IMPLEMENTATION ISSUES FOR HIERARCHICAL, DISTRIBUTED STATE ESTIMATORS

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Objectives

Investigate the research issues of implementation:

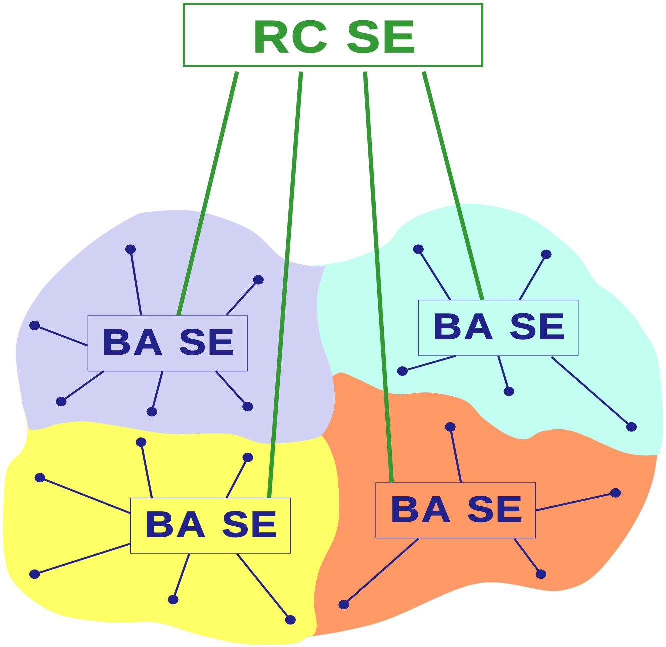
- time skew of the data,
- the accuracy of the network data base,
- the availability of raw data versus SE data,
- the proprietary nature of the data.

Determine:

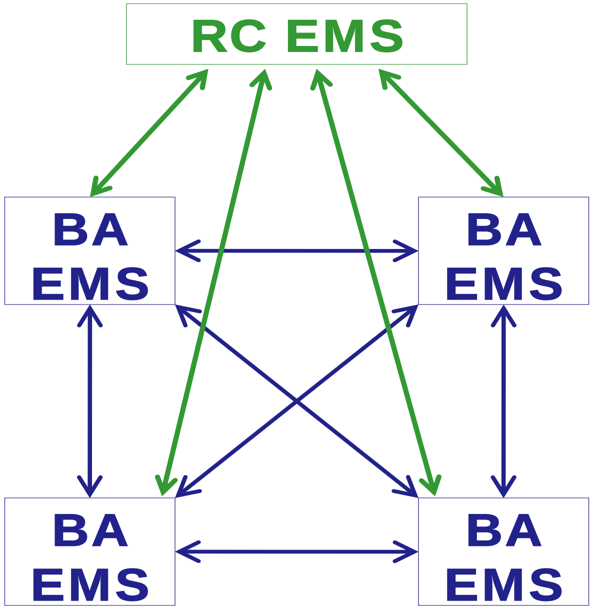
- Requirements that will make such a hierarchical distributed SE feasible

