Vulnerability Analysis of Power Systems Based on Cyber-Attack and Defense Models

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- Defense Model and Algorithm
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Overview

- Smart grids are needed with the increasing demand for reliable energy.
- The technological advancements such as substation automation, PMUs, AMIs, etc., are deployed to improve the traditional power grid capabilities and improve reliability.
- They increases the attack surface due to the increase in cyber components.
- At present cyber-attacks are one of the major obstacles towards reliable system operations and give rise to new system vulnerabilities.

Overview

- Attackers take advantage of such vulnerabilities to cause severe system damage.
  - Example: Recent blackout of Dec 2015 Ukraine.
- Power systems consists of several substations.
- Substations have RTUs to control and monitor the field devices.
- They become the primary target for the attackers.
- Adversary can gain complete control of the RTUs and perform various types of attacks.

Challenges

- Time and effort to compromise an RTU limits the attacker.
- Attacker can access only a few RTUs before they get detected.

Challenges?

1. **To identify critical substations and protection assemblies to compromise in order to maximize system damage.**
2. **To identify critical substations to protect in order to minimize system damage.**

Contributions

- A game-theoretic approach to design an attacker/defender model is provided.
  - A formal attacker model is described.
  - An efficient polynomial-time algorithm for finding worst-case attack is developed.
  - A formal defender model is presented.
  - An efficient polynomial-time algorithm for identifying critical substations to protect is developed.
  - Evaluation results using standard IEEE-14, 39, and 57 bus systems are demonstrated to support the developed models.

Power System Model

- **System:**
  - G_P: power system, U: set of buses, G: set of generators, T: set of transformers, L: set of loads, *R*: set of transmission lines, *P*: set of protection assemblies (distance relays, over-current relays and circuit breakers).
- **Modeling substations**
  - Let $S = \{S^1, \ldots\ldots, S^m\}$ be the substations.
  - $S^i \subseteq P, \forall\, i \in \{1, \ldots, m\}$.
  - $F(S^i)$ returns the set of protection assemblies in S^i.
  - $\bigcup_{i=1}^{m} F(S^i) = P$
- **Load loss function**
  - Loads are defined by L_j, where $j = 1\ to\ n,\ \ n \in \mathbb{N}$
  - Current flowing through each load is defined by:

    I_j, where $j = 1\ to\ n,\ n \in \mathbb{N}$
  - Load loss is calculated as:

    $J(A_{P'}) = \sum_{j=1}^{n} L_j, \forall\, I_j = 0$

Attacker Model

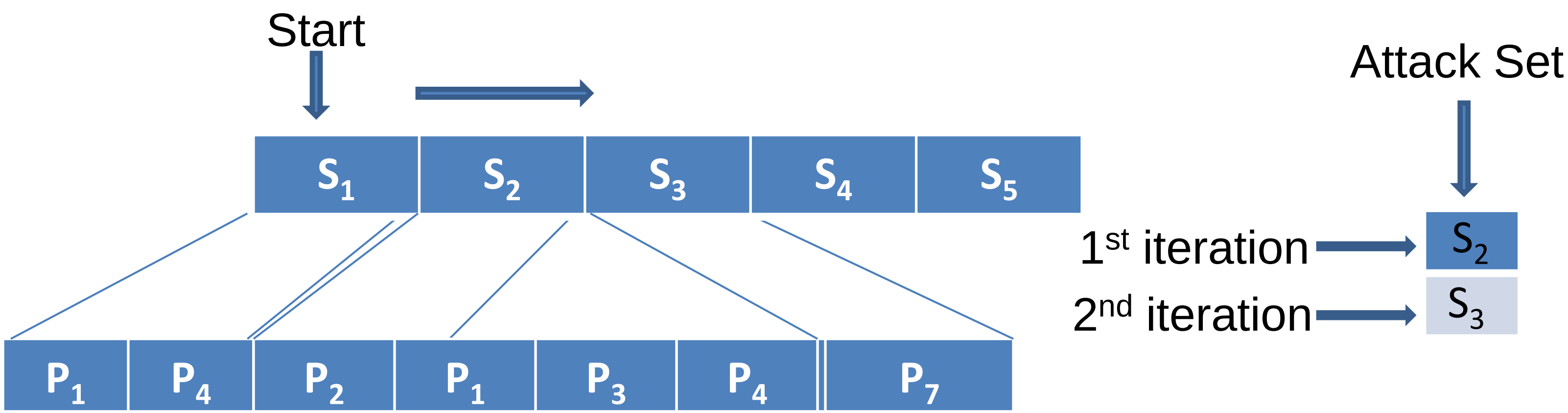
- **Attack Model:**
  - First, attacker identifies substations $S' \subseteq S$ to attack.
  - Attacker has budget B_S where $|S'| \leq B_{S.}$
  - Then, the attacker identifies protection assemblies $P' \subseteq \mathrm{F}(S')$ to manipulate.
  - Attacker has budget B_P where $|P'| \leq B_{P.}$
  - Finally, attacker launches a cyber-attack $A_{P'}$ on protection assemblies $P' \subseteq F(S')$.
  - Uniform, unit cost for attacking a substation.
- **Attacker's Goal:**
  - Goal of the attacker is to maximize the load loss

