Experiences with the Installation and Commissioning of a WAMS in Companhia Paranaense de Energia (COPEL)

Gilmar F. Krefta
gilmar.krefta@copel.com

Rafael Rodrigues
rafael.rodrigues@copel.com

Marcelo N. Agostini
marcelo.agostini@ge.com

Carlos E. F. Pimentel
carlos.pimentel@ge.com

Lucas B. de Oliveira
lucas.oliveira1@ge.com

Adriano O. Pires
adriano.pires@ge.com

Copel Geração e Transmissão (GeT)
Phone: +554133313167
Rua Padre Agostinho, 2600, 80710-000
Curitiba, PR, Brazil

GE Grid Solutions
Phone: +554821080300
Rua Delminda Silveira 855, 88025-500
Florianopolis, SC, Brazil

ABSTRACT

In this paper is described the main topics related to the installation and commissioning of a Wide Area Measurement System (WAMS) of a transmission and generation company in Brazilian power system. The WAMS is owned by Compania Paranaense de Energia (COPEL), which is located at Brazilian south region. All the COPEL grid at 230 kV and most of 525 kV transmission lines and busbars were included at the project, which means that up to 37 substations have their lines and busbars monitored, and most of the corridors that connect the COPEL's grid to the Brazilian Interconnected Power System (BIPS) including the connection with Itaipu power plant, are monitored by synchrophasors measurements. It is the largest WAMS operating in BIPS nowadays. In this paper it is presented examples of the main benefits for COPEL's real time operation personnel when there is a disturbance at the system as well as results obtained from post-event analysis from disturbances electrically near to COPEL's grid.

KEYWORDS

Wide Area Measurement Systems, PMU, Phasor Measurement, BIPS, COPEL WAMS.

1. INTRODUCTION

The increase in operating complexity of power systems has required the constant improvement of its monitoring and control instruments, both real-time and offline. This demand has led to the development of innovative technologies, scenario in which stands the wide area measurements. Wide Area Measurement Systems (WAMS) are formed basically by Phasor Measurement Units (PMU) installed in substations, which measure voltage and current synchrophasors and send them to Phasor Data Concentration systems (PDC) usually installed in operating centers. The PMU shall be synchronized from a common time base, usually through the GPS system. This ensures that a single set of synchrophasors measured by all devices on a particular instant of time represent the instantaneous condition of the power system. Comparing to traditional supervisory systems, WAMS have synchronized sample and a higher sample rate which allows the dynamics of these systems to be monitored.

WAMS are being developed in many countries. In Brazil, a single synchronized phasor measurement system is being implemented for the National Interconnected System, called SMSF-SIN. This process has been led by the National Electric Power System Operator (ONS). Deployment initiatives of other WAMS can be identified in electrical transmission and generation agents at different stages of development. The pioneering project for wide area measurement in South America was led by the Federal University of Santa Catarina (UFSC), with the participation of Reason Tecnologia S.A. The project named MedFasee, installed PMU in 23 partner universities in the low voltage electrical system, covering the five geographic regions of Brazil.

The need of high-resolution continuous monitoring of the power system is being studied by COPEL in the past years, as the power system and energy market is becoming more complex. Also, in BIPS, power system's operation is led by ONS. As ONS is responsible for all Brazilian system, this situation leads the transmission owners in Brazil to a challenge that is to monitor if their own system is being operated properly according to the equipment and installation.

For fault analysis, COPEL has traditionally used GPS-synchronized Digital Fault Recorders (DFR) and a management system for these records based on web interface. The usage of synchronized recorders has proven to be important as it is possible to display at the same software several waveforms from different recorders and see the behavior of the system for a given fault. However, for large system disturbances, the manipulation of data from several recorders is not an easy task, and takes a long time to be carried out.

The real time operation is performed by a traditional Supervisory Control and Data Acquisition (SCADA) system and Estate Estimator software, based on unsynchronized data acquisition. As data is unsynchronized, analysis of the system can only be performed by estimating the state that the system is operating. These systems are well known by transmission owner worldwide, and are proven to be important for static system observation and system's operation. However, as power systems are increasing its complexity, there is an increasing need to have a more accurate system that would show not only the static, but also the dynamic behavior of the power system.

