The Wide World of Wide-Area Measurement

THE INTEREST IN PHASOR MEASUREMENT TECHNOLOGY HAS REACHED A PEAK in recent years, as the need for the best estimate of the power system's state is recognized to be a crucial element in improving its performance and its resilience in the face of catastrophic failures. In most countries installing the phasor measurement units (PMUs) and getting to know the PMU system behavior through continuous observations of system events has been the first step. All installations are reaching for a hierarchical wide-area measurement system (WAMS) so that the measurements obtained from various substations on the system can be collected at central locations from which various monitoring, protection, and control applications can be developed. In this article, experts from several countries summarize their WAMS-related activities in some detail. It is of course not possible to claim that this is a complete list of countries pursuing this technology. To the best of our knowledge similar activities are also progressing in South Africa, Taiwan, Japan, and several other countries. However, the contributions here provide an account of the most advanced stages in WAMS development in major world economies.

—A.G. Phadke

WAMS Initiatives in Brazil

By Hector Volskis and Rui Menezes de Moraes

The Brazilian National Interconnect Power System (SIN) is characterized with a dominant hydroelectric power generation and long-distance power transfers from generation parks to load centers (Figure 1). Studies for phasor measurement applications in Brazil were started in the early 1990s by the Study Committee of the Interconnected Operation Coordination Group (GCOI), prior to the deregulation of the Brazil energy sector. Difficulties faced by the Brazilian economy during that decade and the restructuring process of the electric energy sector delayed the project.

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A Look at Wide-Area Measurement System Initiatives from Around the World

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BRAZIL
CHINA
INDIA
EUROPE
MEXICO
NORDIC COUNTRIES
NORTH AMERICA
RUSSIA

Since late 2000, the Brazilian independent system operator ONS has launched two WAMS-related projects aiming to implement a large-scale synchronized phasor measurement system (SPMS) for both offline and real-time applications:

- ✔ **Deployment of a Phasor Recording System:** The main goal of this project is to specify and deploy a SPMS to record SIN system dynamics during long-duration wide-area disturbances, envisioning the most probable future real-time applications.
- ✔ **Application of Phasor Measurement Data for Real-Time System Operation Decision Making:** The main goal of this project is to extend the initial SPMS for control center real-time applications, such as phasor visualization, modal frequency alarming, and state estimator improvement for supporting system dispatcher real-time decisions.

The ONS deployment plan for the Brazilian SPMS consists of three main components: 1) a top-down system design approach to avoid potential future integration problems in its phased deployment plan, 2) a strict equipment qualifying test process [for PMUs and phasor data concentrators (PDCs)] to ensure the global performance of the Brazilian SPMS, and 3) a phased deployment plan allowing the system flexibility and scalability for easy system expansion.

figure 1. Brazilian National Interconnected Power System (SIN).

The contributions here provide an account of the most advanced stages in WAMS development in major world economies.

SPMS Architecture Design

ONS has completed the system architecture design of the SPMS. The PDC will be acquired and installed by ONS, while individual PMUs will be acquired and installed by the utility who owns the associated substation or power plant. In addition, the design considered the possible use of the utilities' PDCs at their control centers without compromising the maximum specified time for data latency from the substations to ONS PDCs. Under the regulatory framework, utilities have the responsibility for making the PMU data available at the main PDC site by providing the necessary telecommunication channels.

In SPMS system design, a substation phasor data concentrator (SPDC) in each substation was specified for PMU data storage, aggregation, processing, repacking, and forwarding the data to the next level of the hierarchy. Data storage at the substation level helps to guarantee data availability if telecommunication systems fail.

PMU/PDC Qualification Testing

As the main transducers in the SPMS, the correct and consistent performance of all PMUs deployed by the different utilities will be the key to the overall performance of the system. Proper tests will allow conforming PMUs to best meet the present and future requirements of the Brazilian SPMS. Currently, ONS is in the process of hiring a consultant/testing institution with an expert team and facilities to perform the qualifying tests. ONS also intends to apply the same strategy to verify the compliance of the SPDC and main PDCs to the Brazilian SPMS requirements and specifications.

Proof-of-Concept PMU Application Analysis

During 2007, ONS investigated the effective use of phasor measurement technology to improve real-time SIN operation. The project identified a number of candidate applications, and the following four were chosen for a proof-of-concept pilot implementation:

- ✔ **DampMon:** A tool to monitor system oscillations in SIN and alarm dispatchers for oscillations with poor damping.
- ✔ **StressMon:** A tool to monitor the stresses of the electric power transmission system based on the angle differences.
- ✔ **SyncAssist:** A tool to assist the dispatchers to resynchronize islands using angle differences information.
- ✔ **LoopAssist:** A tool to assist the dispatchers to close loops in parts of the SIN using angle differences information.

Conclusions

ONS and the Brazilian electric power industry have been attempting to deploy a wide-area synchrophasor measurements system for the Brazilian interconnected power grid. It is very important to recognize that synchrophasor technology is moving from the research and development stage to practical operational applications, but to a great extent there are still no commercial off-the-shelf solutions. Even the most fundamental piece of those systems, the PMU, has not proved that all are in full compliance with industry standards to allow realistic interoperability in a multisupplier PMU system. The project has been progressing well according to this approach and has achieved many of its objectives in the completed tasks, such as system design and specifications and proof-of-concept pilot application implementations.

WAMS Initiatives in China

By Tianshu Bi

The installation of PMUs in the Chinese power grid began in 1995. Ouhua Technology Co. Ltd. of Taiwan's ADX3000 system was used on the Chinese power grid as a PMU. From 1995 to 2002, about 30–40 ADX3000s were installed and the main data concentrator stations of WAMS were established in East China, South China, Northwest and Sichuan power grid, and the state power dispatching center (SPDC) successively. The ADX3000 adopted a modem as the communication media leading to a phasor reporting rate of once every second. The installed ADX3000 system successfully recorded dynamic processes of low-frequency oscillations in the Chinese power grid confirming the value of synchronized phasor measurement technology in the area of power system dynamic monitoring. By the end of 2002, Chinese manufacturers began to offer commercial PMUs, which have been commissioned in the Chinese power grid since 2003. By the end of March 2007, about 400 PMUs had been commissioned. These are installed at the substations and power plants of 500-kV and 330-kV voltage levels. The number of PMUs installed in China over the years is shown in Figure 2.

With more than one manufacturer of PMUs, a Chinese standard on PMUs and WAMS was drafted by the State Grid Company and manufacturers in 2003 and issued in 2005. The standard defines the transmission protocol of historical

As the only tool capable of capturing the oscillation data, the WAMS plays an important role in low-frequency oscillation identification and control in China.

data on the basis of the IEEE Synchrophasor Standard 1344–1995 (R2001). The synchrophasor standard provides technical specification for manufacturers and allows interchange of data between a wide variety of users of both real-time and offline phasor measurements.

