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Integer Linear Programming Based Optimal Placement of Phasor Measurement Units for Power System Observability in Khouzestan Province in Iran

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ABSTRACT

Nowadays, phasor measurement units are used in power networks for different purposes, such as Linearization of state estimation equations and speed improvement of controlling and protecting systems. Optimization of position and number of these equipments is considerably important because of their high costs. Effective parameters on position and number of PMUs optimization are: Network topology and zero injection buses in power networks. In this paper an objective function based on integer linear programming (ILP) is presented to determine the number and optimized position of PMUs, in order to complete observability of power systems. The effect of zero injection buses on objective function in power networks is evaluated. Simulation results are implemented in MATLAB software on the IEEE 14 buses system, and also 230kv and 400kv networks in Khouzestan province.

I. Introduction

Due to some reasons such as increase in the consumption demands and structural improvements, that increases the pressure on transfer loads, power systems mostly work near the unstable boundary. In this condition using the current SCADA system and its sub functions seem inconvenient for ensuring the stable performance. For a power system it is necessary to have all the system states to make it controllable and all its variables become available. But today measurements are not capable of measuring the phase angles directly. Moreover it is possible that voltmeters are not installed on all the buses or the data transferring to dispatching centre can be halted. Accordingly, it is necessary to estimate all the system states in some way. Estimating the performance state means giving a value to a variable that is unknown based on some statistical methods. In SCADA system states estimation is done based on stored data in a time period. Totally it can be said that SCADA system used for measuring has some important weakness points. SCADA measurements normally are not concurrent and have some time difference that is ignored. On the other hand, data collection does not have a high rate because of equipments limitations or insufficient communication capacity.

Accordingly, the displayed information by the SCADA shows the stable state of the power system or in the best condition it shows the semi stable state and it makes the operator not to see the dynamic condition of the system. Recently, another system that is called WAMPC (wide area monitoring, protection and control) was favored by many researchers that its main goal was to compensate the shortcomings in SCADA.

Main elements of the WAMPC is PMU (phasor measurement unit) that were introduced by advances in signal processing technology for the first time in the mid 80s.

PMU can measure the voltage and current phasors with high accuracy (less than 0.1 %) and high speed (60 samples in a second); they use the GPS to synchrony the measured data. If enough number of PMU is installed on bus systems them the states estimation can be done by PMU data and have a very high accuracy. Because the PMUs measure the current and voltage in all the linkages, it is not necessary to install them on all the buses. Finding the optimal position to install the buses and the sufficient number of them is a main goal that is done based on the application and goal. The first and most fundamental criterion that the PMUs should have is that the variables of network state become displayable. More than display ability and estimation of states, the PMU data are used to find the error position in transfer lines [1], and even for applications such as estimation of real time transient stability of power system [2], security in large scale adaptive relay, heat purity for current lines and voltage stability[3,4]. In this paper the conditions to find the number and position of PMU is considered. Up to now, various plans have been suggested to find the optimal position of PMU. In references [5, 6] the authors applied electroplating to find the optimal position of PMUs. This method requires an initial accidental guess. The calculation is a heavy work and does not necessarily result in optimal values. In reference [7] GA (genetic algorithm) is used to find the optimal position of PMU. The advantage of GA is that it gives a number of solutions that gives the companies the chance of choosing one. The shortcoming of this method is that it cannot give the minimum number of PMU to make the system displayable and the optimal number of PMUs should be given first. PSO (Particle Swarm Optimization) and BPSO (Binary Particle Swarm Optimization) are among the other methods used by the researchers [8].

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In this paper positioning the PMU with the minimum number of them and making them displayable is done with ILP (integer linear programming). This method is simple, understandable and applicable with high calculation speed. ILP gives the best total answers for all the systems. This method is simulated on standard IEEE with MATLAB and it is compared with other positioning methods for PMU. These comparisons show that this method is a sufficient and acceptable one. The 230 and 400 KV network form Khouzestan province is chosen as a case study.

II.Observability Analysis with Pmu

A PMU installed on a certain bus is able to measure the voltage magnitude and phase angle of the local bus and the branch current phasor of all branches emerging from this bus.

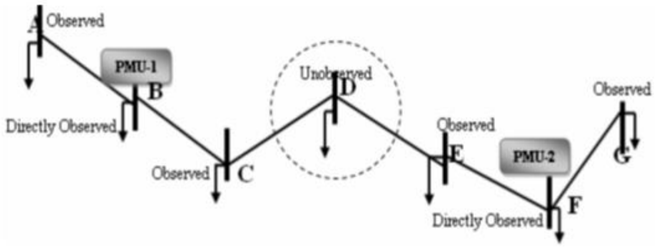


Fig 1. PMU Observability Analysis.

