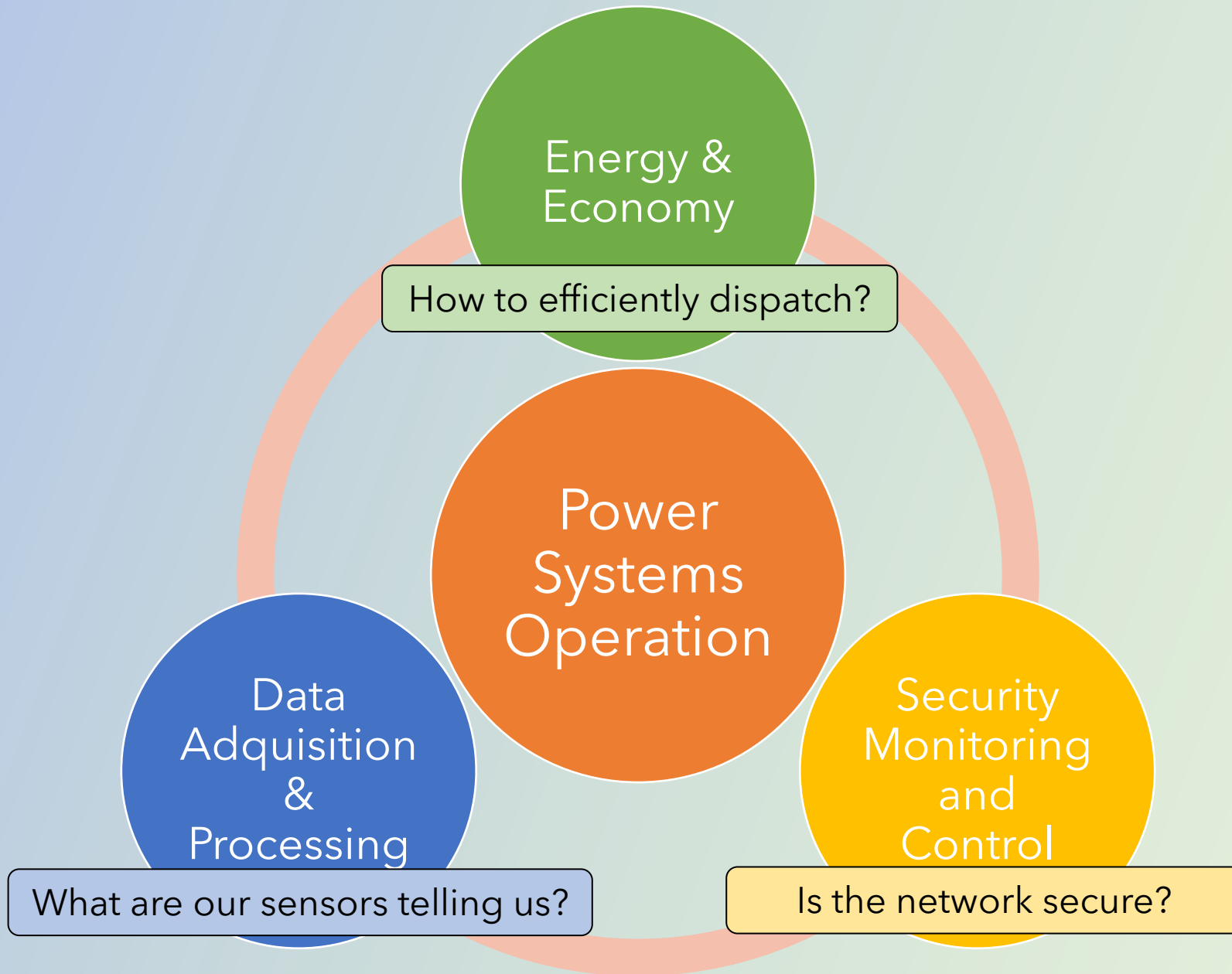


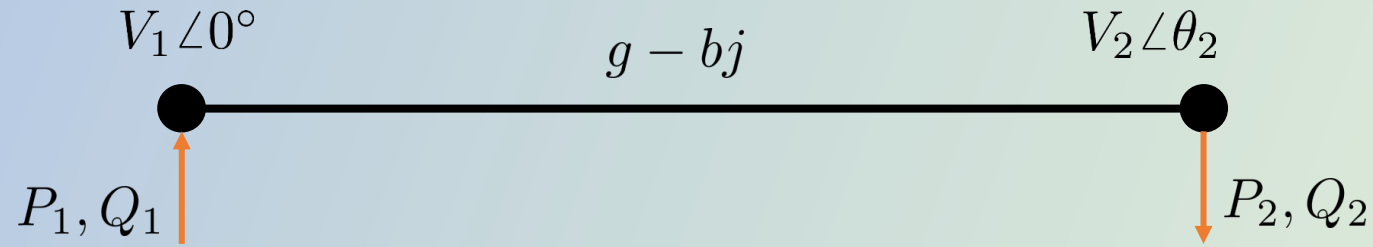
Learning-based State Estimation in Distribution Systems with Limited Real-Time Measurements

Jose Gómez de la Varga

Joint work with S. Pineda, J. M. Morales and Á. Porras







$$h_{P_1} = V_1 V_2 (-g \cos(-\theta_2) + b \sin(-\theta_2)) + g V_1^2$$

$$h_{Q_1} = V_1 V_2 (-g \sin(-\theta_2) - b \cos(-\theta_2)) - b V_1^2$$

