Phasor-Only State Estimation

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PSERC
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Talk Outline

Background and terminology

State estimation

Phasor measurements

Phasor-only state estimation

- WLS: exact cancellations
- LAV: improved robustness
- Extension to 3-phase networks

Observability and error identification

Closing remarks

Background and terminology

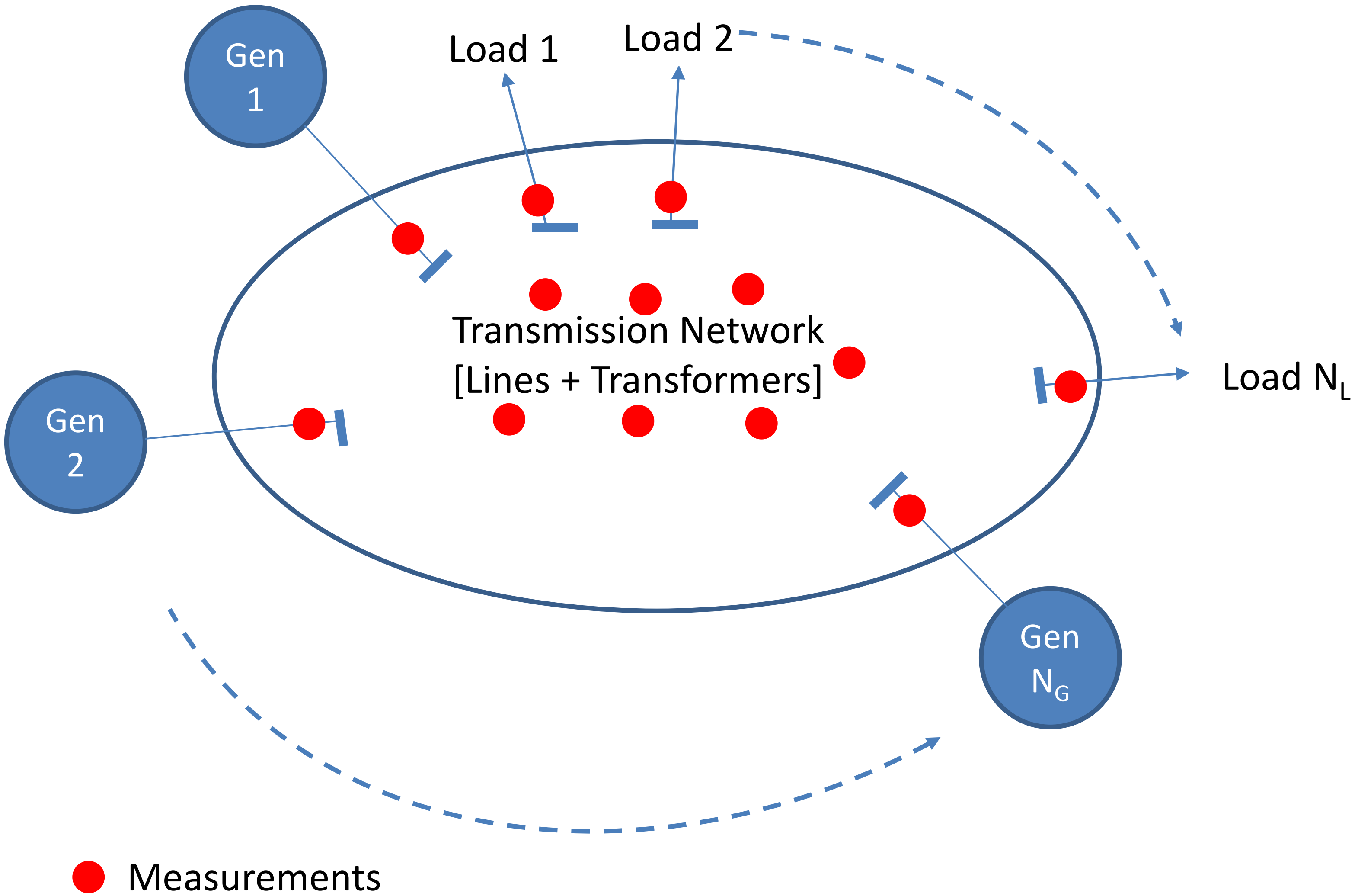
(Static) state estimation

- Measurement type: SCADA / Synchrophasor
- Formulation: Nonlinear / Linear
- Network model: + sequence / 3-phase

Dynamic state estimation

- Wide-area, using gen/load/network variables
- Local, using gen variables, boundary measurements or estimates

Modeling

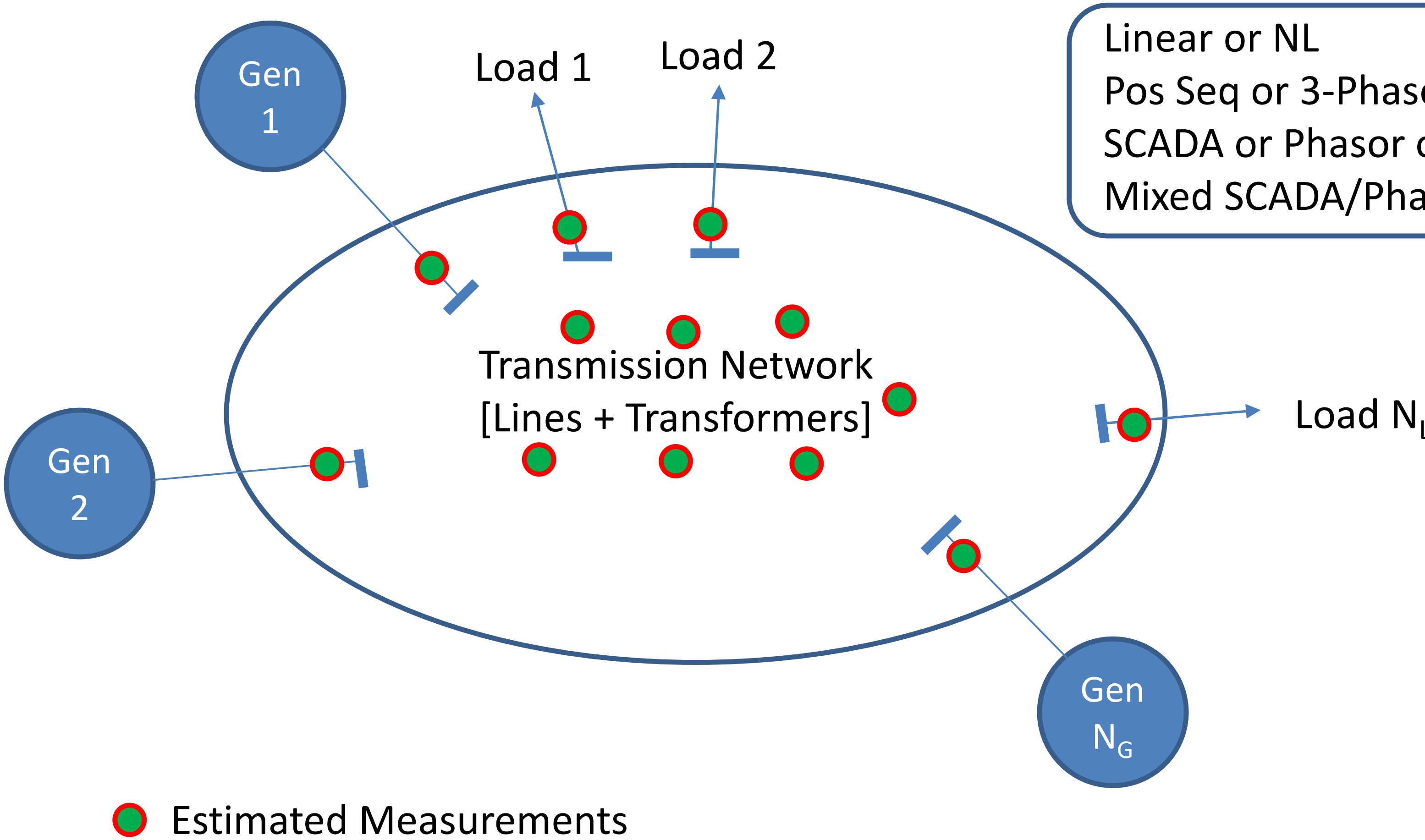


Gen 1
Load 1
Load 2
Transmission Network
[Lines + Transformers]
Gen 2
Load N_L
Gen N_G
Measurements

Modeling [SSE]

SSE: Estimation of the snap-shot at time "t"

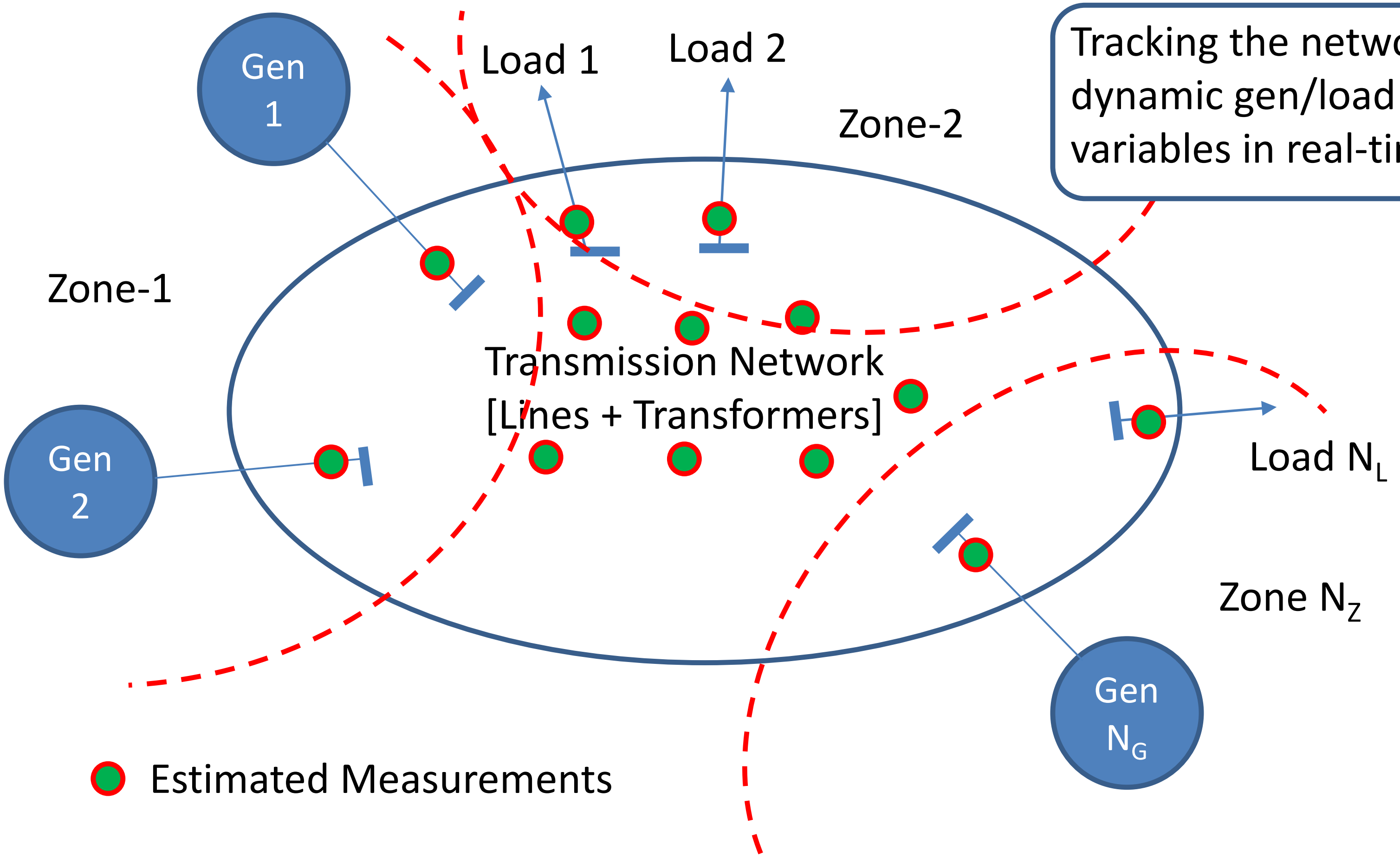
Linear or NL
Pos Seq or 3-Phase
SCADA or Phasor or
Mixed SCADA/Phasor



