GRID MODERNIZATION INITIATIVE PEER REVIEW

GMLC 1.4.17 – Extreme Event Modeling

RUSSELL BENT

April 18-20

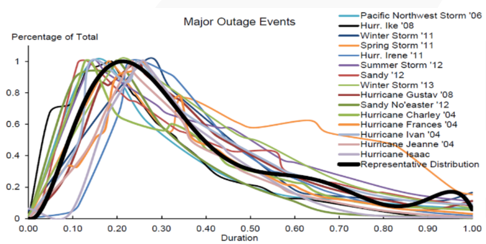
Sheraton Pentagon City – Arlington, VA

Extreme Event Modeling

High Level Summary

Project Description

- Natural and man-made extreme events pose enormous threats



Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

- Cascading and N-k modeling have large gaps
  - Inadequate modeling
    - Reliability standards (NERC Standard TPL-001-4) challenged
  - Computational efficiency
    - Considerable speed up required for faster than real time planning
  - N-k contingency analysis
    - Existing k=3 analysis misses large-scale adversary attacks
    - Neglects high likelihood failures

Project Objectives

- ✓ A prototype set of tools for efficient cascade modeling and probabilistic N-k identification.
- ✓ Tools that are 500x faster than existing industry cascade simulation packages
- ✓ Identify the worst (probabilistic) k contingencies where k is twice as big as existing practices
- ✓ Demonstration on a large-scale system (WECC)

Value Proposition

- ✓ Identify extreme event risk prior to event occurrence
- ✓ Plan proactively

Extreme Event Modeling
Project Team

Project Participants and Roles

- **Russell Bent** (LANL): PI, Task Lead for *3.4: Most probable N-k identification*
- **Yuri Makarov** (PNNL): +1, Task Lead for *1.1: Integrating multiple temporal scales, 1.2: Inadequate Modeling—Integrating Protection System models*
- **Liang Min** (LLNL): Task Lead for *1.3: Integrating renewables, 2.3: Parallel computing for massive dynamic contingency*
- **Junjian Qi** (ANL): Task Lead for *2.1: Predicting critical cascading path*
- **Yilu Liu** (ORNL): Task Lead for *2.2: Model Reduction Techniques*
- **Meng Yue** (BNL): Task Lead for *3.1: Component Failure Probabilities*
- **Kara Clark** (NREL): Task Lead for *3.2: Mitigation Plan Modeling*
- **Jean-Paul Watson** (SNL): Task Lead for *3.3: Worst Case N-k identification*

PROJECT FUNDING			
Lab	FY16 $	FY17$	FY18 $
LANL	155K	130K	145K
PNNL	210K	235K	180K
LLNL	160K	260K	210K
ANL	125K	95K	125K
ORNL	125K	95K	125K
BNL	50K	45K	45K
NREL	50K	45K	45K
SNL	125K	95K	125K

<u>Industry and Academic Partners:</u> GMLC, NERC, FERC, IEEE Cascading Failure Working Group, Dominion Virginia Power, PJM, ERCOT, UTK

- Webinar participation
- Power system data

Extreme Event Modeling

Relationship to Grid Modernization MYPP

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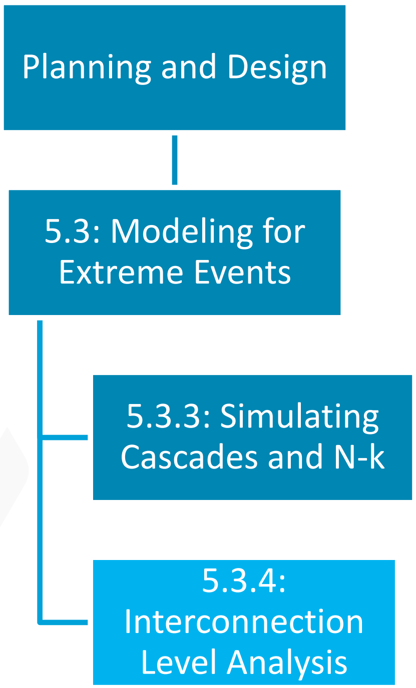
Primary MYPP Goal: A 10% reduction in the economic costs of power outages by 2025

