PSO algorithm for PMU placement on IRAN's electricity grid considering system observability

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Abstract— This paper utilizes different conventional algorithms for optimal placement of Phasor Measurement Units (PMUs) and compare them by testing on IEEE standard test cases with different number of buses. Two factor is considered in objective functions; first, the number of PMUs should be minimum, second, the number of observable buses in the systems should be maximized for total observability of the system. Ultimately, the PSO algorithm proposed for proper placement algorithm, and the real electricity grid of IRAN is applied to test the proposed algorithm. Results shows the efficiency of the proposed algorithm comparing to other methods and since the number of assigned PMUs to buses is approximately one third.

Key-Words- wide area measurement; phasor measurement units; placement algorithms; particle swarm optimization(PSO); observability.

1 INTRODUCTION

Previously, the supervision of a power system is performed through an open-loop type centralized control. The control actions are taken by operators with the help of computer-aided software programs that implement steady-state security function [1]. This is due to the fact that the measurements collected through a SCADA system are designed to capture only quasi-steady state operating conditions, preventing the monitoring of transient phenomena. With the advent of real-time Phasor measurement Units (PMU's), fast transients can be tracked at high sampling rates [2]. Hence it become possible to close the loop, that is, to perform an automatic monitoring and control of the system. This is a faster than real time control that aims at steering the system away from transient or voltage instability through corrective actions initiated during an emergency state. A prerequisite to system monitoring and control is the development of an adequate meter placement scheme. Various placement methodologies have been proposed in the literature [2-6]. Most of them advocate the use of pilot points located at the center of the coherent regions of the system. These regions either contain load buses with similar voltage trends for voltage stability analysis or encompass groups of stiffly interconnected machines with common slow modes of oscillations for transient stability analysis . The only control that has so far been implemented is the secondary voltage control scheme which has been applied to the French [5] and Italian systems [6]. Two major drawbacks of the coherency approach may be foreseen. First, the system may not be decomposable into meaningful clusters, signifying the necessity to monitor all load buses and/or all machine terminals. Second coherent regions are not stationary but exhibit dynamic behavior. Indeed they may split or coalesce as the loading condition of the system change. Consequently, a pilot placement that is optimal at a particular operating condition may perform poorly at another. This may have an adverse effect on voltage or transient stability control since large parts of the network may no longer be observed. Hence the system would no longer be properly monitored, especially when the system is heavily loaded and the stability margins are small. A better method is to place the PMU's so that the system becomes observable. Exploiting the ability of a PMU placed at a bus to measure the voltage as well as all the currents phasors of that bus. Phadke et al. [2] explore the possibility of providing all the nodes of the system with PMU's for state estimation purpose. However the relatively high cost of these unites prevents the adoption of such a solution at the present time. Therefore , it is important to investigate alternatives which account for the fact that the PMU's are being installed in the field in an incremental fashion. The problem which has been defined in [7] is to determine the placement of the minimal set of PMU's which makes the system observable. This paper expand this work with the introduction of a new topological concepts such as measurement–assigned subgraphs and coverage of a set of PMU's . Resulting from an extension of the work by Clements et al. [8-11], these concepts account for the fact that it is not possible to provide the system with exactly 2N-1 measurements, where N is the number of buses. This is due to the fact that a PMU provides a redundant collection of current and voltage phasor measurement at the node where it is located. From a measurement assignment point of view, this means that it is not a spanning measurement tree but a spanning measurement subgraph that results from the placement assignment process. This subgrah contains all the nodes of the network and has an actual or a calculated pseudo-measurement assign to each of its branch. A pseudo-measurement is assigned to either a non-metered branch where the voltage phasor at both ends are known, or to a non-metered branch which is incident to a bus where all but the current of that branch are known. Based on these assignment rules various search methods have been investigated and assessed.

