DOE/OE Transmission Reliability Program

Automated Reliability Reports (ARR) – Grid Performance Metrics Using Model-less Algorithms

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Project Objectives

- Provide automated reliability measures of closeness to operations limits with minimal model data
- Verify adequacy and accuracy of voltage, thermal and stability transmission reliability metrics and model-less algorithms for automated reports
- Develop algorithms for predicting post-contingency reliability measures <u>without relying on the system power flow model</u>
    - Reliance on linear sensitivity distribution factors (DFs) obtained from PMU measurements

Accomplishments this Year

- **Completed** — Off-line test and validation of grid reliability performance metrics using model-less pre-contingency algorithms
- **Completed** — Develop model-less post-contingency algorithms
- **Completed** — Initial testing of model-less post-contingency algorithms
- **In progress** — Larger scale testing of model-less post-contingency algorithms using MISO data

Deliverables and Schedule

- Development of model-less post-contingency algorithms – concept completed, April 2013
- Evaluating model-less post-contingency algorithms using large scale data (MISO), September 2013

Factors Affecting Timely Completion

- **Grid Phasor Data Availability** — Waiting for Host PMU installations and readiness
- **Grid Phasor Data Quality** — Experience using phasor measurements is demonstrating the need for better phasor data quality filters and estimation of grid performance metrics uncertainties
- **Completion of Prototype Deployment at MISO** — MISO personnel and IT Contractors availability
- **Effectiveness of post-contingency algorithms** — MISO data and computations will provide important validation results

Possible Follow on Funding for FY 14

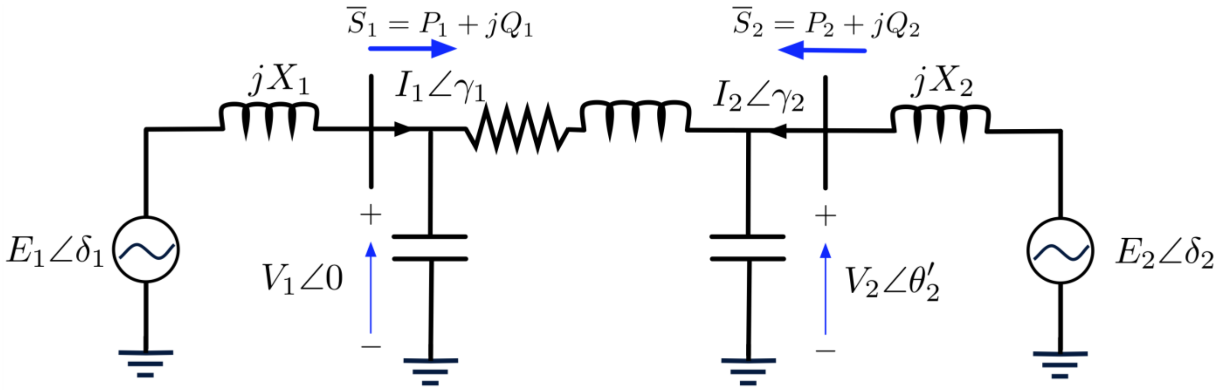
- Complete the Field Demonstration with MISO for improving models, performance metrics, monitoring visualization, and tracking automatic reports
- Assess grid phasor data quality and availability using field demonstration results and research more effective phasor data quality filters and estimation of grid performance metrics uncertainties
- Research identification and definition of a grid reliability composite index using this project grid performance metrics and MISO reliability coordinators experience during the Field Demonstration