Executive Summary: *greater resilience to hazards of all type*

MYPP Activities

- Planning and Design Activity 2: Developing and Adapting Tools for Improving **Reliability** and **Resilience**
- Sub Activity 5.3: Modeling for Extreme Events
  - *Task 5.2.3:* Develop methodologies to simulate cascading events and protection systems and improve solution times by 500x via scalable computational math algorithms and automation techniques. Include probabilistic approaches in N-k contingency analysis
    - Project Deliverable: Tools that are 500x faster than existing industry cascade simulation packages (2019)
    - Project Deliverable: Tools that identify the worst (probabilistic) k contingencies where k is twice as big as existing practices
  - *Task 5.2.4:* Develop tools needed to perform interconnection level analysis of extreme events such as weather, EMP, GMD, and cyber and physical attacks.
    - Project developments are a necessary foundation for future tools and capabilities for mitigating the consequences of such events and modeling of sources of extreme events



* As of https://energy.gov/sites/prod/files/2016/01/f28/Grid%20Modernization%20Multi-Year%20Program%20Plan.pdf

Extreme Event Modeling

Approach

- Cascade Modeling: Inadequate Modeling
  - Integrating multiple temporal scales
    - Description: Develop new methods for modeling phenomena at different time multiple time scales
    - Key Issues: Fundamentally different methods used at different time scales, difficult to integrate
    - Novelty: Unique hybrid approach for combining phenomena and mathematics at different time scales
  - Integrating protection system models
    - Description: Develop models of Zone 3 protection
    - Key Issues: The extent and ordering of protection execution is often unknown
    - Novelty: New methods for estimating the behavior of protection during cascades.
  - Integrating Renewables
    - Description: Develop mathematical models and implementations of long-term wind dynamics
    - Key Issues: No stability simulation platform that combines computational capabilities with models needed for assessing the implications of wind energy resources dynamics
    - Novelty: new mathematical models of wind dynamics suitable for cascades
- Cascade Modeling: Computational Efficiency
  - Predicting critical cascading paths
    - Description: Develop statistical methods for identifying cascading paths
    - Key Issues: The number of possible cascade evolutions can be to large to enumerate
    - Novelty: Models and software tools that statistically characterize component interactions that significantly limit the number cascade evolutions that need to be simulation
  - Model Reduction techniques
    - Description: Methods and software for reducing the size of networks
    - Key Issues: Network models can be too large for exhaustive cascade modeling
    - Novelty: New approaches for model reduction based on measurement data
  - Parallel computing for massive dynamic contingency analysis
    - Description: Leverage HPC to improve efficiency of cascade modeling
    - Key Issues: The number of cascades are too many to enumerate serially
    - Novelty: Extensive leveraging of DOE and lab investments in HPC to improve computation by 500x
- Probabilistic N-k
  - Component failure probabilities
    - Description: Develop probabilistic models of component failure based on data
    - Key Issues: Utilities currently do not have rigorous approaches for build probabilistic models of failure
    - Novelty: Formal probabilities for N-k
  - System failure probabilities
    - Description: Develop probabilistic models of system failures based during extreme events
    - Key Issues: Data is sparse for examples of extreme event system failures
    - Novelty: Formal probabilistic of extreme event system failures
  - Worst-Case N-k Identification
    - Description: Tools for identifying sets of k component failures with the biggest impact
    - Key Issues: It is computationally intractable to find k > 3 worst failures
    - Novelty: New approaches for doubling the size of k
  - Most probable N-k Identification
    - Description: Tools for identifying sets of k component failures whose probabilistic outcome is worst.
    - Key Issues: Computationally very difficult to find sets of large k
    - Novelty: Tools that combine probabilistic models with N-k optimization

