# Recent Advances and Applications of Synchronized Phasor Measurements in Power Systems

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*Abstract:* - Present power systems operate in more and more difficult conditions generated by various physical and economic factors. Pushing the power system closer to its physical limits worsens the reliability and security of the general operating conditions. Hence, a better control across the entire grid, through more intensive online analysis is needed. At present, a common point of view considers that Synchronized Phasor Measurement (SPM) units and Flexible AC Transmission Systems, along with distributed generation and storage devices are the main technologies that can successfully and efficiently address such problems. This paper presents the state of the art of the SPM technology and its applications to power systems, including results of research projects developed by the Romanian scientific community. A series of ongoing projects implemented in different countries are briefly presented.

*Key-Words:* - Synchronized phasor measurements, Global Positioning System, Power system monitoring, Power system control, Wide area monitoring and control, State estimation.

## 1 Introduction

Among the present applications of the Global Positioning System (GPS), such as location, navigation, tracking, mapping and timing, the last one seems to be the most attractive to be used in dedicated applications for power systems monitoring and control.

Since, at present, the accessibility of current and voltage phasors across the system becomes more and more a basic condition to monitor system state and initiate preventing control actions against undesired system events, very narrow timekeeping intervals are needed to accurately measure such phasors. For instance, if clocks are synchronized to within about 1 µsec, the angles of the phasors will be within a 0.018 degree confidence interval for a 50 Hz frequency. GPS systems can successfully provide such accuracy, and also can act as a joining link between all measurement points in actual Wide Area Power Systems (WAPS) to synchronize phasor angles.

Paper [1] proposed a globally clock synchronization approach based on radio signals in 1981. A new phasor measurement and computation technique was proposed in 1983 by [35], and the first Phasor Measurement Unit (PMU) was developed at Virginia Polytechnic Institute by Professor Arun Phadke in 1988. Based on this prototype, the first commercial PMUs were manufactured at Macrodyne Co. in 1991 [27, 36].

Due to the high synchronization accuracy of 1 µsec or better achieved by the most recent PMU technologies, the PMU data measurements are far better than traditional SCADA ones. In fact, as suggested in [13], if SCADA represents the old X Ray technology, than PMU is the basic tool of the modern MRI (Magnetic Resonance Imaging) technology.

The author assumed the task to prepare the presentation of the recent advances and applications in SPM in power systems considering the fact that most numerous and valuable contributions belong to the worldwide scientific community. Results of research undertaken by the author, together with other fellows, were added with modesty to the numerous other theoretical and practical results presented in this paper.

## 2 General SPM Characteristics

A phasor $\overrightarrow{X}$ is a complex mathematical representation of a sinusoidal signal *x(t)*, like voltages or currents:

$$x(t)=X \cdot \sin(\omega \cdot t+\Theta)=X \cdot \sin(2\cdot\pi\cdot f\cdot t+\Theta)$$

$$\overrightarrow{X}=X\ e^{j\cdot\Theta} \qquad \overrightarrow{X}=X\ \angle\Theta$$

It is completely defined by two values: a magnitude and a phase angle (Fig. 1). The magnitude is the amplitude or peak value *X* of the original signal, but the RMS or effective value *X* / √2 is also. The phase angle depends on the frequency *f* and a time reference, which can be arbitrarily chosen (e.g. the zero-crossing moment of the original signal *x*(*t*)).

Synchrophasors are extensions of the basic phasor concept that use as reference the nominal power system frequency and the coordinated universal time (UTC), the

