Measurement-Based Estimation of Linear Sensitivity Distribution Factors and its Application in Online Analysis Tools

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 3-4, 2014

CERTS
Consortium for Electric Reliability Technology Solutions

Outline

Motivation

- To maintain operational reliability, operators rely on online studies conducted on a model of the system obtained from
  1. A mix of a priori information, including
     - Historical electricity demand patterns
     - Equipment maintenance schedules
     - Up-to-date network topology
  2. Observations in the form of measurement data

- When SCADA systems provide only low-bandwidth, unsynchronized measurement data to a control center:
  - A priori information and observations contributed similarly in, e.g., topology error identification and contingency analysis

- The availability of high-bandwidth, time-synchronized PMU data shifts this balance, creating a larger role for observations
  - This reduces the need for full model information, thereby opening the door to much faster health monitoring

Overall Project Objective

- Linear sensitivity distribution factors (DFs) are used in many online analysis tools:
  - Contingency analysis, generation re-dispatch, congestion relief

- Existing approaches to computing DFs typically employ a 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 sensitivity DFs by exploiting measurements obtained from PMUs without the use of a power flow model
  2. Utilize measurement-based DFs to improve the performance of online tools for monitoring and control

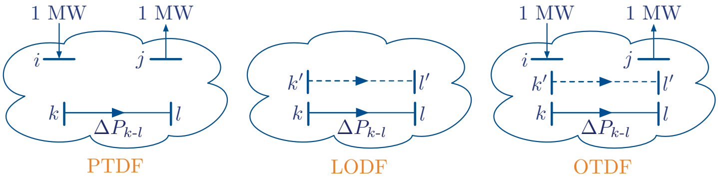
Looking Back

- Developed measurement-based methods for DF estimation:
  - They rely on PMU measurements
  - They do not use of a power flow model
  - Estimation can be achieved with fewer measurements
- Demonstrated key advantages of proposed measurement-based methods:
  - Eliminate reliance on system models and corresponding accuracy
  - Resilient to undetected system topology and operating point changes
  - They can be utilized for detecting topology changes, which enables updating the model in near real time
- Demonstrated effectiveness of proposed methods for improving the performance of online tools for monitoring and control:
  - Contingency analysis
  - Transmission loading relief

Outline

Distribution Factors

- Power transfer distribution factor (PTDF) — the MW change in a branch flow for a 1 MW exchange between two buses
- Line outage distribution factor (LODF) — the MW change in a branch flow due to the outage of a branch with 1 MW pre-outage flow
- Outage transfer distribution factor (OTDF) — the MW change in a branch flow for a 1 MW exchange between two buses with a line outage



These can all be computed once *injection shift factors* are known!

Injection Shift Factor (ISF)

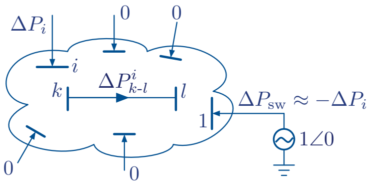
Definition (ISF of line $L_{k\text{-}l}$ w.r.t. bus i)

$\Psi^i_{k\text{-}l}$ is the partial derivative of $P_{k\text{-}l}$ — the real power flow through line $L_{k\text{-}l}$, with respect to P_i — the real power injection at bus i:

$$\Psi^i_{k\text{-}l} := \frac{\partial P_{k\text{-}l}}{\partial P_i}$$

- Let $\Delta P_i(t) = P_i(t + \Delta t) - P_i(t)$
- Denote the change in line $L_{k\text{-}l}$ flow resulting from $\Delta P_i(t)$ by $\Delta P^i_{k\text{-}l}(t)$
- Based on the definition of ISF, it follows that

$$\Psi^i_{k\text{-}l} := \frac{\partial P_{k\text{-}l}}{\partial P_i} \approx \frac{\Delta P^i_{k\text{-}l}(t)}{\Delta P_i(t)}$$



Injection Shift Factor (ISF)

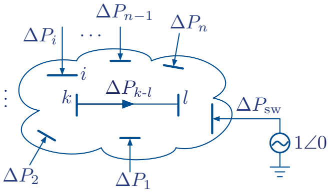
Definition (ISF of line $L_{k\text{-}l}$ w.r.t. bus i)

