Experience of WAMS Development and Applications in Brazil

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Abstract - In this paper, the development and applications of WAMS (Wide Area Measurement Systems) in Brazil is presented. Currently, all geo-electric regions of the country are covered by a low voltage WAMS. Monitoring of oscillation modes, evaluation of controllers robustness, assessment of protection settings, model validation and large events and black-outs diagnosis are the main applications to the Brazilian Interconnected System and are described in the paper.

Keywords - WAMS, PMU, Power System Dynamics

1 Introduction

THE Brazilian Interconnected Power System (BIPS) is a large system covering an extensive geographical region. It has several main transmission corridors associated to the Itaipu and Tucuruí large power plants and to the interconnection between the Northern and Southeastern regions. Isolated power systems in the Northern region are being interconnected to the rest of the system and new generation plants are being built in the Amazon region. BIPS constitutes an environment suited to assess the benefits brought by the WAMS technology.

The development of synchronized phasor measurements in Brazil started in 2003 aiming to develop and disseminate the new technology and to acquire real system data for educational purposes. The small initial prototype evolved to a nation wide system covering all geo-electric regions of the country. The project academic origin led to a low voltage system where the measurements are carried out at outlet voltage. One result of the project has been the analysis of BIPS using low-voltage recordings, allowing the evaluation of the benefits and limitations of the application of WAMS to the BIPS. The results have shown the capability of a synchronized phasor measurement system to provide significant information on the BIPS performance and data acquired by the WAMS have been used by the System Operator.

In this paper an overview of the experience and benefits of the utilization of WAMS in Brazil is presented. The characteristics and expansion of the WAMS is described and its main applications and results are discussed.

The paper is organized as follows. In Section 2, the Brazilian Interconnected Power System is depicted. In Section 3, the MedFasee WAMS Project is described. In Section 4, applications to the BIPS are presented. Finally in Section 5, the paper closes with an evaluation of the current results and the potential benefits of a future larger scale application of synchronized phasor measurements to the BIPS.

2 The Brazilian Interconnected Power System

The BIPS has an installed capacity of about 100 GW, with predominant hydroelectric generation (about 70%). The high voltage transmission grid has about 90000 km of transmission lines, with voltages ranging from 230 kV to 765 kV.

The system comprises five geographical regions: North, Northeast, South, Southeast and Midwest. All these regions are interconnected. There are several small isolated power systems in the Northern region.

The largest powerplant, Itaipu, has 20 generators with a generation capacity of 14000 MW, half in 60 Hz and half in 50 Hz. Itaipu 60 Hz generated power is transmitted to the Southern and Southeastern regions by three transmission lines of 765 kV. Most of the 50 Hz generated power is transmitted to the Southeastern region by a 600 kV DC link with the remaining generation supplying Paraguay.

BIPS is characterized by vast areas with dense population and load concentration with a strong network. These areas are connected by a few very long transmission lines, going through sparsely populated regions.

Recently, isolated systems in the Northern region were or are being connected to the rest of the system in order to meet the requirements of a growing economic activity in regions close to the country Northern borders. Long transmission lines are required for these connections. The construction of large hydroelectrical powerplants in the Amazon region (Madeira River) will require 2500 km long lines to supply the main load in the Southeastern region.

As a large interconnected system, BIPS has several interarea oscillation modes. Their frequency ranges are presented in Table 1. These oscillation modes are well damped but in several operating conditions their damping can be reduced.

Mode	Frequency range (Hz)
North-South	0.20-0.40 Hz
South-Southeast	0.60-0.80 Hz
North-Northeast	0.55-0.65 Hz
Mato Grosso state-BIPS	0.55-0.65 Hz
Rio de Janeiro state-BIPS	0.40-0.45 Hz
São Paulo state-BIPS	0.65-0.75 Hz

Table 1: BIPS interarea oscillation modes

The BIPS is presented in Figure 1.

