

Optimal Placement of Phasor Measurement Units for State Estimation (Project S-23G)

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Outline

- Introduction
- Motivation and Objectives
- Problem Statement and Formulation
- Proposed Solution
- Case Studies
- Impact on Bad Data Processing
- Impact on SE Accuracy
- Conclusions

Introduction

- State estimators facilitate on-line monitoring of power systems.
- Available measurements have traditionally excluded phase angle (phasor) measurements.
- Phasor measurement units (PMU) are devices, which use synchronization signals from the global positioning system (GPS) satellites and provide the phasors of voltage and currents measured at a given substation.

Motivation

TVA is in the process of installing PMUs for enhanced monitoring of the TVA system and wishes to determine the optimal locations for them.

Project Objectives

- Make use of a minimum number of PMUs in order to make the system fully observable.
- Since installation of PMUs will be a gradual process, determine the best possible locations for a limited number of PMUs at the beginning.
- Develop a systematic method for finding the best locations for new PMUs in the presence of other already placed PMUs and/or conventional measurements.

Preliminary Observations

- PMUs typically have higher accuracy than conventional measurements, however their accuracy will be reduced due to the instrument transformers used at their inputs.
- They are useful for other applications such as system protection, control and stability assessment.
- May aid topology error identification, parameter error detection and correction.
- May improve state estimation, subsequently improving market functions (e.g. LMP).

Secondary Objectives

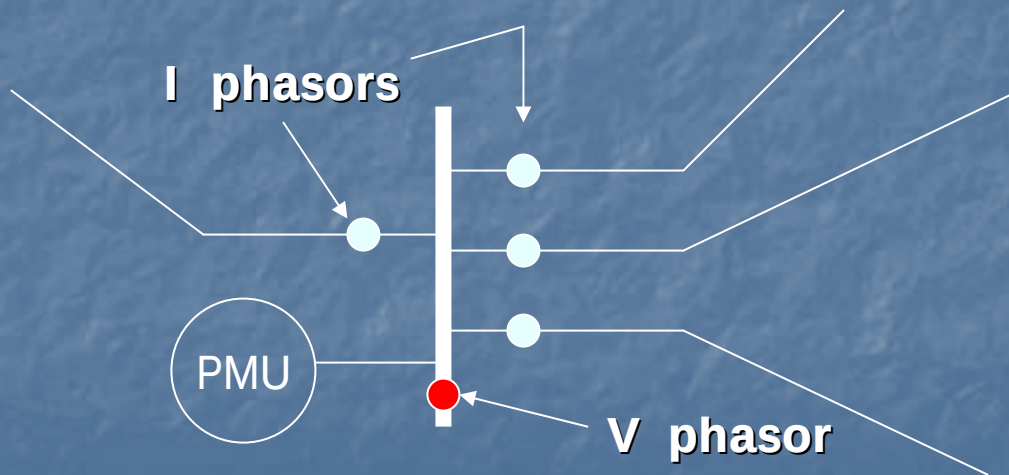
- Determine strategies of placing PMUs in order to also improve bad data processing.
- Study the impact of PMUs on the accuracy of state estimation. Specifically, address the questions:
 - Do more PMUs translate into more accuracy?
 - Is there a trade off between incremental increase in accuracy and investments in PMUs?
 - How do we quantify and value SE accuracy?

PMU Placement Problem

Assumption:

A PMU placed at a bus makes that bus and all its neighbors observable.

If the number of PMU channels is not sufficient, then this assumption will be relaxed.



PMU Placement Problem

Approach:

Set up an integer programming problem where all the system buses are made observable by placing PMUs at a minimum number of buses throughout the system.

If there are PMUs already installed or planned to be installed at specific buses, start with these already pre-assigned to their respective buses.