2 DIFFERENT APPROACHES AND ALGORITHMS

In this chapter we describe different methods for Phasor Measurement Unit (PMU) placement with the aim of linear static state estimation of power system networks. These methods are depth first, graph theoretic procedures and bisecting search-simulated annealing which proposed in Baldwin et al. [12], as well as recursive and single shot N security and recursive and single shot N-1 security algorithms which were proposed in Denegri et al. [13]. An example of the procedures is done by assuming 14-bus IEEE test system as well, and these different procedures compared at the end.

2.1 Linear Static State Stimation

This section briefly describes basic concepts of power system static state estimation based on what propose in Schweppe et al. [14] and Clements et al. [8-11]. The static state estimation problem is generally formulated as a non-linear set of equations, as follows:

$$z = h(x) + \epsilon \tag{1}$$

Where,

$z(z\epsilon R^m)$: measurement vector

$x(x\epsilon R^n)$: state vector

$\epsilon(\epsilon \in R^m)$: measurement error vector

h($h: R^n \to R^m$): vector of the relationships between states and measurements.

The above equation is typically solved by means of Newton- Raphson technique Schweppe et al. [14], Allemong et al. [15], Monticelli and Garcia[16].Using devices able to provide voltage and current phasors, such as PMUs, yield a linear relationship between state variable and measurement variables, as follows:

$$z = Hx + \epsilon \tag{2}$$

Where H ($H\epsilon R^{m*n}$) is the "state" matrix of the system. Typically $m > n$, and the solution of (2) is obtained by a least mean squre technique Thorp et al. [17]. By splitting the vector z into the m_v*1 voltage and m_I*1 current subvectors, z_v and z_I and the vector x into the $n_M * 1$ and n_C *1 non-measured subvectors V_M and V_C relationship (2) becomes:

$$\begin{bmatrix} Zv \\ ZI \end{bmatrix} = \begin{bmatrix} I & 0 \\ YIM & YIC \end{bmatrix} \begin{bmatrix} VM \\ VC \end{bmatrix} + \begin{bmatrix} \epsilon_V \\ \epsilon_C \end{bmatrix} \tag{3}$$

Where I is the identity matrix, and YIM, YIC are sub-matrices whose elements are series and shunt admittances of the network branches. Neglecting shunts, the matrix H is as follows:

$$\text{H}=\begin{bmatrix} I & 0 \\ M_{IB}Y_{IB}A_{MB}^T & M_{IB}Y_{BB}A_{CB}^T \end{bmatrix} \tag{4}$$

Where M_{IB} is the $m_I * b$ measurement to branch incidence matrix associated with the current phasor measurements, Y_{BB} is the b*b diagonal matrix of the branch admittances, and $A_{MB} and\ A_{CB}$ are the $n_M * b$ and $n_C * b$ calculated node-to branch incidence submatrices, respectively Baldwin et al. [12]

A. PMU Placement Rules

The following PMU placement rules were proposed in Baldwin et al. [12]:

Rule 1) Assign one voltage measurement to a bus where a PMU has been placed, including one current measurement to each branch connected to the bus itself Fig. (1)

Rule 2) Assign one voltage pseudo-measurement to each node reached by another equipped with a PMU.

Rule 3) Assign one current pseudo – measurement to each branch connecting two buses where voltages are known. This allows interconnecting observed zones.

Rule 4) Assign one current pseudo- measurement to each branch where current can be directly calculated by the Kirchhoff current law.This rule applies when the current balance at one node is known, i.e. if the node has no power injections (if N-1 current incident to the node are known, the last current can be computed by difference).

3 CONVENTIONAL ALGORITHMS FOR PMU PLACEMENT

3.1 Depth First

This Method uses only Rules from 1 to 3 (it does not consider pure transit nodes). The first PMU is placed at the bus with the largest number of connected branches.

