Strategic PMU Placement for Secure and Resilient Power Grids

Elda Ramirez
Advisor: Dr. Ioannis Zografopoulos

Introduction

- **Power Grid:** electrical network that delivers power from generators to loads

- **Network**: a bus topology where every element is connected through a line (bus)

- **Phasor Measurement Unit (PMU):** a device used to measure voltage and current in phase and amplitude

It is capable to deliver measurement by using Global Positioning System GPS, taking up to 60 measurements per second.

Cost per PMU: roughly **$40,000**

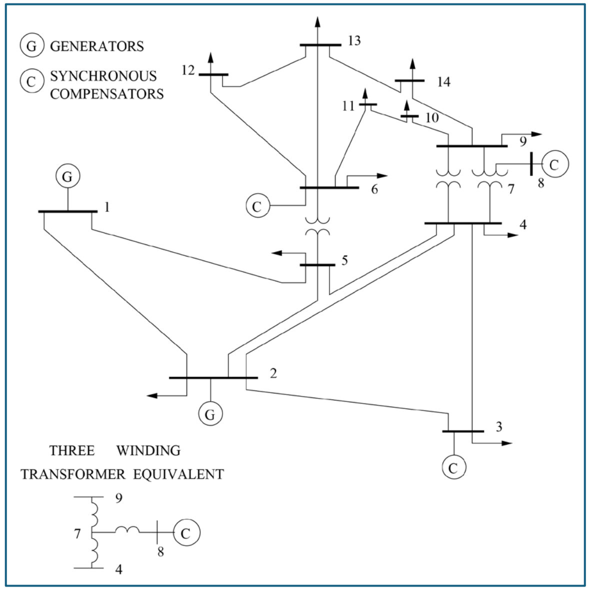
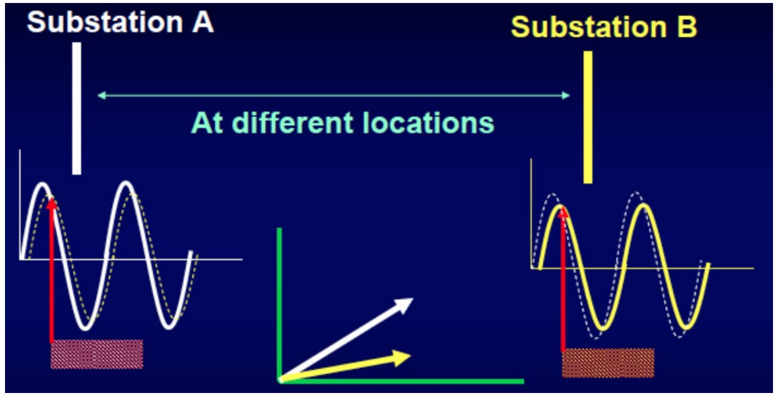


Figure 1: Ali R. Al-Roomi (2015). Power Flow Test Systems Repository [https://al-roomi.org/power-flow]. Halifax, Nova Scotia, Canada: Dalhousie University, Electrical and Computer Engineering



Motivation

- Power Grids are crucial in current society, lot of power is demanded, and generators can only produce a limited level of power.

- Bus network systems are designed to produce and provide the power to the needed areas

These networks to work efficiently, they need to be monitored and accurately acquire them power data.

- PMUs with their synchronized phasor measurements can monitor and facilitate maintenance of the power network

- But, due to the high cost per PMU device, there cannot be a PMU per node.

✓ Designing a strategy to optimize the allocation of PMUs to ensure observability while considering:
  - Cost per PMU
  - Network topology
  - Types of nodes/buses