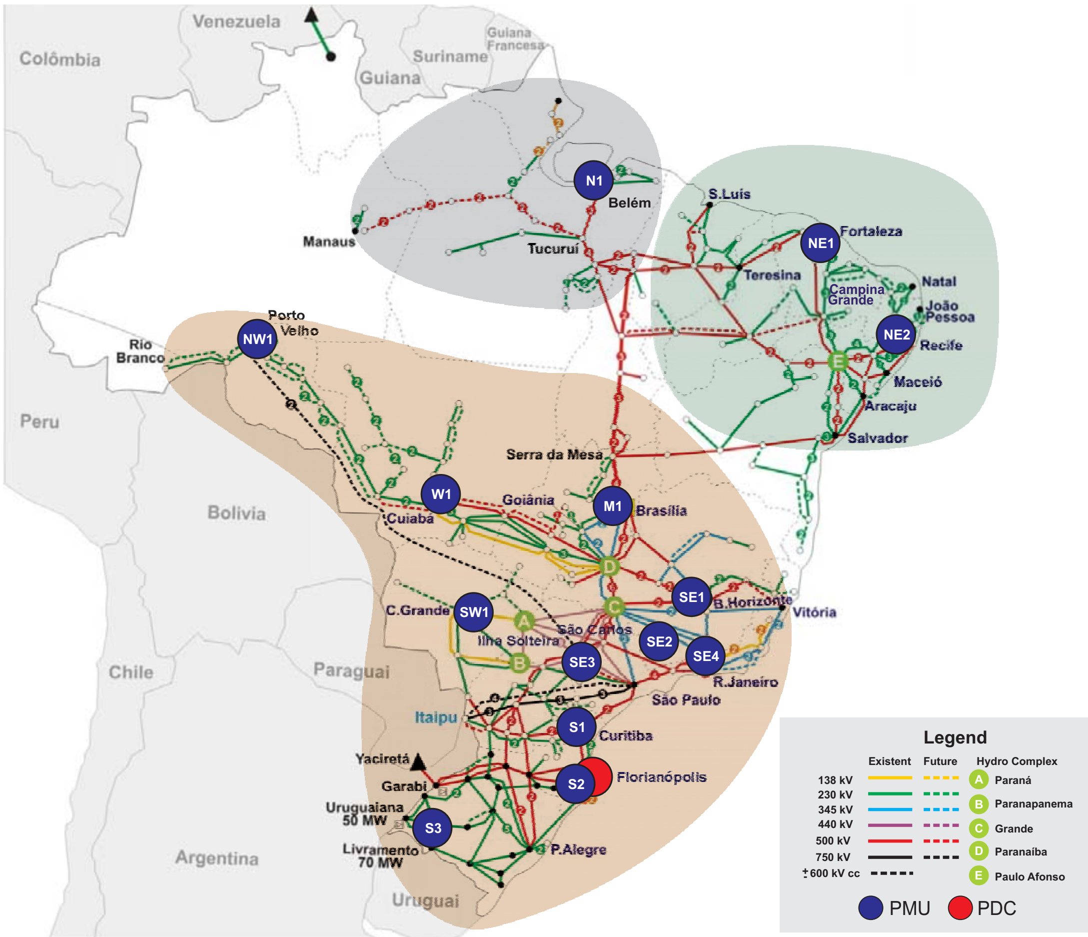

Figure 1: Brazilian Interconnected Power System

3 The MedFasee WAMS Project

The MedFasee project started in 2003 with the main goal to develop the synchronized phasor measurement technology in Brazil and study its applications [1]. The project was developed in three phases.

3.1 *Phase I*

A first prototype with three Phasor Measurement Units (PMUs) and a Phasor Data Concentrator (PDC) was completed by the end of 2004. The PMUs were installed at three universities in Southern Brazil. The PMUs measured the three-phase outlet voltage. The phasors were sent to a PDC installed at Federal University of Santa Catarina (UFSC) in Florianópolis, Santa Catarina state. Although commercial alternatives were available at the time, the PMU prototypes and the PDC were totally developed by the MedFasee team [1] in order to acquire know-how in WAMS technology.

The PDC ran the GNU/Linux operating system with the RTAI for real-time support. Its functions were implemented using the Object Oriented Modeling paradigm and C++ programming language and adhered to the IEEE 1344/95 Standard.

3.2 *Phase II*

In 2008, the prototype was expanded, with the installation of PMUs in another six universities around the country. Since the results from Phase I had shown that from the low voltage relevant information on the high voltage system could be acquired, this expansion would allow a wider monitoring of the BIPS, covering most of its geo-electric regions.