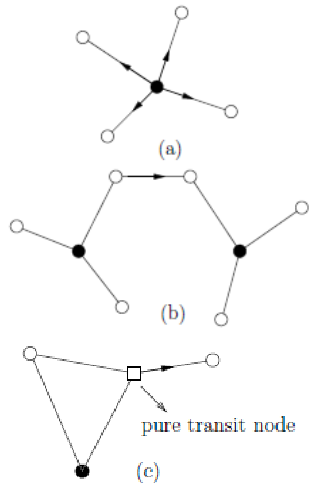


Figure (1): PMU placement rules.

If there is more than one bus with this characteristic, one is randomly chosen. Following PMUs are placed with the same criterion, until the complete network observability is obtained.

3.2 Graph Theoretic Procedure

This method was originally proposed in [12] and is similar to the depth first algorithm, except for taking into account pure transit nodes (Rule 4).

3.3 Bisecting Search Method

The flowchart of the bisecting search method and the pseudo-code of the simulated annealing procedure is according to [12] for the complete description of this method.

3.4 Recursive Security N algorithm

This method is a modified depth first approach. The procedure can be subdivided into three main steps:

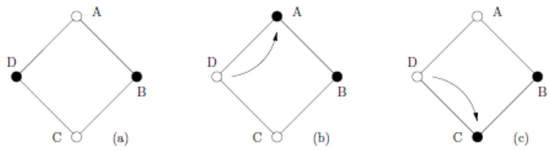
a) Generation of N minimum spanning trees: The algorithm is performed N times (N being the number of buses), using as starting bus each bus of the network.
b) Search of alternative patterns: The PMU sets obtained with the step (a) are reprocessed as follows: one at a time, each PMU of each set is replaced at the a PMU was originally set, as depicted in Fig (2) PMU placement which lead to complete obsevability are retained.
c) Reducing PMU number in case of pure transit nodes: In this step it is verified if the network remain observable taking out one PMU at a time from each set, as depicted in fig(3). If the network does not present pure transit nodes, the procedure ends at step (b).

3.5.Single Shot Security N algorithm

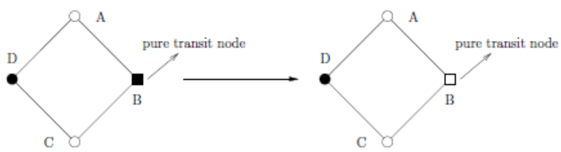
This method was proposed in Denegri et al.[13] . The algorithm is based on topological rules, and determines a single spanning tree.

3.6 Recursive and single-shot security N-1 Algorithms:

The rules for minimal PMU placement assume a fixed network topology and a complete reliability of measurement devices. Simple criteria which yield a complete observability in case of line outages (N-1 security) are proposed in [Denegri et al.[13] and are based on the following definition: A bus is said to be observable if at least one of the two following conditions applies:
Rule 1: a PMU is placed at the node;
Rule 2: the node is connected at least to two nodes equipped with a PMU.
Rule 2 is ignored if the bus is connected to single-end line.
the algorithms for obtaining the N-1 security placement proposed in Denegri [13]. The first method is a slightly different version of the recursive technique.



Figure(2): Search of alternative placement sets.



Figure(3): pure transit node filtering

4 Particle Swarm Optimization algorithm for PMU placement

In this paper, the particle swarm optimization (PSO) algorithm chose for proper placement of phasor measurement units, and will be tested on IEEE test cases and Iran's transmission/distribution electricity grid.
in this algorithm each component is called particle and is optional choice for the best answer of optimization problem. The algorithm follows by birds, fishes and insects in reaching final destination.
In this stage, usually each component assuming best practices by other group members, will choose its direction. The ratio of this practices are different for each member, so, in each stage, different paths are possible in search area.
after some iterations and repetition stages, the ultimate goal will recognize. Basically, we can simulate PSO algorithm as below:
Suppose current location and velocity of i(th) particle in (n) dimension is: $x_i = (x_{i1},...,x_{id},...,x_{in})$, $v_i = (v_{i1},...,v_{id},...,v_{in})$
in each stage the best practice of each member is:

$$pbest_i = (pbest_{i1},..., pbest_{id},..., pbest_{in})$$

and the best practice of group is:

$$gbest = (gbest_1,..., gbest_d,..., gbest_n)$$

and they are store in memory. Therefore, first the (i)th velocity vector updated with following procedure:

$$v_{id}^{(t+1)} = \omega.v_{id}^{(t)} + c_1.rand_1(\circ).(pbest_{id} - x_{id}^{(t)}) + c_2.rand_2(\circ).(gbest_d - x_{id}^{(t)}) \quad (5)$$

