



Cyber Security Analysis of State Estimators in Electric Power Systems

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LCCC Workshop on Dynamics,
Control and Pricing in Power Systems
May 19th, 2011

Outline

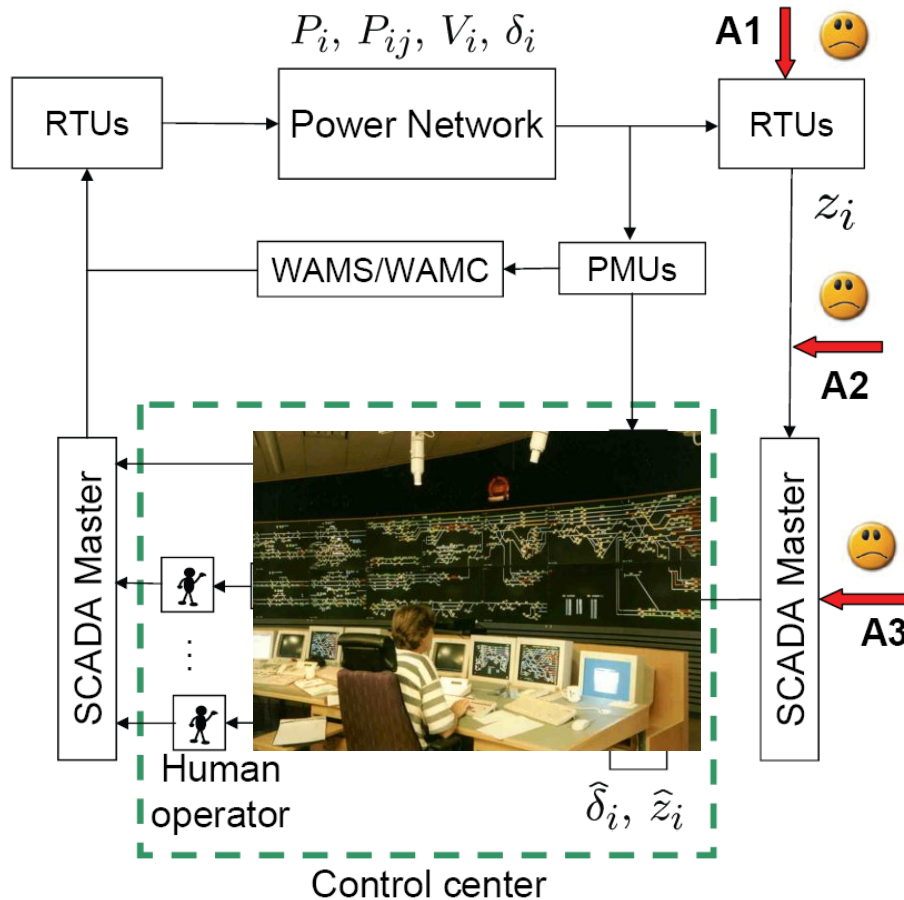
- On state estimation, bad-data detection, and cyber stealth attacks in power systems
- A security index
 - Definition and experimental validation
 - Computation
 - Protection and mitigation strategies
- Conclusions

Background and Motivation

- Northeast U.S. Blackout of August 14th, 2003: 55 million people affected
- Software bug in energy management system stalled alarms in state estimator for over an hour
- Cyber attacks against the power network control center systems pose a real threat to society



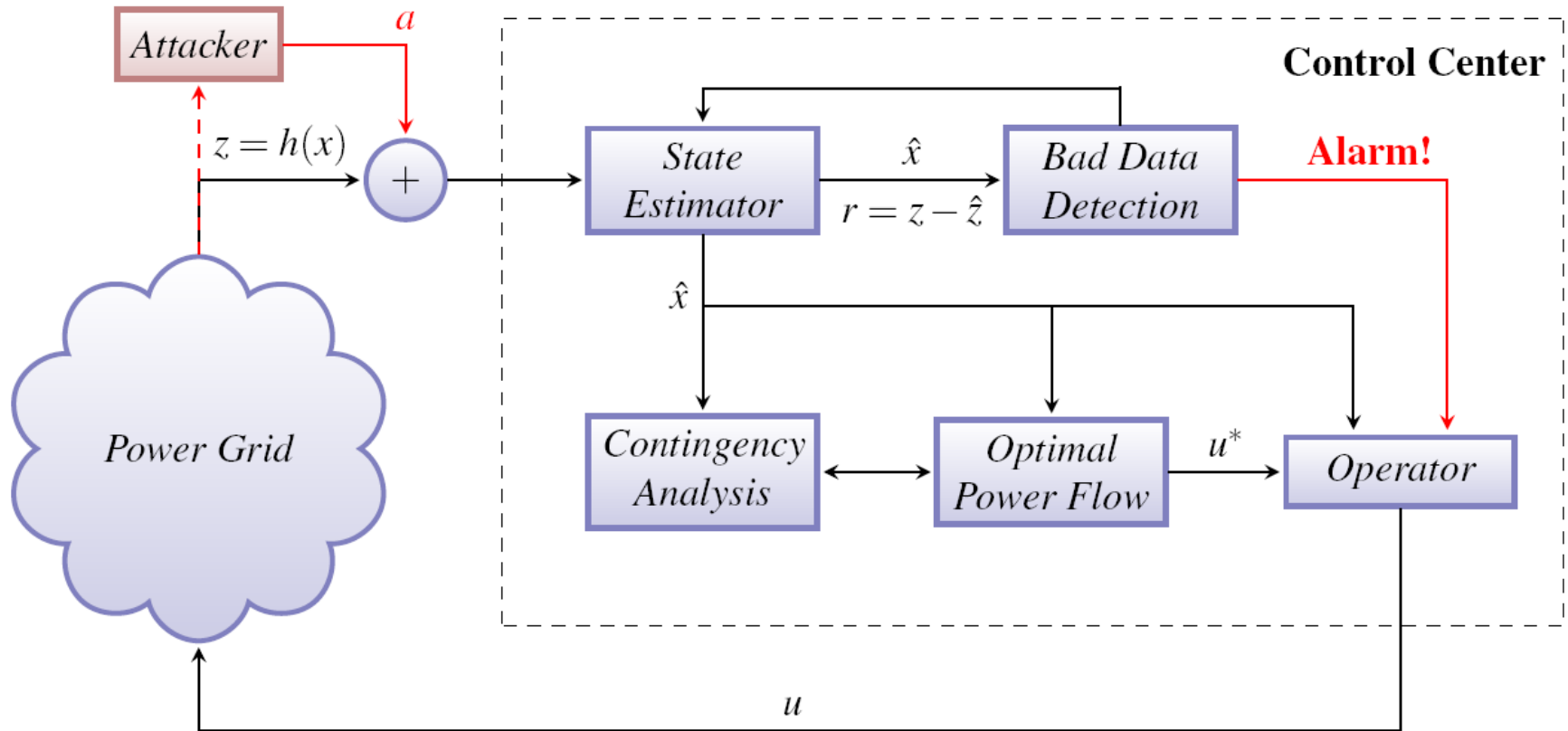
SCADA Systems and False-Data Attacks



- SCADA/EMS used to obtain *accurate state information* to identify faulty equipment, power flow optimization, contingency analysis,...
- Redundant power flow and voltage measurements (z_i) currently sent over *unencrypted communication network*
- How do we strengthen security incrementally against attacks A1-A3?

