# Heuristics-Based Approach for Identifying Critical $N - k$ Contingencies in Power Systems

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# Introduction

- ✓ Reliable operation of power systems is of primary importance.

## Challenge?

Efficient and Effective methods to identify critical multiple $N-k$ contingencies are necessary.

- ✓ Identifying all the possible critical $N-k$ contingencies is computationally infeasible.

# Contingency Analysis

- Consider a power system $G_P$ consisting of buses, transmission lines, transformers, loads and generators.
- Failure(s) can occur in one or more component of the power system.
- These failures are referred to as $N - k$ contingencies.
- System failure causing contingencies are referred to as critical $N - k$ contingencies.

# Contingency Analysis

- ✓ $U$ represents the universal set of all the $N$ possible component outages in a power system.
- ✓ Given a value of k, the search space $S_k$ is defined by:

$$S_k = \{a \mid a \in 2^U, |a| \leq k\}$$

- ✓ $C_f$ denote the system failure criterion.

# Heuristic Algorithms

- ✓ Algorithm I.

Based on the iterative pruning of the current candidate contingency set using the previously identified critical $N - k$ contingencies.

- ✓ Algorithm II.

Based on the frequency distribution curve representing the frequency distribution of the candidate contingency set and the idea from Algorithm I to employ a 2- stage pruning of the candidate contingency set $S_k$.

# Algorithm I

- Let $F \epsilon S_{k'}$ be a contingency.
- If $F$ causes, a system failure then for all $k > k'$, any other contingency $F' \epsilon S_k$, satisfying $F \subseteq F'$ will cause a system failure.
- For example, consider a power system with universal set $U$ containing transmission lines $tl_1, tl_2, \ldots, tl_m$.
- If an outage $F = \{tl_a\}$ satisfies $C_f$ , any contingency $F' = \{tl_a, tl_i\}$, where $i \in \{1, \ldots, m\} - \{a\}$, is assumed to cause a system failure.

# Algorithm II

- For any transmission line $a \in U$, let $z_a$ denote its impedance. Given a value of $k$ and a contingency $F \in S_k$, the mean impedance $\mathcal{Z}(\mathcal{F})$ of the contingency is given by:

$$\mathcal{Z}(\mathcal{F}) = \frac{\sum_{a \in \mathcal{F}} z_a}{|\mathcal{F}|}$$

- Average impedance $\bar{\mathcal{Z}}_k$ of the frequency distribution curve for search space $S_k$ is given by:

$$\bar{\mathcal{Z}}_k = \frac{\sum_{\mathcal{F} \in \mathcal{S}_k} \mathcal{Z}(\mathcal{F})}{|\mathcal{S}_k|}$$

- The standard deviation $\sigma_{\mathcal{Z}}$ of the frequency distribution is defined by:

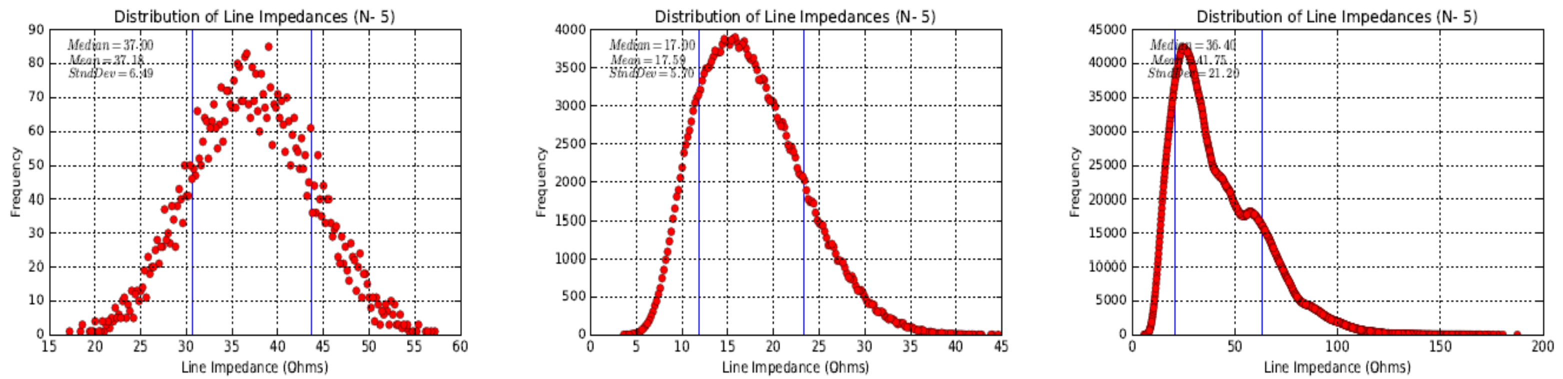
$$\sigma_{\mathcal{Z}} = \sqrt{\frac{\sum_{\mathcal{F} \in \mathcal{S}_k} (\mathcal{Z}(\mathcal{F}) - \bar{\mathcal{Z}}_k)^2}{|\mathcal{S}_k|}}$$