$$\max_{S'} \max_{P' \subseteq F(S')} J(A_{P'})$$
$$\text{s.t.} \quad |S'| \leq B_S, \quad |P'| \leq B_P$$

Attack Algorithm

- Consider a set of substations $S = \{S_1, S_2, S_3, S_4, S_5\}$.
- Consider a set of protection assemblies $P = \{P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8\}$.
- Attack budget is restricted to 2.

Select a substation	Select the protection assemblies with the substations	Identify and record Loss	Select Next Substation



Defender Model

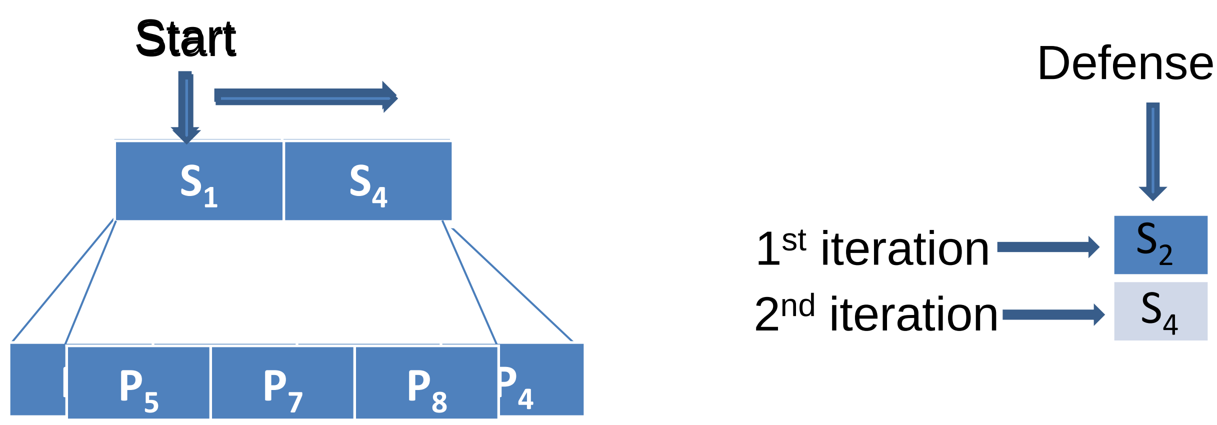
- **Defense Model:**
  - Defender can protect the substations D_S from cyber-attacks.
  - Defender has a budget B_D , where $|D_S| \leq B_{D\,.}$
- **Defender's Goal:**
  - Goal of the defender is to minimize the load loss

$$\min_{D_S} \max_{S' \subseteq S - D_S} \max_{P' \subseteq F(S')} J(A_{P'})$$
$$\text{s.t.} \quad |D_S| \leq B_D, \quad |S^{'}| \leq B_S, \quad |P^{'}| \leq B_P$$