(SCADA/EMS = Supervisory Control and Data Acquisition/Energy Management Systems)

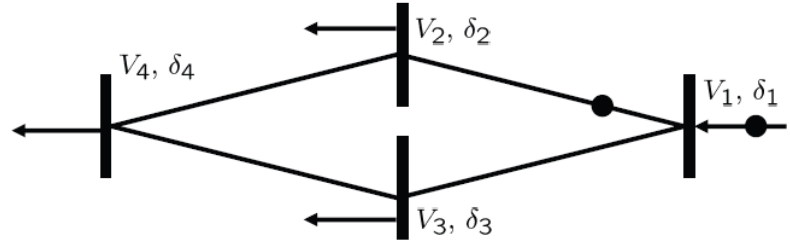
Attacker Model and Bad Data Detection in Control Center



- Scenario: Attacker injects **malicious data** a to corrupt analog measurements in the power grid
- First characterize the set of **undetectable** malicious data a

Power Network and Estimator Models

- Steady-state models:



$$\begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = \begin{pmatrix} \frac{V_1 V_2}{X_{12}} \sin(\delta_1 - \delta_2) + \frac{V_1 V_3}{X_{13}} \sin(\delta_1 - \delta_3) \\ \frac{V_1 V_2}{X_{12}} \sin(\delta_1 - \delta_2) \end{pmatrix} + \begin{pmatrix} e_1 \\ e_2 \end{pmatrix} = h(x) + e \in \mathbb{R}^m$$

- WLS-Estimates of bus phase angles δ_i (in vector \hat{x}):

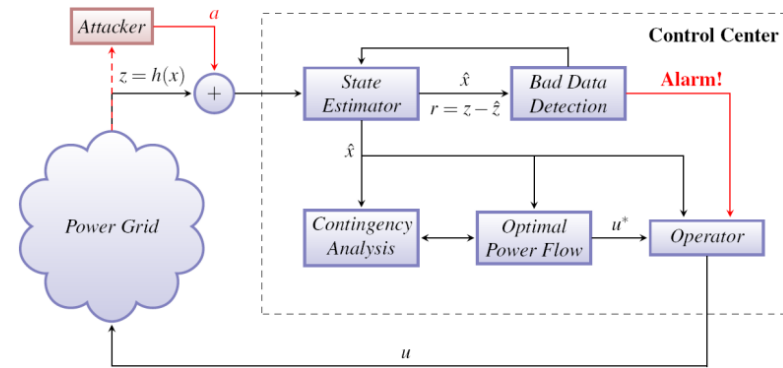
$$\hat{x}^{k+1} = \hat{x}^k + (H_k^T R^{-1} H_k)^{-1} H_k^T R^{-1} (z - h(\hat{x}^k))$$

$$H_k := \frac{\partial h}{\partial x}(\hat{x}_k) \quad R := \mathbf{E} e e^T$$

- Linear DC approximation (\approx ML-estimate):

$$\hat{x} = (H^T R^{-1} H)^{-1} H^T R^{-1} z \quad H := \left. \frac{\partial h(x)}{\partial x} \right|_{x=0}$$

Bad-Data Detection and Undetectable Attacks



- Bad-Data Detection triggers when residual r is large

$$r := z - \hat{z} = z - H\hat{x} = z - H(H^T R^{-1} H)^{-1} H^T R^{-1} z$$

- Characterization of undetectable malicious data a :

$$z_a := z + a$$

$$a = Hc \in \mathcal{R}(H)$$

$$r = z - \hat{z} = z_a - \hat{z}_a$$

- The attacker has a lot of freedom in the choice of a !
- $a_k \neq 0$ means measurement device k is corrupted.
Attacker likely to seek sparse solutions a !

Security Index α_k

- Assume attacker wants to make undetectable attack against measurement k

$$\alpha_k := \min_c \|a\|_0 \quad (\text{sparsest possible attack})$$

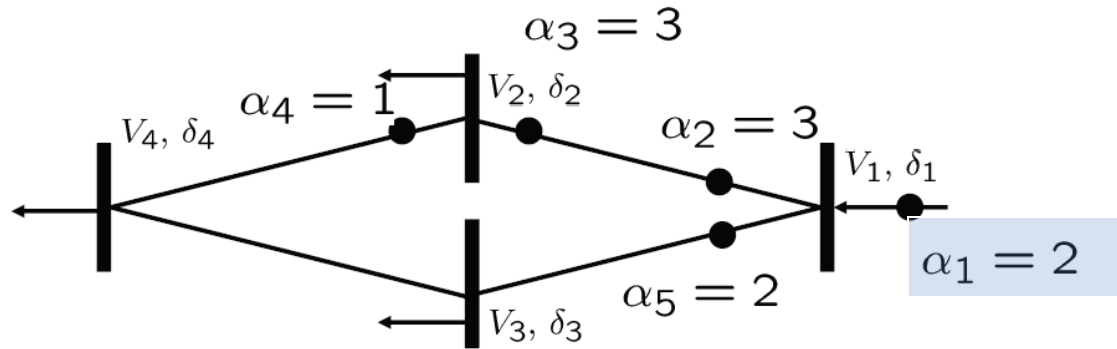
$$a = Hc \quad (\text{undetectable attack})$$

$$a_k = 1 \quad (\text{targets measurement } k)$$

$$(\|a\|_0 := \#\{a_i; a_i \neq 0\})$$

- Estimates complexity of “least-effort undetectable attack” on measurement k
- **Example:** $\alpha_1=2 \Rightarrow$ undetectable attack against measurement 1 involves *at least two* measurements
- Non-convex optimization problem. How solve efficiently?

Example of the Index α_k



- Sparse attack corresponding to α_k :

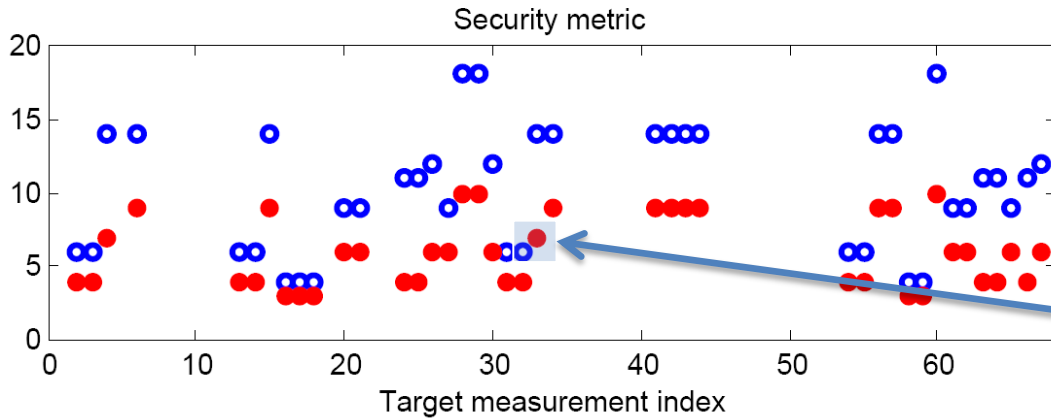
$$\begin{pmatrix} a_1 & a_2 & a_3 & a_4 & a_5 \end{pmatrix} = \begin{pmatrix} 1 & 1 & -1 & 0 & 1 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 1 \end{pmatrix}$$