Reliability Metrics

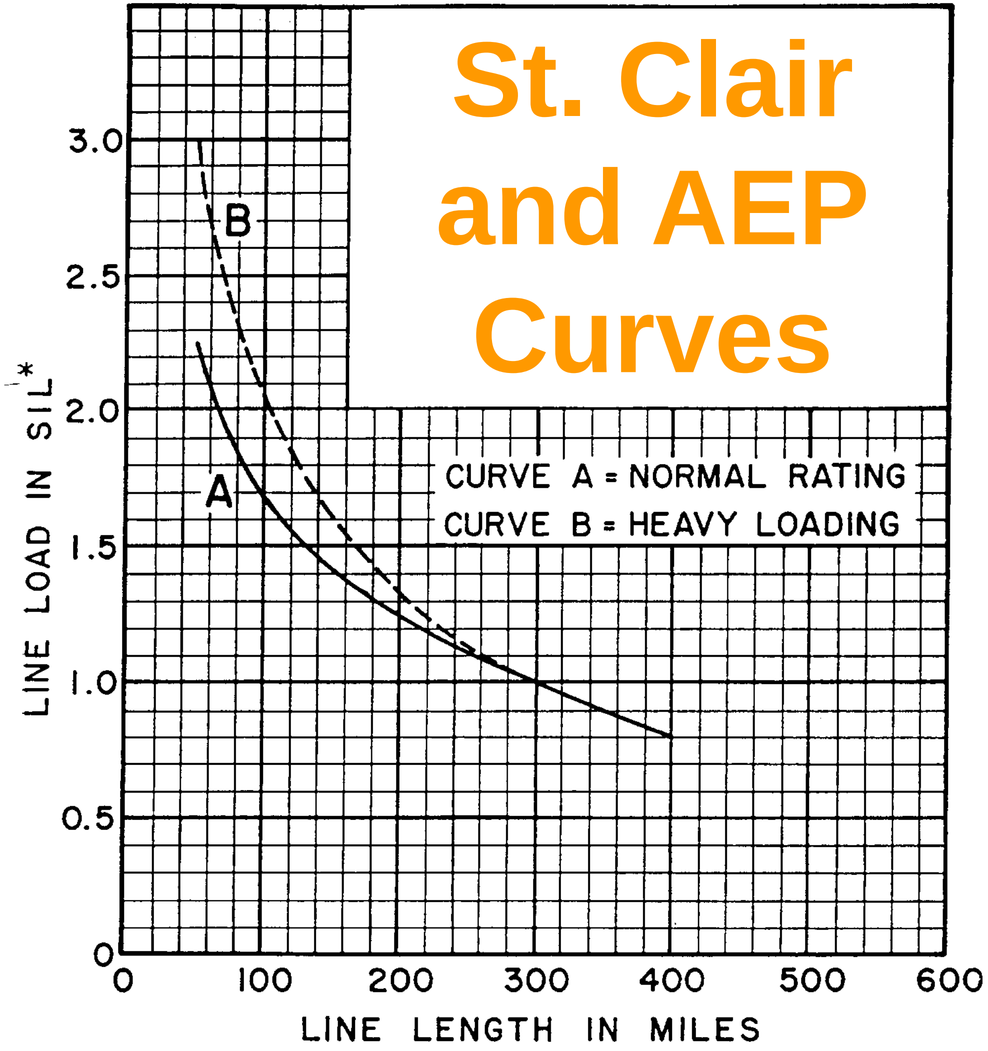
- **Thermal** — Short term and long term – typically measured in Amps or power (MW or MVA) – this one is fairly easy to find from measurements.
- **Voltage** — Plus or minus 5% of nominal – this one is fairly easy to find from measurements.
- **Stability** — Voltage collapse, SS stability, transient stability, bifurcations – margins to each critical point – this one is hard to find.
- **Other**
  - Control limits - Ramp constraints, under/over excitation, taps
  - Short circuit current capability

Conjecture

If you compute a Thevenin Equivalent as seen by both ends of a transmission line, the angle across the system will indicate a level of loading in the system – and this angle should approach 90 degrees at the critical line/equivalent combination. At 45 degrees there would be a 30% margin.



St. Clair and AEP Curves



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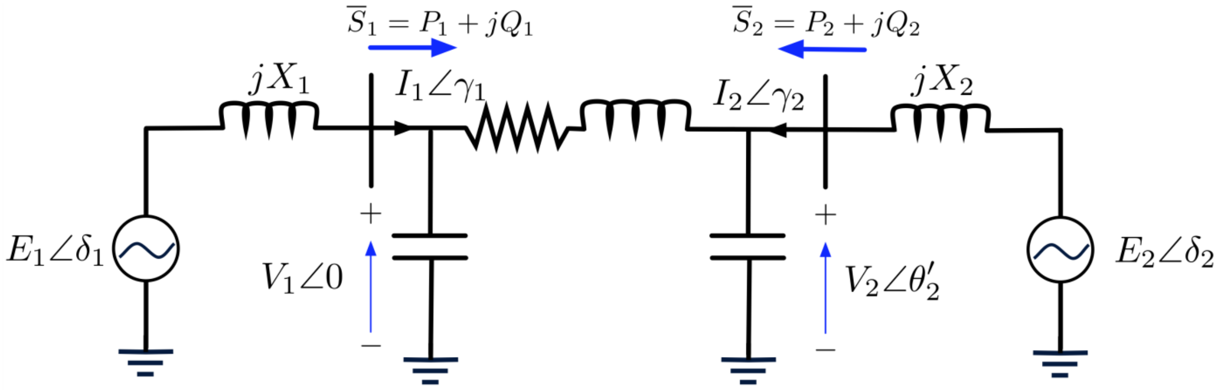
Utilizing PMU Data to Obtain the Equivalent Model



