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

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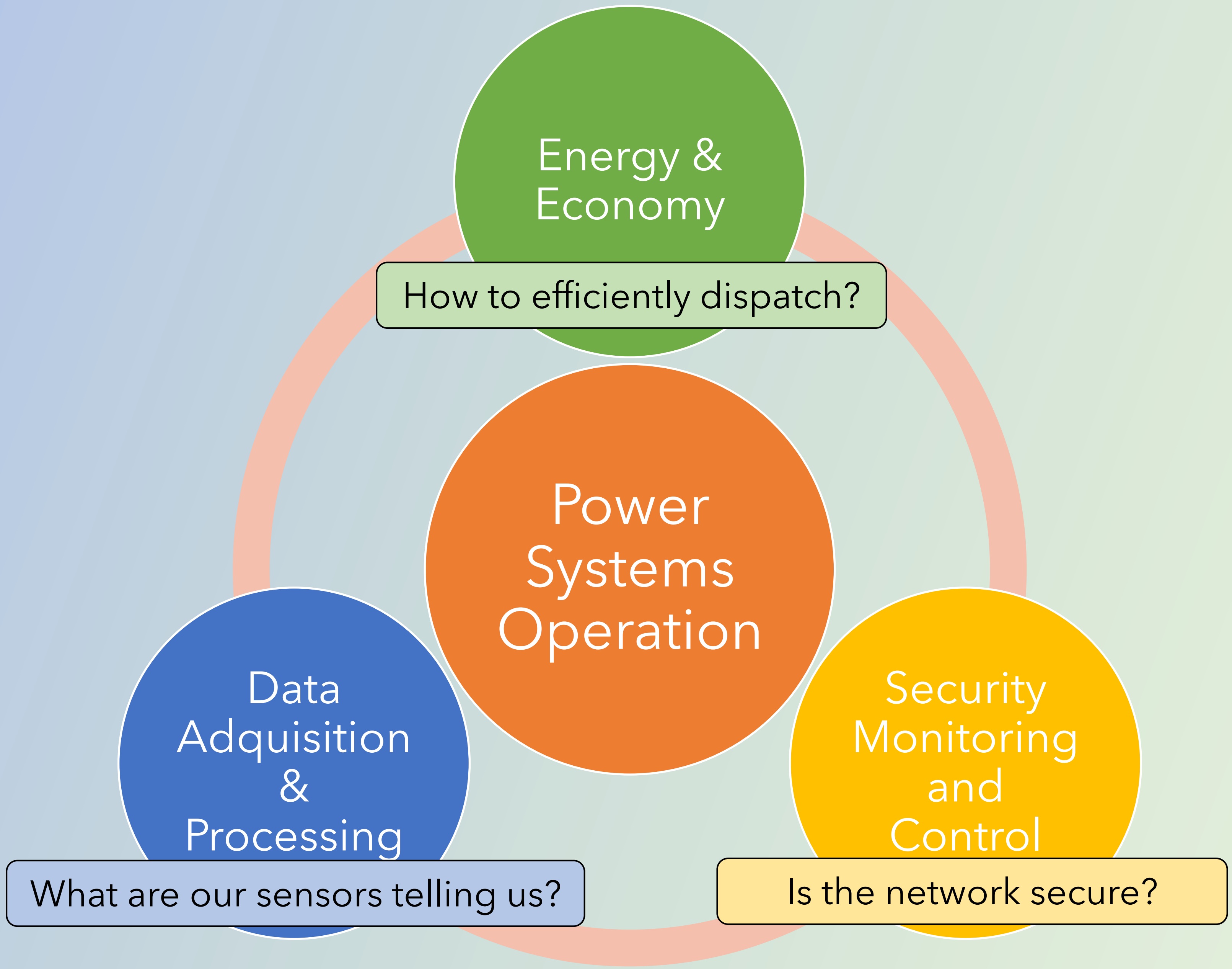
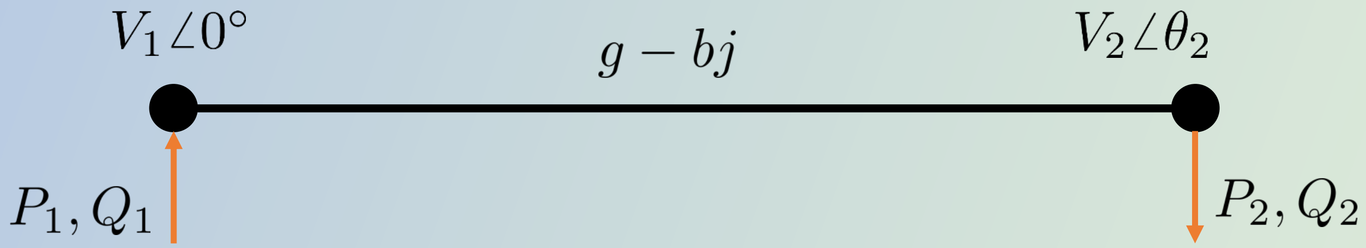
Joint work with S. Pineda, J. M. Morales and Á. Porras

