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A Novel Approach for Placement of Phasor Measurement Unit and Counting Their Optimal Number

Ajit Kumar, Sandeep Bhongade*
Electrical Engineering Department, SGSITS, Indore, India

Abstract

In India power system monitoring is based mainly on measurements provided by remote terminal unit (RTU). For power system measurement synchronized phasor or phasor measurement unit (PMU) is popular choice in abroad and its popularity is increasing day by day because of its several features. Synchrophasor technology was first introduced in India in 2011–2012.[7–9] Direct measurement of voltage or current phasor is possible because of PMU which was not possible earlier. Global positioning system (GPS) provides time synchronized data. In this paper a new approach is used for optimal placement of PMU, counting their number and time elapsed. The approach is applied on IEEE-14 bus system bus system. Here, all the bus which are taken into consideration is either completely observable or at some depth of un-observability is also taken into account.

Keywords: IEEE-14 bus system, observability, phasor, PMU

***Corresponding Author**
E-mail: ajit06jia@gmail.com

INTRODUCTION

Better power system control can be achieved. With the aid of global positioning system (GPS), a new era of measurement technique was developed in mid-1980s called phasor measurement units (PMU). PMUs utilize the synchronization signals from the GPS to provide the phasor values of voltages and currents at the bus or substation wherever it is connected.[1] These types of phasor measurements can improve the monitoring of power system. PMUs can measure the phase angle and amplitude of voltages at the installed bus and current through all branches connected to that bus but it is redundant and not economical to place PMUs at all buses for making the power system completely observable. Finding the optimal locations for PMU is of great interest so that with minimum number of PMUs the power system under consideration will be fully observable.[2,3–5] This paper proposes the optimal placement for PMUs, counting their number and total time elapsed.

PHASOR MEASUREMENT UNITS

The load demand in power system is always varying during whole day. The minimum capacity of generator should be such that it should meet the maximum demand. Stable operation of power system requires accurate and online monitoring of various operating conditions. Conventional method of power system monitoring is accomplished by SCADA (supervisory control and data acquisition system) system. SCADA system usually consists of remote terminal units (RTU). RTUs are the microprocessor controlled electronic devices which can measure real and reactive power flows, magnitude of bus voltages and currents. RTUs are placed at various substations and they send the measured values to the state estimator which is placed inside the central control centre. From the received measurement values and the knowledge about the network topology, state estimator can estimate various electrical quantities related to the power system stability. These estimated values are used for the online power flow control and management. But one of the drawbacks of the RTUs is that it cannot directly measure the phase angles of the voltages and currents at any bus. If we can measure phasor values of bus voltages and currents, better state estimation and thereby.

Figure 1 shows the functional block diagram of a PMU.[1] PMU measures voltages and phase angle on an electricity grid, using a common time source for synchronization. Analog inputs from potential transformers and current transformers are fed to an anti-aliasing. This will restrict the bandwidth of the signal to approximately satisfy the sampling theorem. The signals from the output of anti-aliasing filter are converted to digital using A/D converters. Phase locked loop ensures the synchronization of sampling with reference signal from GPS.

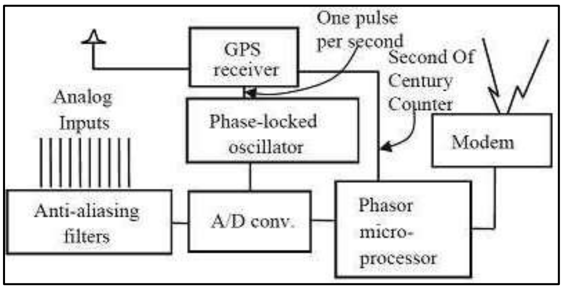

Fig. 1. *Functional Block Diagram of PMU.*

Sampled signals are then fed to the phasor microprocessor, where phasors of phase voltages and currents are computed using recursive discrete Fourier transform (DFT) algorithms.

The computed of phasor values are assembled in a message stream and are then sent via the communication network to the wide area monitoring system. Sampled signals are then fed to the phasor microprocessor, where phasors of phase voltages and currents are computed using recursive DFT algorithms. The computed of phasor values are assembled in a message stream and are then sent via the communication network to the wide area monitoring system.[6–9]

THE CONCEPT OF OBSERVABILITY

A bus is said to be observable if a PMU is located on that bus and the voltage and phase angle are measured directly. A bus is said to be indirectly observable, if the voltage phasor at that bus is estimated using other PMUs.