State Estimator

HIERARCHICAL STATE ESTIMATOR



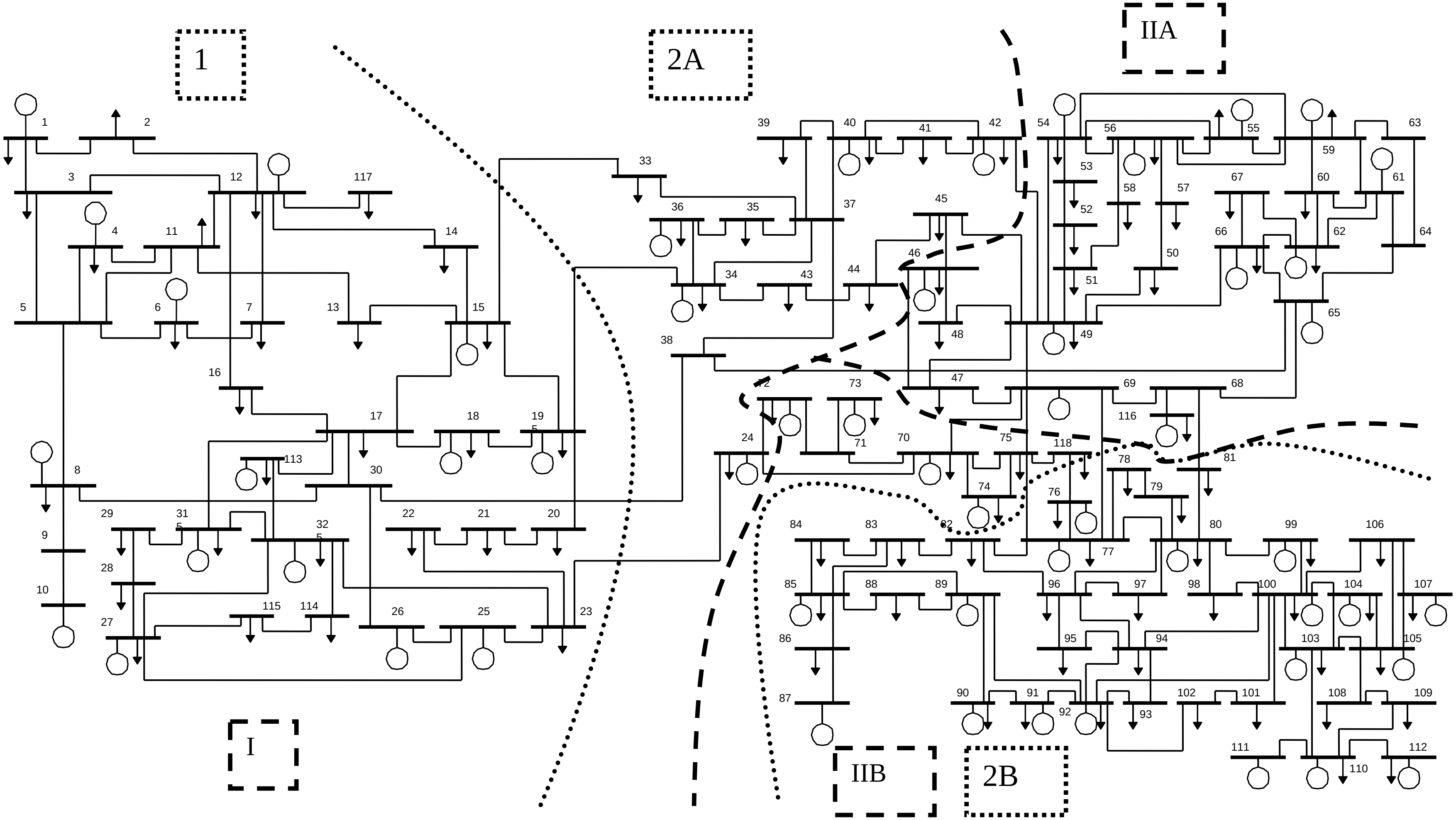
COMMUNICATION NETWORK



Example: 118-Bus IEEE System

- IEEE-118 bus system is adopted as the testbed system for simulations to study the effects of various levels and types of data exchange on internal state estimation accuracy
- IEEE-118 bus system is decomposed into several areas with 2 different configurations

Example: 118-Bus IEEE System



Example: 118-Bus IEEE System

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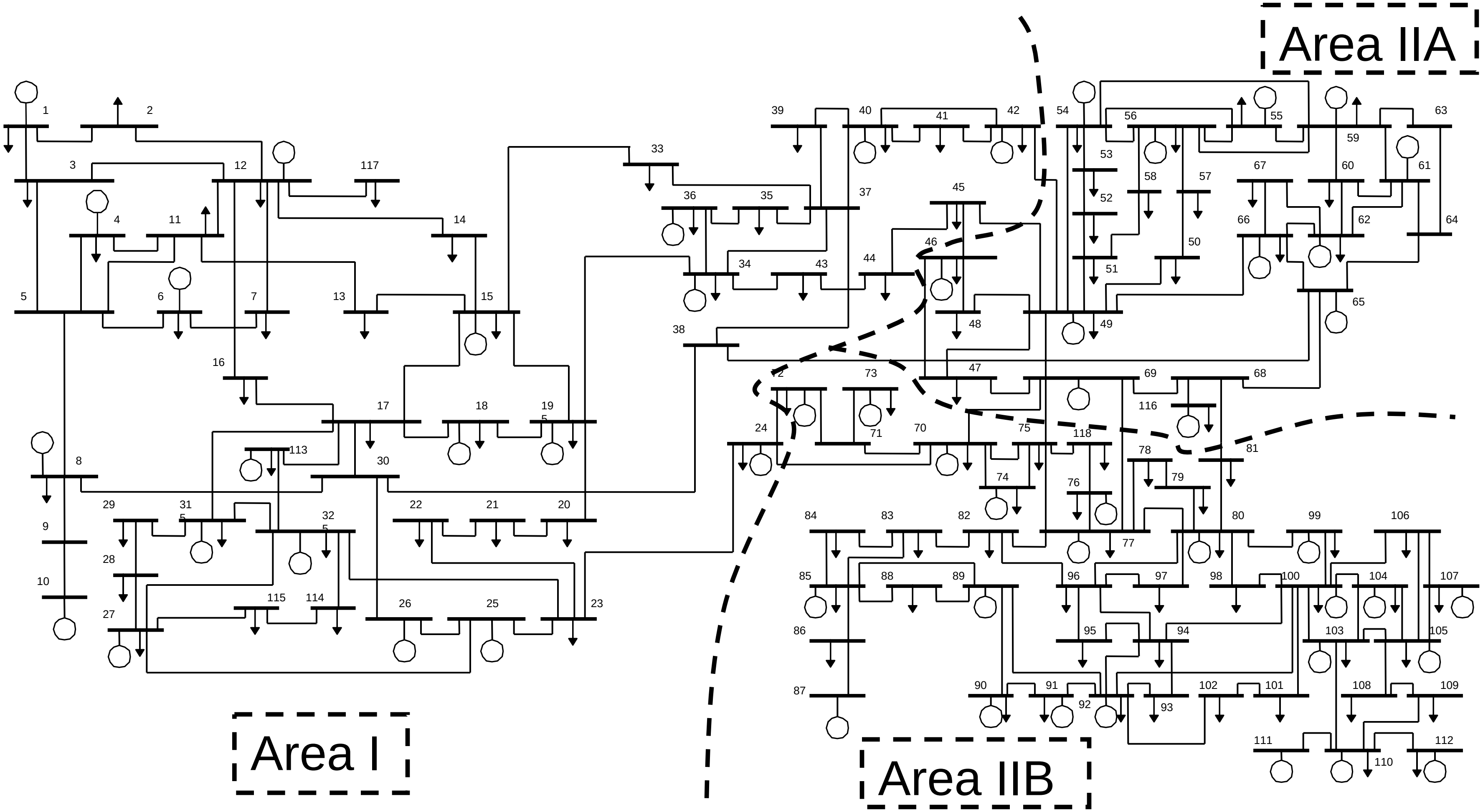
- Preliminary studies
  - A list of cases is created where a single topology change occurs in the external system for each case
  - Simulations are run with different levels of data exchange between internal and external system for state estimation
  - State Estimation accuracy metric