- In the above line plus equivalents, PMU measurements at both ends will provide voltages V_1, V_2, (magnitude and angle) and currents I_1 and I_2 (magnitude and angle)

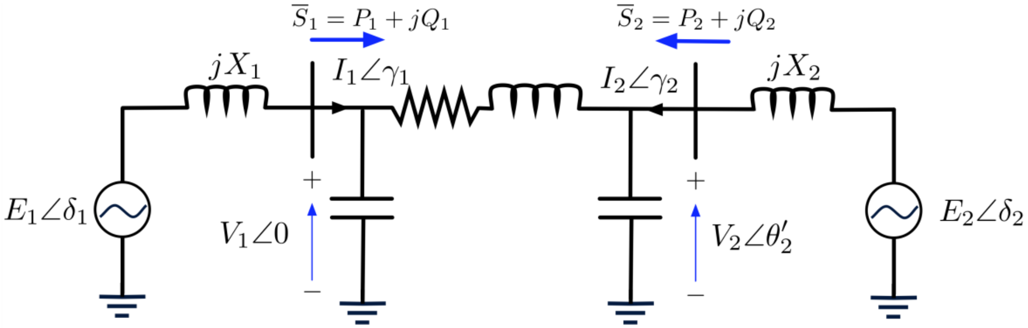
- From these measurements, we only need to compute the angle difference $\delta_1 - \delta_2$ (we really don't care about E or X)

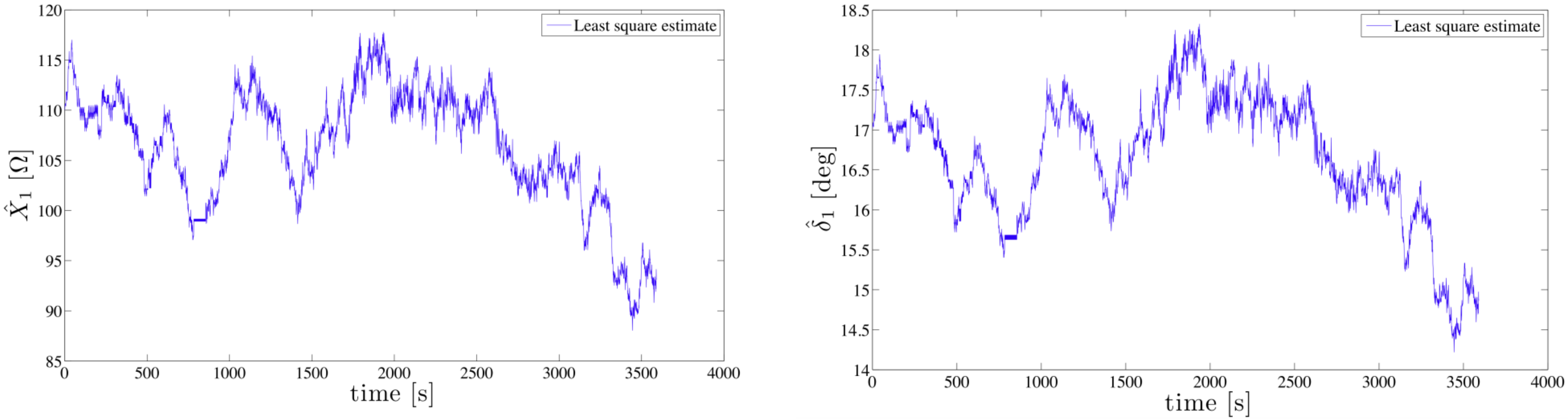
Real Data Example

- The set of measured quantities include
  - Line-to-line voltages at both ends of the line
  - 3-phase complex power flowing into both ends of the line
- Measured quantities are sampled ten times per second
- Pseudo-measurements of line currents are obtained from the relation between complex power, voltage, and current
- Least Squares Errors (LSE) estimation is used to obtain per-second estimates of measurements and pseudo-measurements
- Since the system is at off-nominal frequency, phasor measurements rotate at a speed equal to the difference between the actual system frequency and the nominal frequency