The old PMU prototypes were replaced by new equipment and the PDC was redesigned following the IEEE 37118/2005 standard.

3.3 *Phase III*

In 2010, five PMUs were incorporated to the low voltage WAMS, improving the BIPS observability and covering all BIPS geo-electric regions. The current prototype, with the locations of the PMUs and the PDC, is shown in Figure 1. The labels attached to the PMUs are used for identification in the graphics throughout the paper.

Although the PDC developed for the project was kept, a hierarchical architecture was developed, aiming an application to a Brazilian utility. The openPDC, freely provided by Tennessee Valley Authority (TVA), is currently integrated to the WAMS prototype as a Front End PDC. It has been tested and its performance is comparable, for the project purposes, with the MedFasee PDC.

4 Applications to BIPS

The applications for the evaluation of the BIPS performance constitute the main topic of this paper. The main applications presented are:

1. Monitoring of electromechanical oscillation modes
2. Evaluation of system controls performance and robustness
3. Evaluation of special protection systems
4. System wide model validation
5. Diagnosis of large events and blackouts

4.1 Monitoring of electromechanical oscillation modes

The frequencies of the BIPS dominant oscillation modes have been monitored by the low voltage WAMS. Continuous monitoring can be performed using the FFT (Fast Fourier Transform) algorithm [2, 3]. Although damping can not be directly estimated, the algorithm is important to detect the main electromechanical oscillation modes found in near-real time operation. An application using C++ was implemented to capture real-time data and to process them using data blocks. System frequency and voltage angle differences are suitable signals to detect local and inter-area mode oscillation, respectively. The data block size is configurable according to the oscillation mode period. This application is working in near real-time at UFSC and its graphical output is shown in Figure 2.

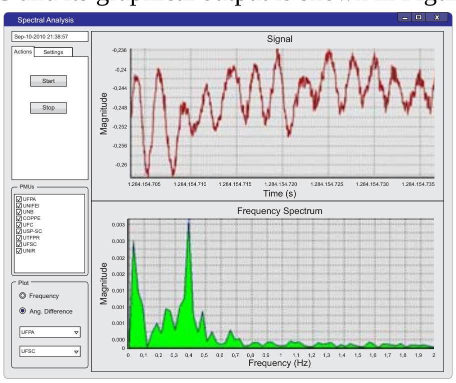

Figure 2: Ambient Data Frequency Spectrum

4.2 Evaluation of damping controllers performance and robustness

Adequate damping of the BIPS electromechanical oscillation modes is provided mainly by Power System Stabilizers (PSSs), tuned by the System Operator. The TCSC (Thyristor Controlled Series Capacitor) at the North-Southeast interconnection, installed in order to damp the North-South oscillation mode, has currently little effect on damping.

The PSS tuning requires a minimum damping for the dominant electromechanical oscillation modes for very different topologies. Tripping of the N-SE and S-NE interconnections lead to topological configurations for which the PSSs must provide adequate damping. The ANATEM [4], a simulation program, and PACDYN [5], a small-signal stability program, are used to evaluate the system performance. Although typical load configurations are used for that evaluation, it is difficult to assess the PSSs performance and robustness for all combinations of system topologies and load levels. The monitoring of the dominant oscillation modes allows the estimation of damping and frequency for any system topology and load configuration, and therefore, the evaluation of the damping controllers in much more diversified operating conditions.

4.2.1 Performance and robustness for powerflow changes

A limited number of scenarios are usually considered for PSS tuning. However, on the course of the day combinations of systems topologies, power dispatch and load demand produce a wide range of scenarios. The mode estimation using WAMS data allows that the PSS performance and robustness for these scenarios be evaluated.

The frequency and damping of the N-S mode are estimated using three scenarios in a single day, February 10, 2010. Since the damping of the N-S mode is highly sensitive to the N-SE power flow, these scenarios were chosen for three N-SE power flow levels:

1. Low power flow, time window 04:00 to 04:30
2. Intermediate power flow, time window 14:00 to 14:30
3. Heavy power flow, time window 18:00 to 18:30

Ambient data and the N4SID subspace method [6, 7] are used for this estimation. A set of signals formed by frequencies measured by the PMUs, in a sliding ten-minute time window, provided the input data for the method. A 10 min data block is required to start the identification. The estimates for the frequency and damping for the N-S mode are presented in Figure 3 and Figure 4, respectively.