# Algorithm II

- ✓ The window size is then obtained by:

$$\mathcal{Z}_w = [\bar{\mathcal{Z}}_k - \sigma_{\mathcal{Z}}, \bar{\mathcal{Z}}_k + \sigma_{\mathcal{Z}}]$$

- ✓ Most critical $N - k$ contingencies fall within this region.
- ✓ A contingency $F \in S_k$ that appears within $\mathcal{Z}_w$ is considered as the critical contingency and is pruned from $S_k$ (Stage-1 prediction and pruning).
- ✓ Stage-2 prediction and pruning is done based on Algorithm I.




(a) IEEE-14 bus system (b) IEEE-39 bus system (c) IEEE-57 bus system

Fig. 11: Frequency distribution curves of the candidate contingency set ($\mathcal{S}_5$) for different standard power systems.

# Simulator and Approach

- ✓ OpenDSS, a steady state simulator is used to compute the results.

**Algorithm 1** Algorithm for Finding $N-k$ Contingencies

**Input:** $\mathcal{G}_p, \mathcal{U}, C_f, k$
**Initialize:** $\mathcal{T} \leftarrow \emptyset, \mathcal{R} \leftarrow \emptyset$, $c_{pre} \leftarrow 0$
**for all** $\mathcal{F} \in \mathcal{S}_1$ **do**
  $loss \leftarrow$ `simulate_contingency`$(\mathcal{G}_p, \mathcal{F})$
  **if** $loss \geq C_f$ **then**
    $\mathcal{R} \leftarrow \mathcal{R} \cup \mathcal{F}$
  **end if**
**end for**
**for** $p = 2, \ldots, k$ **do**
  $\mathcal{P} \leftarrow \emptyset, \mathcal{R}_{cur} \leftarrow \emptyset$
  **for all** $\mathcal{F}' \in \mathcal{S}_p$ **do**
    **for all** $\mathcal{F} \in \mathcal{R}$ **do**
      **if** $\mathcal{F} \subseteq \mathcal{F}'$ **then**
        $\mathcal{P} \leftarrow \mathcal{P} \cup \mathcal{F}'$
      **end if**
    **end for**
  **end for**
  $\mathcal{T} \leftarrow \mathcal{T} \cup \mathcal{P}$
  $\hat{\mathcal{S}}_p \leftarrow \mathcal{S}_p \setminus \mathcal{P}$ ▷ prunes search space $\mathcal{S}_p$
  **for all** $\mathcal{F} \in \hat{\mathcal{S}}_p$ **do**
    $loss \leftarrow$ `simulate_contingency`$(\mathcal{G}_p, \mathcal{F})$
    **if** $loss \geq C_f$ **then**
      $\mathcal{R}_{cur} \leftarrow \mathcal{R}_{cur} \cup \mathcal{F}$
    **end if**
  **end for**
  $\mathcal{R} \leftarrow \mathcal{R} \cup \mathcal{R}_{cur}$
  **if** $|\mathcal{R}_{cur}| \leq c_{pre}$ **then**
    **break**
  **end if**
  $c_{pre} \leftarrow |\mathcal{R}_{cur}|$
**end for**
**return** $\mathcal{T}$