OASYS

Optimization and Analytics for Sustainable energY Systems


Energy & Economy
How to efficiently dispatch?
Power Systems Operation
Data Adquisition & Processing
What are our sensors telling us?
Security Monitoring and Control
Is the network secure?



$$h_{P_1} = V_1V_2\left(-g\cos\left(-\theta_2\right) + b\sin\left(-\theta_2\right)\right) + gV_1^2$$
$$h_{Q_1} = V_1V_2\left(-g\sin\left(-\theta_2\right) - b\cos\left(-\theta_2\right)\right) - bV_1^2$$

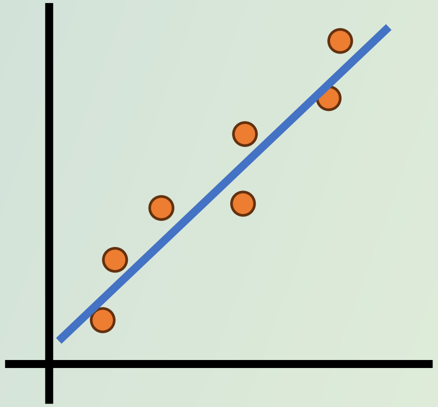
$$h_{P_2} = V_2V_1\left(-g\cos\theta_2 + b\sin\theta_2\right) + gV_2^2$$
$$h_{Q_2} = V_2V_1\left(-g\sin\theta_2 - b\cos\theta_2\right) - bV_2^2$$

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

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

Weighted Least Squares

$$\hat{x} \in \arg\min_{x} \left(z - h\left(x\right)\right)^T W \left(z - h\left(x\right)\right)$$
$$W = diag\{\sigma_1^{-2}, \ldots, \sigma_m^{-2}\}$$

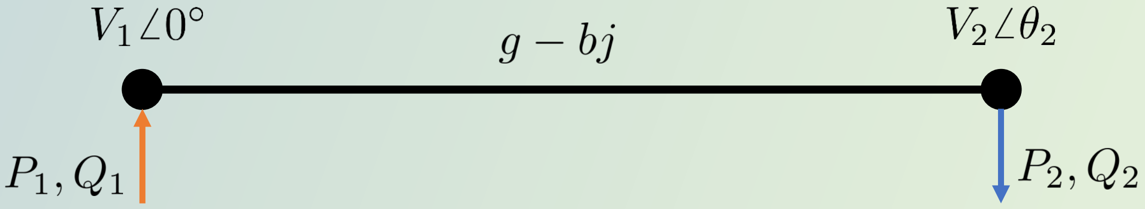


In theory...