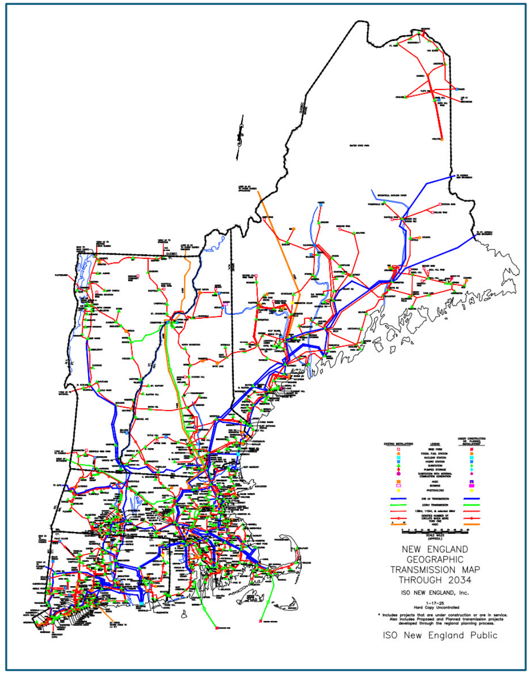
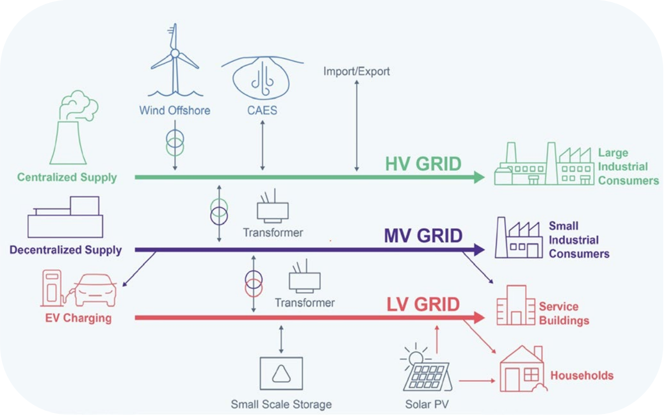
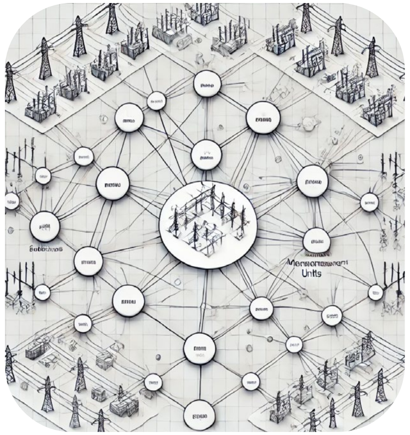


Figure 3: New England Geographic Transmission Line, ISO New England Inc,

Research Overview





GAMS + MATLAB

Modern Power Grid Observability Issues due to insufficient Monitoring Devices

Phasor Measurement Units (PMUs) Collecting Data

Optimal Placement of PMUs for Grid Control

Preliminary Definitions

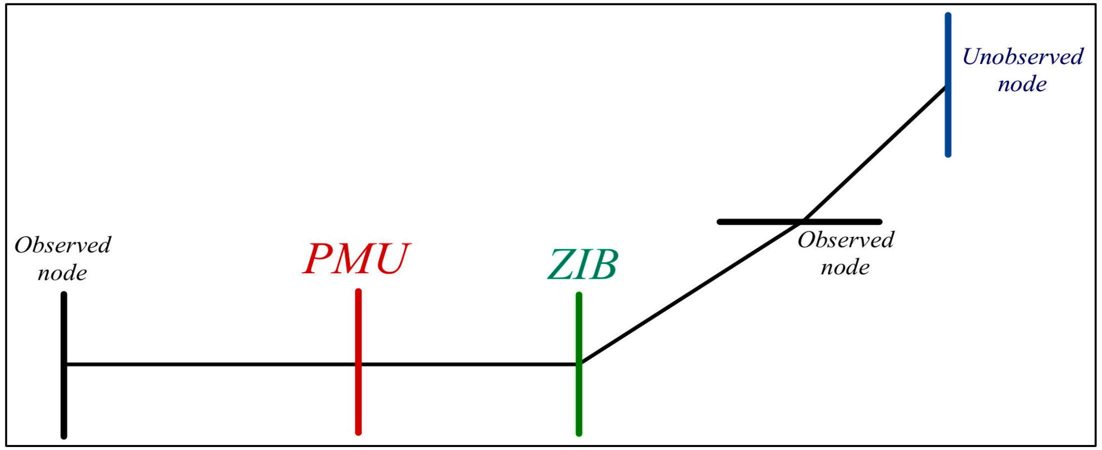
- Observability: the ability to measure a system's inputs and output data:

- PMU facilitates observability for the node it resides and adjacent nodes

- Power grids will require at **least** 100% observability on any network.