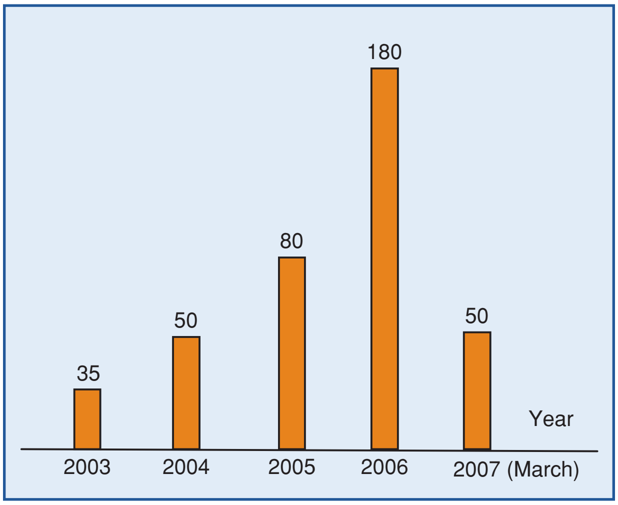

figure 2. PMUs installed on the Chinese power grid.

As an example of the benefits of the PMU measurements, the State Grid Company measured the actual angle difference between two key buses to be 6° while simulation studies had indicated that the angle would be 20°. Information of this type is of particular significance to power system planning, operation, and control personnel. In addition, recent world-wide blackouts also confirm the urgent need for WAMS so that appropriate control actions could be taken. Therefore, for the next five years, all 500-kV substations and 300-MW and above power plants in the Chinese power grid will install PMUs according to the *11th 5-Year Plan of Power Grid*.

Seven regional WAMSs were constructed in the SPDC and the North China, Northeast, Northwest, East China, Central China, and South China power grids. Except for Qinghai, Tibet, Hainan, and Jiangxi, WAMSs have been established in all other provincial grids. Moreover, real-time data exchange is realized among SPDC, North China, and Northeast WAMSs (the schematic diagram of a WAMS is shown in Figure 3).

figure 3. Schematic diagram of a WAMS in China.

In China the main station of the WAMS is located at the regional or provincial dispatching center and composed of an advanced application station, database server, and data concentrator. The advanced application station retrieves data from a data concentrator via LAN instead of Ethernet, which reduces the time delay of the data. From this point of view, the data concentrator in use in China is not as defined in the new IEEE Synchrophasor Standard C37.118.

The data concentrator is one of the key elements of the WAMS in China. Currently, some data concentrators already contain 5,000 phasor measurements and the storage rate of the phasor is 100 Hz. With the fast development of WAMSs, how to construct the data concentrator with 100 PMUs and 10,000 phasor measurements and provide corresponding high-speed storage and retrieval is also a challenging task.

It is expected that PMUs will contribute to improved monitoring, protection, and control of the Mexican power networks in the coming years.

The functions of an advanced application station include visualization of dynamic processes and available transmission capacity, wide-area data recording and playback, and online low-frequency oscillation analysis. Due to the long transmission distances and weak interconnections, low-frequency oscillations are a severe problem in China. As the only tool capable of capturing the oscillation data, the WAMS plays an important role in low-frequency oscillation identification and control in China. The closed-loop low-frequency identification and damping control system has passed the field test. Other PMU applications, such as state estimator, security assessment, adaptive protection, and emergency control are also currently undergoing development.

WAMS Initiatives in India

By R.N. Nayak, Y.K. Sehgal, and Subir Sen

The Indian power system, with installed capacity of about 138 GW, is growing at an accelerated pace. The power system is divided into five electrical regions: Northern, Eastern, Western, Southern, and Northeastern. The Eastern, Western, Northern, and Northeastern regions operate as a synchronous grid with than 90 GW capacity geographically spread over about 2.6 million km^2, and the Southern region with 37-GW capacity is asynchronously connected to the rest of the network.

By 2012, it is estimated that peak demand would be about 157 GW for which installed capacity of about 210 GW has been envisaged. This peak demand is further expected to increase to over 500 GW by 2027 and beyond, for which total installed capacity of about 700 GW is required. Various large-capacity power plants of about 4,000 MW each are being set up in the next four to five years. Most of the generation addition would be confined to a few areas requiring transfer of large amounts of power over long distances to different load centers. In order to optimally utilize rights-of-way, high-capacity corridors of about 6,000–7,000 MW capacity need to be developed. A hybrid system comprising an ±800-kV, 6,000-MW high-voltage dc (HVDC), and 765-kV ac system is being developed that shall also provide control and regulation of power flow to maintain system parameters under different conditions.

The Need for an Intelligent Grid

In India, large generation addition is taking place, and continuous expansion of the grid through increasing grid connectivity is leading to the spread of the grid geographically. Power flow is taking place in multiple directions coupled