$\Psi^i_{k\text{-}l}$ is the partial derivative of $P_{k\text{-}l}$ — the real power flow through line $L_{k\text{-}l}$, with respect to P_i — the real power injection at bus i:

$$\Psi^i_{k\text{-}l} := \frac{\partial P_{k\text{-}l}}{\partial P_i}$$

- Let $\Delta P_i(t) = P_i(t + \Delta t) - P_i(t)$
- Denote the change in line $L_{k\text{-}l}$ flow resulting from $\Delta P_i(t)$ by $\Delta P^i_{k\text{-}l}(t)$
- Based on the definition of ISF, it follows that

$$\Psi^i_{k\text{-}l} := \frac{\partial P_{k\text{-}l}}{\partial P_i} \approx \frac{\Delta P^i_{k\text{-}l}(t)}{\Delta P_i(t)}$$

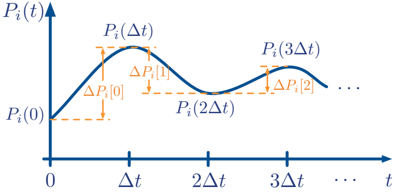


ISF Computation Approach

$$\Psi^i_{k\text{-}l} \approx \frac{\Delta P^i_{k\text{-}l}(t)}{\Delta P_i(t)} \implies \Delta P^i_{k\text{-}l}(t) \approx \Delta P_i(t)\Psi^i_{k\text{-}l}$$

Total variation as sum of partial variations:

$$\Delta P_{k\text{-}l} \approx \Delta P^1_{k\text{-}l} + \cdots + \Delta P^i_{k\text{-}l} + \cdots + \Delta P^n_{k\text{-}l}$$
$$\Delta P_{k\text{-}l} \approx \Delta P_1\Psi^1_{k\text{-}l} + \cdots + \Delta P_i\Psi^i_{k\text{-}l} + \cdots + \Delta P_n\Psi^n_{k\text{-}l}$$



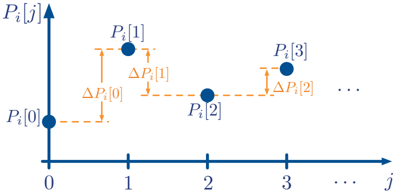
- $\Delta P_i(t) = P_i(t + \Delta t) - P_i(t)$
- $\Delta P_{k\text{-}l}(t) =$ $P_{k\text{-}l}(t + \Delta t) - P_{k\text{-}l}(t)$

ISF Computation Approach

$$\Psi^i_{k\text{-}l} \approx \frac{\Delta P^i_{k\text{-}l}(t)}{\Delta P_i(t)} \implies \Delta P^i_{k\text{-}l}(t) \approx \Delta P_i(t)\Psi^i_{k\text{-}l}$$

Total variation as sum of partial variations:

$$\Delta P_{k\text{-}l} \approx \Delta P^1_{k\text{-}l} + \cdots + \Delta P^i_{k\text{-}l} + \cdots + \Delta P^n_{k\text{-}l}$$
$$\Delta P_{k\text{-}l} \approx \Delta P_1 \Psi^1_{k\text{-}l} + \cdots + \Delta P_i \Psi^i_{k\text{-}l} + \cdots + \Delta P_n \Psi^n_{k\text{-}l}$$



- Discretize with $t = j\Delta t$
- $\Delta P_i[j] = P_i[j+1] - P_i[j]$
- $\Delta P_{k\text{-}l}[j] = P_{k\text{-}l}[j+1] - P_{k\text{-}l}[j]$

