Phasor Measurement Unit Integration: A Review on Optimal PMU Placement Methods in Power System

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***Abstract*—The Phasor Measurement Unit (PMU) is an imperative part for monitoring, protecting and controlling the current power system. For the current power systems, PMUs not only offer the synchronized measurements of real-time data of voltage but also the current and frequency. Placement of PMUs in each bus for monitoring the system is not feasible from economic point of view and also for big data handling. So it is an obligatory matter to reduce the number of PMUs in the bus system with the aim of attaining the maximum power system observation. Different techniques are being applied from past to present to solve this optimum PMU placement (OPP) problem such as heuristic method, mathematical programing. Heuristic method is a quick experience-based technique for solving the optimization problems. Various optimization methods for solving the OPP problems are being reviewed in this paper.**

Keywords*—Phasor Measurement Unit (PMU), Global Positioning System (GPS), Optimal Placement of PMU (OPP), State Estimation (SE), Supervisory Control and Data Acquisition (SCADA), Heuristic algorithm.

I. Introduction

For the dynamic characteristics of the power system, close monitoring and secure controlling of the power system has no other alternatives. Major contingencies and disturbances have occurred in the past years causing major blackouts throughout the world. Disturbances like single/three phase line faults, generator losses, load change etc. can deviate the system's operating values from the thresholds points. In this condition, for proper and stable power system operation, a system state monitoring and accurate measurement device is compulsory. The most means of system data measurement is Supervisory Control and Data Acquisition (SCADA) system [1]. In 1990s, Phasor measurement unit (PMU) was first introduced [2]. It started utilizing in the wide area monitory systems (WAMS) for providing synchronized time-tag measurements of bus voltage and branch current phasors [1, 2]. Its inbuilt global positioning system (GPS) provides accurate timestamped synchronized signal within 1 ms [3]. PMU measurement techniques use linear state estimation for the measurements. PMU offers high speed voltage control along with faster sampling rate than SCADA/EMS system [4]. When a PMU is installed in a bus, it provides not only the voltage phase of the installed bus but also the current phasor of all the other connected and adjacent lines to that bus [5]. Making the power system fully observable, it requires adequate measurements of SE, and this rises the optimal placement problem. In a real scenario, power system of a country may have hundreds to thousands buses in a system. So it is neither cost-effective nor feasible to deploy PMUs in each buses to make the system completely and directly observable. Thus, obtaining the optimum number of PMUs and their configuration in the system is propounded as a considerable challenge called the OPP problem [6]. Different optimization techniques are proposed from many years to solve this optimization problem [6]. This paper gives a review based on the past and current works and ongoing researches in the field of OPP in power system. Main focus is given on the conventional and heuristic optimization techniques. The introduction of PMU is described in Section II, in continuation of formulation of the problem are defined in section III. Different methods to solve the OPP problem are discussed in Sections IV. Section V contains the conclusion for this work.

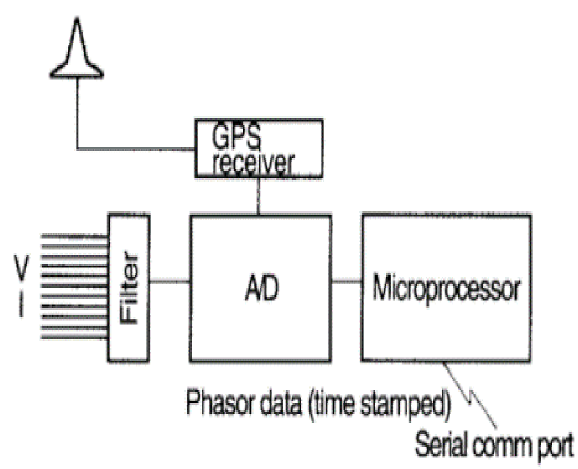


Figure 1. Featured Component of PMUs [7]

II. PHASOR MEASUREMENT UNIT

A. What is Phasor Measurement Unit

Phasor measurement unit (PMU) is a unit of measuring the voltage, current and frequency phasors from the electric grid using local/global time source for synchronization. Because of this time synchronized characteristic, it become possible to measure time synchronized real-time measurements data from distant measurement points on the grid. This measurement process is known as a synchrophasor. At present PMUs are the key measuring devices for current and future power systems [7].

