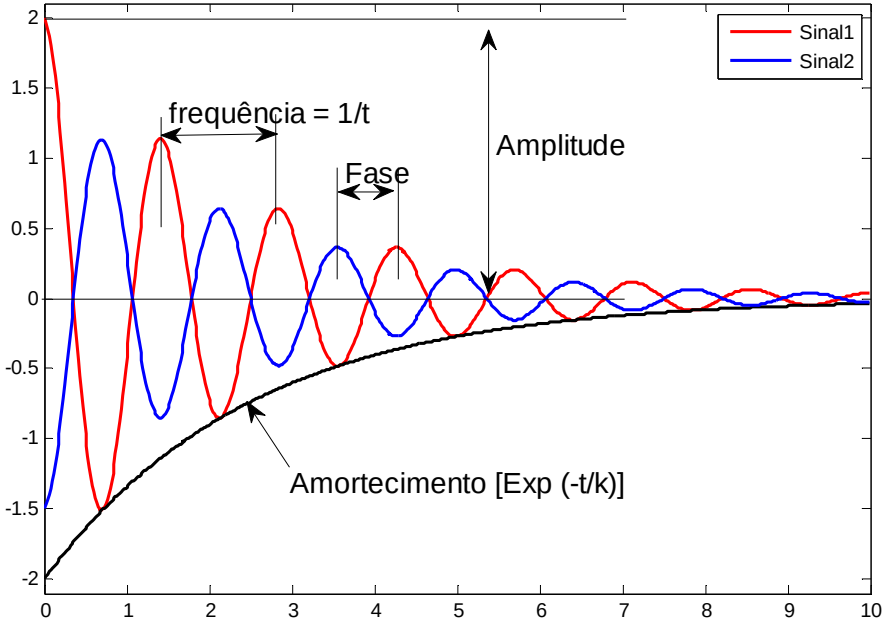
- **System Wide Model Validation of the Brazilian Interconnected Power System: Conclusion**
  - ✓ Models and simulation tools employed by ONS were validated

Selected Applications

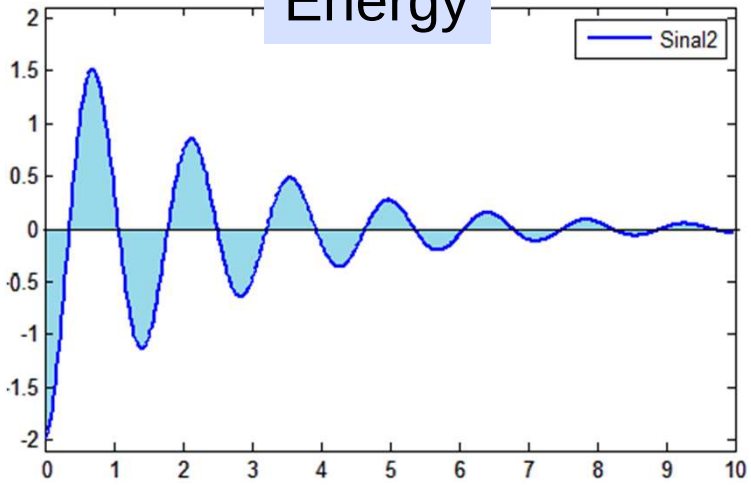
Monitoring Of Electromechanical Oscillations

- **Oscillation modes**
  - ✓ They can be characterized by:
    - Oscillation frequency
    - Amplitude
      (RMS or peak value)
    - Energy
    - Damping rate
    - Mode-Shapes

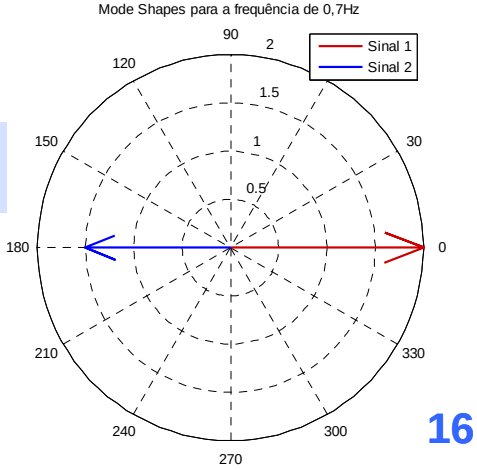
Frequency, Amplitude, Damping



Energy



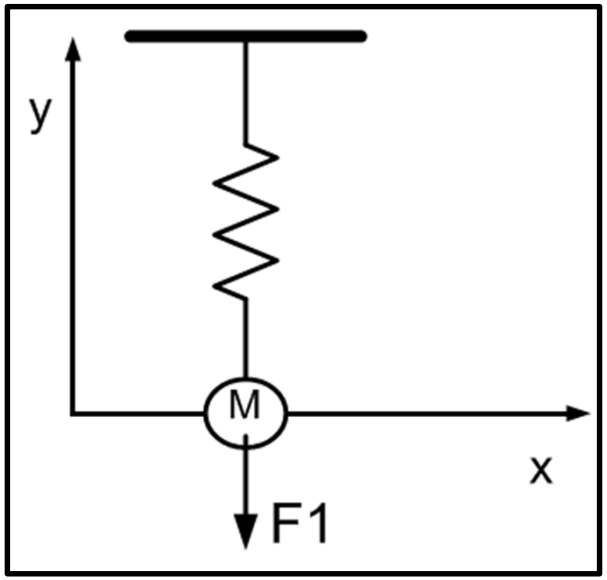
Mode-Shapes



Selected Applications

Monitoring Of Electromechanical Oscillations

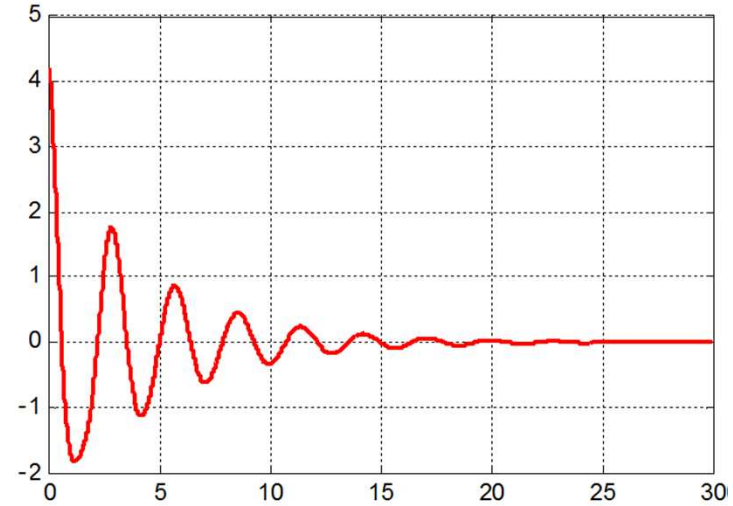
- **Selection of the adequate methodology:**
  - ✓ Analogy between a mechanical system (spring-mass) and the power system

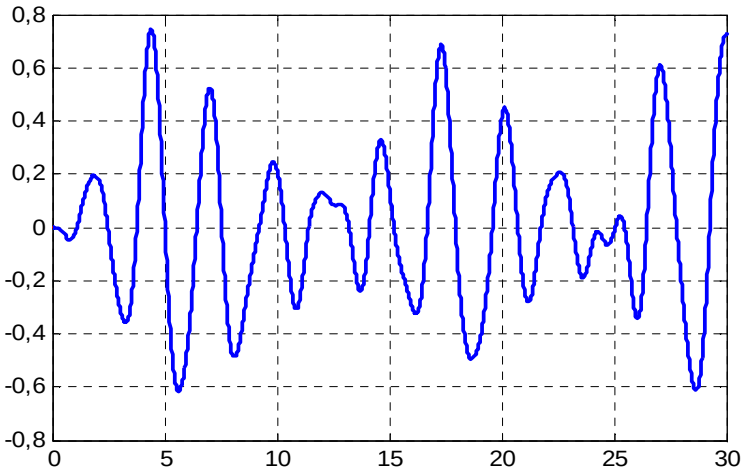


F1 = Impulse

F1 = Constant Perturbation

Position x Time:



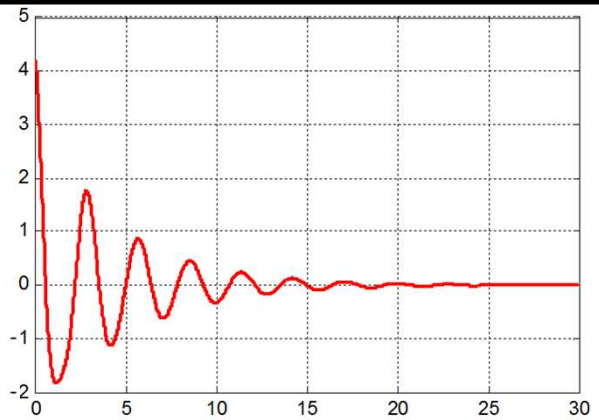


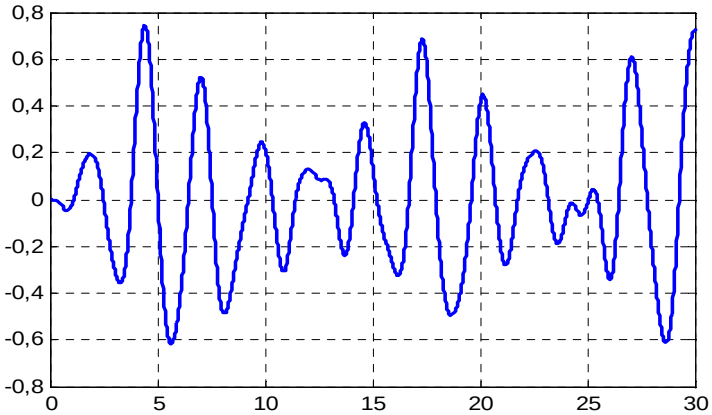
What methodology is the most adequate to ambient data? What about ringdown?

Selected Applications

Monitoring Of Electromechanical Oscillations

Spectral decomposition method (DFT) can be used for both data.





Ringdown

- The damping is clear in the signal
- Signal reconstruction methods are adequate
- Model estimation methods are not applicable because they require a large window

Ambient Data

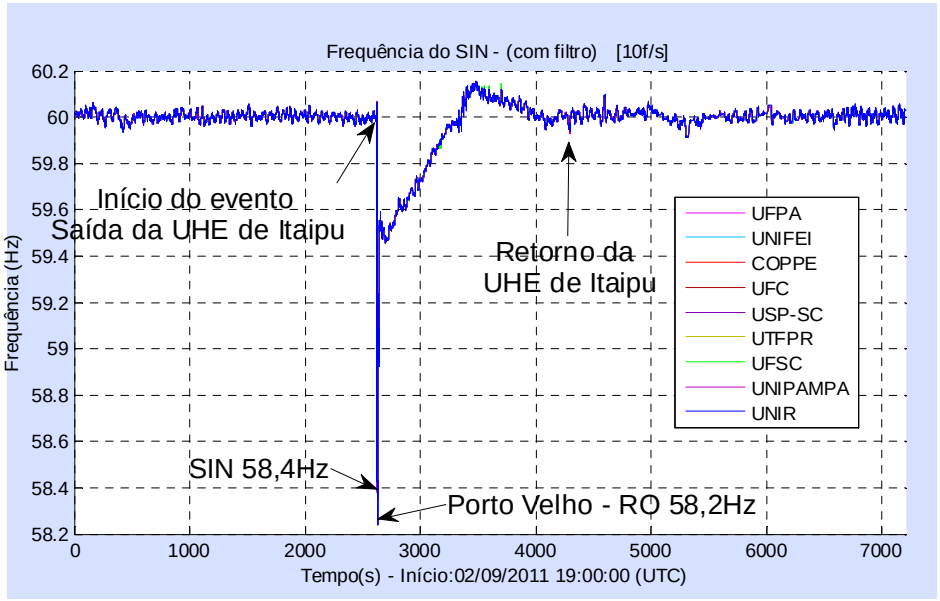
- From the signal, the damping is apparently zero
- However, the damping is present at the system
- Signal reconstruction methods are not appropriated
- Linear model estimation methods and methods based on correlation are adequate

Selected Applications

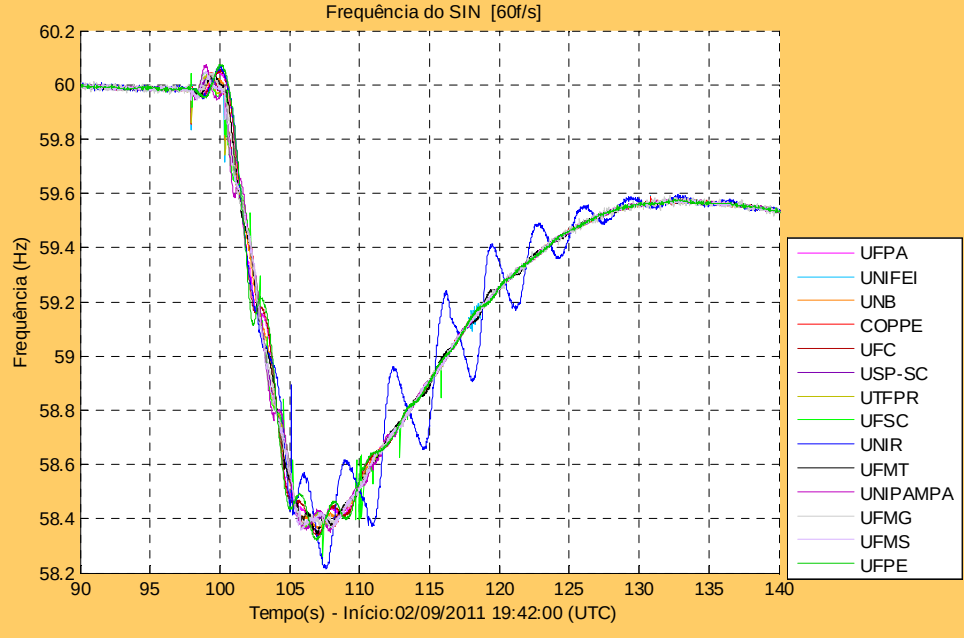
Monitoring Of Electromechanical Oscillations

- ✓ **Case 1 – Disconnection of the Itaipu Hydro Plant in 02/09/2011:**
  - Loss of 5100 MW generation at Itaipu Hydro Plant – 60 Hz
  - Load Shedding Scheme (ERAC): ~2500 MW