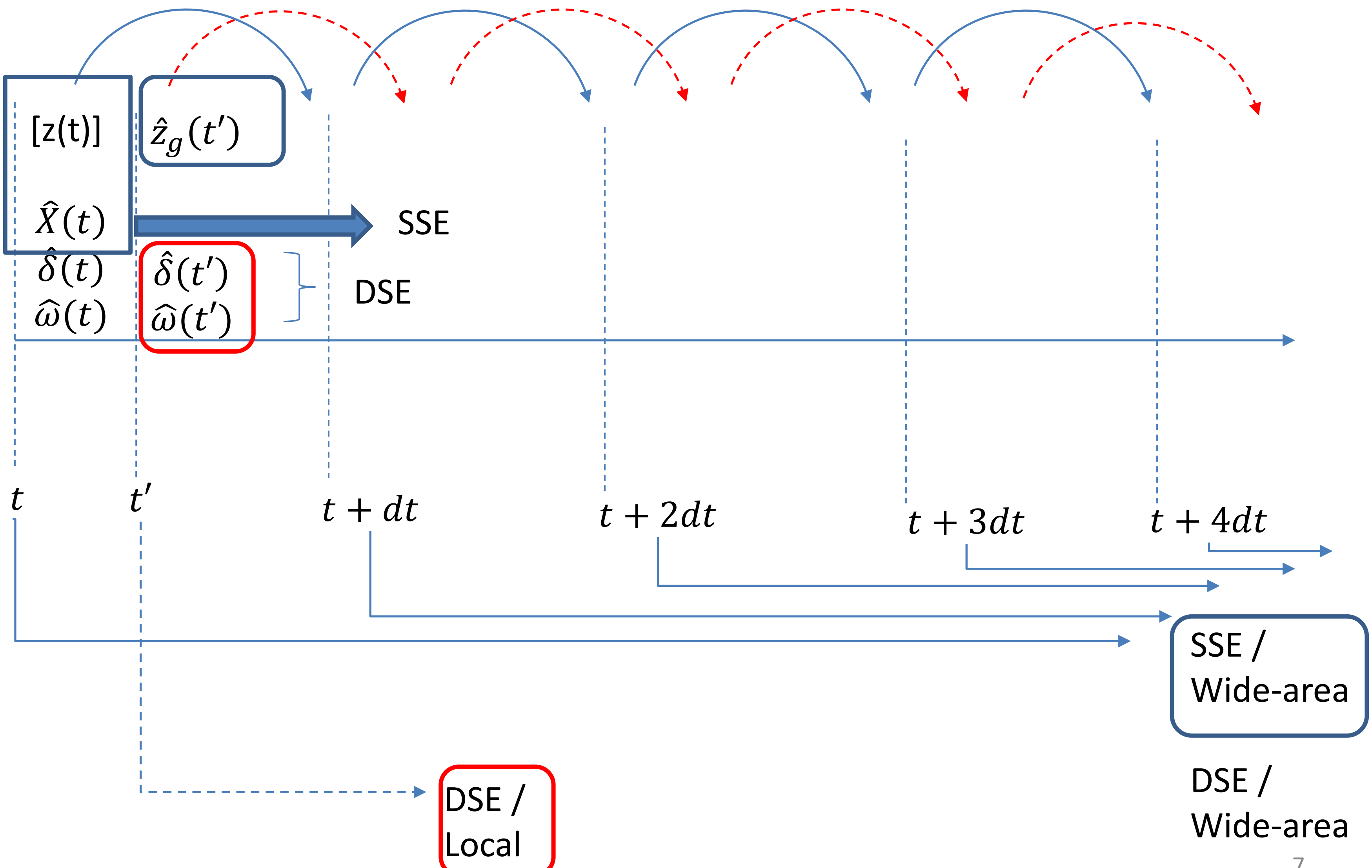
Modeling [DSE]

DSE: Single machine / zonal / wide-area
Detailed Gen and Load models
Frequency and power angle estimation

Tracking the network and dynamic gen/load state variables in real-time

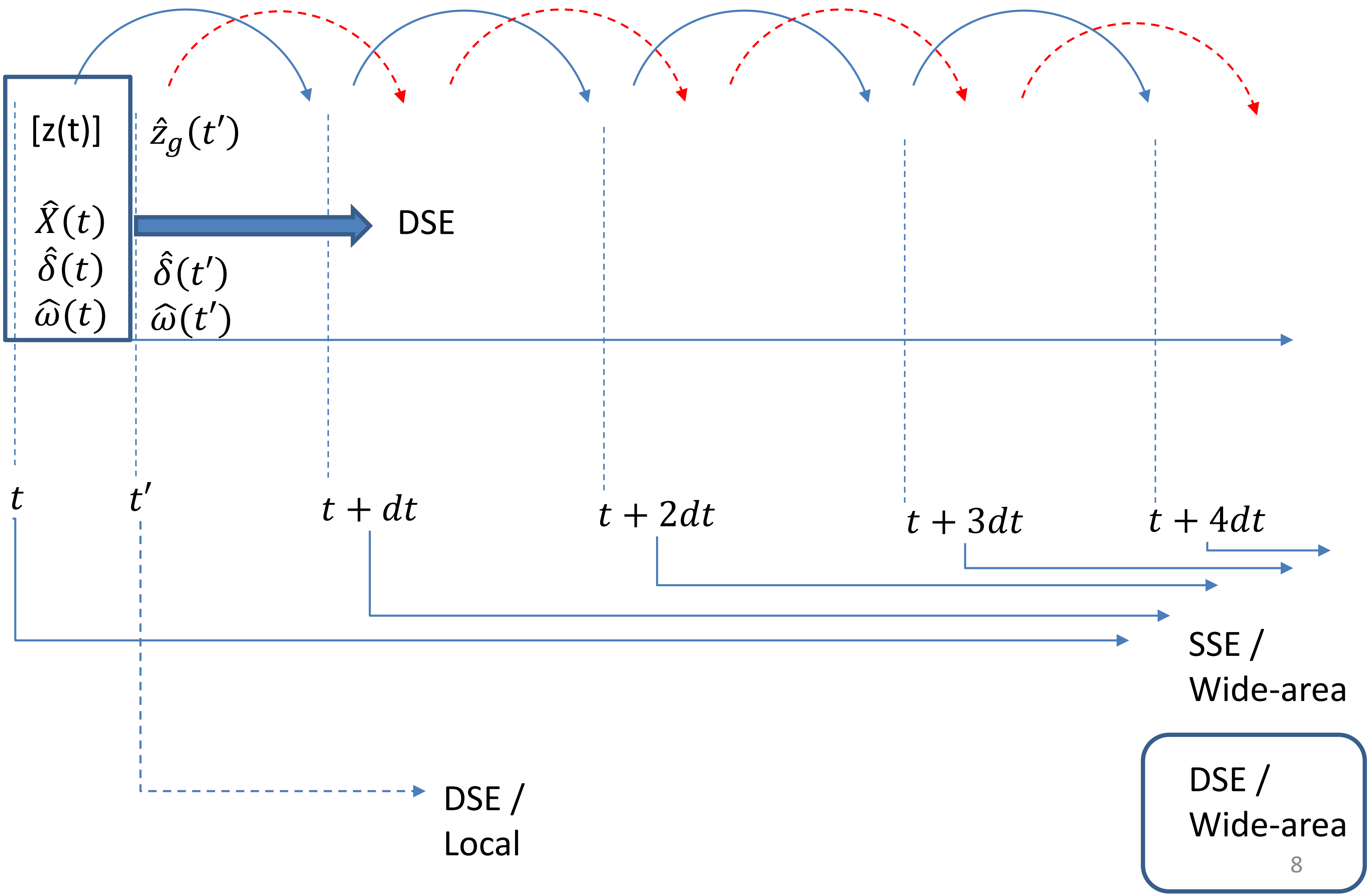


Timeline



[z(t)]
$\hat{z}_g(t')$
$\hat{X}(t)$
SSE
$\hat{\delta}(t)$
$\hat{\omega}(t)$
$\hat{\delta}(t')$
$\hat{\omega}(t')$
DSE
t
t'
$t + dt$
$t + 2dt$
$t + 3dt$
$t + 4dt$
SSE / Wide-area
DSE / Wide-area
DSE / Local

Timeline



[z(t)]
$\hat{z}_g(t')$
$\hat{X}(t)$
$\hat{\delta}(t)$
$\hat{\omega}(t)$
DSE
$\hat{\delta}(t')$
$\hat{\omega}(t')$
t
t'
$t + dt$
$t + 2dt$
$t + 3dt$
$t + 4dt$
SSE / Wide-area
DSE / Local
DSE / Wide-area

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Static state estimation: Objective and measurements

Introduced by Schweppe and his co-workers in 1969.

Schweppe, F.C., Wildes, J., and Rom, D., "Power system static state estimation: Parts I, II, III", *Power Industry Computer Applications (PICA)*, Denver, CO, June 1969.

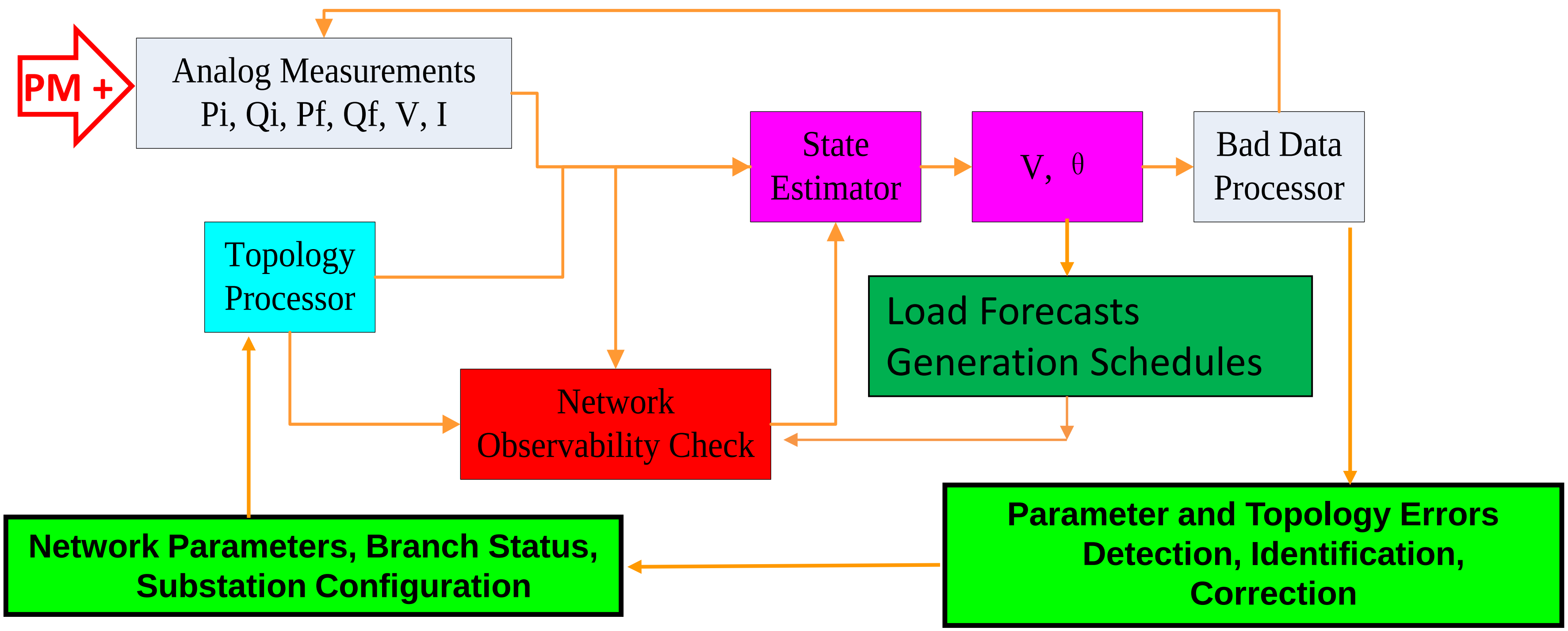
Objective: To obtain the best estimate of the state of the system based on a set of measurements.