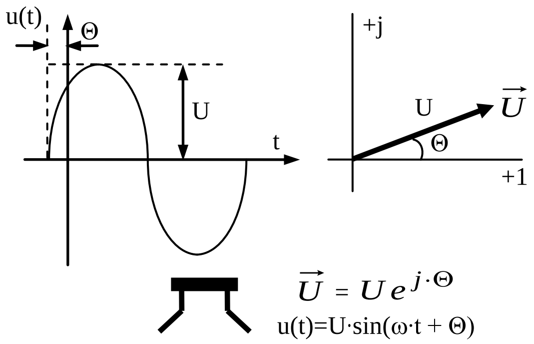

**Fig. 1** – Phasor representation.

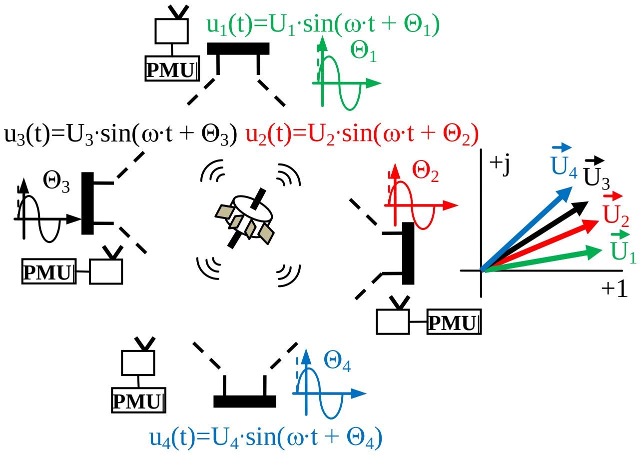

**Fig. 2** – Synchrophasors representation.

time on which all GPS signals are synchronized. According to IEEE Standard C37.118/2005 [18], the phase angle of a synchrophasor represents the angular separation between the reporting instant and the peak of the sinusoidal signal, where the reporting instant is a timetag that defines the reference for the synchrophasor representation. Basically, the synchrophasor concept makes sense in a group of synchrophasors that use the UTC as common reference (Fig. 2). A single synchrophasor is nothing more than a simple phasor.

Algorithms to compute phasors from measured signals use a time window of data samples to estimate the phasor parameters. Simple algorithms assume a fixed nominal frequency value and compute only the magnitude and the angle of the phasor. More elaborated algorithms estimate all of the three parameters yielding, in general, more accurate results [11]. One of the most widely used phasor estimation approach is based on the Discrete Fourier Transform that computes phasor $\vec{X}$ (its real $X_R$ and imaginary $X_I$ parts) as:

$$\vec{X} = X_R + j\cdot X_I = \frac{\sqrt{2}}{N}\sum_{k=1}^{N} x_k \cdot e^{-j\cdot\frac{2\cdot\pi\cdot k}{N}} =$$

$$\frac{\sqrt{2}}{N}\sum_{k=1}^{N} x_k \cdot\left(\cos\frac{2\cdot\pi\cdot k}{N} - j\cdot\sin\frac{2\cdot\pi\cdot k}{N}\right)$$

**Table 1** – Equivalent PME for independent errors.

| PME | Errors located in: | | |
|---|---|---|---|
| | Angle [deg.] | Magnitude [p.u.] | Freq. [Hz] |
| 0.0001 | 0.01 | 0.000175 | 0.0033 |
| 0.0011 | 0.10 | 0.001750 | 0.0333 |
| 0.0111 | 1.00 | 0.017452 | 0.3315 |
| 0.1104 | 10.0 | 0.174320 | 3.1837 |

where $N$ is the number of samples in one period of the fundamental frequency component and $x_k$ are the waveform samples. Phasor $\vec{X}$ can also be estimated using other methods, such as the Kalman filter [4] or artificial neural networks [21].

Phasor Measurement Units (PMUs) are electronic devices that use digital signal-processing components to measure AC waveforms and convert them into phasors, according to the system frequency, and synchronize these measurements under the control of GPS reference sources. The analog signals are sampled and processed by a recursive phasor algorithm to generate voltage and current phasors. PMUs are growing in number, and it is anticipated that over the next five years, up to 5,000 PMUs will be deployed at key substations from the power system worldwide [13].

## 2.1 Phasor measurements accuracy

Phasor measurements are made relative to a nominal system frequency. Hence, due to frequency deviation from its nominal value, the phase angle will change constantly. Thus, higher deviation of the frequency from its nominal value and higher measurement non-synchronism will cause higher synchrophasor angle measurement errors.

The equivalent Phasor Measurement Error (PME), computed as the integral of absolute deviations between the actual samples and the reconstructed ones from the estimated phasor, will vary with the phase angle error, considered as reference, as shown in the Table I, based on [11]. These values represent the case when the error for each parameter occurs individually. On the other hand, according to the synchrophasor standard [18], the maximum phase-shift accuracy one may need for state estimation, monitoring, control, and relaying of power systems is 0.1. Consequently, considering the values from Table 1 the PMU accuracy analysis can be conducted based on the global PME.