- Compare with the “hat matrix”:

$$\begin{pmatrix} \hat{z}_1 \\ \hat{z}_2 \\ \hat{z}_3 \\ \hat{z}_4 \\ \hat{z}_5 \end{pmatrix} = \underbrace{\begin{pmatrix} 0.60 & 0.20 & -0.20 & 0 & 0.40 \\ 0.20 & 0.40 & -0.40 & 0 & -0.20 \\ -0.20 & -0.40 & 0.40 & 0 & 0.20 \\ 0 & 0 & 0 & 1.00 & 0 \\ 0.40 & -0.20 & 0.20 & 0 & 0.60 \end{pmatrix}}_{=H(H^T R^{-1} H)^{-1} H R^{-1}} \begin{pmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \end{pmatrix}$$

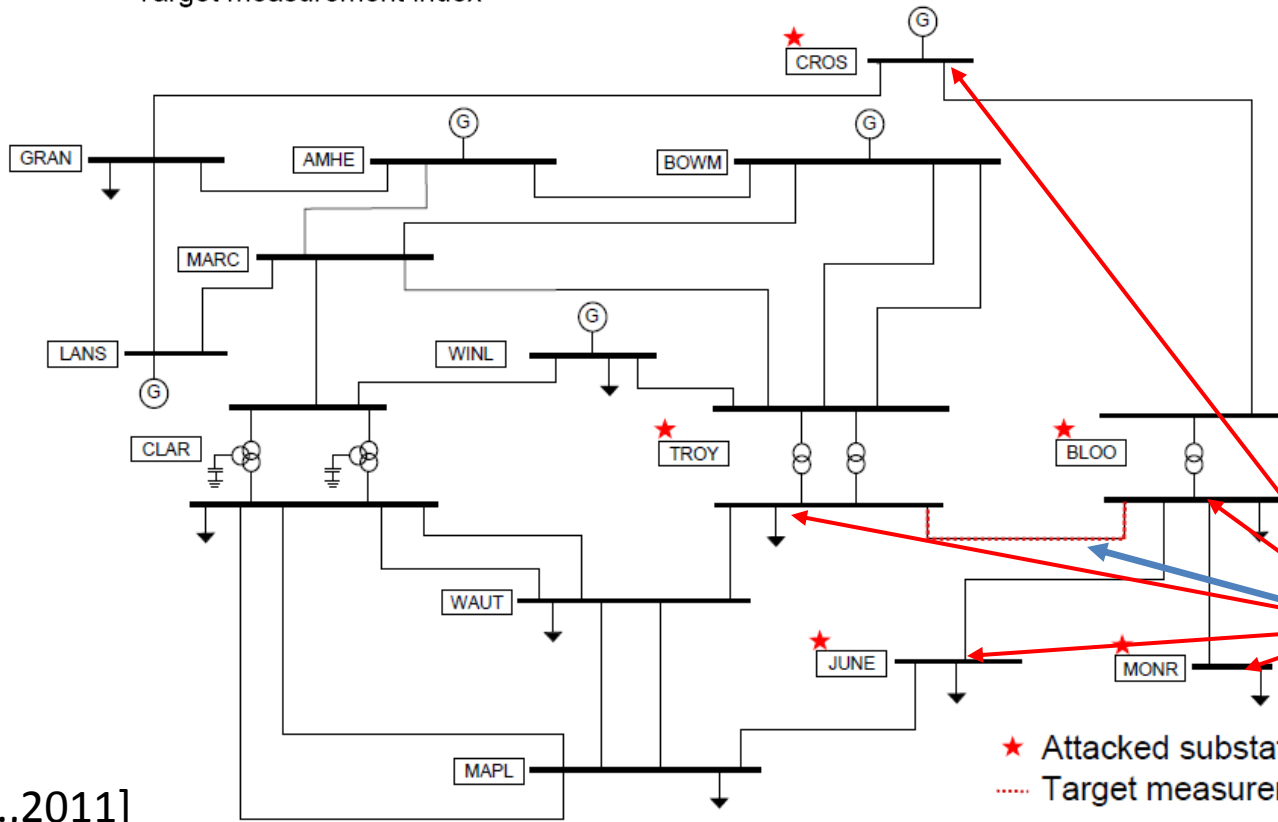
- Hat matrix misleading for judging sparsity of attacks!

Security Metric α_k for 40-bus Network



• = Current measurement config.
 ○ = Upgraded measurement config.

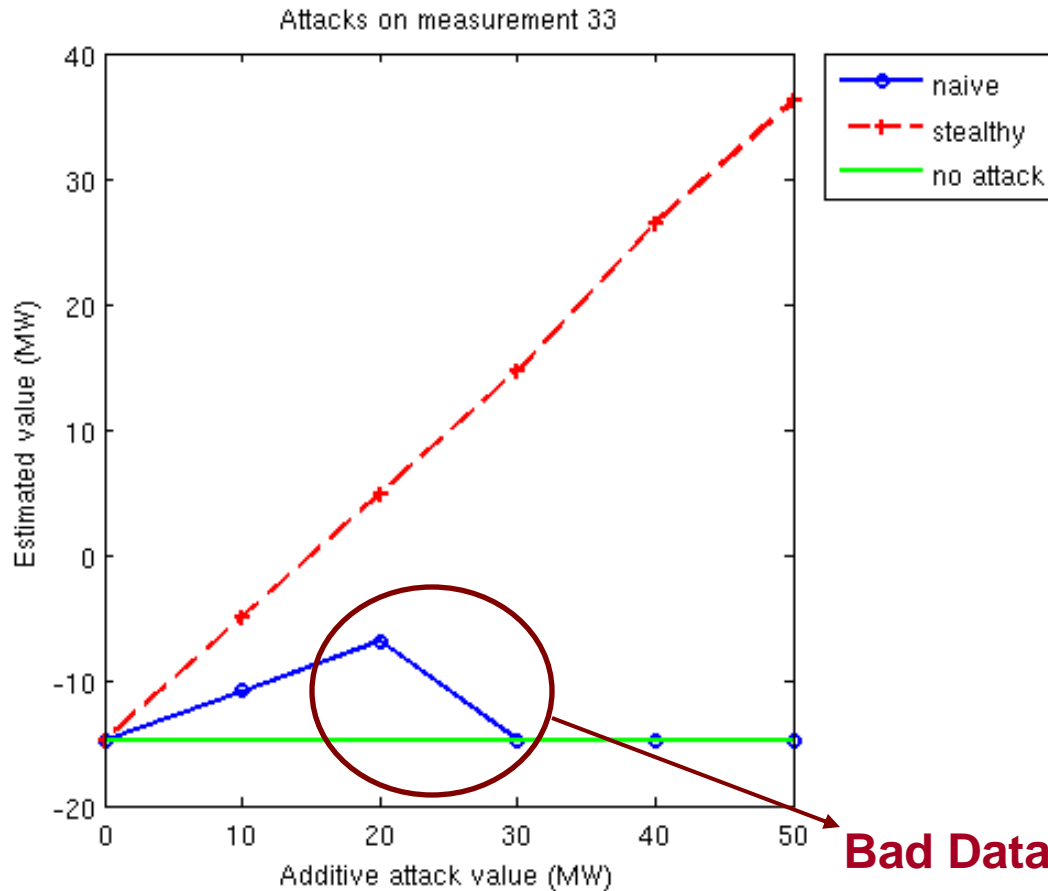
At least 7 measurements need to be involved in an undetectable attack



Attack 33
 (7 measurements)

★ Attacked substations
 Target measurement

Experiments on KTH SCADA/EMS Testbed



False value (MW)	Estimated value (MW)	# BDD Alarms
-14.8	-14.8	0
35.2	36.2	0
85.2	86.7	0
135.2	137.5	0
185.2	Non convergent	-

Bad Data Detected & Removed

- Attacks of 150 MW ($\approx 55\%$ of nominal value) pass undetected in a real system!