$$h_{P_2} = V_2 V_1 (-g \cos \theta_2 + b \sin \theta_2) + g V_2^2$$

$$h_{Q_2} = V_2 V_1 (-g \sin \theta_2 - b \cos \theta_2) - b V_2^2$$

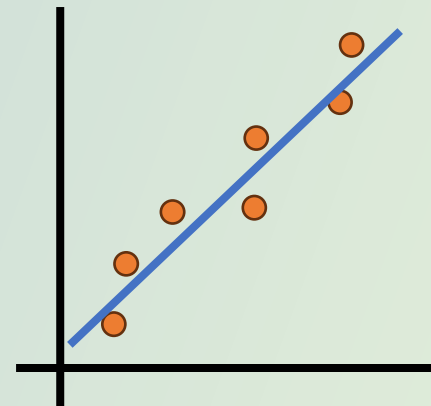
Measurements $z = [P_1, Q_1, P_2, Q_2]^T$

State Vector $x = [V_1, V_2, \theta_2]^T$

Weighted Least Squares

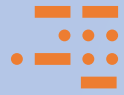
$$\hat{x} \in \arg \min_x (z - h(x))^T W (z - h(x))$$

$$W = \text{diag}\{\sigma_1^{-2}, \dots, \sigma_m^{-2}\}$$



In theory...