**1-stage pruning**

**Algorithm 2** Algorithm for Finding $N-k$ Contingencies

**Input:** $\mathcal{G}_p, \mathcal{U}, C_f, \mathcal{Z}_w, k$
**Initialize:** $\mathcal{T} \leftarrow \emptyset, \mathcal{R} \leftarrow \emptyset$, $c_{pre} \leftarrow 0$
**for all** $\mathcal{F} \in \mathcal{S}_1$ **do**
  $loss \leftarrow$ `simulate_contingency`$(\mathcal{G}_p, \mathcal{F})$
  **if** $loss \geq C_f$ **then**
    $\mathcal{R} \leftarrow \mathcal{R} \cup \mathcal{F}$
  **end if**
**end for**
**for** $p = 2, \ldots, k$ **do**
  $\mathcal{P} \leftarrow \emptyset, \mathcal{R}_{cur} \leftarrow \emptyset, \mathcal{S}_p' \leftarrow \emptyset$
  **for all** $\mathcal{F} \in \mathcal{S}_p$ **do**
    **if** $\mathcal{Z}(\mathcal{F}) \notin \mathcal{Z}_w$ **then**
      $\mathcal{S}_p' \leftarrow \mathcal{S}_p' \cup \mathcal{F}$ ▷ prunes search space $\mathcal{S}_p$
    **end if**
  **end for**
  $\mathcal{T} \leftarrow \mathcal{T} \cup (\mathcal{S}_p \setminus \mathcal{S}_p')$
  **for all** $\mathcal{F}' \in \mathcal{S}_p'$ **do**
    **for all** $\mathcal{F} \in \mathcal{R}$ **do**
      **if** $\mathcal{F} \subseteq \mathcal{F}'$ **then**
        $\mathcal{P} \leftarrow \mathcal{P} \cup \mathcal{F}'$
      **end if**
    **end for**
  **end for**
  $\mathcal{T} \leftarrow \mathcal{T} \cup \mathcal{P}$
  $\hat{\mathcal{S}}_p \leftarrow \mathcal{S}_p' \setminus \mathcal{P}$ ▷ prunes search space $\mathcal{S}_p'$
  **for all** $\mathcal{F} \in \hat{\mathcal{S}}_p$ **do**
    $loss \leftarrow$ `simulate_contingency`$(\mathcal{G}_p, \mathcal{F})$
    **if** $loss \geq C_f$ **then**
      $\mathcal{R}_{cur} \leftarrow \mathcal{R}_{cur} \cup \mathcal{F}$
    **end if**
  **end for**
  $\mathcal{R} \leftarrow \mathcal{R} \cup \mathcal{R}_{cur}$
  **if** $|\mathcal{R}_{cur}| \leq c_{pre}$ **then**
    **break**
  **end if**
  $c_{pre} \leftarrow |\mathcal{R}_{cur}|$
**end for**
**return** $\mathcal{T}$

**2-stage pruning**

# Contingency Simulator

- ✓ Integrated OpenDSS power system model and cascade simulation model with the OpenDSS contingency simulator.
- ✓ Captures critical $N - k$ contingencies causing severe cascading outages resulting in system failure.

