False Data Injection Attacks against State Estimation in Electric Power Grids

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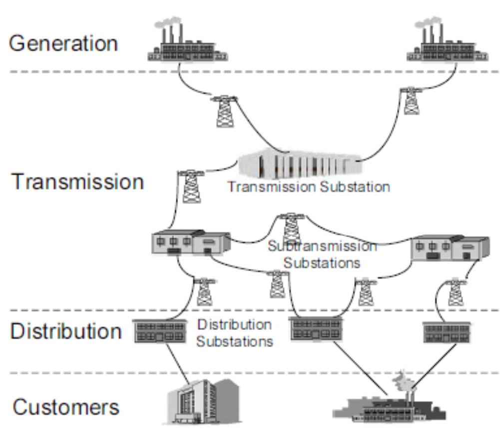
Introduction (1/2)



- System monitoring is necessary to ensure the reliable operation of power grids.
- The meter measurements
  - Bus voltages, bus real and reactive power injections, and branch reactive power flows in every subsystem of a power grid.
- These measurements are typically transmitted to a control center.

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Introduction (2/2)

- State estimation
  - the process of estimating unknown state variables in a power grid based on the meter measurements.
- The output of state estimation is used to control the power grid components
  - e.g., to increase the yield of a power generator to maintain the reliable operation even if some faults may occur next.
- It is possible for an attacker to compromise meters to introduce malicious measurements.
- Bad measurements may result in catastrophic consequences such as blackouts in large geographic areas.

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State estimation (1/2)

$$\mathbf{z} = \underline{\mathbf{h}(\mathbf{x})} + \mathbf{e}, \qquad \text{to find an estimate } \hat{\mathbf{x}} \text{ of } \mathbf{x}$$

state variables $\mathbf{x} = (x_1, x_2, ..., x_n)^T$

measurements $\mathbf{z} = (z_1, z_2, ..., z_m)^T$

measurement errors $\mathbf{e} = (e_1, e_2, ..., e_m)^T$

$\mathbf{h}(\mathbf{x}) = (h_1(x_1, x_2, ..., x_n), ..., h_m(x_1, x_2, ..., x_n))^T$

Nonlinear
= difficult!!!

Approximate as a linear model

$$\mathbf{z} = \mathbf{H}\mathbf{x} + \mathbf{e},$$

$$\mathbf{H} = (h_{i,j})_{m \times n}$$

less accurate, but simpler

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State estimation (2/2)

- Least-square estimation

$$\hat{\mathbf{x}} = (\mathbf{H}^{\mathbf{T}}\mathbf{W}\mathbf{H})^{-1}\mathbf{H}^{\mathbf{T}}\mathbf{W}\mathbf{z},$$

$$\mathbf{W} = \begin{bmatrix} \sigma_1^{-2} & & & & \\ & \sigma_2^{-2} & & & \\ & & \cdot & & \\ & & & \cdot & \\ & & & & \sigma_m^{-2} \end{bmatrix}$$

σ_i^2 is the variance of the i-th meter $(1 \le i \le m)$

the presence of bad measurements is assumed if $\|\mathbf{z} - \mathbf{H}\hat{\mathbf{x}}\| > \tau$

measurement residual

Of course, with a fixed probability of false alarm

How can bad guys avoid being detected?

$$\mathbf{z_a} = \mathbf{z} + \mathbf{a}$$

$\mathbf{z} = (z_1, ..., z_m)^T$ original measurements

$\mathbf{a} = (a_1, ..., a_m)^T$ malicious data added

$$\hat{\mathbf{x}}_{\mathbf{bad}} = \hat{\mathbf{x}} + \mathbf{c}$$

$\mathbf{c}$ estimation error injected by the attacker

Suppose the original measurements can pass the bad measurement detection

$$\|\mathbf{z} - \mathbf{H}\hat{\mathbf{x}}\| \le \tau.$$

if the attacker can use $\mathbf{Hc}$ as the attack vector $\mathbf{a}$ (i.e., $\mathbf{a} = \mathbf{Hc}$)

$$\begin{aligned} \|\mathbf{z_a} - \mathbf{H}\hat{\mathbf{x}}_{\mathbf{bad}}\| &= \|\mathbf{z} + \mathbf{a} - \mathbf{H}(\hat{\mathbf{x}} + \mathbf{c})\| \\ &= \|\mathbf{z} - \mathbf{H}\hat{\mathbf{x}} + (\mathbf{a} - \mathbf{Hc})\| \\ &= \|\mathbf{z} - \mathbf{H}\hat{\mathbf{x}}\| \le \tau. \end{aligned}$$

undetected!

False data injection attacks

- Assume the attacker knows the matrix **H** of the target power system, and can manipulate some of meter measurements.
  - Is this possible?
- Random false data injection attacks
  - the attacker aims to find any attack vector as long as it can result in a wrong estimation of state variables.
- Targeted false data injection attacks
  - the attacker aims to find an attack vector that can inject a specific error into certain state variables.