Summary so Far

- *Multiple interacting bad data* is hard to detect. What if attacker exploits this well-known fact?
- Security index α_k identifies measurements that are relatively “easy” to attack (it locates weak spots)
- Analysis of the hat matrix can be misleading for judging the sparsity of possible attacks
- How do we compute α_k , and can we use it for protection and mitigation?

Combinatorial Optimization Problem

$$\alpha_k := \min_{\Delta\delta} \|H\Delta\delta\|_0$$

$$\text{subject to } H(k,:) \Delta\delta = 1$$

- Mixed integer linear program (MILP)
- Combinatorial optimization problem. **Expensive!**
- Typical convex heuristics: LASSO ($\|\cdot\|_0 \rightarrow \|\cdot\|_1$)
- We will exploit structure in H instead:

$$H = \begin{bmatrix} ADA^T \\ DA^T \\ -DA^T \end{bmatrix}, A = \text{arc-to-node incidence matrix}, D = \text{pos. diag. matrix}$$

Graph Interpretation

$\Delta\delta$ phase angles

$H\Delta\delta$ injections and flows induced by phase angles

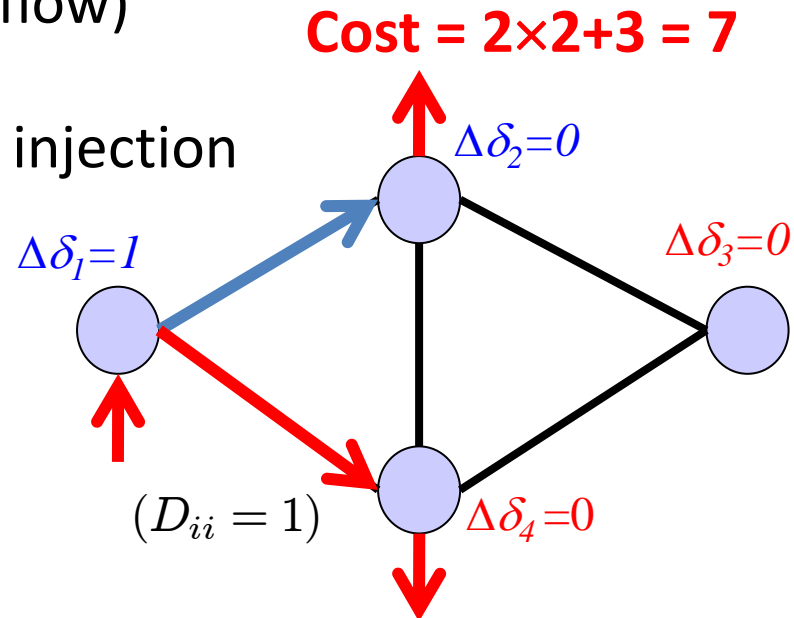
$$\|H\Delta\delta\|_0 = 2\|DA^T\Delta\delta\|_0 \quad 2\times(\# \text{ arc with flow})$$

cost

$$+ \|ADA^T\Delta\delta\|_0 \quad \# \text{ node with injection}$$

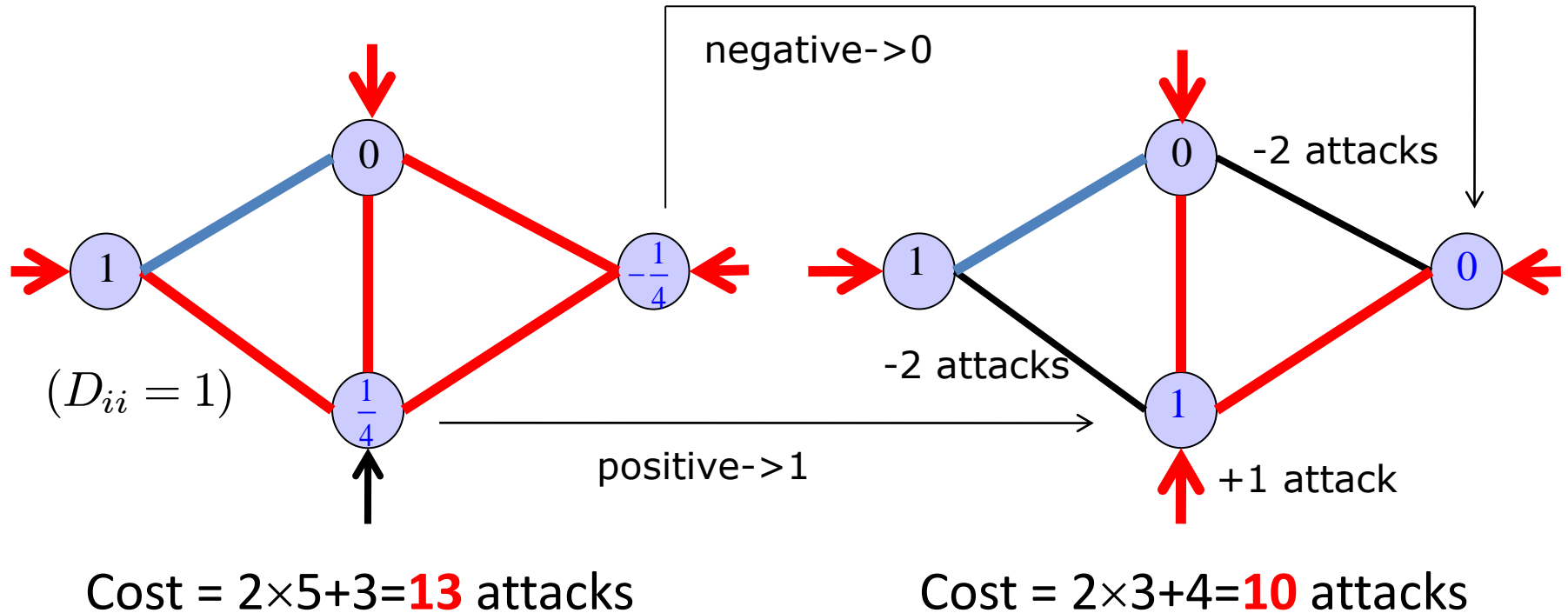
$H(k,:) \Delta\delta = 1$ Fix two phase angles