Extreme Event Modeling

Key Project Milestones

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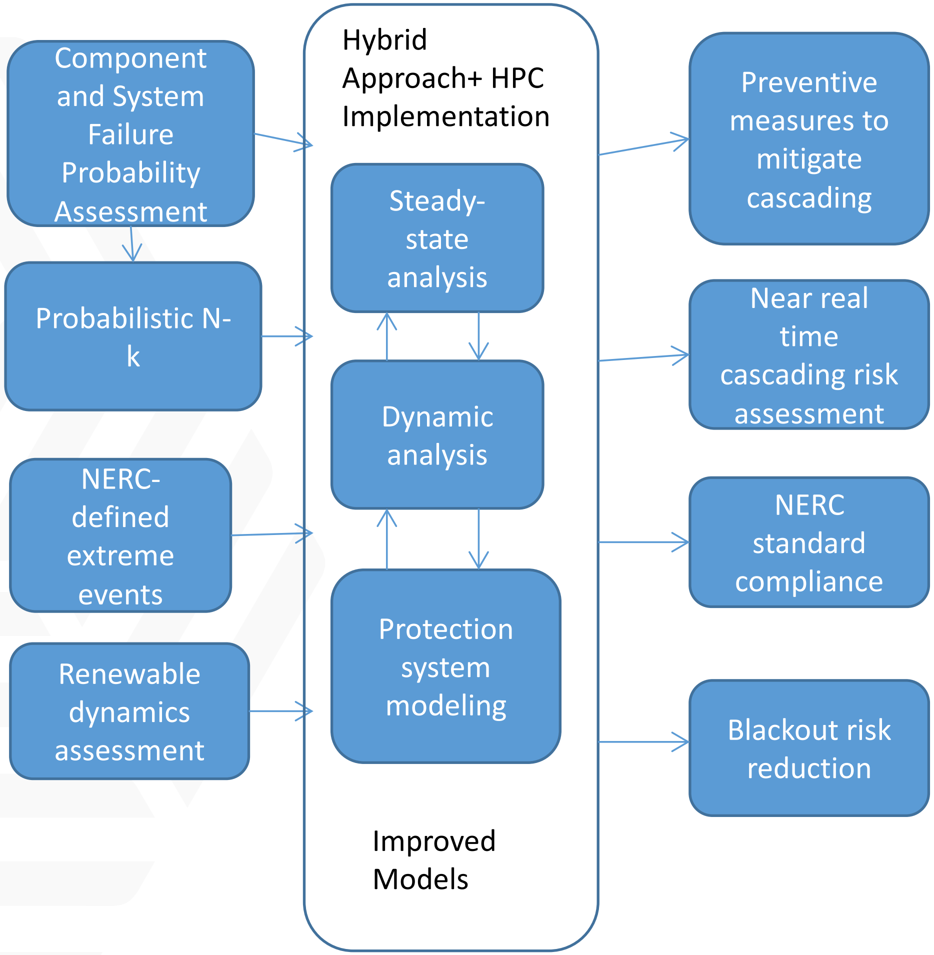
Milestone (FY16-FY18)	Status	Due Date
Protective measures approach identified and a strategy for implementation in DCAT completed	Complete	10/1/16
Implementation of protective measures in DCAT	Complete	1/1/17
Report detailing survey of past outages and extreme events	Complete – Delivered on GMLC share site	1/1/17
Cascade modeling demonstrates 10x of cascade simulations as compared to existing tools	Started: Work focused on developing underlying HPC architecture	10/1/17
Scale N-k approaches to networks that are 10x larger than existing tools can handle	Started: Initial N-k software framework developed in Pyomo	10/1/17
Cascade modeling demonstrates 100x of cascade simulations as compared to existing tools	Not started	10/1/18
Open source prototype release that 1) Integrates multiple temporal scales, protection system modeling, and renewables into cascade models, 2) demonstrates 500x speedup of cascade simulations as compared to existing tools, and 3) improves computation of N-k by increasing k by twice as much over existing practices.	Not started	4/1/19