$$J = \frac{1}{N}\sum_{i}^{N}\left[(\vec{V}_i - V_i^{PF})\bullet(\vec{V}_i - V_i^{PF})^*\right]$$

  - Having some level of data exchange suffices to improve internal state estimation accuracy
  - Having an excessive amount of data does not necessarily improve state estimation accuracy once the data exchanged already guarantees a high level of accuracy

Example: 118-Bus IEEE System

- Effects of loss of communication with part of external system on accuracy of internal state estimator



Example: 118-Bus IEEE System

- A list of topology errors was created and simulations were run for the entire list

$$J = \frac{1}{N}\sum_{i}^{N}\left[(\vec{V}_i - V_i^{PF})\bullet(\vec{V}_i - V_i^{PF})^*\right]$$

	J (Mean)
No data exchange	**2.188×10^{-1}**
Loss of communication (data exchange (P,Q) with area IIA only)	**2.065×10^{-3}**
Normal situation (data exchange (P,Q) with areas IIA and IIB)	**5.0×10^{-5}**

Example: 118-Bus IEEE System

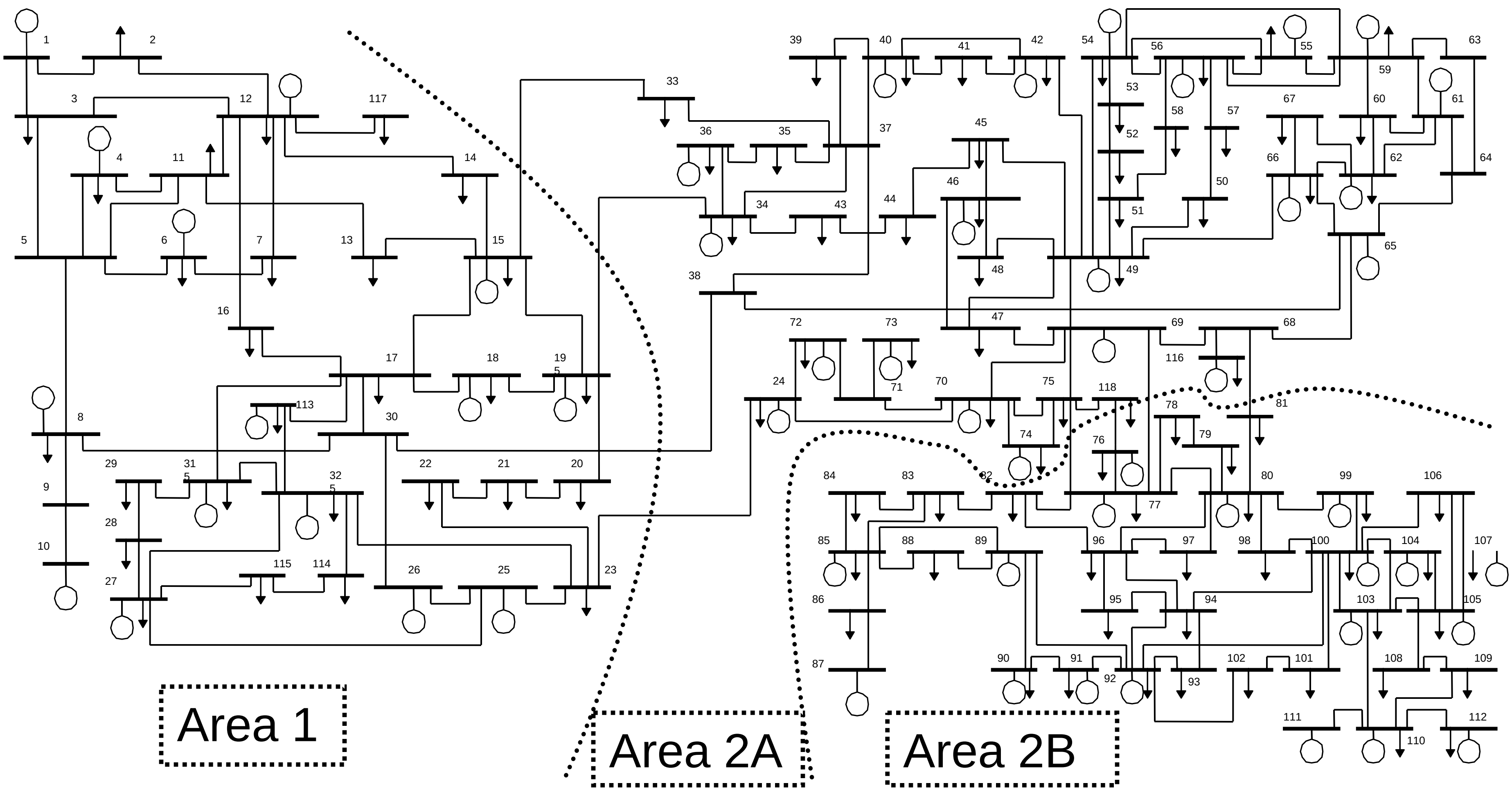
- Lack of knowledge of topology errors can lead to large errors at certain buses
- Even data exchange with some areas of the external system helps improve accuracy of the internal state estimator in some cases
- Obviously full data exchange is ideal