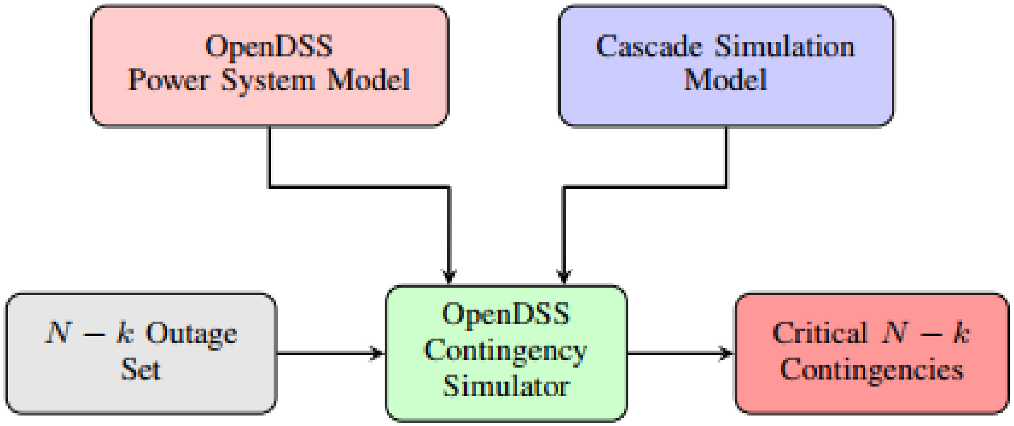



Fig. 2: Cascade Simulator Framework

# Cascade Simulation Model

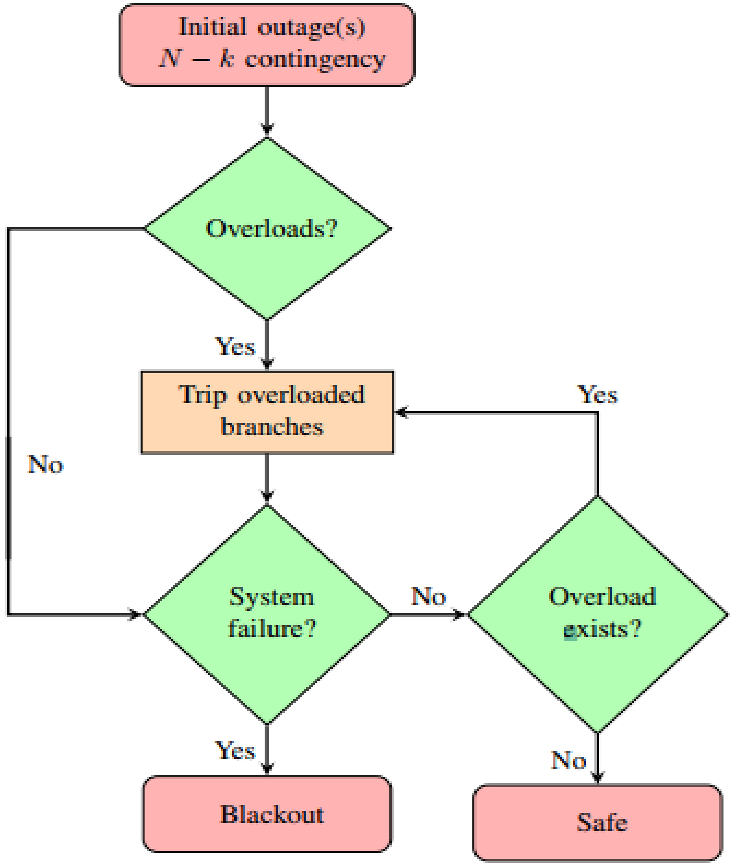
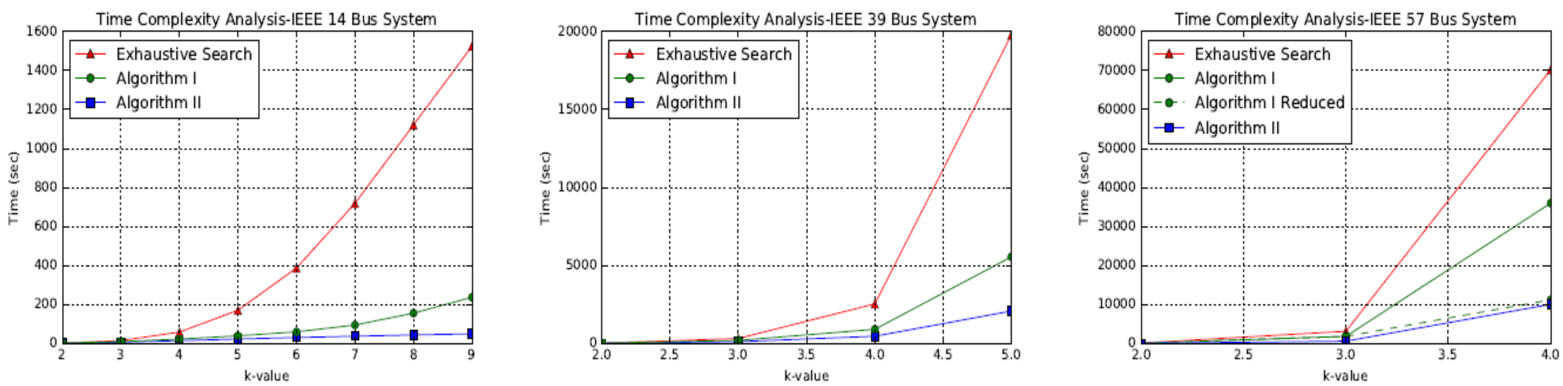


Fig. 3: Cascade Simulation Model

# Evaluation

✓ **Execution Time Analysis of the Algorithms**

- For IEEE-57 bus system exhaustive search for $N-4$ analysis identifies a total of 346,214 critical contingencies out of 722,865 contingencies.
- Algorithm I uses 24,469 simulations to identify the same 345,662 critical $N-k$ contingencies out of the 346,214 critical contingencies.
- To identify the remaining 552 critical $N-4$ contingencies, Algorithm I uses 259,600 simulations in its final iteration.