$\|H\Delta\delta\|_0 \rightarrow \min$ Determine the rest to minimize cost



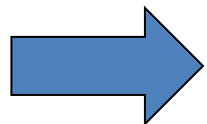
Optimal Solution is Binary Vector

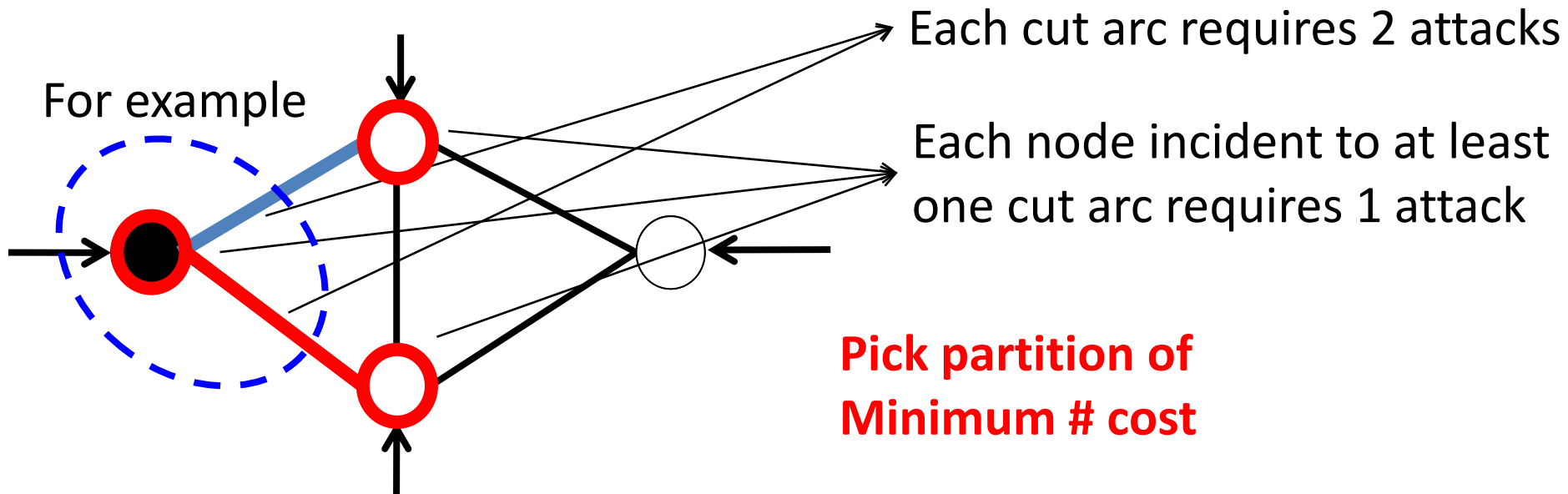
Can always construct no worse 0-1 feasible solution



Reformulation as Graph Partitioning

Optimal $\Delta\delta_i$ are either 0 or 1, for all i

 Consider only partitioning of nodes

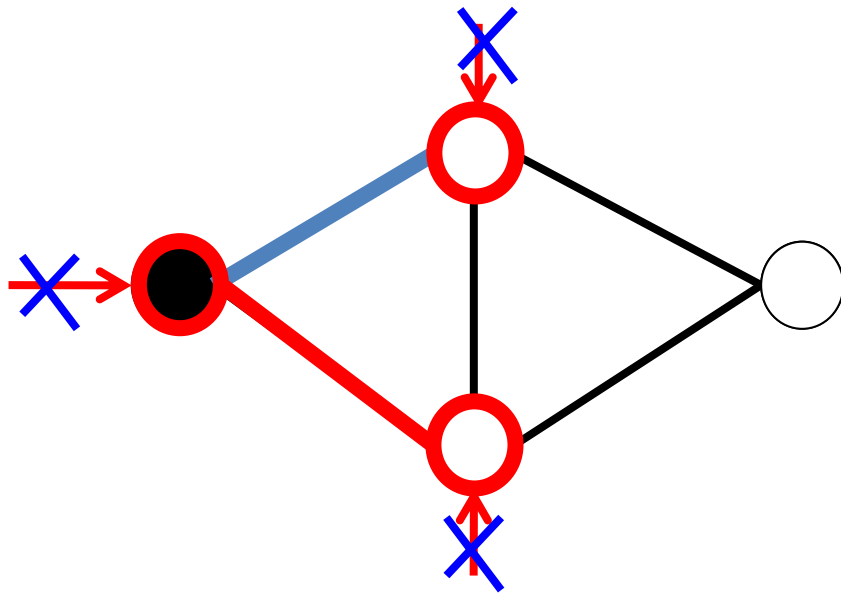


MIN-CUT Relaxation

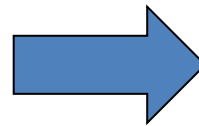
Min cost partitioning difficult; **Relaxation**: ignore injection cost

$$\|H\Delta\delta\|_0 = 2\|DA^T\Delta\delta\|_0 + \cancel{\|ADA^T\Delta\delta\|_0}$$