ISF Computation Approach

- Stacking m of these measurement instances up:

$$\underbrace{\begin{bmatrix} \Delta P_{k\text{-}l}[1] \\ \vdots \\ \Delta P_{k\text{-}l}[j] \\ \vdots \\ \Delta P_{k\text{-}l}[m] \end{bmatrix}}_{\Delta P_{k\text{-}l} \in \mathbb{R}^m} \approx \underbrace{\begin{bmatrix} \Delta P_1[1] & \cdots & \Delta P_i[1] & \cdots & \Delta P_n[1] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Delta P_1[j] & \cdots & \Delta P_i[j] & \cdots & \Delta P_n[j] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Delta P_1[m] & \cdots & \Delta P_i[m] & \cdots & \Delta P_n[m] \end{bmatrix}}_{\Delta P \in \mathbb{R}^{m \times n}} \underbrace{\begin{bmatrix} \Psi^1_{k\text{-}l} \\ \vdots \\ \Psi^i_{k\text{-}l} \\ \vdots \\ \Psi^n_{k\text{-}l} \end{bmatrix}}_{\Psi_{k\text{-}l} \in \mathbb{R}^n}$$

- Proposed measurement-based approach relies on inherent fluctuations in load and generation
- Other assumptions:
  - The ISFs are approximately constant across the $m+1$ measurements
  - The regressor matrix ΔP has full column rank

Solution Methods

- Let $e = e_l + e_m$
  1. e_l: inherent error arising from the linearization assumption
  2. e_m: PMU measurement noise

$$\Delta P_{k\text{-}l} = \Delta P \Psi_{k\text{-}l} + e$$

where $\Delta P_{k\text{-}l} \in \mathbb{R}^m$, $\Delta P \in \mathbb{R}^{m \times n}$, and $\Psi_{k\text{-}l} \in \mathbb{R}^n$

- Collect $m > n$ measurement instances and solve via Least-squares errors estimation (LSE)
- Collect $m < n$ measurement instances and solve via sparse-vector recovery techniques:
  - Exploit a sparse representation (i.e., one in which many elements are zero) of the ISFs
  - Solve for the transformed sparse representation
  - Compute actual ISFs by applying the inverse transformation

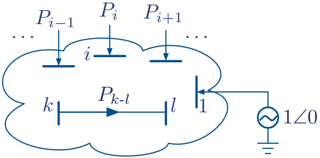
Outline

Case Study Methodology

- Applications Illustrated with IEEE 118-Bus System
- Simulate PMU measurements of random fluctuations in active power injection at each bus

$$P_i = P_i^0 + \sigma_1 P_i^0 v_1 + \sigma_2 v_2$$

  - P_i^0 — nominal power injection at node i
  - $\sigma_1 P_i^0 v_1$ — inherent variability in power injection with time
  - $\sigma_2 v_2$ — measurement noise
  - v_1 and v_2 — pseudorandom values drawn from standard normal distribution
- For each set of random power injection data, compute the power flow, with the slack bus absorbing all power imbalances



Contingency Analysis: Generator Outage

- Consider outage of generator G_{12} as contingency
- Lost generation divided among G_{10}, G_{25}, and G_{26}
- Compare post-contingency line flows obtained via (i) nonlinear power flow model, (ii) model-based ISFs, and (iii) measurement-based ISFs
  - Scenario 1: no undetected topology changes
  - Scenario 2: two undetected transmission line outage

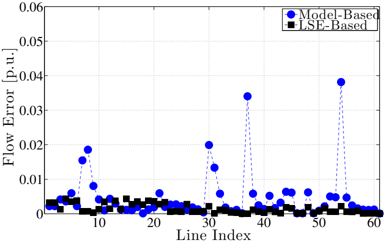


Figure: Error in line flows estimates with respect to full power flow solution for Scenario 1

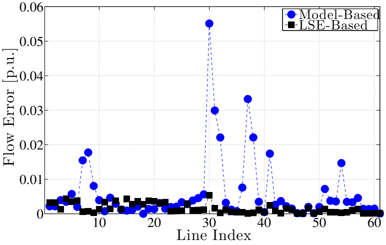


Figure: Error in line flows estimates with respect to full power flow solution for Scenario 2

Contingency Analysis: Line Outage

- Consider outage of line $L_{37\text{-}40}$ as contingency
- Undetected outages of lines $L_{41\text{-}42}$ and $L_{42\text{-}49}$ at $j = 200$
- ISFs computed using previous $m = 500$ sets of measurements at $j = 500$ and $j = 800$