The first commercial initiative of a WAMS in Brazilian Interconnected Power System (BIPS) is described in this paper. It was led by COPEL, a Brazilian generation, transmission and distribution owner, and started its operation in mid-2015. It covers 230 kV and 525 kV busbars controlled by the company. In this system, all PMU are a multifunction fault and disturbance recorders, used first from COPEL for fault waveform recording.

2. SYSTEM DESCRIPTION

COPEL's WAMS was installed in mid-2015 and is being used by the real-time operation team for dynamic system observation. The system intends to support post-event analysis and the engineering studies team, providing them information for post-event, system performance, generators response and dynamic intersystem oscillation analysis.

The system is composed by 37 PMU distributed in all Paraná State territory, located at the South region of Brazil. The system is composed by two central PDC servers installed in COPEL's control center in Curitiba, the capital of Paraná state. As a result, in some cases the distance from the substations where the PMU are installed and the control center are of over 500 km. Figures 1 and 2 shows, respectively, Paraná state map and Curitiba metropolitan region map where each blue circle represents a substation that one or more PMU are installed and used by the measurement system.

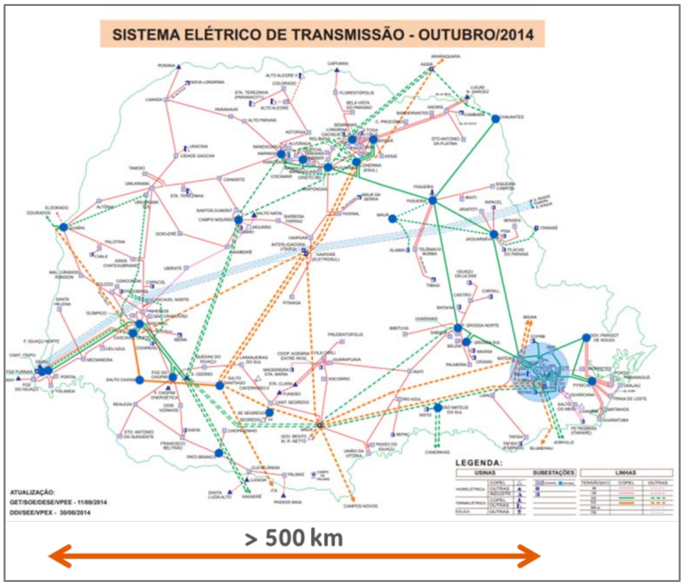

Figure 1. Paraná State system map and PMU locations.

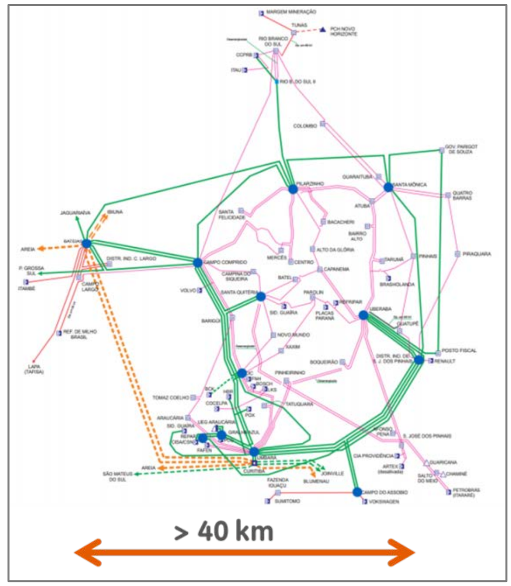

Figure 2. Curitiba Metropolitan Region system map and PMU locations.

2.1 SYSTEM'S ARCHITECTURE

The main components of the WAMS installed are the PMU, the communication link, which provides a communication path between the substations and the control center, and finally the PDC, which receives, organizes and display the data sent from the substations by the PMU.

All PMU used by COPEL in its WAMS are composed by Reason's multifunction fault recorders (RPV-310 and RPV-311 models) and GPS clocks (RT420 and RT430 models), and it sends synchrophasors at a rate of 60 frames-per-second. The same equipment performs fault and disturbance recording, PMU function and Traveling Wave Fault Location.