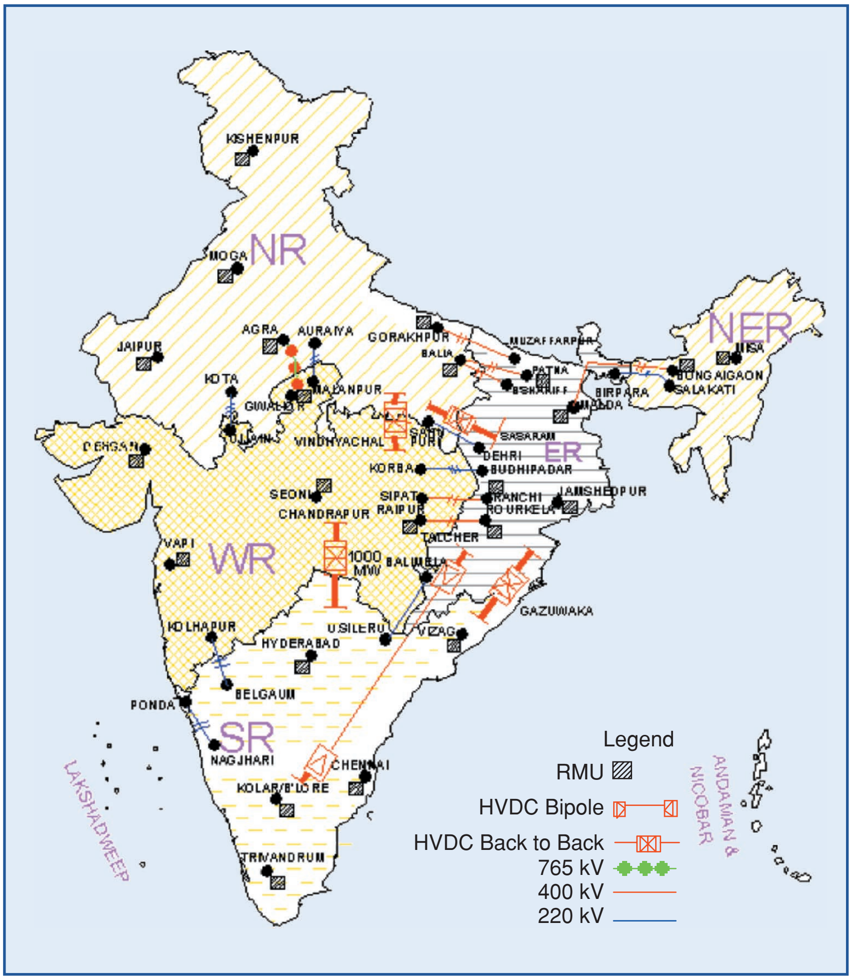

figure 4. Proposed PMU locations at critical buses in India.

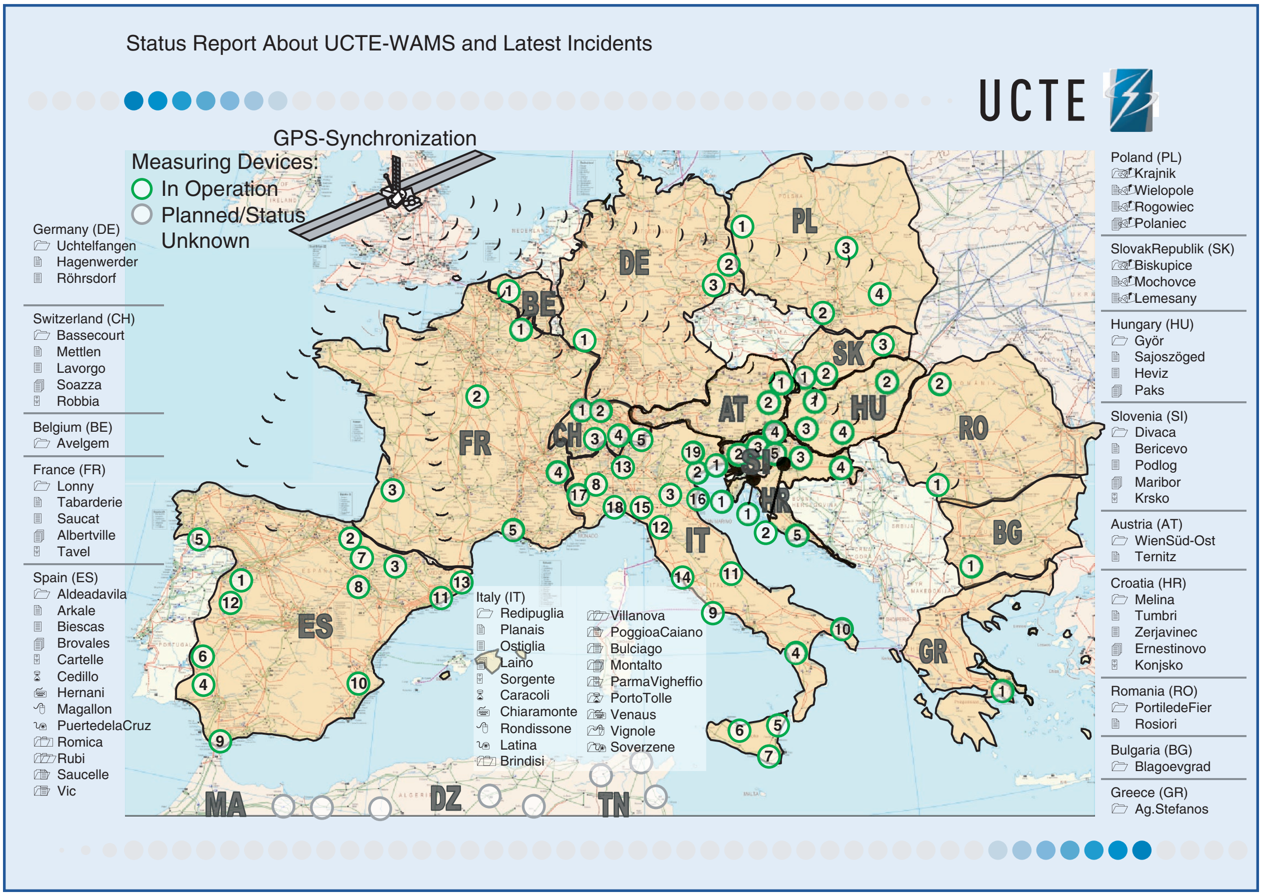

figure 5. Central European WAMS devices (used with permission from UCTE).