B. Major Component of PMU

1) GPS receiver: This receiver gives the 1 pulse/sec (pps) signal with time tag. The main feature of this time tag is that it comprises of the second, minute, day and year information of a local area along with UTC.
2) Microprocessor: Microprocessor controls the phasors by using recursive algorithm. It can identify the sample number by taking consideration of the information received from the GPS timing message at the very initial stage. Remote sensing can be done by using modems.
3) Phase-locked oscillator: For sampling the acquired signal, it is required to divide the 1 pps into the preferred number of pulses/second. The sampling rate of a standard PMU is 30-48 cycle/sec.
4) Surge Filtering: These filtering offer the identical attenuation and phase shift of the output of secondary of current and voltage transformers.

III. FORMULATION OF OPTIMAL PMU PLACEMENT PROBLEM

PMU can obtain the information about the value of phase voltage from where it is being installed. It can also measure the branch currents from connected buses. Figure 2 shows the standard PMUs connectivity into a system. Phasor Data Concentrators (PDC) are being used to collect measured signal from different locations sent by PMUs. The PDC accumulates and categories the phasor measurements whereas the signal processor transforms data of PMUs into useful information which is observable on Human Machine Interface (HMI) State [8].

The Major two techniques for system observability analysis are topological and numerical observability techniques. Numerical analysis faces high matrix calculation analysis for few years so it is being used widely now a days. On the other hand, there are many simple and improved topological analysis are being introduced to check the system observability now a days. Some of the rules are defines below.

1) Direct measurement: In direct measurement technique, the PMU measures the phase voltage of that PMU installed bus along with the connected brunch current from all joint lines to it (Figure 3a).

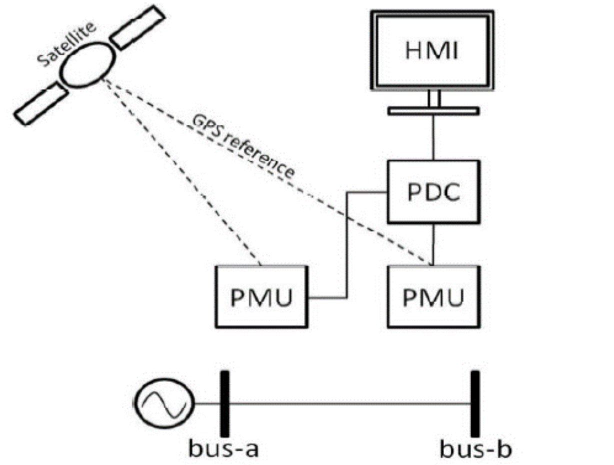


Figure 2. Outline of PMU with GPS reference signals [8]