Frequency: overview



Frequency: beginning of the event

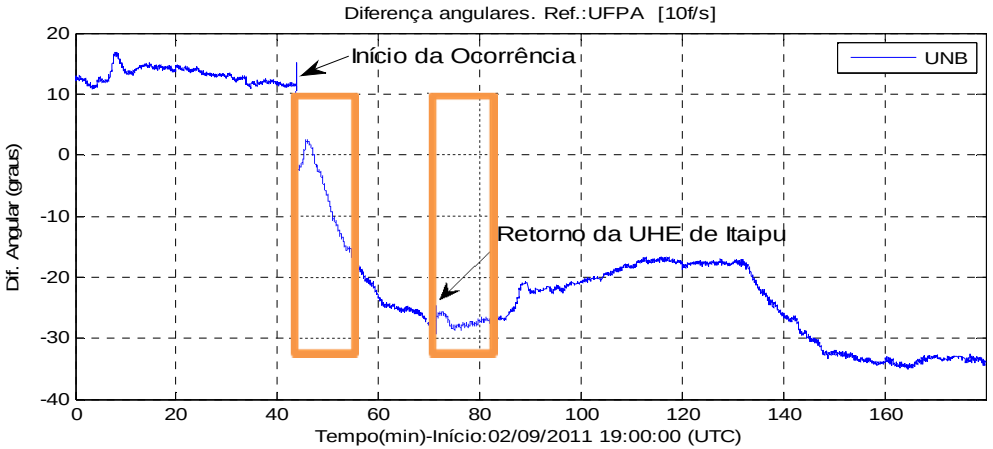


Selected Applications
Monitoring Of Electromechanical Oscillations

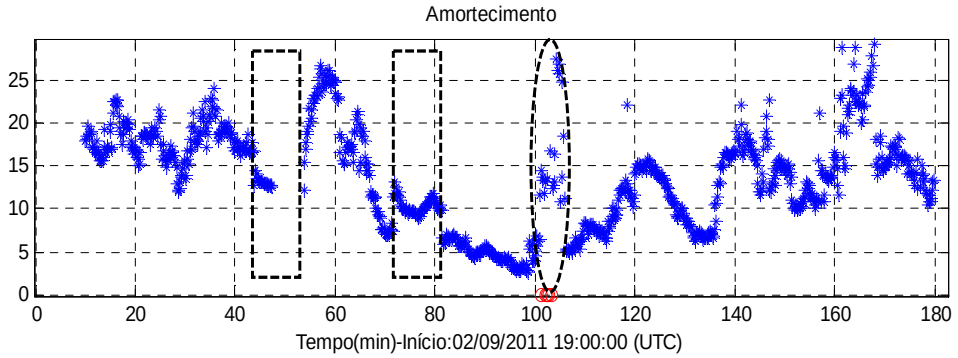
➢ **Case 1 – Disconnection of the Itaipu Hydro Plant in 02/09/2011:**

✓ Analysis of the North x South mode (~ 0,35 Hz) by the:

- Stochastic Balanced Realization (**SBR**)



Topology changes



Damping: failures in the identification

Selected Applications
Monitoring Of Electromechanical Oscillations

➢ **Case 1 – Disconnection of the Itaipu Hydro Plant in 02/09/2011:**

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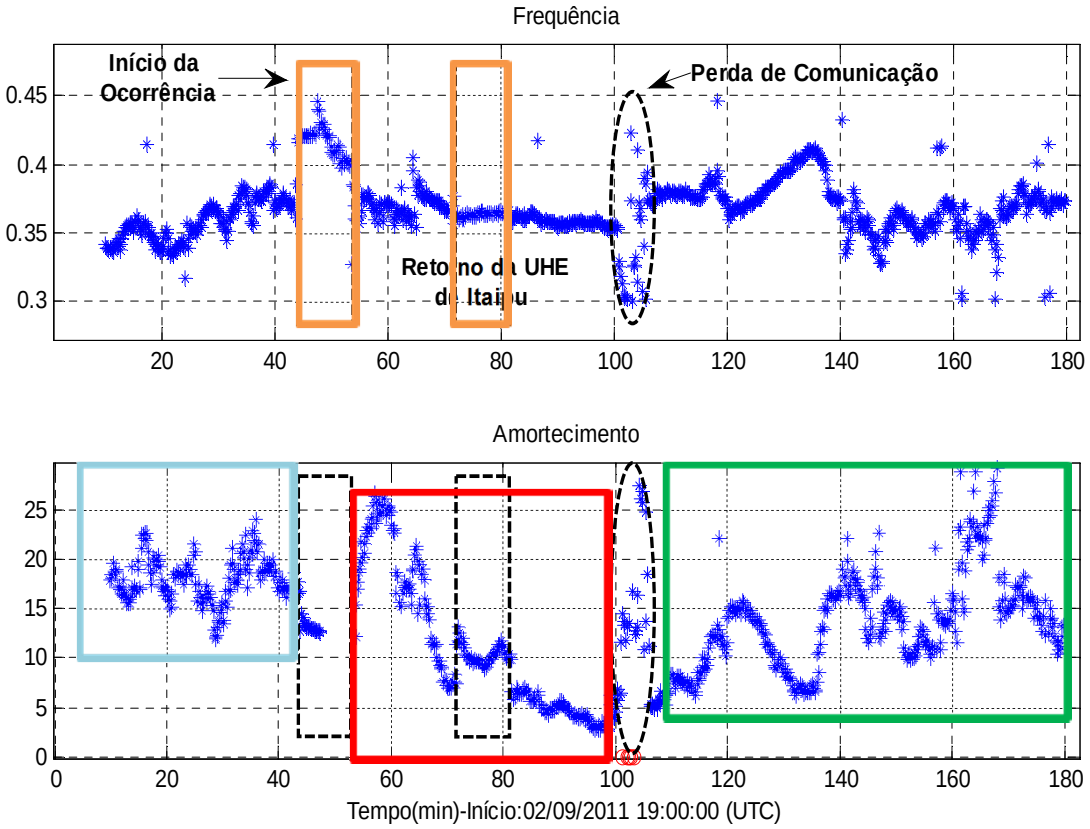


Behaviour

Damping > 10%

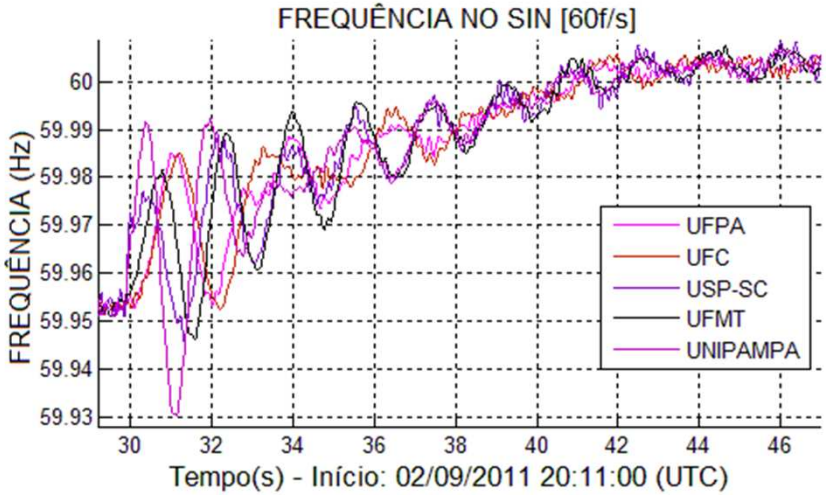
Damping reduction: 20% to 5%

Damping increase

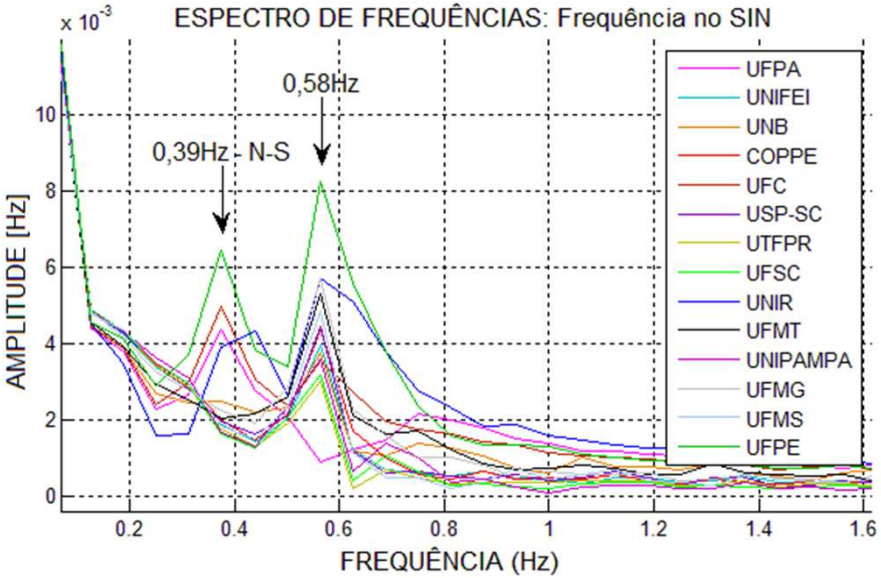
Selected Applications

Monitoring Of Electromechanical Oscillations

✓ **Case 1 – Disconnection of the Itaipu Hydro Plant in 02/09/2011**

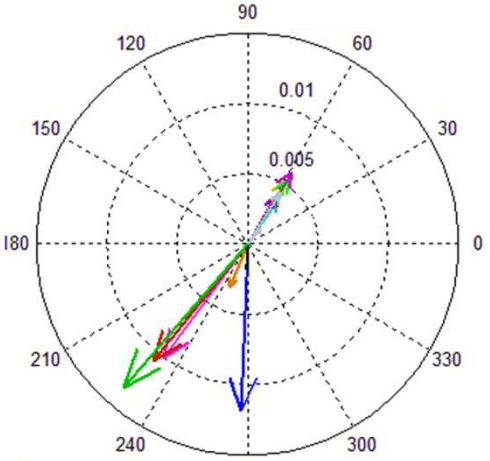


DFT

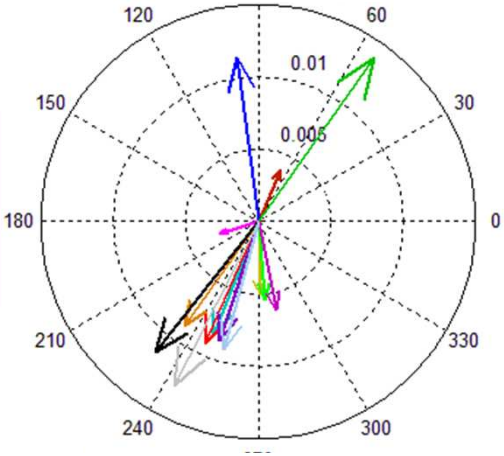


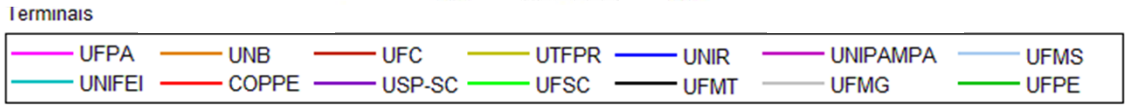
Prony

North-South: 0,37 Hz



Northeast-System: 0,58 Hz



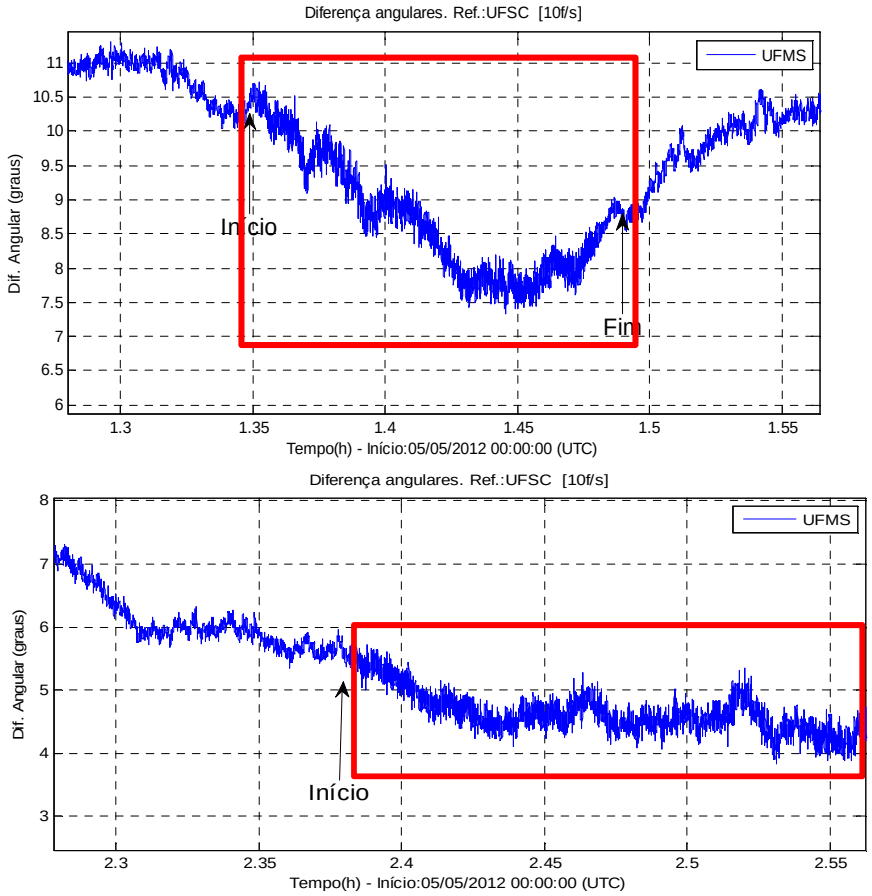


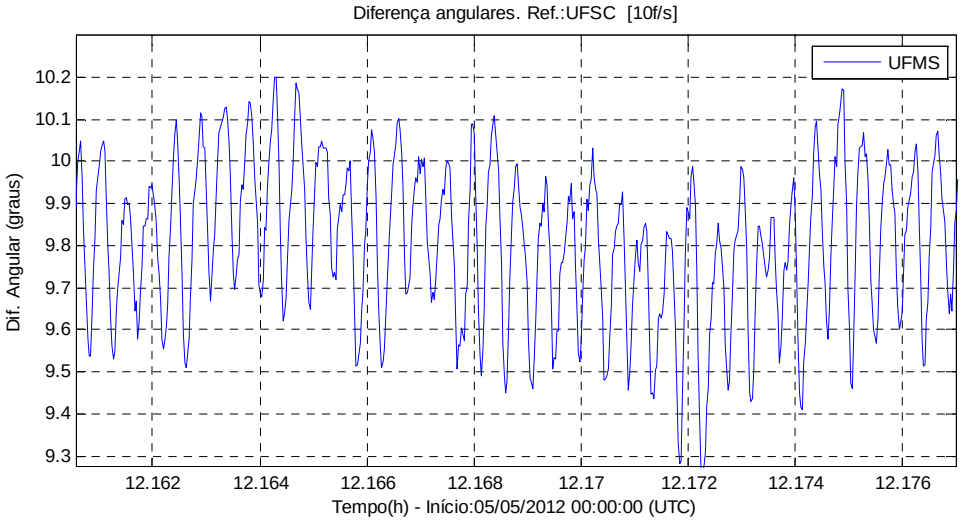
Selected Applications

Monitoring Of Electromechanical Oscillations

- ✓ **Case 2 – Sustained oscillations in Mato Grosso do Sul (MS), observed at the PMU installed in Campo Grande (State Capital):**
  - **May, 2012**

Angle Difference: UFSC (Florianópolis) x UFMS (Campo Grande)





First period: 1h27min + 30min (UTC)

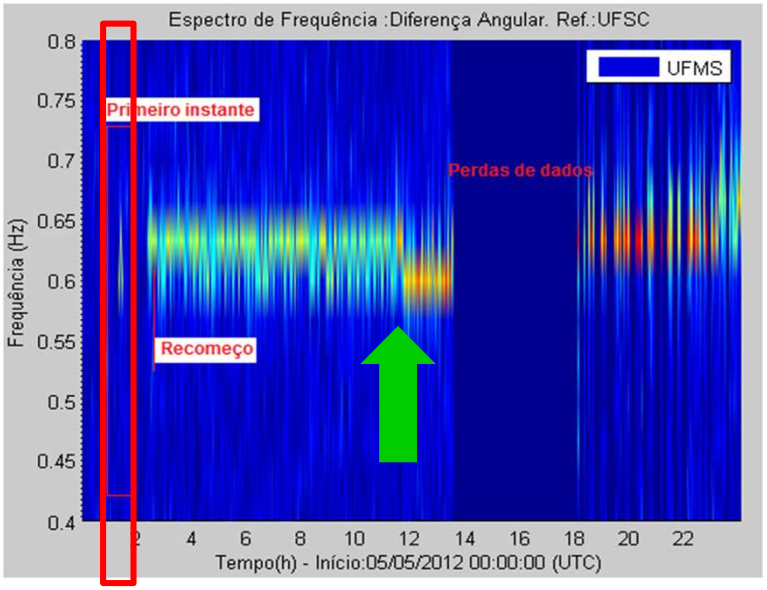
Restart: 2h23min + 4,5 days (UTC)