- Incrementation of observability percentage will:
  - Increase the number of PMU needed
  - Increase monitoring around CN
  - Increase the total cost

Observability depth system:



- Zero injection Bus (ZIB): buses that don't consume nor produce power

- Critical Node (CN): node that is directly connected to a generator

Notation

- Bus-Node connection and constrains.

$$i, j \rightarrow bus\ index$$
$$\Omega_B \rightarrow Set\ of\ all\ busses$$
$$\Omega_{ij} \rightarrow Set\ of\ bus\ i\ connected\ to\ j$$
$$\gamma_i \rightarrow Observability, integer\ variable$$
$$a_i = \begin{cases} 1 & node\ contains\ a\ PMU \\ 0 & else \end{cases}$$
$$c \rightarrow cost\ per\ PMU$$
$$n \rightarrow number\ of\ PMU\ channels\ used$$
$$C_i \rightarrow total\ PMU\ cost\ based\ on\ n$$

- Consideration of ZIBs:

$$\Omega_Z \rightarrow Set\ of\ ZIBs$$
$$\Omega_{Za} \rightarrow Set\ of\ adjecent\ buses\ to\ ZIBs$$
$$\Omega_n \rightarrow Set\ of\ normal\ Buses\ (Not\ ZIBs\ or\ CN)$$

- Consideration of critical nodes:

$$\Omega_C \rightarrow Set\ of\ critical\ nodes$$

Critical nodes
$a_i + \sum_{j \in \Omega_{ij}^l} a_j \geq 1 + \gamma_i \quad \forall i \in \Omega_c$
Normal Buses
$a_i + \sum_{j \in \Omega_{ij}^l} a_j \geq 1 \quad \forall i \in \Omega_n$
Abnormal buses (not in normal set, not CN)
$\sum_{j \in \Omega_{ia}^l} \left\langle a_a + \sum_{j \in \Omega_{aj}^l} a_j \right\rangle \geq |\Omega_{za}| - 1 \quad \forall i \in \Omega_{za}$

Methodology

Objective Functions

Minimization of PMU's based on cost

$$C_i = (1 + 0.1 * n)c$$

$$min\ OF = \sum_{i \in \Omega_B} C_i * a_i$$

Maximizing Observability

$$\gamma_i \geq 1$$

$$max\ OBS = \sum_{i \in \Omega_B} \gamma_i$$

Critical nodes

$$a_i + \sum_{j \in \Omega_{ij}^l} a_j \geq 1 + \gamma_i \qquad \forall i \in \Omega_c$$

Normal Buses

$$a_i + \sum_{j \in \Omega_{ij}^l} a_j \geq 1 \qquad \forall i \in \Omega_n$$

Abnormal buses (not in normal set, not CN)

$$\sum_{j \in \Omega_{ia}^l} \left\langle a_a + \sum_{j \in \Omega_{aj}^l} a_j \right\rangle \geq |\Omega_{za}| - 1 \qquad \forall i \in \Omega_{za}$$

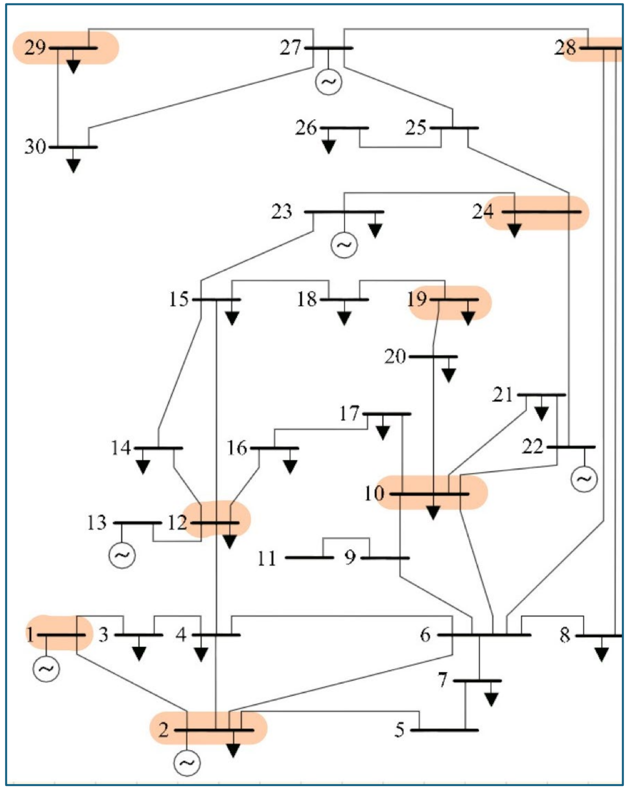
Optimal PMU placement in 30-IEEE

Observations:
Minimum number of PMUs needed to obtain 100% observability in the IEE-30 bus system