Example: 118-Bus IEEE System

- The effects of loss of communication with certain parts of the external system is studied for the general case
- Further investigation on effects of loss of communication
  - Focus is on effect of incorrect topology on state estimation accuracy
  - Testbed system is decomposed in a different way
  - Lost of communication is with immediate neighbor (Area 2A)
  - All topology changes will occur in Area 2A

Example: 118-Bus IEEE System

- Further studies on effects of loss of communication with part of external system



Example: 118-Bus IEEE System

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- A list of topology errors in area 2A was created and simulations were run for the entire list

$$J = \frac{1}{N}\sum_{i}^{N}\left[(\vec{V}_i - V_i^{PF})\bullet(\vec{V}_i - V_i^{PF})^*\right]$$

	J (Mean)
No data exchange	1.85×10^{-2}
Loss of communication (data exchange (P,Q) with area 2B only)	1.86×10^{-2}
Normal situation (data exchange (P,Q) with areas 2A and 2B)	6.15×10^{-5}
Normal situation (full data exchange with areas 2A and 2B)	1.97×10^{-5}

Example: 118-Bus IEEE System

- Specific values of J for topology changes on i) line 42-49 ii) line 69-70 iii) line 69-75

$$J = \frac{1}{N}\sum_{i}^{N}\left[(\vec{V}_i - V_i^{PF})\bullet(\vec{V}_i - V_i^{PF})^*\right]$$

	J (scen i)	J (scen ii)	J (scen iii)
No data exchange	**2.102×10^{-1}**	**7.949×10^{-2}**	**1.824×10^{-2}**
Loss of communication (data exchange (P,Q) with area 2B only)	**2.097×10^{-1}**	**7.811×10^{-2}**	**1.907×10^{-2}**
Loss of communication (data exchange (line flows) with area 2B only)	**2.595×10^{-1}**	**8.574×10^{-2}**	**4.155×10^{-2}**
Normal situation (data exchange (P,Q) with areas 2A and 2B)	**9.96×10^{-5}**	**9.06×10^{-5}**	**1.16×10^{-5}**
Normal situation (full data exchange with areas 2A and 2B)	**2.04×10^{-5}**	**1.15×10^{-5}**	**1.62×10^{-5}**

Example: 118-Bus IEEE System

- Effects of loss of communication
  - Data exchange with external system does not necessarily improve internal state estimation accuracy when topology data is incorrect
  - Greater knowledge of analog data may not produce any effect in improving internal state estimator accuracy
  - It appears that topology data plays an important role in ensuring the accuracy of state estimation

Example: 118-Bus IEEE System

- Exchange of SCADA data versus state estimated data
  - Results obtained are practically equivalent to exact solution when either up to date SCADA or state estimated data is exchanged
  - For SCADA data exchange, state estimation of the full external model is required
  - For state estimated data exchange, state estimation of the full external model is not required
  - Large errors may appear at boundary buses when state estimated data which is not up to date is exchanged