$2\times(\# \text{ cut arcs})$ $\# \text{ node with injection}$



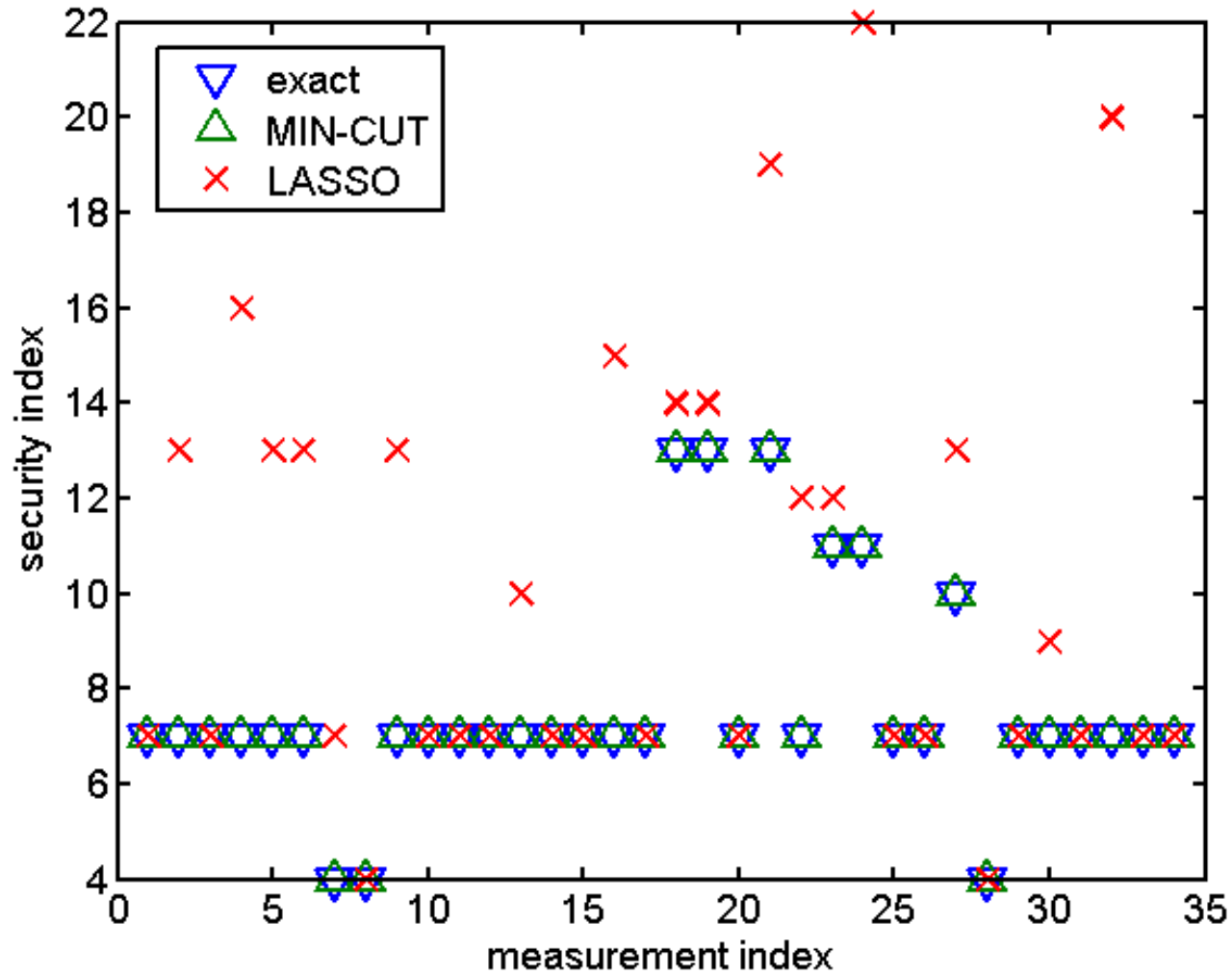
Partitioning with minimum
#of cut arcs



MIN-CUT problem

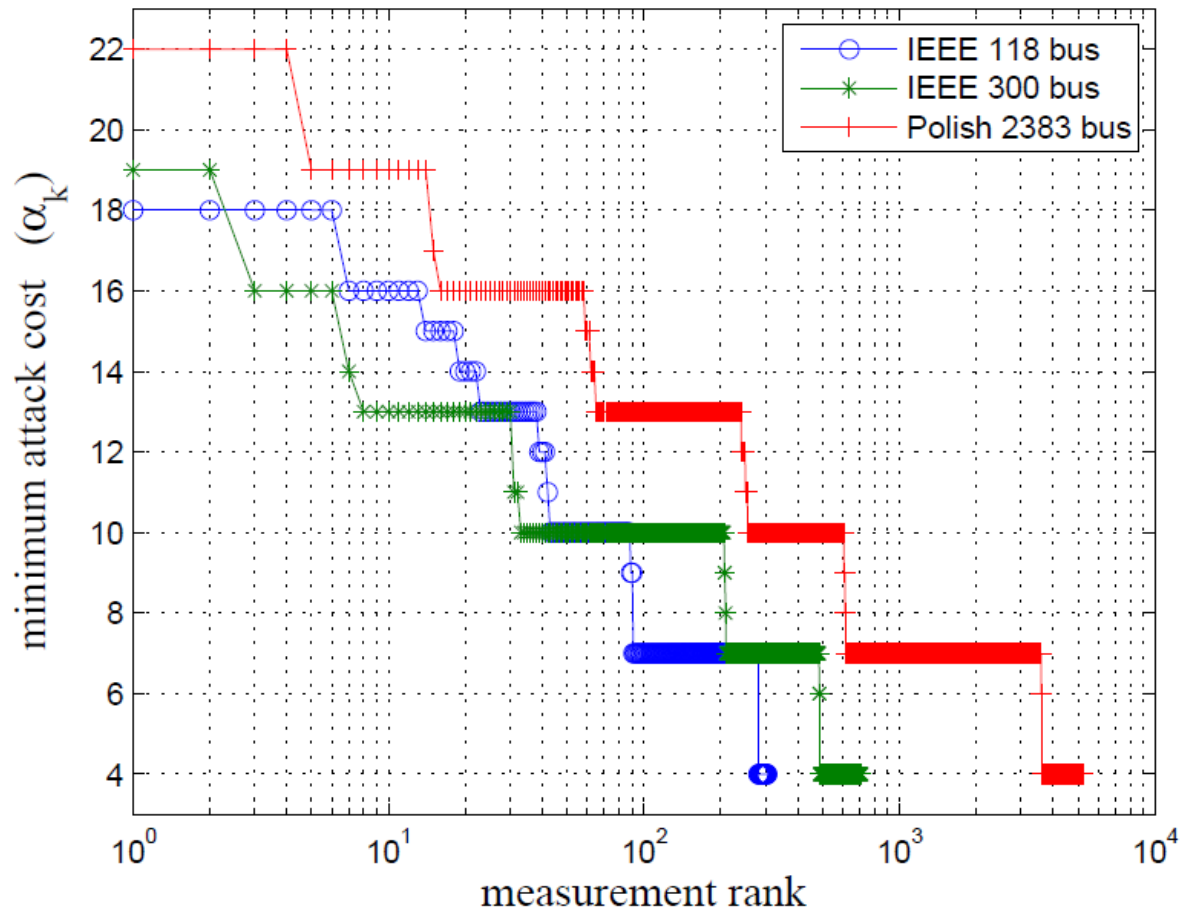
Enumerate **ALL** MIN-CUT
partitions for best relaxation!

IEEE 14-bus Security Indices



MIN-CUT incurs no error, LASSO is very bad here

Large-Scale Examples



- IEEE 300-bus: Exact 6700 sec., LASSO 42.5 sec., MIN-CUT 0.044 sec.
- Polish 2383-bus: Exact \approx 5.7 days, MIN-CUT 30 sec.

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 - Computation
 - **Protection and mitigation strategies**
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Protection Against Stealth Attacks

- Set of protected measurements \mathcal{P}

- Cost of protection $C_M(\mathcal{P})$

- Protection goals

- Perfect protection

$$\min_{\mathcal{P}} C_M(\mathcal{P}) \quad s.t. \quad \alpha_k = \infty \quad \forall k$$

- Limited budget $C_M(\mathcal{P}) \leq \pi$

- *Max-min*

- *Max-ave*

Protection with Limited Budget π

- Maximize minimum attack cost α_k

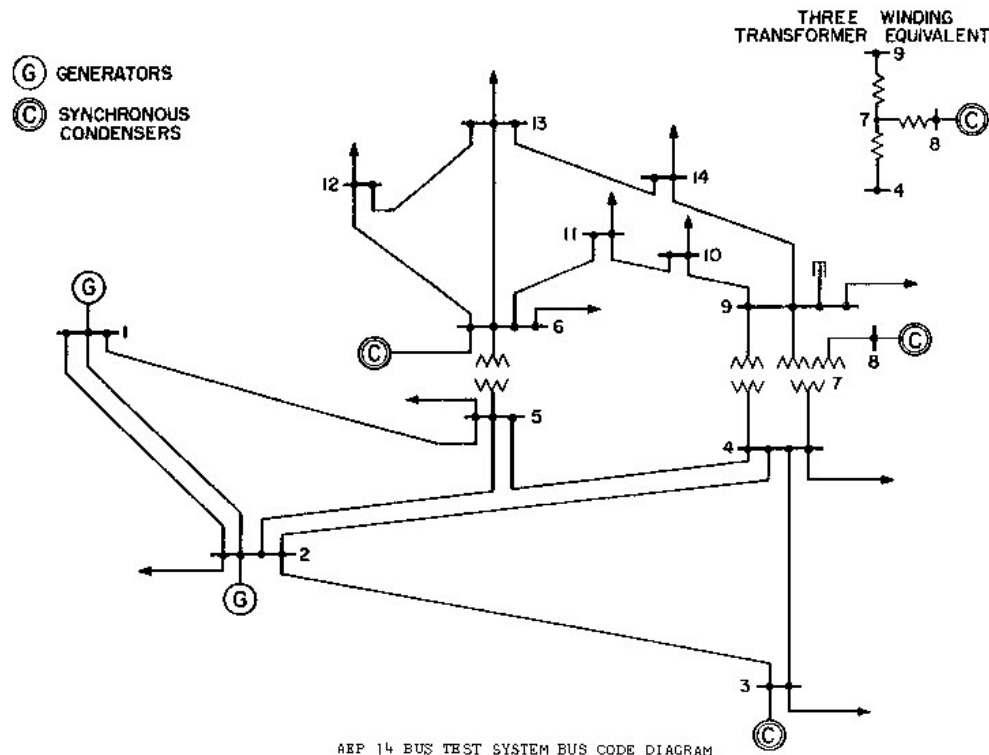
$$P^{MM} = \arg \max_{P: C_M(P) \leq \pi} \min_k \alpha_k$$