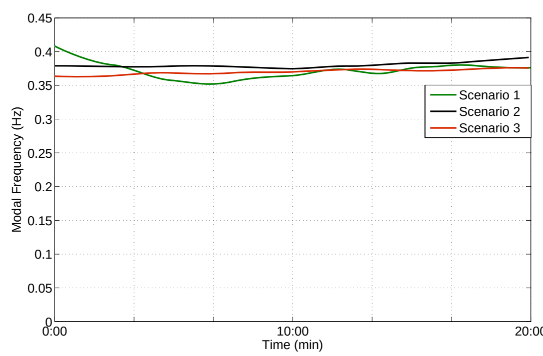

Figure 3: Frequency of the North-South mode.

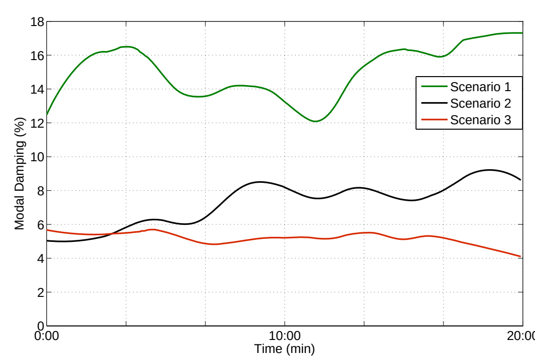

Figure 4: Damping of the North-South mode.

There is a strong correlation between the damping and the power flow curves. The damping of the N-S mode increases as the N-SE power flow decreases. A high damping is achieved for most of the operating conditions. For heavy power flow on the N-SE interconnection, the damping is reduced to about 5%. This confirms the robustness of the PSS tunings which guarantees a minimum performance for a wide range of operating conditions.

4.2.2 Performance and robustness for large topological changes

On February 2, 2010, the North-Southeast, North-Northeast and Southeast-Northeast interconnections tripped sequentially reducing the BIPS to three isolated subsystems: North, Northeast and South/Southeast/Midwest as shown in Figure 5.

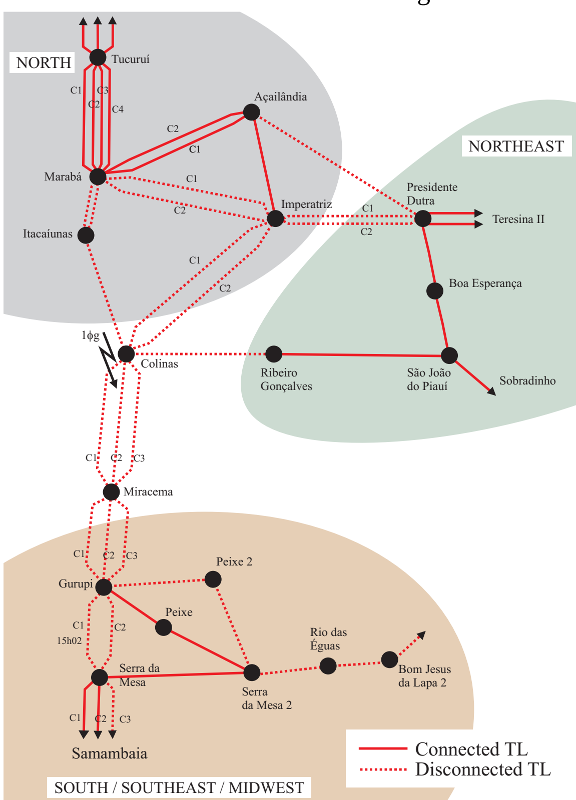

Figure 5: System topologies

A large overfrequency in the Northern region, aggravated by failure of protection, and underfrequency in the Southern region, shown in Figure 6, followed the islanding.