According to standard [18], the accuracy of a synchrophasor is measured using the Total Vector Error (*TVE*) defined as the percentage difference between the theoretical phasor *XT* and the estimated one *XE*, the reference value being *XT*:

$$TVE = \sqrt{\frac{(XE_R - XT_R)^2 + (XE_I - XT_I)^2}{(XT_R + XT_I)^2}} \cdot 100 \quad [\%]$$

**Table 2** – Delays for various communication solutions.

| Communication solution | Delay (msec.) |
|---|---|
| Fiber optic | 100 – 150 |
| Digital microwave | 100 – 150 |
| Power line carrier | 150 – 350 |
| Telephone lines | 200 – 300 |
| Satellite | 500 - 700 |

where indices *R* and *I* denote the real and imaginary parts of complex synchrophasors.

Some limitations on the global accuracy of phasor measurement systems can be induced by the accuracy of primary signal sources; critical from this point of view are voltage and current transformers. However, reports cited by [27] indicate that present phasor measurement systems could be considered adequate for actual synchrophasors applications.

## 2.2 Data communication

Standard C37.118 [18] provides a specific protocol for real-time communication of synchrophasors. On the other hand, data communications between PMUs and PDC or between PDCs and the central computing unit can be implemented using a wide variety of solutions that support this protocol.

Present day communication options include telephone lines, fiber-optic cables, power line carriers, microwave links or satellites. Choosing a communication solution is basically a problem that must be considered in terms of bandwidth, safety, flexibility, availability and reliability. Delays are also an important aspect that must be considered; for instance, Table 2 shows the delays produced by various communication solutions applied with PMUs, as reported in [30].

## 2.3 WAMC architectures

As a general rule, the architecture of Wide Area Monitoring and Control (WAMC) systems is a problem dependent on the specific requirements and available resources of each utility. However, as described in [23], three major types of architecture are widely used at present:

- SCADA/EMS based architecture
- Flat architecture, based on system protection terminals and
- Multilayered PMU architecture.

The simplest way of integrating the WAMC system in general and PMUs in particular, in the existing monitoring and control systems is to use existing SCADA/EMS system capabilities. However, due to the limited possibility of extending SCADA /EMS systems with new functions, this solution must be considered as a transition to more dedicated ones.

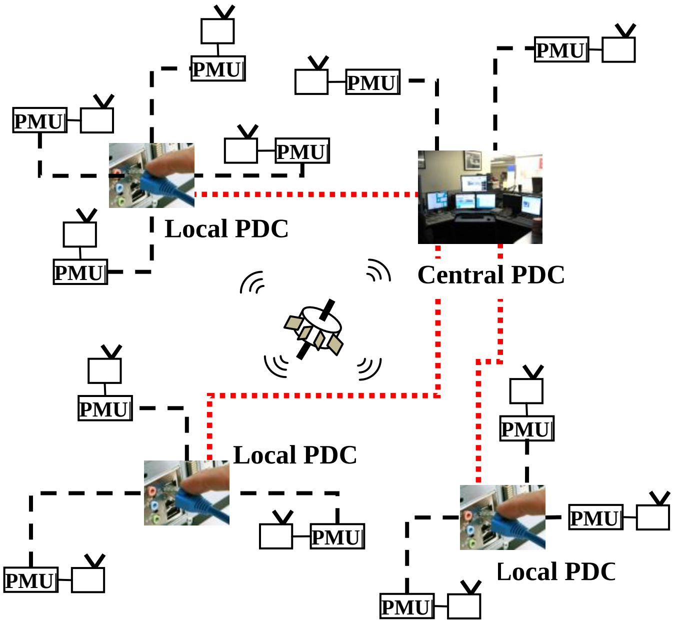

**Fig. 3** – Typical architecture for a SPM system.

Flat architectures use as terminals special protection devices, which act as intelligent agents that process data collected locally or from other remote devices. This type of architecture is suitable for different protection schemes, such as distance protection, load shedding, voltage stability, frequency stability or angular stability.

