PMU Based Linear State Estimator for Electric Power System: A Review

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***Abstract*— The most commonly used weighted least square state estimator in power industry is nonlinear and formulated by using conventional measurements such as line flow and injection measurements. PMUs (Phasor Measurement Units) are gradually adding them to improve the state estimation process. Traditional state estimators were non-linear in nature takes very high computation times. Hybrid state estimator with a measurement model combining the state-estimate from the classical state estimator with the direct state measurement from the PMUs was linear and the solution is direct and non-iterative. In Hybrid state estimator by addition of even a few PMUs can significantly increase the accuracy of the system state. Previous PMU placement research has focused primarily on network topology, with the goal of finding configurations that achieve full network observability with a minimum number of PMUs due to high cost of PMUs. The cost associated with these devices has fallen over the last several decades as computer & GPS technology has improved while the cost of PMUs has decreased. In this paper the way of corporation the PMU data to the conventional measurements and a linear formulation of the state estimation using only PMU measured data are investigated. To develop Topology processor, which will take breaker statuses and line current phasors and determine topology of the network, and the actual three phase linear state estimator which will use PMU data to determine the state of the system.**

***Index Terms*— State estimation; Phasor measurement unit,**

I. Introduction

Electric power systems account for a critical part of our society's energy infrastructure. Over the years, we have grown to depend on the near perfect reliability of these systems that have become a necessary part of our everyday lives. When we enter a room, we instinctively reach for the light switch without the slightest concern that it won't turn on. All of our household appliances, communication devices, and almost all of our tools ranging from construction sites to our offices require electricity for operation. It is not as if we assume electricity will always be available, it is that we believe electricity will always be available.

State estimation is facet of electric power engineering that has evolved out of these needs. Beginning in the 1960's, engineers began developing ways to monitor their systems from a central control room. They developed communications systems to collect measurement information across the systems and developed system models that could portray the structure of the network. A computer then took in all of this information and computed an optimized portrait of the systems operating conditions called the system state. With this set of information, an adequately trained professional could understand that is going on in the system and make operation and control decisions accordingly.

State estimation is a key element of the online security analysis function in modern power system energy control centers. The function of state estimation is to process a set of redundant measurements to obtain the best estimate of the current state of a power system. State estimation is traditionally solved by the weighted least square algorithm with conventional measurements such as voltage magnitude, real and reactive power injection, real and reactive power flow [1].

Recently, synchronized phasor measurement techniques based on a time signal of the GPS (Global Positioning System) are introduced in the field of power systems. A PMU, when placed at a bus, can measure the voltage phasor at the bus, as well as the current phasors through the lines incident to the bus. It samples the ac voltage and current waveforms while synchronizing the sampling instants with a GPS clock. The computed values of voltage and current phasors are then time stamped and transmitted by the PMUs to the local or remote receiver [2] [3]. The traditional state estimation is by nature a nonlinear problem. The most commonly used approach is Weighted Least Squares which converts the nonlinear equations into the normal equations by using first-order Taylor series. However, the state estimation equations for PMU measurements are inherently linear equations. Some research has been conducted to try to formulate the mixed set of traditional and PMU measurements. The natural approach is to treat PMU measurements as additional measurements to be appended to traditional measurements, which causes the additional computation burden of calculation. Another approach is to use the distributed scheme for the mixed state estimation [4] [5]. The problem of finding optimal PMU locations for power system state estimation is well investigated in the literature [6] [7].

II. LITERATURE REVIEW

The main idea is to measure the voltage and current phasors in the same time at the selected locations in the network, transmit them into a central point, where they can be compared, evaluated and further processed. The devices performing the measurements are called PMU (Phasor Measurement Unit). PMU is basically a conventional RTU (Remote Telemetry Unit) equipped with the receiver of GPS signal synchronizing the measurements and tagging the time stamp to them. PMU is also capable of pre-processing of data (Fourier transformation etc.).

The PMU technology was originally developed in eighties by Thorp, Phadke and others at Cornell, Virginia Polytechnic

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Institute and American Electric Power. [Bhargava, 1999] writes about the plans and experience with PMU measurements for monitoring and post fault-analysis purposes in Southern California Edison Company (SCE). SCE is one of the participants within WSCC (Western Systems Coordinating Council) in the PMU research project started in 1995 by EPRI. In SEC, 50 phasors are collected from different locations at rate of 30 samples per second in the unit called Phasor Data Concentrator and used for analysis of the stresses in the network.