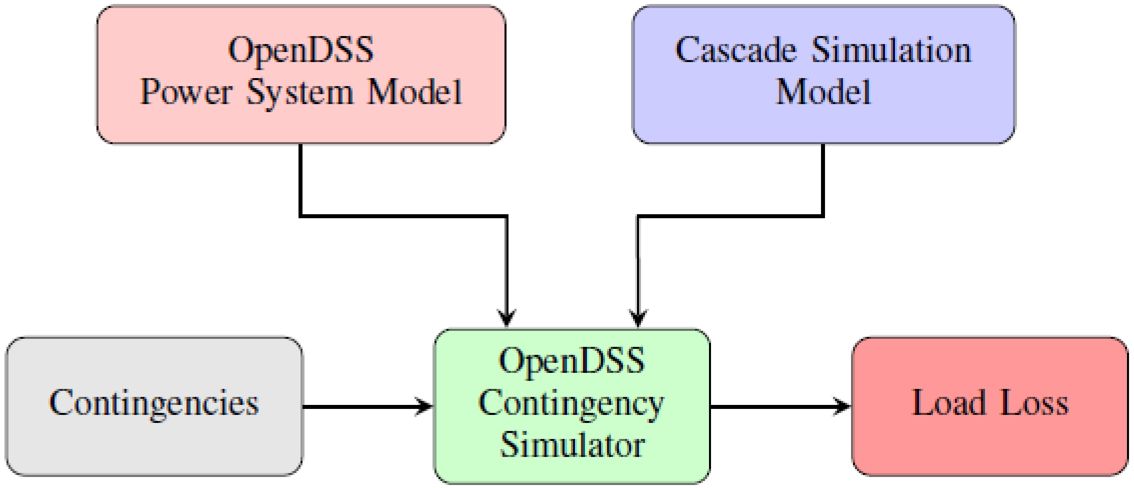
Defender Algorithm

- Consider a set of substations $S = \{S_1, S_2, S_3, S_4, S_5\}$.
- Consider a set of protection assemblies $P = \{P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8\}$.
- Defense budget is restricted to 2.

Run Attack Sequence based on the attack budget	Select a substation to protect and remove it from rest of the attack set.	Identify and record Losses	Select next Substation