Selected Applications

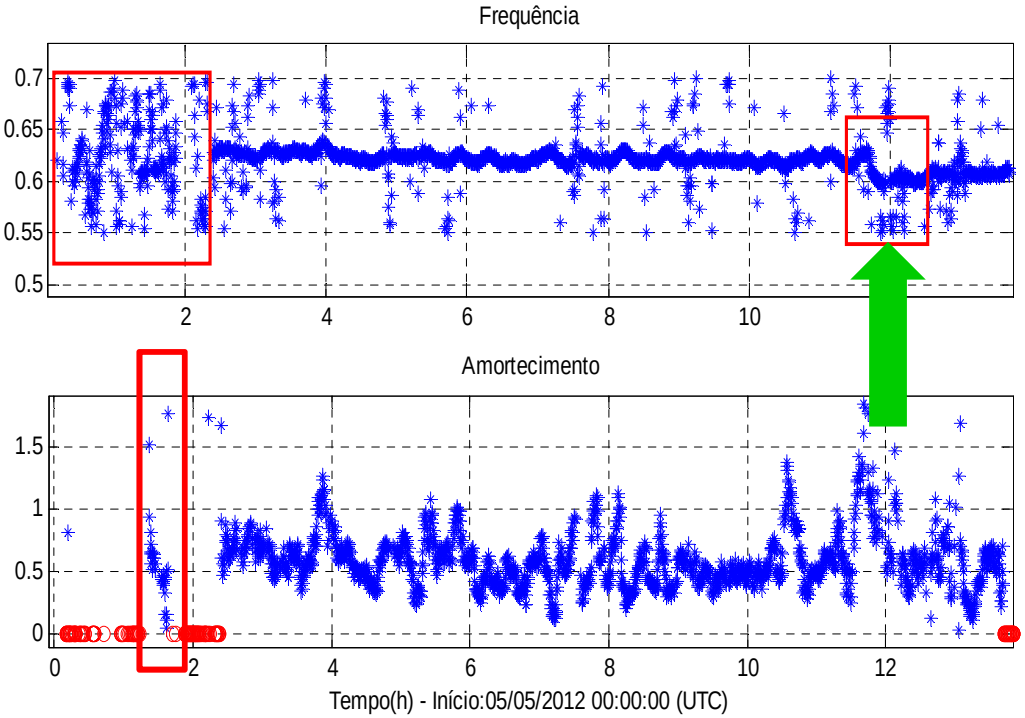
Monitoring Of Electromechanical Oscillations

- **Case 2 – Sustained oscillations in MS**
  - ✓ **Ambient Data Acquired in 05/05/2012**

DFT



Stochastic Balanced Realization (SBR)



The DFT results are coherent with the SBR results

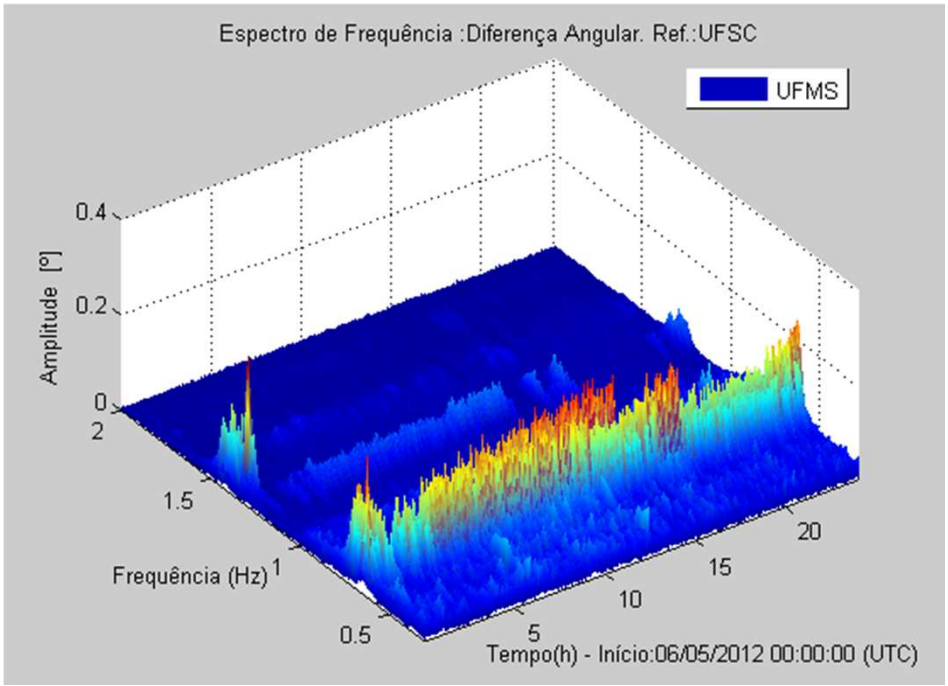
Importance of employing more than one methodology

Selected Applications

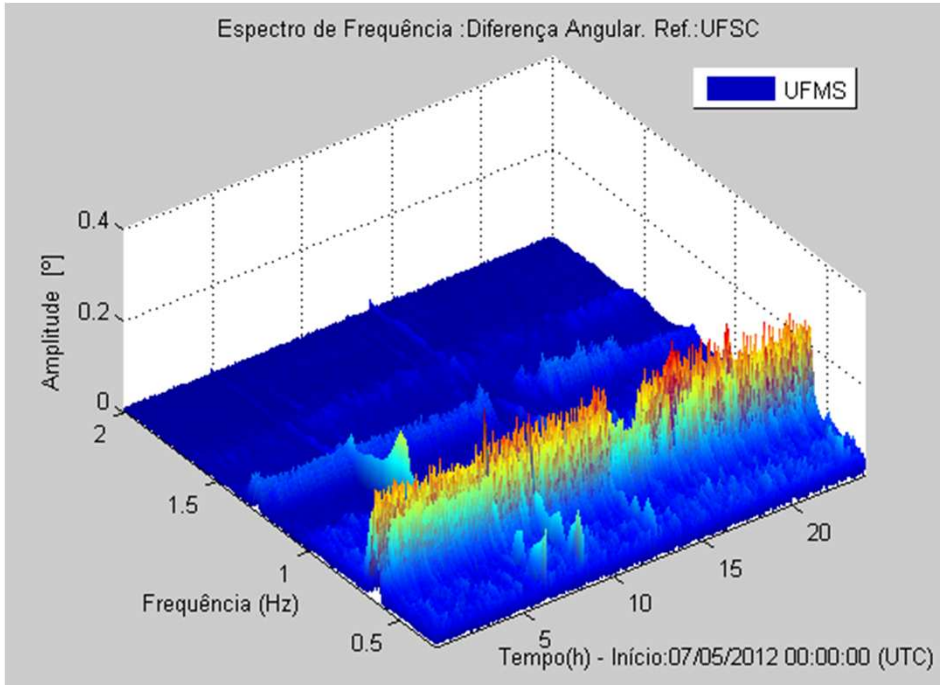
Monitoring Of Electromechanical Oscillations

- **Case 2 – Sustained oscillations in MS**
  - ✓ **Ambient Data Acquired in:**

06/05/2012



07/05/2012

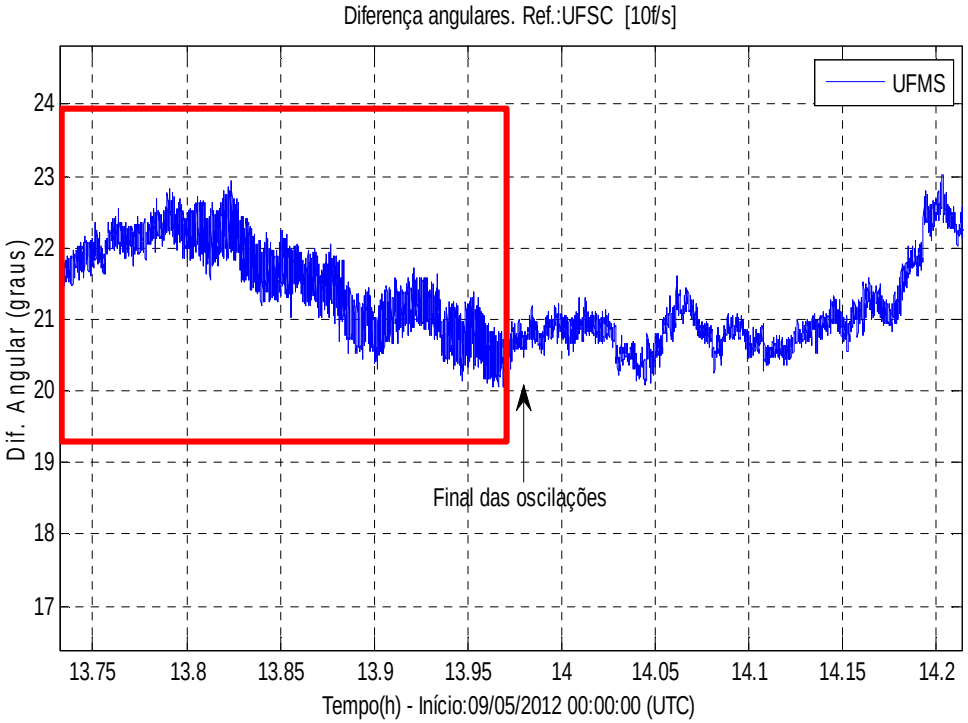


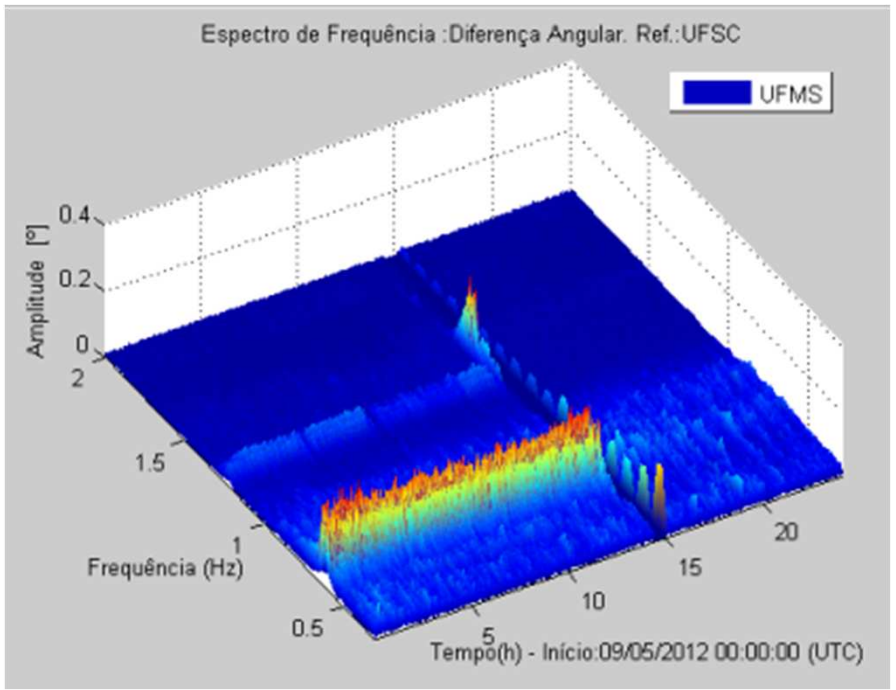
Selected Applications

Monitoring Of Electromechanical Oscillations

- **Case 2 – Sustained oscillations in MS**
  - ✓ **Ambient Data Acquired in:**

09/05/2012: Disappearance of oscillations at 13h58min (UTC)

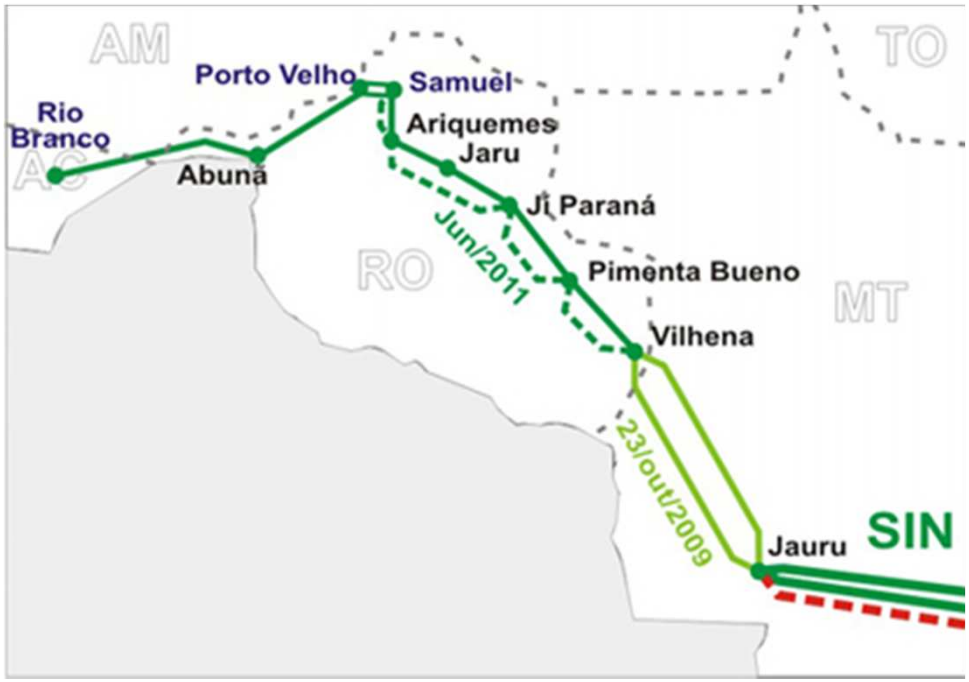




- **Cause:**
  - ✓ **Associated with biomass driven generators in Mato Grosso do Sul**

Selected Applications
Evaluation of Special Protection Schemes

- **Performance of the Acre/Rondônia Interconnection (Northwestern Brazil):**
  - ✓ **Characteristics:**
    - Acre/Rondônia Interconnection:
      - Jauru/Vilhena C.1 and C.2 (230 kV): with 354 km
    - Generation:
      - Acre: 95 MW
      - Rondônia: 740 MW



Events:

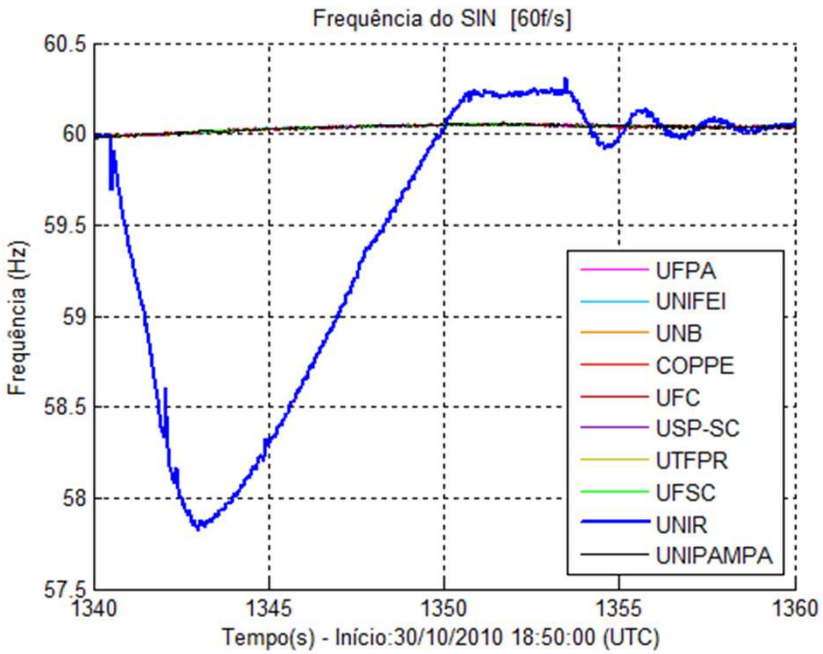
Date	Opened Circuits	Load Shedding
30/10/2010	Jauru/Vilhena C.1 e C.2	71 MW
13/11/2010	Jauru/Vilhena C.1 e C.2	120 MW
27/05/2011	Jauru/Vilhena C.1 e C.2	182 MW
24/11/2011	Jauru/Vilhena C.1 e C.2	278 MW
30/11/2011	Ji-Paraná/Pimenta Bueno	119 MW