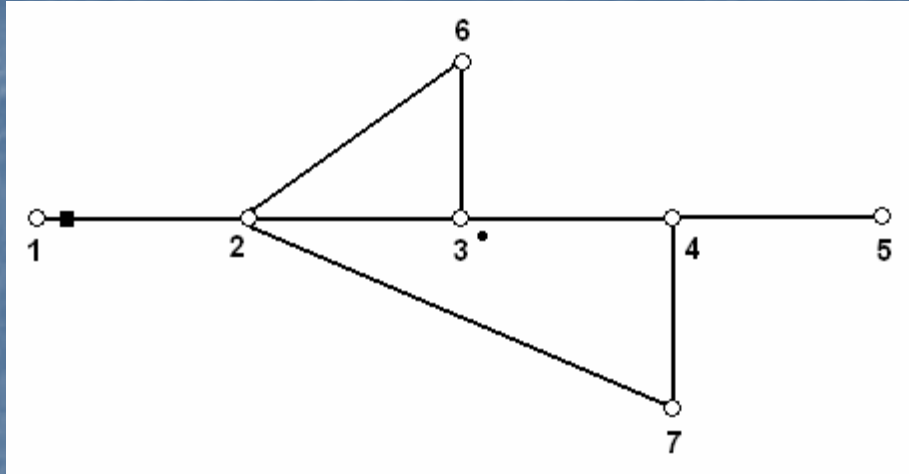
If there are zero injection buses, incorporate this information into the placement logic and save as many PMUs as possible.

PMU Placement Problem

$$\begin{array}{ll}\text{minimize} & \sum_i^n w_i \cdot x_i \\ \text{subject to} & f(X) \geq \hat{1}\end{array}$$

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

Illustrative Example

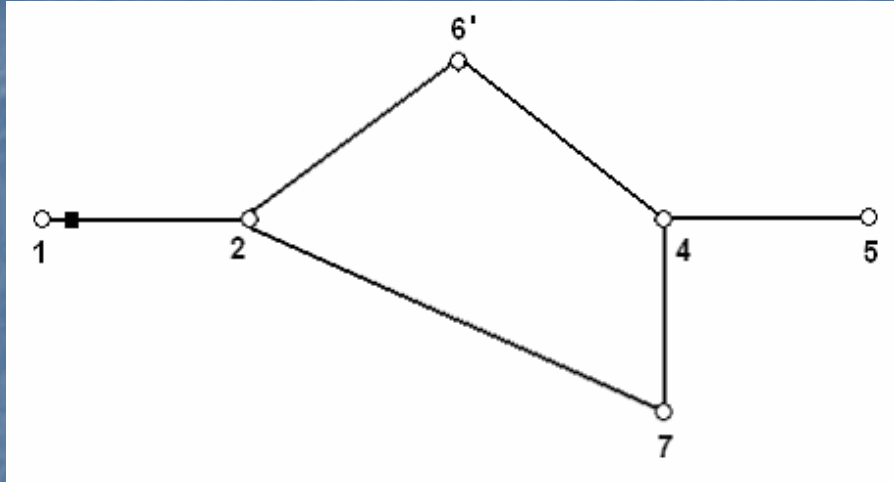


$$A_{k,m} = \begin{cases} 1 & \text{if } k = m \\ 1 & \text{if } k \text{ and } m \text{ are connected} \\ 0 & \text{if otherwise} \end{cases}$$

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

$$f(X) = A \cdot X = \begin{cases} f_1 = x_1 + x_2 & \geq 1 \\ f_2 = x_1 + x_2 + x_3 + x_6 + x_7 & \geq 1 \\ f_3 = x_2 + x_3 + x_4 + x_6 & \geq 1 \\ f_4 = x_3 + x_4 + x_5 + x_7 & \geq 1 \\ f_5 = x_4 + x_5 & \geq 1 \\ f_6 = x_2 + x_3 + x_6 & \geq 1 \\ f_7 = x_2 + x_4 + x_7 & \geq 1 \end{cases}$$