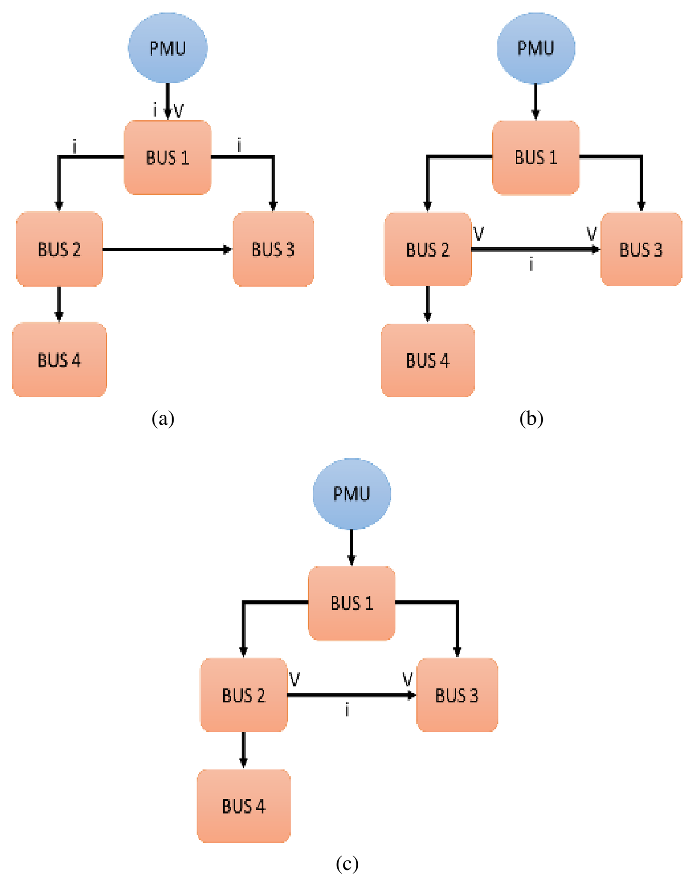
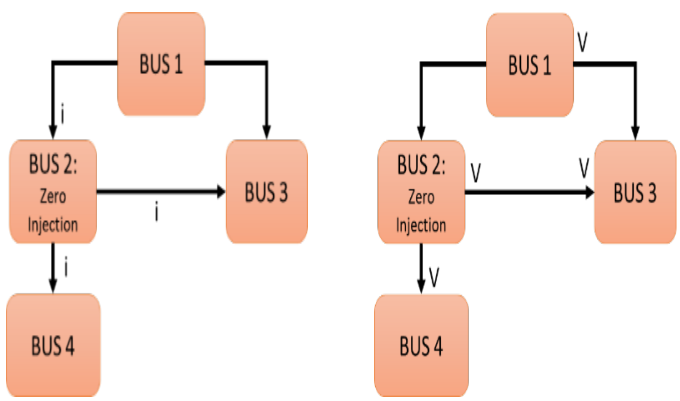


Figure 3. (a) Direct Measurement (b) Pseudo Measurement (c) Pseudo Measurement considering line current.

2) Pseudo Measurement: In this measurement techniques, the voltage and current of the PMU installed bus are known along with the line current of the connected buses. And the voltage of the other buses can be ob-

servable. The relation between Bus 1 and Bus 2 can be observed using this rule (Figure 3b). This rule can be applied also if the voltage of the two connected buses are known. In that case the current can be easily calculated between them (Figure 3c).

3) Zero-Injection Bus Measurement: Several conditions are being considered if there is a zero injection bus present in the system. a) Voltages of all joint lines are known. b) Voltage of the zero-injection bus is unknown but all other adjunct bus voltage are known. For the 1st case, Kirchhoff's current law gives the simple solution for the current measurement for those joint lines (Figure 4a). For the 2nd case, it will be easy to apply the node equation to find out the known parameters from the figure 4b. Kirchhoff's current law and Voltage law both present simple calculation for finding the unknown parameter in power system.



(a) (b)

Figure 4. Zero-Injection Bus Measurement Techniques applying KCL and KVL theories.

The main purpose of the OPP problem is to define the least number of PMUs in the system and also validate the full system observability. The mathematical representation of that objective is given below [1]:

$$min \sum_{j}^{n} X_{ij} \tag{1}$$

$$s.t \qquad Y * X \geq I \tag{2}$$

$$X(i) = \begin{cases} 1 & \text{if the Bus } i \text{ is a PMU installed Bus.} \\ 0 & \text{if No PMU installed in the Bus.} \end{cases}$$

$$Y(i,j) = \begin{cases} 1 & \text{if } i = j \\ 1 & \text{if } i \text{ and } j \text{ buses are joint together.} \\ 0 & \text{otherwise} \end{cases}$$

IV. OPTIMUM PMU PLACEMENT METHODS

A. Conventional Methods

1) Integer Quadratic Programming (IQP): OPP problem is described by using the connectivity matrix which represents network topology. The quadratic objective function will be optimized considering the linear constrained and taking consideration of variable integer value. This process will reduce the number of PMUs by giving a full system observability under normal and also under outage circumstances.
2) Integer Linear Programming (ILP): Integer Linear Programming techniques, specially known as Binary integer programming, take consideration of both the injection and power calculation of the system in addition with PMU failure error calculation through state estimation. Formulation of ILP is based on eigenvectors obtained from the spanning tree's adjacency matrix. To curtailing the installation rate, after decomposition, the PMUs are placed optimally in the sub networks using ILP theory.

B. Heuristic Methods

As it's not cost-effective to install PMUs at each and every bus to analyze and control the faulty area,it is essential to implement different placement techniques which will provide a complete observability of the system. At present there are several heuristic methods.
A small description of several heuristic methods are given in a tabular form.