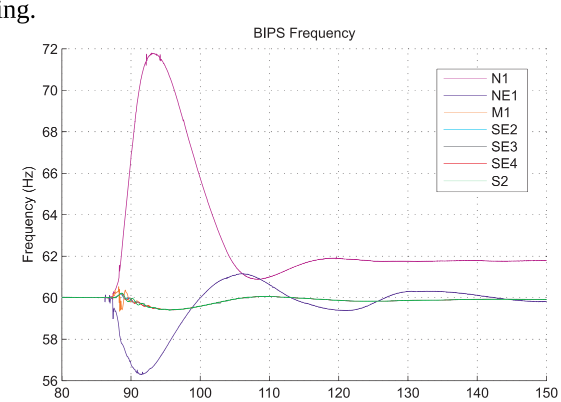

Figure 6: BIPS Frequency.

Four main topologies associated with the system disconnection and restoration are identified.

Topology 1 (Three-island topology): this configuration follows the tripping of the North-Southeast and Southeast-Northeast interconnections. The North, the Northeast and the South/Southeast/Midwest systems form three islands.

Topology 2 (Two-island topology): is associated with the North-Northeast system restoration through the 500 kV Imperatriz-Presidente Dutra (C1) transmission line, forming a two-island topology, the North/Northeast and the South/Southeast/Midwest.

Topology 3 (weakly restored topology): this follows the reconnection of the North/Northeast with the South/Southeast/Midwest subsystem through the 500 kV Imperatriz-Colinas(C2). The 500 kV transmission lines Açailândia-Presidente Dutra, Marabá-Imperatriz (C1 and C2), Colinas-Miracema (C2), Miracema-Gurupi (C1) and Gurupi-Serra da Mesa (C1) were already reconnected.

Topology 4 (complete system topology): all lines represented on Figure 5 were reclosed with exception of the 500 kV transmission line Miracema-Colinas (C1).

Multisignal Prony analysis [8] and the N4SID subspace method were used to estimate the dominant oscillation modes for these topologies. In Table 2, the damping and frequency of the N-S, N-NE and S-SE oscillation modes, estimated by the Prony analysis, are shown. Comparable results were obtained by the subspace method.

Modes	Topology 1		Topology 2		Topology 3		Topology 4	
	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)	f (Hz)	ζ (%)
N-S	–	–	–	–	0.21	8	0.34	11
N-NE	–	–	0.49	11	–	–	–	–
S-SE	0.64	10	–	–	0.63	7	0.70	6

Table 2: Identification of the dominant modes by Multisignal Prony method.

For Topology 1, the FFT analysis of the signals acquired by the WAMS was used to detect the S-SE, as shown in Figure 7. In Table 2, its damping and frequency, calculated by the parametric method, are shown. The damping is about 10%.

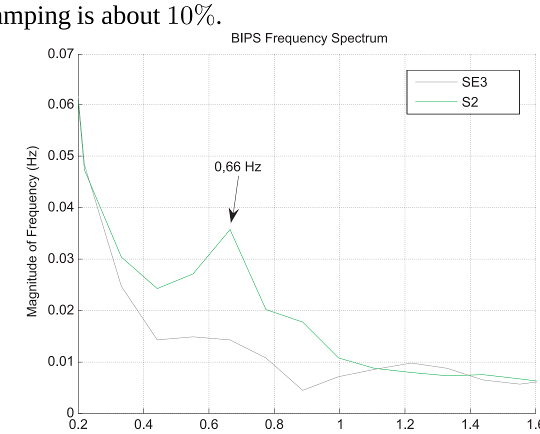

Figure 7: Frequency magnitude spectrum for Topology 1

For Topology 2, the FFT spectrum, given in Figure 8, shows the N-NE oscillation mode. From the Prony analysis in Table 2, damping of this oscillation mode is about 11%. The absence of the S-SE oscillation mode for this topology is due to the lack of ringdown data for the Prony analysis, since only the North and Northeast were involved in the topological change.