Handling Injections



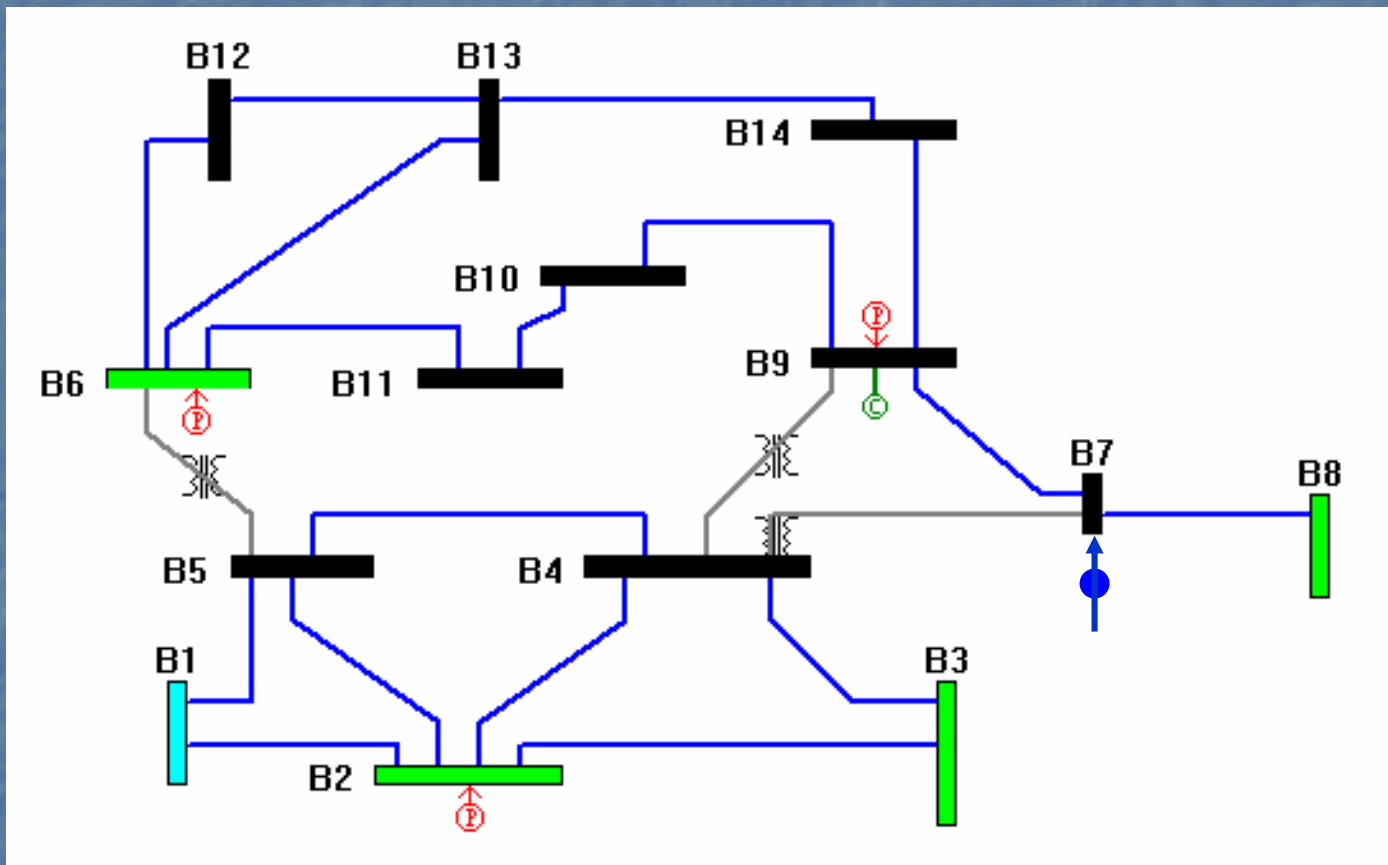
$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

$$f(X) = \begin{cases} f_1 = x_1 + x_2 & \geq 1 \\ f_2 = x_1 + x_2 + x_{6'} + x_7 & \geq 1 \\ f_4 = x_4 + x_5 + x_{6'} + x_7 & \geq 1 \\ f_5 = x_4 + x_5 & \geq 1 \\ f_{6'} = x_2 + x_4 + x_{6'} & \geq 1 \\ f_7 = x_2 + x_4 + x_7 & \geq 1 \end{cases}$$

