Cyber-Security Analysis of Electric Power Systems: Deception Attacks on the State Estimator

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ACCESS Linnaeus Centre, KTH Royal Institute of Technology

IFAC World Congress 2011
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The story of Bob, the System Operator... ... and Mallory, a malicious hacker

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Outline

1. Bob and Mallory
   - Meet Bob
   - Meet Mallory
   - Bob vs Mallory
2. Modeling Bob and Mallory
   - Bob's model knowledge
   - Mallory's model knowledge
   - Modeling Mallory's attacks
   - Summary of Bob and Mallory
3. Experimental Results
   - Scenario
   - Mallory's Effort
   - Mallory's Achievements
4. Reporting to Bob

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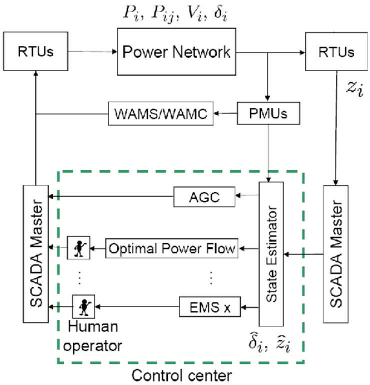
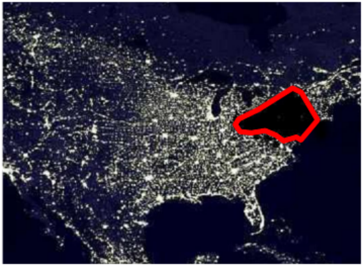
Meet Bob

Bob - The System Operator



- Has many years of experience!
- Is the core of the higher control layer
- Operates the Grid using a SCADA/EMS system that provides
  - the full detailed model of the Grid
  - large amount of measurement data
  - filtering of measurement data (State Estimator)
  - pre and post-filtering outlier detection
  - highly customized software components

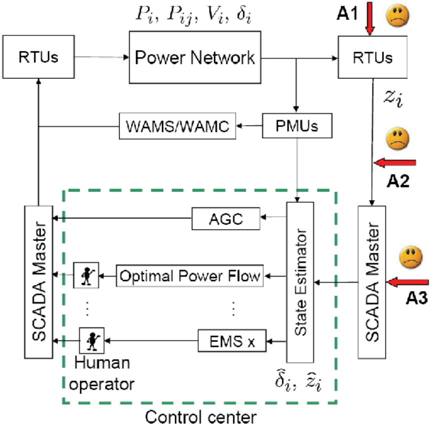


- Ensure the Grid's safe operation
- Avoid major disruptions
- Meet load demand
- Minimize operation costs

- This was a bad day for Bob... (US-Canada 2003 Blackout)

Meet Mallory

Mallory - a malicious hacker



- Has great IT and hacking skills
- Has "some" knowledge about the system model
- Is able to inject false data in a few measuring devices

Meet Mallory

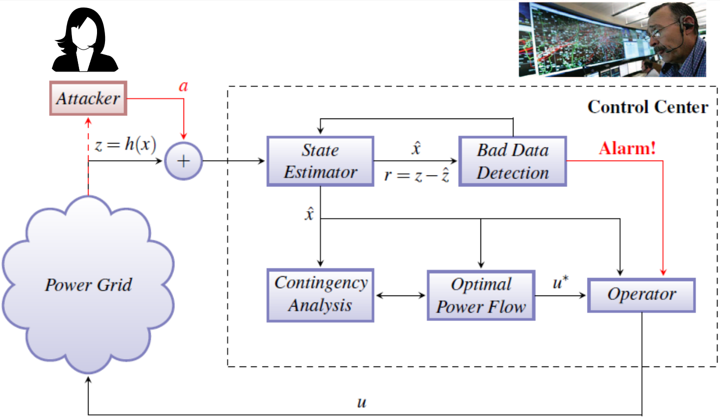
Mallory's Objectives

- Will Bob have another bad day?

- Make Bob have a "bad day" by either:
  - Disrupting the Grid's operation
  - Increasing the operation costs
  - Making money from perturbing the Grid's operation
- Perform the attacks while remaining undetected

Bob vs Mallory

Deception Attacks on the SE



- Bob wants to know
  - if his system is vulnerable to Mallory
  - if adding more measurements would help decrease vulnerabilities
  - where to deploy protection devices to eliminate vulnerabilities
- So he hired us to analyze the situation!

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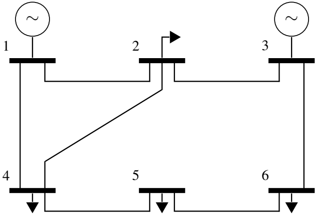
Modeling Bob and Mallory
Bob's model

- **Detailed Steady-State Model:**
  $z = h(x) + \epsilon$
  measurements: $z \in \mathbb{R}^m$
  state: $x = [\theta^\top V^\top]^\top \in \mathbb{R}^n$
  noise: $\epsilon \sim \mathcal{N}(0, R)$.
  For simplicity, assume $R = I$.