765 kV Line Case Study

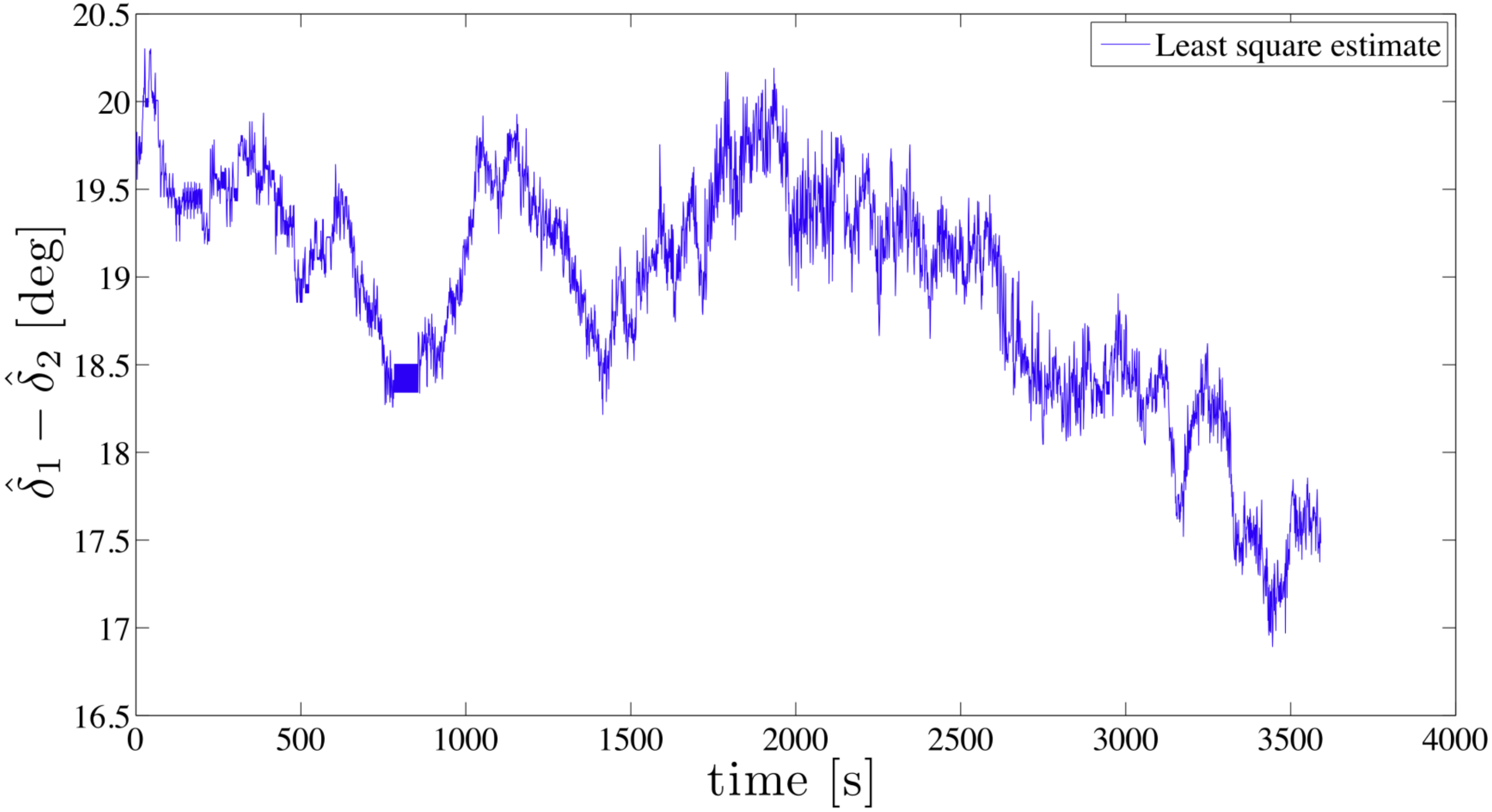
- Stability margin analysis
- Date:
  - 09/03/10
- Time horizon:
  - 18:07:12EDT-19:07:12EDT
- E_1=E_2=765 kV (assumed)