Effects of considering zero injections

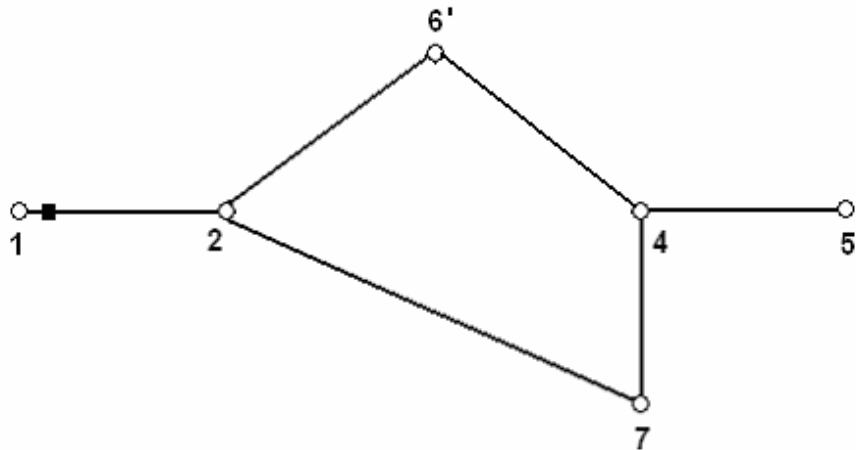
Systems	No. of zero injections	Number of PMUs	
		Ignoring zero Injections	Using zero injections
14-bus	1	4	3
57-bus	15	17	12
118-bus	10	32	29

Illustrative Example



Only **3 PMUs** make the entire system observable.
Note that **bus 7** is a **zero injection** bus.

Handling Flows



$$\begin{cases} f_1 = x_1 + x_2 & \geq 1 \\ f_2 = x_1 + x_2 + x_{6'} + x_7 & \geq 1 \end{cases} \Rightarrow$$

$$f_{1_new} = f_1 + f_2 = x_1 + x_2 + x_{6'} + x_7 \geq 1$$

$$f(X) = \begin{cases} f_{1_new} = x_1 + x_2 + x_{6'} + x_7 & \geq 1 \\ f_4 = x_4 + x_5 + x_{6'} + x_7 & \geq 1 \\ f_5 = x_4 + x_5 & \geq 1 \\ f_{6'} = x_2 + x_6 + x_{6'} & \geq 1 \\ f_7 = x_2 + x_4 + x_7 & \geq 1 \end{cases}$$

Use of existing flows

Meas. set no.	Flow measurements in the set				
1	1-2	21-20	21-22	17-113	86-87
2	41-42	43-44	46-48	53-52	53-54
3	90-89	90-91	91-92	101-100	101-102

System	Flow measurement set	Number of PMUs
118-bus	none	29
	1	26
	1 and 2	23
	1, 2 and 3	21

Placement against the loss of a single PMU

Choose two independent PMU sets, a primary set and a backup set, each of which can make the system observable on its own.

If any of the PMUs is lost, the alternative set of PMUs will guarantee network observability.

Choose the backup set by removing all the x_i terms in the constraint functions, where bus i is in the primary set.

Effects of considering loss of single PMUs

Systems	No. of zero injections	Number of PMUs	
		Ignoring zero injections	Using zero injections
14-bus	1	9	7
57-bus	15	35	26
118-bus	10	72	66

TVA's Network

- A prototype PMU placement program is developed.
- Four cases are studied:
 - No installed PMUs
 - 11 existing PMUs
 - 43 existing and planned PMUs
 - No installed PMUs but considering 330 zero injection buses