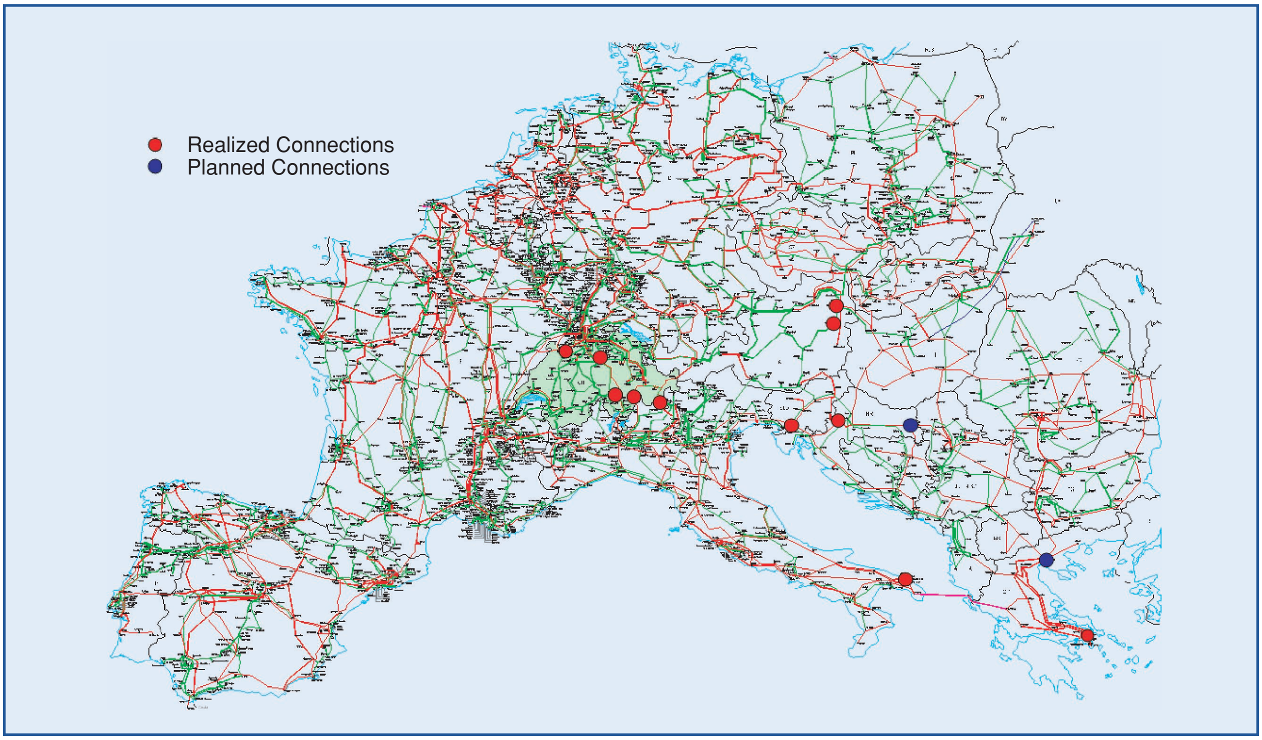

figure 6. Central European WAMS monitoring devices connected to the Swissgrid system in January 2008.

with wide variation in generation as well as demand on a daily/seasonal basis.

With the above features in view, it is important to know the dynamic state of the grid in terms of

- ✔ angular stability and voltage stability
- ✔ how much increase in transfer capacity can take place at different instances on various transmission elements
- ✔ control and regulation of power flow to maintain grid parameters
- ✔ remedial action scheme(RAS) and system integrated protection scheme(SIPS)
- ✔ identifying what corrective actions to take in the event of severe contingency, which may lead to grid disturbances
- ✔ how various corrective actions can be physically implemented.

These issues call for development of an intelligent grid comprising a WAMS, adaptive islanding, and self-healing aspects.

Approach for Development of the Intelligent Grid

Toward achieving these objectives, POWERGRID, the central transmission utility, initiated the work for development of an intelligent grid comprising a WAMS, RAS, SIPS, etc., for dynamic state estimation and control purposes. For this, the following staged approach is adopted:

- ✔ In the first stage, a few PMUs (four to five in each region) are to be installed at critical buses in all the regional grids as shown at Figure 4. Output of these PMUs can be used to validate the offline simulation models, especially exciter and governor characteristics of large generators. PMU output rate can be one every two to five cycles (with a primary sampling rate of at least 12 samples per cycle). PMUs to be installed shall comply with IEEE standard C37.118. Based on the output of these PMUs, a common state estimator is to be developed by combining regional state estimators.
- ✔ Based on the success of stage 1, more PMUs are to be installed at various buses, with locations determined through optimal placement studies with certain levels of observability. All the PMU data are to be stored in different PDCs through an optical-fiber communication system. Further, data from a number of PDCs will be collected at a central location. After installing PMUs, many phenomena hitherto unknown, such as poorly damped oscillations can, be detected.
- ✔ In the final step, an RAS and a SIPS for regulation and control purpose is to be developed. For this, a nomogram is to be developed, which with real time phasor data will lead to the necessary corrective actions.

WAMS Initiatives in Continental Europe

By Walter Sattinger

Within the highly meshed power system of central Europe a multitude of WAMSs are currently in operation (see Figure 5).

The main common characteristics of these devices are the following:

- ✔ high time resolution between two measurements (20–100 ms)
- ✔ high accuracy of voltage and current (class 0.2)
- ✔ precise time synchronization (GPS or DCF77)
- ✔ measurement file length of up to several minutes.

However, from the point of view of the technology used, a distinction should be made between offline measurement devices and online measurement devices. The offline device measurements are mainly based on predefined trigger conditions and their data acquisition is performed by dial-in techniques. The online solutions are all based on PMUs and their data are acquired in central data concentrators that have permanent connections to the remotely located PMUs. This approach enables the user to perform online analysis of the measurements followed by automatic generation of a dedicated alarm, linking in this way the WAMS with the transmission system operator's (TSO) supervisory control and data acquisition (SCADA) system.

Inside the UCTE, the WAM measurements are exchanged between the TSOs in order to calibrate the system dynamic models or for postmortem analysis. One major focus currently is the permanent monitoring of the sporadic appearance of poorly damped inter-area oscillations. In the center of the system and the southeast part, activities of exchanging online measurements between several data concentrators have already started and are in the phase of further extensions. Current partners of these plans are the TSOs from Austria, Croatia, Greece, Italy, Slovenia, and Switzerland (see Figure 6). It should be noted that the Italian data concentrator already receives measurements from about 20 PMUs and the data concentrator in Slovenia from four PMUs and in Croatia from five PMUs.

The additional basic functions of these online devices can be summarized as:

- ✔ voltage phase angle difference monitoring
- ✔ line thermal monitoring (medium value between two substations)
- ✔ voltage stability monitoring (online P–V curves)
- ✔ online monitoring of system damping (online modal analysis with online parameter estimation).

WAMS Initiatives in Mexico

By Enrique Martínez

PMUs have been in use in Mexico since the 1990s. Initial interest was in observing the power system through the eyes of the high-precision synchronized measurement system provided by the PMUs. The data obtained from the PMUs over the years have been invaluable in observing underdamped low-frequency oscillations on the network and the performance of protection systems during power system disturbances.

On 10 March 2005 two of the four electric systems in Mexico (Northwest and the National Grid), which had operated asynchronously until that date were synchronized (see Figure 7). As soon as the tie lines were connected and the systems synchronized, sustained inter-area oscillations were observed throughout the system that eventually led to separating the systems again. These low-frequency oscillations spread throughout the whole power system of the country, especially affecting the most remote points in the network, subjecting the generators and turbines to extraordinary control actions and putting at risk the integrity of the whole electric system.

The challenge for the engineers of the Comisión Federal de Electricidad (CFE) was to know the origin of these oscillations and to determine the oscillation modes and the participation factors of the main generators in the two systems. This process required many simulations for different conditions of generation, load, and network configurations. The PMU recordings were the most important tool in the investigation and analysis performed to determine safe procedures for the interconnection.

Thanks to a WAMS implemented in the CFE, it was possible to record and simulate the oscillations that were present during the synchronous operation. The strategic location of the PMUs was a decisive factor in the analysis and the visualization of the oscillations in real time. PMUs also make possible direct visualization of power system frequency, voltage, phase angle, active and reactive power, etc. However, to find the origin of the oscillations and to correct the settings for excitation controls and power system stabilizers of generators it was necessary to calculate the curves of real power versus frequency (P–F) and reactive power versus voltage (Q–V) of machines and connection circuits among systems. Figure 8(a) and (b) shows the behavior of speed and voltage regulators of generators with strong participation in the undamped oscillations present during 20 s of systems interconnection.