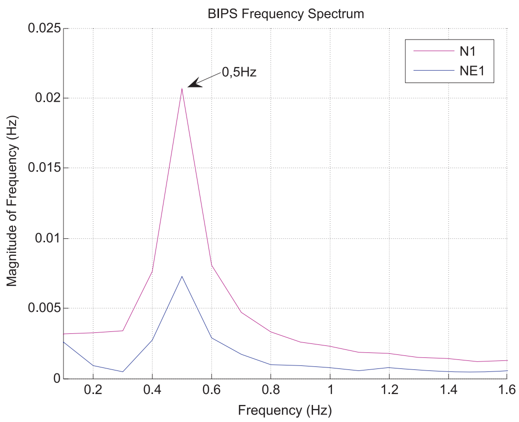

Figure 8: Frequency magnitude spectrum for Topology 2

For Topology 3, corresponding to the weakly restored system, the frequency spectrum shown in Figure 9, indicates the re-emergence of the N-S mode.

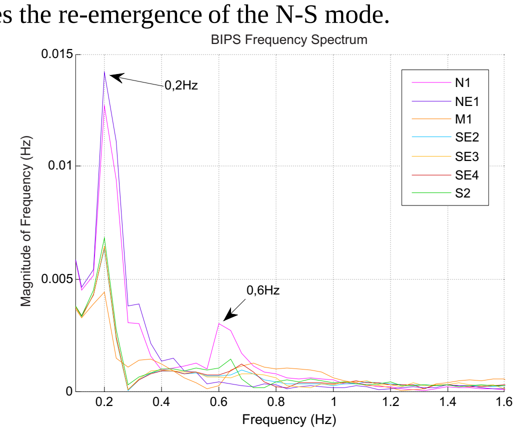

Figure 9: Frequency magnitude spectrum for Topology 3

The damping and frequency of the N-S and S-SE oscillation modes, calculated by the Prony method, are presented in Table 2. The N-S mode presents a frequency around 0.21 Hz, lower than its usual value in the range $0.35 - 0.4$ Hz, as given in Figure 3. The minimum damping for the N-S and S-SE oscillation modes are about 8% and 7%, respectively. The N-NE mode was not detected by the Prony method.

For Topology 4, the N-S mode presents a higher frequency and damping compared to the preceding weaker configuration, as shown in Table 2. The minimum damping for Topology 4 is about 11%.

These results have shown that the main interarea oscillation modes have kept a minimum damping above 5%, even for critical configurations involving large topological changes. This confirms that the PSSs have provided adequate robustness margins.

4.3 Evaluation of Special Protection Systems

Special Protection Systems(SPS) schemes are fundamental to keep the BIPS security following large events. The performance of these schemes depends on the correct time settings for the protection actuation.

Although the System Operator has access to time records of the system variables which can provide information on the protection performance, the decentralized nature of most of the records requires effort to assemble and analyze the data. The WAMS prototype gives global and prompt information on the main system variables allowing the time correlation between system events and protection actuation. In this section, the use of the WAMS for the evaluation of the SPS in the North-Southeast and Acre-Rondônia interconnections, is presented.

4.3.1 SPS at the N-SE interconnection and N/NE load-shedding scheme

The North/Northeast and South/Southeast power system are connected by three 500 kV transmission lines between the Northern and Southeastern regions and by one 500 kV transmission line between the Southeastern and Northeastern regions. These interconnections improve the BIPS energy efficiency. The North-Southeast interconnection is the main transmission corridor to the Southeastern region for the energy produced by the 8.4 GW Tucuruí hydroeletrical power plant. The Northeastern region presents generation deficit, importing energy from the Northern and South/Southeastern regions.

A SPS is installed at the North-Southeast interconnection with the following goals:

- To avoid loss of synchronism between the North and Southeast systems
- To avoid overload on the 500 kV transmission system

The SPS is activated by the disconnection of the 500 kV transmission line between Serra da Mesa(SE)-Imperatriz (N). It is a complex scheme and its main actions are:

- tripping of the North-Southeast and Southeast-Northeast interconnections
- tripping of generators in Tucuruí and other power plants
- tripping of capacitor banks

This SPS actuates few times a year. Recently an increasing number of trippings in the North-Southeast interconnection has been recorded. This increase is related to forest fire around the interconnection transmission lines, leading to short-circuits and trippings.

A five-step load shedding scheme (LSS) is also implemented in the N/NE region in order to avoid large frequency excursions, specially after the loss of the N-SE and SE-NE interconnections. This scheme is triggered when the frequency reaches a low limit of 57.3 Hz (instantaneous), 58.5 Hz (with a time delay) or a decrease rate above 0.7 Hz/s.