It is also plan for the future use of synchronized measurements for the following purposes, which shows their great general potential:

- System monitoring/state estimation
- Event recording
- Analysing and understanding system/load characteristics
- System control

The PMU capability of providing the measurements taken in the same time offers a lot of advantages. The major one is that the dynamic behaviour of the system can be observed. This together with a high sampling frequency can be utilized for precise load modelling (voltage and frequency dependency). This allows a good prediction of the future behaviour of the loads if the evolution of consumed active and reactive power of the loads is observed immediately after a disturbance. That may give a basis for new algorithms assessing stability, for application on voltage instability. An importance of precise load modelling is demonstrated in [Hiskens, 1995] where the impact of load dynamics on damping of oscillations is examined.

Since the quantities measured by PMUs are voltage and current phasors, the linear relation between them holds when modelling the branches in the network (i.e. π - equivalent of line and transformer). This feature/property permits linear State Estimation process, thus avoiding repetitive manipulations with large matrices in iterative procedure as it is in the traditional case. This significantly reduces the computational time and errors level. This approach has probably been derived first time in [Phadke, 1986] where they have formulated the linear State Estimation equations and applied them on 118 buses IEEE test system. They assume that all substations are equipped with PMUs measuring all voltages and some selected currents. The high cost of both PMUs themselves (although nowadays this is not as critical issue as it used to be, the price of PMU is approximately 3500 USD) and the communication links to all substations force to keep the number of installed PMUs to a minimum. [Baldwin, 1993] has presented a method for placement of a minimal number of PMUs such a way that the system is still observable and all relevant quantities (all bus voltages and all branch currents) can be extracted from measurements by employing linear State Estimation. According to him simulation results, only each third or fourth bus has to be provided with PMU. Baldwin and Cho both examine what they call topological observability of the power system. That means that the measurements coming from the given placement of PMUs are sufficient for State Estimation yielding all voltages and all branch currents under an assumption that the topology is known, although it is not so clearly/explicitly formulated but it is obvious. If the system relying only on PMUs is being built, other criterion is of bigger importance – observability of topology. That implies that statuses of all elements (lines, transformers, shunt elements, generators, loads) can be determined only from the delivered PMU measurements as well as the ratio of ULTC transformers. Another issue, which was neglected, is a redundancy, i.e. what to do in case of an outage of the communication or PMU. In the practical applications these factors have to be considered as outlined in [Rehtanz, 2002].

The criterions for PMU placement, not directly related to the execution of State Estimation, are used in [Kamwa, 2001b]. There the main goal is to achieve the highest degree of information contained in the time-response signals under all possible contingencies and realistic operating scenarios with a minimal set of PMUs. Thus this criterion is probably less demanding than those above. Very important feature is that the methods described incorporate mandatory locations for the placement of PMUs, such as tie-line buses and large generator step-up transformers. This criterion is really crucial for observing some phenomena like angle and frequency instabilities. Therefore it should be adopted in the PMU placement procedure as an important constraint also in the case of PMUs installation for intended State Estimation purpose.

The linear State Estimation and use of PMUs as measurement means, brings the protection system on a qualitatively new level. The further development of computers and reduction of cost of the wide band communication links (fibre optics or conventional modem connection can be utilized but the capacity and reliability/availability are important) will make possible to establish the centralized system serving functions of protection, control and optimisation of existing power systems assets as envisioned in [Fardanesh, 2002].

David G. Hart et.al. [8] described PMU and GPS system with block diagrams. They described different type of Communication issues related to PMU and Power system applications of PMU.

Jonathan Horne et.al. [9] addresses some of the issues regarding integration and modelling of Combined Cycle Gas Turbines (CCGTs), and Wind Turbine Generator (WTG) technology on a small islanded power system. They focus on frequency stability in small island power systems. Frequency instability results when a power system cannot settle to a new equilibrium following a large generation / load imbalance. It is generally caused by tripping of large capacity tie-lines or generators. However, there is no set definition of what a 'small' system actually is. From a frequency stability point of view, and for the purposes of this paper, it can be described as one in which any individual generator in-feed represents a substantial portion of the total demand. Furthermore, a 'small' system will not be heavily interconnected with other larger systems.

Reynaldo F. Nuqui [10] proposed integration model improves on prior phasor-in-state estimation methods by accounting for the full set of current phasor data. This hybrid weighted least squares (WLS) and linear SE model could also be performed in wide area measurement system platforms and does not require communicating PMU data via SCADA channels.

