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OPTIMAL PMU PLACEMENT: AN INCLUSIVE REVIEW

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Abstract: The control and monitoring of power system isa very important task which can be accomplished by Phasor measurement Unit for power system stability. Phasor Measurement Units are the sensing devices, which give real time, synchronized measurements of voltages and current phasors (magnitude and angle) of the buses where the Phasor Measurement Units are located.Due to the high cost involved it is not feasible to place Phasor Measurement Unit at each bus. For the entire observability of the power network it is necessary to determine the optimal number of phasor Measurement Units . There are various techniques used for the optimal placement of Phasor Measurement Units such as mathematical programming: Integer linear programming,integer nonlinear programming and integer quadratic programming. Meta heuristic techniques : Genetic Algorithms, Particle Swarm Optimization, Topology and Tree search .This paper presents a comprehensive literature review on these technologies to solve optimal placement problem.

Keywords – Smart grid, Phasor measurement unit, Wide area monitoring and control (WAMPAC), Network Observability, Optimization Techniques.

I. INTRODUCTION

The frequent occurrence of black outs in power grid around the world, increasing population and environmental concerns are the factors which has given a new momentum for wide scale implementation of wide –area measurement systems using Phasor measurement Units (PMU ,s).For the secure operation of powers systems ,the close monitoring is required. Traditionally it has been performed by Supervisory Control and Data Acquisition system (SCADA).The measurements obtained from SCADA have limitations and errors like delay in measurement, because of slow duty cycle and telecommunication bias. Wide Area Monitoring Protection and Control (WAMPAC) are used to overcome this limitation. It consists of PMU's as fundamental component [1] - [2].The precision and accuracy is achieved by PMU's by using the Global Positioning System. It has precise reference timing signals which are used to achieve the synchronized measurement of voltage and current phasors. There is an increase application of PMU's in recent years. As PMU's and communication services are very expensive it is not possible to place these units on entire system buses .So, the need to determine the optimal number of PMU's and its optimum location for overall observability of the system is very important. To solve this Optimal PMU Placement (OPP) problem a proper methodology is required. Number of methods has been employed to locate the OPP.

Many methods have been proposed in literature by the researchers to find optimal locations of PMU's .These methods can be broadly categorized as mathematical deterministic method and artificial Intelligence based Heuristic and Meta heuristic methods .This paper presents the overview of Smart Grid application of phasor technology to monitor and control the power system. This paper is divided into five sections .Section II discusses the smart grid .Section III discusses the WAMPAC and PMU .Section IV presents the mathematical programming , advanced heuristic and meta heuristic techniques. Section V concludes the paper.

II. SMART GRID

The electric power infrastructure has revolutionized the way of living around the globe. As the energy needs are increasing at a very rapid rate, due to emission of greenhouse gases carbon footprint is also increasing .The climatic conditions are changing .To use energy in a sustainable manner we need a solution, which lies in the

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concept of Smart grid. It is an intelligent grid which is equipped with advanced electric power system of tomorrow. It integrates the state of art power electronics, Computers, ICT. The traditional power grids are used to carry power from generating stations to a large number of consumers. In contrast to this smart grid uses two way flows of electricity and information. The wide objectives of smart grid can be laid as optimum utilization of resources, higherreliability, higher efficiency, resilience, self-healing in nature adaptation of distributed energy resources. In addition to this it haveNew Energy Storage options, increased consumersatisfaction, enabling new products, services and markets [5]-[9].