In the future, the offline analysis will be implemented in real time to detect risks of instability, using PMUs, and establishing limits with alarms for oscillations of P–F, Q–V, P–V, etc., curves, for generators, tie lines, or critical points of systems during various levels of load, generation, or for different system configurations. Also, in the future it will be possible to use the three-dimensional analysis of oscillations in transmission lines and the dynamic behavior of distance

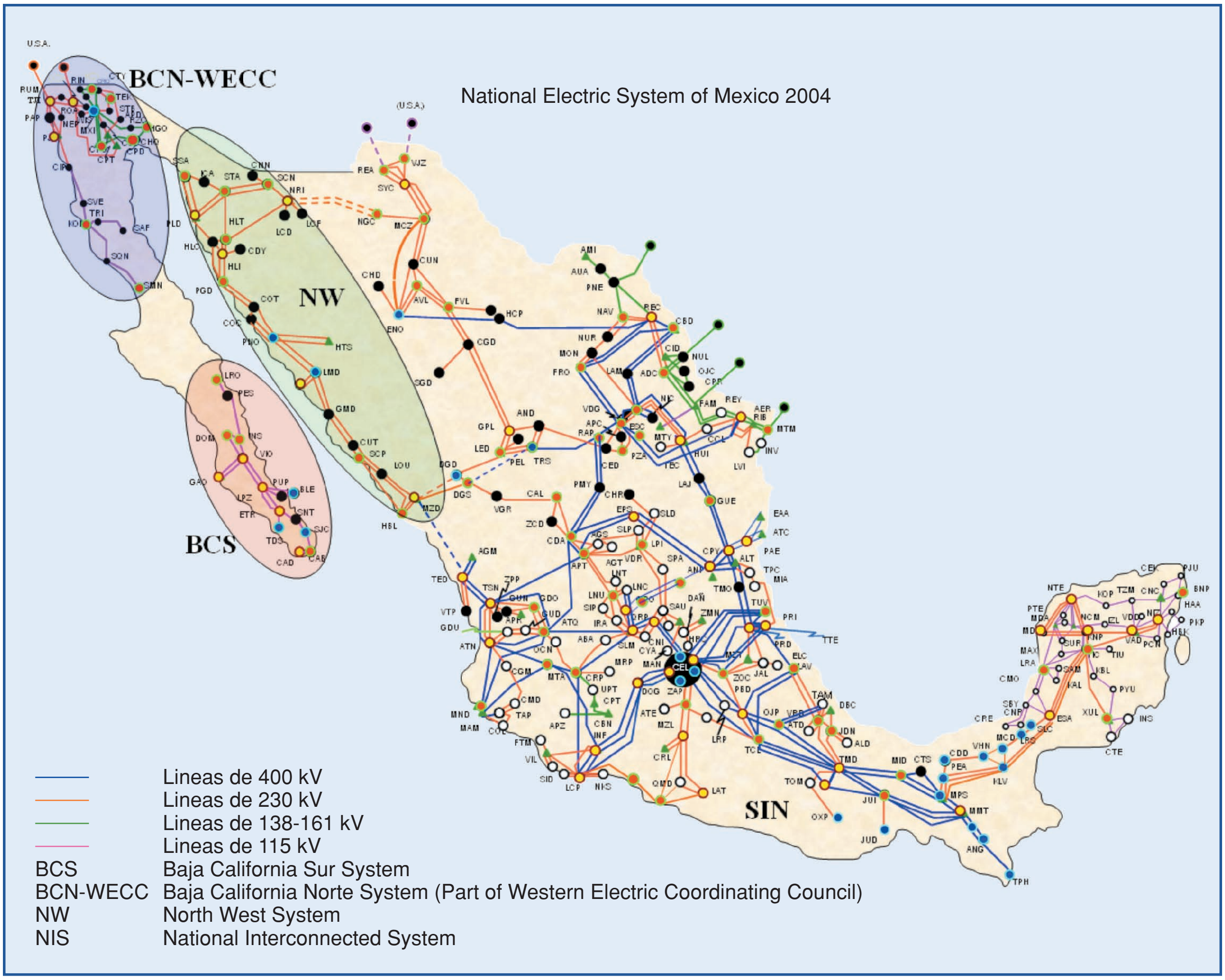

figure 7. Systems that conformed the National Electric System of Mexico as of 10 March 2005.

relays. It is expected that PMUs will contribute to improved monitoring, protection, and control of the Mexican power networks in the coming years.

WAMS Initiatives in Nordic Countries

By Olof Samuelsson

During the last few years the activity in the field of phasor measurements has increased considerably in the Nordic countries. Today all the TSOs have PMUs installed in their networks as shown in Figure 9, but motivations, experience, and future plans for each system are different. The electromechanical oscillations between Finland and Norway have motivated these to be the most active subject for investigation in PMU projects in the Nordic countries. They have taken the lead in the exchange of data and today one Norwegian PMU sends data to Finland and one Finnish PMU is accessible from Norway. It is also natural that Finland and Norway consider PMU-based feedback control of HVDC links and static var compensators (SVCs) to improve damping.

The PMU activities in Norway started around the year 2000. Through several projects the TSO Statnett has built experience on PMU installation, communication, data storage, and analysis tools. The PMU data are integrated with the Statnett SCADA system and recently a visualization tool based on LabVIEW was developed to combine PMU data and digital fault recorder data. In the very near future a project on phasor-based damping control of SVC and HVDC devices will be launched.