Tanabe et.al. [11] presents the Decomposition State Estimation (DSE) method and the algorithm for determining the Optimal PMU placement Ranking (OPR) based on a parameterized PMU constrained OPF. Specifically they contributes the estimation error caused by bad data can be confined to limited areas; DSE can improve bad data processing capability. Lagrange multipliers of PMU placement can represent the sensitivity of objective function (sum of squares of residuals). Since Lagrange multipliers of PMU placement are the efficient information to improve SE accuracy, the obtained PMU placement ranking can be useful information.

Saikat Chakrabarti et.al.[12] proposes an exhaustive search approach to determine the minimum number and optimal placement of PMUs for state estimation, considering single branch outages. It is also possible to use this approach to ensure observability for single PMU outages. The method overcomes the shortcomings of the evolutionary algorithms and integer programming in finding the minimum number of PMUs for state estimation, and their optimal locations. An exhaustive binary search method is implemented in this paper to determine the minimum number of PMUs needed to make the system observable. In case there is more than one placement set having the same minimum number of PMUs, a method is proposed to select the one resulting in the most preferred pattern of measurement redundancy. Due to its exhaustive nature, the method gives the global optimal solution, and hence the results for a number of standard test systems are reported to provide benchmark solutions for researchers investigating various methods of optimal PMU placement.

Bei Gou et. al.[13] described optimal PMU placement problem is re-studied for the cases of redundant PMU placement, full observability and incomplete observability. Based on the author's newly proposed integer linear programming algorithm in, the PMU placement problem is re-studied and a generalized integer linear programming formulation is presented.

Ruisheng Diao et. al.[14] focuses on the voltage collapse problems caused by severe disturbances in the system and presents a three-step decision tree-based scheme for online voltage security assessment using phasor measurements.

Jinghe Zhang et.al.[15] develop a stochastic model that captures dynamic state estimation uncertainties, to facilitate the assessment of PMUs installed on a subset of the buses. They design an optimal PMU placement evaluation algorithm by incorporating uncertainty estimates into topological considerations for the specific network. They present an approach to the comparison among alternative configurations via quantitative measure of expected uncertainties.

R. Sodhi et. al.[16] devolve methodology, it is suggested first for determining the optimal number and locations of PMUs ensuring complete observability of the system and, subsequently, placing these PMUs in a phased manner utilising a multi-criteria approach, based on certain criteria like tie-line oscillation observability and voltage control area observability. The main contribution of this work is the development of the multi-criteria framework to prioritise different optimal PMU locations and, subsequently, using it to install PMUs in stages according to their relative ranking.

V. K. Agrawal et.al [17] shares the experience gained during the first few months after the commissioning of the first synchrophasor pilot project in Northern India

K.Jamuna et.al [181] introduced a new method for the selection of PMU, Power Flow measurements and Power Injection measurements, such that the entire power network is observable. Only the bus - branch model of the network is needed to identify the minimum PMUs, traditional measurements and their locations. Using these measurements, system states have been evaluated using Hybrid State Estimation. A step by step procedure for replacement of SCADA by PMU has been proposed.

III. BACKGROUND OF STATE ESTIMATION

We review the current state estimation formulation and solution methods and provide motivation for further improvement. Several excellent review papers [2, 3, 5] cover this topic in detail. When we say power system state estimation we mean the original and most widely used problem definition in practice. That is, an over determined system of nonlinear equations solved as an unconstrained weighted least-squares (WLS) problem.

As shown equation 1, this method minimizes the weighted sum of squares of the residuals

$$J(x) = \sum_{i=1}^{N_m} \frac{(Z_i - h_i(x))^2}{\delta_i^2} = [Z - h(x)]^T R^{-1} [Z - h(x) \quad (1)$$

Where in this equation z is measurement vector, x state vector, σ standard deviation and h is the nonlinear function relating measurement i to the state vector x. R is measurement covariance matrix is given by (2).

$$R = diag[\delta_1^2, \delta_2^2, \dots, \delta_{Nm}^2] \quad (2)$$

At the minimum value of the objective function, the first order optimality conditions have to be satisfied. These can be expressed in compact form as follows:

$$g(x) = -\frac{\partial J(x)}{\partial x} = -H^T(x) R^{-1} \big(Z - h(x)\big) = 0 \quad (3)$$