The Multilayered PMU architecture is one of the most common approaches used for WAMC applications. In this case more PMUs are connected to a local Phasor Data Concentrator (PDC). Further, more PDCs, combined with other PMUs, can be connected to a central PDC located in a control center. This type of architecture is suitable at both local and central level for a wide range of applications, such as system visualization, state estimation or post-disturbance analysis. This architecture type is shown in Fig. 3.

## 2.4 Standardization

The first standardization initiative was assumed in 1995 by an IEEE working group that prepared the IEEE Standard C1344 for Synchrophasors for Power Systems [43]. Ten years later, the new IEEE Synchrophasor Standard C37.118-2005 was developed to specify the requirements that must be met by PMUs and other devices used with synchrophasors [18]. The new standard specifies two levels of compliances that can be met independently with different type of applications (e.g. control or state estimation).For the most demanding level, Standard C37.118 requires a *TVE* less than 1%.

Recently, [34] suggests the need for future revision of the synchrophasors standard, especially to include new concepts and ideas of phasor and frequency measurement under transient conditions.

## 3 General SPM Applications

Using information provided by PMUs, utilities can drastically improve their ability to monitor and control system dynamics. Examples of EMS real-time applications that can benefit from SPM deployment are [12, 39, 46]: visualization of power systems and components, enhanced state estimators, coordination of line transfer capability ratings, optimal allocation of static and dynamic VAR resources, on-line transient stability assessment, identification and analysis of voltage swings, prediction of angular and voltage instability, development of simulation tools to prevent cascading events and islanding phenomena or performance assessment of advanced digital measurement and protection systems. Few of the most cited SPM applications are briefly described forward.

**Real time visualization, monitoring and control** – Real-time monitoring aims to provide operators from control centers with on-line information and knowledge of system state and operating conditions. More PMUs deployed across the power system, time-tagged by GPS satellite systems, and supported by dedicated communication systems, data concentrators and local / central data processors defines a typical WAMS.

**State Estimation** – State estimation (SE) is a widely used EMS application run at system operators’ facilities to provide basic inputs for other real-time applications, such as contingency analysis or congestion management. SPM-based estimation models bring benefits such as better accuracy, better bad data detection and correction techniques, faster numerical algorithms, and more accurate results for multi-area SEs [49].

**Congestion management –** The traditional approach to real-time congestion management is based on the Nominal Transfer Capability, computed off-line using conservative hypothesis concerning thermal, voltage or stability limitations. The SPM technology, based on synchronized measurement data from the congested corridors, allows computing the Real-time Transfer Capability of the corridor, for the actual operating conditions [5]. PMU data can also be used to better control the loading of transmission corridors closer to their real stability limits [20].

**Protection and Control for Distributed Generation –** Considering the wide perspectives of potential applications and supporting governmental policies for Distributed Generation (DG), as suggested in [41], SPM technology seems to be a promising approach to monitoring and islanding DGs and distribution / micro grids. However, a major demand that must be met by the future SPM technology for a wider penetration is to obtain a low cost design.

**Adaptive Protection** – The adaptive or intelligent characteristic of a digital relay is based on its software-centered operation and its communication capability with other relays or other devices, such as PMUs or PDCs. Two of the most promising applications of SPM in adaptive protection are the line outage detection [44] and the measurement with higher accuracy of line impedance for fault-locating applications [2].

**Angular and Voltage Stability -** Static and dynamic angular stability can be efficiently monitored using SPMs, which track the operating point on the power transfer curve P-$\delta$, warning the operator when this point is getting closer to a possibly unstable region. On the other hand, voltage instability usually occurs in heavily loaded systems, with high reactive load flows and very low voltage profiles. Voltage stability conditions can also be effectively tracked using PMUs at both terminals of the tie-line and the Power-Voltage characteristic curve [32].

**Controlled Power System Islanding –** Using real-time PMU measurements instead of the traditional pre-assumed states approach can improve in a great extent the performance of the planned islanding strategy into two directions: identification of groups of generators with imminent loss of stability and identification of most appropriate islanding points [15].