- State variables: voltage phasors at all buses in the system
- Measurements:
  - Power injection measurements
  - Power flow measurements
  - Voltage/Current magnitude measurements
  - **Synchronized phasor measurements**

SCADA Measurements

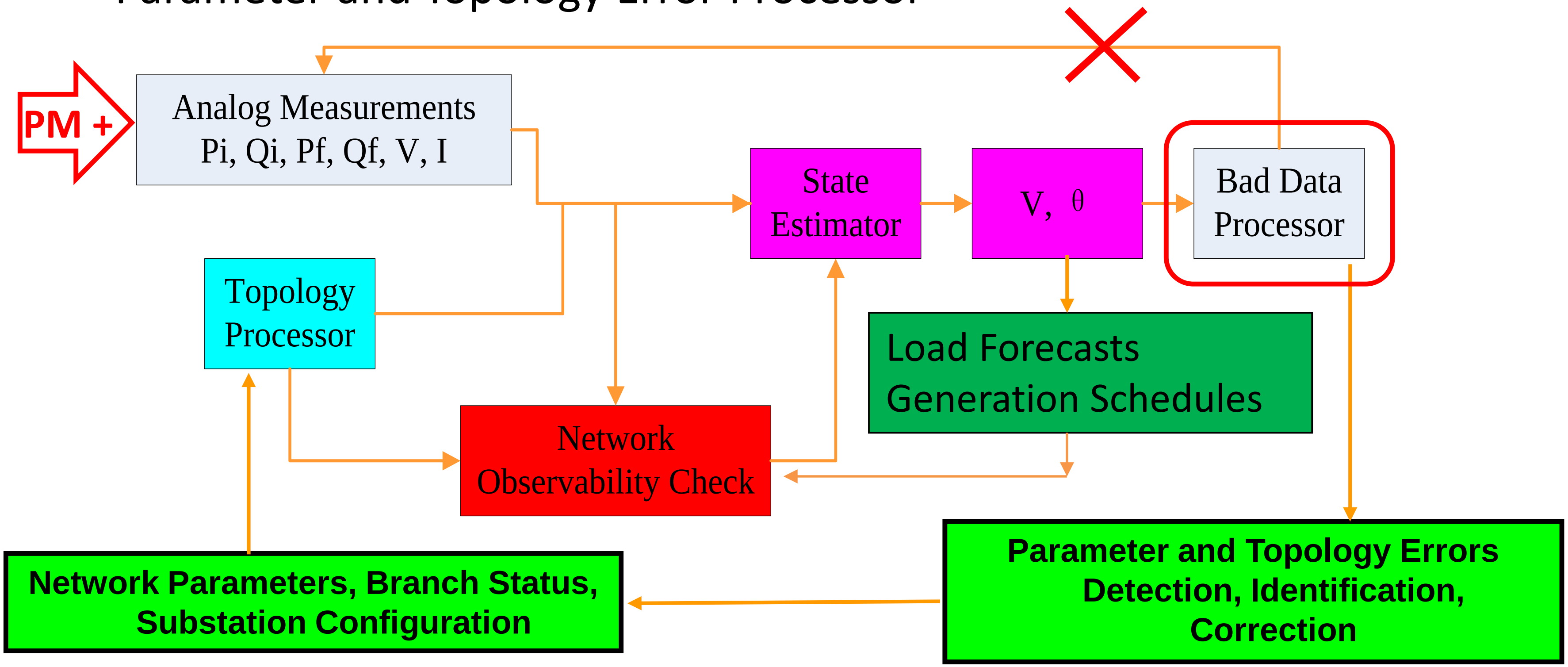
State estimation: data/info flow diagram

- Topology Processor
- Network Observability Analysis
- **WLS State Estimator**
- Bad Data Processor
- Parameter and Topology Error Processor



State estimation: data/info flow diagram

- Topology Processor
- Network Observability Analysis
- **Robust LAV State Estimator**
- Bad Data Processor
- Parameter and Topology Error Processor



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Phasor measurement units (PMU)

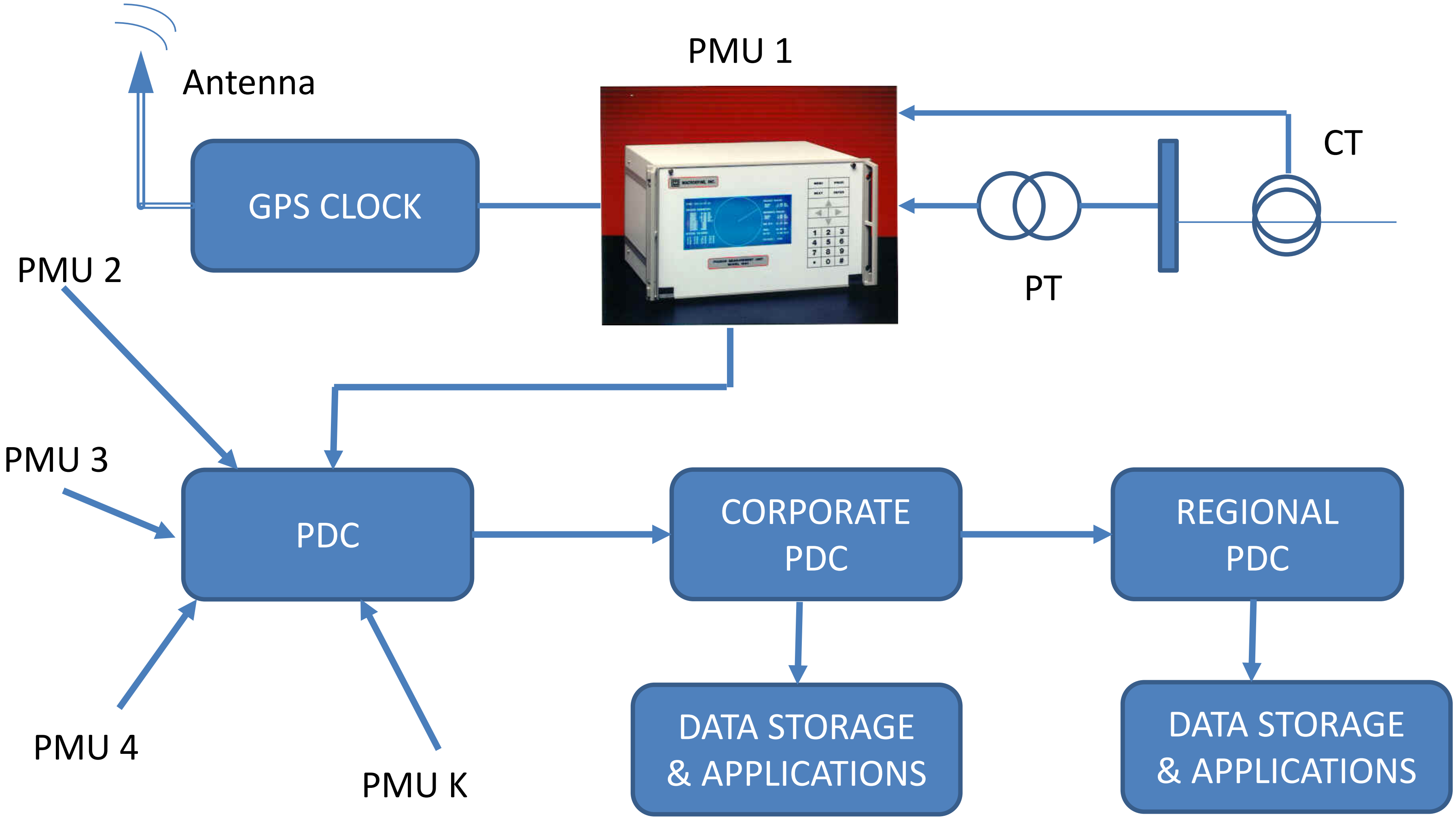
"Synchronized Phasor Measurements and Their Applications" by A.G. Phadke and J.S. Thorp

Invented by Professors Phadke and Thorp in 1988.

They calculate the real-time phasor measurements synchronized to an absolute time reference provided by the Global Positioning System.

PMUs facilitate direct measurement of phase angle differences between remote bus voltages in a power grid.

Phasor Measurement Units (PMU) Phasor Data Concentrators (PDC)[*]



[*] IEEE PSRC Working Group C37 Report

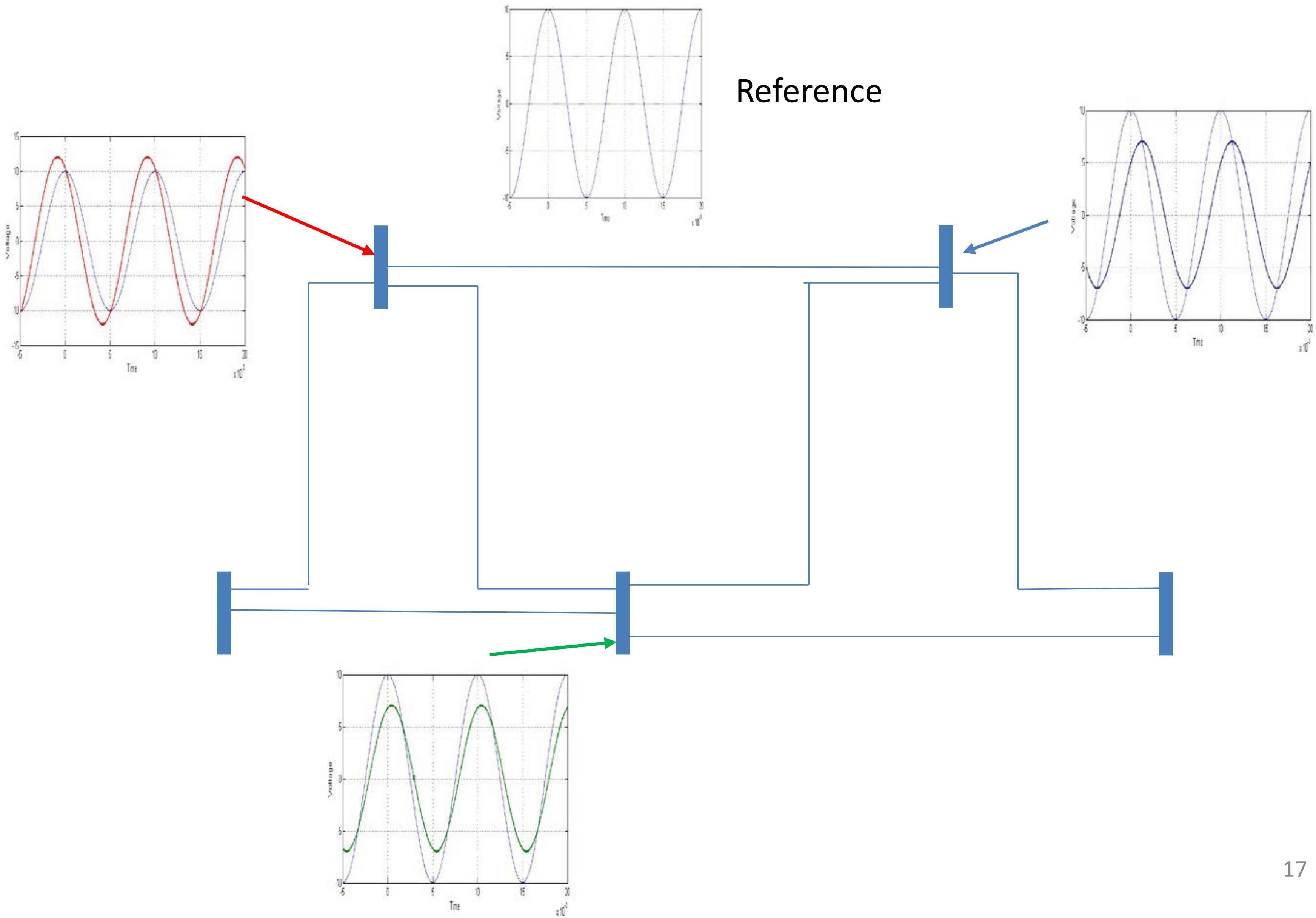
Phasor Data Concentrator (PDC)