The voltage magnitude and phase angle of the neighboring bus can be computed using voltage drop equations. Thus the buses monitored by a PMU are directly observable, the neighboring buses connected to the PMU buses are indirectly observable and the other buses which are not associated with the PMU buses are unobservable. The following graph explains the bus observability in a system[9].

In Fig. 1, the network has 7 buses from A to bus G. Assume two PMUs are located on bus B and bus F, so bus B and F are directly observable. Bus A, C, E and G are all connected to bus B and F so they are indirectly observably. Bus D is not associated with any PMU bus, so bus D is unobservable. So in this 7-bus system example, 6 buses are observable and 1 bus is not observable. Thus, this system is not a completely observed system. A completely observed system means all the buses in this system should be directly or indirectly observed with a proper PMU placement scheme.

III. PMU PLACEMENT PROBLEM FORMULATION

A PMU is able to measure the voltage phasor of the installed bus and the current phasors of all the lines connecting to this bus. That is to say, a PMU can make the installed bus and its neighboring buses observable. The objective of placing PMUs in power systems is to determine a minimal set of PMUs such that the whole system is observable.

Therefore the placement of PMUs makes a problem that is to find a minimal set of PMUs such that a bus must be reached at least once by the set of the PMUs.

Now the optimal placement of PMUs can be formulated as a problem of Integer Linear Programming (ILP) [10]:

$$Min \sum_{i=1}^{n} w_i . x_i \tag{1}$$

$$s.t \quad y = A_{n \times n} X_{n \times 1} \geq b_{n \times 1}$$

Where n is total number of buses in the network and w is the cost function for the installed PMUs or the weight matrix for the buses that can vary based on the importance of every bus. w is normally equal to unit $n \times n$ matrix. In this equation, x, A and b are defined as bellow:

$$A_{n \times n}(i, j) = \begin{cases} 1 & i = j \\ 1 & \text{if buses } i \text{ and } j \text{ are connected} \\ 0 & \text{otherwise} \end{cases}$$

$$x_{n \times 1}(i) = \begin{cases} 1 & \text{if PMU installed in bus } i \\ 0 & \text{otherwise} \end{cases}$$

$$b_{n \times 1} = [1 \;\; 1 \;\; 1 \;\; \ldots \;\; 1 \;\; 1]^T$$

The inequality in function (1) is used for complete monitoring the system. The ith row in Ax matrix is the number of times that the ith bus is monitored which should be at least one.

Consider the IEEE-14 bus system shown in Figure 2. Let x_i be a binary decision variable associated with the bus i. Variable x_i is set to one if a PMU is installed at bus i, else it is set to zero.

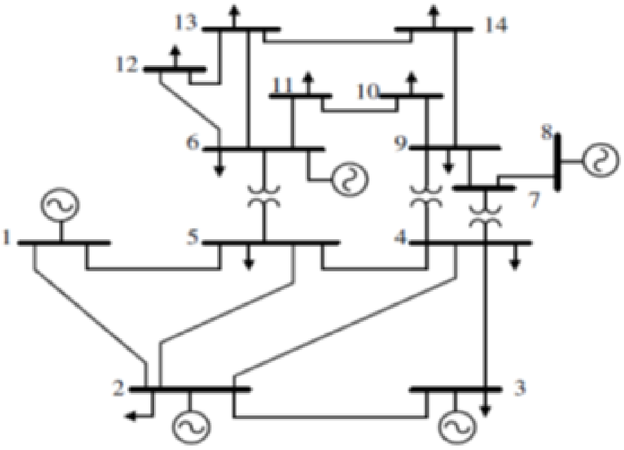


Fig 2. IEEE 14 Bus Test System (seventh bus is a zero injection bus).

Now if we arrange the equations (1) for IEEE-14 bus system in matrix form the results can be formulated as function (2).

$$\min \sum_{i=1}^{14} w_i . x_i \tag{2}$$

$$\underbrace{\begin{bmatrix} 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \end{bmatrix}}_{x} \geq \underbrace{\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}}_{b}$$

The A matrix can be directly obtained by making the admittances matrix a binary one.

Solving the function (2) in ILP solver leads to an optimal number of 4 PMUs for making the system observable, with location of PMUs being on busses 2, 6, 7 and 9.