Case Results

Total no. of buses = 1375

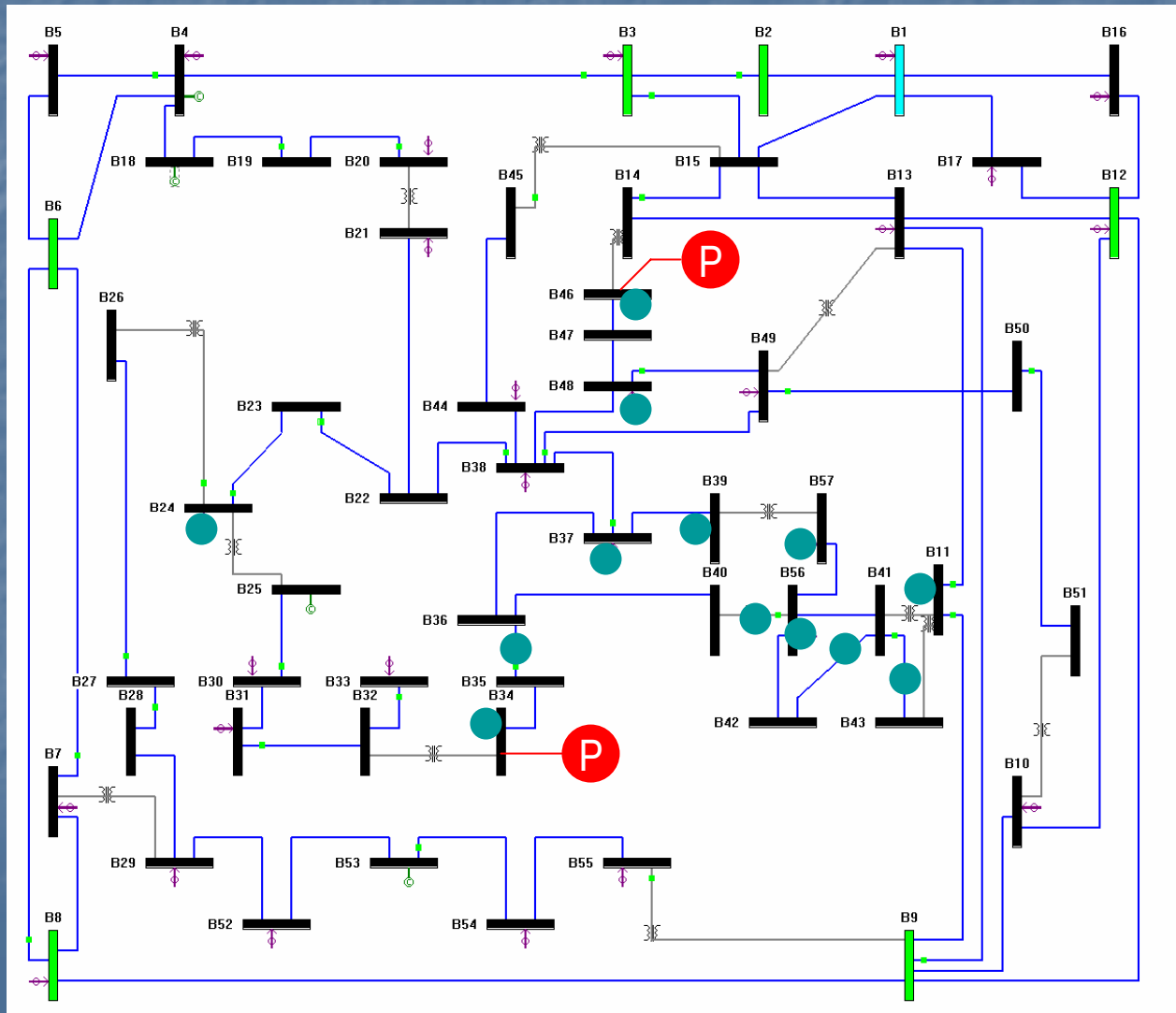
No. of zero injection buses = 330

	Required PMUs	New PMUs
Case 1: No installed PMUs	377	377
Case 2: Existing PMUs (11)	378	367
Case 3: Existing and planned PMUs (43)	390	347
Case 4: No installed PMUs but considering zero-injection buses	295	295

How can PMUs help to improve Bad Data Detection?

- A measurement is said to be “critical” if the system becomes unobservable upon its removal.
- Bad data appearing in critical measurements can NOT be detected.
- Adding new measurements at strategic locations will transform them, allowing detection of bad data which would otherwise have been missed.

Transforming Critical Measurements



Critical Meas.	Type
1	F41-43
2	F36-35
3	F42-41
4	F40-56
5	I-11
6	I-24
7	I-39
8	I-37
9	I-46
10	I-48
11	I-56
12	I-57
13	I-34

Effect of PMUs on SE Accuracy

- If PMUs are more accurate than all other conventional meters, then estimation error variances for system states are expected to be reduced.
- Other application functions, such as LMP calculations will be carried out with higher accuracy when the state estimates are more accurately obtained.