Then the location of that particle transfer according to the direction of the vector:

$$x_{id}^{(t+1)} = x_{id}^{(t)} + v_{id}^{(t+1)} \quad (6)$$

t, is the iteration number, and rand2(0) is the value given from the output of accidental numbers function between 0,1. C1,C2 are coefficient of learning that reflect the direction importance in personal or group best practice. These coefficients are normally chosen equal to two. and *W* is chosen less or equal to one:

$$\omega^{(t+1)} = \omega^{\max} - \frac{\omega^{\max} - \omega^{\min}}{t_{\max}} \times t \quad (7)$$

the mentioned explanation was for continuous problems, and for discrete problems like phasor measurement units placement, this problem will change slightly.
In this paper, the velocity of each particle is assumed as an input for a sigmoid function, and the output is a decision of whether the function output is zero or one.
the function is as below,

$$s(v_{id}) = \frac{1}{1 + \exp(-v_{id})} \quad (8)$$

then for decision about new values of variables, we have:

$$If\ \ rand(\circ) < s(v_{id}) \tag{9}$$

$$x_{id} = 1;$$

$$else$$

$$x_{id} = 0;$$

$$End$$

In this paper we consider the previous velocity of the particle in the new location, and the resulting discrete PSO equations is as below,

$$d_{1,id}^{k} = pbest_{id} \oplus x_{id}^{k} \tag{10}$$

$$d_{2,id}^{k} = gbest_{d} \oplus x_{id}^{k} \tag{11}$$

$$v_{id}^{k+1} = v_{id}^{k} + c_1 \oplus d_{1,id}^{k} + c_2 \oplus d_{2,id}^{k} \tag{12}$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \tag{13}$$

In which $d_{1,id}^{k}, d_{2,id}^{k}$ are dependent variables that calculated for each particle and dimension. C1, and C2 are discrete vectors that are generated accidentally and their dimensions are equal to problem variables.
the purpose of sign $\oplus$, is XOR in logic. Number of particles and iterations depend on system type. The more larger the dimention of the system, the more number of particles and maximim iterations in it.

The objective function of this paper is to minimize the number of PMUs considering the obsevablity of the power system. Therfore we have:

$$\text{minimize} \quad \sum_{i=1}^{N} PMU_i \qquad \text{subject to}: \ N_{nobs} = 0 \tag{14}$$

In which $PMU_i = 1$, if PMU is installed in (i)th bus, otherwise its zero.

N_{nobs}, is number of non-observable buses. The aggregative objective function using PSO algorithm considering number of measurement units and observability factor will be as below,

$$f = c_1 * \sum_{i=1}^{N} PMU_i + c_2 * N_{nobs} \tag{15}$$

For each particle, observability algorithm executed, and the number of non-observable buses calculated, then the objective function will calculate for each particle and the best personal and group practice delineated. Then, the velocity and location vectors of particles calculated and if the last iteration didn't achieve, the process will repeat to finally achieve the best practice for the group.

5 Comparison of Methods by Case Studies

The described methods are applied to some networks, i.e. the IEEE 14, 39, 57, 118 bus test systems, for which minimal PMU placement sets obtained by the simulated annealing technique and other techniques. Results for all the methods, included the simulated annealing are shown in Table I.