Selected Applications

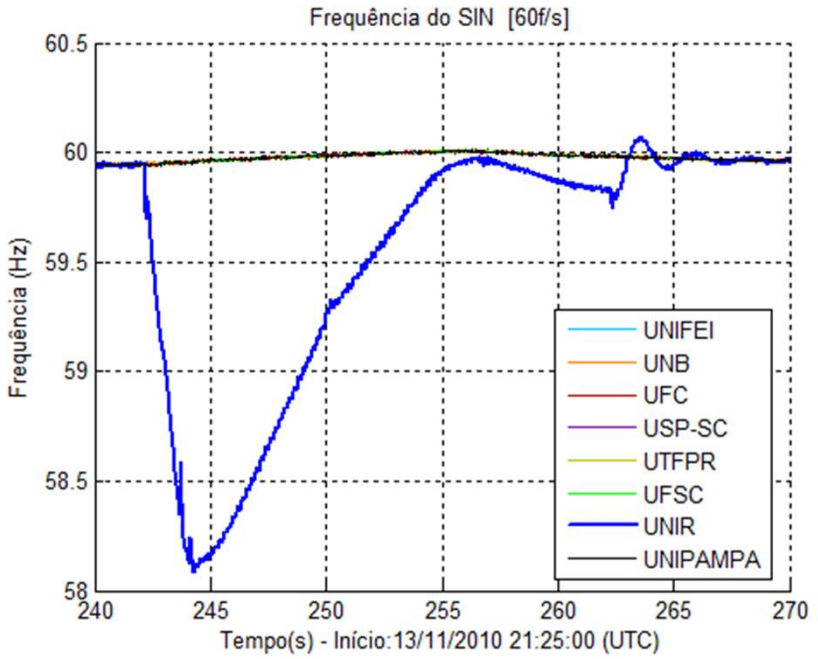
Evaluation of Special Protection Schemes

- **Performance of the Acre/Rondônia Interconnection:**
  - ✓ **Automatic Reclosing:**
    - After the line tripping, there is an automatic reclosing of the line
    - For the reclosing several values are checked:
      - Difference in phase, frequency deviation, and voltage difference

30/10/2010 **tr= 12,917s**



13/11/2010 **tr= 20,153s**



Selected Applications

Evaluation of Special Protection Schemes

- **Performance of the Acre/Rondônia Interconnection:**
  - ✓ **Load Shedding Scheme (ERAC) in islanding conditions:**
    - Settings: ERAC must act in 350 ms (maximum)

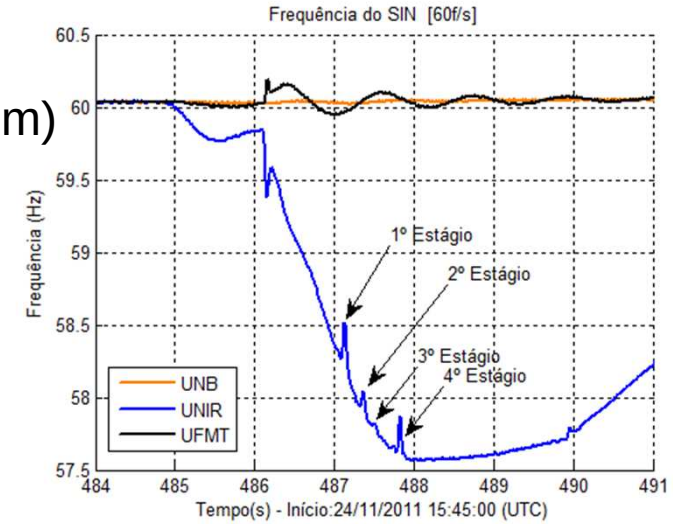
Settings:

Stage	Freq. (Hz)	Load Shedding (%)
1º	58,5	15
2º	58,2	10
3º	57,9	10
4º	57,7	10
5º	57,5	10

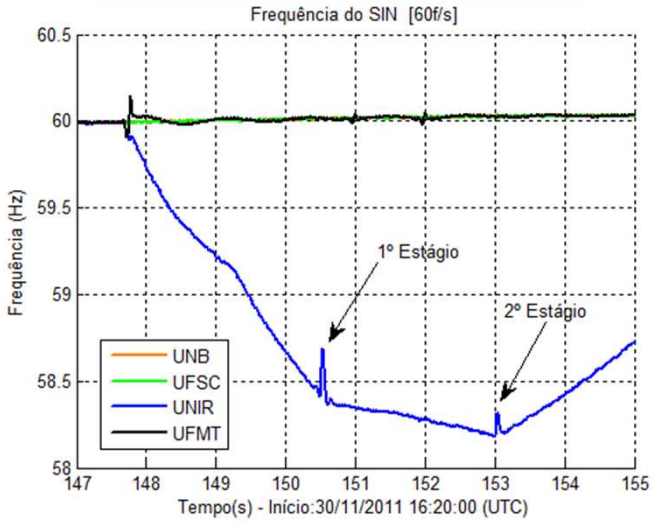
Actuation:

Stage	24/11/2011		30/11/2011	
	f	Δt	f	Δt
1º	58,27	161	58,41	169
2º	57,94	166	58,19	189
3º	57,72	166	-	-

24/11/2011:



30/11/2011:



MedFasee: the Brazilian Low-Voltage WAMS

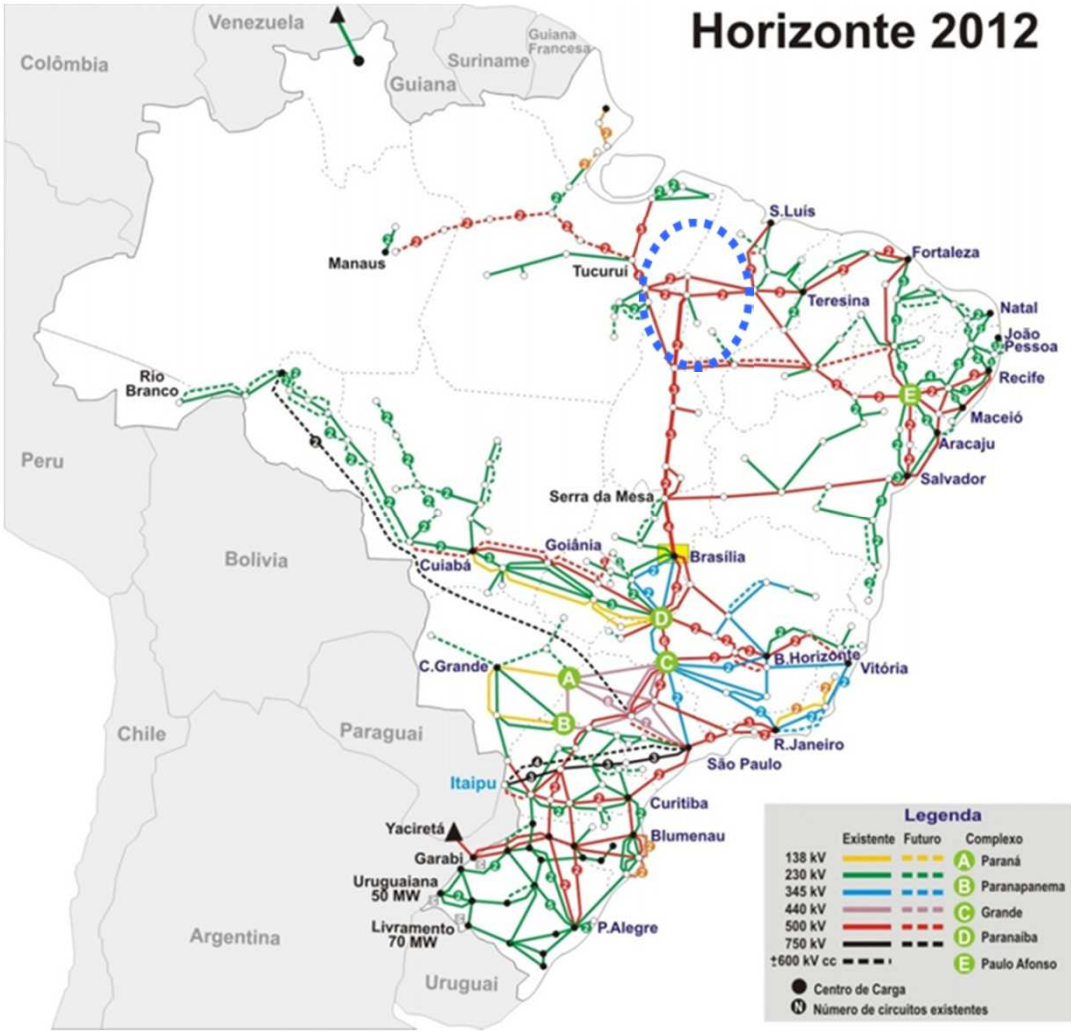
Analysis of a Disturbance in the Brazilian Power System:

- **Disturbance in the North/Northeast Subsystems – 22/09/2012**

Analysis of a Disturbance in the Brazilian Power System

Disturbance in the North/Northeast Subsystems – 22/09/2012

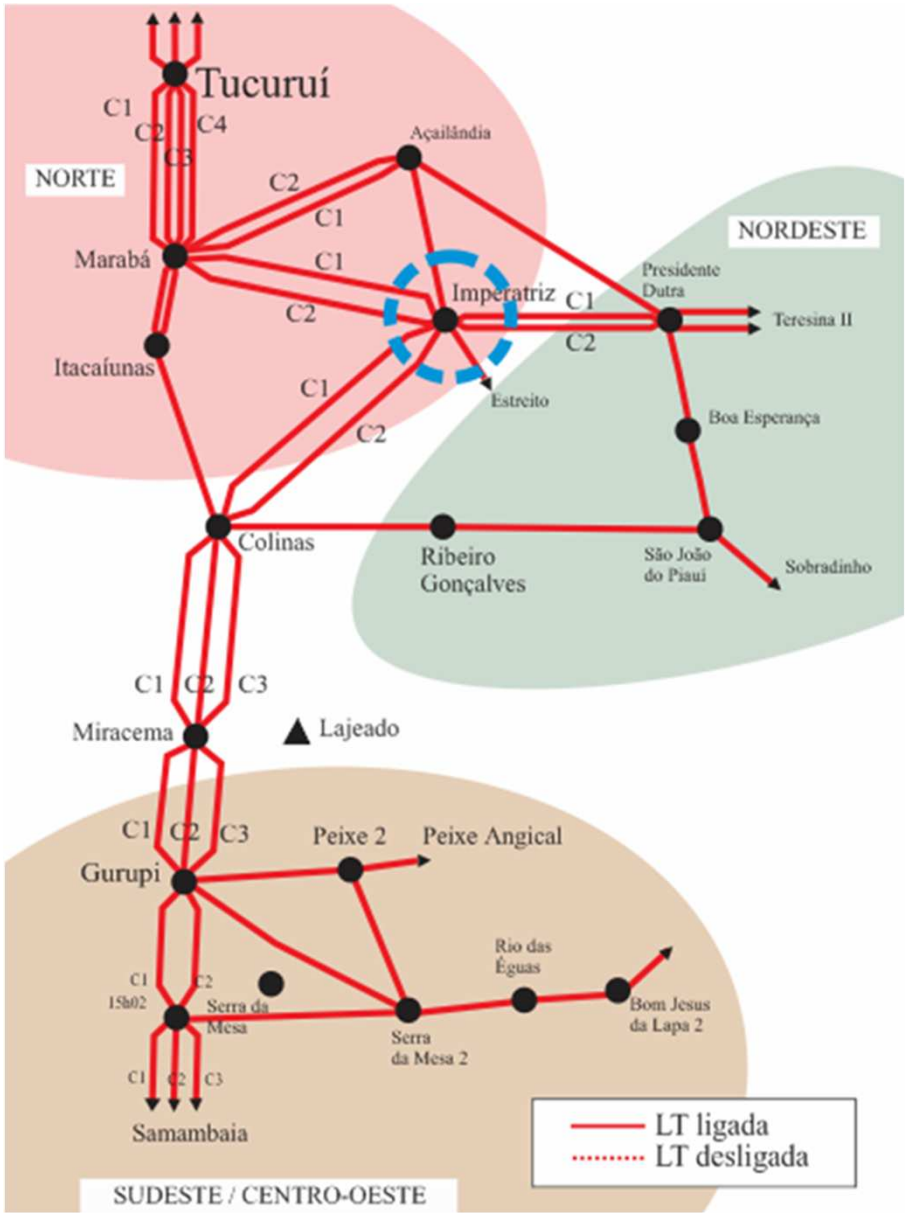
- **Event Description – Start: 18h50min (UTC)**
  - ✓ Phase to ground fault at the Imperatriz Substation:
    - 500 kV bus reactor



Analysis of a Disturbance in the Brazilian Power System

Disturbance in the North/Northeast Subsystems – 22/09/2012

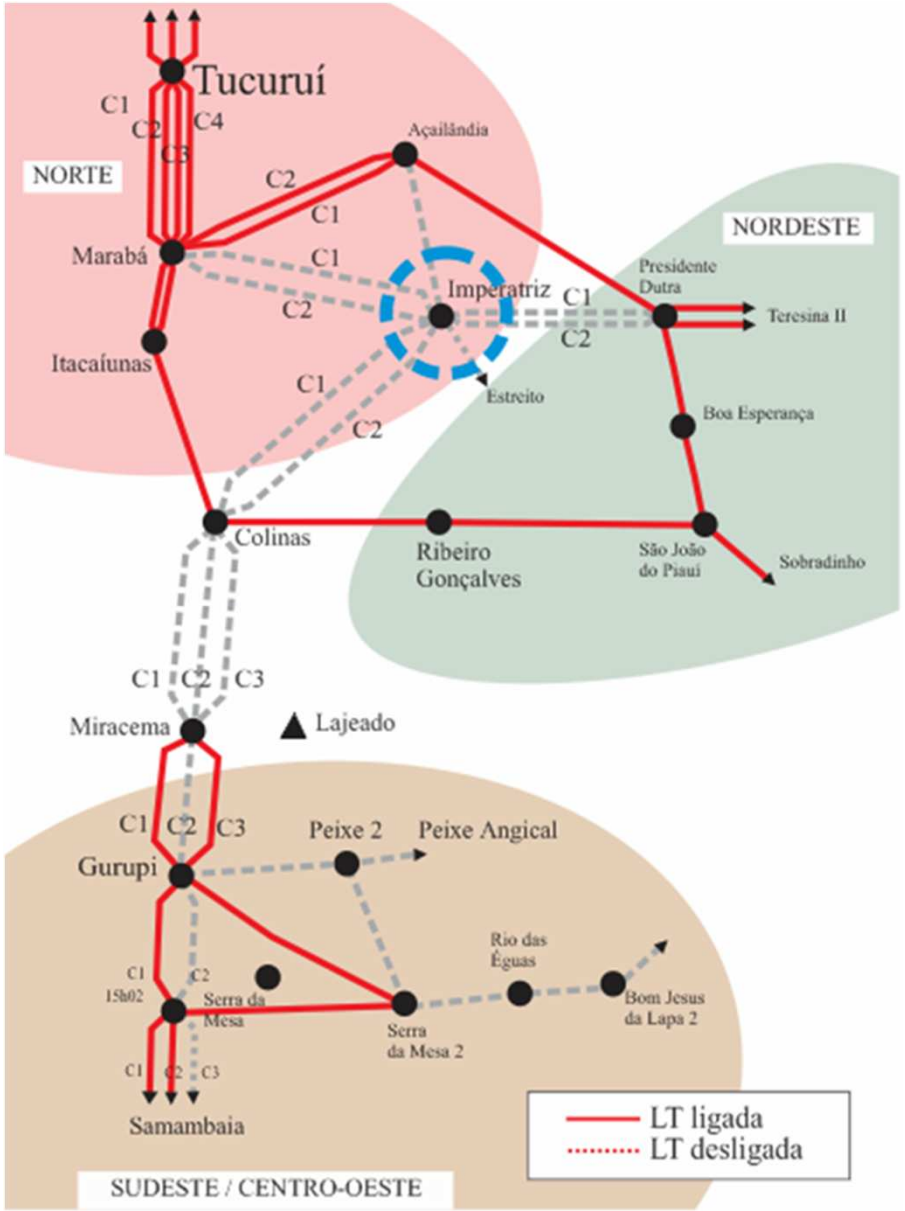
- **Event Description – Start: 18h50min (UTC)**
  - ✓ Phase to ground fault at the Imperatriz Substation:
    - 500 kV bus reactor
  - ✓ Disconnection of the Imperatriz Substation (remote protections):
    - Separation: North/Northeast – Southeast/Midwest



