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Application of Phasor Measurement units (PMUs) in electric power system network

Kinjal G. Shah[1], Piyush J. Parmar[2]

[1]*Electrical engineering dept., Vadodara Institute of Engineering, Vadodara-391510, Gujarat, India*
[2]*Electrical engineering dept.,Vadodara Institute of Engineering, Vadodara-391510, Gujarat, India*

Abstract
Now a day's electrical system becomes very much large and Power demand will be increasing more and more. So monitoring of power system becomes biggest task. This paper presents a review on different application of phasor measurement units (PMUs) in electric power system network for advance monitoring, protection and control.

Keywords—*Electric power system network, Phasor measurement units (PMUs), Synchronized phasor measurement, Wide area measurement, GPS*

I. INTRODUCTION

Synchronized phasor measurements are becoming an important element of wide area measurement systems used in advanced power system monitoring, protection, and control applications. Phasor measurement units (PMUs) are power system devices that provide synchronized measurements of real-time phasors of voltages and currents. Synchronization is achieved by same-time sampling of voltage and current waveforms using timing signals from the Global Positioning System Satellite (GPS). Synchronized phasor measurementselevate the standards of power system monitoring, control, and protection to a new level (Heydt et al., 2001). The present and possible future applications of phasor measurement units have been well documented (EPRI final report, 1997). A number of PMUs are already installed in several utilities around theworld for various applications such as post-mortem analysis, adaptive protection, system protection schemes, and state estimation. One of the most important issues that need to be addressed in the emerging technology of PMUs is site selection. The intended system application influences the required number of installations. The cost of PMUs limits the number that will be installed although an increased demand in the future is expected to bring down the cost. The placement sites are also limited by the available communication facilities, the cost of which may be higher than that of the PMUs. A judicious choice of PMU locations is necessary to meet the criteria of cost and the intended PMU applications. PMUs become more and more attractive to power engineers because they can provide synchronized measurements of real-time phasors of voltage and currents (Nuqui et al., 2005). As the sole system monitor, state estimator plays an important role in the security of power system operations. Optimal placement of PMUs in power systems to enhance state estimation is a problem that needs to be solved. Several algorithms and approaches have been published in the open literatures.In Chen et al. (2006), a strategic PMU placement algorithm is developed to improve the bad data processing capability of state estimation by taking advantage of the PMU technology. Techniques for identifying placement sites for PMUs in a power system based on incomplete observability are presented in (Nuqui et al., 2005), where simulated annealing method is used to solve the pragmatic communication-constrained PMU placement problem. A network of PMUs, known as the Wide Area Monitoring System (WAMS) (Hauer, 1997), is already available in Western Electricity Coordinating Council (WECC). The WAMS data had been analyzed for multiple purposes, including major blackout analysis (Kosterev D. N., 1999), model validation (Pereira, 2003), modal analysis (Hauer, 1991), and special control actions (Kosterev et al., 1998). Several major utilities have recently shown an interest in the synchronous phasor measurement technology. These include Hydro-Québec (Missout et al.,1993), American Electric Power (Schulz et al., 1997), the New York Power Authority, Electricity de France (EDF) (Faucon O., 1997) and many utilities of the Western Southern Coordinating Council (WSCC) (Mittelstadt, 1995; Bhargava, 1999; Kosterev, 1998) such as 65 Singh et al. / International Journal of Engineering, Science and Technology, Vol. 3, No. 3, 2011, pp. 64-82 BPA and Southern California Edison Co. Accelerated by the fast convergence between high-capacity fiber-optics-based telecommunication network and a more effective management of distributed information systems through LANs and WANs, this trend will soon provide a reliable source of wide-area measurement of the dynamic state of the power systems (Mittelstadt, 1995).

II. FUNDAMENTALS OF PMUs

Synchronized Wide Area Measurements (WAMs) is a relatively recent practice worldwide in the operation and control of electric power transmission. It consists of makingsynchronized measurements of phasor quantities of voltages and currents at several points spaced hundreds or thousands of kilometers apart. Phasor Measurement Unit (PMU) technology provides phasor information (both magnitude and phase angle) in real time. The advantage of referring phase angle to a global reference time is helpful in capturing the wide area snap shot of the power system. The importance of data provided by PMUs has been well recognized after a number of major blackouts in many power systems in different parts of the world. PMU is animportant component of WAMs.With the advancement in technology, the microprocessor based instrumentation such as protection Relays and Disturbance Fault Recorders (DFRs) incorporate the PMU module along with other existing functionalities as an extended feature.