TableI. Comparison of Algorithms by IEEE test cases

Test systems	buses	Depth first	PSO	Rec. Span. Tree	Dir. Span. tree	Rec. N-1 Spa.	Dir N-1 Spa.
IEEE 14 bus	14	4	3	3	4	8	8
IEEE 39 bus	39	12	8	9	10	18	18
IEEE 57 bus	57	19	15	17	18	22	24
IEEE 118 bus	118	34	29	31	34	63	72

In each column, the end left quantities shown the minimum number of PMU's that was determined by the respective algorithm in order to achieve the spanning tree of the network. Best results are from the simulated annealing and the recursive security N methods. The single shot method seems to provide generally slightly higher number of PMU's about (10%). However the simulated annealing becomes extremely lengthy as the number of nodes increases, since its computations increases with the factorial of this number.

Furthermore, differences between the simulated annealing and proposed methods are limited to few units and tend to be negligible For bigger networks. It has to be noted that also the annealing method could find more than one solution, but only by running the algorithm many times. Clearly this would imply a very extensive computational effort.
For the N-1 security methods , the quantities in square bracket indicate the additional PMU's required for accomplishing a complete observability also in case of measurement device outage. These results were obtained after the determination of the PMU sets, taking out, one at a time, each PMU and determining if the network would remain still observable. When this is not the case, a new PMU can be placed either on the same bus or on a neighboring bus. As it can be noted these numbers are at least about half of the PMU's needed for an N-1 security which covers only line losses. However, it has also to be remarked that in about the 50% of the cases, taking out one PMU does not affect the complete observability of the network, while in the 45% of the cases only one bus results not observable. Thus, when planning a PMU placement, it should be evaluate if the advantage of adopting a complete N-1 sequrity criterion would pay back the installation costs. It has been chosen to apply a redundancy to the existing ones rather than set PMU's on different buses. As it can be seen buses connected to the network by a single line are lost when the line is out of service. Summarizing the N Security criterion lead to PMU sets about the 25-30% of the total bus numbers, while in case of N-1 security up to the 75% when considering also PMU outages.

6 Conclusion

The objective function of optimization problem in this study was to minimize the number of phasor measurement units install in the system, while the system be observable through maximum observable buses in the system.

Particle Swarm optimization proposed for PMUs placement, and the algorithm tested in comparison to conventional placement algorithms. The algorithms are implemented in IEEE standard test cases and the number of assigned PMUs compared accordingly.

PSO algorithm is most suitable when the number of buses are more and the power system is larger. Therefore the proposed PSO algorithm tested in local IRAN's transmission and distribution system that the result of optimization for placement of phasor measurement units, appropriately shows in about one third of buses in the system PMUs should be installed, in order to the system being totally observable. The result of location of PMUs and their voltage level with the local dispatching codes show in appendix A.

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APPENDIX A.

The result of PMU placement with PSO algorithm in IRAN's electricity grid is shown through the table as below. There are totally 165 PMUs placed in a 901 buses system and 1407 lines(distribution and transmission), in which number of transmission lines are around 500. Other buses that doesn't mentioned are not assigned to any PMUs.

Dispatch Code	Bus Name	Voltage (KV)
1030	BONAB2	230
1040	KHOY 2	230
1050	MAHAB2	230
1070	MIANEG2	230
1150	TABRI2	230
1170	TAGHI2	230
1180	TEKME2	230
1350	N-HAM2	230
1380	PSOVEH14	400
1400	SHAZN2	230
1440	BEHRA2	230
1450	CHLST2	230
1480	ESFA12	230
1490	ESFA22	230
1500	ESGRT2	230
1510	ESGRT4	400
1630	NISIC4	400
1650	SHRKO4	400
1660	TIRAN4	400
1670	ZOBAH2	230
1720	BUATM4	400
1730	BUSH22	230
1820	FAPSO 2	230
1890	KAZER2	230
1900	KAZER4	400
1920	MARVD2	230
1930	N-SHI2	230
2020	BAKHT2	230
2030	BISTN2	230
2050	DIVAN2	230
2060	E.KRMSH2	230