Analysis of a Disturbance in the Brazilian Power System

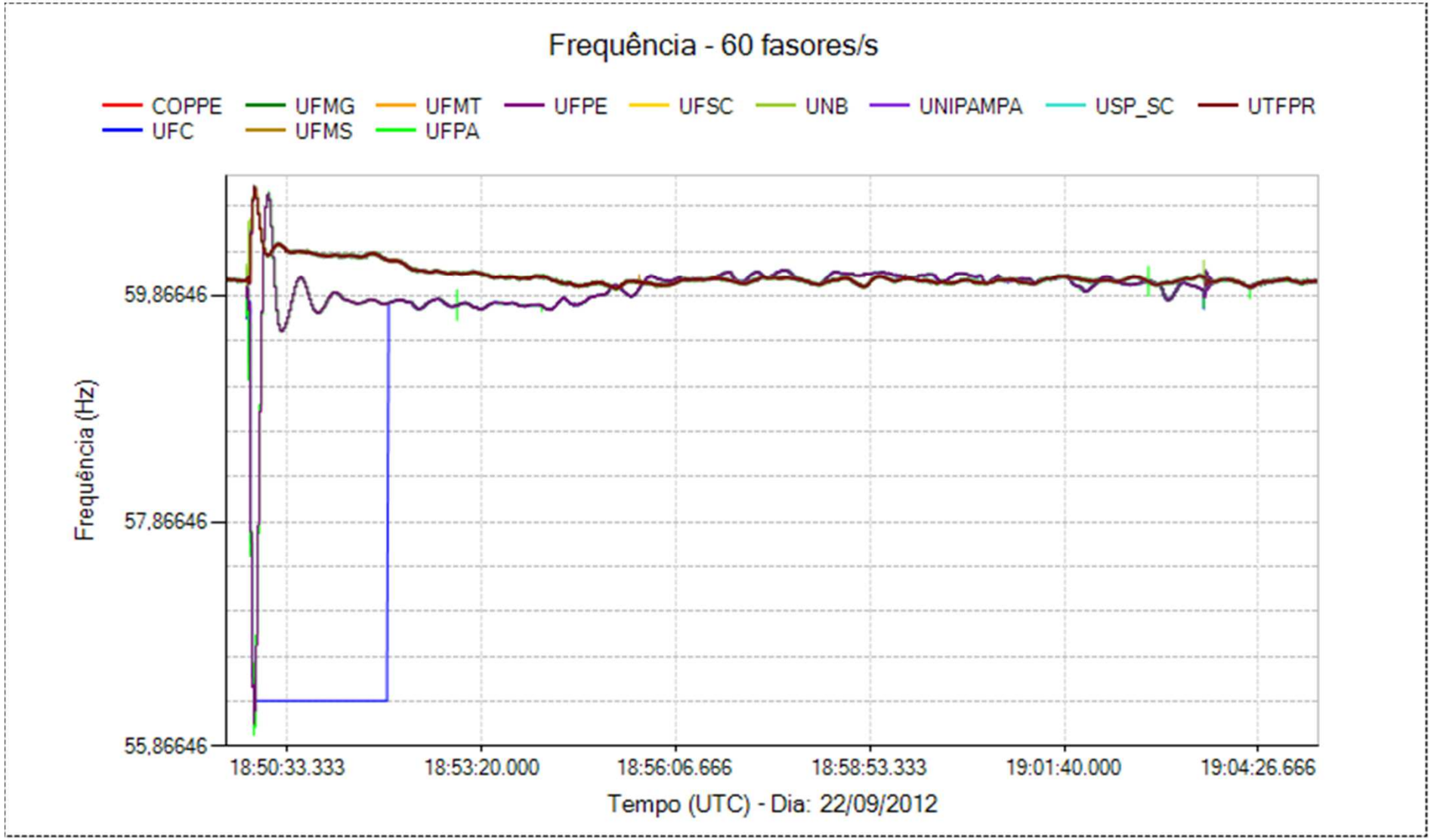
Disturbance in the North/Northeast Subsystems – 22/09/2012

- **Event Description – Start: 18h50min (UTC)**
  - ✓ Phase to ground fault at the Imperatriz Substation:
    - 500 kV bus reactor
  - ✓ Disconnection of the Imperatriz Substation (remote protections):
    - Separation: North/Northeast – Southeast/Midwest
  - ✓ North/Northeast: importing
    - 3648 MW
  - ✓ Load shedding:
    - ~ 1800 MW (North)
    - ~ 3100 MW (Northeast)
  - ✓ Sub-frequency:
    - North/Northeast: 56 Hz
  - ✓ System restoration: 19h06min (UTC)



Analysis of a Disturbance in the Brazilian Power System

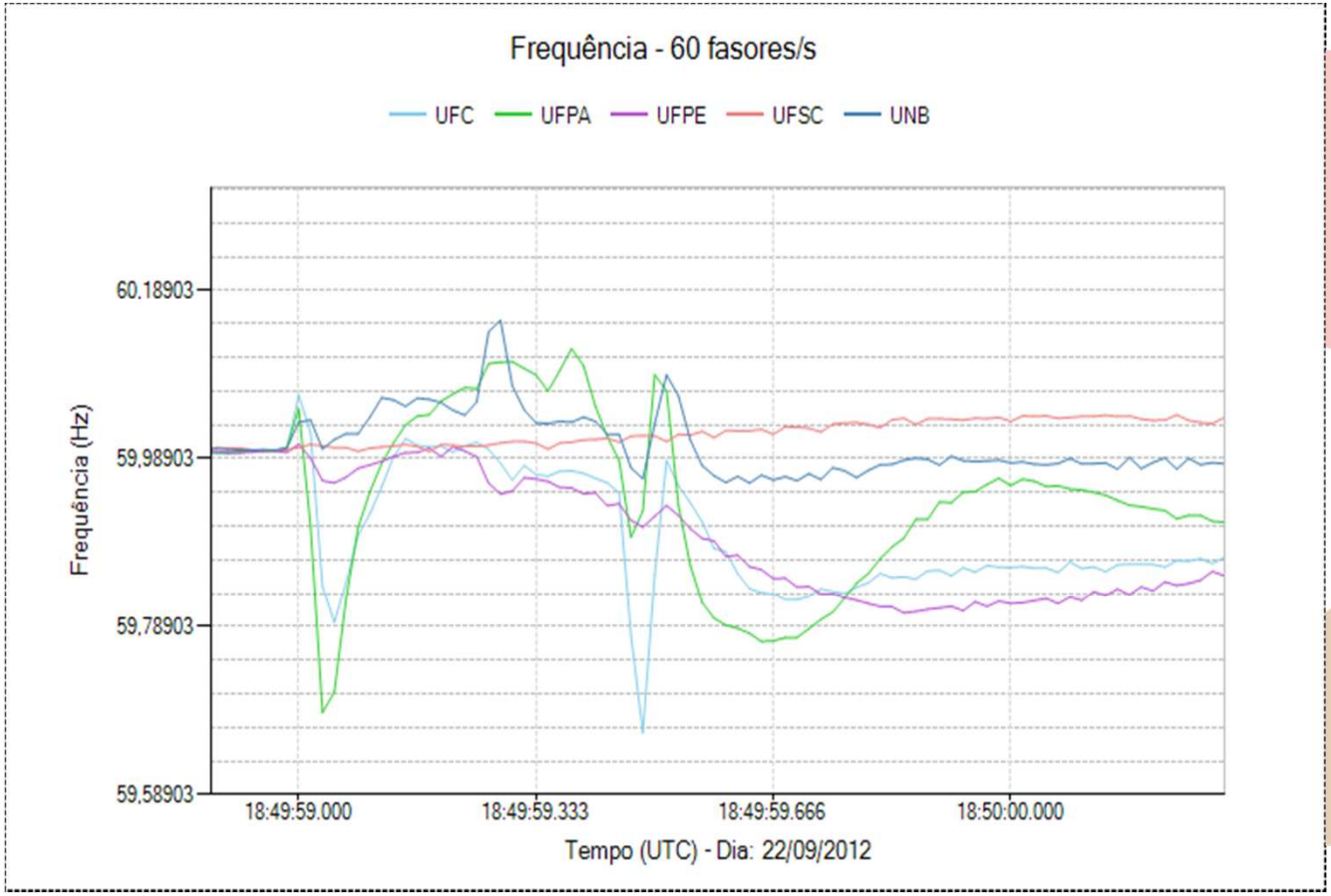
Disturbance in the North/Northeast Subsystems – 22/09/2012

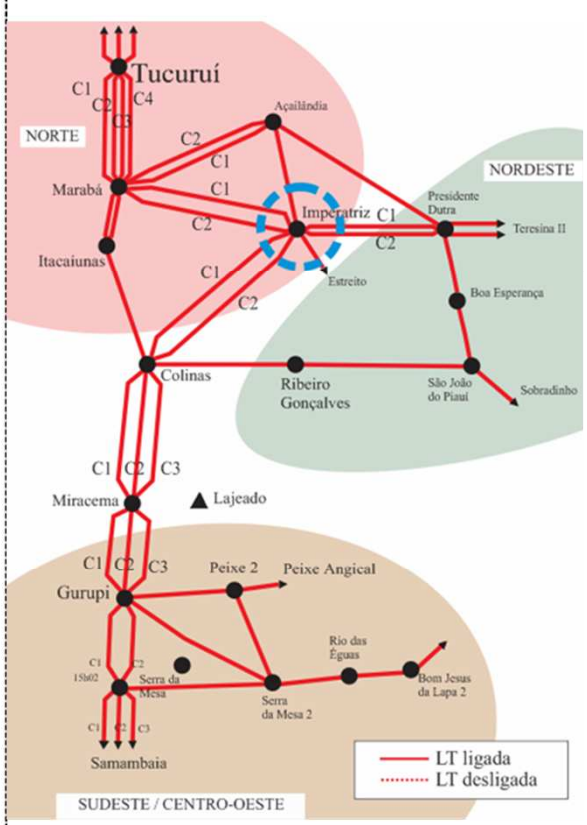


Analysis of a Disturbance in the Brazilian Power System

Disturbance in the North/Northeast Subsystems – 22/09/2012

- ✓ Fault: 18h49min59s (UTC)

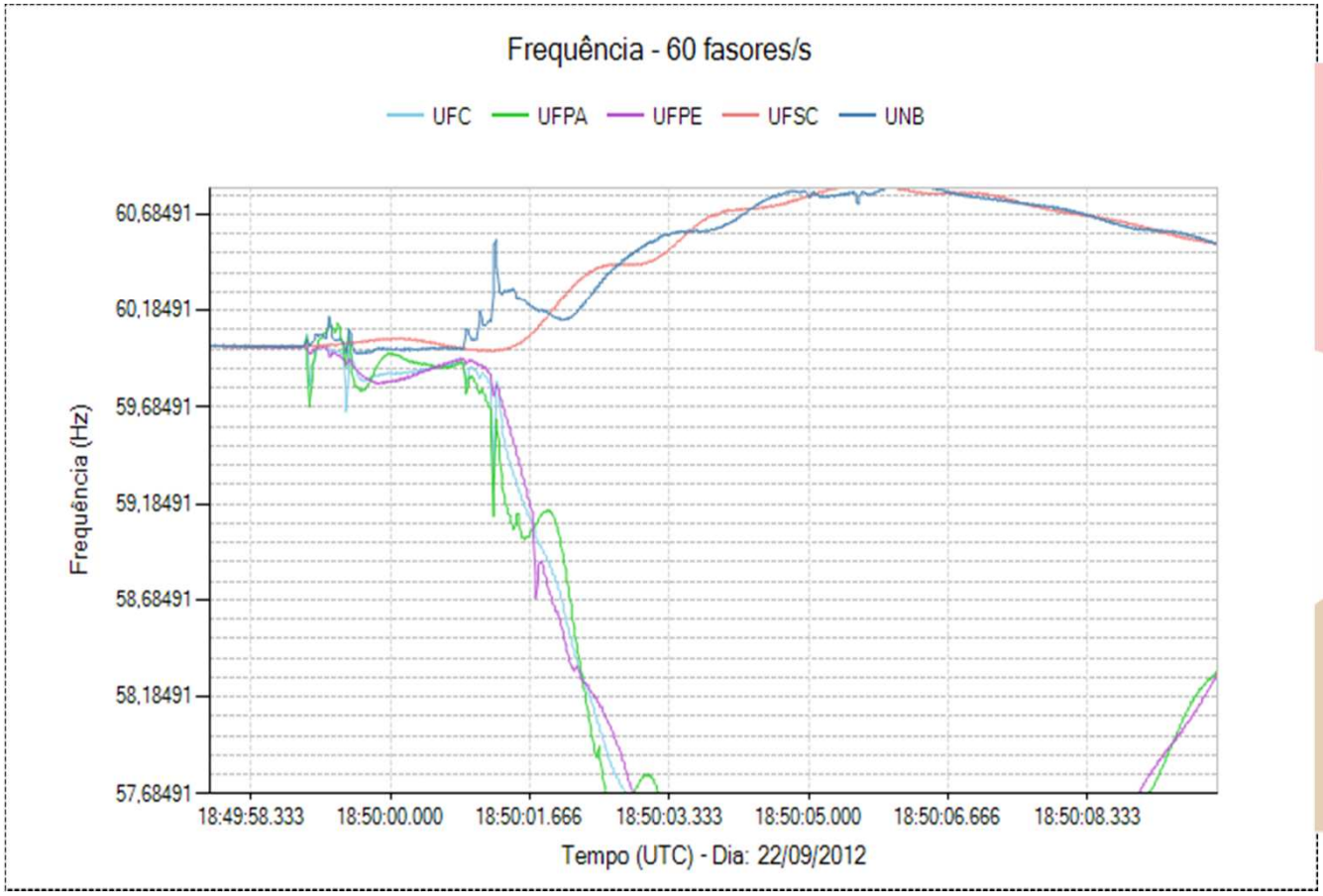


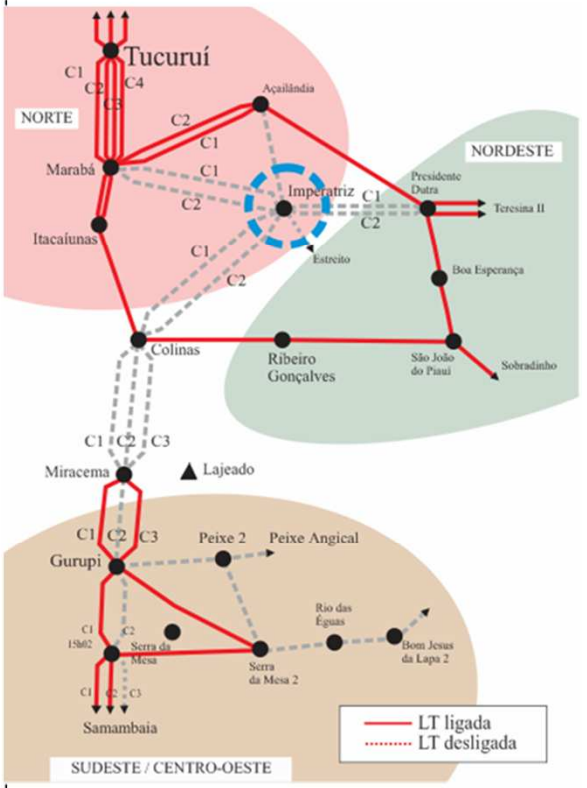


Analysis of a Disturbance in the Brazilian Power System

Disturbance in the North/Northeast Subsystems – 22/09/2012

- ✓ Opening of the North/South Interconnection: 18h50min (UTC)