Scenario I – Limited access to meters

- The attacker is restricted to accessing *k* specific meters due to, for example, different physical protection of meters.

$\mathcal{I}_m = \{i_1, ..., i_k\}$ the set of indices of those meters

the attacker needs to find a non-zero attack vector

$$\mathbf{a} = (a_1, ..., a_m)^T \text{ such that } a_i = 0 \text{ for } i \notin \mathcal{I}_m \text{ and}$$

$$\mathbf{a} = \mathbf{Hc}$$

Scenario I: Random false data injection attacks

$$\mathbf{P} = \mathbf{H}(\mathbf{H}^T\mathbf{H})^{-1}\mathbf{H}^T \qquad \mathbf{B} = \mathbf{P} - \mathbf{I}$$

$$\begin{aligned} \mathbf{a} = \mathbf{Hc} \quad &\Leftrightarrow \quad \mathbf{Pa} = \underline{\mathbf{PHc}} \Leftrightarrow \mathbf{Pa} = \underline{\mathbf{H}}\mathbf{c} \Leftrightarrow \mathbf{Pa} = \underline{\mathbf{a}} \\ &\Leftrightarrow \quad \mathbf{Pa} - \mathbf{a} = \mathbf{0} \Leftrightarrow (\mathbf{P} - \mathbf{I})\mathbf{a} = \mathbf{0} \\ &\Leftrightarrow \quad \mathbf{Ba} = \mathbf{0}. \end{aligned}$$

$$\mathbf{a} = (0, ..., 0, a_{i_1}, 0, ..., 0, a_{i_2}, 0, ..., 0, a_{i_k}, 0, ..., 0)^T$$

$$\mathbf{B}' = (\mathbf{b}_{i_1}, ..., \mathbf{b}_{i_k}) \qquad \mathbf{a}' = (a_{i_1}, ..., a_{i_k})^T$$

$$\mathbf{Ba} = \mathbf{0} \Leftrightarrow \mathbf{B}'\mathbf{a}' = \mathbf{0} \qquad [b_1 \quad b_2 \quad b_3]\begin{bmatrix} a_1 \\ 0 \\ a_3 \end{bmatrix} = [b_1 \quad b_3]\begin{bmatrix} a_1 \\ a_3 \end{bmatrix}$$

If # of equations is more than # of unknowns, no solution exists.

Attacker needs to compromise more than a certain number of meters, to inject an error into the state estimation.

Scenario I: Targeted false data injection attacks (1/2)

$$\mathcal{I}_v = \{i_1, ..., i_r\}$$

the set of indexes of the r target state variables

- Constrained Case:

$$\mathbf{c} \quad \begin{cases} \text{the chosen value when } i \in \mathcal{I}_v \\ 0 \text{ when } i \notin \mathcal{I}_v \end{cases}$$

  - Attacker can substitute **c** back into the relation **a = Hc**, and check if $a_i = 0 \text{ for } \forall i \notin \mathcal{I}_m$
  - If yes, the attacker succeeds in constructing the (only) attack vector **a**. Otherwise, the attack is impossible.

Scenario I: Targeted false data injection attacks (2/2)

- Unconstrained Case:
  - the other elements c_j for $j \notin \mathcal{I}_v$ can be any values.

$$\mathbf{c_s} = (c_{j_1}, ..., c_{j_{n-r}})^T$$
$$\mathbf{H_s} = (\mathbf{h}_{j_1}, ..., \mathbf{h}_{j_{n-r}})$$
$$\mathbf{b} = \sum_{j\in\mathcal{I}_v} \mathbf{h}_j c_j$$
$$\mathbf{P_s} = \mathbf{H_s}(\mathbf{H_s^T H_s})^{-1}\mathbf{H_s^T}$$
$$\mathbf{B_s} = \mathbf{P_s} - \mathbf{I}$$
$$\mathbf{y} = \mathbf{B_s b}$$

$$\begin{aligned}
\mathbf{a} = \mathbf{Hc} \quad &\Leftrightarrow \quad \mathbf{a} = \sum_{i\notin\mathcal{I}_v} \mathbf{h}_i c_i + \sum_{j\in\mathcal{I}_v} \mathbf{h}_j c_j = \mathbf{H_s c_s} + \mathbf{b} \\
&\Leftrightarrow \quad \mathbf{P_s a} = \underline{\mathbf{P_s H_s}}\mathbf{c_s} + \mathbf{P_s b} \\
&\Leftrightarrow \quad \mathbf{P_s a} = \underline{\mathbf{H_s}}\mathbf{c_s} + \mathbf{P_s b} \\
&\Leftrightarrow \quad \mathbf{P_s a} = \underline{\mathbf{a} - \mathbf{b}} + \mathbf{P_s b} \\
&\Leftrightarrow \quad (\mathbf{P_s} - \mathbf{I})\mathbf{a} = (\mathbf{P_s} - \mathbf{I})\mathbf{b} \\
&\Leftrightarrow \quad \mathbf{B_s a} = \mathbf{B_s b} \Leftrightarrow \mathbf{B_s a} = \mathbf{y}.
\end{aligned}$$