2190	B.ABB2	230	3500	REY G2	230	4380	ZARGA2	230	5480	SHMLSH2	230
2290	JASK 2	230	3520	REY N4	400	4390	AGARA2	230	5510	GHOM24	400
2300	JONAH2	230	3580	SHUSH2	230	4430	IMISH3	330	5550	KHONDAB2	230
2340	RUDAN2	230	3630	TEHPS2	230	4480	PSORAB2	230	5560	KHALIJ4	400
2350	PSORKN2	230	3650	ZIARA2	230	4530	N-KHORM4	400	5750	CHKHOSH2	230
2390	BAM 2	230	3680	JAKIG1	132	4550	BOOKSHN2	230	5770	MARKZB2	230
2450	N-KER2	230	3710	LOTAK2	230	4560	N-CHLST4	400	5850	HARAZD4	400
2490	SIRJA2	230	3730	N-IRN2	230	4570	BOTASL14	400	5910	F-OMID2	230
2540	ASTAR1	110	3810	GHAE24	400	4580	BOTFARS4	400	5920	SRDASHT2	230
2590	LOSHA2	230	3830	NEISH4	400	4590	N-JAHRM2	230	5970	PETMR2	230
2610	N-GIL2	230	3860	SHIRV4	400	4610	N-PSON2	230	6000	N-CHABA2	230
2640	RASHN2	230	3880	TOOS 4	400	4620	N-SEY2	230	6050	ALGHDIM2	230
2670	SEFID2	230	3890	ARDAK2	230	4640	TAZIN2	230	6090	SERAHZA4	400
2740	BABOL2	230	3900	CHADR2	230	4660	N-KER4	400	6120	BOOZAN44	400
2770	DANYL2	230	3930	N-YAZ2	230	4690	TURKM2	230	6150	BOTASL24	400
2850	KORDK2	230	3950	YAZD14	400	4720	BOOZAN14	400	6170	BOOALIA2	230
2860	MINOD2	230	3960	YAZD22	230	4740	SHAR 4	400	6190	ZARGABO2	230
2870	NARIV2	230	3990	ABADA4	400	4760	DAMAV4	400	6240	KASHMR4	400
2890	NEKA 2	230	4000	ABSPO4	400	4770	LAVAR2	230	6260	BOOSIST2	230
2900	NEKA 4	400	4050	AHWAN2	230	4780	N-PRN2	230	6270	BOOQES12	230
2920	PSORI 2	230	4100	BEHBN2	230	4790	N-RUD4	400	6320	BOOKAHN4	400
3000	TAKES2	230	4110	DEZ 2	230	4800	SIABI4	400	6330	BOOKAHN2	230
3020	ZANJ22	230	4120	DOGON2	230	4820	BOOTOOS4	400	6350	BOOGNAV2	230
3090	SEMNA2	230	4130	GODAR4	400	4840	PSORKH4	400	6370	BOOHOR12	230
3100	SHARO2	230	4140	GOTVA4	400	4970	N-ARDBL2	230	6390	BOOMAZ2	230
3210	GHOM22	230	4160	KARKH4	400	4980	N-ORUM2	230	6400	BOOYAZ12	230
3240	GILAV2	230	4170	KARU34	400	5020	MANOJ2	230	6420	BOOKERM2	230
3320	KAN2 2	230	4180	KARU44	400	5120	DYLAM2	230	6430	BOOSEMN2	230
3330	KARAJ2	230	4200	MARUN2	230	5170	S-AHW32	230	3321	KAN1 3	230
3360	MONTG2	230	4230	N-ABD2	230	5180	KHORAMS4	400			
3370	MONTZ2	230	4240	NAVAR2	230	5270	KHODA2	230			
3380	MOPSOL2	230	4250	NISIC2	230	5310	N-KHOR22	230			
3390	MOSHR2	230	4270	OMID14	400	5330	AMIRK2	230			
3480	RAJAB4	400	4310	RAMIN2	230	5390	GOVADIR2	230			
3490	RAJAG4	400	4370	YASUJ4	400	5430	PSORBAZ2	230			