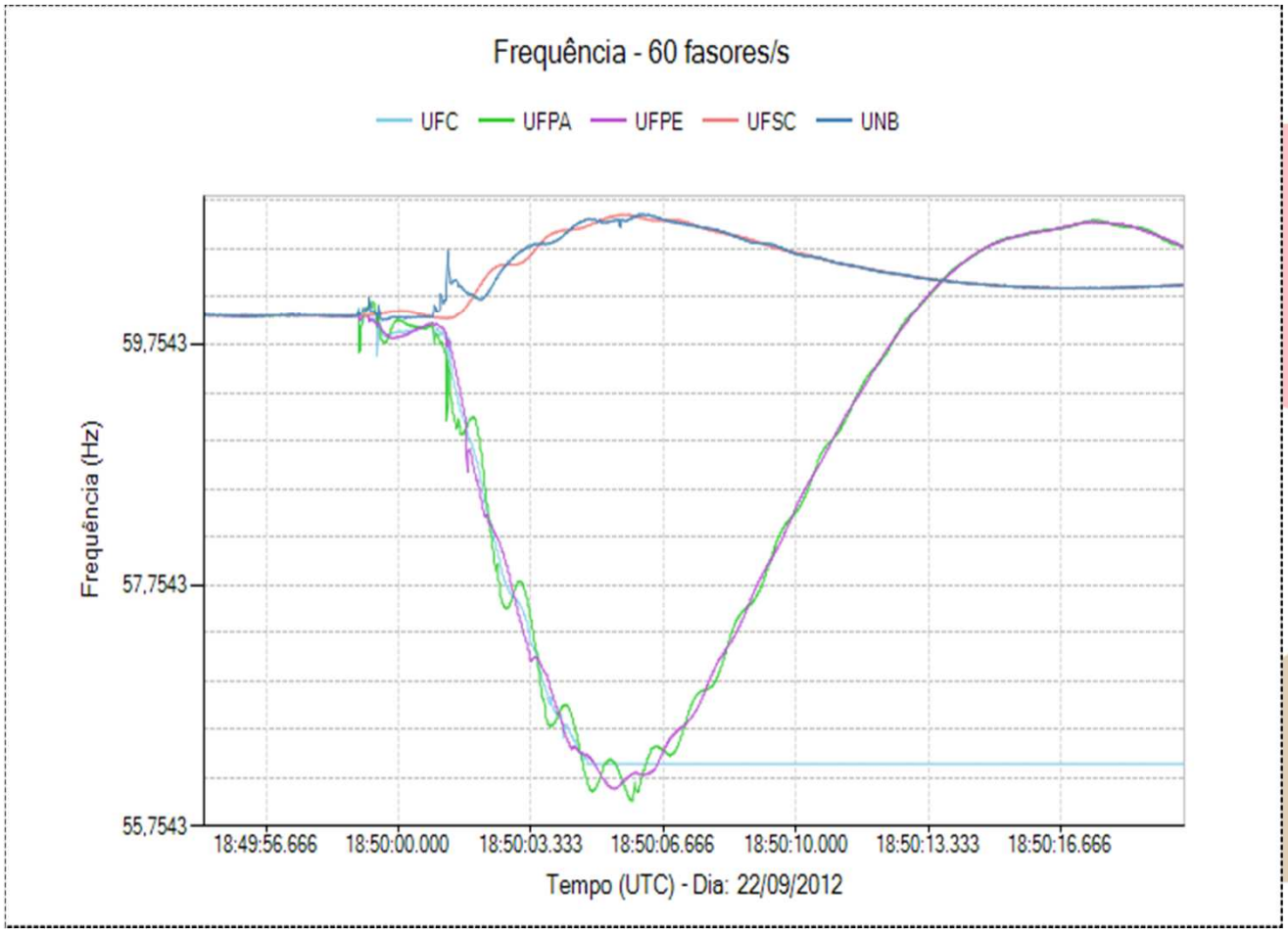


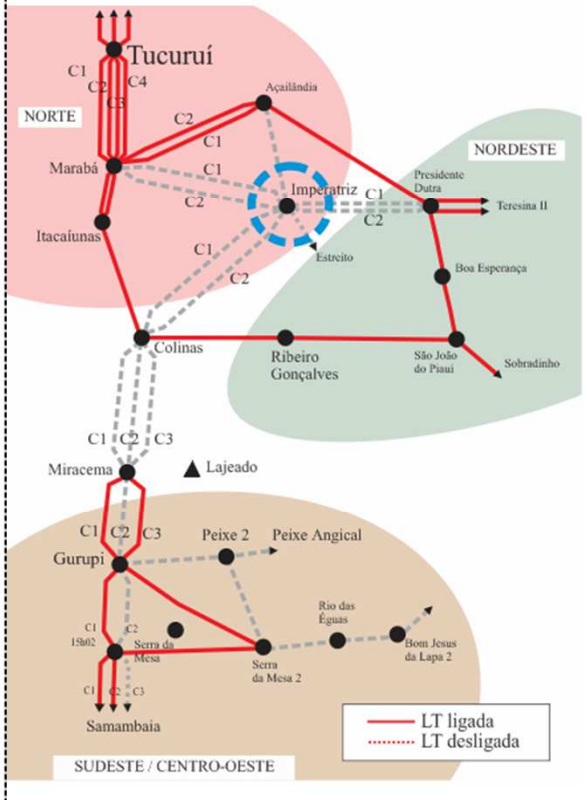


Analysis of a Disturbance in the Brazilian Power System

Disturbance in the North/Northeast Subsystems – 22/09/2012

- ✓ Frequency:

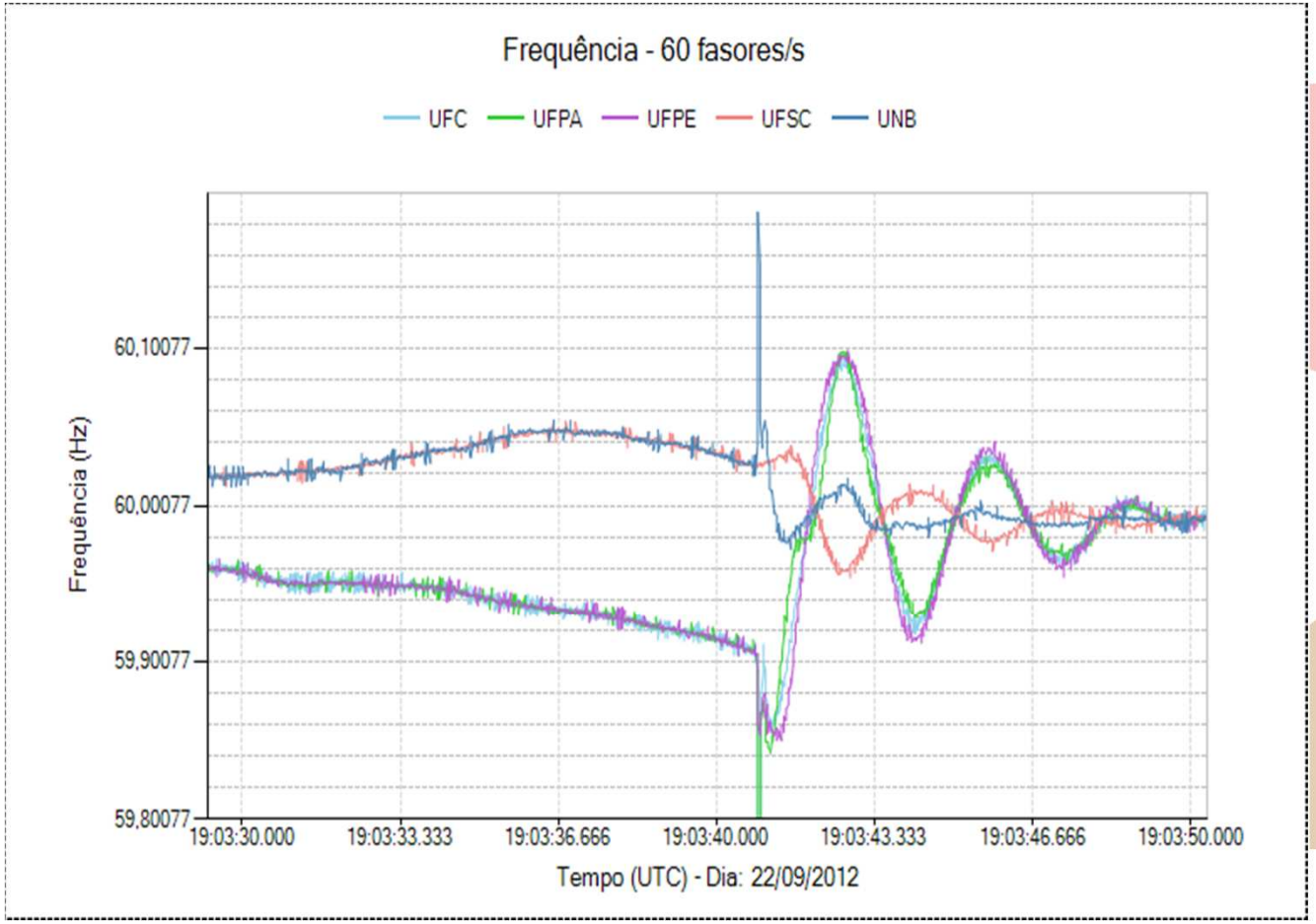


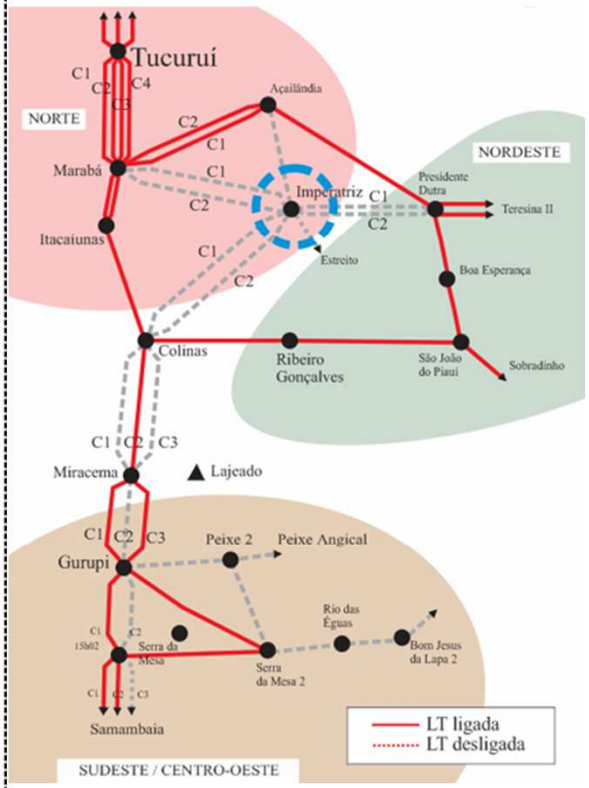


Analysis of a Disturbance in the Brazilian Power System

Disturbance in the North/Northeast Subsystems – 22/09/2012

- ✓ Reconnection North/South (Line: Colinas-Miracema C.2): 19h03min41s (UTC)