Ugly truth

… but in practice

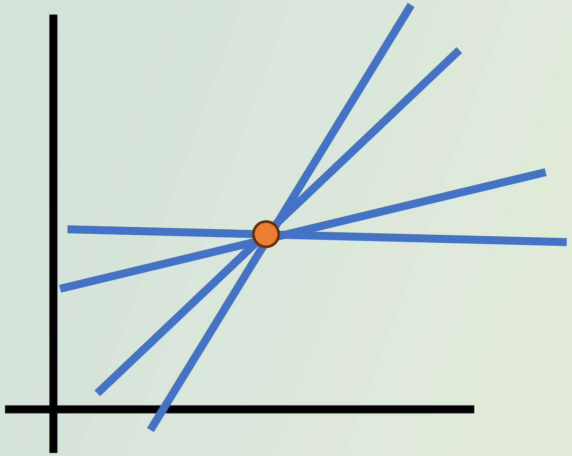
- Heterogenous scan rates
- Sensor failures
- Communication errors or saturation
- Malicious attacks
- Electrical blackouts



Available

Delayed

Unobservable in real time



Multiple solutions

Unobservable in real-time. Now what?

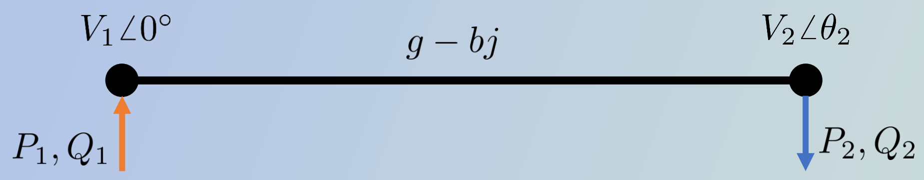
Pseudo-measurement Generation

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

State Forecasting

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

Pure Statistics! Both ignore Physics & Network



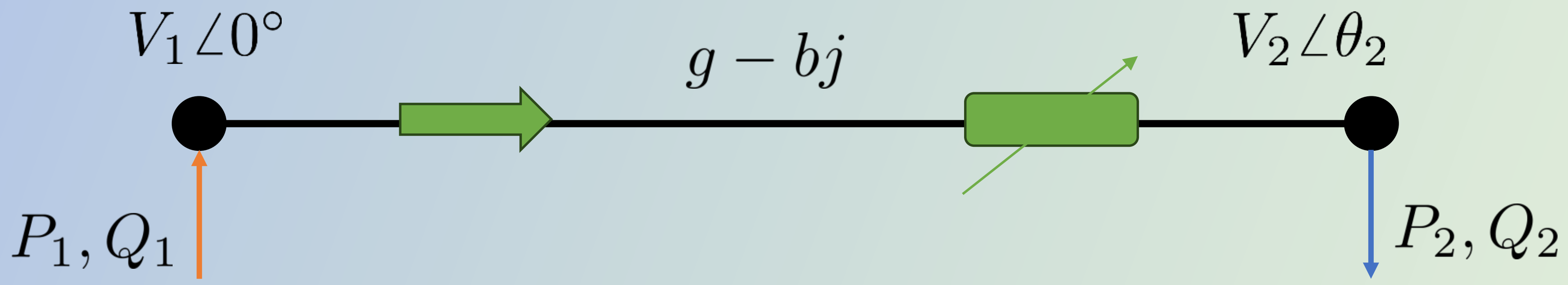
What if…?

① Find Any $\tilde{V}_1, \tilde{V}_2, \tilde{\theta}_2$

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

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

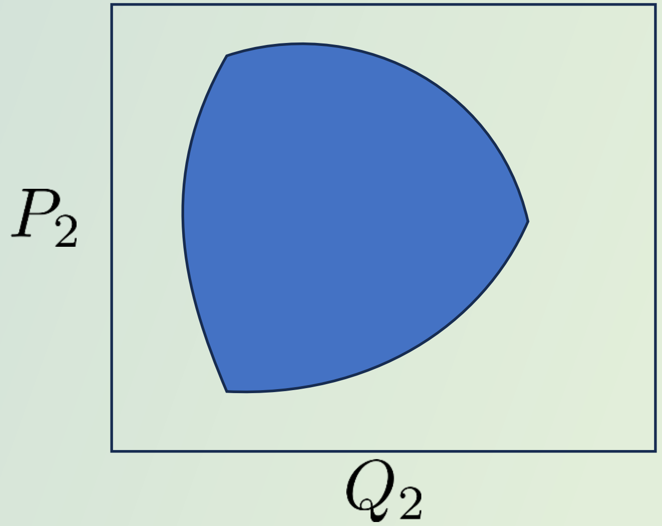


100 MW

~~200 MW~~ ~~-10 MW~~

Connected through network parameters (losses)