... but in practice



Heterogenous scan rates

Sensor failures



Communication errors or saturation

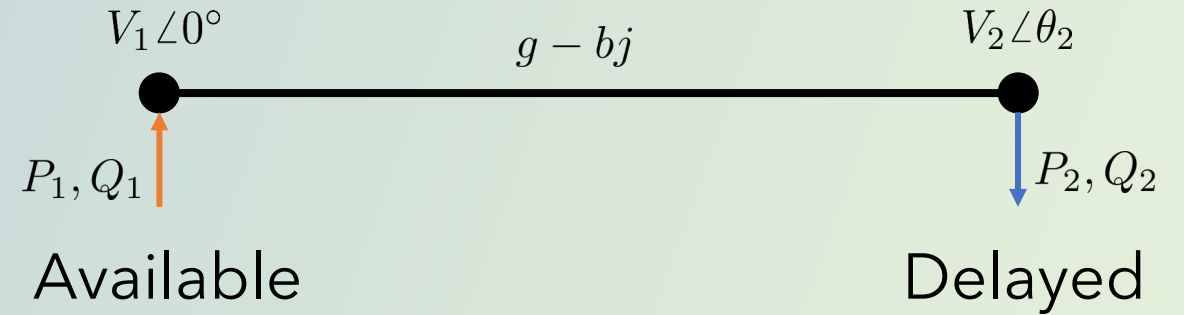
Malicious attacks



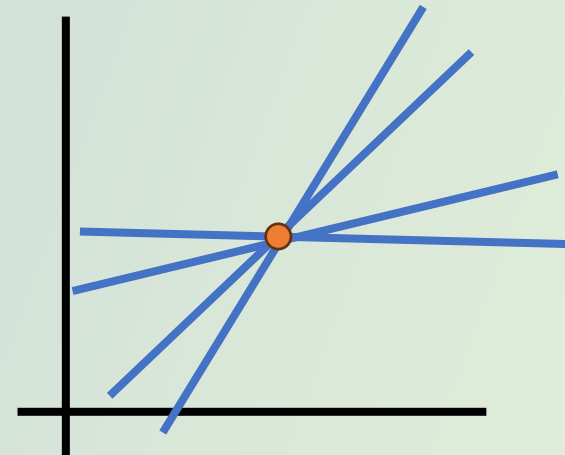
Electrical blackouts



Ugly truth



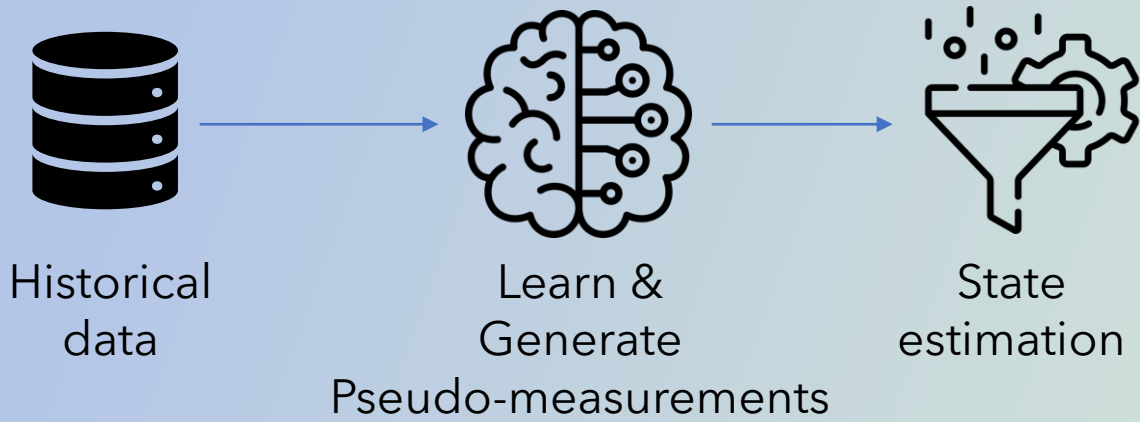
Unobservable
in real time



Multiple
solutions

Unobservable in real-time. Now what?

Pseudo-measurement Generation



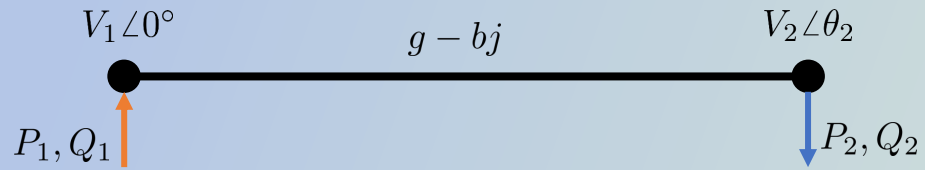
$$\hat{P}_2, \hat{Q}_2 = f(P_1, Q_1)$$

State Forecasting



$$\hat{V}_1, \hat{V}_2, \hat{\theta}_2 = g(P_1, Q_1)$$

Pure Statistics! Both ignore Physics & Network



What if...?



Find Any $\tilde{V}_1, \tilde{V}_2, \tilde{\theta}_2$

1

such that

$$P_1 = \tilde{V}_1 \tilde{V}_2 \left(-g \cos(-\tilde{\theta}_2) + b \sin(-\tilde{\theta}_2) \right) + g \tilde{V}_1^2$$