**Post-Mortem Analysis –** The post-mortem analysis of power system disturbances is widely based on recordings collected from various data loggers installed in the systems. The GPS synchronization introduces the time-correlation of recordings, and the entire timeline of a power system disturbance can be reconstructed, allowing a simpler understanding of the sequence of events that have caused the disturbance. Deployment of PMUs on the main substations of power systems has strengthened after major blackouts, like the ones from Italy or U.S.A. in 2003 [38, 40].

## 4 Specific SPM Applications

More details about a set of typical applications of SPM in wide area monitoring and control for power systems are presented in this section.

### 4.1 System State Visualization

A direct application of real-time monitoring using PMUs is the visualization of voltage angles across the network under control. The approach described in [33] reduces the system under consideration to an equivalent system comprising only the PMU buses. In the reduced system, voltage angles are displayed so that phasors that are moving away one another indicate a highly stressed system, approaching instability.

Since wide-area measurement systems based on SPMs provide access to a very large amount of data, the role of data processing and data visualization at control centers become central. To demonstrate the benefits of PMUs applications in power systems, paper [24] presents a specially designed simulation environment. The basic tool for visualizing the system state is a specially designed Graphical User Interface (GUI) that allows approaching certain features like: 2-D or 3-D dynamic contour mapping, branch loading visualization, transmission corridor capacity, contingency assessment, voltage and angle stability assessment, visualization of line power oscillations, and islanding identification and assessment. For better understanding and identifying the system state the GUI widely uses color representation associated to traditional characteristic curves and new contour maps or other modern representation tools.

### 4.2 State Estimation

State estimation (SE) is a critical application function used by the EMS in control centers. Based on measurements provided by the SCADA system, SEs compute an estimate of voltage phasors at all system buses. In the conventional SE model there are no phase angle measurements available, and the voltage phasors are referred to the phase angle of the slack bus.

Including SPM in the traditional model of the SE is quite a simple task since voltage and current phasor measurements are linear complements of a basically non-linear traditional model. This is the reason why, in the general case, PMUs installation is a gradual process, requiring decisions on the optimal location of a limited number of devices. Different optimization criteria, with different constraints can be used to define the PMU optimal placement problem.

For instance, paper [5] approaches this problem using a methodology that determines the optimal PMU placement so that the number of PMUs required to make the system completely observable is minimized, the measurement redundancy is maximized, and the system remains topologically observable during normal operating conditions, as well as during the loss of a single transmission line or measurement unit. A similar approach is presented in [37], where measurements are rearranged using a heuristic algorithm in order to minimize the number of PMUs. The same problem was approached in [29] using a genetic algorithm approach and a bus ranking methodology.

A completely different approach, based on integer programming, is presented in [14], which considers the particular case of the linear state estimation problem that is obtained when using only PMUs measurements.

For the distributed state estimation problem, recent approaches [48] perform multi area state estimation using PMUs, where the measurements at the boundary buses are used to augment the state variable vector from a given subsystem by the state variables in the neighboring subsystems. A different approach is presented in [19], where the main system is decomposed into subsystems based o geographical criteria, and PMUs are placed in the slack buses of each subsystem, to be used as reference for the independently run state estimators. The final state estimation is computed using measurements and / or pseudo-measurements for a set of selected buses.

### 4.3 Fault Detection / Location

Most research works conducted so far for transmission line fault detection/location use local fault information (voltages and currents) at one end or both ends of the faulted line, and apply traditional or artificial computational techniques approaches [3].

The problem of fault location observability was approached in [25], where a new fault-location scheme for transmission networks using the minimal number of PMUs is proposed. The computational model uses measurements taken from PMUs and an innovative fault-location algorithm.

A PMU-based fault detection / location technique for both permanent and arcing faults is presented in paper [26]. PMUs are installed at both ends of the line to synchronously measure three-phase fundamental and harmonic voltage and current phasors. The proposed technique processes fundamental frequency voltage and current phasors at both ends of the line, and uses a spectral algorithm that processes synchronized harmonic phasors for arcing fault discrimination.

