Measurement-Based Sensitivity Estimation for Online Power System Monitoring and Control

Alejandro D. Domínguez-García and Peter W. Sauer

Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

Email: {aledan, psauer}@ILLINOIS.EDU

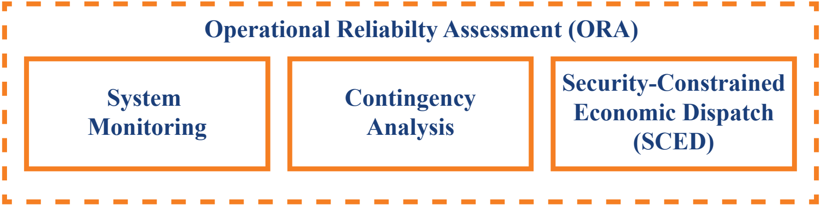
CERTS-DOE Transmission Reliability Program Internal Review
Washington, DC
June 7–8, 2016

CERTS
Consortium for Electric Reliability Technology Solutions

Outline

Motivation

- The primary goal of power system operators is to economically maintain operational reliability
- A system is said to be operationally reliable if it can tolerate a limited number of equipment outages without jeopardizing continued operation
  - e.g., a system that meets the N-1 reliability criterion can tolerate the outage of any single piece of equipment
- Real-time operational reliability assessment (ORA) is the main toolset used by system operators to meet their goal



ORA Shortcomings Contribute to Blackouts

- "With an operational state estimator and real-time contingency analysis, MISO operators ... [could have taken] timely actions to return the system to within limits." -NERC, 2004
- "The system was not being operated in a secure N-1 state. This failure stemmed primarily from weaknesses in ... operations planning and real-time situational awareness." -NERC, 2012

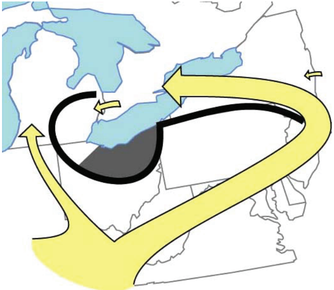


Figure: 2003 Northeast Blackout

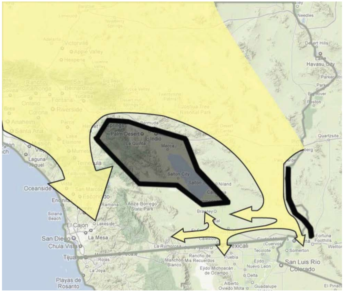
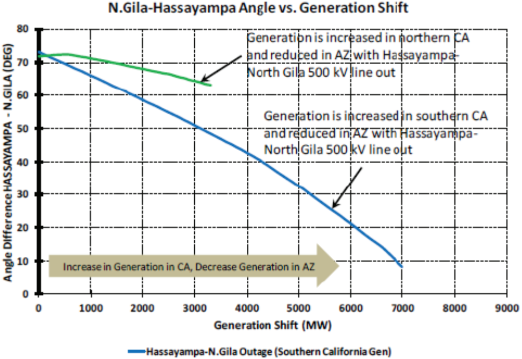


Figure: 2011 San Diego Blackout

source: NERC

Conventional ORA Limitations

- "APS operators erroneously believed that they could return the line to service in approximately 15 minutes, even though they had no situational awareness of a large phase angle difference caused by the outage."
  -NERC, 2012
- "Underlying factors that contributed to the event... [included] not providing effective tools and operating instructions for use when reclosing lines with large phase angle differences across the reclosing breakers."
  -NERC, 2012



source: NERC

Overall Project Objective

- Linear sensitivities, e.g., Injection Shift Factors, Loss Factors, are used in many online ORA tools
- Existing approaches to computing such sensitivities typically employ an AC or DC **model**; this is not ideal because
  1. Accurate model containing up-to-date topology is required
  2. Results may not be applicable if actual system evolution does not match predicted operating points
- Phasor Measurement Units (PMUs) provide high-speed voltage and current measurements that are time-synchronized
- Objectives:
  1. Estimate linear sensitivities by exploiting measurements obtained from PMUs without the use of a power flow model
  2. Utilize measurement-based sensitivities to improve the performance of ORA tools