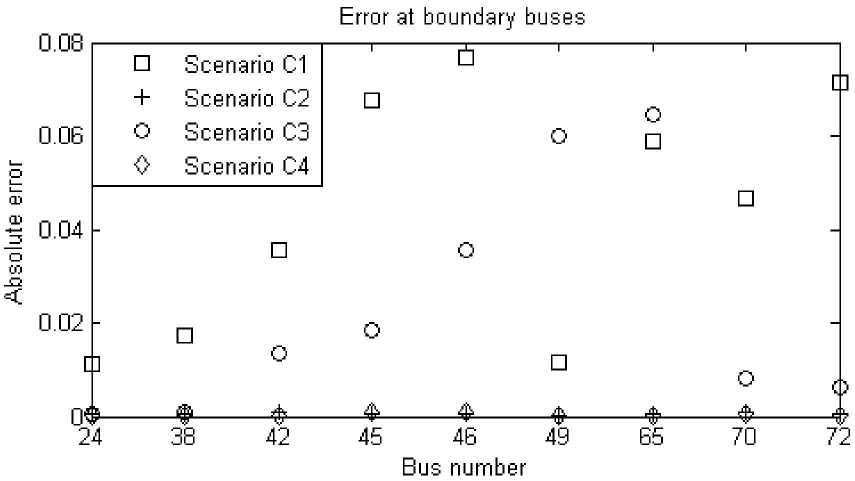
Example: 118-Bus IEEE System

- Exchange of SCADA data versus state estimated data

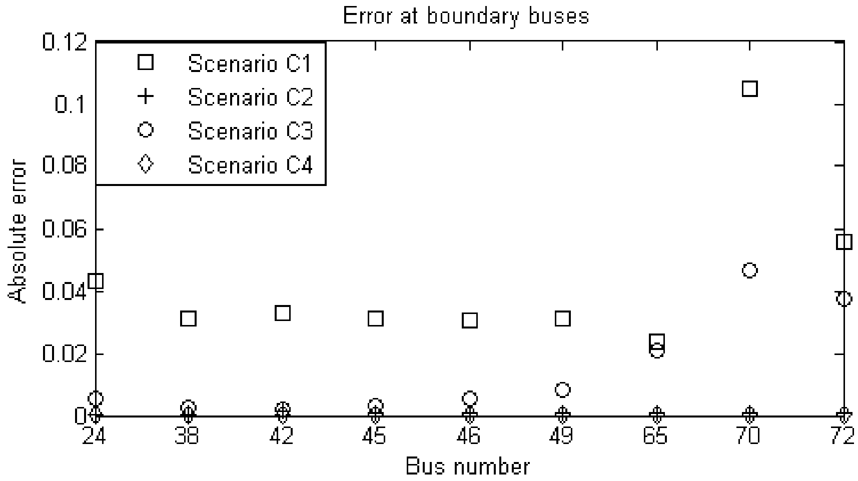
Scenario	Type of data exchange
C1	No data exchange
C2	SCADA data exchange with external system
C3	State estimated data exchange where data is initially not up to date
C4	State estimated data exchange where data is up to date initially

Example: 118-Bus IEEE System

- SCADA data exchange VS state estimated data exchange (configuration 1)