Where

$$H(x) = \frac{\partial h(x)}{\partial x} \quad (4)$$

The nonlinear function g(x) can be expanded into its Taylor series around the state vector x^k neglecting the higher order terms. An iterative solution scheme known as the Gauss-Newton method is used to solve (3):

$$x^{k+1} = x^k - [G(x^k)]^{-1} . g(x^k) \quad (5)$$

Where, k is the iteration index and x^k is the solution vector at iteration k. $G(x^k)$ is called the gain matrix, and expressed by:

$$G(x^k) = \frac{\partial g(x^k)}{\partial x} = H^T(X^k) R^{-1} H(x^k) \quad (6)$$

$$g(x^k) = -H^T(X^k) R^{-1} [z - h(x^k)] \quad (7)$$

These iterations are going on until the maximum variable difference satisfies the condition, ' Max$|\Delta x^k| < \in$'. Consider a system having (N) buses; the state vector will have (2N-1) components which are composed of (N) bus voltage magnitudes and (N-1) phase angles.

IV. PHASOR MEASUREMENT UNIT (PMU)

The Phasor Measurement Unit (PMU) [1] is a power system device capable of Measuring the synchronized voltage and current phasor in a power system. Synchronicity among Phasor Measurement Units (PMUs) is achieved by same-time sampling of voltage and current waveforms using a common synchronizing signal from the global positioning satellite (GPS) [1]. The ability to calculate synchronized phasors makes the PMU one of the most important measuring devices in the future of power system monitoring and control. The technology behind PMUs traced back to the field of computer relaying. In this equally revolutionary field in power system protection, microprocessors technology made possible the direct calculation of the sequence components of phase quantities from which fault detection algorithms were based.

The phasor are calculated via Discrete Fourier Transform applied on a moving data window whose width can vary from fraction of a cycle to multiple of a cycle. Equation (2.1) shows how the fundamental frequency component X of the Discrete Fourier transform is calculated from the collection of X_k waveform samples.

$$X = \frac{\sqrt{2}}{N} \sum_{k=1}^{N} X_k \, \varepsilon^{-j2k\pi/N} \quad (8)$$

Synchronization of sampling was achieved using a common timing signal available locally at the substation. Timing signal accuracy in the order of milliseconds suffices for this relaying application. It became clear that the same approach of calculating phasors for computer relaying could be extended to the field of power system monitoring. However the phasor calculations demand greater than the 1-millisecond accuracy. It is only with the opening for commercial use of GPS that phasor measurement unit was finally developed. GPS [1, 4] is capable of providing timing signal of the order of 1 microsecond at any locations around the world. It basically solved the logistical problem of allocating dedicated land based links to distribute timing pulses of the indicated accuracy.

Bock diagram of a PMU shows in figure 1. In the following figure shows anti-aliasing filters is meant to filter out from the analog input waveform frequencies more than the Nyquist rate. The other block is phaselocked oscillator (PLL) converts the GPS (Global Positioning System) pulse per second into the sequence of high-speed timing pulses used in waveform sampling. The microprocessor performs the FFT Phasor calculations.

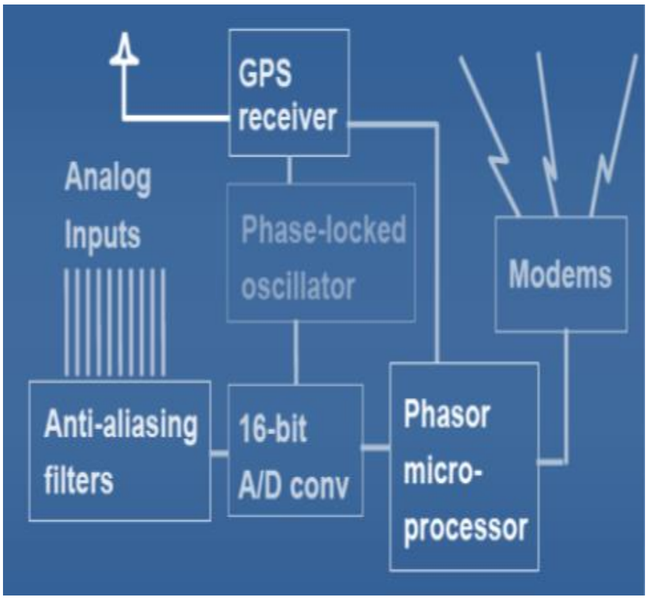

Figure 1: Block Diagram of a PMU

GPS system consists of 24 satellites in six orbits at an approximate altitude of 10,000 miles above the surface of the earth [1]. 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. The civilian-use channel [1] of the GPS system transmits positional coordinates of the satellites from which the location of a receiver station on earth could be determined.