IV. Modeling of Zero Injection Busses

Zero injection bus is a bus such that no current or power is injected into the system through this bus, which means no active or reactive load is associated with this bus. Figure 3 shows a zero injection bus in a network [9].

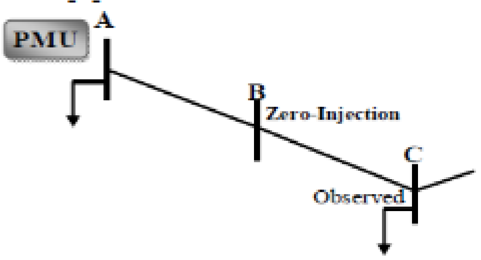
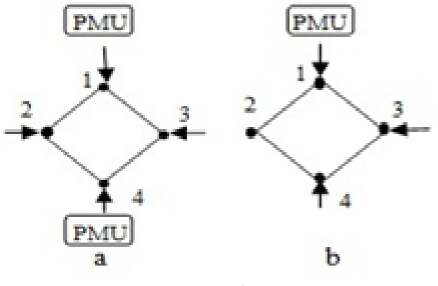


Fig. 3 Zero Injection Case.

In the network above, bus A is a PMU bus, bus B is a zero-injection bus and bus C is a PQ bus in power system. Bus A is directly measured by the PMU installed at bus A, so bus A is directly observable; bus B which is connected to the PMU bus (bus A) is as well an observable bus by computing the voltage information with the voltage drop equations. Because bus B is a zero-injection bus, the current flowing through line A-B equals the current flowing through line B-C. Knowing the voltage information on bus B and the current phasor on line B-C, the voltage data on bus C can be calculated using Ohm’s law. So in conclusion, bus A, B and C are all observable when bus B happens to be a zero injection bus. In contrast, if bus B is not a zero-injection bus, the assumption that the current phasor on line A-B equals that on line B-C will be invalid and thus the voltage information on bus C cannot be calculated without the current information on line B-C.

In this case, only bus A and B are observable when bus B is not a zero injection bus. In short, considering the influence of zero injection busses in a power system, the number of observed busses is expected to be increased and the optimal number of PMUs required will be further minimized.

To understand this subject, 4 busses network that is shown in figure 4 is investigated [11].



a b

Fig. 4 PMU placement for a 4 busses system

Figure 4(a) depicts the system with injections in all the busses. Figure 4(b) shows a similar system with zero injection in bus 2 and injections in bus 1, 3 and 4. For system in figure 4(a) it can be easily known that at least 2 PMUs are required for full system monitoring. These two PMUs can be installed on any of these four busses. But in figure 4(b), if bus number 2 is considered as the zero injection bus, the current in branch 4_2 is equal to the current in branch 2_1 ($I_{24}=I_{12}$). Accordingly, knowing the line parameters, voltage can be calculated in bus 4 ($V_4=V_2-I_{12}Z_{24}$). Finally there is no necessity to install a separate PMU in bus number 4. Accordingly, investigating the zero injections busses helps in reduction of the number of required PMUs to monitor the system.

V. Modeling of Zero Injection Busses in the Ilp Framework

For modeling of zero injection busses in the ILP framework a new variable that is called U_i is defined to confirm the monitoring ability for bus i. if $U_i=1$, it means that the i bus can be monitored and $U_i=0$ means that I bus cannot be monitored.

The set of busses that are connected to zero injection bus are called A_i and the A_i with zero injection bus are called B_i ($B_i = A_i \cup \{i\}$). Any zero injections cause a new constraint that this condition is formulated in ILP as function (3) [11].

$$Objective: \ \min \sum_{i=1}^{n} w_i . x_i \tag{3}$$

$$Subject\ to:$$

$$Ax \geq u$$

$$and$$

$$u_j = 1 \quad \forall j \notin B_1 \bigcup B_2 ... \bigcup B_z$$

$$and$$

$$\sum_{k \in B_i} u_k \geq |A_i| \quad \forall i \in Z$$

$$or$$

$$a_i \, u \geq |A_i|$$

Here, $B_i = A_i \cup \{i\}$ and $|A_i|$ is the size of A_i set.

Here we consider IEEE 14-bus system in figure 2, This system has bus 7 as zero injection bus. Thus, $Z=\{7\}$, $A_7=\{4,8,9\}$ and $B_7=\{4,7,8,9\}$. Thus, Additional constraints on zero injection busses modeling in the ILP will be as follows:

$$u_4 + u_7 + u_8 + u_9 \geq 3$$

Solving the above formulation in ILP solver leads to an optimal number of 3 PMUs for making the system observable, with location of PMUs being on busses 2, 6 and 9.