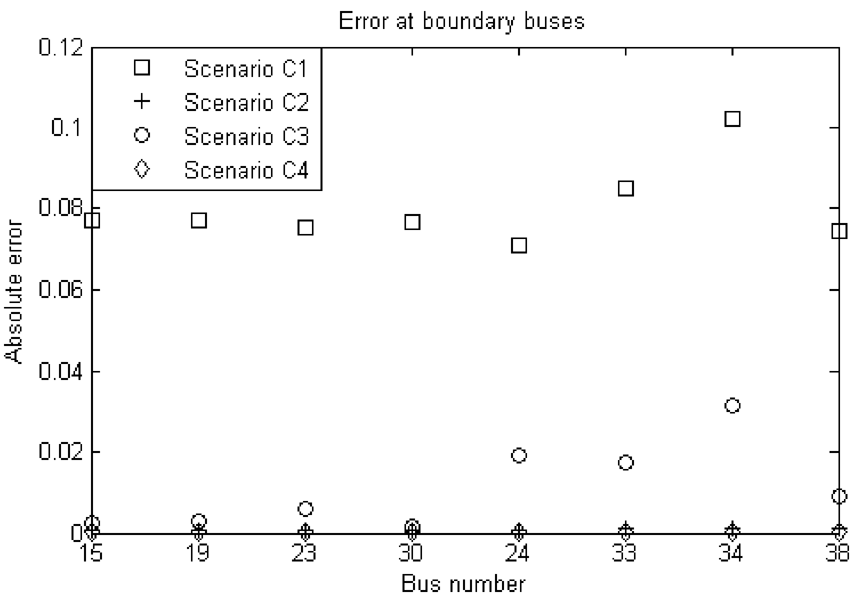
Topology change on line 49-66



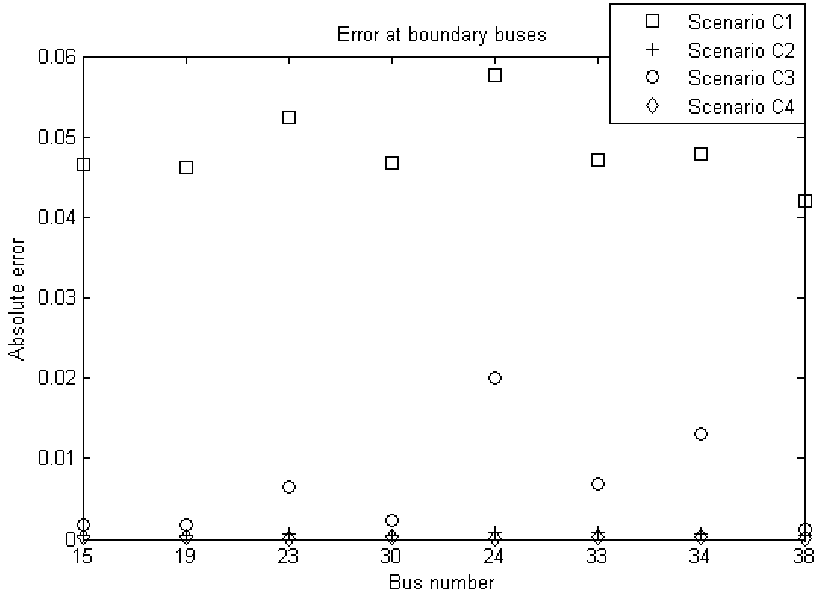
Topology change on line 69-70

Example: 118-Bus IEEE System

- SCADA data exchange VS state estimated data exchange (configuration 2)



Topology change on line 42-49



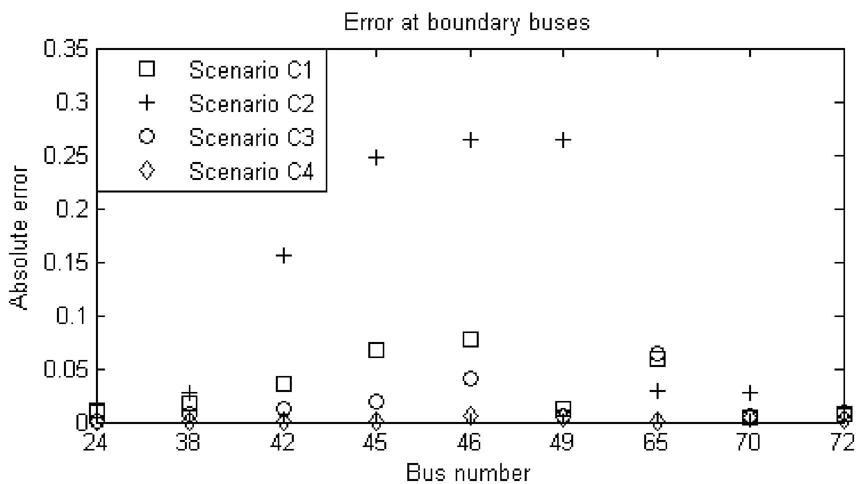
Topology change on line 69-70

Example: 118-Bus IEEE System

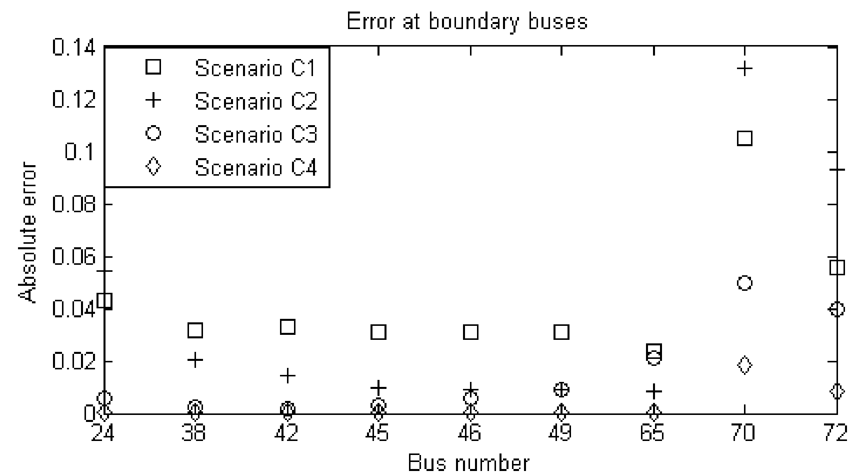
- Exchange of SCADA data versus state estimated data
  - Simulations are run for the situation where the topology processor in the external system is malfunctioning, i.e. topology processor does not see topology changes
  - SCADA data exchange – all analog measurements are correct, but topology data used during internal state estimation will be incorrect
  - SE data exchange – SE results of external system are obtained based on incorrect topology data

Example: 118-Bus IEEE System

- SCADA data exchange VS state estimated data exchange (with topology error in external system) (configuration 1)