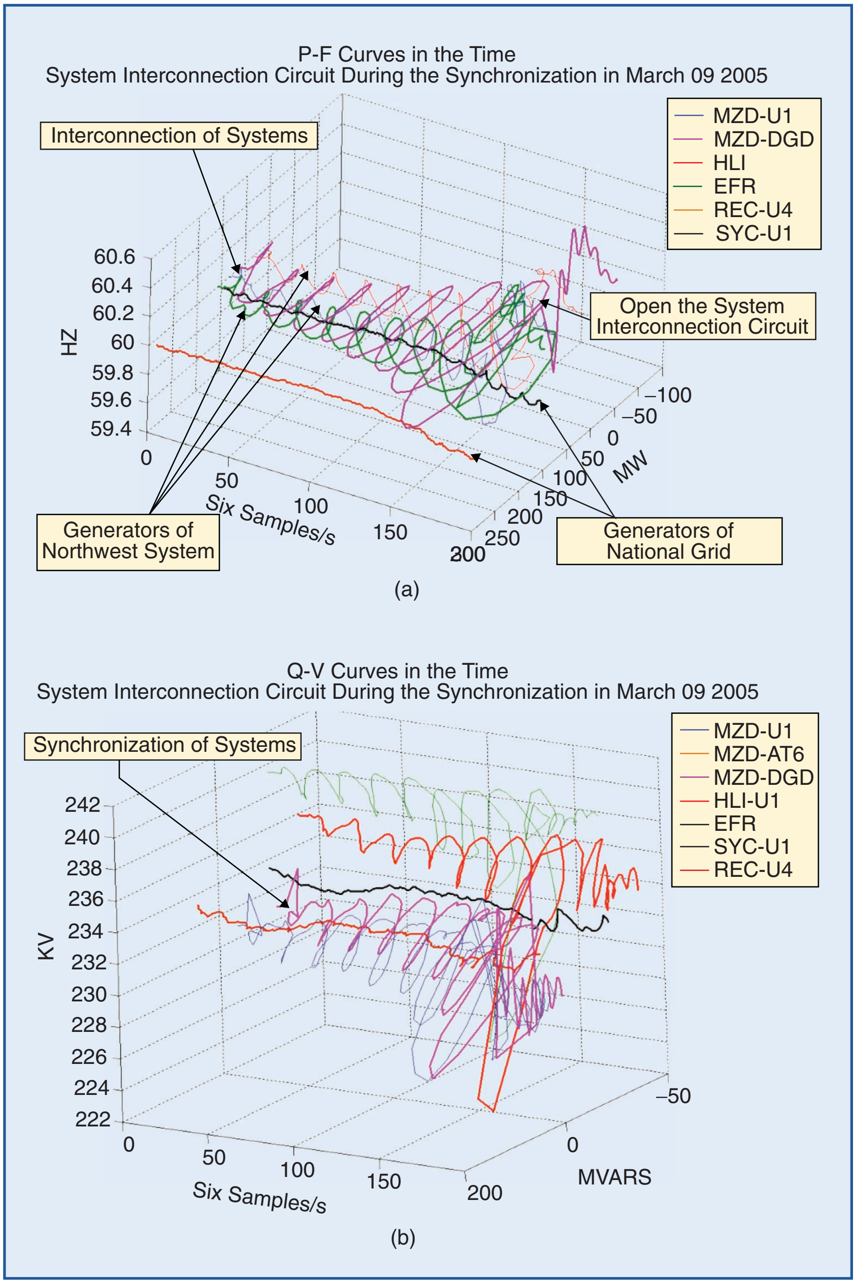

figure 8. (a) P–F curves during 20 s of system interconnection. (b) Q–V curves during 20 s of system interconnection.

The interest in Finland in system dynamics is accentuated by two large projects to be finalized in 2010—the new 1,600-MW Olkiluoto 3 nuclear unit and the expansion of the Fennoskan HVDC link to Sweden. The TSO Fingrid has installed a considerable number of PMUs. They are currently used for disturbance monitoring, but their capability to monitor subsynchronous oscillations has also been investigated. A near-term goal is to present damping information in real-time, which may be extended to feedback control of an HVDC link or SVC to improve damping of inter-area oscillations. Furthermore, a mobile PMU has been used to measure signals at several locations; so far to monitor load variations, but in the future also to monitor dynamic behavior of generators and wind farms.

Since 2005, streaming PMUs have been installed by the TSO Energinet.dk in Denmark. In order to monitor the ac interconnection with Germany, one of these is actually located in Germany. The main application so far is disturbance analysis, but future applications include monitoring of power plant operation, thermal line monitoring, and stability indicators. Four research-grade PMUs with local data storage have been in use for offline disturbance analysis since 2002. They have

Today one Norwegian PMU sends data to Finland and one Finnish PMU is accessible from Norway.

provided insight into data quality and challenges regarding installation and communication. Getting started is easier with offline monitors, but as realized in the 1990s at BPA streaming data has a higher value.

In Sweden the TSO Svenska Kraftnät installs PMUs in their main stations as these are upgraded, which is done with a pace of about two stations a year. The plan is to integrate phasor data with the SCADA system; therefore, the decision about a data concentrator is linked to the next SCADA upgrade. Once the concentrator is in place, disturbance analysis is expected to be the first application of the phasor data, and future use includes real-time monitoring of oscillations in the control center and improved state estimation. In addition to the TSO PMUs, four units in Sweden and one in Finland connected at the 230-V level form a PMU network with a concentrator at Lund University.

Situated in the Atlantic Ocean, Iceland is isolated from the other countries in the Nordel system. The transmission system is relatively weak and electromechanical oscillations are an important issue to the TSO Landsnet. The system is therefore monitored using seven PMUs sending data to the national control center, where damping of oscillatory modes is presented in real time. The monitoring system has also been used for tuning of power system stabilizers with good results.

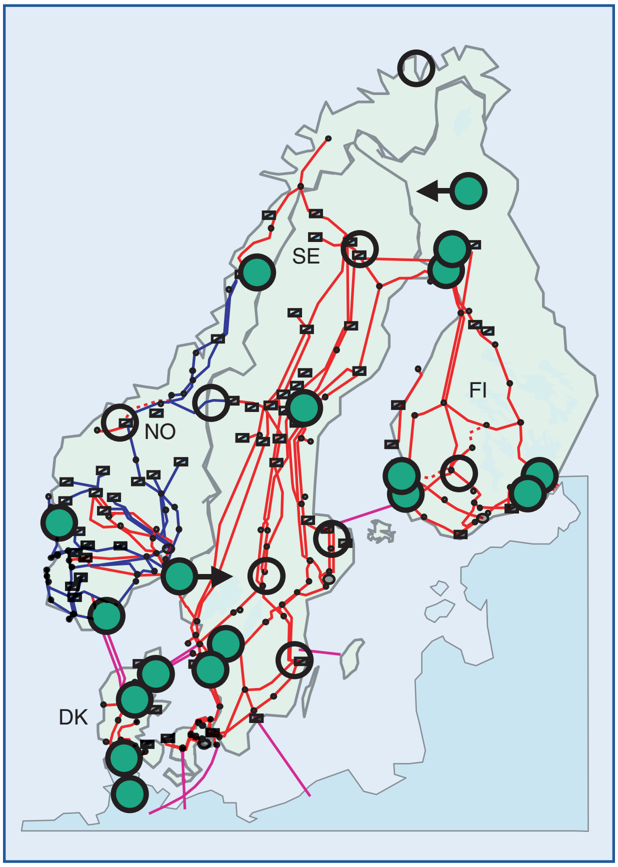

figure 9. The transmission system of the countries in the synchronized Nordel system. Circles indicate TSO installations of streaming data PMUs that are in place (filled circles) and planned (empty circles). Arrows indicate data exchange between Statnett in Norway and Fingrid in Finland. The TSO Landsnet in Iceland (not shown on map) has an additional seven PMUs installed.