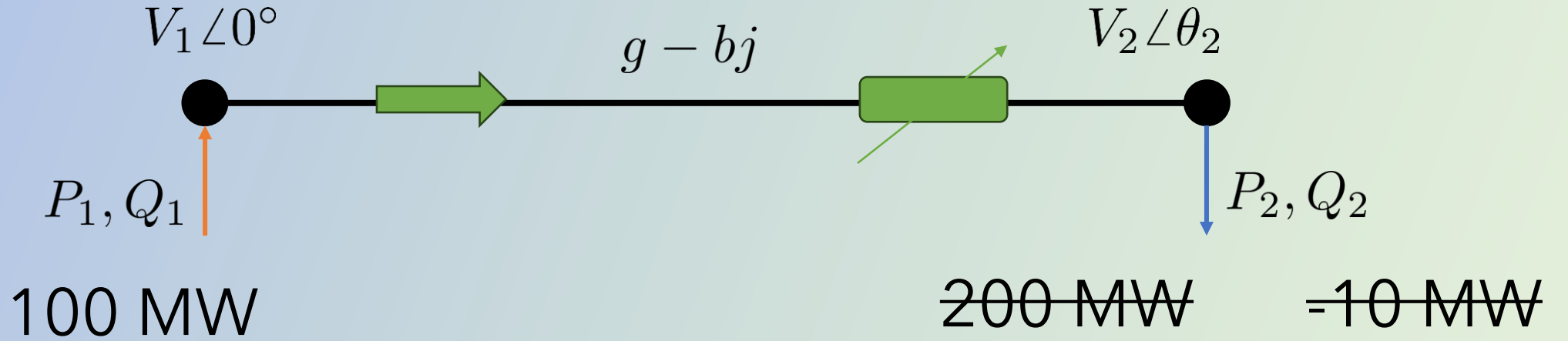
$$Q_1 = \tilde{V}_1 \tilde{V}_2 \left(-g \sin(-\tilde{\theta}_2) - b \cos(-\tilde{\theta}_2) \right) - b \tilde{V}_1^2$$

2

Create
New Features

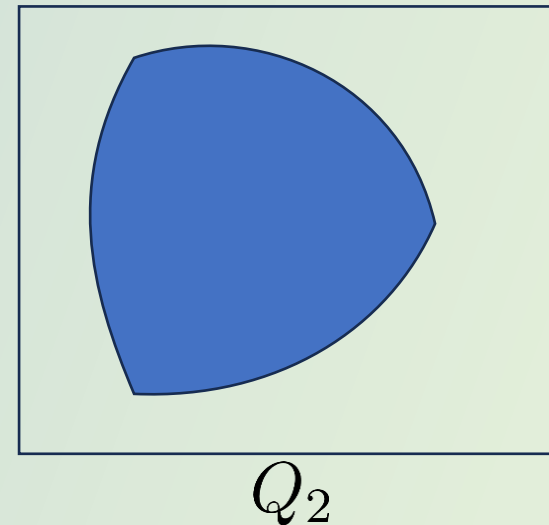
$$\tilde{P}_2 = \tilde{V}_2 \tilde{V}_1 \left(-g \cos \tilde{\theta}_2 + b \sin \tilde{\theta}_2 \right) + g \tilde{V}_2^2$$

$$\tilde{Q}_2 = \tilde{V}_2 \tilde{V}_1 \left(-g \sin \tilde{\theta}_2 - b \cos \tilde{\theta}_2 \right) - b \tilde{V}_2^2$$

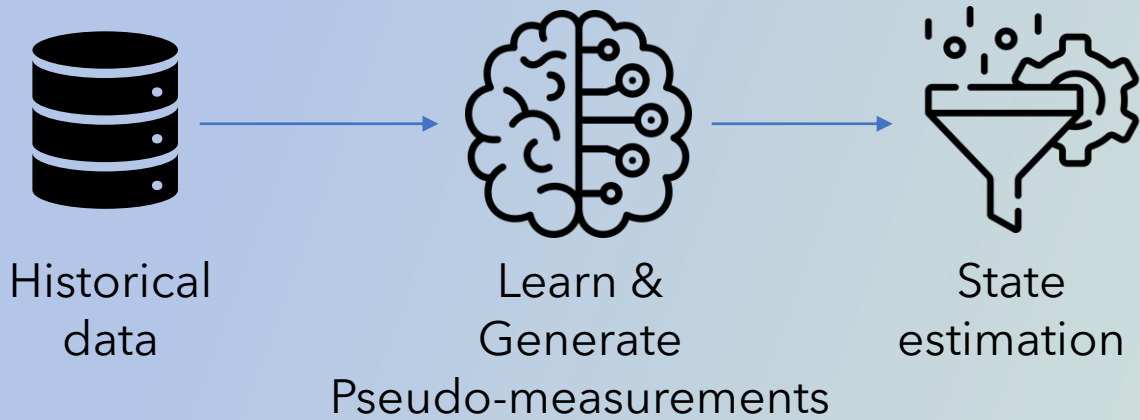


Connected through network parameters (losses)