Looking Back

- Developed measurement-based estimation methods for
  - Power flow Jacobian [TSG '16]
  - Injection shift factors [NAPS '14, TSG '16]
  - Line outage angle factors [NAPS '15]
  - Loss factors
- Demonstrated key advantages of proposed measurement-based methods:
  - Eliminate reliance on system models and corresponding accuracy
  - Resilient to undetected system topology, incorrect model data, and operating point changes
- Demonstrated effectiveness of proposed methods for improving the performance of online tools for monitoring and control:
  - Security-constrained economic dispatch [GM '15, TPWRS '16]
  - Locational marginal price formation [TPWRS '16]

Outline

Power System Sensitivities

Fundamental sensitivities:

- Power flow Jacobian (J)
- Injection shift factors (ISFs)
- Participation factors (PFs)

Derived sensitivities:

- Power transfer distribution factors (PTDFs)
- Line outage distribution factors (LODFs)
- Outage transfer distribution factors (OTDFs)
- Loss factors (LFs)
- Line outage angle factors (LOAFs)

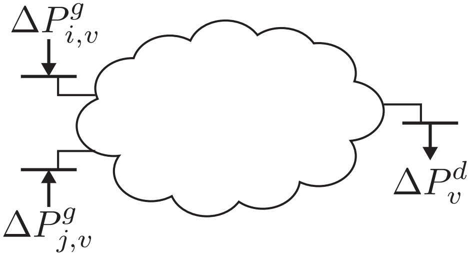
PMU-Based Sensitivity Estimation

- Proposed measurement-based approach relies on inherent fluctuations in net injections
- Collect PMU measurements of, e.g., active flows and injections
- Cast estimation of fundamental sensitivities as an overdetermined linear relationship between measured quantities
- Overdetermined linear system can be solved using, e.g., least-squares error estimation (LSE)
- Other assumptions:
  - Sensitivities are approximately constant across the measurements used in the estimation
  - The regressor matrix has full column rank
- Derived sensitivities can be computed from fundamental ones

Participation Factor Definition

- The Participation factors (PFs) provide the sensitivity of the generator outputs to load net active power injections
- For a generator i and load v, the PF is given by:

$$\Upsilon^p[v,i] = \frac{\text{change in generator } i \text{ output}}{\text{change in load } v \text{ demand}} \approx \frac{\Delta P^g_{i,v}}{\Delta P^d_v}$$



- PFs are typically selected on the basis of generator physical characteristics, e.g., generator capacity or inertia constant

PF Estimation Approach

- We use the PFs and $M > 2D$ load and generation measurements to form an overdetermined linear system:

$$\Delta P_i^g \approx \left[\Delta P^d \; \Delta Q^d\right] \left[(\Upsilon_i^p)^T \; (\Upsilon_i^q)^T\right]^T$$

- Overdetermined linear system can be solved with various approaches, e.g., least-squares error estimation (LSE)

- Proposed measurement-based approach relies on inherent fluctuations in load and generation

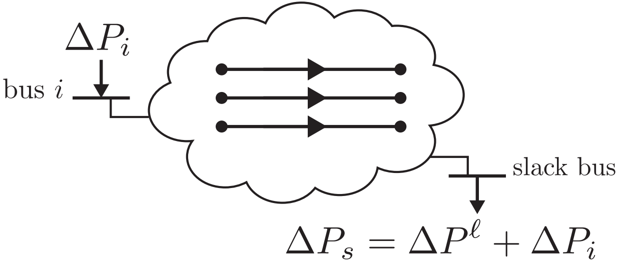
- Other assumptions:
  - The PFs are approximately constant across the M measurements
  - The regressor matrix $\left[\Delta P^d \; \Delta Q^d\right]$ has full column rank