- Greedy iterative algorithm (MSM)

- $P=0$
- Iterate until $C_M(P) = \pi$
 - Calculate α_k given P ($k=1, \dots, M$)
 - Find most frequently appearing meters in minimal attacks corresponding to $\min_k \alpha_k$ and put in M_j
 - Set $P = P \cup M_j$

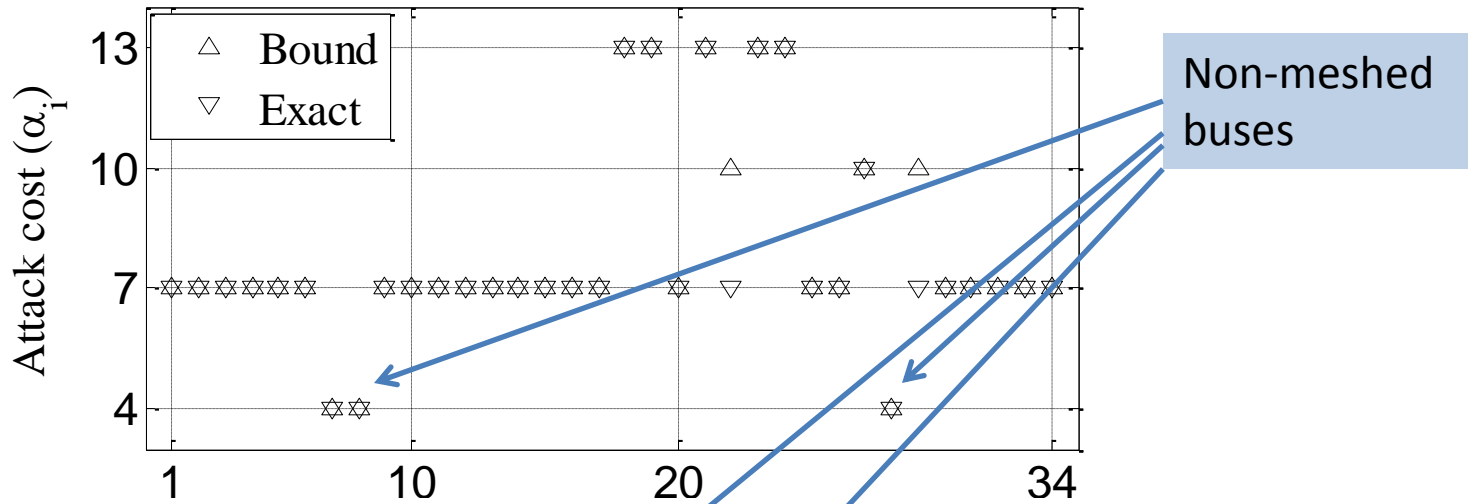
Numerical Results

- IEEE 14-bus and 118-bus networks
- Meters on every load and transmission line
 - 54 and 490 measurements