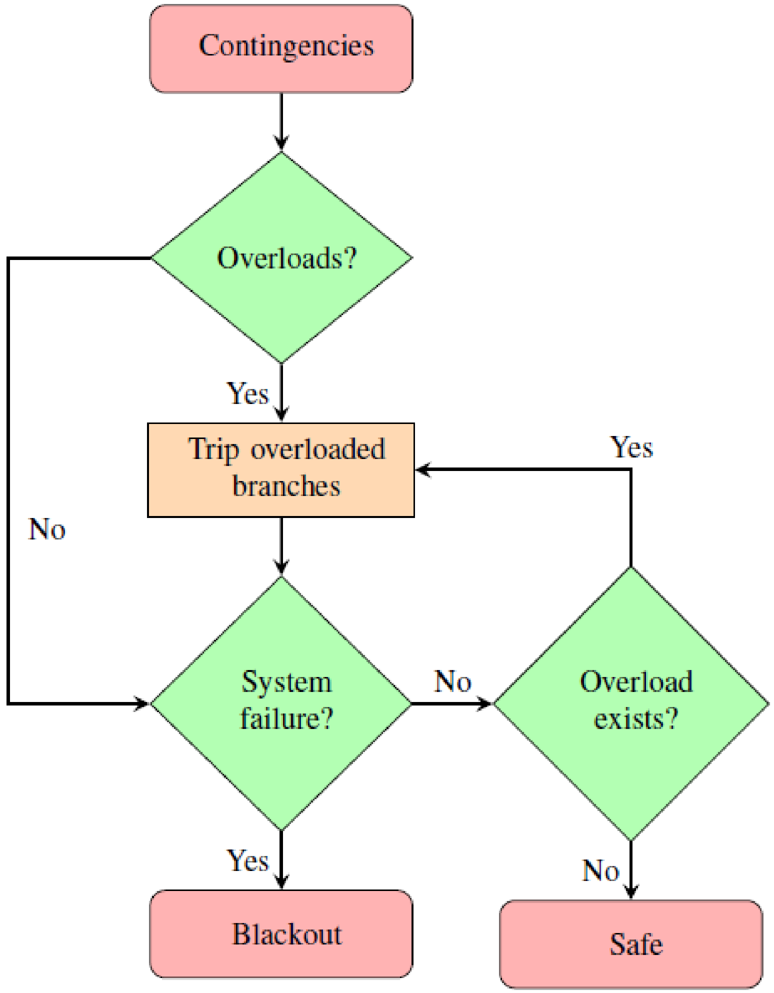


Contingency Simulator



Contingency simulator Framework

Cascade Simulation Model



Cascade Simulation Model

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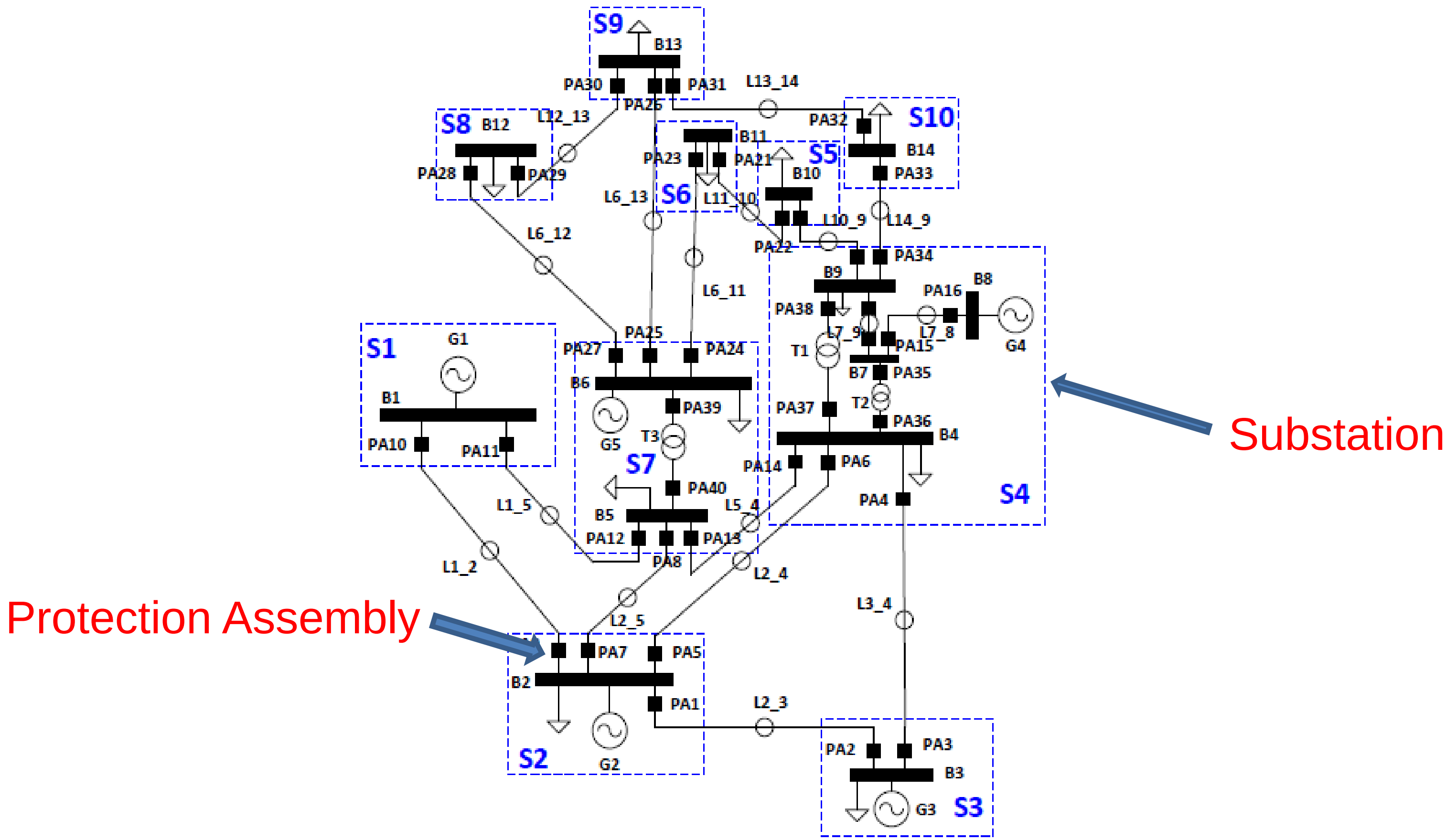
Example System

- Blue colored dotted boxes represent the substations.