V. LINEAR FORMULATION OF STATE ESTIMATION USING ONLY PMUS

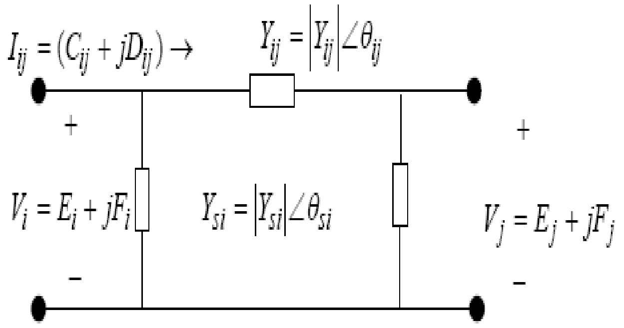

Figure 2: Transmission Line Model

If the measurement set is composed of only voltage and current measured by PMUs, the state estimation can be formulated as a linear problem. The state vector and measurement data can be expressed in rectangular coordinate system. As shown in Fig. 2 a PMU located at bus i measured voltage Vi and line current I_{ij}. The voltage measurement ($V_i = |V_i|\angle\delta_i$) can be expressed as ($V_i = E_i + jF_i$), and the current measurement can be expressed as ($I_{ij} = C_{ij} + jD_{ij}$). In this condition of estimation, measurement vector z and sate vector x are:

$$Z = [E_i \; C_{ij} \; F_i \; D_{ij}]^T \quad (9)$$

$$x = [E_i \; E_j \; F_i \; F_j]^T \quad (10)$$

In Fig. 1, line current flow Iij can be expressed as a linear function of voltages.

$$C_{ij} + jD_{ij} = [(g_{ij} + jg_{ij}) + (g_{si} + jb_{si})](E_i + jF_i) - (g_{ij} + jb_{ij})(E_j + jF_j) \quad (11)$$

Jacobian matrix H components are expressed by

$$\frac{\partial C_{ij}}{\partial E_i} = g_{ij} + g_{si} \quad (12)$$

$$\frac{\partial C_{ij}}{\partial E_i} = -g_{ij} \quad (13)$$

$$\frac{\partial C_{ij}}{\partial F_i} = -b_{ij} - b_{si} \quad (14)$$

$$\frac{\partial C_{ij}}{\partial F_i} = b_{ij} \quad (15)$$

$$\frac{\partial D_{ij}}{\partial E_i} = b_{ij} + b_{si} \quad (16)$$

$$\frac{\partial D_{ij}}{\partial E_i} = -b_{ij} \quad (17)$$

$$\frac{\partial D_{ij}}{\partial F_i} = g_{ij} + g_{si} \quad (18)$$

$$\frac{\partial D_{ij}}{\partial F_i} = -g_{ij} \quad (19)$$

Then, the estimated value $\hat{x} = \hat{E}_i + j\hat{F}_i$ can be obtained by solving the linear equation below:

$$\hat{x} = (H^T R^{-1} H)^{-1} H^T R^{-1} \hat{z} \quad (20)$$

This is very simple and fast, because it doesn't need any iteration. In addition covariance matrix R in "(20)" is very smaller than covariance matrix of conventional measurement, so the estimated variables are very accurate.

VI. Conclusion

In this paper presents a new approach for solving PMU based Three phase linear state estimator. The performance of the three phase linear state estimator was tested on the standard IEEE network cases and results are discussed thoroughly. A sound theoretical support as well as practical efficiency and robustness are the strong arguments supporting the trust region method to be applied in practical power system state estimators. The objective is to provide a more reliable and robust state estimator, which can successfully cope with all kinds of errors (bad data, topological, parameter) faced in power system models.

An important advantage of this method is non-iterative which reduces the computation time and suitable to implement in the near future. In view of extension in this work, analysis can be done taking into account the loss of measurements, failure of PMU and effectiveness of PMU. With the increasing use of computers and digital information in power systems, the availability of information about a system has become easier. Online data, artificial neural networks, fast computations and real time control are beginning to take over the theoretical and analytical solutions. However, the conventional methods of power system analysis still provide the element of theory to the latest methods of computations and estimations. Within this environment, there will be an increasing need of more and more such application oriented studies which can help minimize the resources and computation time.

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