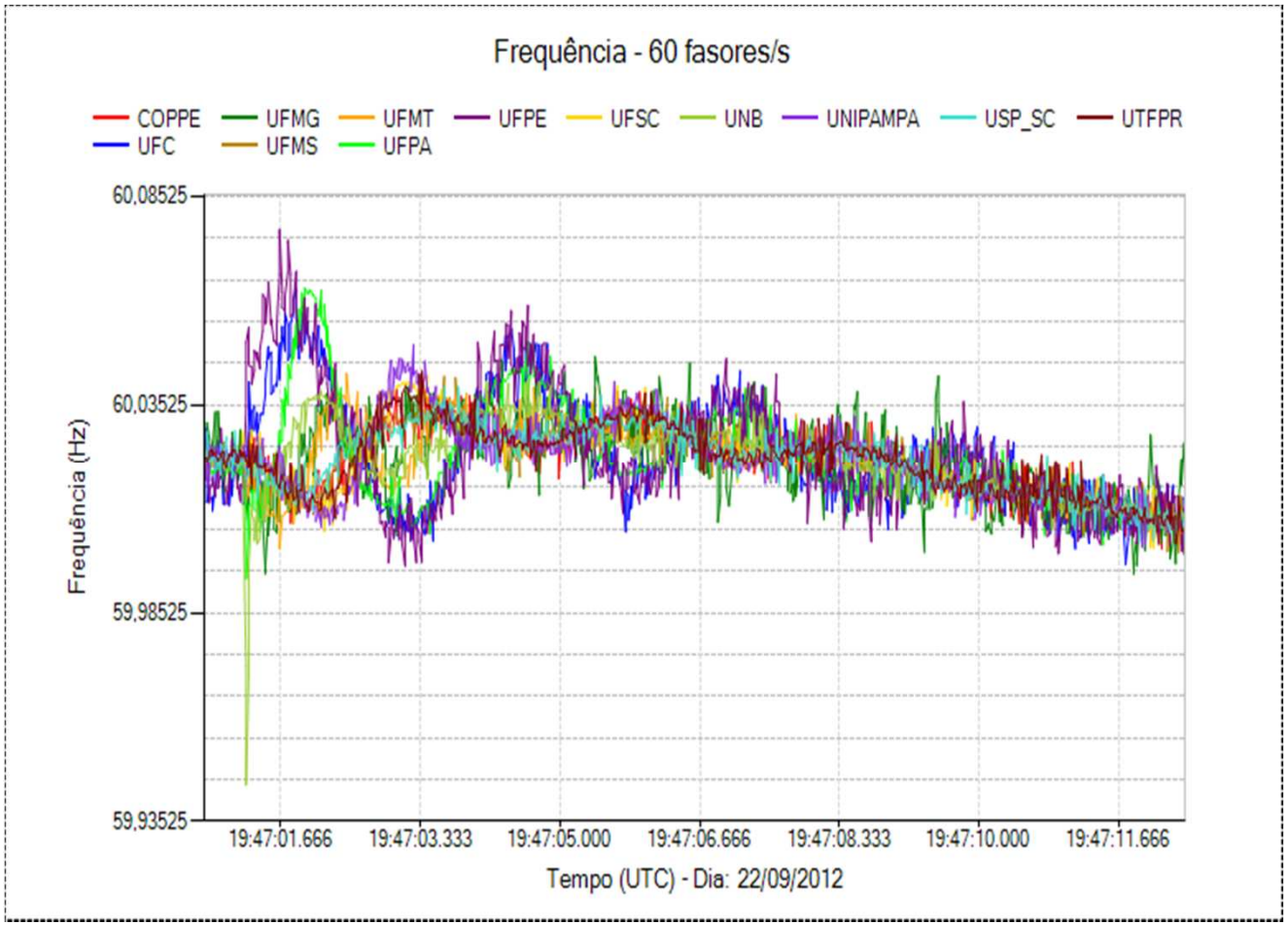


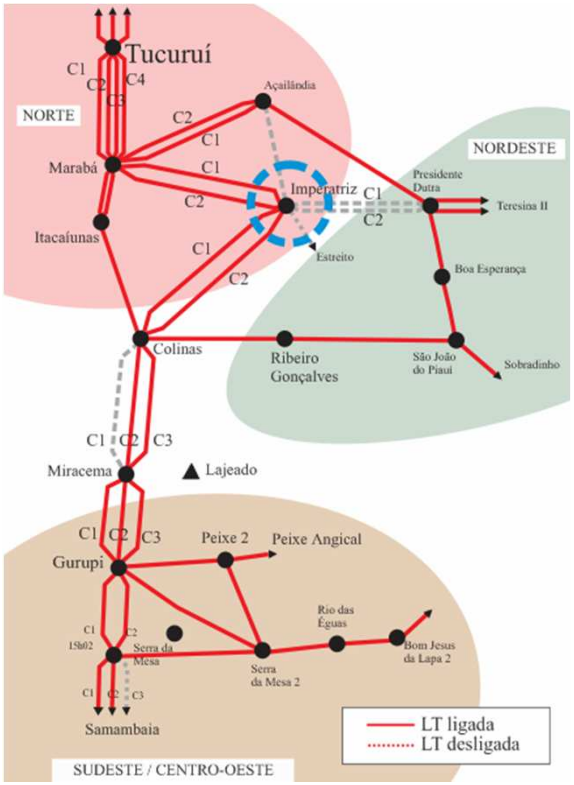


Analysis of a Disturbance in the Brazilian Power System

Disturbance in the North/Northeast Subsystems – 22/09/2012

- ✓ Reconnection Southeast/Northeast: 19h47min01s (UTC)

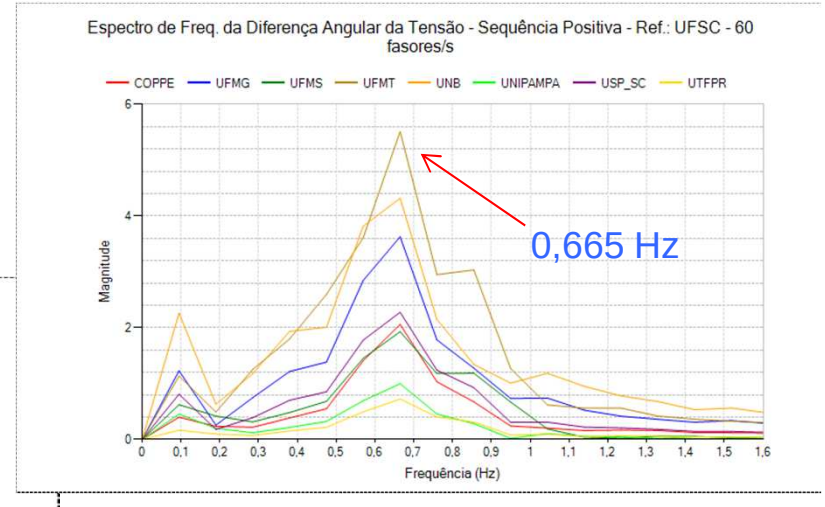


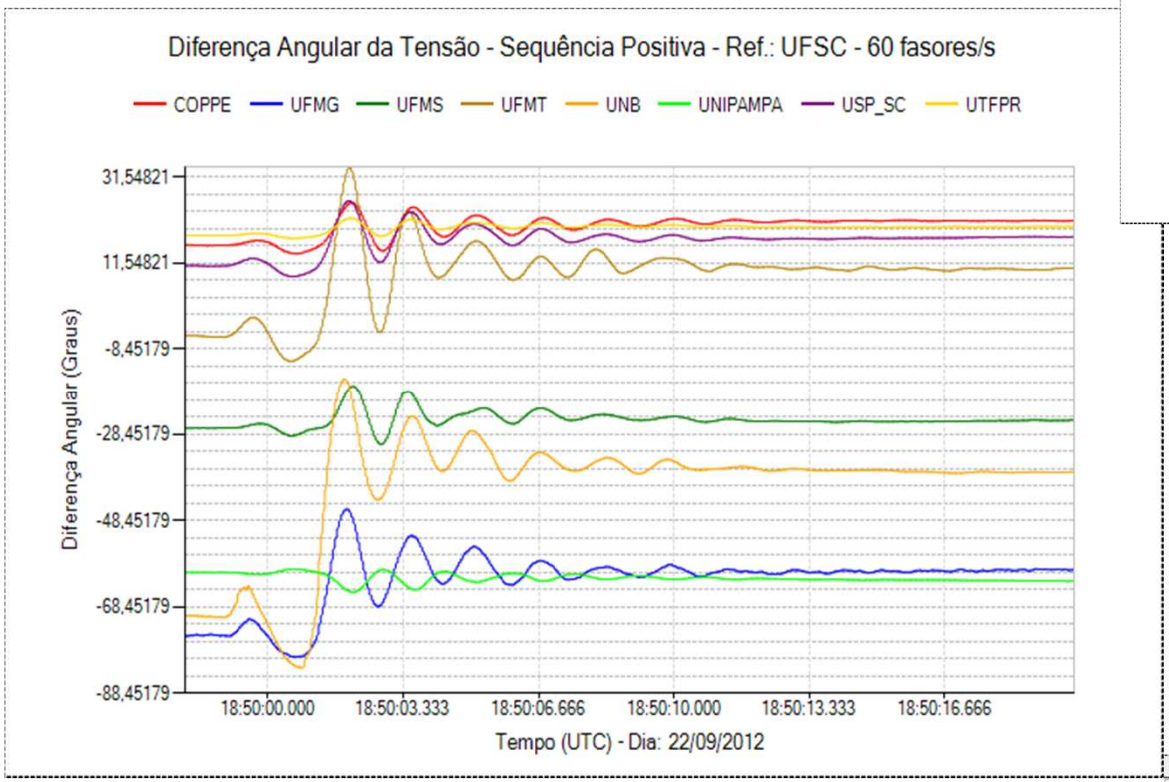


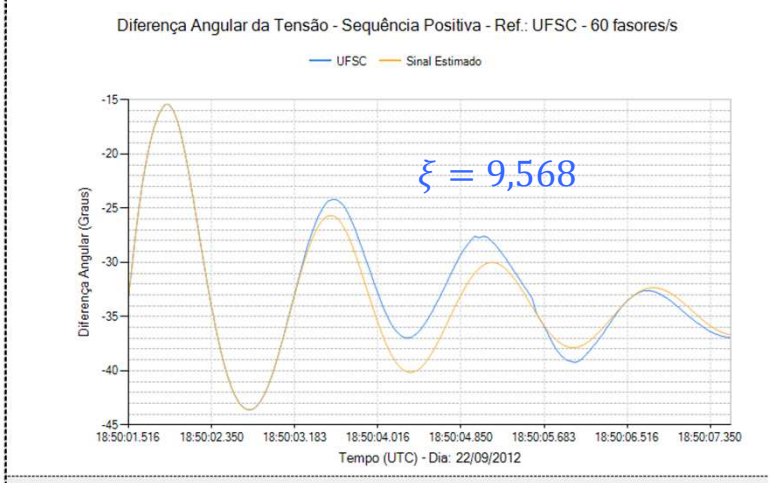
Analysis of a Disturbance in the Brazilian Power System

Disturbance in the North/Northeast Subsystems – 22/09/2012

- **Electromechanical oscillations:**
  - ✓ Angle difference:
    - South, Southeast and Midwest





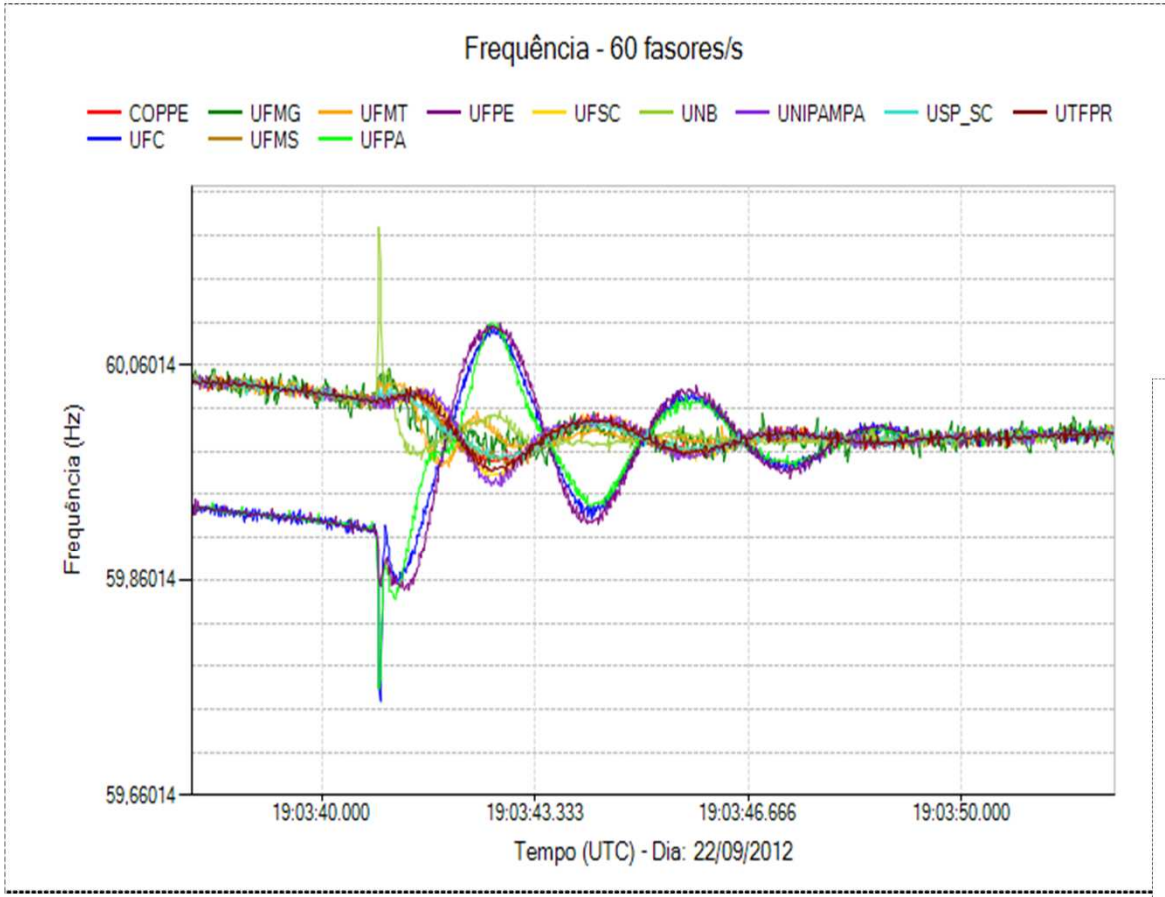


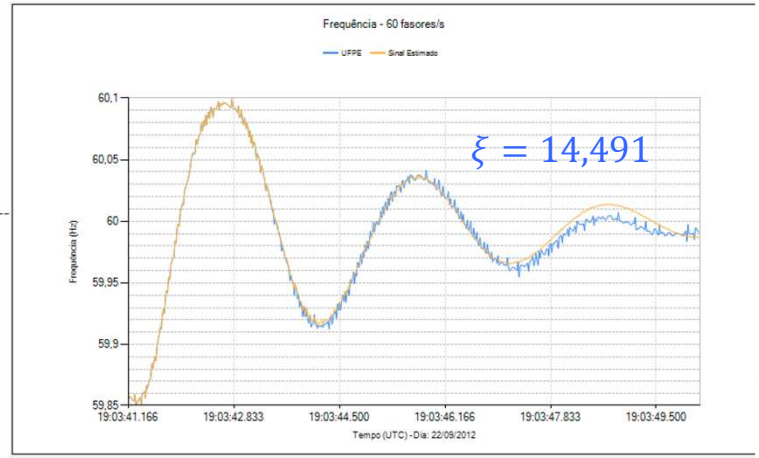
Energia	Frequência (Hz)	Amortecimento (%)	Amplitude	Fase (rad)	Real	Imaginário
173709,545	0,616	9,568	8,655	-1,684	-0,372	3,869
1076,411	1,137	15,032	1,196	-2,867	-1,086	7,142
71,792	2,891	30,441	0,741	-3,032	-5,805	18,164
6,773	1,847	6,863	0,076	-0,537	-0,798	11,605
0,553	3,192	4,201	0,023	0,609	-0,843	20,058

Analysis of a Disturbance in the Brazilian Power System

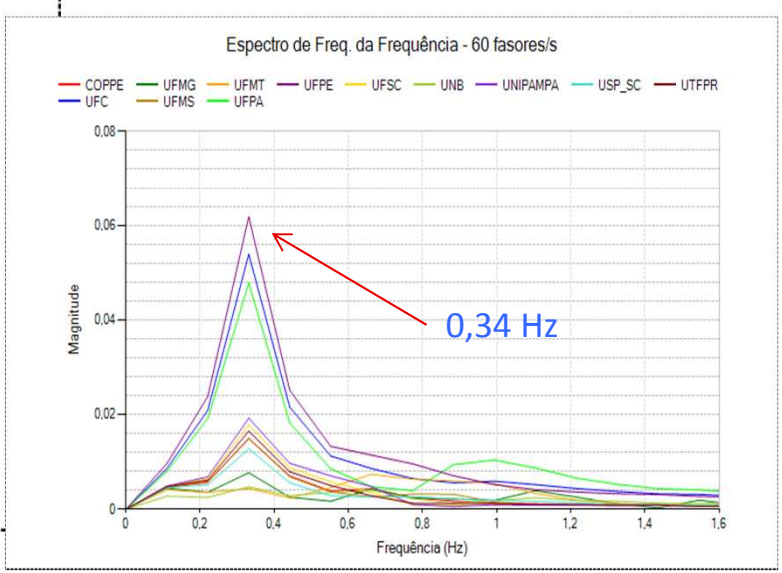
Disturbance in the North/Northeast Subsystems – 22/09/2012

- **Electromechanical oscillations:**
  - ✓ Reconnection:
    - North/South Interconnection





Energia	Frequência (Hz)	Amortecimento (%)	Amplitude	Fase (rad)	Real	Imaginário
25,626	0,332	14,491	0,09	2,896	-0,306	2,087
0,213	0,729	16,245	0,013	2,166	-0,754	4,579