Line $L_{k\text{-}l}$	Actual [p.u.]	Model-based [p.u.]	Measurement-based [p.u.] $j = 500$, $f = 1$	Measurement-based [p.u.] $j = 500$, $f = 0.98$	Measurement-based [p.u.] $j = 800$, $f = 1$
$L_{23\text{-}24}$	0.0344	0.0497	0.0523	0.0296	0.0360
$L_{26\text{-}30}$	2.2564	2.2509	2.2499	2.2589	2.2564
$L_{23\text{-}32}$	0.9465	0.9410	0.9402	0.9481	0.9459
$L_{15\text{-}33}$	0.0930	0.0860	0.0842	0.0933	0.0908
$L_{33\text{-}37}$	-0.1374	-0.1445	-0.1462	-0.1372	-0.1396
$L_{34\text{-}36}$	0.3088	0.3066	0.3064	0.3093	0.3085
$L_{34\text{-}37}$	-0.8849	-0.9049	-0.9125	-0.8855	-0.8928
$L_{38\text{-}37}$	2.6145	2.5585	2.5446	2.6274	2.6052
$L_{37\text{-}39}$	1.2548	1.1697	1.1451	1.2673	1.2346
$L_{37\text{-}40}$	—	—	—	—	—

Table: Post-outage actual and estimated line flows

Generation Re-Dispatch

- Consider undetected outages of lines $L_{41\text{-}42}$ and $L_{42\text{-}49}$ at $j = 200$
  - Pre-outage flow through line $L_{k\text{-}l}$: $P^0_{k\text{-}l}$
  - Post-outage flow through line $L_{k\text{-}l}$: $\tilde{P}^0_{k\text{-}l}$
- Consider outage of transformer $T_{37\text{-}38}$ as contingency
- ISFs computed using previous $m = 500$ sets of measurements at $j = 800$

Line	Pre-contingency [p.u.]		Post-contingency $P_{k\text{-}l}$ [p.u.]		
$L_{k\text{-}l}$	$P^0_{k\text{-}l}$	$\tilde{P}^0_{k\text{-}l}$	Actual	Model-based	Measurement-based
$L_{15\text{-}33}$	0.0470	0.0752	1.0378	0.9001	1.0742

- Suppose thermal limit of line $L_{15\text{-}33}$ is 1 p.u.
- Measurement-based method flags violation, while model-based approach does not

Generation Re-Dispatch to relieve $L_{15\text{-}33}$

- For each generating unit i, define

$$\rho_i := \frac{\overline{\gamma} - \gamma_i}{\Psi^i_{15\text{-}33}}$$

where $\overline{\gamma}$ is the so-called *dispatch* rate, and is determined by the pre-contingency economic dispatch solution

- In order to relieve $L_{15\text{-}33}$, choose unit with the lowest ρ_i

G_i	γ_i [$/MWh]	ISF $\Psi^i_{15\text{-}33}$ Model-based	Meas.-based	ρ_i [$/MW Effect] Model-based	Meas.-based
G_{34}	40.05	-0.0627	-0.0620	**10.6688**	10.7909
G_{36}	40.10	-0.0650	-0.0666	11.0480	10.7933
G_{40}	40.00	-0.0566	-0.0707	10.9217	**8.7546**

- Model-based: dispatch of G_{34} is optimal
- Measurement-based: dispatch of G_{40} is optimal

Outline

Looking Forward

- Major technical accomplishments to be completed in FY14:
  - T1 Test the effectiveness of the DF estimation algorithms using real PMU and SCADA data provided by MISO
  - T2 Define distributed architectures for computation and develop distributed algorithms that adhere to this architectures
  - T3 Develop health monitoring applications that rely on DFs for voltage collapse and small signal stability
- Deliverables and schedule for activities to be completed under FY14 funding
  - T1 Technical report [due at the end of FY14 Q2]
  - T2 Conference submission to NAPS [due at the end of FY14 Q3]
  - T3 Conference submission to HICSS [due at the end of FY14 Q4]
- Risk factors affecting timely completion of planned activities as well as movement through RD&D cycle
  - T1 Failure to obtain appropriate data from MISO