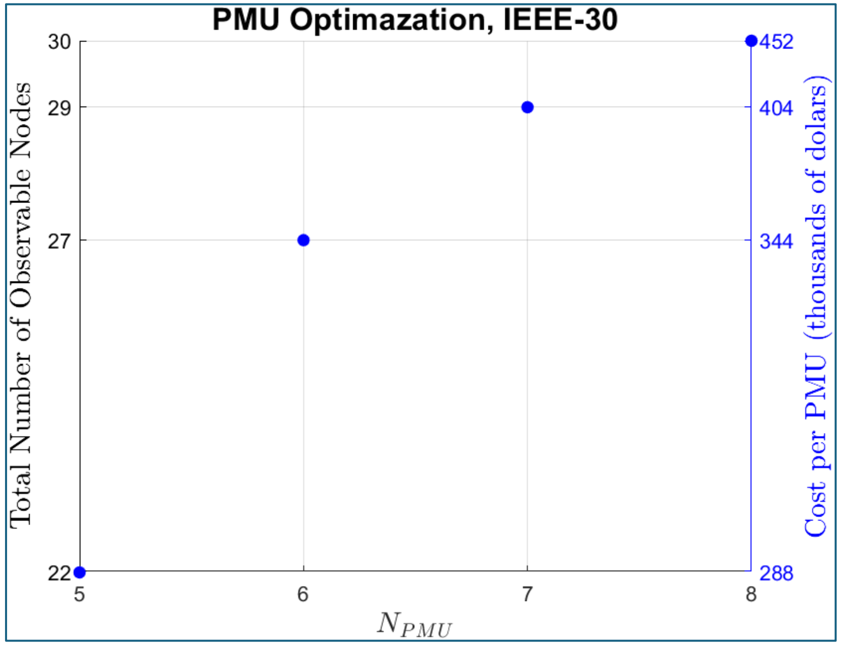
- $N_{PMU} = 8$

Cost per PMU varies based on the number of channels needed at the node it resides.

- Final cost based in N_{PMU}:
    - Total cost: C = Cost based on channel * c
    - c = is the cost per PMU (i.e. c = $43,400)



$N_{PMU} = 8$



Optimal PMU placement in 57-IEEE

Observations:
Minimum number of PMUs needed to obtain 100% observability in the IEE-30 bus system

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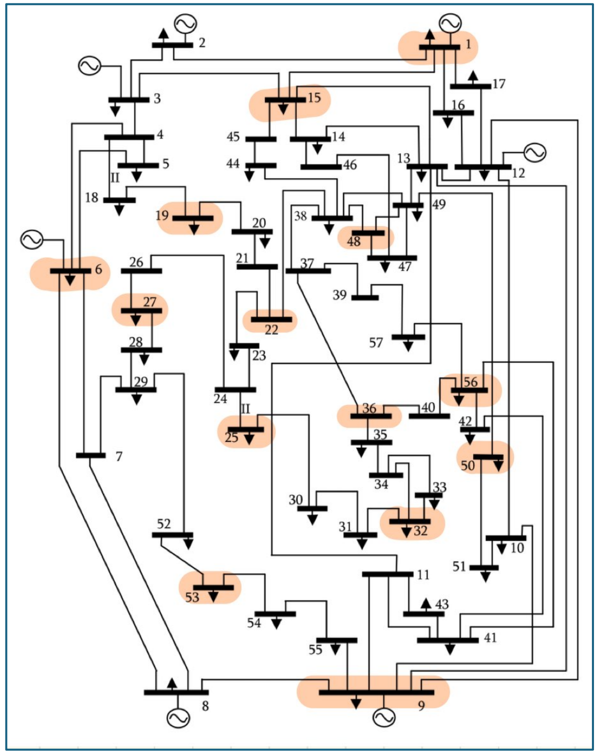
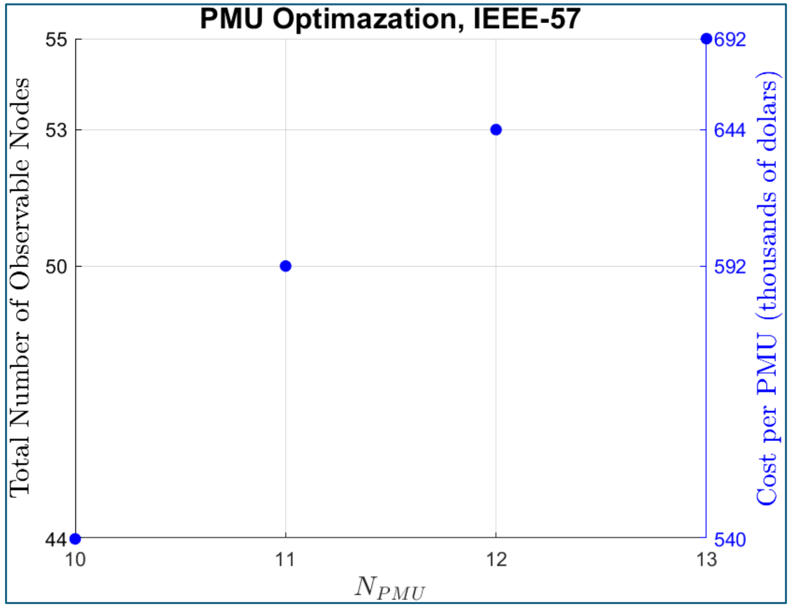