2.1Fundamentals of PMUs

A pure sinusoidal waveform can be represented by a unique complex number known as a phasor. Consider a sinusoidal signal

$$x(t) = X_m \cos(\omega t + \varphi) \quad (1)$$

The phasor representation of this sinusoidal is given by

$$x(t) = \frac{X_m}{\sqrt{2}} e^{j\varphi} = \frac{X_m}{\sqrt{2}} (\cos\varphi + j \sin\varphi) \quad (2)$$

Note that the signal frequency ω is not explicitly stated in the phasorrepresentation. The magnitude of the phasor is the rms value of the sinusoid $\frac{X_m}{\sqrt{2}}$and its phase angle isφ , the phase angle of the signal in equation (1). The sinusoidal signal and its phasor representation given by equation (1) and (2) are illustrated in Fig. 1.

The positive phase angles are measured in a counterclockwise direction from the real axis. Since the frequency of the sinusoidal is implicit in the phasor definition, it is clear that all phasors which are included in a single phasor diagram must have the same frequency. Phasor representation of the sinusoidal implies that the signal remains stationary at all times, leading to a constant phasor representation. These concepts must be modified when practical phasor measurements are to be carried out when the input signals are not constant, and their frequency may be a variable.

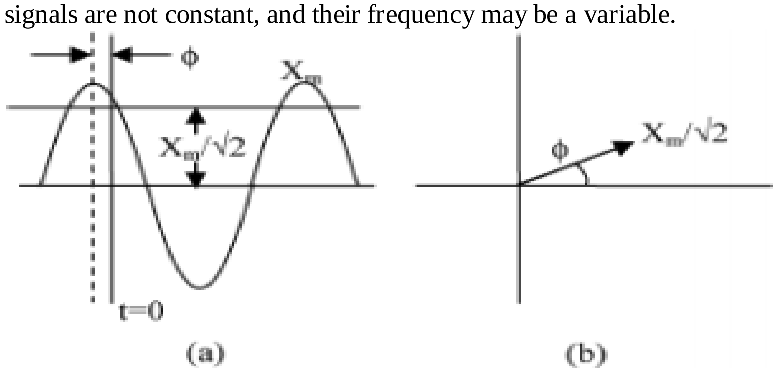

Fig. 1 Phasor representation of a sinusoidal signal. (a) Sinusoidal signal (b) Phasor representation.

2.2 Phasor Measurement Concepts

Although a constant phasor implies a stationary sinusoidal waveform, in practice it is necessary to deal with phasor measurements which consider the input signal over a finite data window. In many PMUs the data window in use is one period of the fundamental frequency of the input signal. If the power system frequency is not equal to its nominal value, the PMU uses a frequency-tracking step and thus estimates the period of the fundamental frequency component before the phasor is estimated. It is clear that the input signal may have harmonic or non-harmonic components. The task of the PMU is to separate the fundamental frequency component and find its phasor representation. The most common technique for determining the phasor representation of an input signal is to use data samples taken from the waveform, and apply the Discrete Fourier Transform (DFT) to compute the phasor. Since sampled data are used to represent the input signal, it is essential that antialiasing filters be applied to the signal before data samples are taken. The antialiasing filters are analog devices which limit the bandwidth of the pass band to less than half the data sampling frequency (Nyquist criterion). If X_k, k {=1, 2, 3... N-1} are the N samples of the input signal taken over one period, then the phasor representation is given by (A.G. Phadke and Thorp, 2008)

$$X = \frac{\sqrt{2}}{N} \sum_{k=0}^{N-1} x_k \, e^{-jk\frac{2\pi}{N}} \quad (3)$$

The multiplier in front of the summation sign have some logical explanation that for real input signals, the components of the signal at a frequency ω appear in the DFT at ±ω and are complex conjugates of each other. They can be combined, giving a factor of 2 in front of the summation sign in equation (3). The peak value of the fundamental frequency thus obtained is then converted to rms value by dividing by$\sqrt{2}$. The DFT calculation eliminates the harmonics of the input signal. However, the non-harmonic signals and any other random noise present in the input signal leads to an error in estimation of the phasor. The error of estimation due to these effects has been discussed in the open literatures.