For the evaluation of the SPS, three events started by line trippings between the transmission line Gurupi-Miracema were selected:

- Event 1 - September 9, 2010
- Event 2 - September 24, 2010
- Event 3 - September 25, 2010

In Figure 10, the frequency response for Event 1, is presented.

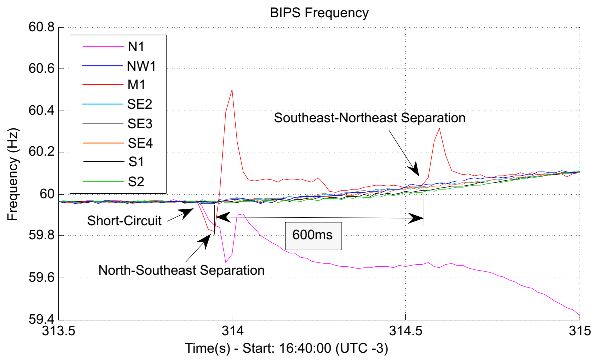

Figure 10: September 9, 2010 SPS actuation

The total actuation time of the SPS, consisting of the tripping of the N-SE and then the tripping of the SE-NE interconnections, for the three events, are summarized in Table 3.

Event	Protection time (ms)
September 9, 2010	600
September 24, 2010	566
September 25, 2010	467

Table 3: SPS actuation times

The field tuning for the actuation time for these events were 200 ms. After a reconfiguration of the SPS, the results by the WAMS allowed the detection of delays in the actuation time, as shown in Table 3.

Following the interconnections tripping, the LSS in the N/NE region is triggered. Three steps were activated in the first and third events. In the second event only the first step of the LSS was activated. The LSS actuation for Event 1 is illustrated in Figure 11.

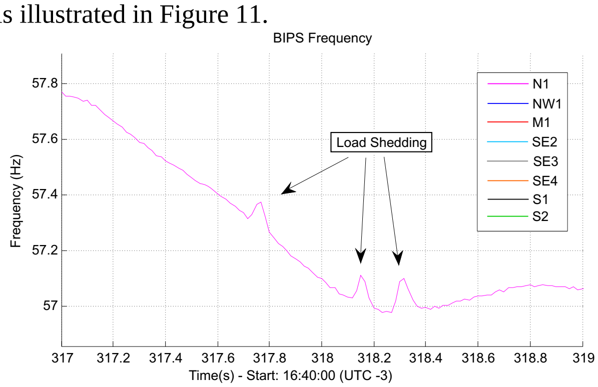

Figure 11: September 9, 2010 SPS actuation

In Figure 11, the protection actuations at 317.7, 318.1 and 318.3 s. are clearly seen. The LSS actuation in the three events is triggered primarily by the frequency falling rate (0.85 Hz/s). The settings for the load shedding steps are summarized in Table 4.

SPS step	Event 1	Event 2	Event 3
1	57.31	57.3	58.6
2	57.03		57.3
3	56.97		56.9

Table 4: Load shedding actuation thresholds (in Hz)

These results have confirmed the correct actuation of the SPS logic for the events and of the LSS at the intended frequency thresholds. Delays in the actuation time of the SPS, as a result of changes in the protection logic, were detected. The main gain of the WAMS, as compared with other recordings, is the readiness in accessing data that give a system wide overview of the protection actuation.

4.3.2 SPS at Acre-Rondônia Interconnection

The isolated Acre-Rondônia power system, in the far Northwestern region, was recently connected to the BIPS. The isolated power system was supplied by three thermal and one hydroelectric power plants. The BIPS integration is aimed at decreasing the energy price in the region using cheap hydroelectrical generation from other BIPS regions and increasing the system reliability.

The Acre-Rondônia system is connected to the BIPS by a weak 230 kV transmission system. The system depends on the thermal plants to avoid blackouts in the region while other transmission are built, and has experienced frequent disturbances that cause large frequency excursions and variable topologies.

For a fast system restoration, an automatic reclosing scheme for the 230 kV interconnection was recently implemented. Besides that, a five-step load shedding scheme is in operation.

Results for the evaluation of these schemes by the WAMS are presented in this section for line trippings in the following dates:

- October 30, 2010
- November 11, 2010
- November 13, 2010

The protection actuation is illustrated for the first event in Figure 12.