Extreme Event Modeling

Accomplishments to Date

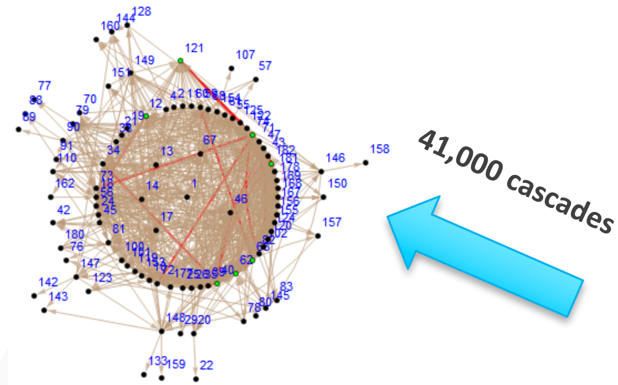
- Technical Insights and Accomplishments
  - Extreme event strategy document
    - Gaps in extreme modeling, directions for addressing gaps
  - Dynamic Contingency Analysis Tool (DCAT)
    - Hybrid models, zone 3 protection, ACOPF
  - Survey of Past Outages and Extreme Events
    - Lack of statistical data and rigorous analysis of the data can lead to misleading or even erroneous information for making decisions
  - Predicting Cascading Paths
    - Cascading path reduction can lead to 100X speed up
  - N-k Contingency Analysis
    - Developed methods for computing exact deterministic N-k solutions, to realistic N-k power flow models from American Electric Power
    - Demonstrated that probabilistic N-k is complimentary to deterministic N-k



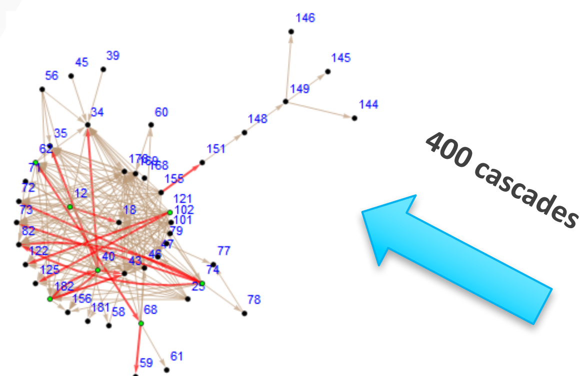
Extreme Event Modeling
Accomplishments to Date

- Stakeholder engagement
  - Industry webinars
    - June 16, 2016, Jan. 25, 2017
    - FERC, Caiso, Idaho Power, MISO, PLM, DOM, SPP, NERC, DVP
  - DCAT shared with Idaho Power, NERC, and ERCOT
  - Model Reduction
    - The ARX transfer function approach has been applied to a measurement based oscillation damping control tool for the NYPA system.
    - Research stage for the TERNA (Italy) Grid.
- Publications
  - X. Zhang, Y. Xue, Y. Liu, J. Chai, L. Zhu, and Y. Liu, *Measurement-based System Dynamic Reduction Using Transfer Function Models*, submitted to 2017 North American Power Symposium (NAPS), Morgantown, WV, Sept. 17-19, 2017.
  - Q. Huang, B. Vyakaranam, R. Diao, Y. Makarov, N. Samaan, M. Vallem, and E. Pajuelo, *Modeling Zone-3 Protection with Generic Relay Models for Dynamic Contingency Analysis*, PES General Meeting, 2017
  - Wenyun Ju, Kai Sun, and Junjian Qi, *Multi-Layer Interaction Graph for Analysis and Mitigation of Cascading Outages*, IEEE Journal on Emerging and Selected Topics in Circuits and Systems, under review
  - J. Qi. *Efficient Estimation of Component Interactions for Cascading Failure Analysis by EM Algorithm*, IEEE Transactions on Power Systems, under review.
  - A. Florita, M. Folgueras, E. Wenger, V. Gevorgian, and K. Clark. *Grid Frequency Extreme Event Analysis and Modeling in the Western Interconnections. Solar and Wind Integration Workshop*, under review.