Thevenin parameter estimates for equivalent

Angle Across the System Measure



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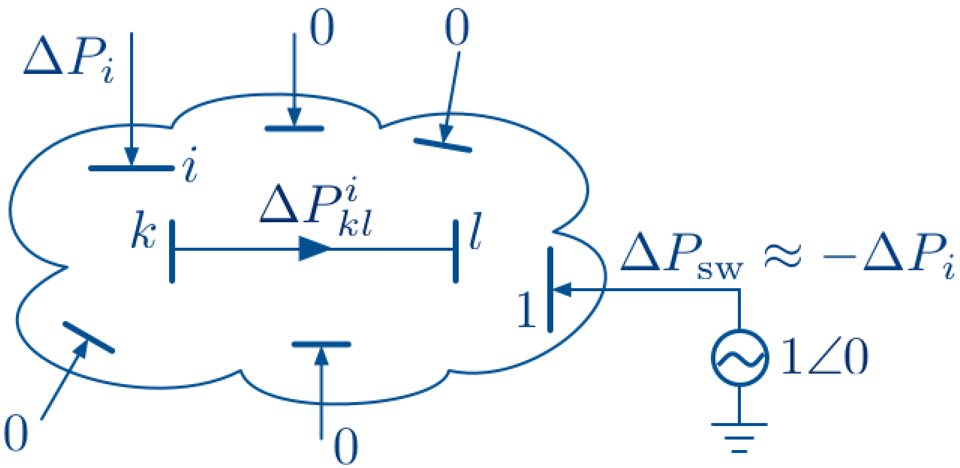
Post-Contingency Analysis

- Create the Thevenin equivalents using the pre-contingency key line flow data.
- For a list of contingencies, compute the change in the key line flow data and the corresponding Thevenin equivalent parameters using standard distribution factors (computed from phasor data across the grid).
- Determine the closeness to operating limits using the same algorithms as for the pre-contingency case.
- Compute the system equivalent inertia from monitored frequency.
- Evaluate transient stability for specified faults on key lines using a single machine vs infinite bus from the pre-contingency Thevenin equivalents and inertia dynamics for the fault-on trajectory.

Injection Shift Factor (ISF)



- Ψ_{kl}^{i}: the ISF of line kl w.r.t. bus i
- ISF definition: partial derivative of the real power flow through line kl due to real power injection at bus i w.r.t. to the real power injection at bus i
- Thus, the ISF gives the estimated change in power flow on a transmission line due to a unit change in power injected at a particular bus

$$\Psi_{kl}^{i} := \frac{\partial P_{kl}}{\partial P_i} \approx \frac{\Delta P_{kl}^{i}(t)}{\Delta P_i(t)}$$

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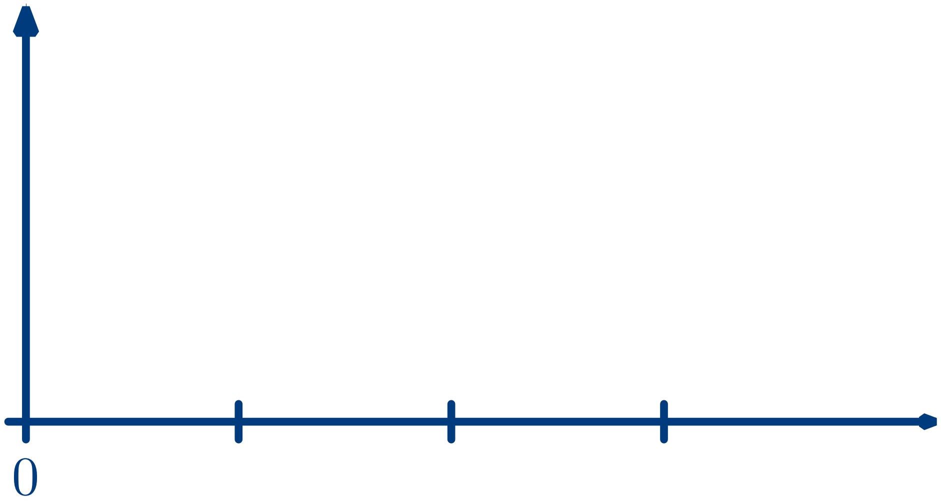
Other Distribution Factors

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

These can all be computed once ISFs are known!