No	Methods Name	Description	Benefits
1	Genetic Algorithm (GA)	Giving a full observable power system with minimal PMU units along with their geographical distribution [9]. It takes the relationship between the PMU units with current phasors.	The key advantage of this method is that it provides the best Pareto-optimal solution rather than single solution.
2	Simulated Annealing (SA)	It is a genetic probabilistic metaheuristic method. Its main purpose is to find an approximately reasonable solution regardless of the best solution in a fixed time. A practical sensitivity analysis method is adopted to calculate parameter sensitivities of every bus [10]. Incidence matrix methods are being used to place the initial PMUs for the system observability.	This method provides full observability of the power system along with valuable dynamic data measurement from the power systems at the same time.
3	Particle Swarm Optimization (PSO)	Particle swarm optimization (PSO) is a population based stochastic optimization technique [11]. By this techniques it is possible to map the configuration criteria along with data loss modeling.	Offers multiple solution instead of one solution against data losses at the marked PMUs.
4	Tabu Search(TS)	Tabu Search (TS) is a metaheuristic local search algorithm [12]. This methods is applied to solve combination optimization problems by tracking and guiding the search. TS comprises of augments incidence matrix which manipulates Tabu Search (TS) algorithm and integer numbers.	More accurate results with fast computational time.
5	Artificial Neural Network (ANN)	ANN's is capable of making approximate functional relationship between voltage stability indices and system parameters [13].	Provides multiple solutions based on computational models.
6	Immune Genetic Algorithm(IGA)	It is based on genetic algorithm principles and here the mechanism of protection of living organisms from viruses and bacteria [14].	Significant process speed, can be easily applied to a large scale system.
7	Differential Evaluation (DE)	Differential Evolution (DE) is also a metaheuristic process which develops a candidate solution by optimizing a problem iteratively using both integrated from Differential Evolution and Pareto Non-dominated Sorting algorithm [15].	Easy and quick finding on the number of Pareto-optimal solutions which provides accurate solution with full observability
8	Matrix Reduction	This method minimize the number of PMUs using preprocessing method [16]. And solve the OPP problem based on mathematical methods like Virtual data elimination preprocessing, matrix reduction algorithm or Lagrangian relaxation.	Computational time will be reduced and easy to apply in large scale power system for full observability.
9	Mutual Information	Minimizing the number of PMUs using an information theoretic concept, namely Mutual information, uncertainty modeling [6].	System uncertainty can be modeled easily.
10	Ant Colony Optimization	It's a classical probabilistic technique which uses graphs which will reduce computational problems complexity.[13]	Reduce computational complexity.
11	Iterated local search	It is a combination of page rank placement algorithm (PPA) and ILS. [16]	Easy understanding and implementing.
12	Exhaustive Search(ES)	The method is known as exhaustive because this method has given guarantee to provide all accessible states before it dismisses with unit failure.[6]	System failure can be easily detected.

Table I: Various Optimal PMU Placement methods

No	Characteristics	Programming Based Algorithm		Heuristic Methods		
		Integer Quadratic Programming	Integer Linear Programming	Genetic Algorithm	Matrix Reduction	Particle swarm optimization
1	Computational Efficiency	Moderate	High	Moderate	Moderate	High
2	System Observability	High	High	High	High	High
3	Computation Time	Moderate	High	Moderate	Less	Moderate
4	System Complexity	High	Low	Moderate	Low	High
5	PMU Requirements	High	Moderate	Low	Low	High

Table II: Comparison between different OPP Methods

Based on the above mentioned OPP methods characteristics and benefits, a comparison studies are being presented in the Table II.

V. CONCLUSION

Numerous methods have been implemented to analyze and to acquire the desired solution on this optimum location for installing the PMUs. For Power system stability and control the optimum PMU placement is now a smart tool.A handsome number of algorithms are discussed here shortly. It will give a platform for researchers to categorize these algorithms before applying for PMU placement and find the suitable solution. The analysis of optimization techniques refered in this work to mitigate the Optimal Placement Problem (OPP) will be a guideline and help to find the future trends optimization crieterion.

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