WAMS Initiatives in North America

By Damir Novosel and Vahid Madani

The 2003 blackout in the Northeast of the United States and Canada has been a major driver in taking steps to improve reliability of the North American grid. The U.S. Department of Energy (DOE) report to Congress emphasized benefits of synchronized measurement stating that:

- ✔ technology currently exists that could be used to establish a real-time transmission monitoring system to improve the reliability of the nation's bulk power system
- ✔ emerging technologies hold the promise of greatly enhancing transmission system integrity and operator situational awareness, thereby reducing the possibility of regional and inter-regional blackouts.

The first prototype of PMU technologies was developed at Virginia Tech with sponsorship from the U.S. DOE, U.S. Electric Power Research Institute (EPRI), and U.S. National Science Foundation in 1988. Research projects on applying PMUs have been ongoing in collaboration with American Electric Power, Bonneville Power Authority (BPA), New York Power Authority, Southern California Edison (SCE), and Western Area Power Administration (WAPA) since the early 1990s.

In the Western part of the United States, starting in 2002, the research and prototype testing efforts were combined with a real-time dynamic monitoring system (RTDMS) workstation for offline analysis by the California Independent System Operator (CAISO). In parallel, the deployment of real-time PMU data analysis, voltage, and dynamic stability assessment and data visualization applications were further enhanced by deploying the latest technology at BPA, Pacific Gas & Electric Co. (PG&E), SCE, and WAPA. One example of a direct benefit is SCE's Power Systems Outlook software, which has been used for postdisturbance analysis and is currently demonstrating its real-time capabilities in the grid control center. Currently, the following companies are involved: California ISO, BPA, SCE, PG&E, BC Hydro & Power Authority; Alberta Electric System Operator; Arizona Public Service Company (APS), Sempra Utilities, ESBI Alberta, Los Angeles Department of Water and Power (LADWP), PacifiCorp., Salt River Project (SRP), and WAPA.

The establishment of the Eastern Interconnection Phasor Project (EIPP) was a direct result of the Northeast North America blackout of August 2003. As AEP installed the PMU technology before the 2003 blackout, the PMU data captured during the blackout were used for the event analysis. EIPP has started by sending data from several PMU systems (e.g., AEP, Ameren, Entergy, NYPA) to the Tennessee Valley Authority's (TVA) central PDC and then rebroadcast back to the utility PDCs. The following companies have been involved with EIPP: Ameren, AEP, American Transmission Company, ConEdison, Entergy, Exelon (ComEd/PECO), First Energy, Hydro One, Manitoba Hydro, Midwest ISO, NY ISO/NYPA, PPL, Southern Company, and TVA. Since early 2007, the two eastern and western North America efforts have been

table 1. Some applications of PMU technology in North America (excluding Mexico).

Application	Utility
Analysis of system performance: postdisturbance; system oscillation modes (low frequency oscillations), generator performance and model validation, HVDC model validation, phase-angle alarm	BPA
Dynamic data monitoring and analysis (angle, frequency, flows), restoration: synch check, and black start	PG&E
Situational awareness for reducing blackouts, increasing power transfers, power system oscillation monitoring, quicker situation assessment, real-time grid control center applications, intelligent system integrity protection scheme	SCE
Disturbance analysis, dynamic analysis	AEP
Postmortem analysis, data visualization using geographical maps	Entergy
Disturbance analysis	FP&L
State estimation, system harmonic monitoring	NYPA/NY ISO
Trending display of frequency, phase angle monitoring	TVA
State estimation (with AREVA)	Entergy, TVA, PG&E, Manitoba Hydro
State estimation	British Columbia
Voltage and transient stability are being evaluated in conjunction with state estimation	Transmission

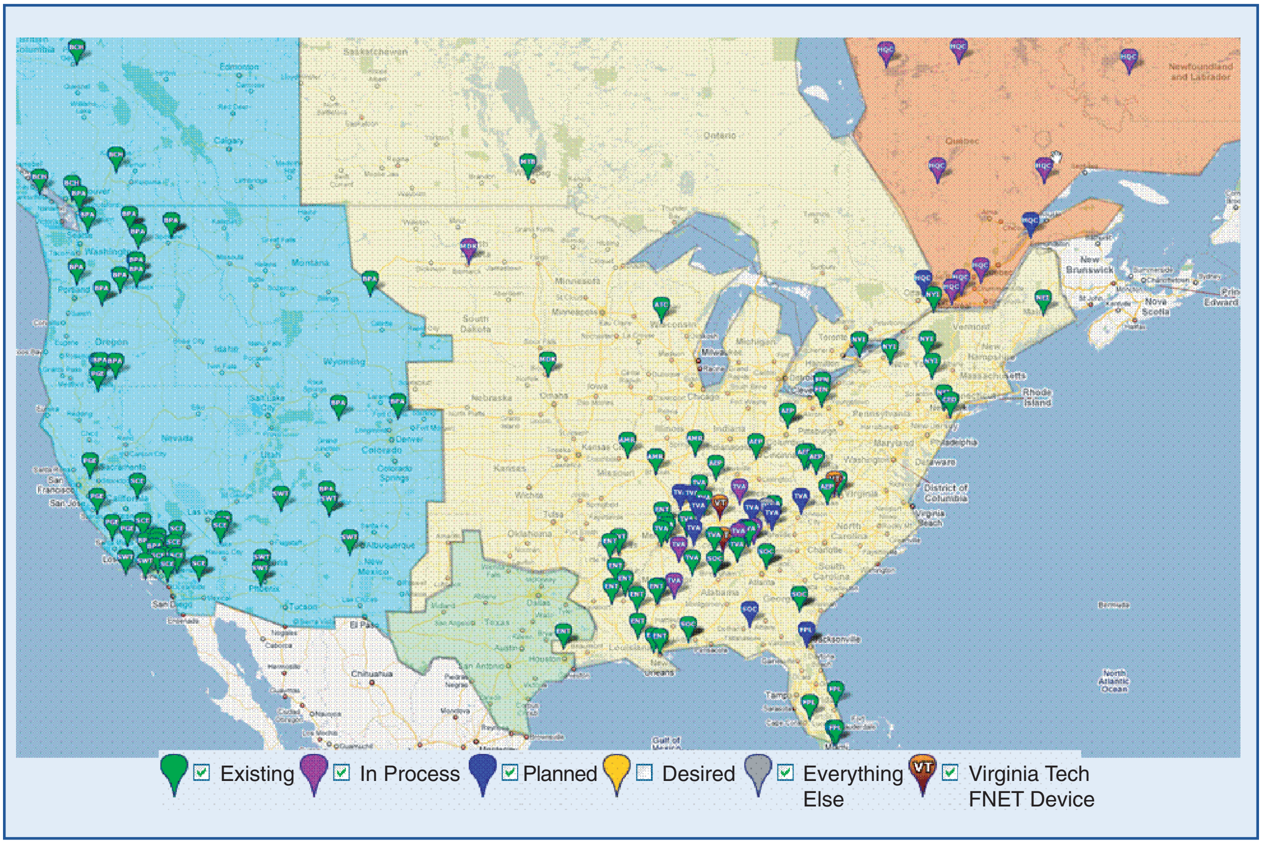

figure 10. Phasor measurement units in North America as of February 2008 (used with permission from NERC).