ISF Computation Approach

- Measurements are taken every Δt units of time



$$\Delta P_i(t) = P_i(t + \Delta t) - P_i(t)$$

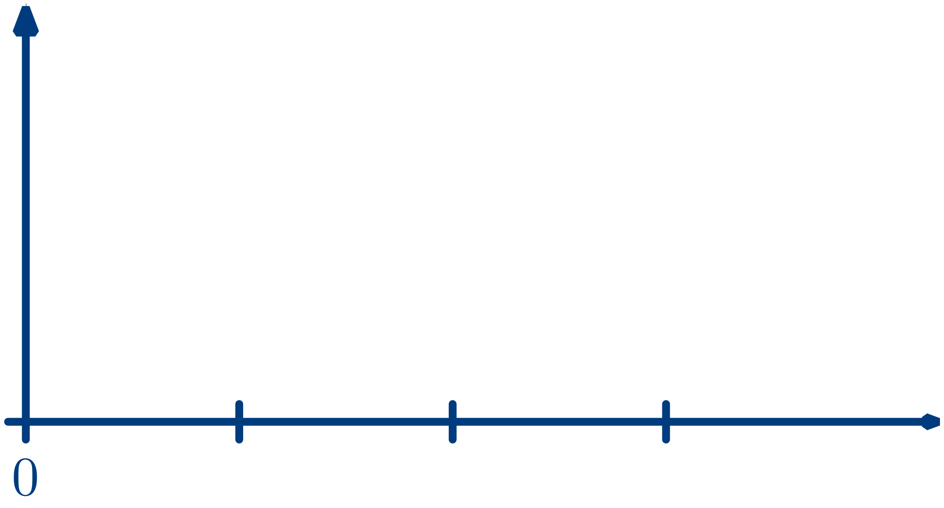
$$\Delta P_{kl}(t) = P_{kl}(t + \Delta t) - P_{kl}(t)$$

- The total change in active power flow in line kl can be approximated as the sum of the change due to the real power injection at each bus by superposition, i.e.,

$$\begin{aligned}\Delta P_{kl}(t) &\approx \Delta P_{kl}^{1}(t) + \cdots + \Delta P_{kl}^{i}(t) + \cdots + \Delta P_{kl}^{n}(t)\\ &\approx \Delta P_1(t)\Psi_{kl}^{1} + \cdots + \Delta P_i(t)\Psi_{kl}^{i} + \cdots + \Delta P_n(t)\Psi_{kl}^{n}\end{aligned}$$

ISF Computation Approach

- Measurements are taken every Δt units of time



Discretize with $t = j\Delta t$

$$\Delta P_i[j] = P_i[j+1] - P_i[j$$

$$\Delta P_{kl}[j] = P_{kl}[j+1] - P_{kl}[j$$

- The total change in active power flow in line kl can be approximated as the sum of the change due to the real power injection at each bus by superposition, i.e.,

$$\begin{aligned}\Delta P_{kl}[j] &\approx \Delta P_{kl}^{1}[j] + \cdots + \Delta P_{kl}^{i}[j] + \cdots + \Delta P_{kl}^{n}[j] \\ &\approx \Delta P_1[j]\Psi_{kl}^{1} + \cdots + \Delta P_i[j]\Psi_{kl}^{i} + \cdots + \Delta P_n[j]\Psi_{kl}^{n}\end{aligned}$$

ISF Computation Approach

- Stacking m of these measurement instances up, where $m > n$, we obtain

$$\underbrace{\begin{bmatrix} \Delta P_{kl}[1] \\ \vdots \\ \Delta P_{kl}[j] \\ \vdots \\ \Delta P_{kl}[m] \end{bmatrix}}_{y} = \underbrace{\begin{bmatrix} \Delta P_1[1] & \cdots & \Delta P_i[1] & \cdots & \Delta P_n[1] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Delta P_1[j] & \cdots & \Delta P_i[j] & \cdots & \Delta P_n[j] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Delta P_1[m] & \cdots & \Delta P_i[m] & \cdots & \Delta P_n[m] \end{bmatrix}}_{H} \underbrace{\begin{bmatrix} \Psi_{kl}^{1} \\ \vdots \\ \Psi_{kl}^{i} \\ \vdots \\ \Psi_{kl}^{n} \end{bmatrix}}_{x}$$

- An over-determined system of the form $y = Hx$, which we solve via least-squares estimation:

$$\hat{x} = (H^T H)^{-1} H^T y$$

- Method relies on inherent fluctuations in load and generation
- Other assumptions
  1. The ISFs are approximately constant across the $m+1$ measurements
  2. The regressor matrix H has full column rank