In the WAMS, each PMU has a unique identifier in the system, the PMU ID, which is used by PDC software to manage and organize the data to be displayed and stored. As the system commissioned has several PMU distributed in a wide area, it was used as method to choose which PMU ID the equipment in field should have. PMU ID in COPEL WAMS is composed by 4 numbers. The first indicates geographic region of the state (Curitiba metropolitan region, southeast, old-north, north and west). The second and third are increasing numbers that indicates the substation where the PMU is installed and the last indicates the PMU of the substation. This method allowed system administrator to quickly have information about where the PMU is installed, so system's upgrades, diagnostics and maintenance had its complexity decreased.

The communication link from the substations to the control center is the Fault Recorder VLAN based on Ethernet and TCP/IP communications link, mainly interconnected from the substations to the control center by OPGW fibers over the transmission lines owned by COPEL.

There are two PDC installed to receive data from the PMU, named the Master and Slave PDC. The PMU sends three-phase busbar voltages and three-phase currents from the substations of 230 kV and above pertaining to the power system. Where available, three-phase voltage, measured at line terminal, is also sent to the PDC.

Synchrophasors streams are transmitted using UDP protocol, and the control of the transmission is performed by the PDC, which periodically sends commands to the PMU to maintain the communication. To guarantee that Master and Slave PDC will receive data independently, each PDC receive a stream in a specific UDP port. Thus, each PMU sends two streams of data through distinct UDP ports, which are received at each PDC.

Finally, the PDC are installed at the control center, in Curitiba. PDC hardware comprises commercial industrial servers running software that is capable to manage all synchrophasors data in a local database. It is responsible for displaying data to operators, for real-time operation, and offline to users performing system studies and post-event analysis.

For offline analysis, the PDC software has two automatic historical archives, and one triggered storage where the user can select the period manually. The automatic storage files are composed by a 3-month full resolution (60 phasors-per-second) file and a 6-month down sampled (1 phasor-per-second) file that stores data from all PMU at the server. The triggered storage is a full resolution file that is user configurable in size and signal to trigger the software. Also, it is possible to manually move data from the full resolution 3-month file to this storage, so the period will not be down sampled after three months. In COPEL WAMS, frequency and voltage magnitudes are being used as triggers for this storage, and some disturbances were moved from the rolling file to this permanent storage file manually.

Figure 3 and Figure 4 shows communication architecture of the system operating in COPEL.

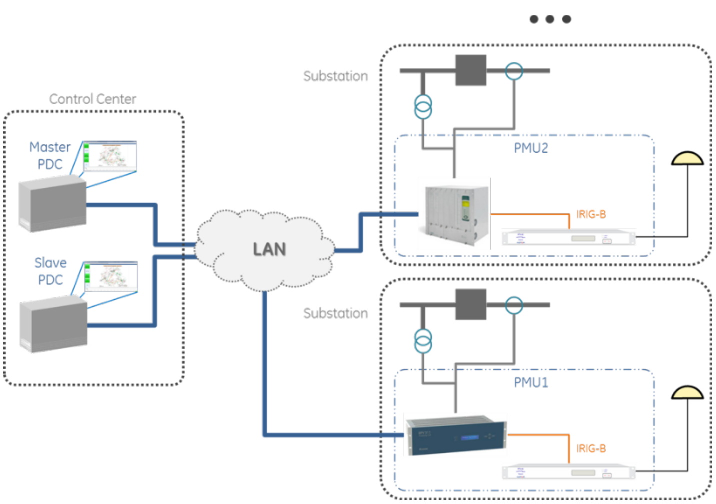

Figure 3. COPEL's WAMS communication architecture.

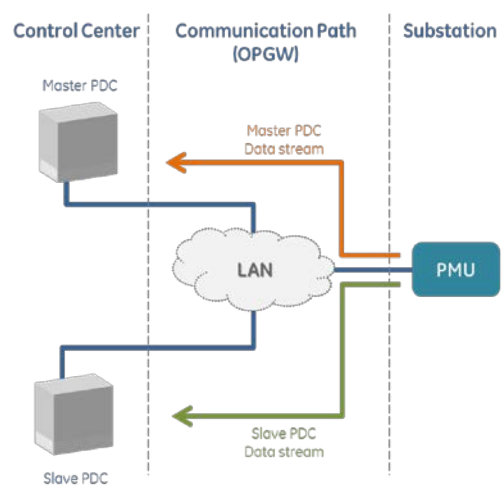

Figure 4. Communication strategy used for redundancy of data.