Taken verbatim from: IEEE C37.244-2013 PDC Guide

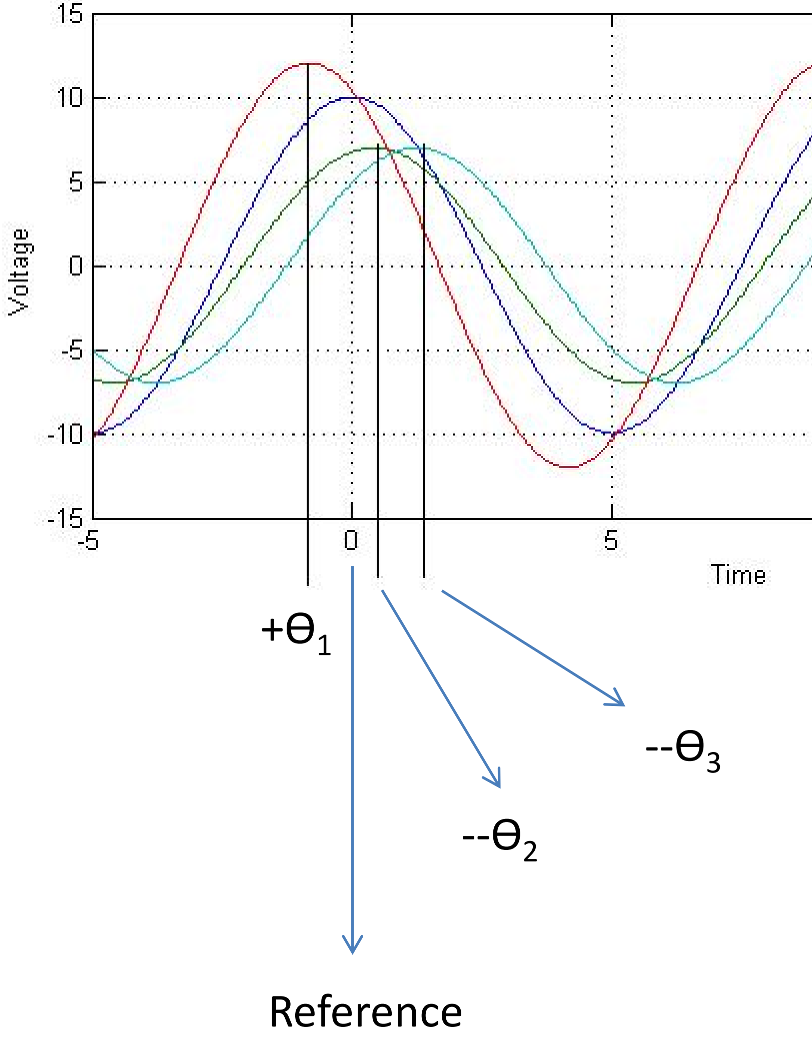
PDC Definition:
A function that collects phasor data, and discrete event data from PMUs and possibly from other PDCs, and transmits data to other applications.

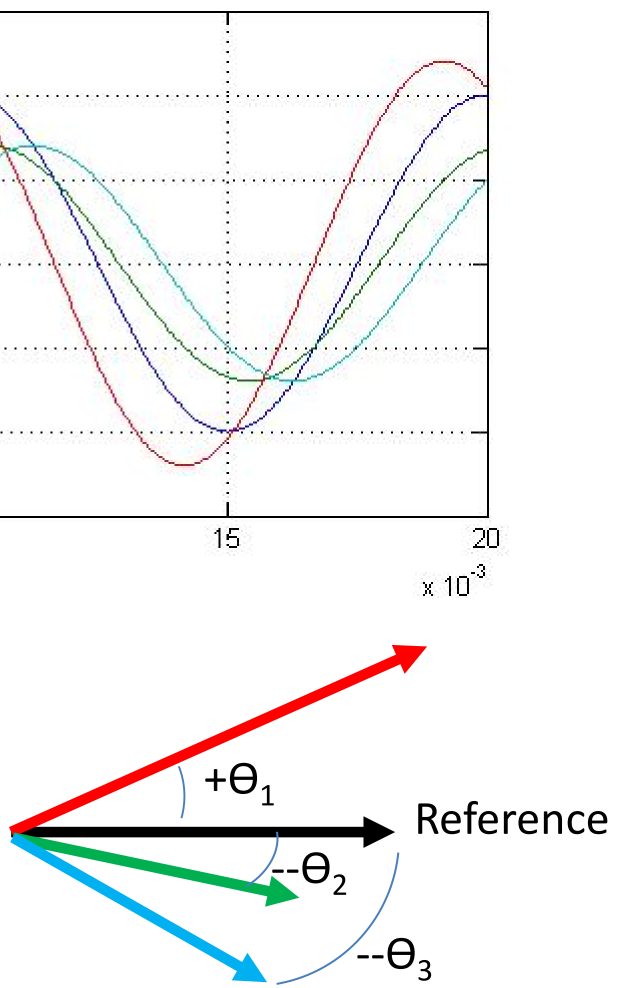
PDCs may buffer data for a short time period, but do not store the data. This guide defines a PDC as a function that may exist within any given device.

Phasor voltage measurements

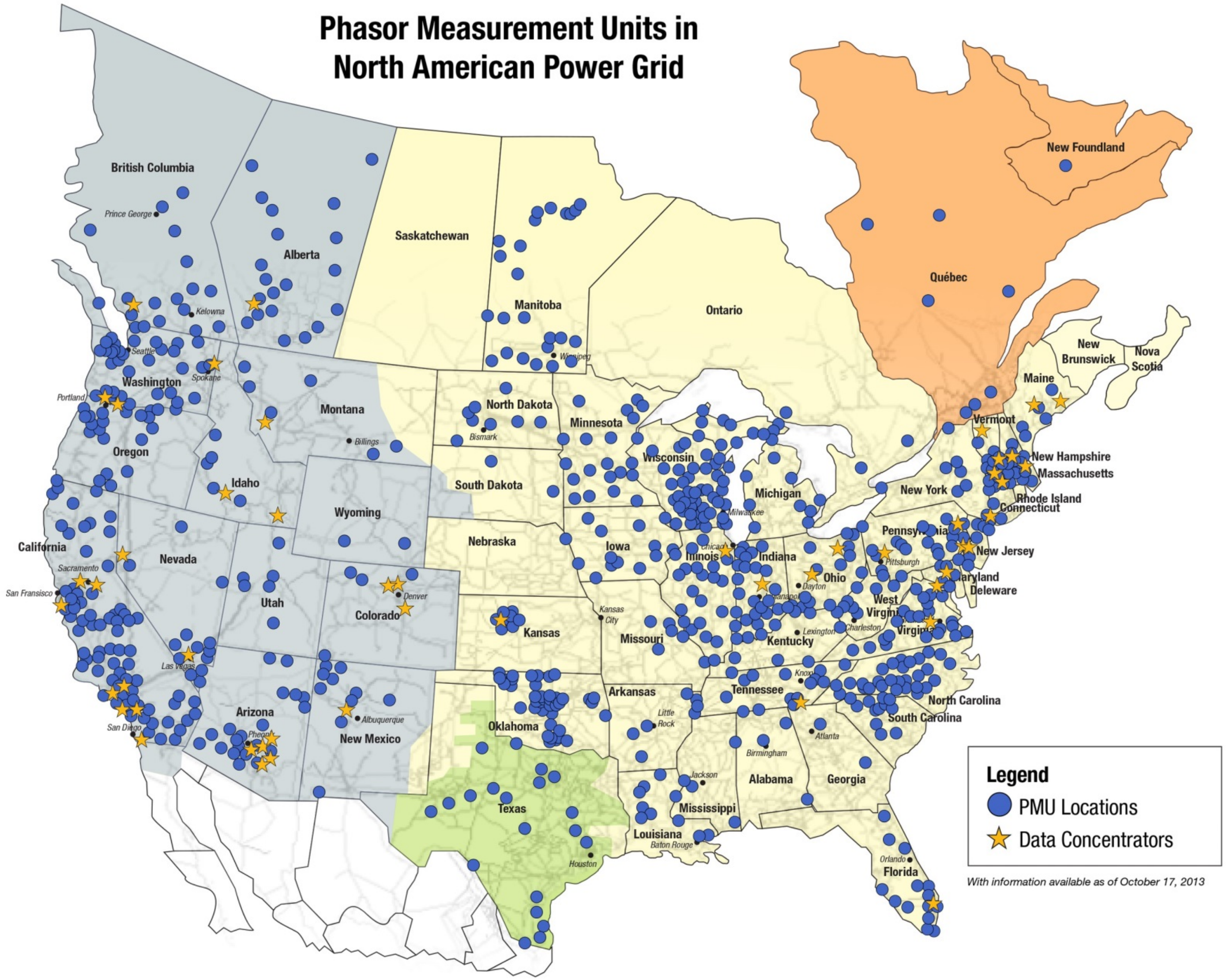


Reference phasor



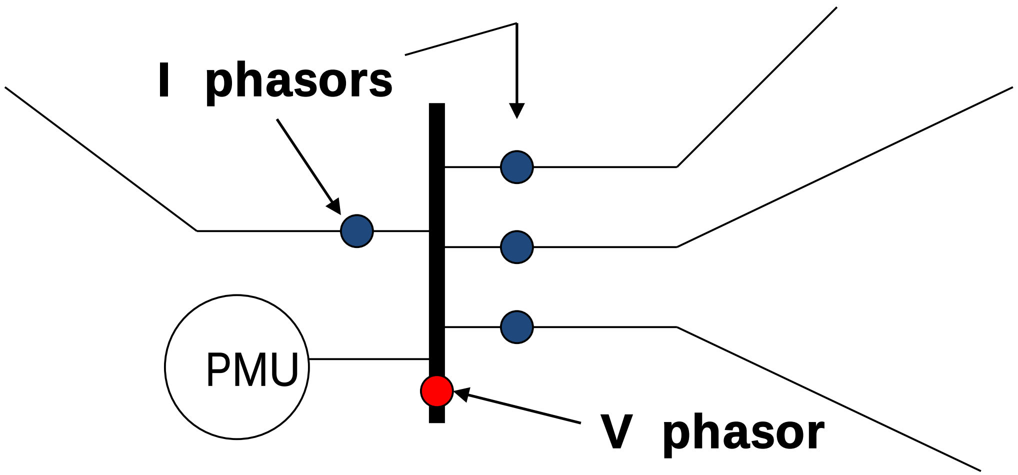


Under the Recovery Act SGIG and SGDP programs, their numbers rapidly increased : 166 → 1126



US Energy Information Administration: http://www.eia.gov/todayinenergy/detail.cfm?id=5630

Measurements provided by PMUs



ALL 3-PHASES ARE TYPICALLY MEASURED
BUT
ONLY POSITIVE SEQUENCE COMPONENTS ARE REPORTED

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = [T] \begin{bmatrix} V_0 \\ V_+ \\ V_- \end{bmatrix} \Rightarrow V_+ = \tfrac{1}{3}[V_A + \propto V_B + \propto^2 \ V_C]$$

$$\propto = e^{\frac{j2\pi}{3}}$$

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Measurement equations

$$SCADA\ Measurements$$

$$Z = h(X) + \upsilon \quad Non-linear\ Model$$

$$H_x : \nabla h(X)$$

$$Phasor\ Measurements$$

$$Z = H \cdot X + \upsilon \quad Linear\ Model$$

$$H \ : Function\ of\ network\ parameters\ only$$

A.G. Phadke, J.S. Thorp, and K.J. Karimi, “State Estimation with Phasor Measurements”, IEEE Transactions on Power Systems, vol. 1, no.1, pp. 233-241, February 1986.