Consider $\theta_{ij} = \theta_i - \theta_j$.

- Power injection measurement model

$$\begin{aligned} P_i &= V_i \sum_{j \in N_i} V_j \left(G_{ij} \cos(\theta_{ij}) + B_{ij} \sin(\theta_{ij}) \right) \\ Q_i &= V_i \sum_{j \in N_i} V_j \left(G_{ij} \sin(\theta_{ij}) - B_{ij} \cos(\theta_{ij}) \right) \end{aligned},$$

- Power flow measurement model

$$\begin{aligned} P_{ij} &= V_i^2 (g_{si} + g_{ij}) - V_i V_j \left(g_{ij} \cos(\theta_{ij}) + b_{ij} \sin(\theta_{ij}) \right) \\ Q_{ij} &= -V_i^2 (b_{si} + b_{ij}) - V_i V_j \left(g_{ij} \sin(\theta_{ij}) - b_{ij} \cos(\theta_{ij}) \right) \end{aligned},$$

Ex.: $P_{14} = V_1^2 (g_{s1} + g_{14}) - V_1 V_4 (g_{14} \cos(\theta_1 - \theta_4) + b_{14} \sin(\theta_1 - \theta_4))$

- **Nonlinear Least-Squares:**

$$\hat{x} = \arg\min_{x \in \mathbb{R}^n} r(x)^\top r(x),$$

where $r(x) = z - h(x)$ is the measurement residual

  - $r(\hat{x}) \approx S\epsilon$, $S = S^\top = S^2$
  - $J(\hat{x}) = r(\hat{x})^\top r(\hat{x})$

- **BDD - Performance index test:**
  $J(\hat{x}) = \epsilon^\top S \epsilon \sim \chi^2_{m-n}$:
  No bad data if $\|r\|_2 \leq \tau_\chi(\alpha)$

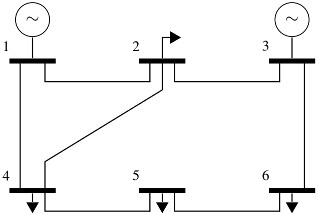
  - $\alpha \in [0,\ 1]$ is the **desired** false alarm rate

- **General expression:** $\|Wr(\hat{x})\|_p < \tau$, for suitable W, p and τ.

Modeling Bob and Mallory

Mallory's model

- **Simplified Steady-State Model (DC-Model):** $z = Hx + \epsilon$
  state: $x = \theta \in \mathbb{R}^{\tilde{n}}$, $\tilde{n} = \frac{n-1}{2}$
  Assumption: $V_i = 1$ for all buses
  No reactive power flows or injections!



- Power injection measurement model

$$P_i \quad = \quad \sum_{j \in N_i} b_{ij}\theta_{ij}$$

- Power flow measurement model

$$P_{ij} \quad = \quad -V_i V_j b_{ij}\theta_{ij}$$

Ex.: $P_{14} = -V_1 V_4 b_{14}(\theta_1 - \theta_4)$

Modeling Bob and Mallory

Mallory's SE model

- **Linear Weighted Least-Squares:**

$$\hat{x} = \left[H^\top H\right]^{-1} H^\top z = H^\dagger z,$$

  - $r(\hat{x}) = z - H\hat{x} = (I - HH^\dagger)(Hx + \epsilon) = S\epsilon,\ S = (I - HH^\dagger)$

- **Mallory corrupting measurements:**

$$z^a = z + a \Rightarrow \hat{x}^a = H^\dagger z^a = H^\dagger (z + a),$$

- **Mallory's idea for stealthy attacks:**
  $a \in \mathrm{Im}(H) \Rightarrow Sa = 0 \Rightarrow r(\hat{x}) = r(\hat{x}^a)$
  [Clements et al. 81, Liu et al. 09]

Modeling Bob and Mallory

Modeling Mallory's stealthy attacks

- **Mallory's Goals**
  - Convergence of the estimator (trivial for the linear model);
  - Stealthiness: $\|Wr(\hat{x}^a)\|_p < \tau$;
  - Induce a desired bias on a subset of measurements - "making Bob have a bad day"

- **Minimum "Effort" Attack Synthesis**

$$\min_a \|a\|_p$$
$$\text{s.t. } a \in \mathcal{G} \cap \mathcal{U} \cap \mathcal{C}$$

  - $\mathcal{G}$ - set of goals
  - $\mathcal{U}$ - set of stealthy attacks
  - $\mathcal{C}$ - set of constraints

- **Different metrics for "effort"**
  - $p = 0$: cardinality of a ($\#$ of measurements to be corrupted) - not convex, can be solved through MILP
  - $p = 1$: may be used as a convex approximation of $p = 0$

Summary of Bob and Mallory

	Bob	**Mallory**
Model	Detailed Nonlinear	Simplified Linear
# Measurements	Large	Small
Active Power	+	+
Reactive Power	+	0
Pre-SE BDD	+	-
Post-SE BDD	+	-

- Does Bob really have reasons to be worried?!