Quantifying Accuracy

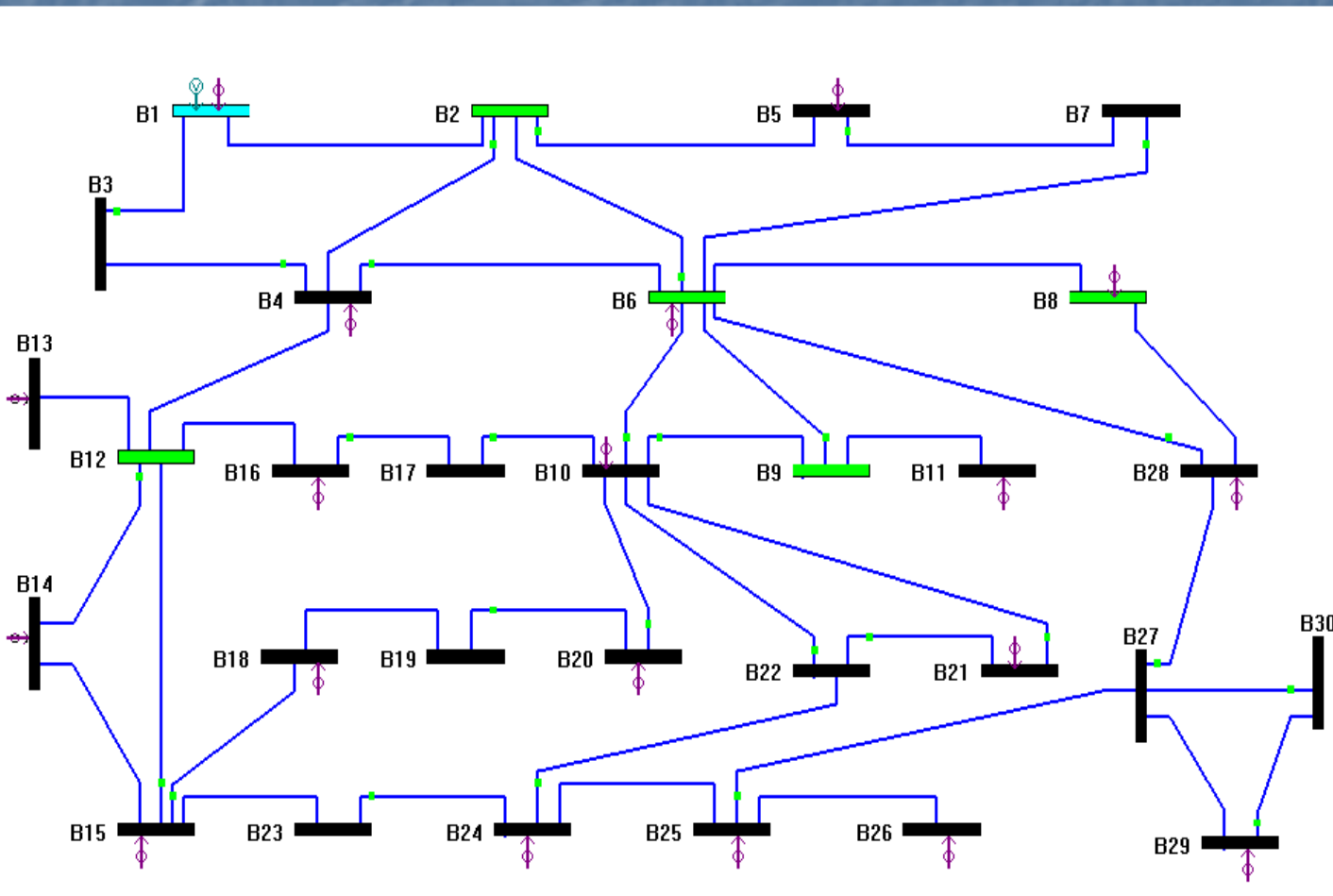
$$G^{-1} = \text{cov}(\hat{x})$$

$$D = G^{-1} \quad \sqrt{D_{ii}} = \sigma_{e\hat{x}}$$

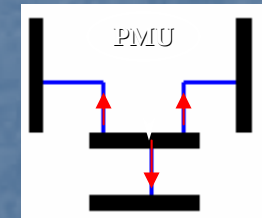
$$D = G^{-1} = \begin{bmatrix} d_{11} & & & \\ & d_{22} & & \\ & & 0 & \\ & & & d_{88} \\ & & & & d_{99} \end{bmatrix}$$