IEEE-14 Bus System

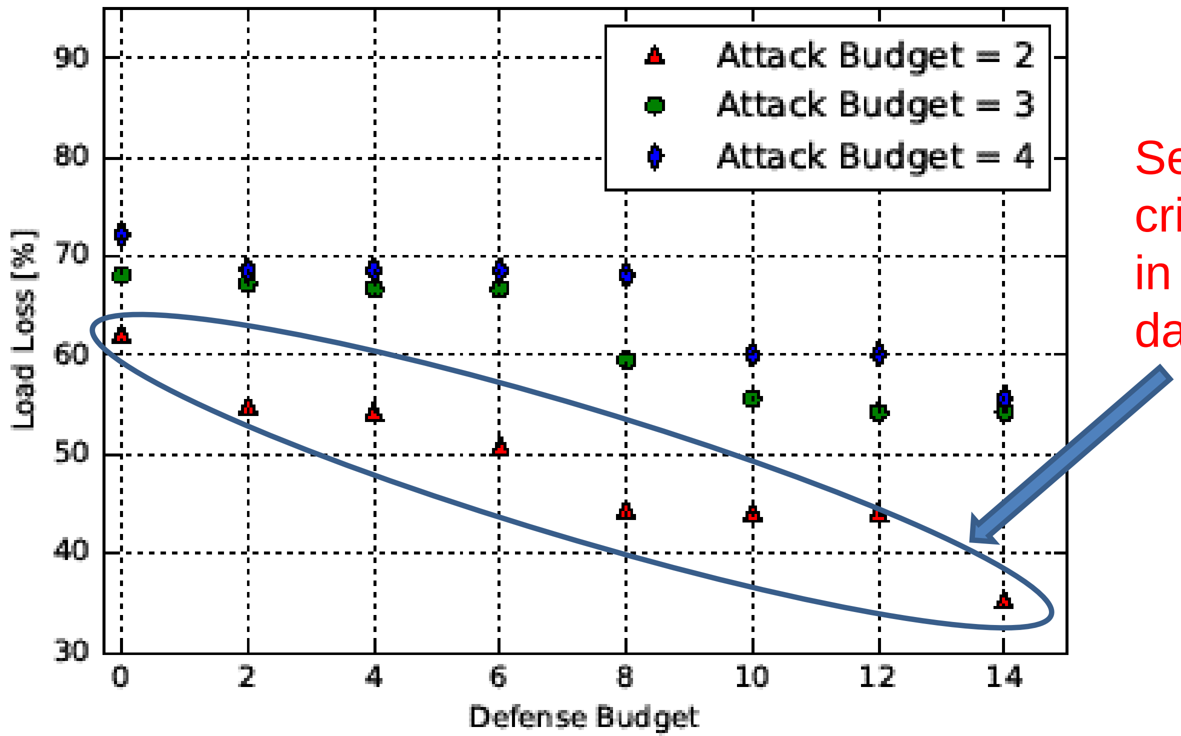
Evaluation

- Attack-Defense Scenario
- With only half the number of substation protection budget the load loss is minimized by 57.31%.

TABLE I: IEEE-14 Bus System Attack-Defense Scenario

Attack Budget (B_S)	B_P	Defense Budget (B_D)	Pre-Defense Load Loss	Post-Defense Load Loss	Substations Attacked	Substations Defended	Improvement (%)
2	2	3	51.17	48.30	S7	S4, S3, S2	5.61
2	2	4	51.17	43.46	S1, S6	S4, S3, S2, S7	15.07
2	2	5	51.17	29.55	S8, S9	S4, S3, S2, S7, S6	42.25
2	2	6	51.17	21.84	S5, S10	S4, S3, S2, S7, S6, S9	57.31