Paper [51] proposes a fault location technique based on formulas derived using synchronized voltage measurements taken by PMUs at the buses of a power system. The mathematical model uses the nodal admittance matrix, and needs voltage PMU measurements at all buses in the power system to locate the fault. An improved technique, which uses fault voltages of the buses of the faulted line and from their neighboring buses, is also presented.

### 4.4 Stability and Complex Protection Schemes

SPMs can efficiently be used to monitor and control angle instability in power systems. For instance, paper [17] presents the application of SPMs in the frame of new algorithms for detecting the emergence of angle instability phenomenon in progress. These algorithms are used to detect the fast separation of phase angles among critical areas, and to command the tripping of critical generators in the accelerating area, and the load shedding in the decelerating area to keep synchronism.

In the time frame of transient stability, paper [9] proposes an artificial neural network approach to the rotor angle estimation problem, using locally available measurements from PMUs installed at the EHV bus of a substation, close to a power plant. To control the relative motion of each power plant, the authors conclude that PMUs must be installed close to each power plant where synchronism is controlled, and must receive a reference phase measurement provided by another PMU installed close to the load centre.

The possibility of using WAMS as information platforms for Dynamic Vulnerability Assessment (DVA) was proposed in [22]. This subject was approached using again the optimal PMU placement problem formulated as a problem of power system bus group coherency identification. PMU location selection was assessed based on a "rms-coherency" index, computed as a function of time variations of angle and frequency. Based on this coherency index, [22] proposes a fuzzy algorithm for segregating a power system into two or more areas which can be effectively used for DVA.

In the field of complex protection schemes [51] proposes a SPM-based Remedial Action Scheme against transient instability caused by Extra High Voltage transmission line outages. The method was intended to predict instability conditions and to avoid cascading faults that could result in system blackout. The proposed algorithm aims to determine the timing and amount of remedial control actions against instability based on the equal-area control criterion widely used in transient stability studies.

Another protection scheme intended to improve existing generation shedding in the 400 kV transmission network of the Mexican power system, based on angle differences between SPMs is presented in [28].

## 5 SPM Programs and Pilot Projects

This section presents a concise review of present SPM programs and pilot projects for WAMC systems around the world. For a simpler referencing procedure, the author preferred an alphabetical order of the countries were different projects were implemented.

**Austria -** The shortage in power in the southern part of Austria, as opposed to the surplus power produced in the northern part of the country was aggravated in 2006 by the addition of 1000 MW wind generation in the northeast region and the shutdown of coal-fired power plants in the south region. This is the general background on which the APG introduced WAMS to support actions like: detecting and counteracting contingencies and overloading conditions, power flow monitoring and control on interconnection corridors, collecting data and gaining experience to optimally control the north-south power flow in the Austrian system using phase shifting transformers [6].

**Brazil** – The Brazilian ISO has initiated in 2000 two WAMS-projects aiming at recording disturbance data and applying SPM for system monitoring and control [5]. Another research project installed a number of PMU prototypes in geographically distant locations in Southern Brazil to monitor power system disturbances in normal and abnormal conditions [8].

**Canada** – The large electrical distances along transmission corridors between the northern and southern areas of Canada gives occasion to various electrical problems affecting voltage, angular or frequency stability. Between 1976 and 2004 the Hydro Quebec system monitoring capabilities were enhanced by adding up to 8 PMUs in the 735 kV transmission network. Since then the WAMS changes only in the type and functional characteristics of the original PMUs [6]. Typical applications in the Canadian system are: post-mortem analysis of major events, validation and fine-tuning of simulation models used in power system stability programs and tools for enhanced state estimators [6].

**China** – Since 1996, when a university research group from China tested the first Chinese prototype PMU, and until 2001 about 30 devices that mimic SPM capabilities were installed in China's power system. As reported in [6], up to the mid of 2007, 10 new WAMS projects have been completed, and about 88 PMUs have been put into service and another 45 PMUs were under development at that moment. After the last standardization of PMUs and WAMS in 2005, more than 700 PMUs were installed in the Chinese power system and are already in operation for applications like visualization of system dynamics and transmission capacity, post-mortem analysis or monitoring of inter-area oscillations [5].