2.3 Synchrophasor Definition and Measurements

Synchrophasor is a term used to describe a phasor which has been estimated at an instant known as the time tag of the synchrophasor. In order to obtain simultaneous measurement of phasors across a wide area of the power system, it is necessary to synchronize these time tags, so that all phasor measurements belonging to the same time tag are truly simultaneous. Consider t = 0 in Fig. 1 is the time tag of the measurement. The PMU must then provide the phasor given by equation (2) using the sampled data of the input signal. Note that there are antialiasing filters present in the input to the PMU, which produce a phase delay depending upon the filter characteristic. Furthermore, this delay will be a function of the signal frequency. The task of the PMU is to compensate for this delay because the sampled data are taken after the antialiasing delay is introduced by the filter. This is illustrated in Fig. 2. The synchronization is achieved by using a sampling clock which is phase-locked to the one-pulse-per-second signal provided by a GPS receiver. The receiver may be built in the PMU, or may be installed in the substation and the synchronizing pulse distributed to the PMU and to any other device which requires it. The time tags are at intervals that are multiples of a period of the nominal power system frequency. It should also be noted that the normal output of the PMU is the positive sequence voltage and current phasors. In many instances the PMUs are also able to provide phasors for individual phase voltages and currents (Revision of IEEE Std 1344, 1995).

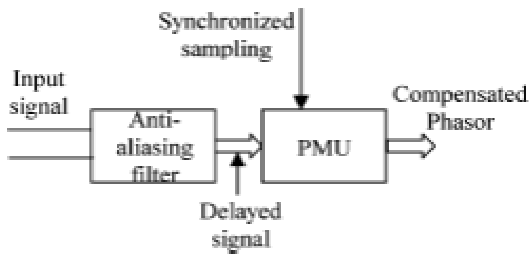

Fig. 2. Compensating for signal delay introduced by the antialiasing filter

2.4 Applications of PMUs in Power Systems

The synchronized phasor measurement technology is relatively new, and consequently several research groups around the world are actively developing applications of this technology. It seems clear that many of these applications can be conveniently grouped as follows:

- Power system Real Time Monitoring, Recording & Control
- PMU assisted state estimator
- Post- Disturbance Analysis
- Power System Restoration
- Protection and control application for Distributed Generation (DG)
- Overload monitoring
- Adaptive Protection
- Phase Angle Monitoring
- Voltage Stability Monitoring

2.5 Outlook of PMUs

PMUs facilitate innovative solutions to traditional utility problems and offer power system engineers a whole range of potential benefits, including:

- Precise estimates of the power system state can be obtained at frequent intervals, enabling dynamic phenomena to be observed from a central location, and appropriate control actions taken.
- To ensure acceptable quality of the power supplied to the consumers.
- Post-disturbance analyses are much improved because precise snapshots of the system states are obtained through GPS synchronization.
- To analyze the vulnerability of the system against any contingency. This is known as security assessment of the power system networks.
- Advanced protection based upon synchronized phasor measurements could be implemented, with options for improving overall system response to catastrophic events.
- Advanced control using remote feedback becomes possible, thereby improving controller performance.

2.6 The Global Positioning Satellite (GPS) Systems

The GPS system consists of 24 satellites in six orbits at an approximate altitude of 10,000miles above the surface of the earth. They are thus approximately at one half the altitudes corresponding to a geo-synchronous orbit. The positioning of the orbital plane and the positioning of the satellites in the orbits is such that at any given instant at least four satellites are in view from any point on the surface of the earth. Often, more than six satellites are visible.