Topology change on line 49-66



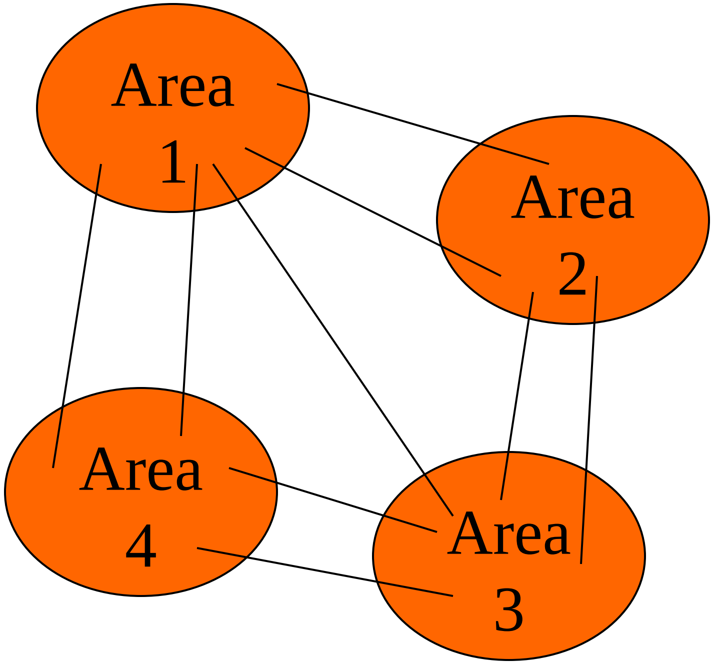
Topology change on line 69-70

Example: 118-Bus IEEE System

- Exchange of SCADA data versus state estimated data with external system topology errors
  - During occurrence of topology errors, implementing SCADA data exchange may lead to even worse state estimation results
  - Correct topology data in previous cycles may alleviate the issue of having incorrect topology data in the current cycle when state estimated data exchange is implemented

Impact on Static Security Analysis

Consider a 4-area system shown below and focus on area 1 state estimator:



Area 1 State Estimator

Input:

- Area 1 measurements
- Limited exchange with areas 2,3,4.

Output:

- Area 1- accurate power flow model
- Areas 2,3,4 -- approx power flow model due to missing measurements

Real-time Contingency Analysis

Area 1 : Contingency Analysis

- Use State Estimation output for area 1
- Use Network Equivalents for areas 2,3,4. Equivalents will be updated using State Estimation results for external areas.

Questions:

- Can a limited number of strategically placed PMUs in the external system help to minimize security analysis errors ?
- What is the optimal strategy to select external real-time measurements to be exchanged in real-time for best results ?

Use of PMUs from the External System

Given a set of buses with phasor measurements in the external system:

- **Determine the effect of using the real-time phasor information from selected external buses on the internal system state estimation solution**
- **Form the updated real-time model for the external system**
- **Evaluate the improvement in the static security assessment (i.e. real-time contingency analysis)**

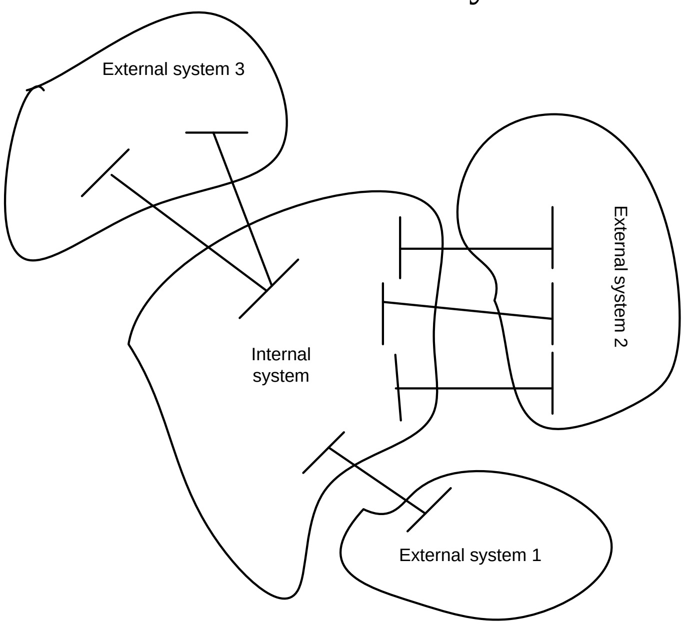
Example: 118-Bus IEEE System

$$J = \frac{1}{n}\sum_{i=1}^{n}(V_i^{ref} - \hat{V}_i)^2 + (\theta_i^{ref} - \hat{\theta}_i)^2$$

Number of PMUs	PMU List	J
No PMUs	(N/A)	1.4906
3 PMUs	89,69,80	1.1012
5 PMUs	61,86,93, 102,90	0.5436
12 PMUs	69,80,89,66, 100,61, 107,102,86, 93,84,108	0.1694