**Denmark** – Due to the increasing penetration of wind power production and utilization of combined heat and power units, and a simultaneous low predictability of power flows due to deregulation of electricity market, the ISO from the Danish power system was opposed to the need of handling a changing pattern of electricity production and transmission availability. The project covers research subjects like: PMU measurement method, model verification, stability assessment, system protection schemes and oscillation modes [6].

**France** – The French operator (EDF – Electricite de France) uses PMUs in complex protection schemes designed to avoid collapse conditions on the basis of centralized comparison of voltage angles in different system nodes [32].

**India** – As reported in [5], Powergrid of India is planning to install 20 to 25 PMUs to be used for model validation and wide area state estimation. A longer-term goal of the Indian WAMS system is the development of new remedial action schemes and system integrity protection schemes.

**Italy** – The WAMS in the Italian power system was developed following the blackout from September 2003, aiming to enhance the monitoring facilities and capabilities for system reliability and operational security improvement [7]. During the project development, 30 PMUs were installed in the system, supported by special data concentrators and a dedicated monitoring and data processing application installed at the TERNA's Control Center. The locations of PMUs in the network were selected based on specific optimization criteria, which aimed to maximize the operational value of phasor measurements [6].

**North America** – The Eastern Interconnection Phasor Project (EIPP) was started in 2002, to demonstrate the capabilities of SPM technology and to create a robust and secure WAMS infrastructure over the Eastern Interconnection system from U.S.A. In 2006, Entergy (one of the founding utilities of the EIPP) has 15 PMUs installed in the system under observation [12].

The North American Synchrophasor Initiative (NASPI) was developed to improve power system reliability and visibility based on Wide Area Measurement and Control Systems [31]. At present the WAMCS contains more than 200 PMUs.

In May 2007 the Western Electric Coordinating Council (WECC) system has over 80 PMUs, among which at least 73 were connected in real-time systems. Data exchanges in WECC include now major power utilities like BPA, SCE, PGE et al. Major PMUs applications used in the WECC address phasor real-time display & recording, phasor data analysis, EMS functions and Wide Area Control System (WACS) [27].

**Russia** – The first experiment with WAMS prototypes was carried out in Russia during November 2005, in the Far East Interconnected Russian Power System, to analyze the possibility of using special protection schemes [16]. At present, more than 25 PMUs are installed in the interconnected power systems of 14 countries from Eastern Europe, Russia, Central Asia, and Siberia. The main applications that use this WAMS are system monitoring, model validation and inter-area oscillation monitoring [5].

**Spain** – The Spanish operator has developed special models and algorithms to enhance the traditional state estimator function using measurements provided by PMUs. Based on an extensive research and test program [32], CSE has designed a new robust, effective and accurate phasor-based state estimator module that was incorporated in its SCADA system.

**Switzerland** – Due to high power flows on interconnected lines between the Swiss and the Italian power systems, an enhanced control of the corridors loading became obvious. The most appropriate approach was considered to be the monitoring of the angle difference between substations located at the corridor ends of the Swiss power system [42]. One of the demonstrations of the Swiss WAMS applicability was the resynchronization process between the first and second UCTE zones on October 2004 [6].

## 6 SPM research projects in Romania

The research projects presented in this section are focused on three directions: network reduction techniques, state estimation techniques and fault detection / location methods. The first two directions are based on the concept of network reduction or equivalencing technique, used to replace a large part of the original system, which is of no immediate interest, with a simpler, but enough accurate model. One of the most known and widely used network equivalents is the REI equivalent introduced by Paul Dimo [10].

In this framework, the following subsections present the possibility of using SPMs to enhance the model accuracy of the traditional REI equivalent technique, and to increase the precision and observability of SEs. Finally, results of the implementation of two SPM-based fault location algorithms in an ATP-EMTP program are presented in Section 6.3.

Parts of these works are partial results of the research project 22-126 under the PNCDI-Partnership program supported by the Romanian Government.

### 6.1 Network Equivalents with SPMs

Basically, any network reduction technique splits the original power system into an External system (ESys) and an Internal System (ISys) , separated by a boundary system (BSys). Then, the system or network equivalent is computed for the ESys using a fixed set of operating conditions in both systems and is used to replace the ESys for any other operating conditions in the whole system. Traditional equivalencing techniques do not provide efficient methods to assess the influence of changes occurring in the ESys over the operating conditions of the ISys.