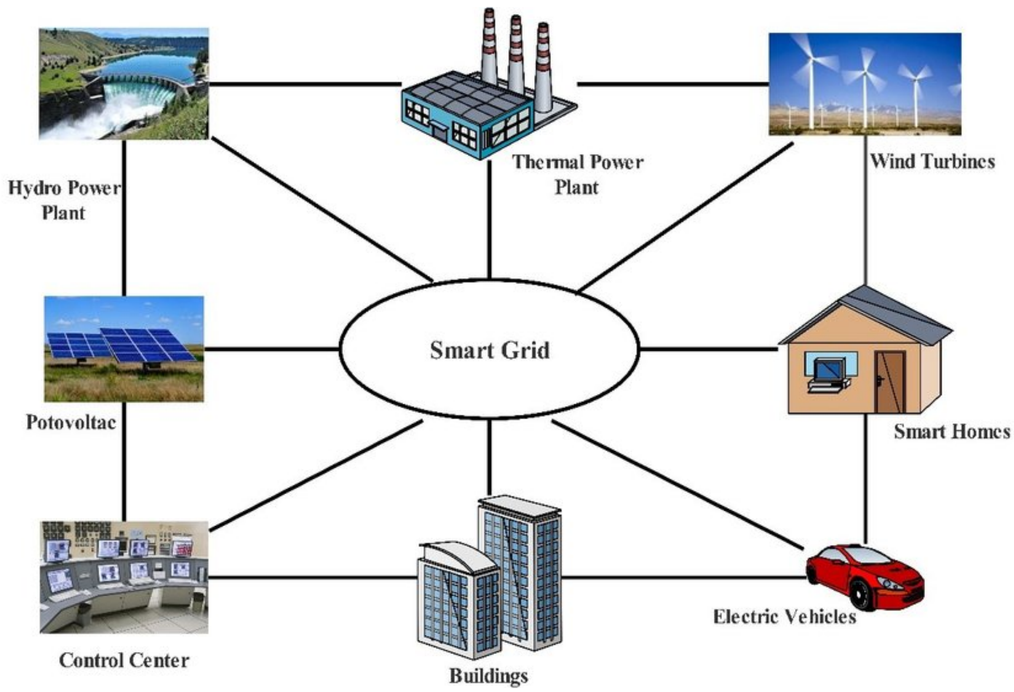

Figure 1. Lay out of a Smart grid

III. PHASOR MEASUREMENT UNIT AND WIDE AREA MONITORING SYSTEM

Wide Area monitoring is an essential feature of smart grid .It relates to a system consisting of new digital metering devices (like PMU's)co- ordinated with communication system which is designed to monitor ,operate and control power system in a wide geographic area. Phasor measurement Units are the most sophisticated time synchronized tool available to power system for wide area measurement. The first PMU equipment was born in Virginia Tech, 1980's in USA by Prof.Arun G. Phadke and James Throp [10]. PMU is a remote measurement intelligent device which is used to measure the phase values of voltage and branch current where it is installed [11].The figure 2 below shows PMU's isolated to form a Wide Area Monitoring system (WAMS).

.It is a component of broad application of global positioning system.Except the GPS receiver the basic structure and principle of operation of PMU is similar to a relay used in computer. With the use of synchronized clock signals from GPS, PMU'sdispersedly equipped in the electrical network can obtain the same sampling clock.These GPS time stamped signals are fed to the Phasor Data Concentrator (PDC) for collection, sorting and converting into useful information. This information is further sent to Human Machine Interface (HMI) that can easily be accessed by the operator.Data acquisition, data transmission and data processing are three different interconnected functions of WAMS. The input data is taken by WAMS from conventional and new metering devices.The transmission is done through communication system and thereafter data is processed. [12] –[13]

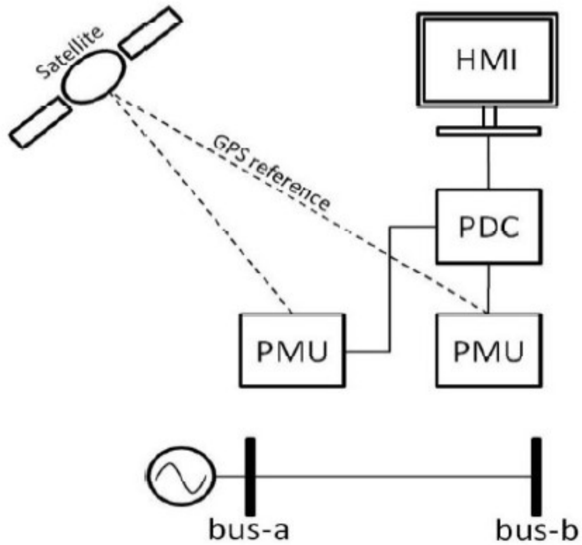

Figure2- LAYOUT OF PMU ALONG WITH GPS TIME STAMPED SIGNAL

IV. METHODS OF OPP TECHNIQUES

A. Mathematical Programming Method

The Integer Programming is a numerical Programming method .It is used for solving optimization problem which has integer design variables .On the basis of type of objective function(linear ,nonlinear or quadratic) and the constraints it is divided into :

- Integer Linear Programming (ILP)
- Integer Non Linear Programming (INLP)
- Integer Quadratic Programming (IQP)

Reference [14] the objective of the author is to minimize the number of PMU'S for the purpose of eliminating critical measurement in the entire system. The placement problem is extended with conventional measurement.It allowed a design of measurement systems subjected to degrees of vulnerability against loss of measurement and bad data.