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



Pseudo-measurement Generation

Historical data → Learn & Generate Pseudo-measurements → State estimation

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

State Forecasting

Historical data → Historical State Estimation → Learn & Generate States

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

New Features

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

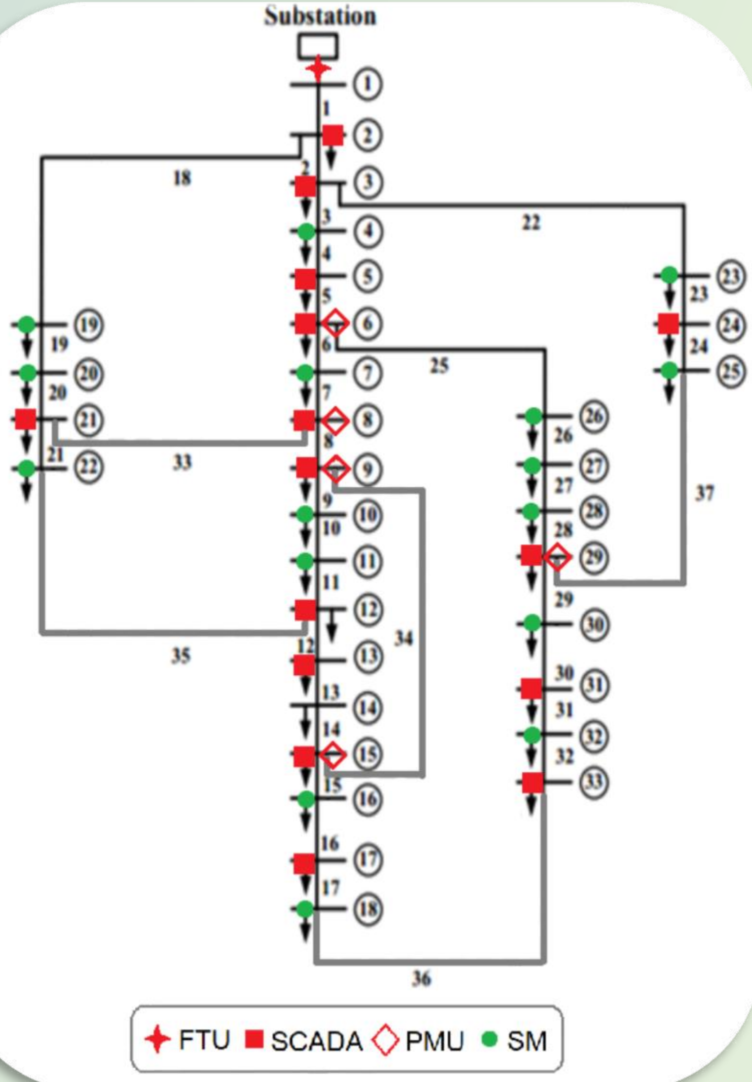
Enhanced Pseudo-measurement Generation

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

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

$$h_{P_1} = V_1 V_2 \left(-g\cos\left(-\theta_2\right) + b\sin\left(-\theta_2\right)\right) + gV_1^2$$
$$h_{Q_1} = V_1 V_2 \left(-g\sin\left(-\theta_2\right) - b\cos\left(-\theta_2\right)\right) - bV_1^2$$

$$h_{V_1} = V_1$$
$$h_{\theta_1} = \theta_1$$

PMU

Takeaways…
in a nutshell

Real-time observability

Available

Delayed

Worthless?

State Variability	High	Low
Measurements	SCADA	PMU

Learning

Unobservable SE

Improved Estimation

Off-the-self

Thanks for your attention!

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