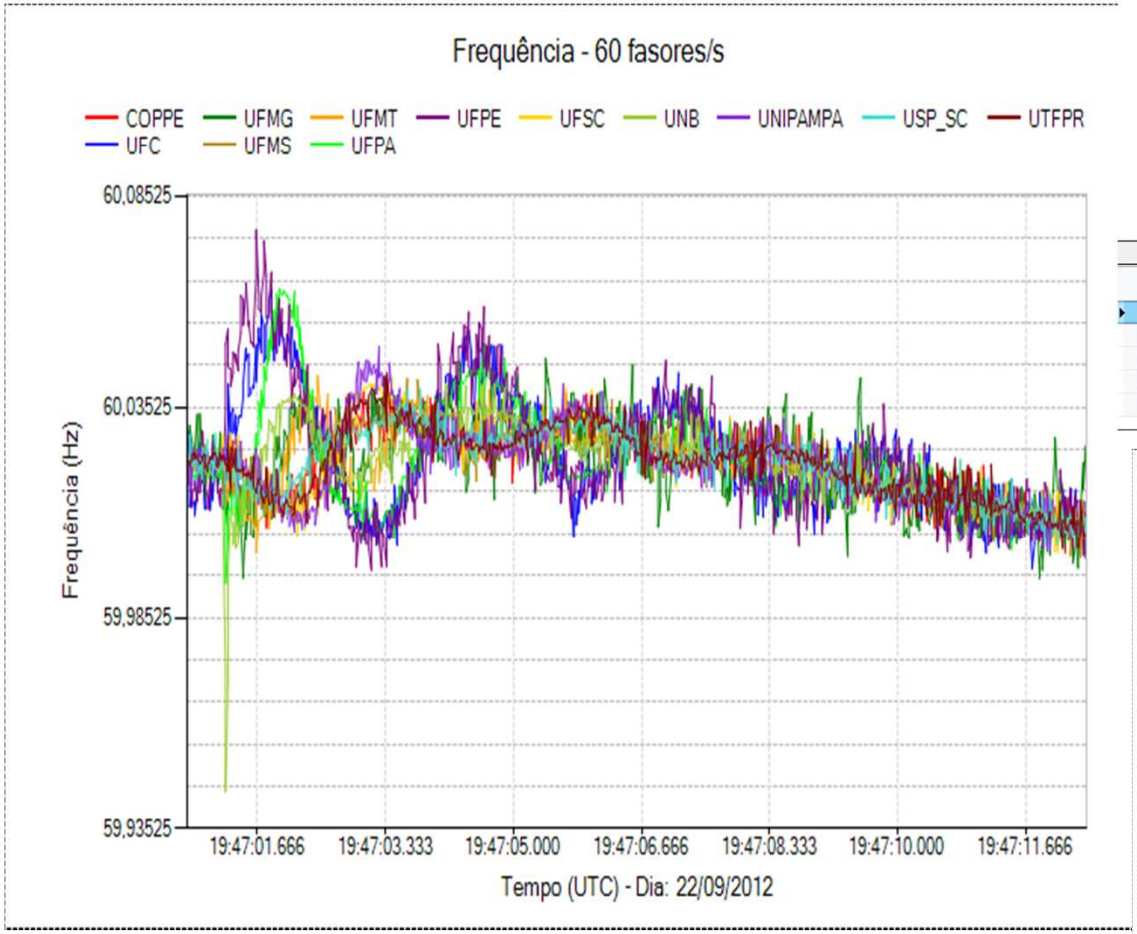


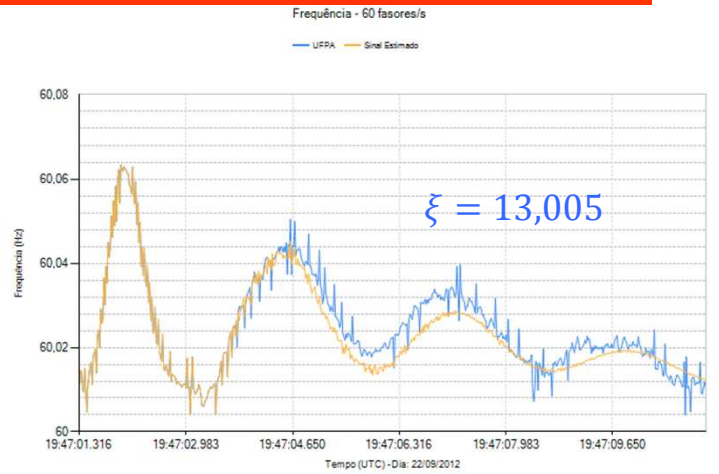
Analysis of a Disturbance in the Brazilian Power System

Disturbance in the North/Northeast Subsystems – 22/09/2012

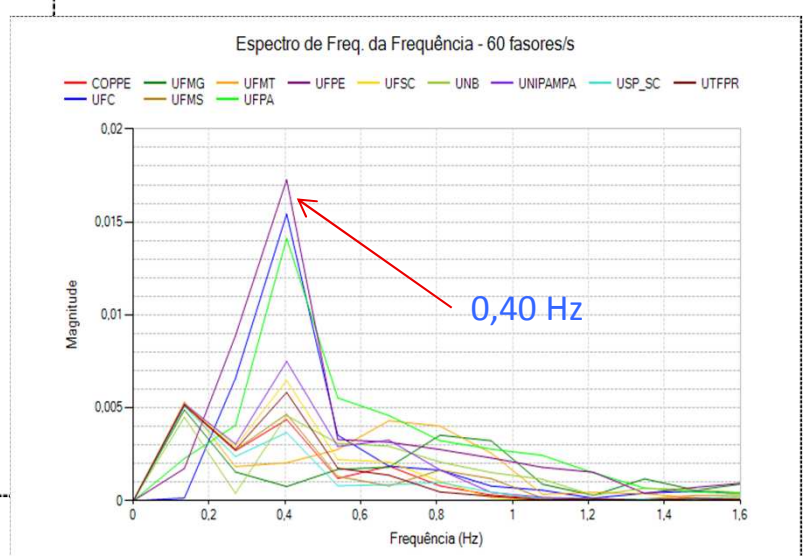
- ✓ Reconnection Northeast/Southeast:

  19h47min01s (UTC)





Energia	Frequência (Hz)	Amortecimento (%)	Amplitude	Fase (rad)	Real	Imaginário
1,222	0,365	13,005	0,019	-1,17	-0,3	2,291
0,046	1,119	12,377	0,007	0,754	-0,877	7,03
0,013	0,858	17,252	0,004	1,453	-0,944	5,391
0,002	1,798	8,043	0,001	-1,309	-0,912	11,299
0,001	4,448	3,602	0,001	-0,807	-1,007	27,948



The MedFasee CTEEP Project

A High-Voltage WAMS:

- General Characteristics
- Phasor Data Concentrator System - PDCS
- Substations and Monitored Circuits

The MedFasee CTEEP Project

General Characteristics

- **Objective:**
  - ✓ To implement a WAMS prototype at the 440 kV transmission system of the CTEEP Company (São Paulo State)

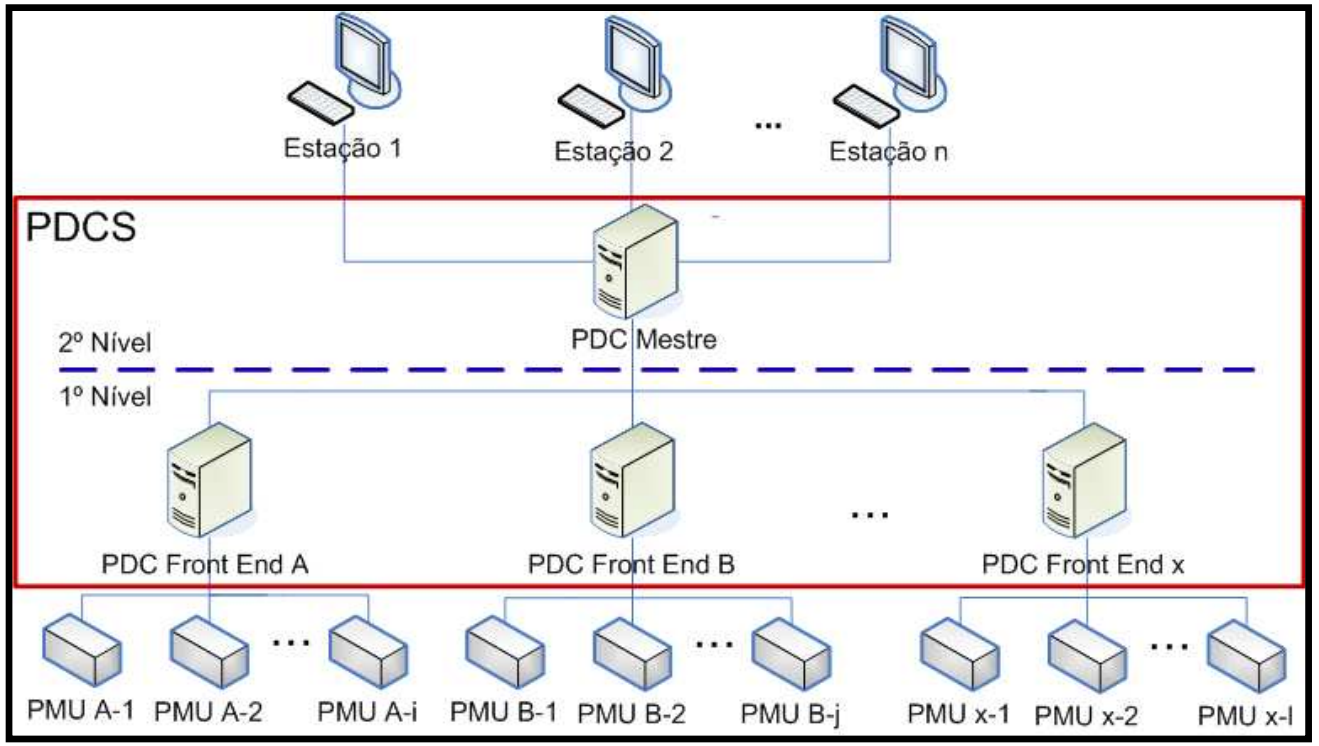
- **Developments:**
  - ✓ Installation of all system architecture composed by 5 PMUs and 1 PDCS (Phasor Data Concentrator System)
  - ✓ Customized design of the PDCS:
    - 2 hierarchical levels
  - ✓ Monitoring applications in real time
  - ✓ Applications for off-line disturbance analysis
  - ✓ Comparative analysis on the use of Current Transformers (CTs) for protection and measurement

The MedFasee CTEEP Project

Phasor Data Concentrator System – PDCS

- **Hierarquical Architecture:**
  - ✓ PDCs structure in 2 levels: Front-end and Master
  - ✓ Descentralized data aquisition
  - ✓ Redundant data store

- **Front-end PDCs:**
  - ✓ Manage the connection with the PMUs
  - ✓ Receive data from the PMUs
  - ✓ Send data to Master PDC



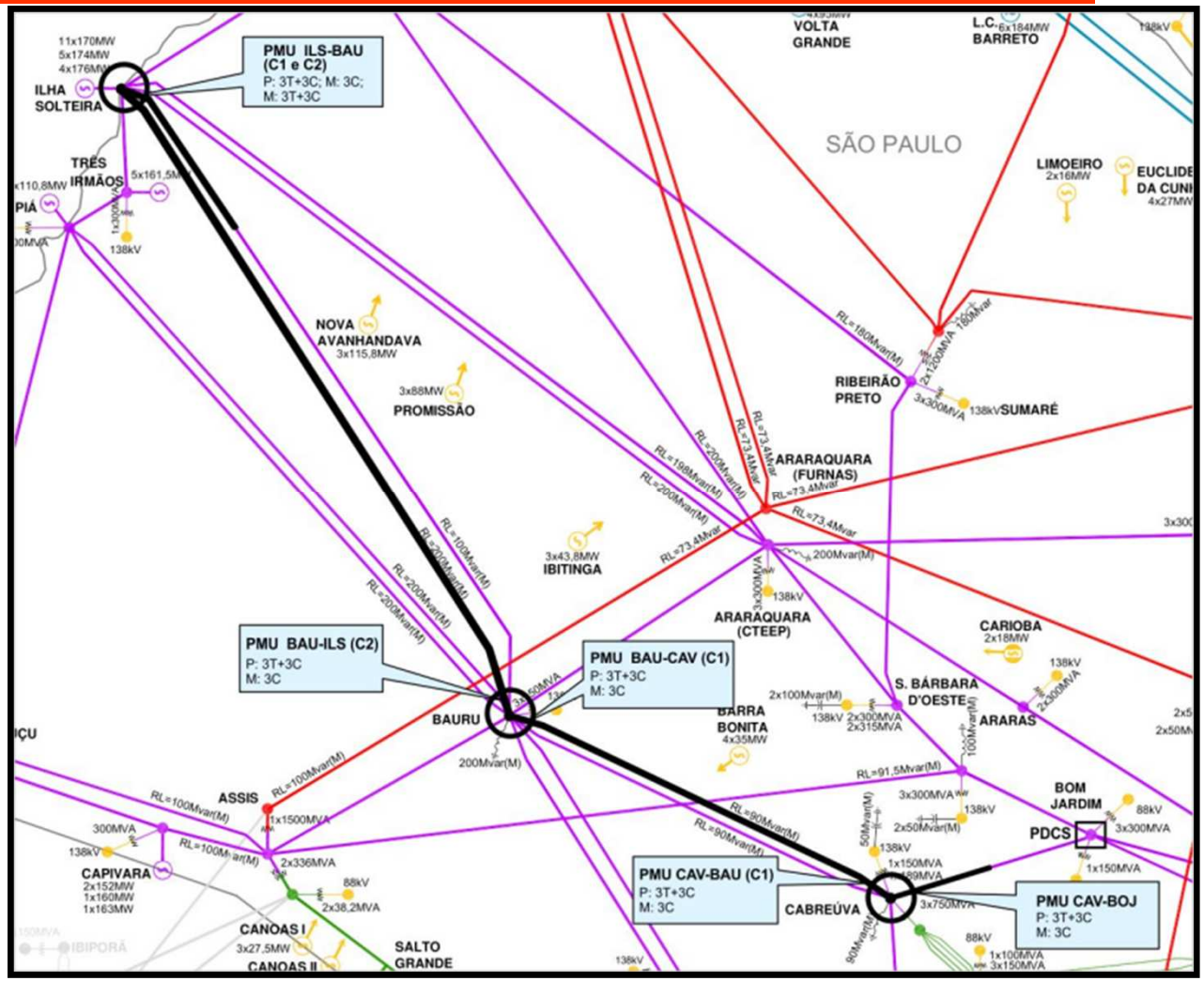
- **Master PDC:**
  - ✓ Receives data from the Front-end PDCs
  - ✓ Stores historical data
  - ✓ Provides data for real time applications

The MedFasee CTEEP Project

Substations and Monitored Circuits

- **Substations (3):**
  - ✓ Ilha Solteira: 1 PMU (RPV304)
  - ✓ Bauru: 2 PMUs (RPV304 + RPV310)
  - ✓ Cabreúva: 2 PMUs (RPV304 + RPV310)

- **Monitored Circuits (4):**
  - ✓ 440 kV Ilha Solteira – Bauru C2: both terminals
  - ✓ 440 kV Ilha Solteira – Bauru C1: Ilha Solteira Terminal
  - ✓ 440 kV Bauru – Cabreúva C1: both terminals
  - ✓ 440 kV Cabreúva – Bom Jardim: Cabreúva Terminal



Conclusions

- The project resulted in know-how and developments in all aspects of the Synchronized Phasor Measurement tecnology.
- Training of engineers and research topics for M.Sc. and Ph.D. students
- Consolidation of the manufacturer, partner in the project, as a provider of technological solutions
- Implementation of an independent system, covering all the country, which monitors the performance of the Brazilian Power System.
- Partnerships were established with Universities, Manufacturers and agents of the electrical industry.

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The MedFasee Project

Thanks for your Attention

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