3. SYNCHROPHASORS APPLICATIONS AVAILABLE IN COPEL'S WAMS

WAMS can be used by real-time operation of the system, supporting operator to make decisions when it is required to act at the power system, and for historical analysis, if an historical archive is available. The system installed in COPEL has both proposals: to support real time operators to take their actions and to support off-line studies personnel, providing them a great resolution data to be used at their applications.

3.1 REAL-TIME APPLICATIONS

For real time application, the operator can check system's health based on alerts and alarms that are user configurable. He can check voltage magnitude, angle and frequency condition in a colored representation of the substations and view all measurements from the PMU. It is also possible to create views of the angle differences from given busbars, so is possible to monitor in real-time theses values. Finally, the system administrator can create custom views to display new information that may increase the capacity of the operator to make decisions faster.

A novel application that being deployed within the scope of this project is line parameter estimation based on PMU incoming data. In this case, the operator can verify in real time the impedance measured of a transmission line that has both ends monitored.

The alarms applied are based on voltage magnitude (over and under voltage), angle and frequency condition (over and under frequency). Information of all PMU are displayed at an Overview screen using color coding to indicate it’s measurements status: green means that no limits are violated, yellow means that the alert limit was violated and red means that the alarm limit was violated at the PMU displayed. Figure 5 shows the main screen of COPEL’s WAMS system, and Figure 6 shows a customized view that displays angle difference in real-time for the main subsystems inside COPEL power system.

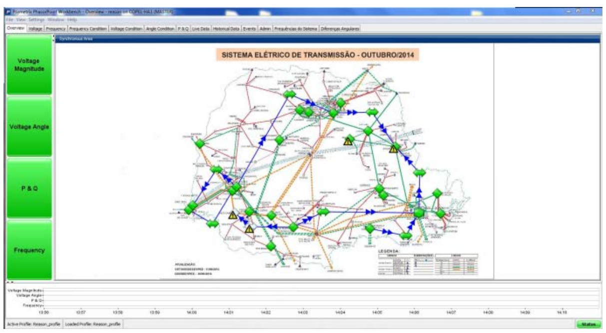

Figure 5. WAMS software overview tab.

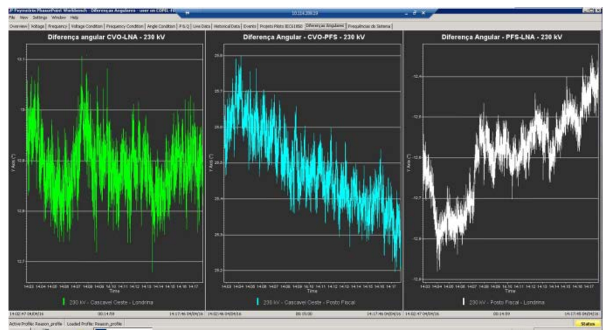

Figure 6. Customized view showing angle differences that are of interest for real-time operation.

3.2 OFFLINE SYSTEM APPLICATION DESCRIPTION

In offline applications, the WAMS displays to the user all data that is received from the PMU, such as voltage and current angles and frequency of the system. There is also the capacity to shows some derived quantities, such as active and reactive power, power factor, positive, negative and zero sequences, angle difference (once the variable was created) and line parameter estimation (once the variable was created).

These data can be used directly for a first-step quality analysis of a chosen period of time. It is displayed in several charts, so it is user friendly to build report. The raw data received from the PMU can be also exported to a CSV or COMTRADE file, for further analysis outside the software. The results obtained with the direct analysis of the PDC software proved to be good for reports, operational documents and disturbance impact reports. Besides, synchrophasors data is an important tool to improve system’s studies and check data against mathematics models.

Figure 7 shows an example of the historical view, showing the angle difference in a given time between a generation (Segredo) and load (Bateias) busbars. Figure 8 shows, for the same time period, the values of positive sequence and angle of Bateias 525 kV busbar.

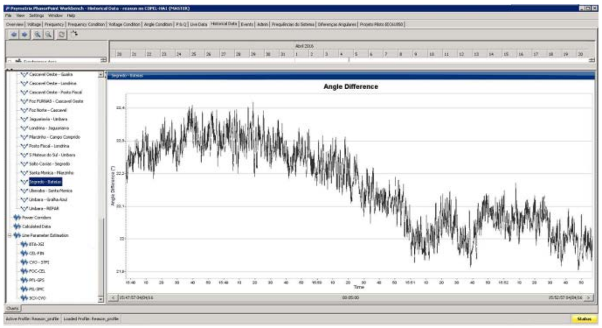

Figure 7. Angle difference from Segredo to Bateias 525 kV busbars.