This is possible using PMUs installed on the buses of the ESys. The method was developed around the REI equivalent, but it can be used with any other equivalencing technique. As the voltage phasors of the PMU buses are continuously monitored, this information can be used for a better representation of the ESys without the need to recalculate the REI equivalent.

The proposed model was tested on the IEEE 14-bus and 57-bus systems. Based on these case studies it can be concluded that the applications of real-time measurements provided by PMUs installed in the ESys can considerably improve simulation results produced by traditional REI equivalents. However, if measurement data from two or more PMUs installed in the ESys are to be used, then PMUs location must be optimized for better results. As a general rule, the use of a single PMU in the ESys is sufficient and its best location corresponds to the bus the most exposed to outages, with a high value of generation or load.

## 6.2 State Estimation

For the SE problem, the traditional set of measurements (power injections, line power flows and bus voltage magnitudes) can be complemented with voltage and/or current phasor measurements provided by PMUs.

### 6.2.1 New State Estimators based on REI Equivalents

This subsection presents a short description of a method used to improve the results of the WLS state estimation algorithm by using REI network equivalents and PMUs. The method has been tested on the standard IEEE 14 and IEEE 57 bus networks. For each test system, the ESys, BSys and ISys were separated. A WLS estimation was carried out on a reduced system comprising the ISys and BSys only, with power injections to replace the ESys. Then the ESys was replaced by its REI equivalent with or without PMU buses, and the SE was run in the equivalent system (ISys+BSys+ESys_REI), considering also a bus contingency in the ESys, to increase the difficulty in the estimation of the state of the ISys .

Results from the original SE and the new REI-based SE were compared. For instance, in the case of the IEEE 57 bus test system, all scenarios of PMU placement produced an improvement for the estimation of voltage magnitudes and power flows in the ISys, while the voltage angles estimates remains almost the same as in the original SE.

### 6.2.2 PMUs Optimal Location

This subsection contains a brief description of an original approach to the determination of the minimum number of PMUs to be installed in a system in order to make the system fully observable. The new approach is based on clustering techniques.

The task of PMU’s area identification is formulated as a problem of bus connectivity. The basic assumption considers that the time variation of all phasors in a coherent group or area can be satisfactorily approximated by observing a single phasor appropriately selected from that group. With this aim in view, a hierarchic clustering method was applied, which well overcomes problems related to the generation of coherent and representative groups. The clustering-based approach has the advantage of partitioning the power system and finding the cut–set of the hierarchical tree in an efficient manner.

The performance of the proposed approach was assessed using the IEEE 14-bus, IEEE 57-bus and IEEE 118-bus test systems. The results demonstrate that the proposed methodology can be successfully used in solving optimal PMUs placement in power system state estimation problem.

## 6.3 Distance Protections

This subsection presents in brief the results of the implementation of two fault location algorithms in an ATP-EMTP program. These two algorithms are double-end data type, one of them processing the synchronized power frequency phasors of the voltages and currents and the other one processing only the power frequency phasors of the voltages.

Discrete Fourier Transform and A3 type filters were used to calculate the power frequency phasors of the transient voltages and currents. Both algorithms produce good estimations of fault location, especially for those faults occurring far from the sending end and having small resistances. At the same time, the second algorithm was found to be more responsive to the resistance of the fault than the first one. Test results are obtained through single-phase fault simulations on a 400 kV, 300 km line built on PAS type towers with two conductors of 450 mm$^2$ in the active conductors bundles.

# 7 Conclusions

As electricity becomes more and more a ubiquitous energy carrier and also a commodity, the need for improved reliability and security in transmission and distribution systems will become higher. To meet this need, the power system must change from both structural and operational view point. SPM technology seems to be one of the driving forces that direct power systems towards this aim. The literature shows that expectations for WAMC systems become higher and higher and a growing number of research and utility pilot projects are working on practical applications of SPM technology in power systems. However, a large-scale implementation of SPM-based WAMC sytems is still improbable due to high costs in the SPM technology, but their already proven advantages can support a gradual implementation at different levels of the power system structure.

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