A bus is said to be unobservable, if its voltage phasor cannot be measured. This condition occurs when there is no PMU at that bus and neighbouring buses.

From Figure 2, at bus 2, 6 and 9 a PMU is placed so that voltage magnitude and phase angle at that bus and current through all the branches connected to it can be measured. So the bus 2, 6 and 9 are said to be directly observable since PMU is placed on these buses. Voltage magnitude at buses 1, 3, 4, 5, 7, 10, 11, 12, 13 and14 can be estimated using ohms law. So, these buses are said to be indirectly observable.

But the voltage phasor at buses 8 cannot be estimated using PMU at bus any buses, so we can this bus 8 is unobservable. If all neighbouring buses of an unobservable bus are observable, then it is called depth of one unobservability.[4]

A power system is said to be completely observable, if all the buses in that system are either directly or indirectly observable. A power system is said to be incompletely observable, if some buses are directly or indirectly not observable.

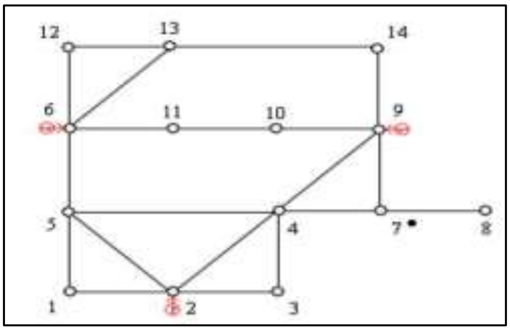

Fig. 2. *IEEE-14 Bus System With PMU Placement.*

BASIC IDEA OF PMU PLACEMENT

The basic idea of PMU placement is to make entire system observable. For this we have two approach first one is to put PMU at all the substation which makes entire system cost very high because PMU is a costlier device, the other thing we can do is to optimized the number of PMU.

x be a binary decision vector whose entity is defined as

$$x_i = \begin{cases} 1 & \text{if a PMU is installed at bus } i \\ 0 & \text{otherwise} \end{cases}$$

and

For an n-bus system, the PMU placement can be formulated as

$$\text{minimize} \quad \sum_{i}^{n} w_i \cdot x_i$$

$$\text{subject to} \quad f(X) \geq \hat{1}$$

Where w is the cost of PMU installed at bus i.f(x) is a vector function, which is non-zero if corresponding bus voltage is solvable zero otherwise.

PROPOSED ALGORITHM

As we know that PMU measures bus voltage phasor and branch current phasor. Each PMU has certain number of channel to record the value of voltage phasor and branch current. It is also assumed that each PMU has enough number of channels. We can limit these number of channel upto some extent because after reducing these number to very small the time elapsed increases above the desirable limit, which is not ideal for our purpose. In this paper a concept of zero injection along with single hop connectivity is used for reducing the number of PMU required for making entire system observable. The Figure 2 shows a zero injection at bus 7. Bus 8 is unobservable because it is not connected with any PMU directly or indirectly so it is not possible to calculate voltage and current here. The concept of zero injection measurement as mentioned in ref.[2] makes the entire system observable and it also reduces the number of PMU by one which was 4 when no zero injection was introduced. The PMU is at bus 2, 6 and 9 makes entire system observable only when a zero injection is done at bus 7. In this paper six steps are defined in form of flow chart and a pseudo code is given following the flow chart. With the help of the flow chart and pseudo code mentioned in this paper we have made the entire IEEE-14 bus system observable. A new concept of zero injection along with single hop connectivity is also defined which is very helpful in achieving the required goal. The first step of the proposed method completes as we have placed the PMU only at those buses which makes the most of branches observable. In second step we have to form a square matrix A(14,14) from the above placement.

$$A = \begin{bmatrix}
1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1
\end{bmatrix}$$

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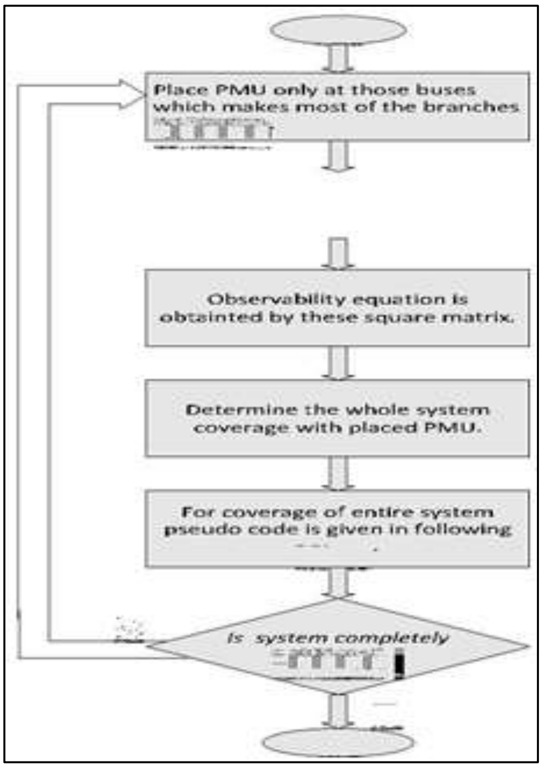
The third step is to make observability equation from the above matrix.