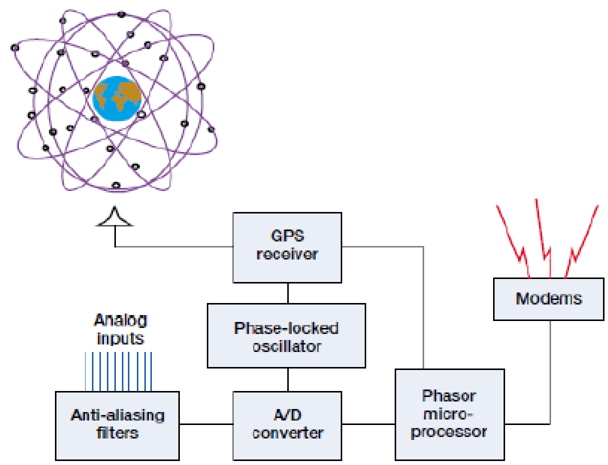

Fig. 3. Block diagram of PMU

The civilian-use channel of the GPS system transmits positional coordinates of the satellites from which the location of a receiver station on earth could be determined. In addition, the satellites transmit a one-pulse per- second signal, along with an identifier for the signal that can be interpreted by the earth station receivers. The civilian-use transmission of the time signal is precise to within 1 microsecond, and often in practice is found to be much more accurate. The time pulse is of critical importance to the application considered here. The normal practice is to phase lock a sampling clock to this pulse. The sampling instant would be identified as the pulse number within a one-second interval identified by the GPS time-tag. The exact format for time-tagging is defined in IEEE standard 1344 (EPRI Final Rep., April, 1997). It should be mentioned that a time standard known as the IRIG-B standard is currently being used by the power industry for time-tagging digital fault recorders and other substation event monitoring systems. However, with standard IRIG-B receivers the synchronization accuracy is of the order of 1 millisecond, which is not enough for precise power system measurement (a tolerance of 1 millisecond corresponds to an uncertainty of about 20°).The Complete block diagram of PMUs and PMUs utilization in power systems are shown in Fig. 3. & 4.

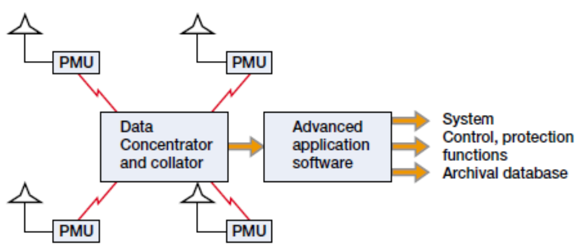

Fig. 4 PMU utilization in Power System

The various features of PMUs are given below as follows:
• PMUs are Measures 50/60 Hz AC waveforms (voltage and current) typically at a rate of 48 samples per cycle.
• PMUs are then computed using DFT-like algorithms, and time stamped with a GPS.
• The resultant time tagged PMUs can be transmitted to a local or remote receiver at rates up to 60 samples per cycle.

2.7 Main strategy of PMU placement based on Power Systems Intrinsic Characteristics

For the purposes of real-time dynamic performance monitoring the power system operating conditions, WAMS should have following monitoring functions:
• Key lines and links reflect the main system characteristics
• Substations on key system interties and major load areas
• Key system generating plants
• Key system substations
• Key devices, such as HVDC, SVC, TCSC and other FACTS devices
• Special protection systems and remedial action schemes
• Real-time observation of system performance
• Recording and analysis of system disturbances

2.8 The Comparisons between SCADA system and PMUs System

Attribute	**SCADA**	**PMUs**
Measurement	Analogue	Digital
Resolution	2-4 samples per cycle	Up to 60 samples per cycle
Observability	Steady State	Dynamic/Transient
Monitoring	Local	Wide-area
Phasor Angle measurement	No	Yes

Table. 1 comparisons between SCADA and PMUs systems

From Above Table1 it is concluded that the PMUs are gives more accurate and efficient results as comparisons of SCADA systems.

III. A LITERATURES SURVEY ON APPLICATIONS OF PMUS IN ELECTRIC POWER SYSTEM NETWORKS

The applications of PMUs such as monitoring, control and protection in power system networks are discussed in details in this section.