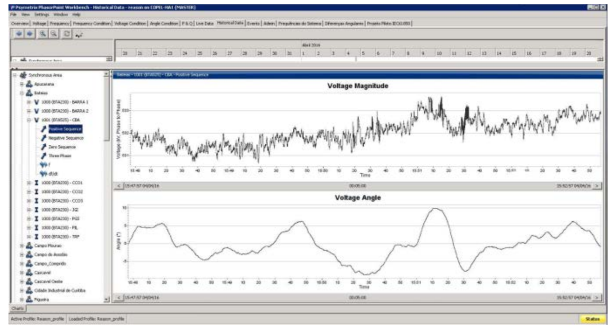

Figure 8. Positive sequence magnitude and angle measured at Bateias 525 kV Busbar.

4. RESULTS OBTAINED FROM A SYSTEM DISTURBANCE

In September 2015, BIPS has suffered from a fault directly linked to the 500 kV Furnas Busbar where the 60 Hz synchronous machines of Itaipu Hydroelectric Power Plant are connected. This fault led to a system disturbance, which mainly impacted on overall system frequency values, creating an under frequency condition that took several minutes to be recovered.

According to national operator (ONS), an automatic shutdown occurred at Itaipu 60 Hz 500 kV substation at the A3 busbar. In total, 4 generators of the hydroelectric power plant were disconnected from the system, which represented a loss of generation of 2,550 MW. This led the system to a frequency of 58.6 Hz, causing a shutdown of Angra Nuclear Power Plant, increasing loss of generation in 650 MW. At this stage, the ERAC system actuated, which is the Brazilian contingency regional load-shedding scheme, and COPEL was affected shedding 164 MW of its load. During this period, there was also a loss of 750 MW of load from other companies in BIPS.

Even though all BIPS suffered from this disturbance, as the system is interconnected, it had a great impact on COPEL's system, as the 60 Hz Itaipu busbar is a frontier busbar between Furnas and COPEL. This frontier is delimitated by a 525 kV transmission line that connects directly COPEL's 525 kV system to this busbar.

The topics below detail the usage of the system for this disturbance both on real-time and historical applications. The real-time application is presented in chronological view, so it represents how the operator can firstly detect a disturbance in the system and decide which application he should view to get more information that is relevant to the disturbance in course. The post-event analysis presents results obtained by the system as a result of the usage of only WAMS, without SCADA or disturbance recorders data, for the analysis.

4.1 REAL-TIME DISTURBANCE PERCEPTION AND DIAGNOSTIC

The overview tab at COPEL's WAMS software displays alarms in real time to the operator. This tab is the main screen of the software, and this is the tab that is generally in use by operators when using the WAMS.

At the beginning of the disturbance, the frequency alert started, showing that there was a problem related to frequency at the system. After that, the alert became an alarm, so the substations were represented in red at the map, indicating the disturbance. The button at the left shows in real-time that the alarm was related to system's frequency. The map containing all PMU in alert is shown at the Figure 9.

To verify if there were over or under frequency condition a simple click at the frequency button was needed, which changes the screen to the frequency condition screen as show in Figure 10. At this screen, all PMU of the system are presented in a color scale: the bluer the substation is displayed, the the smaller the frequency, and the more violet, the larger it is. When this tab was displayed, it was possible to conclude that the system was at under frequency condition, and all COPEL's system was impacted by the disturbance.

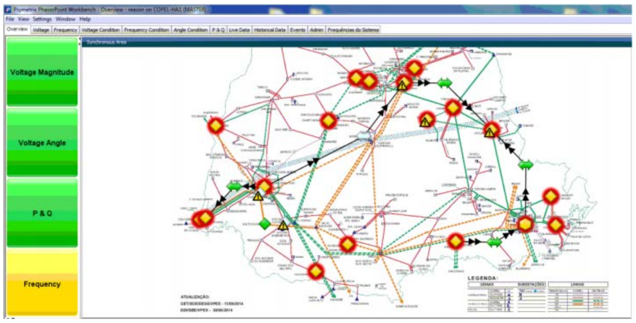

Figure 9. Main software screen indicating that the system was at alert frequency condition.

