Load Curtailment Estimation in Response to Extreme Events

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Introduction

• Hurricanes:
  • Cause significant economic, social, and physical disruptions
  • Result in considerable inconvenience for residents living in disaster areas
  • One of the most recurring events in the United States

• Power System Resilience:
  • Rate and speed of a system in bouncing back to its normal operating condition after an external shock.

• Prediction of Power System Component Outages:
  • An exact prediction of power component outages plays a significant role in restoration, recovery, and improving power system resilience.
Hurricane Irma
Proposed Model

• The problem is solved in three consecutive stages:
  a) Forecasting:
     • The category and the path of an upcoming hurricane
  b) Component Outage Prediction:
     • Using Machine Learning method
  c) Load Curtailment Estimation:
     • Optimization using mixed integer programming

(a) Forecasting  (b) Component Outage Prediction  (c) Load Curtailment Estimation
Machine Learning

• Machine learning is an application of artificial intelligence (AI):
  • Includes data-driven decision-making techniques
  • Explores algorithms that are able to learn from, describe, and make predictions on data.

• Machine learning algorithms are often categorized as:
  • **Supervised machine learning:** algorithms can apply what has been learned in the past to new data using labeled examples to predict future events.
  • **Unsupervised machine learning:** algorithms are used when the information used to train is neither classified nor labeled.
Support Vector Machine

• Support Vector Machines (SVM)
  • Supervised learning models with associated learning algorithms that analyze data used for classification and regression analysis.

• Linear Classifier:
  • The goal is a dimensional hyperplane.

• Best Hyperplane:
  • Represents the largest margin, between the two classes
  • If such a hyperplane exists,
  • It is known as the maximum-margin hyperplane
Component Outage Prediction

• An SVM method is used and trained to determine the decision boundary;
  • Subsequently, power grid component outages in response to upcoming hurricanes can be effectively predicted.

• Classify the components into two states of:
  • Damaged (cross)
  • Operational (circle)

• Based on:
  • Distance
  • Wind speed

• Separated by:
  • A decision boundary
Evaluation

• To evaluate the performance of the classifier, usually a subset of historical data is reserved as the validation/test set.

• The $F_1$-Score is a common and reliable measure of classification performance:

\[
P = \frac{\text{number of correctly predicted outages}}{\text{total number of predicted outages}}
\]

\[
R = \frac{\text{number of correctly predicted outages}}{\text{total number of actual outages}}
\]
The objective of the minimum load curtailment problem is defined as the value-weighted cost of load curtailment in the system:

- Includes the generation cost, and the cost of unserved energy during contingency scenarios.

Subject to:
- Operational constraints
- Load balance
- Generation unit output capacity
- Network line capacity and power flow constraints, Min on/off time limits, etc.
Case Study

- Historical data for the past extreme events at component level are limited
- We generated 300 samples of each component state
  - Following a normal distribution function with a small Gaussian noise.
- The samples belong to two classes of components
  1. High probability of failure
  2. Components that can survive the extreme event.
- The features are normalized to [0, 1] based on the maximum considered values of wind speed and distance.
Role of Hyper-parameters and Kernel Shape

• Table 1 shows the accuracy of SVM with aforementioned combinations of penalty parameters and kernels.
• The polynomial kernel SVM with c=1 outperforms other models in terms of classification accuracy.
• The margin size of the SVM with polynomial kernel is 0.1131, and the average $\varepsilon$ (regularization weight) is 0.4558.

Table 1. Accuracy (%) of SVM with various penalty-parameters and kernels

| Kernel     | c=0.1 | c=1  | c=10 |
|------------|-------|------|------|
| Linear     | 91.0  | 91.4 | 91.2 |
| Quadratic  | 91.3  | 91.2 | 91.2 |
| Polynomial | 92.3  | 92.8 | 92.7 |
| Gaussian   | 91.3  | 91.2 | 91.8 |
Visualizing the Decision Boundary

• This Figure shows the decision boundary of the polynomial kernel with penalty parameter $c=1$, separating outage from operational components based on wind speed and distance from the center of the hurricane.

• The instances are not linearly separable

• A nonlinear kernel is necessary to better classify the components.

Decision boundary of the polynomial kernel with penalty parameter $c=1$
SVM Performance

• Table 2 shows the confusion matrix of this classification.
• The proposed method can effectively classify the components into outage and operational classes.

Table 2. Confusion Matrix of classifying system components

| Actual  | Predicted |          |
|---------|-----------|----------|
|         | Normal    | Outage   |
| Normal  | 91.7%     | 8.3%     |
| Outage  | 6.0%      | 94.0%    |
Load Curtailment Estimation

- Table 3 shows the load curtailment of each contingency scenario based on the predicted outages.

### Table 3. Load Curtailment of Bus Outages along three Hurricane Paths

| Bus number | Total Load (MW) | LC Scenario 1 (MW) | LC Scenario 2 (MW) | LC Scenario 3 (MW) |
|------------|----------------|--------------------|--------------------|--------------------|
| 2          | 423.08         | 0                  | 0                  | 0                  |
| 3          | 46.79          | 44.95              | 0                  | 1.62               |
| 15         | 159.87         | 0                  | 0                  | 0.37               |
| 18         | 62.39          | 0                  | 59.94              | 2.10               |
| 19         | 185.22         | 0                  | 177.95             | 0                  |
| 20         | 42.89          | 0                  | 41.21              | 0                  |
| 23         | 62.39          | 0                  | 0                  | 9.92               |
| 24         | 169.62         | 0                  | 0                  | 162.97             |
| 29         | 46.79          | 0                  | 0                  | 0.31               |
Conclusion

• An SVM model was trained to predict the outage state of power grid components due to an imminent hurricane strike.

• A minimum load curtailment problem was formulated to estimate the amount of load curtailment considering the predicted outage states from a Support Vector Machine method.

• This model provides a practical forward-looking framework for utilities, local governments, and policy makers for a risk-informed operations management, emergency response planning, humanitarian logistics, and restoration of the life-line power grid infrastructure in both strategic level and real-time basis.
Thank you
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