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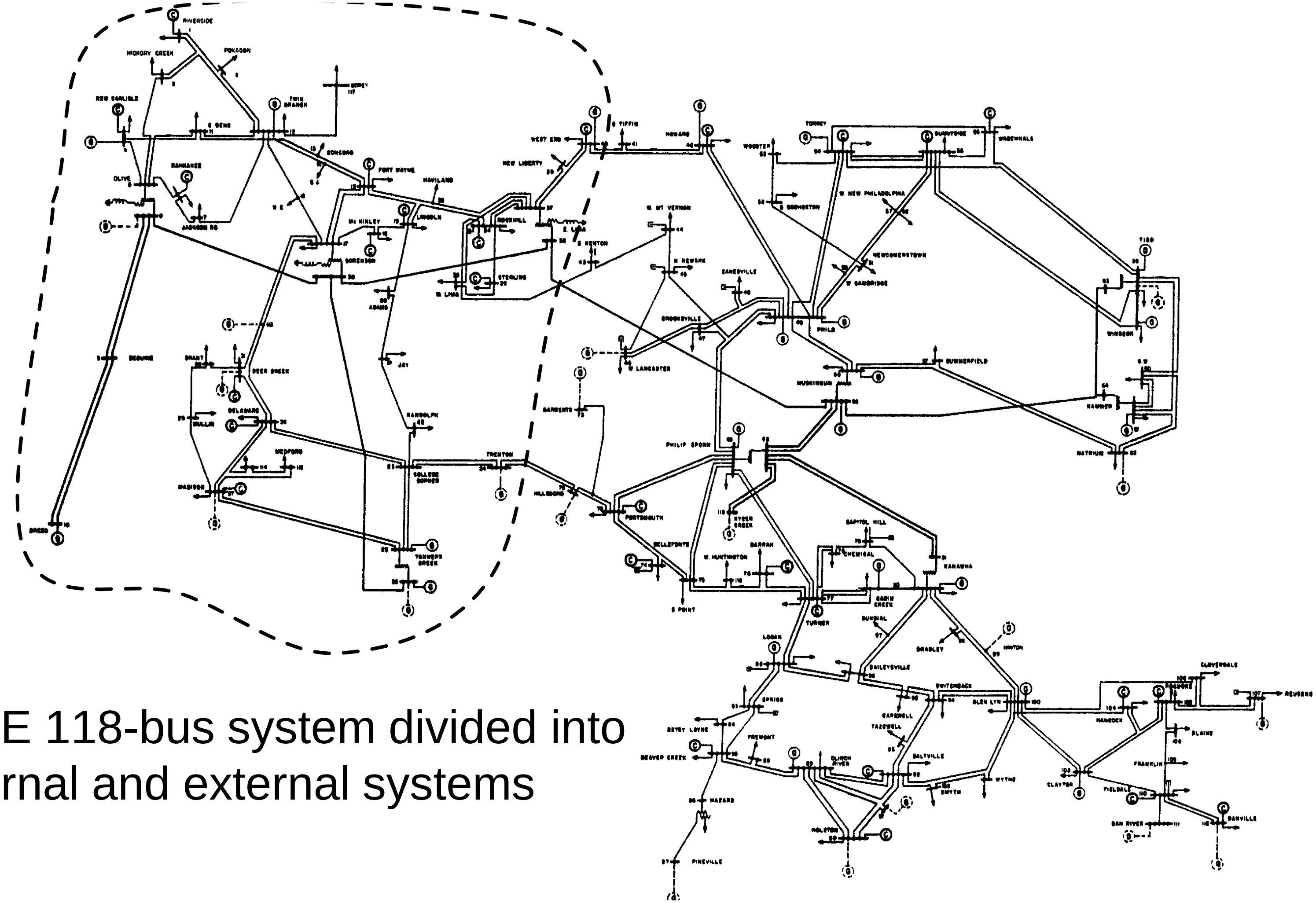
Large Test Case Studies

- IEEE 118-bus system divided into internal and external systems
- Case studies with undetected line outages in external system
  1. Generator outage contingency
     - Redistribute lost generation among nearby generators
     - Investigate effect on internal system transmission line flows
  2. Line outage contingency
     - Investigate effect on transmission line flows caused by outage
  3. Generation re-dispatch in constrained system
     - System is not N-1 secure
     - Dispatch out-of-merit generators optimally using ISFs
- In all case studies:
  - Compare results obtained from actual power flow solutions, model-based approach, and proposed measurement-based approach
  - On average, measurement-based approach is more accurate than model-based