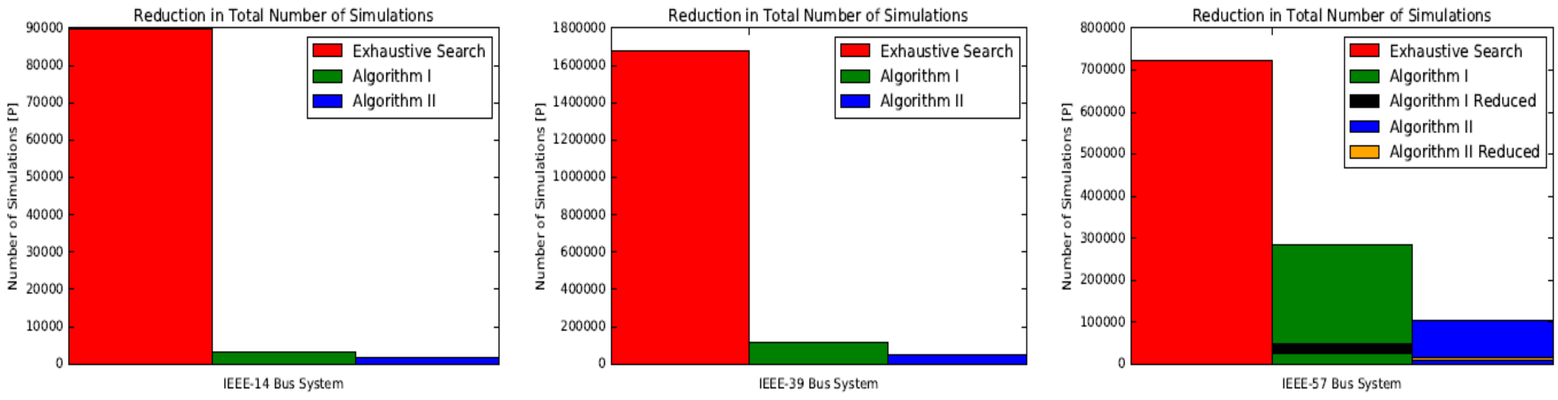

(a) IEEE-14 bus system (b) IEEE-39 bus system (c) IEEE-57 bus system

Fig. 8: Execution Time Analysis-Time taken by Exhaustive search, Algorithm I and Algorithm II to Identify Critical $N-k$ Contingencies

# Evaluation

✓ **Reduction in the Total Number of Simulations**

- For IEEE-14 bus system, there are 89845, 3095, and 1734 number of simulations performed.
- For IEEE-39 bus system, there are 1676115, 117536, and 48046 number of simulations carried out.
- For IEEE-57 bus system, if 259,600 simulations are avoided, the total number of simulations will be reduced to only 24,469.




(a) IEEE-14 bus system (b) IEEE-39 bus system (c) IEEE-57 bus system

Fig. 9: Total Number of Simulations Run using Exhaustive Search, Algorithm I and Algorithm II to Identify Critical $N-k$ Contingencies