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Phasor-only WLS state estimation

$$Z = H \cdot X + \upsilon \quad Linear\ Model$$

$$WLS\ state\ estimation\ problem:$$

$$Minimize \quad \sum_{i}^{m} \frac{r_i^2}{\sigma_i^2}$$

$$Subject\ to \quad r = Z - H \cdot \hat{X} \quad residual$$

$$\hat{X} = G^{-1} H^T R^{-1} Z \quad Direct\ solution$$

$$G = H^T R^{-1} H\ ;\ R = E\{\upsilon \cdot \upsilon^T\} = \mathrm{cov}(\upsilon)$$

$$\sigma_i^2 : R(i,i)\ error\ variance$$

Phasor-only WLS state estimation

Consider a fully measured system:

$$Z^m = \begin{bmatrix} V^m \\ I^m \end{bmatrix} \begin{matrix} \Rightarrow \textit{Bus voltages} \\ \Rightarrow \textit{Branch currents} \end{matrix}$$

$$= \begin{bmatrix} U \\ Y_b \cdot A \end{bmatrix} \cdot [V] + \upsilon$$

U : identity matrix

Y_b : branch admittance matrix

A : branch - bus incidence matrix

Note: Shunt branches are neglected initially, they will be introduced later.

Phasor-only WLS state estimation

$$Let \begin{bmatrix} V^m \\ I^m \end{bmatrix} = \begin{bmatrix} e^m + jf^m \\ c^m + jd^m \end{bmatrix}$$

$$= \begin{bmatrix} U \\ (g + jb) \cdot A \end{bmatrix} \cdot \left[e + jf \right] + \upsilon$$

$$= \left[H_F \right] \cdot \left[e + jf \right] + \upsilon$$

Phasor-only WLS state estimation: Complex to real transformation

$$\begin{bmatrix} e^m \\ f^m \\ c^m \\ d^m \end{bmatrix} = \begin{bmatrix} U & \\ & U \\ gA & -bA \\ bA & gA \end{bmatrix} \cdot \begin{bmatrix} e \\ f \end{bmatrix} + \upsilon$$

$$[Z] = [H] \cdot \begin{bmatrix} e \\ f \end{bmatrix} + \upsilon$$

Phasor-only WLS state estimation: Exact cancellations in off-diagonals of [G]

R is assumed to be identity matrix without loss of generality

$$G = H^T \cdot H = \begin{bmatrix} U & \\ & U \\ gA & -bA \\ bA & gA \end{bmatrix}^T \cdot \begin{bmatrix} U & \\ & U \\ gA & -bA \\ bA & gA \end{bmatrix}$$

$$= \begin{bmatrix} U + A^T\left(g^T g + b^T b\right)A & 0 \\ 0 & U + A^T\left(b^T b + g^T g\right)A \end{bmatrix}$$

[G] matrix:

- Is block – diagonal
- Has identical diagonal blocks
- Is constant, independent of the state

Phasor-only WLS state estimation: Correction for shunt terms

$$[Z] = (H + H_{sh}) \cdot X + \upsilon = H \cdot X + u$$

$$u = H_{sh} \cdot X + \upsilon$$

$$E\{u\} = H_{sh} \cdot E\{X\}$$

$$E\{X\} = \hat{X} = G^{-1} H^T R^{-1} Z$$

$$X^{corr} = G^{-1} H^T R^{-1} (Z - H_{sh} \cdot \hat{X})$$

$$= \hat{X} - G^{-1} \underbrace{H^T R^{-1} H_{sh}}_{\text{Very sparse}} \cdot \hat{X}$$

Fast Decoupled WLS Implementation Results

Test Systems Used

System Label	Number of Buses	Number of Branches	Number of Phasor Measurements
A	159	198	222
B	265	340	361
C	3625	4836	4982

Cases simulated:

Case-1: No bad measurement.

Case-2: Single bad measurement.

Case-3: Five bad measurements.

Fast Decoupled WLS Implementation Results

Average MSE Values (for 100 Simulations)

System	Case	MSE	
		WLS	Decoupled WLS
A	1	0.59	0.59
	2	0.59	0.59
	3	0.62	0.62
B	1	0.61	0.61
	2	0.61	0.60
	3	0.62	0.63
C	1	0.59	0.59
	2	0.58	0.59
	3	0.58	0.59

Fast Decoupled WLS Implementation Results

MEAN CPU TIMES OF 100 SIMULATIONS

System	Case	CPU Times (ms)	
		WLS	Decoupled WLS
A	1	5	2.4
	2	5.7	2.7
	3	9.3	3.9
B	1	7.5	3.5
	2	8.7	3.9
	3	14.8	5.8
C	1	137.4	75.9
	2	169.5	95.7
	3	284.7	165.6

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L_1 (LAV) Estimator

$$\mathit{Minimize}\ \sum_{i=1}^{m} c^T \cdot |r|$$

$$\mathit{Subject\ to}\ \ Z = H \cdot \hat{X} + r$$

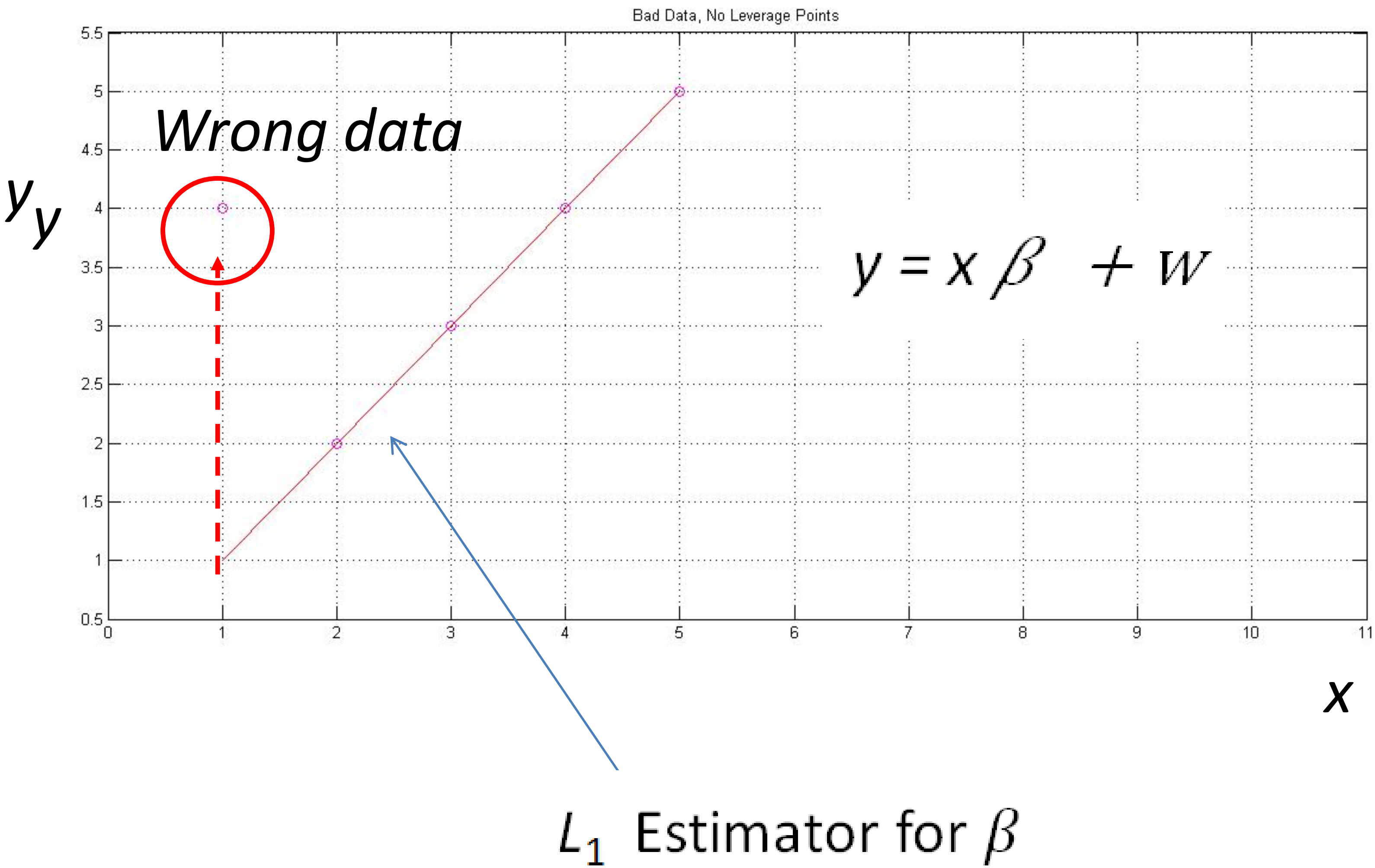
$$c^T = [1,1,\ldots,1]$$

Robust but with known deficiency:

Vulnerable to **leverage** measurements

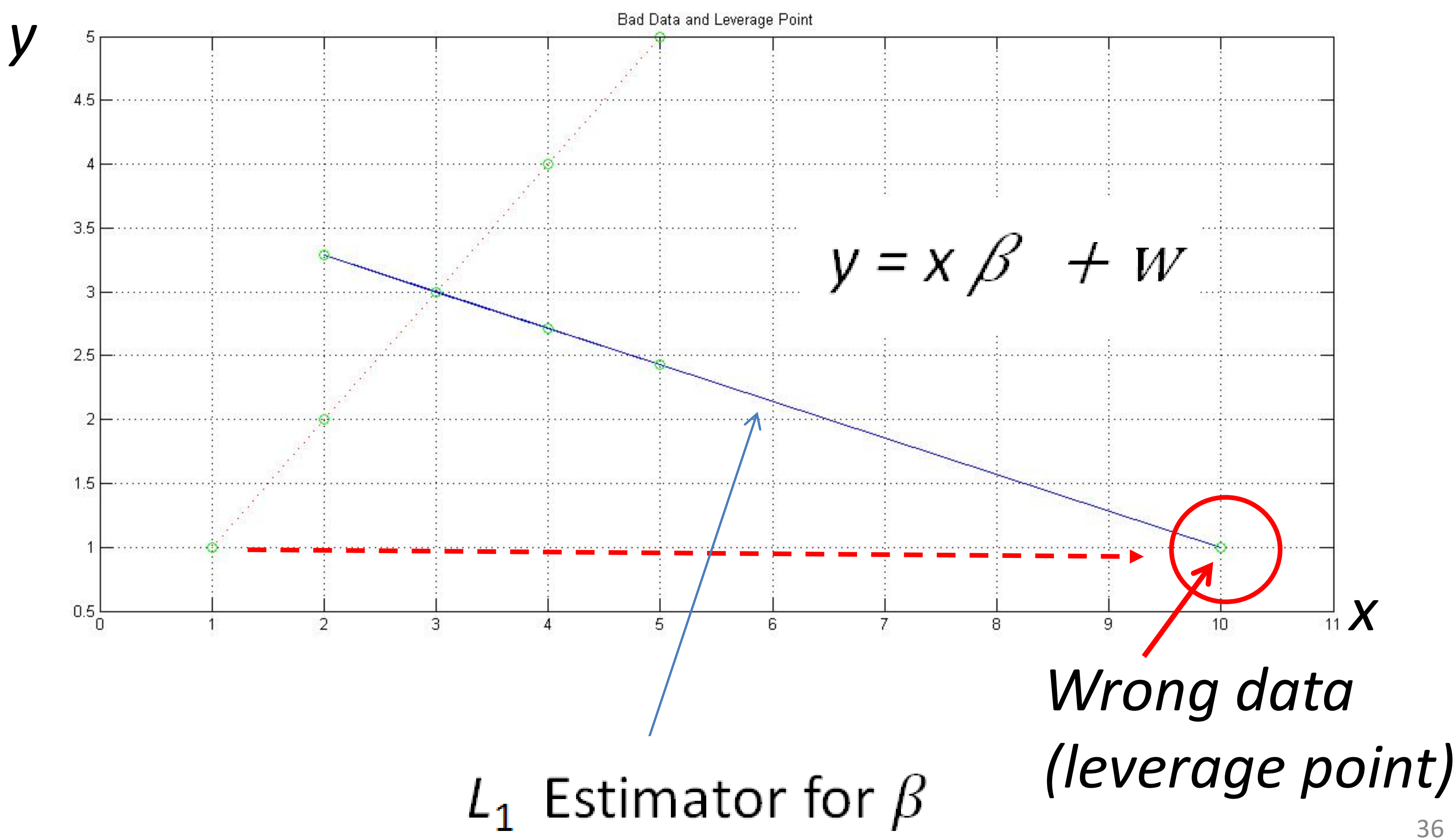
Motivating example: simple regression

No leverage points



Motivating example: simple regression

Leverage point exists and contains gross error: L_1 estimator fails to reject bad measurement



Leverage points in measurement model

Mili L., Cheniae M.G., and Rousseeuw P.J., "Robust State Estimation of Electric Power Systems" IEEE Transactions on Circuits and Systems, Vol. 41, No. 5, May 1994, pp.349-358.

- Flow measurements on the lines with impedances, which are very different from the rest of the lines.
- Using a very large weight for a specific measurement.

$$H\ x + e = z$$

LEVERAGE MEASUREMENT

$$R^{-1}H = \begin{bmatrix} x & x & x \\ x & x & x \\ x & x & x \\ x & x & x \\ Y & Y & Y \\ x & x & x \end{bmatrix}$$

- Scaling both the measured value and the measurement jacobian row will eliminate leveraging effect of the measurement.
- Leave zero injections since they are error free by design. Incorporate equality constraints in the formulation.

Properties of L_1 estimator

- Efficient Linear Programming (LP) code exists to solve it for large scale systems.
- Use of simple scaling eliminates leverage points. This is possible due to the type of phasor measurements (either voltages or branch currents).
- L_1 estimator automatically rejects bad data given sufficient local redundancy, hence bad data processing is built-in.

Conversion to Equivalent LP Problem

$$\min \mathrm{c}^T |r| \quad \text{s.t.} \; Hx + r = z$$

$$\Rightarrow$$

$$\min \mathrm{c}^T y \quad \text{s.t.} \; My = z, \quad y \geq 0$$

$$\mathrm{c}^T = [0_n \quad 0_n \quad c_m \quad c_m]$$

$$y = [X_a^T \quad X_b^T \quad U^T \quad V^T]^T \qquad x = X_a - X_b$$

$$M = [H \quad -H \quad I \quad -I] \qquad r = U \; - V$$

Bad data processing

WLS: Post estimation bad data processing / re-estimation

$\Omega = R - HG^{-1}H^T$ Normalized Residuals Test (NRT):

$G = H^T R^{-1} H$

$r_i^N = |r_i| \Big/ \sqrt{\Omega_{ii}}$ → $z_i^{new} = z_i^{bad} - R_{ii} \Big/ \Omega_{ii} \, r_i^{bad}$ → Update the estimates

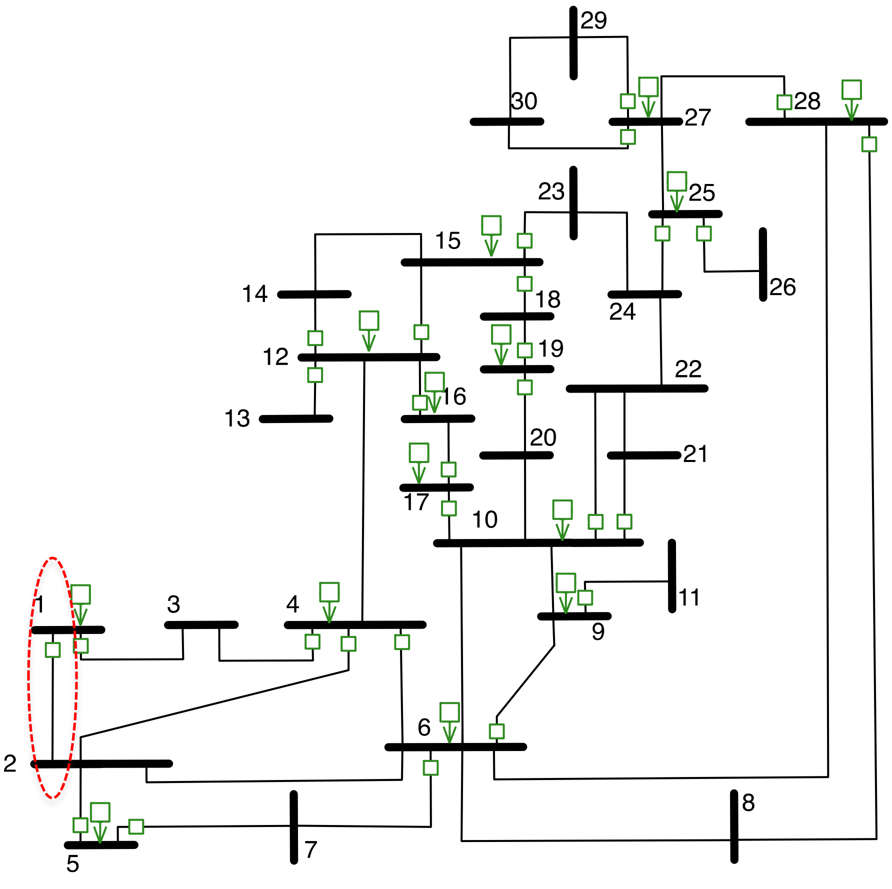
NRT is repeated as many times as the number of bad data.

L₁: Linear Programming Solution

LP problem is solved once. Choice of initial basis impacts solution time/iterations.

Small system example

IEEE 30-bus system



Line 1-2 parameter is changed to transform I_{1-2} into a leverage measurement

Case 1: Base case true solution

Case 2: Bad leverage measurement without scaling

Case 3: Same as Case 2, but using scaling

Small system example

Base case
True Solution

Leverage Measurements
Bad data
No scaling

Leverage Measurements
Bad data
With scaling

	Case-1		Case-2		Case-3	
	V (pu)	**θ (deg)**	**V (pu)**	**θ (deg)**	**V (pu)**	**θ (deg)**
1	1	5.2	1.0118	-3.5462	1	5.2
2	1	-3.74	0.9999	-3.74	1	-3.74
3	0.9952	0.13	1.004	-3.8964	0.9952	0.13
4	0.9992	-4.81	0.9992	-4.81	0.9992	-4.81
5	1	-9.02	0.9999	-9.02	1	-9.02
6	0.9851	-7.41	0.9851	-7.41	0.9851	-7.41
7	0.9869	-8.88	0.9869	-8.88	0.9869	-8.88

Large test case: 3625 bus + 4836 branch utility system

Case a: No bad measurement.

Case b: Single bad measurement.

Case c: Five bad measurements.

	Case a	Case b	Case c
LAV	3.33 s.	3.36 s.	3.57 s.
WLS	2.32 s.	9.38 s.	50.2 s.

Phasor-only state estimation: WLS versus L_1 (LAV)

WLS :

- Linear solution
- Requires bad-data analysis
  - Normalized residuals test
  - Re-weighting (not applicable)
- No deficiency in the presence of leverage measurements, with *scaling*.
- Exact cancellations in [G]

L_1 (LAV):

- Linear programming (single solution) *computationally competitive in s-s*
- Does not require bad-data analysis[*]
- No deficiency in the presence of leverage measurements, with *scaling*.

[*] Kotiuga W. W. and Vidyasagar M., "Bad Data Rejection Properties of Weighted Least Absolute Value Techniques Applied to Static State Estimation," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 4, April 1982, pp. 844-851.

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3-phase operation: motivation and observations

- State estimators implicitly assume balanced operating conditions and use positive sequence network model and measurements. This assumption is sometimes questionable.
- Power measurements are non-linear functions of state variables.
- Phasor measurements are linearly related to the states.

Further motivation

- Develop a state estimator capable of solving state estimation for three-phase unbalanced operating conditions,

yet:

- Utilize existing, well developed and tested software as much as possible.

Proposed approach: Modal decomposition revisited

- Decompose phasor measurements into their symmetrical components
- Estimate individual symmetrical components of states separately (in parallel if such hardware is available)
- Transform the estimates into phase domain to obtain estimated phase voltages and flows.

Modal decomposition of measurement equations

$$Z = HV + e$$

$$Z^T = [Z_V^T Z_I^T]$$

Phasor domain measurement representation
H: 3mx3n
V: 3nx1
Z: 30x1

$$V_S = TV_P \quad \& \quad I_S = TI_P$$

$$T_Z = \begin{bmatrix} T & 0 & \cdots & 0 \\ 0 & T & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & T \end{bmatrix}$$

T: 3mx3m

Modal domain vectors
T: 3x3
V_S and I_S: 3x1

$$T_Z Z = T_Z HV + T_Z e$$

Modal decomposition of measurement equations

$$V = T_V V_M \Rightarrow T_V = \begin{bmatrix} T^{-1} & 0 & \cdots & 0 \\ 0 & T^{-1} & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & T^{-1} \end{bmatrix}$$

$$\underline{\underline{Z_M = H_M V_M + e_M}}$$

$$Z_M = T_Z Z$$
$$H_M = T_Z H T_V$$
$$e_M = T_Z e$$

Zero sequence

$$Z_0 = H_0 V_0 + e_0$$
$$V_0 = G_0^{-1} H_0^T R_0^{-1} Z_0$$
$$G_0 = H_0^T R_0^{-1} H_0$$

Positive/ Negative sequence

$$Z_r = H_r V_r + e_r$$
$$V_r = G_r^{-1} H_r^T R_r^{-1} Z_r$$
$$G_r = H_r^T R_r^{-1} H_r$$

!

Z_0, Z_r : mx1
V_0, V_r: nx1
H_0, H_r: mxn

- Fully decoupled three relations
- Smaller size (Jacobian) matrices

Large scale 3-phase system example: 3625-buses and 4836-branches

Case a: No bad measurement.

Case b: Single bad measurement.

Case c: Five bad measurements.

	Case a		Case b		Case c	
	LAV	WLS	LAV	WLS	LAV	WLS
Zero Seq.	3.52 s.	2.32 s.	3.65 s.	9.28 s.	3.78 s.	25.51 s.
Positive Seq.	3.61 s.	2.62 s.	3.63 s.	9.41 s.	3.66 s.	26.01 s.
Negative Seq.	3.21 s.	2.22 s.	3.45 s.	9.01 s.	3.62 s.	24.82 s.