Loss Factor Definition

- Loss factors (LFs) provide the sensitivity of the system-wide losses to bus net active power injections
- For a bus n, the LF is given by:

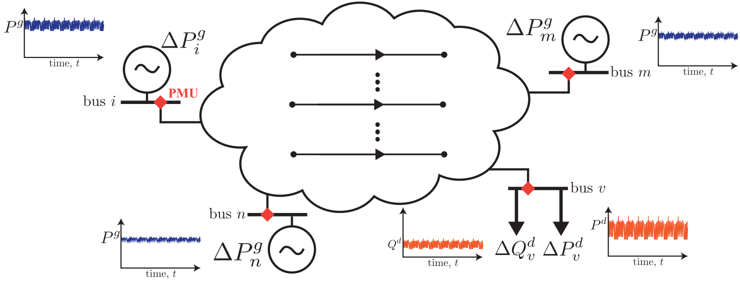
$$\Lambda_n = \frac{\text{change in system-wide losses}}{\text{change in injection at bus } n} \approx \frac{\Delta P^\ell}{\Delta P_n}$$

assuming the injection is balanced by the slack bus



- LFs are typically computed using a power flow model, a given operating point, and a distributed slack policy

Measuring Loss Variation



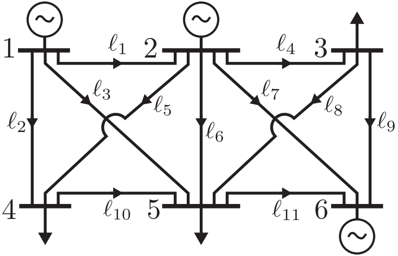
$$\Delta P_i^g[k] = P_i^g[(k+1)\Delta t] - P_i^g[k\Delta t] \qquad \Delta P_v^d[k] = P_v^d[(k+1)\Delta t] - P_v^d[k\Delta t]$$

$$\Delta Q_v^d[k] = Q_v^d[(k+1)\Delta t] - Q_v^d[k\Delta t]$$

- Losses manifest as difference between load injection changes and corresponding generator output changes:

$$\Delta P^\ell[k] = \sum_{i=1}^{G} \Delta P_i^g[k] - \sum_{v=1}^{D} \Delta P_v^d[k] \quad \Longrightarrow \quad \Lambda_v \approx 1 - \sum_{i=1}^{G} \Upsilon^p[v,i])$$

LF Estimation Example



- Simulate 300 measurement instances
- P_3^d increased by 0.2 p.u. between instances 100 and 200
- LFs estimate computed at each measurement instance via LSE with $M = 60$

Table: LFs at instances 75 and 225 (pre- and post-load-change)

			LF error			
	actual LFs		model-based		measurement-based	
bus	pre-change	post-change	pre-change	post-change	pre-change	post-change
1	0.0402	0.0481	-0.00179	-0.00973	0.0015	0.0020
2	0.0404	0.0426	-0.00258	-0.00473	0.0014	0.0014
3	0.0110	0.0047	-0.00243	0.00378	0.0004	0.0002
4	-0.0000	0.0045	0.00108	-0.00348	0.0003	-0.0000
5	-0.0093	-0.0078	-0.00155	-0.00303	0.0006	-0.0006
6	0.0333	0.0308	0.00329	0.00587	0.0013	0.0010
MSE:	-	-	0.0055	0.0137	0.0025	0.0028

[all values in MWh/MWh]

Outline

Online Tools Relying on Linear Sensitivities

- Contingency analysis
- Generation re-dispatch
- Congestion relief
- Real-time security-constrained economic dispatch (SCED)

Security-Constrained Economic Dispatch

SCED problem formulation:

$\max \{\text{social surplus}\}$

$(\min \{\text{generator costs}\})$

subject to:

$$\begin{cases} \text{power balance} \rightarrow \text{requires LFs} \\ \text{equipment limits} \\ \text{network flow constraints} \rightarrow \text{requires ISFs} \\ \text{reliability constraints} \rightarrow \text{requires ISFs, LODFs and LOAFs} \end{cases}$$