Effect of PMU on Accuracy of State Estimation

	No PMU	10% PMU	20%PMU	30%PMU	40%PMU	Only PMUs
Power Injections	38	38	38	38	38	0
Power Flows	56	56	56	56	56	0
Voltage magnitude	1	1	1	1	1	0
PMU (1 v, 3 currents)	0	3	6	9	12	10



-PMU Example-

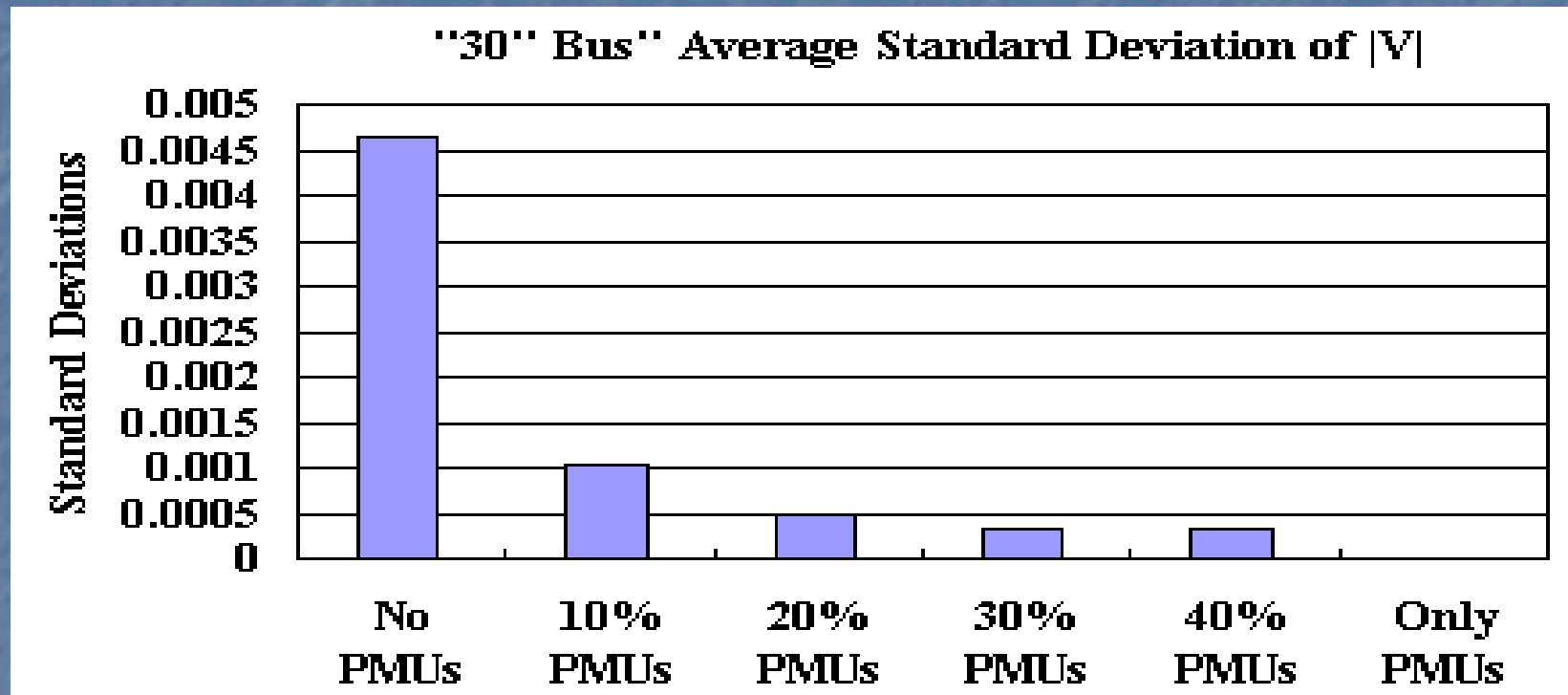


1PMU Measurement
= 1 Voltage + 3 Currents

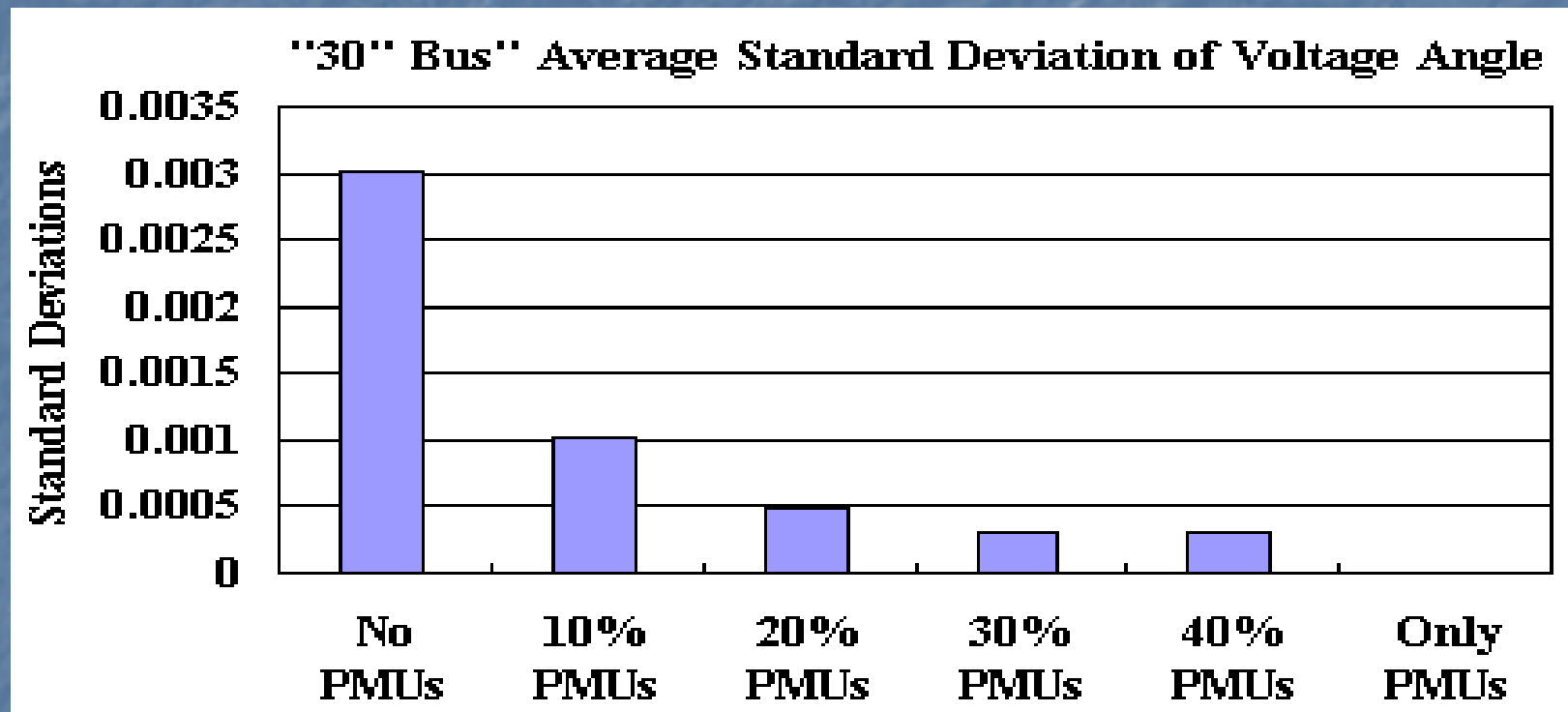
--Measurement--

- Power Injection
- Power Flow

Simulation Results for IEEE 30Bus-System:



Simulation Results for IEEE 30Bus-System:



Conclusions

- In the absence of any other measurements, power systems can be made observable by placing PMUs at roughly 30% of the buses in the system.
- This number may significantly decrease if there are zero injection buses.
- This number will increase if loss of PMUs is taken into account for reliability.

Conclusions ...

- Accuracy of state estimation can be improved by strategically placing PMUs at 10% of the network buses. Increasing the number of PMUs further will not be as effective.
- Placing few PMUs can transform several critical measurements, allowing their gross errors to be detectable.