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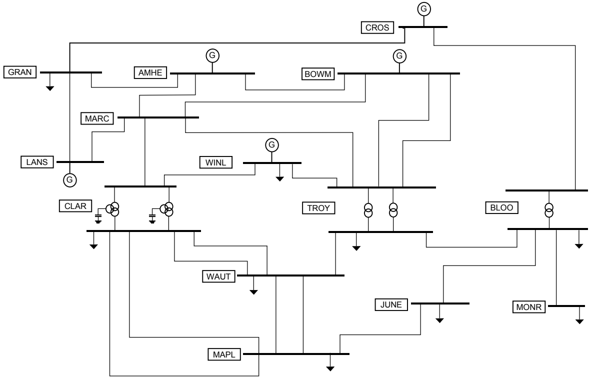
Experimental Results

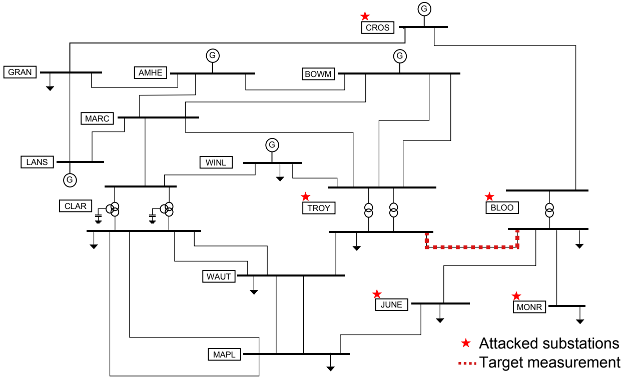
Bob's System



- Typical SCADA/EMS software present in control centers is used
- Virtual grid for training purposes
- Nonlinear model of active and reactive power flows is used

Experimental Results

Mallory's Attack Scenario



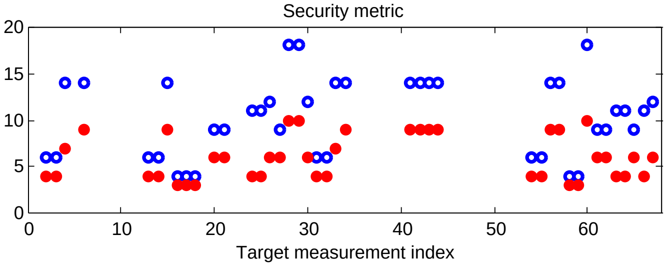
- Only **linear** model of active power flow is known
- Corrupted measurements are sent to the database
- Objective: inject a bias on flow between TROY and BLOO

Mallory's Effort

Adding more measurements vs Deploying protection devices

$$\alpha_k = \min_a \|a\|_0 \quad \text{s.t. } a \in \mathcal{G}_k \cap \mathcal{U} \cap \mathcal{C}$$

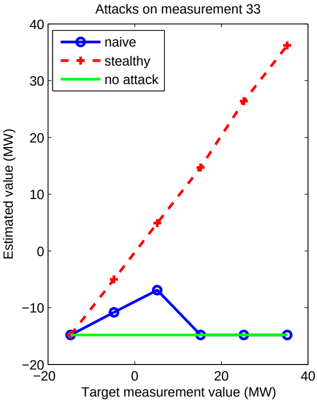
- $\mathcal{G}_k = \{a\colon a_k = 1\}$
- $\mathcal{U} = \mathrm{Im}(H)$
- $\mathcal{C} = \{a\colon a_i = 0, \forall i \in \mathcal{P}\}$ (protected measurements)



Blue circles: α_k with **all** measurements

Red circles: α_k with **only a subset** of measurements

Small attacks



Large attacks

Target bias (MW), a_{33}	Estimate (MW), $\hat{z}^a_{33}$	#BDD Alarms
0	-14.8	0
50	36.2	0
100	86.7	0
150	137.5	0
200	-	-

- Stealthily injected **150MW!** - that's around 60% of the transmission line rating - 260MW.
    - Perhaps Bob would have a "bad day" with this...

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Reporting to Bob

- Mallory has been modeled using a flexible optimization framework that enables the embedding of relevant aspects such as
  - encrypted measurements;
  - pseudo-measurements;
  - finite resources;
  - reduced model knowledge.
- Mallory's model has been applied to Bob's SCADA/EMS software
  - Bob's system seems to be vulnerable to Mallory - reasonably sized biases were injected using linear models;
  - Increasing measurement redundancy of Bob's system does not eliminate all vulnerabilities;
  - Bob got an idea of which measurements are more vulnerable to Mallory.

The End

Thank you!

Questions?