3.1 Optimal Placement of PMUs in Power System Networks

In Almutairi and Milanovi (2009) compare three different methods for optimal placement of PMUs. The objective of the placement methods is to provide the maximum observability information of the electromechanical modes of interest. The first method is based on the observability factor analysis, the second on the sequential orthogonalization algorithm and the third combines coherency identification technique with the observability factor analysis. Kerdchuen and Ongsakul (2008) suggested a hybrid genetic algorithm and simulated annealing (HGS) for solving optimal placement of PMU and RTU for multi-area power system state estimation. Each power system control area includes one PMU andseveral RTUs. Voltage magnitude, voltage angle, and real and reactive current are measured by PMU while the injection and flow of real and reactive power are measured and monitored through RTU. The power injection and flow measurement pairs are placed to observe the raw data of boundary bus and tie line for data exchange in wide-area state estimator. In (Gou B., 2008), presented a simple optimal placement algorithm of PMUs by using integer linear programming. Cases with and without conventional power flow and injection measurements are considered. The measurement placement problems under those cases are formulated as an integer linear programming which saves the CPU computation time greatly. Sodhi and Srivastava (2008) presented a two level approach for solving optimal PMU placement (OPP) problem in order to achieve complete observability of the power system. The proposed approach in this literature is utilizes a heuristic algorithm to partition the powersystem into two or more sub-networks. The algorithm partitions the spanning tree of the network using integer linear programming (ILP). The ILP has been formulated based on eigenvectors of the adjacency matrix of the spanning tree. After decomposition, PMUs have been placed optimally in the sub-networks in order to minimize installation cost of the PMUs. Nuqui and Phadke (2005) presented techniques for identifying placement sites for PMUs in a power system based on incomplete observability.

Modern-day power systemsare being operated under heavily stressed conditions to cater for the rapidly growing demand for electricity, and to maintain an economic operation under a highly competitive deregulated environment (Phadke*et al.*, 1983). A wide area monitoring, protection, and control(WAMPAC) system is therefore becoming increasingly essential for improved power system planning, operation, maintenance, and energy trading (Novosel*et al*., 2008). Baldwin et al. (1993) addressed the placement of a minimal set of PMUs so as to make the system placed at a bus measures the voltage as well as all the current phasors at that bus, requiring the extension of the topological observability theory. Chakrabarti and Kyriakides (2008*)* proposed a method for optimal placement of PMUs for complete observability of a power system for normal operating conditions, as well as for single branch outages. A binary search algorithm is used to determine the minimum number of PMUs needed to make the system observable. In measurement redundancy. (Aminifar*et al.*, 2009), investigated the application of immunity genetic algorithm (IGA) for the problem of optimal placement of PMUs in an electric power network.PMUs have evolved into a practical tool for measurement of positive sequence associated withpower system voltage and current phasors. These devices are synchronized via signals from GPS transmission. They can enhance many present applications such as state estimation and bad data detection, and stability control (Kosterev et al., 1998), remedial action schemes (Bertsch et al.,2005), and disturbance monitoring (Zhong*et al*., 2005). As the voltage and current phasors are measured, the equations of state estimationproblem become linear and the solution can be obtained straightforwardly (Zivanovic and Cairns, 1996). It is neither economical nor necessary to install a PMU at each bus of a wide-area power network. As a result, the problem of optimal PMU placement (OPP) concerns with where and how many PMUs should be implemented to a power system to achieve full observability at minimum number of PMUs.

3.2 Power System Real Time Monitoring

In a power system phasor-based frequency measurement technique has very good steady-state performance, but their dynamic performance is not well documented. This literature analyzes a phasor-based frequency measurement method that considers the effect of dynamic frequency, and proposed a method to improve the dynamic performance of the phasor-based frequency measurements. In this literature, the reliability modeling of PMU is proposed and the proposed model is extended to consider options for the PMU hardware. Recently, wide area monitoring of power system based on multiple phasor measurements has been put into the spotlight by many engineers and practitioners. Phasor measurement unit (PMU), equipped with the GPS, gives the opportunity of data synchronization at a common time reference. With the GPS, the time stamp is accurate to within 1 microsecond at any location on the earth. Accordingly, observed phasor data measured at multiple locations can be synchronized with high accuracy (Kakimoto, et al., 2006). Moreover, oscillation modes, especially the inter-area low-frequency mode with poor damping, can be detected from measured data by modeling measured data via a simplified oscillationmodel (SOM) (Hashiguchi et al, 2004).