Given $g, b, P_1, Q_1 \implies P_2$



Pseudo-measurement Generation



$$\hat{P}_2, \hat{Q}_2 = f(P_1, Q_1)$$

New Features

$$\hat{P}_2, \hat{Q}_2 = f(P_1, Q_1, \tilde{P}_2, \tilde{Q}_2)$$

Enhanced Pseudo-measurement Generation

State Forecasting



$$\hat{V}_1, \hat{V}_2, \hat{\theta}_2 = f(P_1, Q_1)$$

$$\hat{V}_1, \hat{V}_2, \hat{\theta}_2 = f(P_1, Q_1, \tilde{P}_2, \tilde{Q}_2)$$

Enhanced State Forecasting

Simulation setup



IEEE 33 Bus Test Case

33 nodes
37 lines



Operating conditions
chosen randomly

$V = (0.95, 1.05) p.u.$
 $\theta = (-15, +15)^\circ$



Measurements obtained
adding a Gaussian noise

$(V, \theta) \sim \mathcal{N}(0, 0.001^2)$
 $(P, Q) \sim \mathcal{N}(0, 0.01^2)$



a: 1 FTU + 15 SCADA + 5 PMU
 (V, P_f, Q_f) (P, Q) (V, θ)

d: 18 Smart Meters (P, Q)