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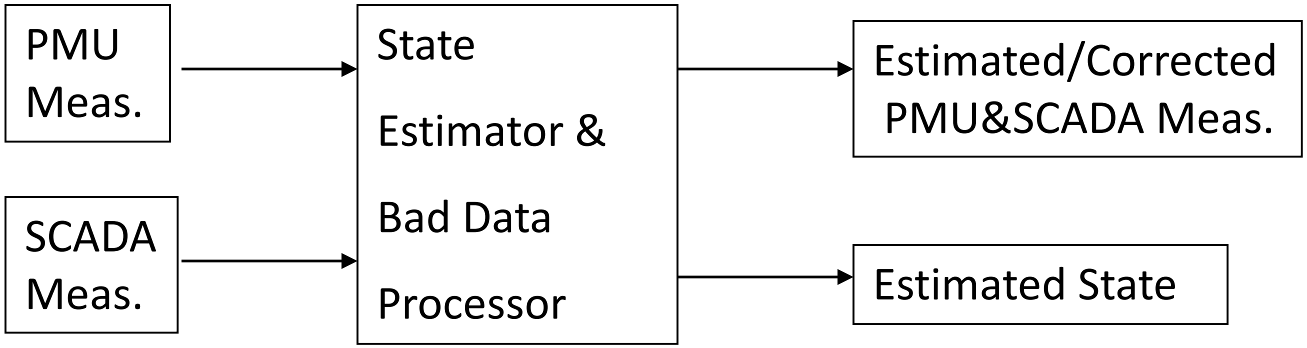
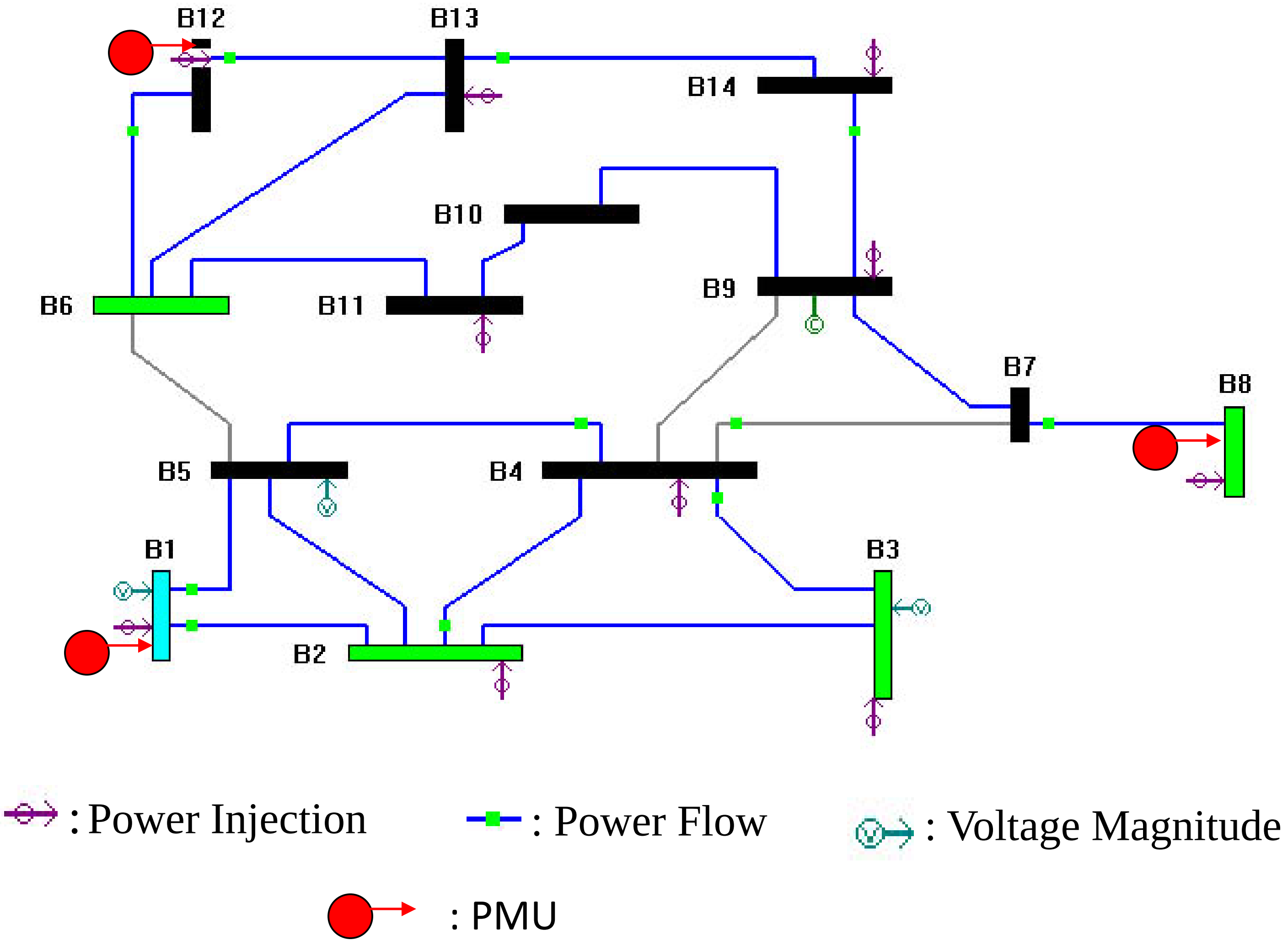
No reference bus or reference PMU is needed or should be used

- Eliminate the reference phase angle from the SE formulation.
- Bad data in SCADA as well as phasor measurements can be detected and identified with sufficiently redundant measurement sets.



Numerical Example



Numerical Example

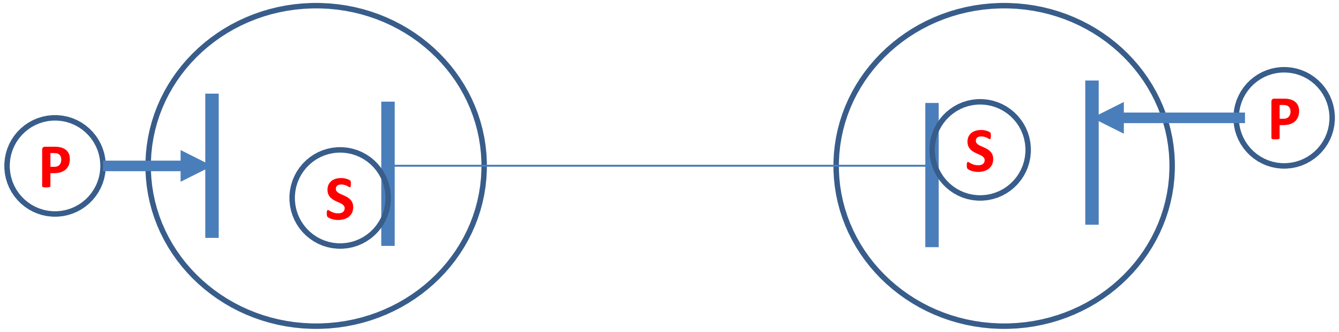
Error in bus 1 phase angle

TEST A	TEST B
Bus 1 is used as the reference bus	No reference is used

Test A		Test B	
Measurement	***Normalized residual***	***Measurement***	***Normalized residual***
θ_8	7.5	θ_1	10.53
p_{4-7}	5.73	θ_8	7.2
p_{5-6}	5.6	p_{4-7}	5.48
θ_{12}	5.2	p_{5-6}	5.35
V_1	4.53	θ_{12}	4.96

Merging Observable Islands

- PMUs can be placed at any bus in the observable island.
- SCADA pseudo-measurements can merge observable islands only if they are incident to the boundary buses.



Robust Metering

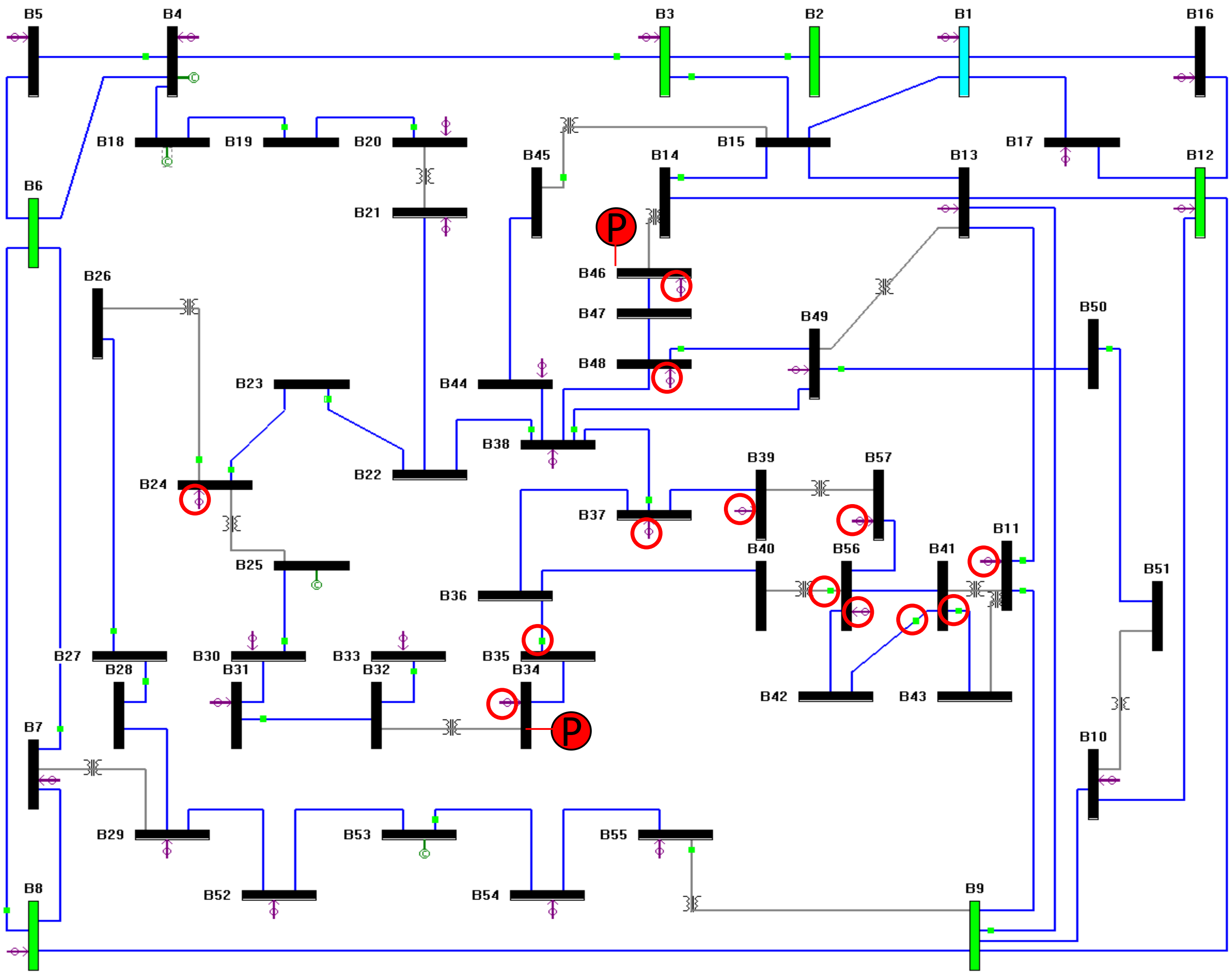
- Bad data appearing in “*critical measurements*” can NOT be detected.
- Adding new measurements at strategic locations will transform them, allowing detection of bad data which would otherwise have been missed.

Note:

When a “critical measurement” is removed from the measurement set, the network will no longer be OBSERVABLE.