3.3. Power System Operation, Control, and Planning

The voltage and current phasors measured by the PMUs at widely dispersed locations are time-stamped with respect to a GPS clock (Phadke et al. 1994). To determine the confidence levels associated with the state variables obtained by using the PMUs, it is needed to evaluate thecorresponding uncertainties. The main sources of measurement uncertainties are: 1) the instrument transformers; 2) the analog interfaces, including cables, connecting the instrument transformer and the digital equipment; and 3) the analog to- digital converters (ADCs) and the associated computational algorithm (Zhu et al., 2006).

Precise time-synchronized phasor measurements are available to us today from the PMUs. One of the most promising uses of the PMU is for during transient control applications. The work reported in this literature by Stewart et al. (1995) investigated the ability of synchronized Phase Angle Measurements to identify impending instabilities through real time measurements and to trigger remedial actions in time to prevent major power system outages.

3.4 Application of PMUs for Fault detection/Location of Power Systems

Lee et al. (2006) presented a new numerical algorithm for fault location estimation and for faults recognition based on the synchronized phasors. The proposed algorithm in this literature is based on the synchronized phasor measured from the synchronized PMUs installed at twoterminals of the transmission lines. Yu et al. (2002) suggested a new fault location algorithm based on PMUs for series compensated lines. Traditionally, the voltage drop of series device is computed by the device model in the fault locator of series compensated lines, but using this approach errors are induced by the inaccuracy of the series device model or the uncertainty operation mode of the series FACTS device. The proposed algorithm does not utilize the series device model and knowledge of the operation mode of the series device to compute the voltage drop during the fault period. Instead, the proposed algorithm uses two-step algorithm, pre-location step and correction step, to calculate the voltage drop and fault location.

3.5 Application of PMUs for power system state estimation

Chawasak et al. (2007) presented a new method for an optimal measurement placement of phasor measurement units (PMUs) for power system state estimation. In (Nabil et al., 2009), PMUs are considered as a promising tool for future monitoring, protection and control of power systems. In this literature, a unified approach is proposed in order to determine the optimal number and locations of PMUs to make the system measurement model observable and thereby can be used for power system state estimation. The PMU placement problem is formulated as a binary integer linear programming (BILP), in which the binary decision variables (0, 1) determine whether to install a PMU at each bus, while preserving the system observability and lowest system metering economy. A straightforward application of state estimation theory treats phasor measurements of currents and voltages as additional measurements to be appended to traditional measurements now being used in most energy management system (EMS) state estimators (Zhou et al., 2006). In Chakrabarti et al. (2009), a method to assign weights to the measurements obtained through PMUs in a weighted least squares (WLS) state estimation is presented. Chakrabarti et al. (2007, 2009) described the use of two approaches: classical uncertainty propagation theory, and the random fuzzy variables, to compute the PMU measurement uncertainties. The problem of finding optimal PMU locations for power system state estimation is well investigated in the literatures (Nuqui et al., 2005; Chakrabarti et al., 2009). However, the propagation of PMU measurement uncertainty along the transmission lines, and consequently the uncertainties in the estimated states is not adequately addressed so far.

3.6 Application of PMUs for power system voltage stability

An operating state of power system changes dynamically due to severe change in system conditions such generation,load or line trip. Such severe disturbances effect voltage phasor, current phasor and system frequency. So, to better monitor the dynamics of large power system, wide area synchronized monitoring of voltage phasor, current phasor and system frequency is vital. For efficient real time monitoring and operation of power system, high resolution based PMUs should be used. PMU can accurately measure node and branch phasors at high sampling rate. With new systems capable of making synchronized phasor measurements there are possibilities for real-time assessment of the stability of a transient swing in power systems. In the future, online control will be necessary as operating points are pushed closer toward the margin and fast reaction time becomes critical to the survival of the system. A piecewise constant-current load equivalent (PCCLE) technique is developed which utilized synchronized phasor measurements to provide fast-transient stability swing prediction for use with high-speed control (Liu et al., 1995). In (Daniel et al., 2008), the frequency and damping of electromechanical modes offer considerable insight into the dynamic stability properties of a power system. The performance properties of three mode-estimation block-processing algorithms from the perspective of near real-time automated stability assessment are demonstrated and examined.