$\boldsymbol{N_{PMU} = 8}$



Optimal PMU placement in 118-IEEE

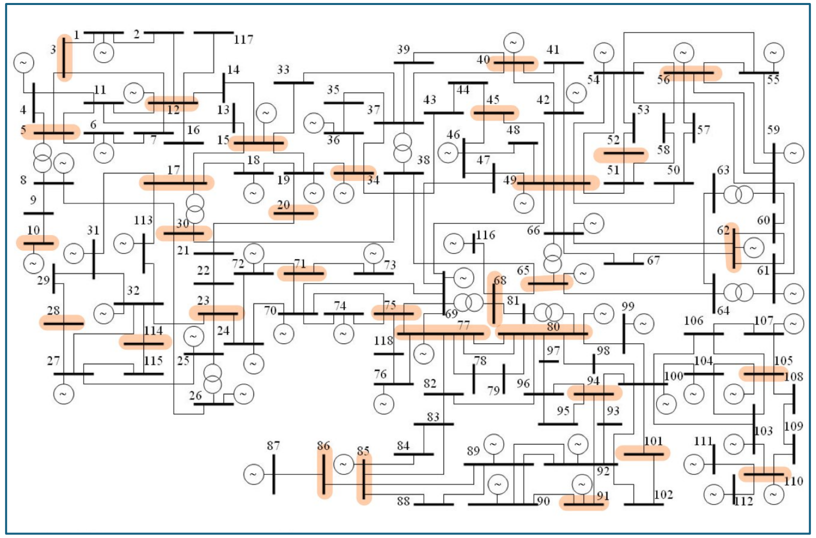
Observations:

Minimum number of PMUs needed to obtain 100% observability in the IEE-30 bus system

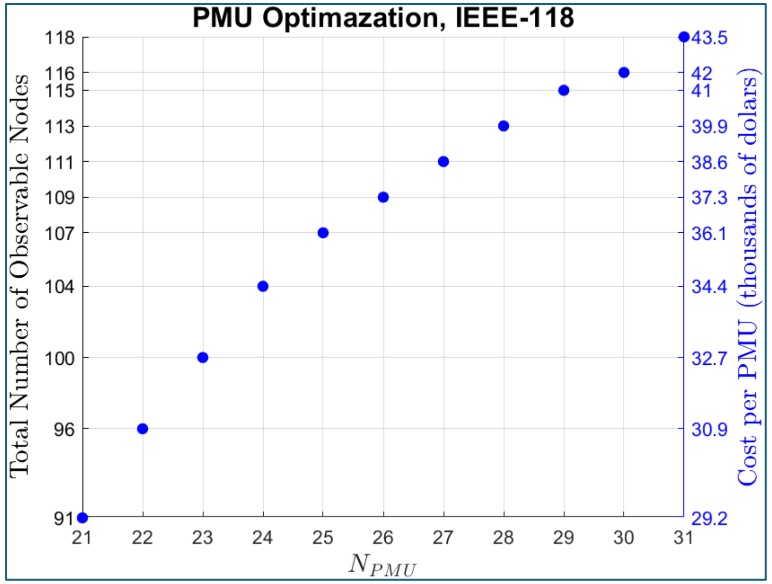
- $N_{PMU} = 31$

Cost per PMU varies based on the number of channels needed at the node it resides.

- Final cost based in N_{PMU}:
    - Total cost: C = Cost based on channel * c
    - c = is the cost per PMU (i.e. c = $43,400)



$N_{PMU} = 31$



Conclusion

- Reflection

ALFRED P. SLOAN
FOUNDATION

ICARUS
INFRASTRUCTURE CYBERSECURITY AND RESILIENCE LAB

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