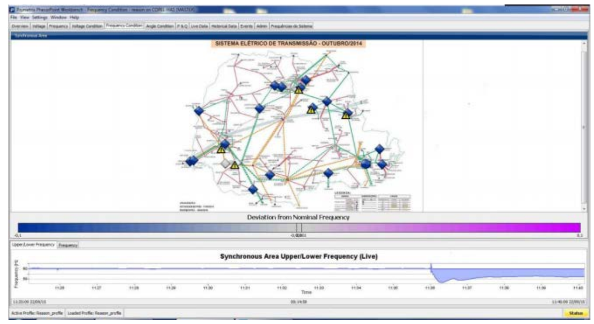

Figure 10. Frequency condition tab displaying information about frequency in real time at disturbance period.

After the diagnostic of under frequency system condition, it was observed the voltage condition at important busbars of COPEL's system. First of all, the reference busbar of the system used by actual SCADA system was observed, 230 kV UMB busbar voltage. Second step, was to observe one of system's frontier, which is the 525 kV BTA busbar. The values shown in real-time are shown at Figures 11 and 12. From these magnitudes, it was concluded that the voltage at Curitiba Metropolitan Region, the most populous region of the state, was not dangerously affected.

Figure 11. Voltage magnitude behavior at the disturbance in Umbará 230 kV substation.

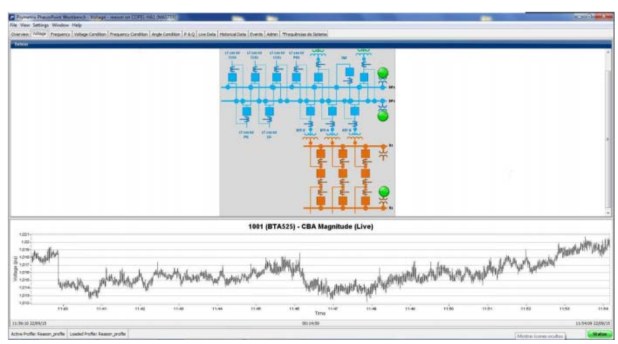

Figure 12. Voltage magnitude behavior at the disturbance in Bateias 525 kV substation.

Finally, after checking voltage magnitudes at some important busbars of the system, it was verified at the sequence of events of the software which PMU had alerted and alarmed first due to the under frequency situation. As the acquisition systems are GPS-synchronized, it is expected that PMU installed closer to the disturbance epicenter would send the values of under frequency first, and the chronological order of the alarms and alerts to indicate where the disturbance started.

From this analysis it was observed that the PMU installed closer to Furnas substation were the first to send under frequency values, STFI 500 kV, FIN 230 kV CVO 525 kV and CEL 230 kV PMU always appeared in the first places when an alarm or alert started. Also, only these PMU were repeated in the alert and alarm starts. As these PMU are installed at Foz do Iguaçu and Cascavel, respectively, in Paraná West region, and they are the closest PMU from Itaipu 60 Hz substation, the conclusion was reached that the disturbance probably started at Furnas system, nearby Itaipu substation.

4.2 POST-EVENT ANALYSIS BASED ON SYNCHROPHASORS DATA

For this event, some off-line analyses were made to verify the new possibilities of disturbance comprehension that the new WAMS system could deliver to the studies personnel.

The benefits of a WAMS are well-known, mainly related to angle measurements. The studies presented in this paper were performed mainly based on Power swings and Overflux conditions observed in this disturbance, as this has an immediate impact in COPEL's operation system. COPEL is the owner of large hydroelectric generators and transformers, which are directly affected by these situations and WAMS can give important information for impact analysis. Applications using angle differences are being studied by the company and will be used in the near future for real-time and offline applications.

Post-hoc to the disturbance, one of the steps was to verify whether the transformers connected to the 525 kV system busbars could have suffered from an Overflux situation, as there was substantial decrease in the frequency, but a significant decrease in voltage magnitude was not observed. The busbar chosen to be analyzed was the CVO 525 kV busbar, which is connected to the 500 kV Furnas substation through the CVO-STFI overhead transmission line. Besides being close to the fault inception, there are also step-down 525-230 kV transformers connected to this busbar.