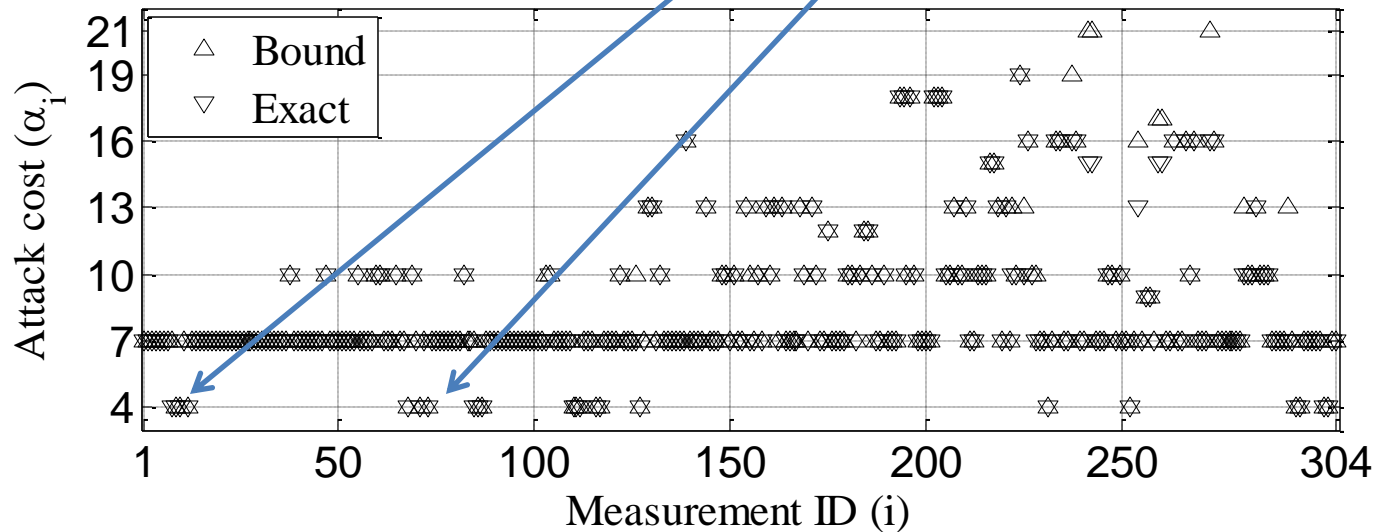


Minimal Attacks - No Protection

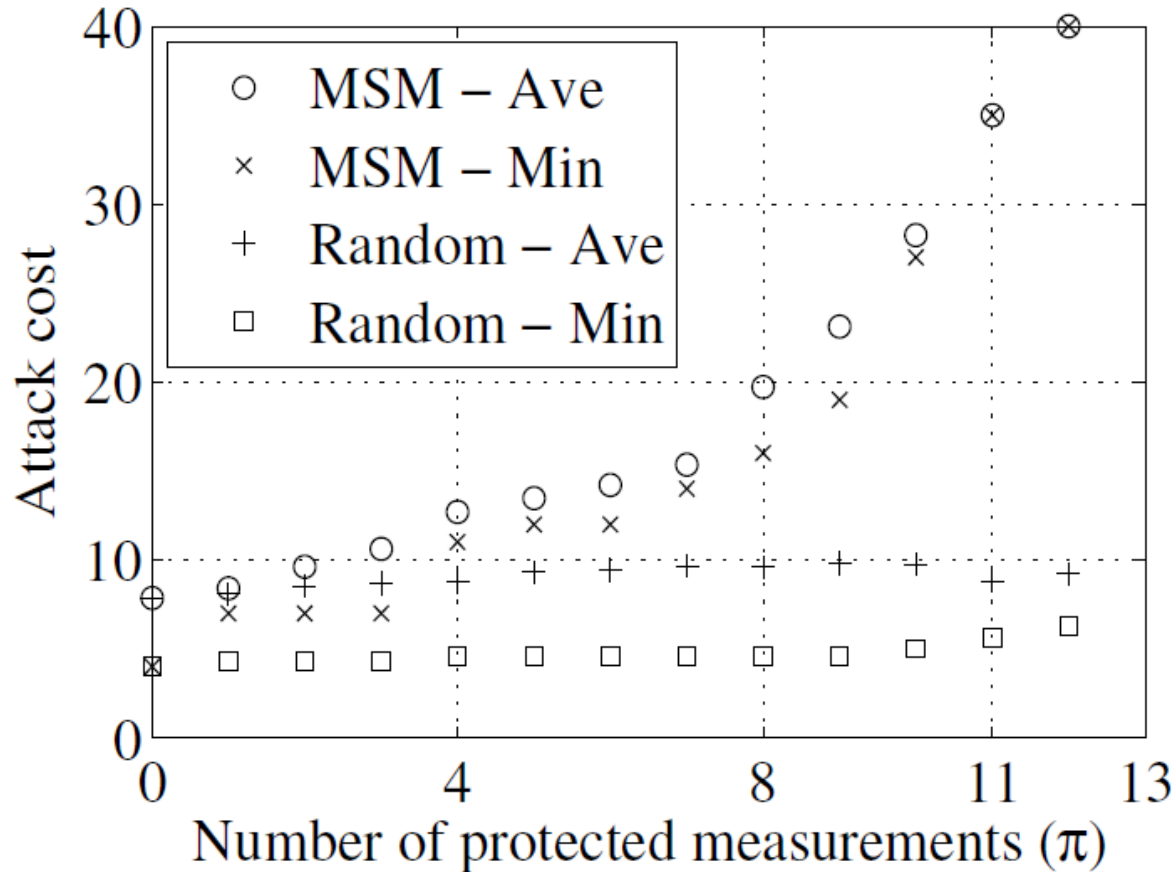
IEEE-14



IEEE-118



Incremental Protection (IEEE 14-bus)

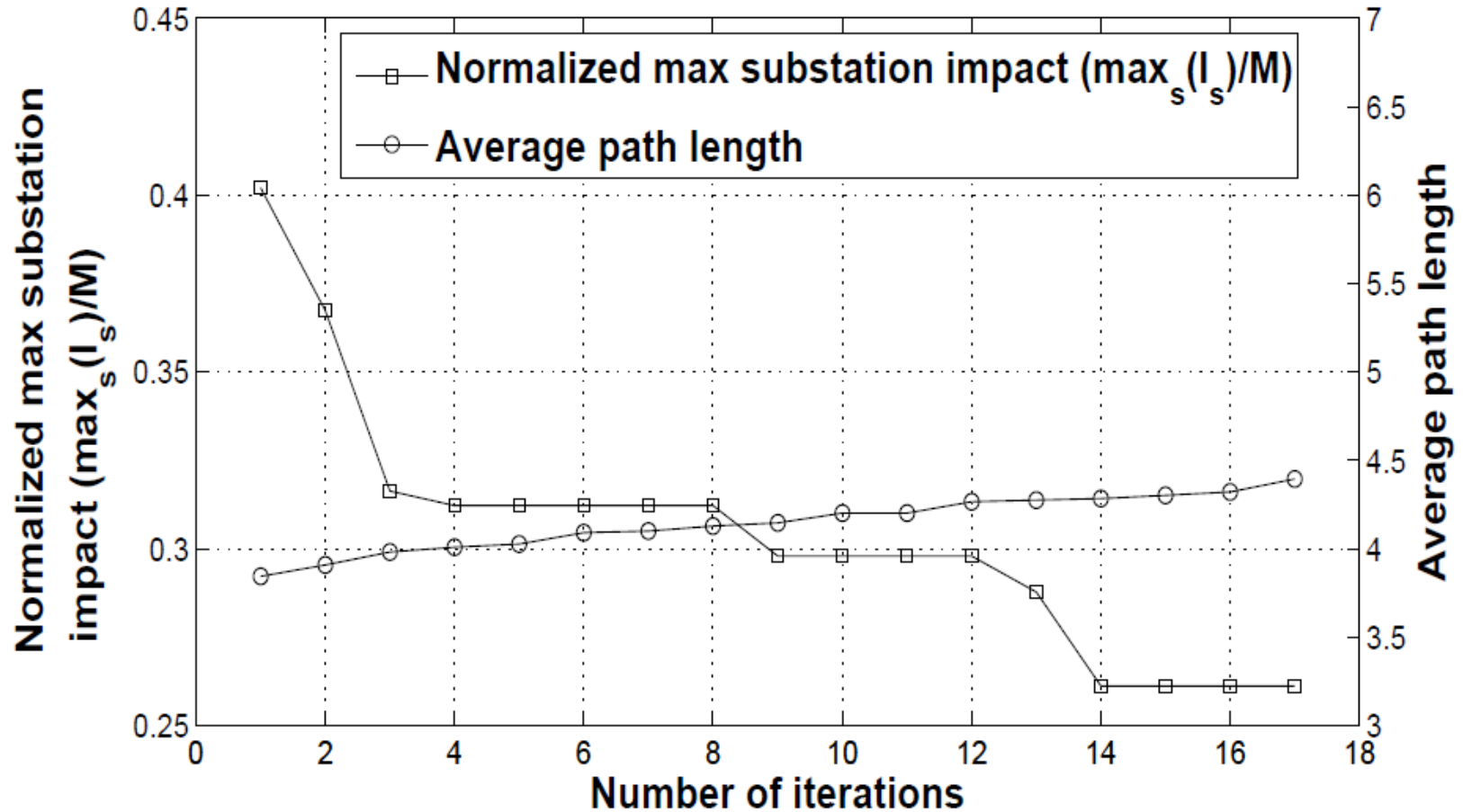


- Increase protection budget $\pi=0,1,\dots,n$
- Perfect protection for $\pi=n=13$
 - Incremental deployment efficient (compare with random deployment)

Impact of the Network Layer

- Optical ground wire topology along transmission lines
- Attack targets
 - Substation switching equipment
- Security metrics
 - Substation attack impact (I_s)
 - # measurements exposed by substation
 - Measurement attack cost (Γ_m)
 - # substations needed to attack measurement
- Mitigation
 - Routing – single and multipath
 - Encryption – tamper proofness
 - Physical protection, surveillance

Reroute Physically Correlated Measurements (IEEE 118-bus)



Summary

- Undetectable false-data attack against power systems possible. Verified both in theory and practice
- Attacks are local, and require basic power systems knowledge
- Why would an attacker do this?
 - Disturb optimal power generation pattern
 - Disturb contingency analysis
- Security metric α_k defined and computed with MIN-CUT/MAX-FLOW relaxation
- Metric α_k used to
 - Allocate limited number of encryption devices
 - Design routing tables that make attacks as hard as possible