$$f(x) = A..X = \begin{cases} f_1 = x_1 + x_2 + x_5 \geq 1 \\ f_2 = x_1 + x_2 + x_3 + x_4 + x_5 \geq 1 \\ f_3 = x_2 + x_3 + x_4 \geq 1 \\ f_{4\_new} = x_2 + x_3 + x_4 + x_5 + x_7 + x_8 + x_9 \geq 1 \\ f_5 = x_1 + x_2 + x_4 + x_5 + x_6 \geq 1 \\ f_6 = x_5 + x_6 + x_{11} + x_{12} + x_{13} \geq 1 \\ f_7 = x_4 + x_7 + x_8 + x_9 \geq 1 \\ f_{8\_new} = x_4 + x_7 + x_8 + x_9 \geq 1 \\ f_{9\_new} = x_4 + x_7 + x_8 + x_9 + x_{10} + x_{14} \geq 1 \\ f_{10} = x_9 + x_{10} + x_{11} \geq 1 \\ f_{11} = x_6 + x_{10} + x_{11} \geq 1 \\ f_{12} = x_6 + x_{12} + x_{13} \geq 1 \\ f_{13} = x_6 + x_{12} + x_{13} + x_{14} \geq 1 \\ f_{14} = x_9 + x_{13} + x_{14} \geq 1 \end{cases}$$

The fourth step is to check whether the whole system is covered by PMU or not. In fifth step the pseudo code (which will be mentioned in this paper after the flow chart) will is mentioned. Now check again the observability of the system, is further any redundancy is possible or not if no stop if yes go again for the first step. In this paper for IEEE-14 bus system a zero is injected at bus number 7 because of this all the bus which are adjacent to this bus are modified in the following manner shown above. Here we have consider if a bus is directly connected to zero injection bus it will be modified in the following manner as shown is observability equation. The flow chart is shown below



PSEUDO CODE

Pseudo-code

Input: A an MxN square matrix;

Output : disp('The optimum number of PMUs is') fprintf('%d\n',sum(x))

Initialize P=[] for j = 1: n for i = 1: j

Check condition A(i,j)=1; If j~=1

P(i,j) = 1;

P(j,i) = 1;

End first for loop; End second for loop;

After execution of above code all the diagonal element of P

set to zero.

Channel Limit = input('Choose a channel limit for the PMUs: ');

Qi = Qout;

Again Initialize Q=[] for k = 1 : n

Check if sum(P(:,k)) < Channel Limit

V = find(P(:,k)); T = zeros(1,n); T(1,k) = 1; T(1,V) = 1;

Q = [Q;T];

If not then execute

V = nchoosek(find(P(:,k)),Channel Limit);

[a,b] = size(V);

T = zeros(a,n); for i = 1 : a for j = 1 : b

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T(:,k) = 1; T(i,V(i,j)) = 1; end
end
Q = [Q; T]; end
fprintf('%d\n',k) end
Q;
Start Timer
For different bus system like IEEE-14 and IEEE-57 Use injection method as mentioned.
Stop timer.

RESULT

The results are coming through MATLAB program is shown in form of table. In first column the channel limit required for PMU is shown. Second and third column shows the number of PMU required and time elapsed in second, respectively.

Channel limit for PMU	IEEE-14 bus system (number of PMU)	Time elapsed in second
1	7	3.286
2	5	3.014
3	4	0.492
4	3	0.059
5	3	0.044

CONCLUSION

PMUs and their application have brought revolution in wide area monitoring. Optimal placement of PMU is one step towards the concept of smart grid. It can be concluded from the above paper that channel limit for PMU is a very important concept because it affects both the total number of PMU used for complete observability as well as time elapsed for its calculation. By optimal placement of PMU we can reduce the overall installation cost as well as make our grid more reliable and smarter.

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