The maximum Overflux value allowed is 5% in liquid-immersed transformers, according to the C57.12.00-2010 IEEE standard. Above this value, the lifetime of the equipment could be decreased or it could suffer from a more severe damage. To check the order of magnitude of the time that the transformers faced Overflux situation, the values of frequency and three-phase voltages were compared, and it was concluded that COPEL's transformers connected to this busbar suffered a period of Overflux for more than 50 seconds during this disturbance. The maximum value was observed in the beginning of the disturbance, more than 50% above the maximum value allowed. The graphic view of the historical data from voltage magnitudes and frequency is shown at Figures 13 and 14.

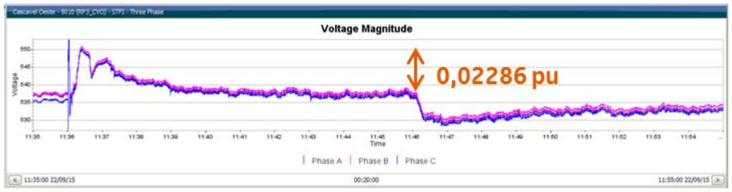

Figure 13. Voltage magnitude behavior at 525 kV CVO busbar at disturbance period.

Figure 14. Frequency behavior at 525 kV CVO busbar at disturbance period.

Another behavior studied was the angle difference between two large hydroelectric power plants owned by COPEL, Salto Caxias (SCX) and Segredo (SGD). The angle difference can show power flux direction, and steps at this angle shows system switching, such as closing and opening of circuit breakers. Figure

15 shows the behavior of the angle between 525 kV SCX and SGD substation busbars, where it is possible to see that in the first 10 seconds, multiple switching operation occurs. Also, as the angle decreased to values close to zero, it can be asserted that power flow in these busbars was close to zero during this period. Figure 16 shows the same busbar angle difference throughout the disturbance period. In Figure 16, it can be seen that power flow from these busbars took more than 20 minutes to recover to previous values.

Figure 15. Angle difference between Salto Caxias and Segredo busbars in the first seconds of the disturbance.

Figure 16. Angle difference between Salto Caxias and Segredo busbars at full disturbance period.

Finally, several power oscillations were observed at Governador Parigot de Souza (GPS) 230 kV substation, where GPS hydroelectric power plant is connected to the system. Figure 17 shows the graphs obtained by the software, and shows all data that could be extracted from the charts.

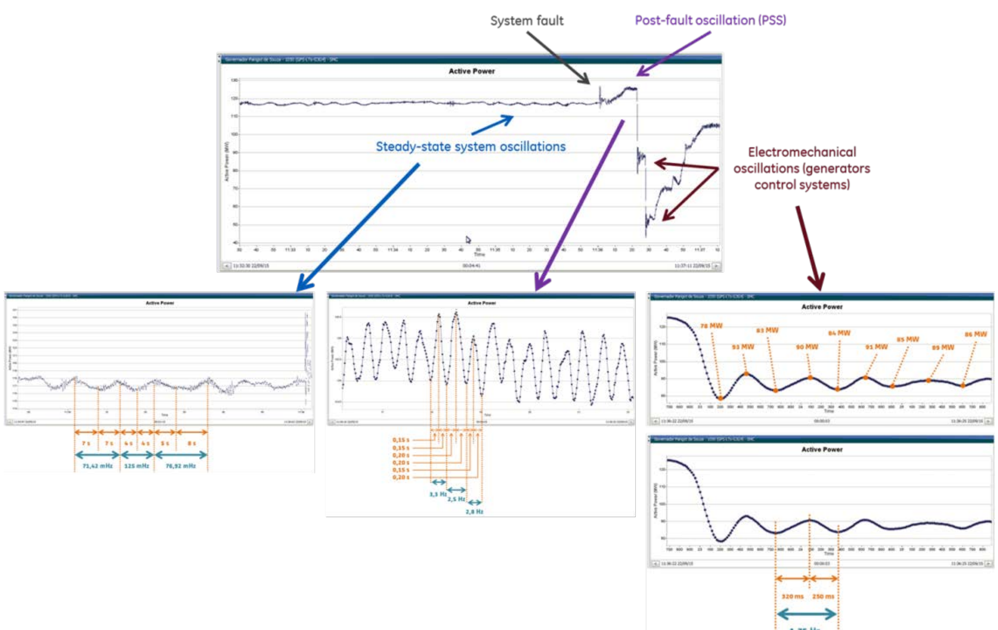

Figure 17. Power oscillations verified at a transmission line connected to GPS 230 kV busbar.