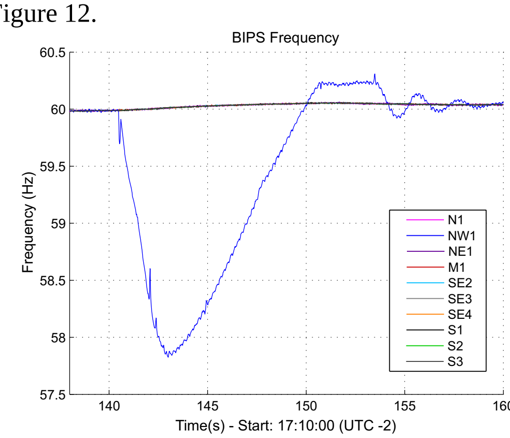

Figure 12: October 30, 2010

The total protection actuation time for the three events are summarized in Table 5.

Event	Reclosing time (s)
October 30, 2010	12.9
November 11, 2010	30.8
November 13, 2010	20.15

Table 5: Reclosing time

The operation of the LSS has been evaluated in a similar manner as already presented for the North-Southeast interconnection.

The information provided on the protection settings allowed the System Operator to confirm the correct actuation of the protection schemes and to fine tune the actuation times.

4.4 System wide model validation

A system wide model validation was performed using data from a large disturbance on July 4, 2009, when two of the three circuits of the 765 kV transmission line Foz do Iguaçu- Ivaiporã tripped following a fault [9].

The low voltage WAMS system, complemented by data from the high-voltage phasor measurement system prototype installed at Eletrosul, a transmission and generation utility in Southern Brazil, provided the data for the validation. The detailed models and data for generators and controllers, loads, FACTS equipment and the network provided by the System Operator were used in ANATEM, the standard simulation program in the industry.

The validation procedure was based on two principles:

1. Qualitative validation: the model simulation and the measurement data from the phasor measurement system for variables such as system frequency, bus voltages, real and reactive power over transmission lines and angle difference should have a similar qualitative behavior.
2. Quantitative validation: the values of frequency and damping of the dominant electromechanical oscillation modes estimated from the WAMS data and calculated from simulation data or from a small-signal program should result in numerical values that are close.

The results presented in [9] have shown a close agreement between the acquired and simulation data and helped to increase the confidence in the models, data and the software currently used for planning and operation of the Brazilian Interconnected Power System.

4.5 Diagnosis of large events and blackouts

Several large events in the BIPS have been monitored by the low voltage WAMS. The data recordings of these events have been used by the System Operator for evaluation and diagnosis.

The monitoring of the large blackout on November 10, 2009 was detailed in [10]. The data allowed the detection of voltage collapse, asynchronous operation and proved to be useful for the determination of the sequence of events that led to the blackout.

4.6 Other results

The MedFasee Project has had a strong impact on teaching and research at the UFSC. The availability of real system data, especially after large events, has stimulated the interest of undergraduate and graduate students in power systems, contributing to the education of a new generation of power system engineers. Phasor measurements are now part of courses in power system. Power system students are stimulated to attend courses on related topics such as signal processing. Topics on the use of synchronized phasor measurements for monitoring, control and protection of power systems have been part of the research of graduate students.

Two projects in collaboration with transmission utilities resulted in the development of two high-voltage phasor measurement system prototypes. A project with Eletrosul led to the installation of four PMUs at 525 kV substations. A second project in with CTEEP, a transmission utility, plans the installation of 5 PMUs in 3 substations at 440 kV.

5 Conclusions

In this paper the experience in Brazil with a low voltage WAMS covering most of the country, is described. Beginning as an academic project with the goal to develop and disseminate the synchronized phasor measurement technology, it proved to be valuable for the monitoring, identification and performance evaluation of the BIPS. The information provided by the WAMS is being used by the Brazilian System Operator. The results give support for the large scale WAMS to be installed by the System Operator.

From the academic viewpoint, the low voltage WAMS has stimulated new research topics for graduate students and attracted undergraduate students for power systems, contributing to the formation of a new generation of power systems engineers prepared for the challenges of of the BIPS in the XXI century.

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