VI. Simulation Results

To evaluate the ability of the mentioned method, standard networks of IEEE buses with numbers such as 14,57, 30, 118 are studied. Table 1 has the properties of the zero injections that are studied. The information related to these buses is obtained from reference [12].

The 230 and 400 KV in Khouzestan province are also used for optimal positioning for the measuring units. Figures 5 and 6 show the single line diagram of such networks and for better resolution and easier analysis of that all the posts names are in table 2.

Table 1. Zero Injection Busses for the Test Systems.

Test system	No. of zero injection busses	Zero Injection Busses Locations
14-bus IEEE	1	7
30-bus IEEE	5	6,9,11,25,29
57-bus IEEE	15	4,7,11,21,22,24,26,34,36,37,39,40,45,46,48
118-bus IEEE	10	5,9,30,37,38,63,64,67,71,81
400KV Khouzestan province	1	8
230KV Khouzestan province	-	-

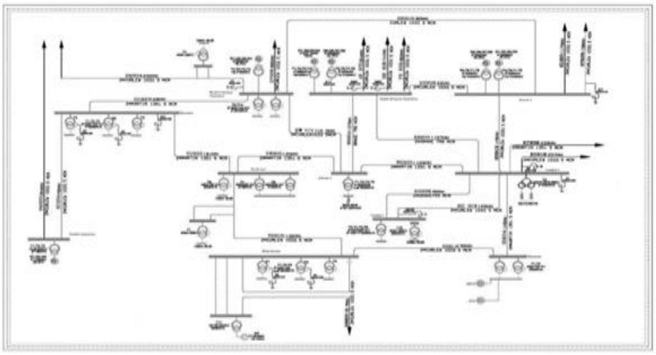


Fig 5. 400KV network in Khouzestan province.

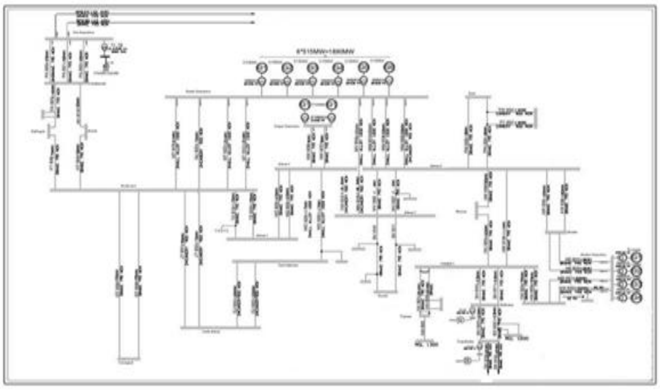


Fig 6. 230 KV network in Khouzestan province.

Table 2. The post names.

230KV Khouzestan province		400KV Khouzestan province	
Post number	**Post name**	**Post number**	**Post name**
1	Ramin Generation	1	Shahid Abaspour Generation
2	Abadan Generation	2	Karoun 3
3	Dez Generation	3	Masjed Soleyman Generation
4	Zergan Generation	4	Karkhe Generation
5	Ahwaz 2	5	Ahwaze 2
6	North-west	6	Milad Abadan
7	South Ahwaz	7	Omidieh 1
8	Steel Industries	8	Omidieh 2
9	Abadan	9	Mahshahr
10	Omidieh 1	10	Shoushtar
11	Behbahan	11	North-west
12	Dogonbadan	-	-
13	Ahwaz 1	-	-
14	Andimeshk	-	-
15	Hafttapeh	-	-
16	Shoush	-	-
17	Ahwaz 3	-	-
18	Navard	-	-
19	Pazenan	-	-
20	Maroun	-	-
21	Kerit	-	-
22	Sousangerd	-	-

Table 3 shows the optimum positioning for standard IEEE networks and Khouzestan province network without considering the information related to zero injections information.

Table 4 shows the number and position of optimal PMUs for the studied networks considering the zero injectionss. Table 5 presents a comparison of the results form different methods and the results from the literature. Results show that by installing 3 PMU in 400KV and 6 PMU in 230 KV networks for Khouzestan province these networks can be monitored.

Table 3. Optimal Number and Locations of PMUs in Test Systems.