In the chart extracted from GPS-SMC 230 kV overhead transmission line, it was verified a pre-event natural system oscillation, post-fault power oscillations and electromechanical power oscillations caused by power switching.

Natural system oscillation will be used by studies personnel for model validation. In Figure 17, it was shown steady-state frequency oscillation estimation, based on power oscillation peaks.

After the disturbance, there is a power oscillation which is close to 3 Hz, that is caused by Power System Stabilizer (PSS) controllers at GPS generators. These values will be used to verify the performance of the controllers, but are a good indication that the PSS is not actuating properly. In this point, it is important to salient that the PSS are operated by ONS, and therefore, reduced asset lifetime due to poor performance of the PSS may be subject to liability penalties from ONS to COPEL.

Finally, it was shown at the graphs that there were power oscillations related to electromechanical oscillations, in this case generated by switching of GPS generators at GPS 230 kV substation. For these oscillations, the WAMS system is capable to display data with resolution enough for oscillation frequency and damping estimation. The results of these analysis will be used for generators control verification and, if necessary, for generator control system calibrating.

5. CONCLUSIONS

This paper introduced the main topics related to COPEL's WAMS architecture and results obtained so far using the system. The extension of the system, its main characteristics, WAMS applications available and some results obtained in real-time and off-line applications were also discussed.

For real time system operation, a method to quickly verify and diagnose a system disturbance was introduced and is based on applications currently available and in operation at COPEL's WAMS. This methodology allows the operators to quickly check a disturbance, diagnose its magnitude and verify a possible location of the disturbance. This may lead to improve decision-making on the regional system operation, which is the responsibility of COPEL.

For offline applications, a system disturbance was analyzed and the main results given by the WAMS were detailed. This analysis covered a method to verify system's stress based on Overflux issues using the system, angle behavior between two generation busbars and power oscillations measured by the system. Thus, this paper presented that a WAMS can be used for several applications and system configuration in addition to the angle differences.

The results obtained so far represent an important step in WAMS usage in COPEL, and is the first step for developing a full WAMS-based operation of the system. The results shown that there are several fronts that can be used to increase power system knowledge based not only on system simulation, but based mainly in the measured system behavior through a disturbance.

6. BIBLIOGRAPHIC REFERENCES

[1] DECKER, I. C.; SILVA, A. S.; AGOSTINI, M. N. et al. Experience and applications of phasor measurements to the Brazilian interconnected power system. In: European Transactions on Electrical Power, Volume 21, Issue 4, May 2011.

[2] AGOSTINI, M. N.; CRUZ, I. H.; Franzen T. A. et al. Merging Unit application for Synchronized Measurement Phasors. In: XII Protection and Control Technical Seminar - STPC. Rio de Janeiro, Brazil, November 2014.

[3] AGOSTINI, M. N.; ZIMATH, S.; ALVES JR., J. R. E. et al. Testing Agreement PMU IEEE Standard C37.118.1-2011. In: XXII National Seminar on Production and Transmission of Electricity - SNPTEE. Brasília, DF, October 2013.

[4] MedFasee project. (2015) [Online]. Available: http://www.medfasee.ufsc.br/

[5] DECKER, I. C .; AGOSTINI, M. N .; Dotta, D. et al. Development and Implementation of a Measurement System Prototype Synchronized Phasor in Transmission System of 440 KV CTEEP. In: XXI National Seminar on Production and Transmission of Electricity - SNPTEE. Florianópolis, SC, October 2011.

[6] IEEE Std. For Synchrophasor Measurements for Power Systems. IEEE Std C37.118.1-2011.

[7] ZIMATH, S.; WILSON, D.; AGOSTINI, M. N. et al. Novel Sub-Synchronous Oscillation Early Warning System for the GB Grid. In: Study Committee B5 Colloquium. Nanjing, China, September, 2015.

[8] Operador Nacional do Sistema (ONS). Informativo Preliminar Diário de Operação: 22 de Setembro de 2015. Available: http://www.ons.org.br/publicacao/ipdo/Ano_2015/M%C3%AAs_09/IPDO-22-09-2015.pdf.

[9] IEEE Std. for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers. IEEE C57.12.00-2010.