combined to become the North American Synchrophasor Initiative (NASPI) that also covers Canada and Mexico. At the time of writing this article, in excess of 200 PMUs are in service across the North America, and approximately 20 systems are being installed and implemented for various applications. Table 1 describes some concrete applications currently deployed in North America. Figure 10 shows currently installed PMUs and PDCs in the NASPI systems.

The experiences from deployed PMU systems have already proven that the synchronized measurement technology is required to accurately analyze and control the North American power grid performance both in real time and offline. PMU technology has been beneficial for postdisturbance data analysis and early warning systems, improving system models for faster system restoration. For some of those applications (such as detecting and analyzing angular and small-signal stability), PMUs offer means and benefits not possible with any other technologies. Individual utilities have started realizing financial benefits of using a basic PMU system infrastructure for several integrated applications.

WAMS Initiatives in Russia

By Yuri A. Kulikov

Synchronous interconnection of the 14 national power systems of Eastern Europe, Central Asia, and Siberia from the western borders of the Ukraine to Baikal and from Tajikistan to Kola Peninsula has been achieved. Interconnection consists of the interconnected power system (IPS) of

TPP: Thermal Power Plant
HPP: Hydroelectric Power Plant
PSP: Pump Storage Plant
SS: Substation
CHPP: Combined Heat Plant

1 SS LENIN GRADSKAYA	10 SS CHIRYURT	20 SS MUKACHEVO
2 SS KONOSHA	11 ZHIGULEVSKAYA HPP	21 SS ZAPADN OUKRAINSKAYA
3 ZAGORSKAYA PSP	12 SS YUZHNAYA	22 KHMELNITSKAYA NPP
4 CHPP - 26 MOSENERGO	13 TROITSKAYA TPP	23 SS YUZHNOU KRAINSKAYA
5 KOSTROMSKAYA TPP	14 REFTINSKAYA TPP	24 SS DON BASSKAYA
5 SURGUTSKAYA TPP - 2	16 SS AL TAY	KAZAKHATAN
6 RYAZANSKAYA TPP	17 NAZAROVSKAYA TPP	25 SS EKIBASTUZSKAYA
7 SS CENTRALNAYA	18 SAYANO-SHUSHENSKAYA HPP	26 UYZHNOKAZAKHST ANSKAYA TPP
8 VOLZHSKAYA HPP	19 KHARANORSKAYA TPP	

figure 11. Russian power system and locations of PMU installations.

Ukraine, Belorussia, Latvia, Lithuania, Estonia, Moldova, Georgia, Azerbaijan, Uzbekistan, Kirgizstan, Tajikistan, Mongolia; and the unified power system (UPS) of Russia and Kazakhstan. It is the most geographically extended power system in the world, spanning eight time zones (see Figure 11).

Dynamic behavior investigation of such an extended power system needs information on electromechanical transient parameters with resolution of 0.02–0.2 s and synchronized by space satellite time tags. Such information is provided by IPS/UPS WAMSs. Development of this system started in 2005. Currently 26 PMUs are located in the major power plants and substations from the east to the west and from the south to the north of this immense interconnected power grid. Three models of PMUs are being used: Smart WAMS (RTSoft, Russia)—17 devices, Regina (ANIGER, Ukraine)—seven devices, and Powerlog (AENEA, Germany)—two devices. Accuracy figures of a SmartWAMS device are shown in Table 2.

The Russian WAMS has the following three-tier control structure: the first level contains the multifunctional measuring transducers and communication server installed at the substations; the second level is the control centers allocated in the interconnected dispatch offices (IDOs) of the UPS of Russia and dispatch centers of the IPS; and the third (the highest) level is the system operator central dispatch office of UPS.

Phasor measurements in the IPS/UPS are currently used primarily for system performance monitoring and analysis. One of the important phasor measurements applications is the reference dynamic model (RDM) validation. The system operator for UPS, in cooperation with NIIPT, developed the procedure of RDM validation. In accordance with this procedure, after a disturbance when significant imbalance of active power is created, the following steps of validation test are undertaken:

1) Identification of disturbance (size of imbalance must be more than 800 MW).
2) Transmission of disturbance archives to the system operator control center.
3) Taking note of predisturbance steady-state operational data by means of the energy management system (operative–informational complex) of the system operator. Acquisition of information on generation structure, amount of generation, and available active power reserves of predisturbance steady-state operation.
4) Power system disturbance simulation by means of EUROSTAG. Calculation of parameters (F, P, Q) for identified disturbance in PMU recordings.
5) Comparison of observed recordings and simulated data. In the case of significant divergence the tuning of the model by modification of load types and the parameters (sensitivity coefficients to frequency and voltage) and regulators sets of generators is carried out.

It is planned to fulfill such procedures four to six times per year for the winter peak load and summer light load of power system operations.

table 2. Accuracy of SmartWAMS devices used in Russia.

Frequency (Hz)	Voltage Angle (°)	Voltage, RMS (%)	Current, RMS (%)
0.001	0.1	0.3	0.3

The next phasor measurement application considered is low-frequency oscillation monitoring, including assessment of amplitudes and decrements of oscillations with a frequency range of 0.02–0.2 Hz. The result of monitoring shows that low-frequency oscillations in the Russian system are well damped and have insignificant amplitudes.

The most efficient PMU technology application is power system control in real time. Nowadays, the pilot project of steady-state stability assessment in the north part of the Tyumen power system (IPS of Ural) in real time is being developed. This project is being expanded following the success of a pilot scheme.

Thus, the WAMS is an effective tool of the dynamic performance investigation of synchronous interconnection and allows system operators to create new schemes and algorithms for power system emergency control.

For Further Reading

Please see the list of publications on page 22 of this issue for additional literature related to this topic.

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