Evaluation

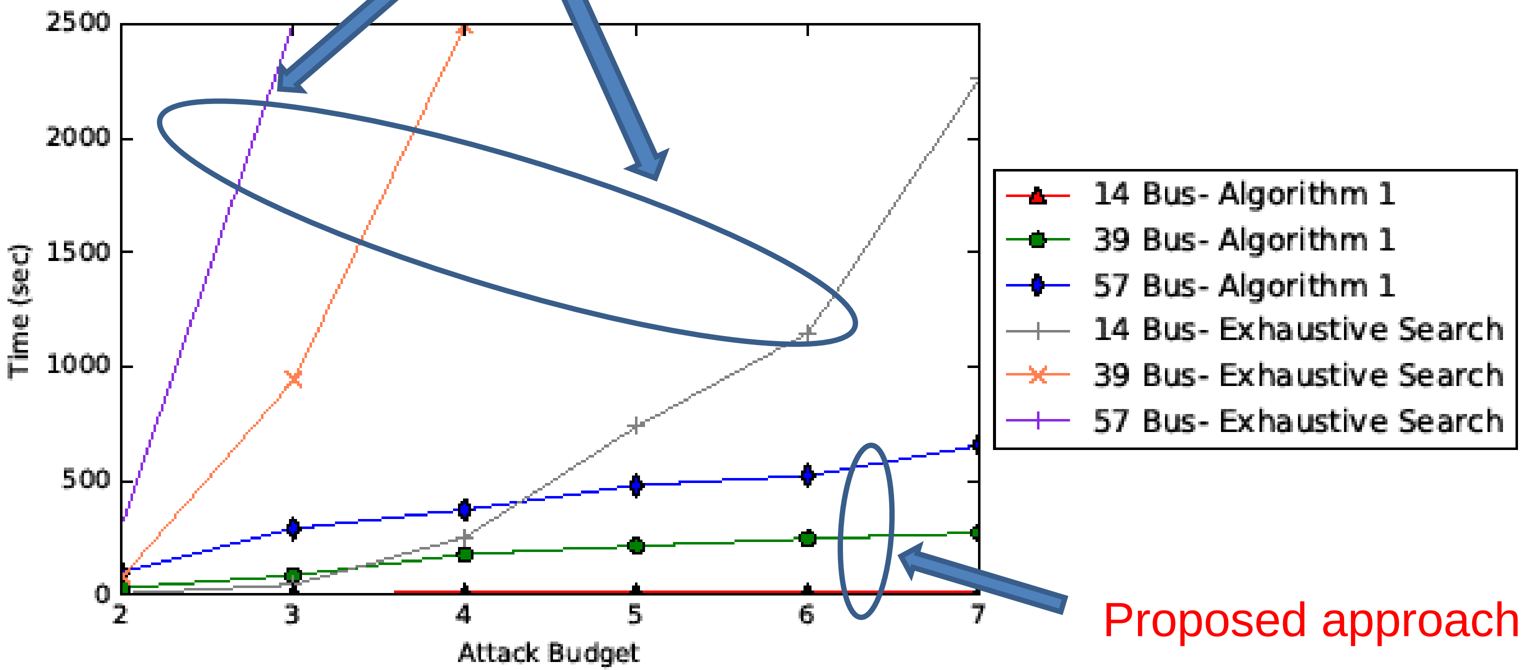


Selecting and protecting critical substations results in minimizing system damage

IEEE-39 Bus System

Evaluation: Attack Execution Time

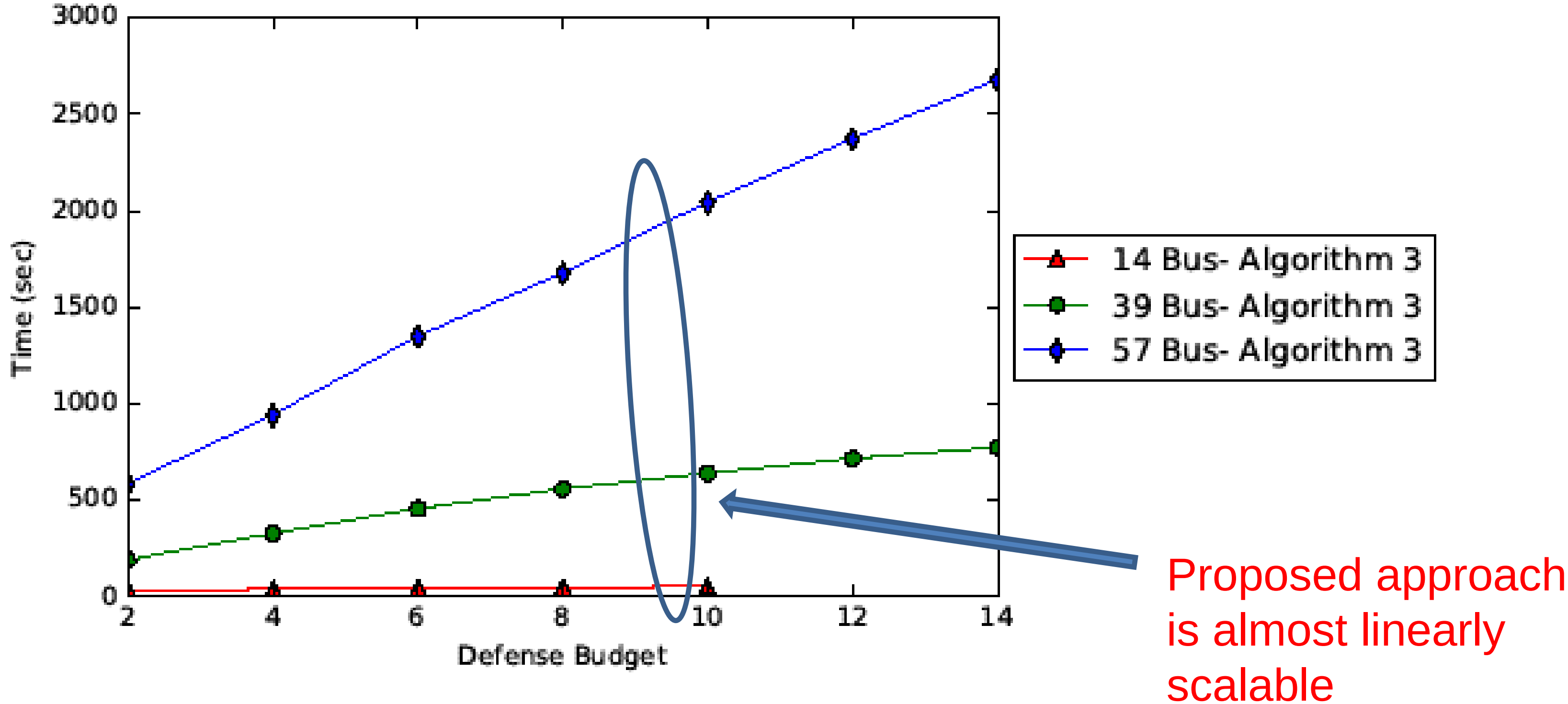
Exhaustive search takes much longer than the proposed approach