3.7 Application of PMUs for Harmonic Measurement in power system

In Carta et al. (2009), a measurement system, based on high-performance Global Positioning System (GPS) receivers and general-purpose acquisition (DAQ) boards, for the evaluation of the synchronized harmonic phasors in the nodes of an electric distribution network, is presented. To meet the requirements of different fields of application, two measurement procedures have been implemented: One is based on a fixed observation window, whereas, in the other one, the observation interval is a function of the actual power system frequency. In (Carta et al.,2007), the measurement procedures have been extended to the field of harmonic quantities, making them suitable to set up an innovative measurement system that is able to perform evaluations of synchronized harmonic phasors on electric distribution networks. In this literature, further refinements of the procedures, along with new experimental results, are presented. Some works existing in the literature (see, for instance, (Zelingher et al., 2006) proposed GPS-based harmonic measurement systems to determine the harmonic state, specifically for transmission systems. Such systems were developed to address issues of harmonic contamination in the transmission network and the associated possibility of harmonic resonances. PMUs are among the most interesting developments in the field of real-time monitoring of electric power systems (Novosel et al., 2007). In this literature, the implementation of digital procedures that are suitable for the evaluation of the synchronized harmonic phasors in a flexible PMUs based on PXI modular hardware is presented. The results of the experimental tests are shown to characterize the measurement system to evaluate the behavior of the designed instrument under real operating conditions on three-phase electric distribution networks (Carta et al., 2009).

IV. CONCLUSION

With the growing interest in PMUs and WAMS throughout the world, it is clear that these systems will be implemented in most major transmission networks. To a large extent the success of this endeavor depends upon adherence to the industry standard governing the PMUs. This paper has been also addressed a survey on Optimal placement of phasor measurement units (PMUs) in power system for enhancement of power system stability such as rotor angle stability, frequency stability, Voltage security, power system oscillations, and voltage stability by using different FACTS controller in an integrated power system networks. Also this paper discussed the current status of the research and developments in the field of the applications in PMUs in power systems for enhancement of power system stability such as rotor angle stability, frequency stability, Voltage security, power system oscillations, and voltage stability enhancement by using different FACTS controllers in an integrated power system networks.

REFERENCES

[1] Heydt G. T., Lie C. C., Phadke A. G., and Vital V., 2001 “Solutions for the crisis in electric power supply,” IEEE Comput. Appl.Power Mag., vol.14, no. 3, pp. 22–30.

[2] EPRI Final Rep., 1997 “Assessment of Applications and Benefits of Phasor Measurement Technology in Power Systems,” GE Power Syst. Eng.,

[3] Chen J., and Abur A., 2006 “Placement of PMUs to enable bad data detection in state estimation,” IEEE Trans. Power Syst., vol.21, no. 4, pp.1608–1615

[4]Nuqui R. F., and Phadke A. G., 2005 “Phasor measurement unit placement techniques for complete and incomplete observability,” IEEE Trans. Power Del., vol. 20, no. 4, pp. 2381, 2388.

[5] Hauer J. F., Trudnowski D., Rogers G., Mittelstadt B., Litzenberger W., and Johnson J., 1997 “Keeping an eye on power system dynamics,” IEEE Comput. Appl. Power, vol. 10, pp. 50–54.

[6] Mittelstadt W.A., Krause P. E., Overholt P. N., Hauer J.F.,Wilson R. E, and Rizy D. T., 1995 “The DOE wide area measurement system (WAMS) project—Demonstration of dynamic information technology for future power system,” in Fault and Disturbance Analysis & Precise Measurements in Power Systems, Session 4, Arlington, VA, Nov., pp. 8–10

[7] Almutairi A. M., and Milanovi J. V., 2009, “Comparison of Different Methods for Optimal Placement of PMUs,” Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania.

[8] Sodhi R., and Srivastava S. C. 2008, “Optimal PMU Placement to Ensure Observability of Power System,” Fifteenth NationalPower Systems Conference (NPSC), IIT Bombay, December 2008.

[9] Carta A., Locci N., and Carlo M., 2007, “GPS-based system for the measurement of synchronized harmonic phasors,” in Proc. IEEE IMTC, Warsaw, Poland, May 1–3, pp. 1–5.