Reference [15] the authors presented technique to place PMU"s properly under a given budget .This issue is dealt with a special case of ILP known as Binary Integer Programming .It also considered the presence of injected and power flow measurement. The loss of single PMU is taken into the account for the minimization of vulnerability of state estimation to failure of PMU.

Gou, B. proposed a generalized formulation in [16]-[17].The modeling of PMU placement was done , considering situation with and without zero injections. The proposal formulation was done in [16] and then he proposed the PMU placement of Integer linear Programming in [17].

Reference [18] the authorspresented a procedure for multistage PMU placement in a given time span using Integer Linear Programming. The zero injection constraints can be modeled as linear constraints. The OPP problem has multiple solutions. The two indices are proposed for ranking of these multiple solutions.A measure of the number of PMU's observing a given bus is given by BOI (bus observability index).The sum of all BOI of the system is given by SORI (System Observability Redundancy index)

Reference [19] The objective of the authors is to find out the optimum number of PMU's and place in such a manner that system can be totally observable .The decision strategy for optimum PMU allocation problem under the conventional measurements with single or multiple PMU loss contingency was taken care of.Binary integer Linear Programming was used for this purpose. The branch bus model of the system was used.

Sodhi, R. et al. The authors presented a simple , easy and a new approach for observability of the power network .It consists of two stages based on topological observability along with numerical observability.The results were tested on standard IEEE bus systems. Tocheck the topological observability, Integer Linear

Programming method was used. To check numerical observability a sequential elimination algorithm (SEA) is used in second stage. [20]

Sodhi, R. et al. The authors proposed a technique for placing the PMU ' s in multiple stages over a given time period .It ensures complete power system observability in case of branch outage or a PMU failure.The technique is based on integer Linear Programming and multi –criteria decision making approach.In the first stage ILP method is used to find out the optimum number of PMU's for the complete observability of the system.[21]

Reference [22]the authors presented an instantaneous PMU's placement and conventional power flow measurement for fault observability in power system using binary integer Programming technique.Initially the formulation is based on a non - linear programming problem .T hen it is transformed from nonlinear integer programming problem to corresponding ILP problem.

Reference [23] the authors represented an optimization model to determine the optimum number of PMU's in power network. The model proposed consisted of observable necessities based on a set of probabilistic criteria.Linearization technique is used to change the model into linear form. It is described as a Mixed Integer Programming problem. It is tested on large scale power systems.

Reference [24] the authors presented the placement of combined phasor and power flow measurements for total power system observability.The method proposed formulated the problem as Non -linear integer problem and then transformed into an ILP problem by considering supplementary variables and constraints. The problem formulation was extended to large scale systems .Two heuristic methods were proposed.

Integer Quadratic Programming (IQP):It is used in solving the optimization problem which involves quadratic objective function and linear constraint .All design variables take only an integer value.

Reference [25] ,the optimal placement method proposed earlier makes the system observable topologically .It is used to optimize the number of PMU's which maintain system fully observable, in case of outage of linear PMU.This method maximizes the redundancy measurement of the system.

Reference [26] the authors presented another integer quadratic linear programming .The determination of solution of optimal placement of PMU's considering connectivity is carried out.Connectivity matrix represents the system topology and also aid in formulating the minimization problem.

B. Advanced Heuristic And Modern Meta Heuristic Methods

These methods constitute of intelligent search processes which can deal with non-continuous cost functions and discrete variables. These methods include Genetic algorithms, Particle Swarm Optimization, Topology and Tree search.

i) Genetic Algorithms

Reference [27] the authors used a GA-based process to solve the OPP Problem. It was based on the technique of generic breeding in which the two operators, mutation and cross over results in optimization of a particular individual that ensures the formulation of new genetics from one generation to another.

Reference [28] the author used a GA known as Immunity Genetic Algorithm (IGA) .The degenerated phenomenon was alleviated .The converging speed was greatly increased. The two operators were introduced to GA method i.e. vaccination and immunity operators. It was tested on IEEE bus system as well as 2746 –bus system. It took 44 hours to converge to a solution.

Reference [29] the author used simple GA and graph theory to estimate optimal solutions of objective functions, so that the system is observable during single branch contingencies and normal operation. To find the best outcome between competing objectives a non-dominating sorting genetic algorithm was used.

ii) Tree Search And Topology

Reference [30] the author introduced two main components: incomplete observability and depth of observability. Power system graph is used. It also dealt with phasing of PMU's .As compared to previous stages phasing of PMU's at specific locations lowered the depth of observability when compared to the previous stage.

Reference [31] the authors to achieve a certain depth of unobservability made use of spanning tree and tree search. Tree search can be defined as a technique where the algorithm moves from bus to bus of the spanning tree to locate the next logical placement for a PMU. When all the buses have been visited the search terminates[31].