Proposed approach

Attack Execution Time

Evaluation: Defense Execution Time

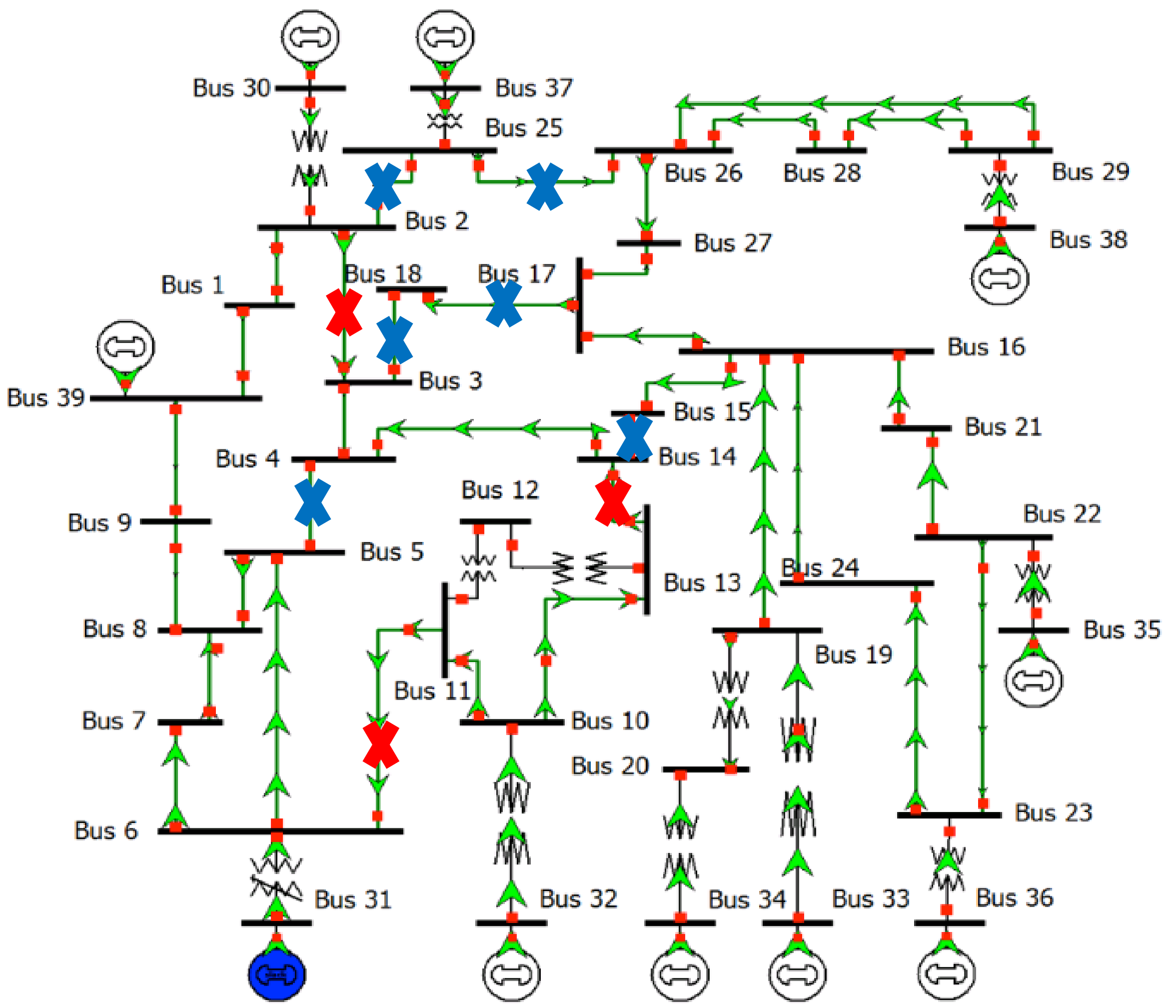


Defense Execution Time

Conclusion and Future Work

- A game theoretic approach for attacker/defender modeling is proposed.
- The models are formally described and developed.
- The algorithms presented are able to identify critical substations to attack and protect given the budget constraints in order to improve power system resilience.
- The algorithms presented perform significantly better than the exhaustive search.