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Scenario II – Limited resources to compromise meters

- The attacker is limited in the resources required to compromise meters. For example, the attacker only has resources to compromise up to k meters (out of all the meters).
  - compromise up to k meters.
- Unlike Scenario I, there is no restriction on what meters can be chosen.

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Scenario II: Random false data injection attacks

- Brute-force approach:
  - attacker may try all possible **a**'s consisting of k unknown elements and $m - k$ zero elements.
- If there exists a non-zero solution of a such that **Ba = 0**, the attacker succeeds in constructing an attack vector. Otherwise, the attack vector does not exist.

Scenario II: Targeted false data injection attacks

- Constrained Case:
  - All elements of **c** are fixed.
  - So the attacker can substitute c into the relation **a = Hc**.
  - If the resulting **a** has k non-zero elements, the attacker succeeds in constructing the attack vector. Otherwise, the attacker fails.
- Unconstrained Case:
  - Attacker needs to find a attack vector **a** of k non-zero elements that satisfies the relation $\mathbf{B_s a} = \mathbf{y}$.
  - Known as a NP complete problem, called Minimum Weight Solution for Linear Equation Problem.

Experimental results

- Configuration of the IEEE test systems, including the IEEE 9-bus, 14-bus, 30-bus, 118-bus, and 300-bus systems.
  - particularly matrix **H**
- MATLAB package for solving power flow problems.
- DELL PC running Windows XP, which has a 3.0 GHz Pentium 4 processor and 1 GB memory.
- Two evaluation metrics:
  - the probability that the attacker can successfully construct an attack vector given the *k* specific meters
    - for each k, we randomly choose k specific meters to attempt an attack vector construction
    - repeat this process 100 times

$$success\ probability\ p_k \text{ as } p_k = \frac{\#\ successful\ trials}{\#\ trials}.$$

  - the execution time required to either construct an attack vector or conclude that the attack is infeasible.

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Experimental results: Scenario I (1/2)

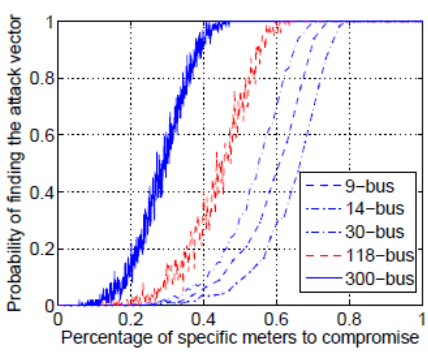

Figure 2: Probability of finding an attack vector for random false data injection attacks

larger systems have higher p_k

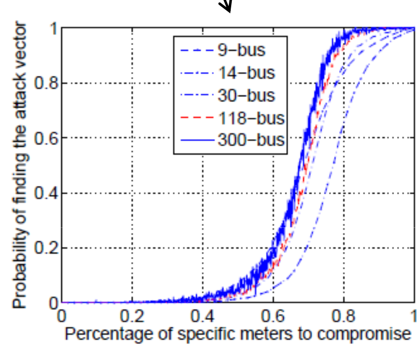

Figure 3: Probability of finding an attack vector for compromising a single state variable in targeted false data injection attacks (unconstrained case)

in general lower than that in Figure 2

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Experimental results: Scenario I (2/2)

- Constrained case:
  - pick 6 sets of meters for the IEEE 118-bus and 300-bus systems.
  - In each set, there are 350 meters and 700 meters, respectively.
  - check the number of individual target state variables that can be affected by each set of meters without affecting the estimation of the remaining state variables.
  - The results show that the attacker can affect 8–11 and 13–16 individual state variables in the IEEE 118-bus and 300-bus systems, respectively.

Table 1: Timing results in Scenario I (ms)

Test system	Random attack	Targeted attack (unconstrained)
IEEE 9-bus	0.17–2.4	0.21–2.2
IEEE 14-bus	0.16–5.6	0.26–11.3
IEEE 30-bus	0.35–14.9	0.24–31.4
IEEE 118-bus	0.34–867.9	0.42–1,874.5
IEEE 300-bus	0.55–8,549.6	0.73–18,510

Conclusion

- We show that an attacker can take advantage of the configuration of a power system to launch such attacks to bypass the existing techniques for bad measurement detection.
- Security protection of the electric power grid must be revisited when there are potentially malicious attacks.

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