Number of Critical Meas.	Number of PMU needed
13	2

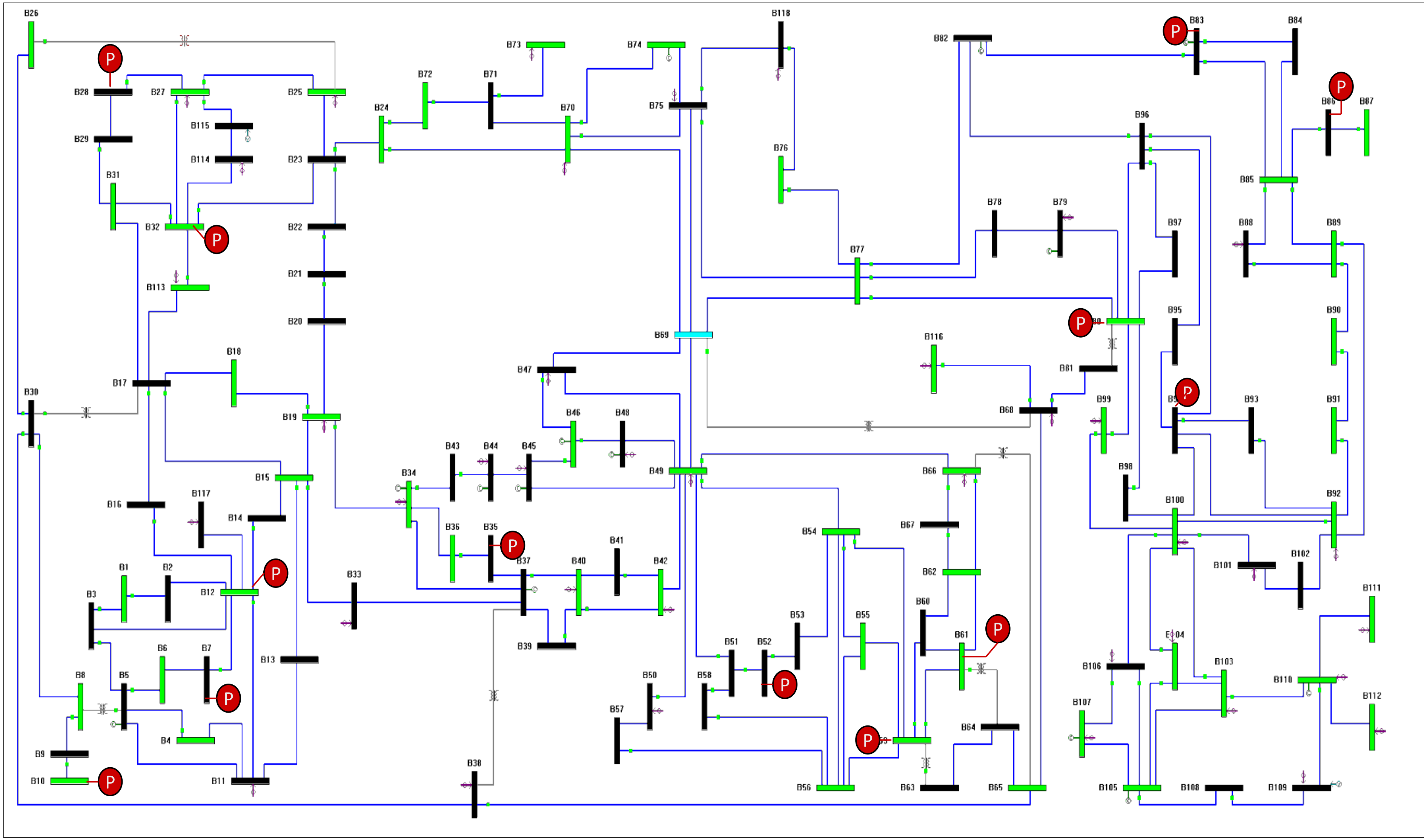
IEEE 57-bus system



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

Number of Critical Meas.	Number of PMU needed
29	13

IEEE 118-bus system

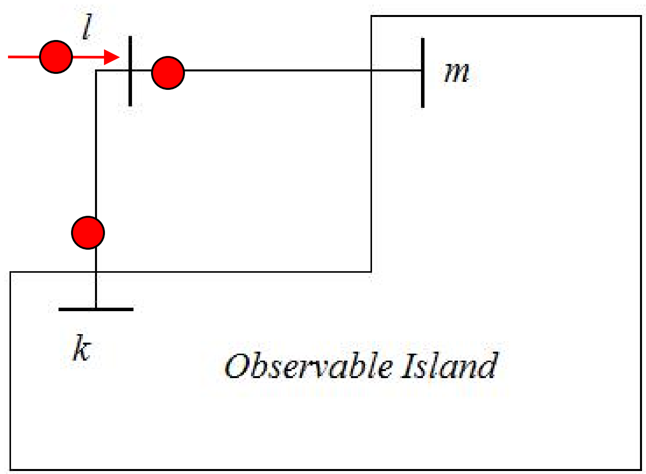


Impact of PMUs on Parameter Error Identification

- Are there cases where errors in certain parameters can not be identified without synchronized phasor measurements?

Cases where more than one set of parameters satisfies all SCADA measurements.

Illustrative Example



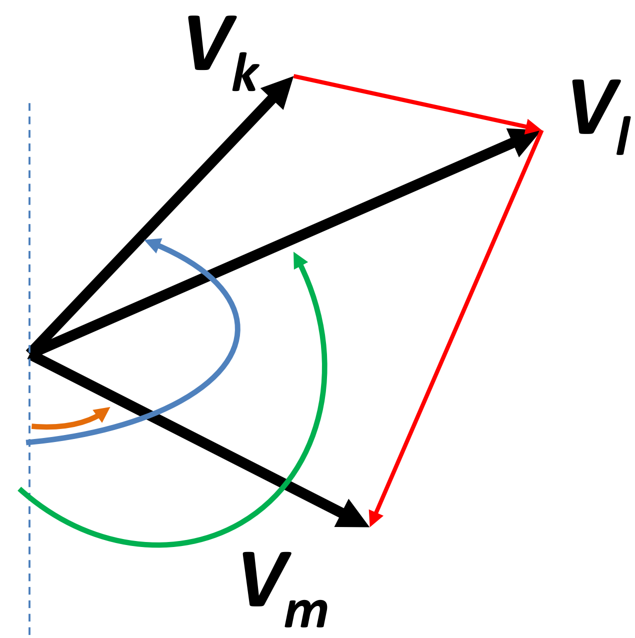
$$\boxed{P_{kl}} = \frac{\theta_k - \theta_l}{x_{kl}} \qquad \boxed{P_{kl}} = \frac{\theta_k - \theta_l'}{x_{kl}'}$$

$$\boxed{P_{lm}} = \frac{\theta_l - \theta_m}{x_{lm}} \qquad \boxed{P_{lm}} = \frac{\theta_l' - \theta_m}{x_{lm}'}$$

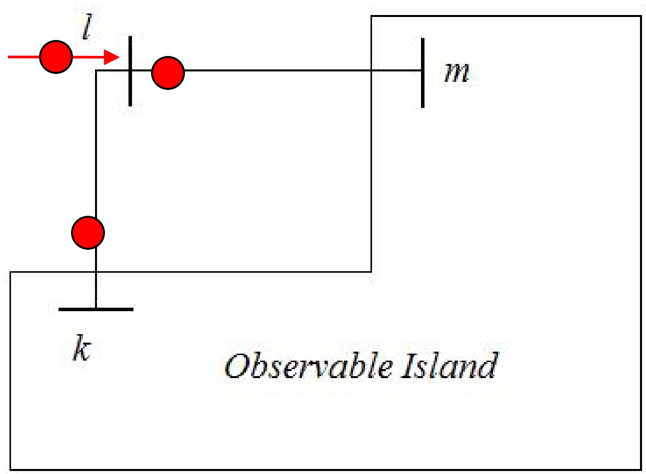
$$J(x, p_1, p_2) = J(x', p_1', p_2')$$

$$\frac{x'_{kl}}{x_{kl}} = \frac{\theta_k - \theta_l'}{\theta_k - \theta_l} \qquad \frac{x'_{lm}}{x_{lm}} = \frac{\theta_l' - \theta_m}{\theta_l - \theta_m}$$

$$\boldsymbol{P_l = P_{lm} - P_{kl}}$$



Illustrative Example



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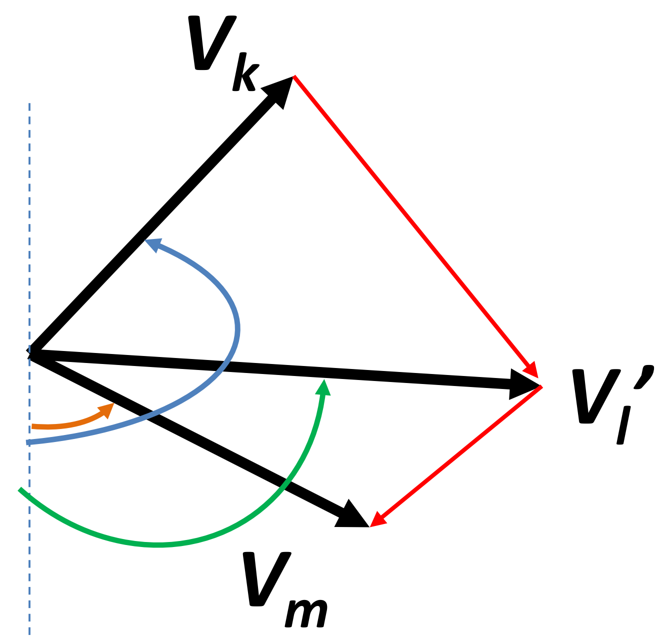
$$\boxed{P_{lm}} = \frac{\theta_l - \theta_m}{x_{lm}} \qquad \boxed{P_{lm}} = \frac{\theta_l' - \theta_m}{x_{lm}'}$$

$$J(x, p_1, p_2) = J(x', p_1', p_2')$$

$$\frac{x'_{kl}}{x_{kl}} = \frac{\theta_k - \theta_l'}{\theta_k - \theta_l} \qquad \frac{x'_{lm}}{x_{lm}} = \frac{\theta_l' - \theta_m}{\theta_l - \theta_m}$$

$$\boldsymbol{P_l = P_{lm} - P_{kl}}$$



Remarks and Conclusions

- LAV estimator will be a computationally viable and effective alternative to WLS estimator when the measurement set consists of only PMUs. Scaling can be a simple yet effective tool in the presence of leverage measurements.
- Use of phasor measurements for SE allows modal decomposition of measurement equations.
- WLS estimator implementation has built-in simplifications due to exact cancellations in the gain [G] matrix.
- Given sufficiently redundant phasor measurements, fast and robust state estimation is possible even for very large scale power grids.

Related Publications:

Göl, M. and **Abur, A.,** "A Hybrid State Estimator for Systems with Limited Number of PMUs," accepted for publication in IEEE Transactions on Power Systems, 2014.

Göl, M. and **Abur, A.,** "LAV Based Robust State Estimation for Systems Measured by PMUs," IEEE Transactions on Smart Grid, Vol. 5, No: 4, July 2014, pp.1808 -- 1814.

Göl, M. and **Abur, A.,** "A Robust PMU Based Three-Phase State Estimator Using Modal Decoupling," IEEE Transactions on Power Systems, Nov. 2014, Vol. 29, No: 5, pp.2292-2299.

Göl, M. and **Abur, A.,** "Observability Analysis of Systems Containing Phasor Measurements," Proceedings of the IEEE Power and Energy Society General Meeting, 22-26 July 2012.

Göl, M. and **Abur, A.**, "Effective Measurement Design for Cyber Security," Proceedings of the 18th Power Systems Computation Conference, August 18-22, 2014, Wroclaw, Poland.

Göl, M. and **Abur, A.**, "PMU Placement for Robust State Estimation," Proceedings of the North American Power Symposium, Sep. 22-24, 2013, Manhattan, KS.

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Murat Gol , Ph.D. 2014

Thank You

Any Questions?