Objective:

- Solve the SCED problem using measurement-based sensitivities in place of model based sensitivities

Measurement-Based LMPs

- LMPs and dispatch targets determined with the measurement-based SCED are:
  - adaptive to changing system conditions
  - not affected by erroneous data in the system model
- Measurement-based LMPs:

$$\lambda = \lambda^r \mathbb{1}_N + \begin{bmatrix} \Psi \\ \Psi^s \end{bmatrix}^T \left(\begin{bmatrix} \bar{\mu}^f \\ \bar{\mu}^s \end{bmatrix} - \begin{bmatrix} \underline{\mu}^f \\ \underline{\mu}^s \end{bmatrix} \right) + \lambda^r \Lambda$$

Ψ	Injection shift factors (ISFs)
Ψ^s	Line flow to bus injection sensitivities for selected generator and line outages
Λ	Loss factors (LFs)
λ^r	Lagrange multiplier for power balance constraint
$\overline{\mu}^f, \underline{\mu}^f$	Lagrange multipliers for network flow constraints
$\overline{\mu}^s, \underline{\mu}^s$	Lagrange multipliers for reliability constraints

Case Study

- IEEE 118-bus system with synthetic PMU measurements
- Compare SCED outcomes obtained with:
  (i) nonlinear power flow model LFs [actual]
  (ii) model-based LFs
  (iii) measurement-based LFs
- Scenario 1: Undetected outage LF and SCED impacts
  - Undetected outage of double circuit ℓ_{141}, ℓ_{142}
  - No binding network constraints
- Scenario 2: Incorrect line impedance data contingency analysis and SCED impacts
  - Scale line impedance on each of top 30% of loaded lines by $\kappa \in [0.7, 1.3]$ drawn from a uniform distribution
  - Lower transmission limits so as to introduce congestion

Impact on Dispatch Targets

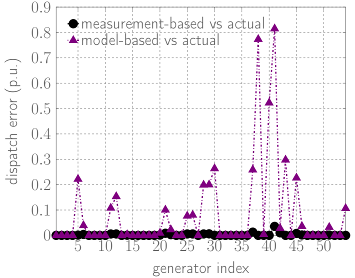


Figure: Errors in P_i^g with respect to ED solution with full power flow LFs for Scenario 1

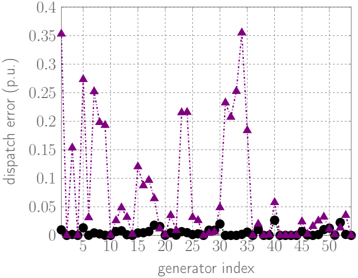


Figure: Errors in P_i^g with respect to ED solution with full power flow LFs for Scenario 2

Impact on LMPs

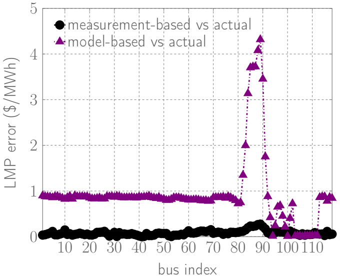


Figure: Errors in prices with respect to ED solution with full power flow LFs for Scenario 1

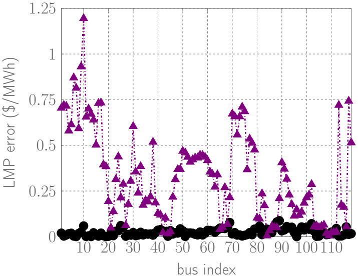


Figure: Errors in prices with respect to ED solution with full power flow LFs for Scenario 2

Outline

Contributions

Developed measurement-based approach for estimating sensitivities

- Utilize PMU measurements to estimate fundamental sensitivities in real-time
- Eliminates the model-dependence of the loss representation in the SCED

Developed measurement-based SCED

- Leverage measurement-based sensitivities, e.g., LFs, to perform contingency selection and to reformulate relevant SCED constraints
- Can be executed without state-estimation or topology processing