Baldwin et al. the author to choose optimal minimum PMU and placement locations a dual bisecting search algorithm and simulated annealing method based on topological observability . The method had a drawback from excessive calculation burden in case of a large power system.[32]

Reference [33] the authors introduced a topological method based on the augment matrix and Tabu search.

Reference [34] the authors used a PMU placement method based on the

To rearrange the measurements to minimize the number of PMU placement sites a heuristic algorithm is used. Single branch outages and measurement loss contingencies are used.[34]

iii) Particle Swarm Optimization

It is a population –based search in which individuals are termed as particles. They fly around in a multidimensional search space, changing their positions with time. Each particle adjusts its position according to its best experience and the best experience of its neighbor's.

Reference [35] the authors useda modified Binary Particle Swarm Optimization for the placement of PMU.The search space is discrete in BPSO .The variables can take on values of 0 &1 .The objective of the algorithm is to maximize the fitness of the entire population. It takes into account the number of installed PMU's and number of unobserved buses as specific fitness parameters to be optimized.

Binary Search

Chakrabarti et al To determine the minimum number of PMU's an exhaustive binary search was implemented. The solution which gave the highest measurement redundancy was selected. In addition to this it also considered the single line outages for each case of the optimal PMU placement solution. One at a time branch was disconnected and if the system remained observable then the PMU combination was labeled as a candidate or solution . It was a time consuming exhaustive search. [31]

The Table -1 summarizes the advantages and disadvantages of each method. The size of the problem and type of application determines the choice of technique. Also one must consider the state of power system under consideration. The adaptability of algorithm and user friendliness is the key requirement

Table 1

Technique	Advantages	Disadvantages
Genetic Algorithm based	It is robust and adaptable. Optimal solution is provided by IGA	Execution Time is long
Binary search	It provides the exhaustive search. The conventional measurements are well dealt.	It is not tested for larger IEEE -bus systems. Time consuming
Integer Programming	Adaptable and has Fast computations.	Non –Linear constraints
BPSO	Optimal solution is reached.	Computational time or contingencies does not get considered. It is not user friendly. Inadaptable
Tree Search and Topology	It is based on simple logic.	It is suitable generally for power systems already equipped with a few observable islands.

From the literature, The table 2 summarizes the lowest minimum number of PMU's to ensure full observe ability .The IEEE bus test system is used as a basis for algorithm comparison by the authors.

Table - 2 Minimum Number of PMU'S For IEEE Bus Test Systems

Test System	Minimum number of optimal PMU 's
IEEE 14- bus	3
IEEE 30-bus	7
IEEE 39- bus	8
IEEE 57- bus	11
IEEE 118- bus	28

Table- 3Comparison of Minimum PMU Placement Algorithm Comparison

Method	Test Systems				
	IEEE 14 –bus	IEEE 30 –bus	IEEE 39 –bus	IEEE 57 -bus	IEEE 118 -bus
Generalized Integer and Linear Programming [17]	3	7	-	11	-
Non dominated sorting genetic algorithm [29]	-	-	8	-	29
Integer Programming [14]	3	-	-	12	29
Optimal Multi – stage [18]	3	-	-	14	29
Contingency constrained [28]	3	7	8	11	28
Immunity Genetic Algorithm [23]	3	7	8	11	28
Genetic Algorithm [27]	3	7	-	12	29
Tabu search [33]	3	-	10	13	-
Particle Swarm Optimization [35]	3	7	-	11	28
Search tree and SA [30]	3	7	-	11	-
Binary search [31]	3	7	8	-	-
Dual Search and SA [32]	3	-	-	-	29

The results of the aforementioned algorithms is tabulated in table 3 .The number in the table depicts the minimum number of PMU required to achieve full system observability.

V. CONCLUSION

The IEEE test bus system formed the basis for comparison of PMU placement algorithm.The conclusion can be drawn that IGA and BPSO give a solution to OPP .However for large power systems there is no adaptability mathematically in terms of the measurement contingencies. The mathematical structure of ILP is easy to understand .There is adaptability in context to phasing and the modeling of contingencies. There is no need of conventional topological techniques for ILP .Further using ILP the two important concepts are introduced BOI and SORI. They are good for the optimal PMU placements to maximize the observability except that the algorithm did not reach to the minimum number of PMU's. The authors suggest modeling of a realistic power network for further work. The testing and development of ILP model will be carried out. This will ensure the authors and utilities a better understanding of the PMU placement and optimization process.

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