- As part of the future work, we will look at the dynamic attacker/defender modeling in power systems.

Static Attack Scenario



- Initial attacks

↓ delay

- Stage1 Line Outages

15.86%

Ultimate Load Loss: 15.86%

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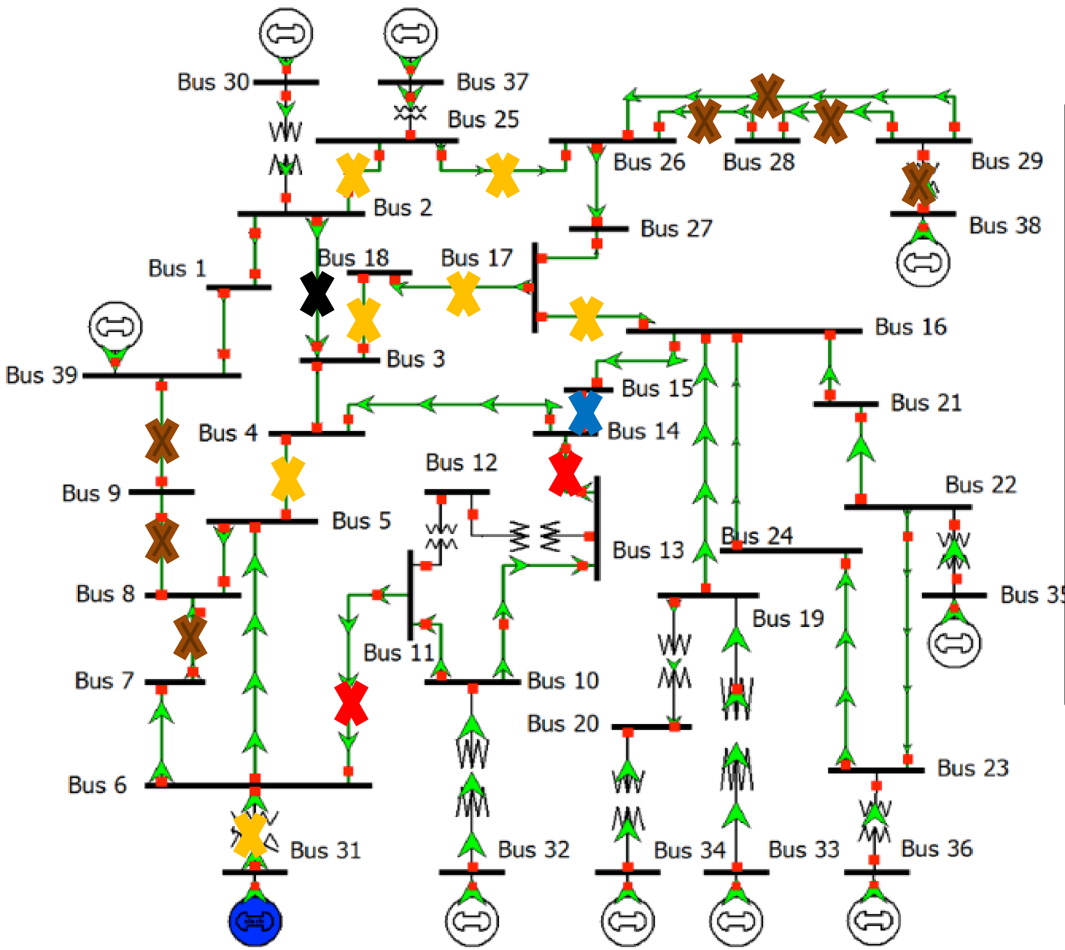
Dynamic Attack Scenario



- Initial attacks
delay
-Stage1 Line Outages + **Stage1 attack**
delay
- Stage2 Line Outages
delay 15.86%
- Stage3 Line Outages
42.78%

Ultimate Load Loss: 42.78%

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THANK YOU!