Large Test Case Studies



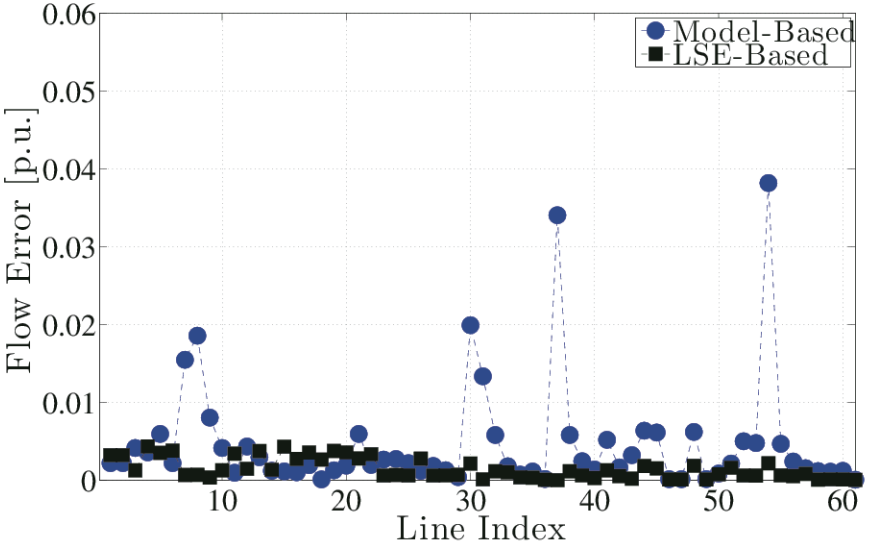
- IEEE 118-bus system divided into internal and external systems

Case 1: Generator Contingency

- Outage in G_{12}; P_{12} redistributed to G_{10}, G_{25}, and G_{26}
- Compare deviations away from actual post-contingency flows resulting from the model- and measurement-based approaches

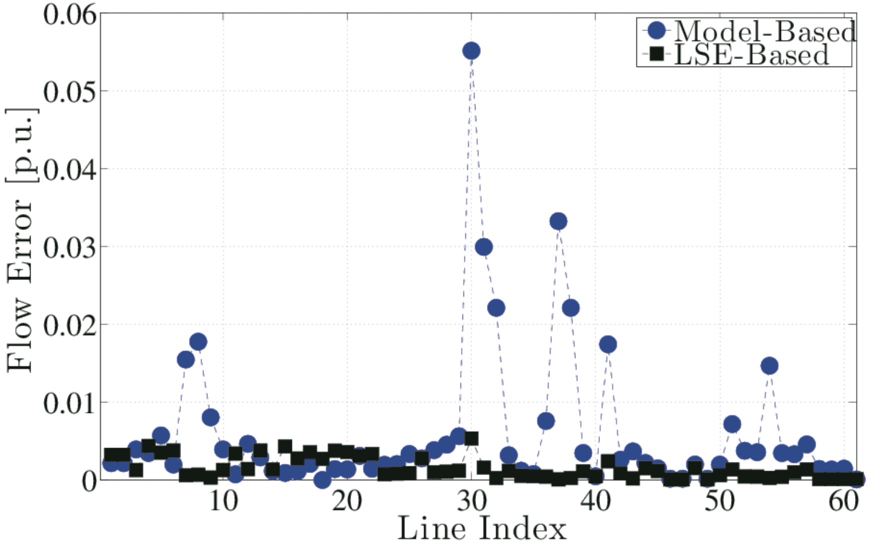
Base Case

Model matches actual system



Modified External System

Outages in l_{65-68} and l_{47-69} but model is not updated



Case 2: Line Outage Contingency

- Undetected outage of l_{41-42} and l_{42-49} in external system at $j = 200$
- Conduct contingency analysis for hypothetical outage of l_{37-40}
- Use data collected from $j = 0$ to $j = 500$

Line	**Pre-contingency**	**Post-contingency [p.u.]**		
	Actual [p.u.]	Actual	Model-based	LSE
l_{23-24}	0.0189	0.0344	0.0497	0.0296
l_{26-30}	2.2624	2.2564	2.2509	2.2589
l_{23-32}	0.9519	0.9465	0.9410	0.9481
l_{15-33}	0.1004	0.0930	0.0860	0.0933
l_{33-37}	-0.1301	-0.1374	-0.1445	-0.1372
l_{34-36}	0.3115	0.3088	0.3066	0.3093
l_{34-37}	-0.8590	-0.8849	-0.9049	-0.8855
l_{38-37}	2.6851	2.6145	2.5585	2.6274

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