$m_a = 43$

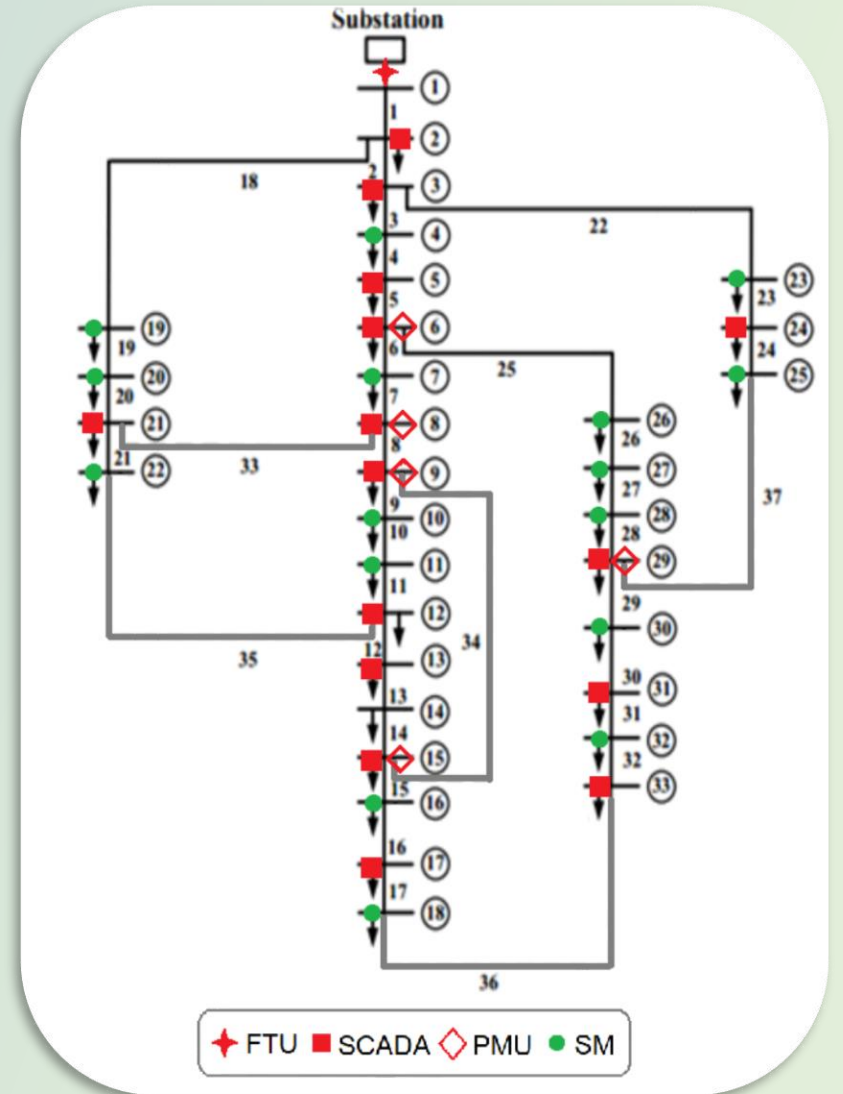
$m_d = 36$

$n = 65 (\theta_1 = 0)$



Learning functions f and
 g : Linear Regression

Training: 8 000 instances
Test: 2 000 instances



ACCURACY (RMSE) IN THE ESTIMATION OF THE STATE AND THE POWER VARIABLES

Method	V	θ	P	Q	P_f	Q_f
State Forecasting (SF)	0.021	0.086	22.03	32.84	14.53	21.56
Pseudo-measurements (PM)	0.085	0.097	21.79	32.76	15.87	22.24
Enhanced State Forecasting (SF*)	0.018	0.085	20.06	31.77	13.40	20.96
Enhanced pseudo-measurements (PM*)	0.041	0.087	19.94	31.59	13.48	20.97

- Enhanced versions improve all variables
- SF/SF* minimizes state error
- PM/PM* minimizes power error

ΔRMSE FOR VARYING VARIABILITY AND MEASUREMENT DATA

PM vs. PM*

Variability	# PMU	# SCADA	ΔRMSE (V)	ΔRMSE (S_f)
Low	5	15	0.015	0.065
Medium	5	15	0.044	0.729
High	5	15	0.070	1.957
Medium	15	5	0.002	0.070

- Improvement increases as variability rises
- Available measurements that connect multiple states (SCADA) work better

SCADA	$h_{P_1} = V_1 V_2 (-g \cos(-\theta_2) + b \sin(-\theta_2)) + g V_1^2$	PMU
	$h_{Q_1} = V_1 V_2 (-g \sin(-\theta_2) - b \cos(-\theta_2)) - b V_1^2$	
	$h_{V_1} = V_1$	
	$h_{\theta_1} = \theta_1$	

Takeaways... in a nutshell

Real-time
observability



Available

Delayed



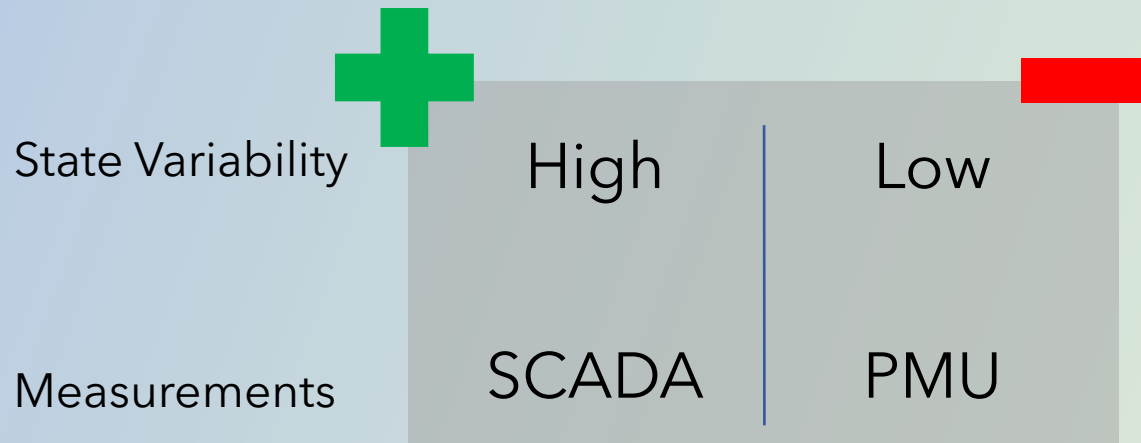
Learning



Unobservable
SE



Improved
Estimation
Off-the-self





Thanks for your attention!

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