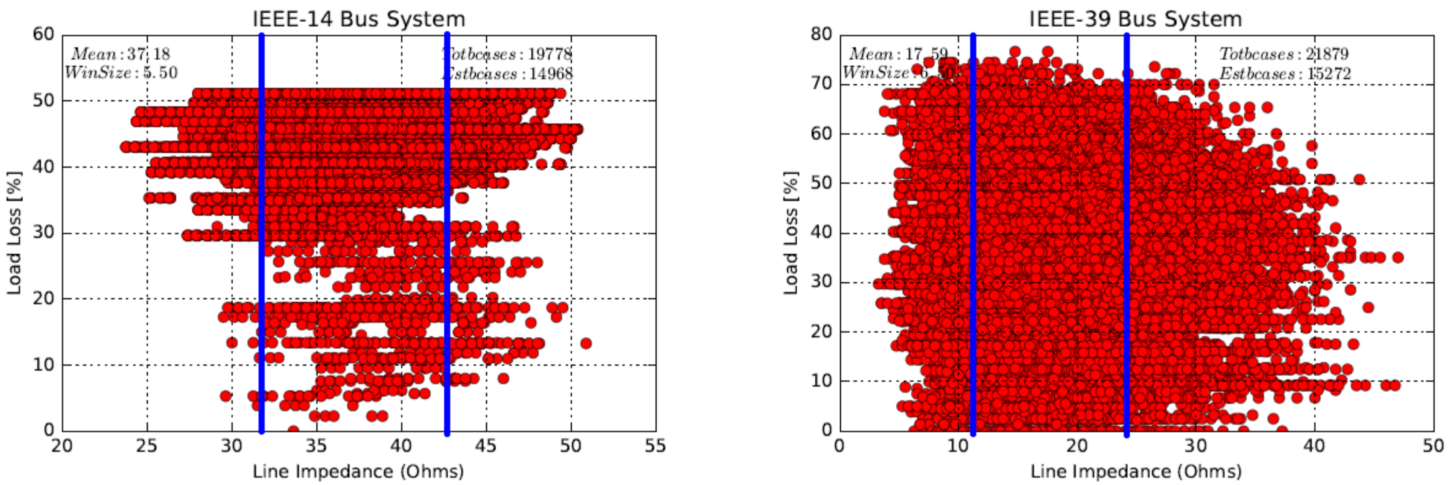
# Evaluation

✓ **Performance Accuracy of the Algorithms**

- A total of 14,968 out of 19,778 and a total of 15,272 out of 21,879 critical contingencies for IEEE- 14 bus and IEEE-39 bus systems respectively are identified.

75.62%

~ 70%



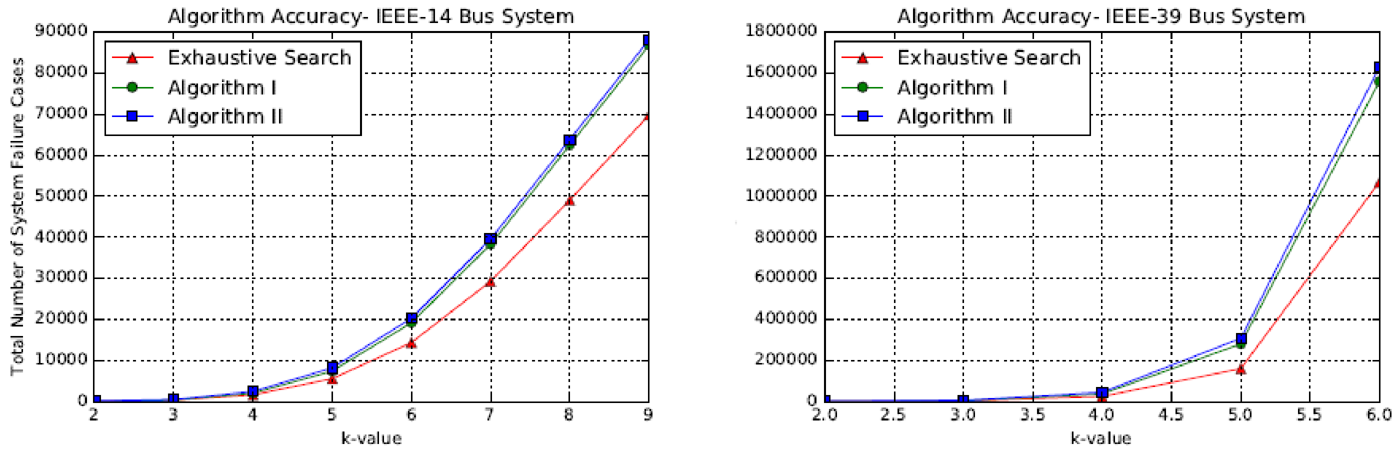

(a) IEEE-14 bus system

(b) IEEE-39 bus system

Fig. 11: Effectiveness of Stage-1 Prediction and Pruning Process of Algorithm II.

# Evaluation

✓ **Performance Accuracy of the Algorithms**




(a) IEEE-14 bus system

(b) IEEE-39 bus system

Fig. 10: Prediction Accuracy of Algorithm I and Algorithm II

# Conclusions

- ✓ Two heuristic algorithms were developed for $N - k$ contingency analysis problem.
- ✓ The approach is able to capture all the critical contingencies without missing any dangerous contingency.
- ✓ Approach is validated on the standard IEEE-14, 39, and 57 bus systems.
- ✓ The algorithms perform significantly better than the exhaustive search.
- ✓ The identified critical $N - k$ contingencies can be used to design effective mitigation strategies to improve system resilience and reliability.
- ✓ **Future Work**
  - Using efficient data structures to improve the algorithms efficiency.
  - Using the concept of distributed computing for optimizing the approach.

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# THANK YOU!!