Optimal Selection of External Measurements

Internal and External Systems

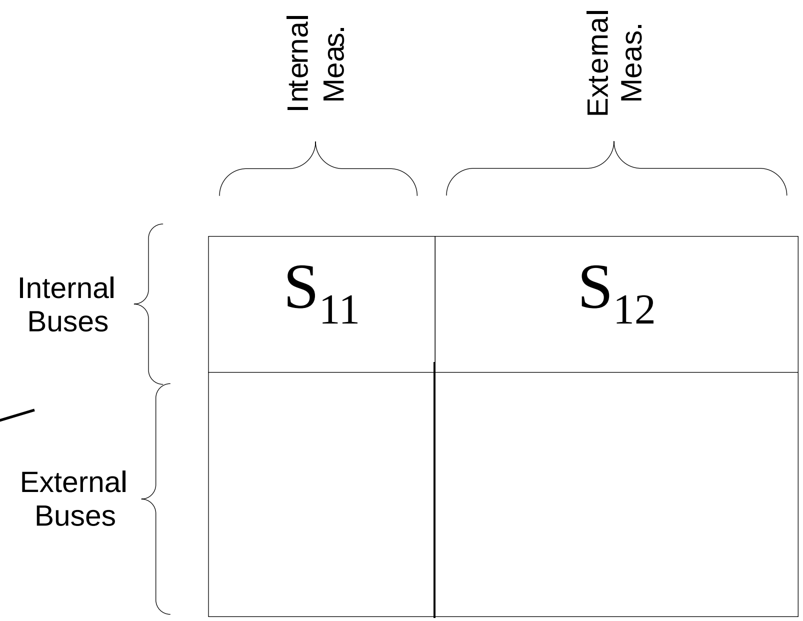


Let the linear model be:

$$[Z] = [H].[X] + [e]$$

Then the estimate for [X] will be given by:

$$[\hat{X}] = S.[Z]$$



$$\begin{bmatrix} \hat{X}_{Int} \\ \hat{X}_{Ext} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} * \begin{bmatrix} Z_{Int} \\ Z_{Ext} \end{bmatrix}$$

Reordered ‘S’ according to internal and external systems

Optimal Selection of External Measurements

$$\Rightarrow \hat{X}_{Int} = S_{11}.Z_{Int} + S_{12}.Z_{Ext}$$

Objective: Determine the significant columns of S_{12}

$$\begin{cases} \min\ K^T \cdot (1-U) \\ \text{subject to } \left|S_{12}(Z_{Ext} \otimes U)\right| < L \end{cases}$$

L: acceptable error limit.
U: is a binary decision vector.
K: is the real-time metering cost.

Validation

Procedure:

1- Simulate real-time internal measurements and selected set of external measurements. Use the base case values for the rest of the external measurements.
2- Run SE and estimate power injections for all external buses in the system.
3- Run contingency analysis, using the external system model.

Example: IEEE 118 Bus system

Chi square test for different error limits.

Chi-square test

$$J = \sum_{i=1}^{n} \frac{(Z_1'(i) - \hat{Z}_1'(i))^2}{R_{ii}}$$

Lower and upper limits	# of picked measurements	J (Chi-square result)
L=0.01	24 out of 166	18637.14
L=1e-4	61 out of 166	3462.20
L=1e-5	69 out of 166	3.453
L=1e-35	166 out of 166	0.521

Accuracy Metric

Error in the Estimated State

$$\rho = \frac{1}{M} \sum_{i=1}^{M} \left(\left(\frac{V_i^{ref} - \hat{V}_i}{V_i^{ref}} \right)^2 + \left(\frac{\theta_i^{ref} - \hat{\theta}_i}{\theta_i^{ref}} \right)^2 \right)$$

Error bounds	# of picked measurements	ρ
L=10	0 out of 166	0.1291
L=0.01	24 out of 166	0.01358
L=1e-4	61 out of 166	3.89*e-4
L=1e-5	69 out of 166	2.04*e-6

Contingency Analysis

Contingency Example: Line 26-30 in the internal system is taken out

Results:

Error bounds	# of picked measurements	β
L=10	0 out of 166	0.2698
L=0.01	24 out of 166	0.00694
L=1e-4	61 out of 166	0.000689
L=1e-5	69 out of 166	0.000579

$$\beta = \frac{1}{M}\sum_{i=1}^{M}\left(\left(\frac{V_i^{ref} - V_i^{up}}{V_i^{ref}}\right)^2 + \left(\frac{\theta_i^{ref} - \theta_i^{up}}{\theta_i^{ref}}\right)^2\right)$$

Metric Used for Contingency Analysis Error

Conclusion

- Detailed External Model
  - Analog meas. errors skew results
  - Topology errors skew results
  - SCADA data exchange VS state estimated data exchange results
  - Data exchange shows great improvement when topology data is correct
- Equivalenced External Model
  - Data exchange requires extending model
  - Even modest exchange of PMU data helps
  - Optimally positioned PMU data helps more
- Status
  - Exchange SE data or raw data
  - More external model requires better static database updates
  - Difficulties with studying real SE databases

Questions