Test system	No. of PMUs	Locations
14-bus IEEE	4	2,6,7,9
30-bus IEEE	10	1,7,9,10,12,18,24,25, 27,28
57-bus IEEE	17	1,4,9,15,20,24,27,29,31,32,36,38, 39,41,47,51,54
118-bus IEEE	32	3,7,9,11,12,17,21,25,28,34,37,41, 45,49,53,62,63,68,70,71,76,79,85 ,86,89,92,96,100,105,110,114
400KV Khouzestan province	4	2,8,9,10
230KV Khouzestan province	6	5,8,10,11,14,17

Table 4. Optimal Number and Locations of PMUs Including Zero Injection Busses in Test Systems.

Test system	No. of PMUs	Locations
14-bus IEEE	3	2,6,9
30-bus IEEE	7	1,5,10,12,18,23,27
57-bus IEEE	14	1,4,9,20,25,27,28,32,36,38,47,5 0,53,56
118-bus IEEE	29	2,5,10,12,15,17,20,23,28,34,40, 45,49,52,56,62,65,71,75,77,80,8 5,86,90,94,101,105,110, 114
400KV Khouzestan province	3	1,6,10
230KV Khouzestan province	-	-

VII. Conclusion

In this paper the optimal positioning of phasor measuring units for the condition with minimum application for monitoring of the complete network was studied. In the presented method here the inequalities related to the monitoring constraints was presented fully linear.

The PMU positioning results using the integer linear programming on the sample IEEE and a comparison with other methods was presented. It was shown that this method gives very accurate results for different networks and also it is a simple one.

After discussing the mentioned method and its equations, the 230 and 400KV networks as real networks are studied. The results from this simulation show that by installing the PMU on 27 percent of 230 and 400KV buses these buses can be totally observed.

Table 5. Comparison of the Results the Proposed Models with Different Methods.

Method Test	ILP (B&B)	Genetic algorithm[5]	Graph search[3]	Tabu search[10]	BPSO[11]
14-bus IEEE	3	3	5	3	3
30-bus IEEE	7	7	11	-	7
57-bus IEEE	14	12	19	12	13
118-bus IEEE	29	29	38	-	29

References

[1]Kai-Ping,Chin-Wen Liu,Chi-Shan Yu, and Joe-Air Jiand, “transmission network fault location observability with minimal PMU placement”, IEEE Transaction on Power Delivery, Vol. 21, No. 3, 1128-1136, july 2006.

[2]C. W. Liu and J. Thorp, “Application of synchronized phasor measurements to real-time transient stability prediction”, Proc. Inst. Elect. Eng.,General Transmission Distribution, vol. 142,355-360, July 1995.

[3]T. T. Nguyen and V. L. Nguyen, “Application of Wide-Area Network of Phasor Measurements for Secondary Voltage Control in Power Systems with FACTS Controllers” ,IEEE, 2005.

[4] Phadke A.G.,”Synchronized Phasor Measurements in Power Systems,IEEE Computer Applications in Power”, 6(2):10-15,1993.

[5]T.L. Baldwin, L. Mili, M. B. Boisen, and R. Adapa, “Power system observability with minimal phasor measurement placement”, IEEE Trans, Power Syst, vol.8,no.2, 707-715, May 1993.

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

[7]B. Milosevic and M. Begovic, “Nondominated sorting genetic algorithm for optimal phasor measurement placement”, IEEE Trans. Power Syst., vol.18, no. 1, 69-75, Feb. 2003.

[8]Y. del Valle, G. K. Venayagamoorthy, S. Mohagheghi, J. C. Hernandez, and R. G. Harley, “Particle Swarm optimization: basic concepts, variants and applications in power systems”, IEEE Trans. Evolutionary computation, vol. 12, no.2, 171-195, Apr. 2008.

[9]Zhao, Z., May 2010, Sensitivity Constrained PMU Placement Utilizing Multiple Methods, Master of Science Thesis, Clemson University, pp. 1-69.

[10]Xu, B., Abur, A., 2004, Observability Analysis and Measurement Placement for System with PMUs, Power Systems Conference and Exposition, 2004, IEEE PES, vol. 2, pp. 943-946.

[11]Dua, D., Dambhare, S., Gajbhiye, R. K., Soman, S. A., (2006), "Optimal multistage scheduling of PMU placement: An ILP approach", IEEE Transactions on Power Delivery, vol.23, no. 4, pp. 1812-1820.

[12]Power Systems Test Case Archive, Available [online] at: http://www.ee.washington.rdu/research/pstca.

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