Example Accomplishment: Statistical modeling of component interactions can reduce the number of cascade simulations by a factor of 100



Identified **top 7 key components** and **top 13 key links** using 400 cascades are the same as those using 41,000 cascades



Extreme Event Modeling

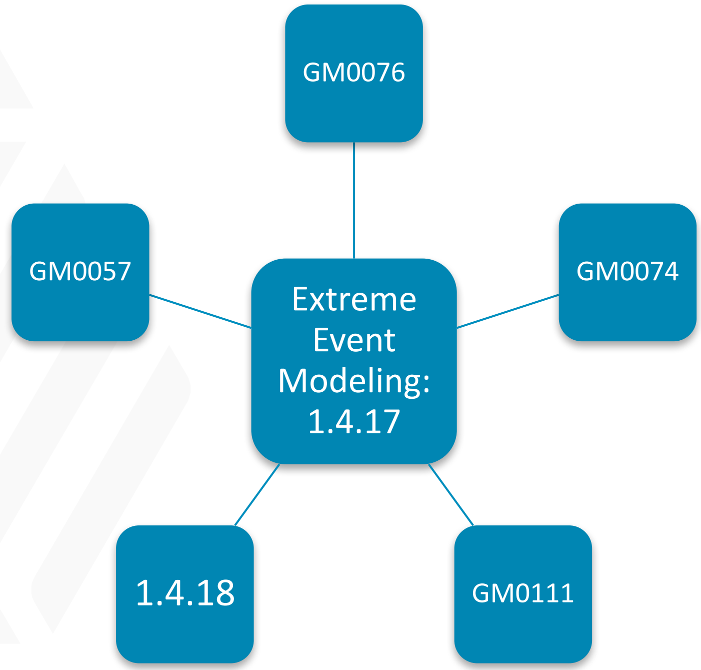
Response to December 2016 Program Review

Recommendation	Response
Please provide the "Strategy Document" due in April to the DOE program managers before the peer review in April 2017.	Strategy Document will be provided to DOE program managers no later than April 7, 2016
Before the April 2017 peer review, please identify at least one strong utility partner that you can work with to evaluate your new models	The team has selected WECC as the utility partner for new models • 2025 planning model with dynamics • Ease of NDA process • Data acquisition process documented • LANL, PNNL, LLNL, ANL have access, other labs are following process.
Please make sure to collaborate with the Metrics Analysis team (project 1.1). Of particular interest will be the report detailing survey of past outages and extreme events. Continue collaborations with New Orleans (1.3.11).	Will reach out to Metrics Analysis Team in FY17 Q2-Q3 with *Survey of Past Outages and Extreme Events* that was completed in Dec. 2016.

Extreme Event Modeling
Project Integration and Collaboration

- GM0076: Emergency monitoring and controls through new technologies and analytics
  - This project addresses a new generation of protection systems based on advanced analytics, frequent measurements, HPC and fast controls.
  - Project collaborations focus on mitigation of extreme events.
- GM0074: Models and methods for assessing the value of HVDC and MVDC technologies in modern power grids
  - This project addresses the use of HVDC for AC grid services.
  - Collaborations focus on the potential of DC modulation to stabilize extreme events and restore the system after disturbances.
- GM0057: LPNORM A LANL PNNL and NRECA Optimal Resiliency Model
  - This project focuses on resilient distribution system design.
  - Collaborations are focused on integrating probabilistic N-k fundamentals into resilient design.
- GM0111: Protection and Dynamic Modeling Simulation Analysis and Visualization of Cascading Failures
  - This project focuses on advancing the state-of-art in dynamic and protection system modeling.
  - Collaborations are focused on connecting the modeling to cascading failure analysis
- 1.4.18 Computational Science for Grid Management
  - This project is focused on foundational computational frameworks.
  - Collaborations are focused on generating use cases for the computational framework and possible future activities that could leverage the framework (cascade mitigation)
- GMLC Planning and Design
  - Data and Software Working Group

Communications
- Regular industry webinars
  - June 16, 2016, Jan. 25, 2017
- IEEE Cascading Failure Working Group
- Feb 2017 Presentation of DCAT at ERCOT Dynamic Working Group
- June 2017: Invited Presentation at NERC Power System Modeling Workshop



Extreme Event Modeling

Next Steps and Future Plans

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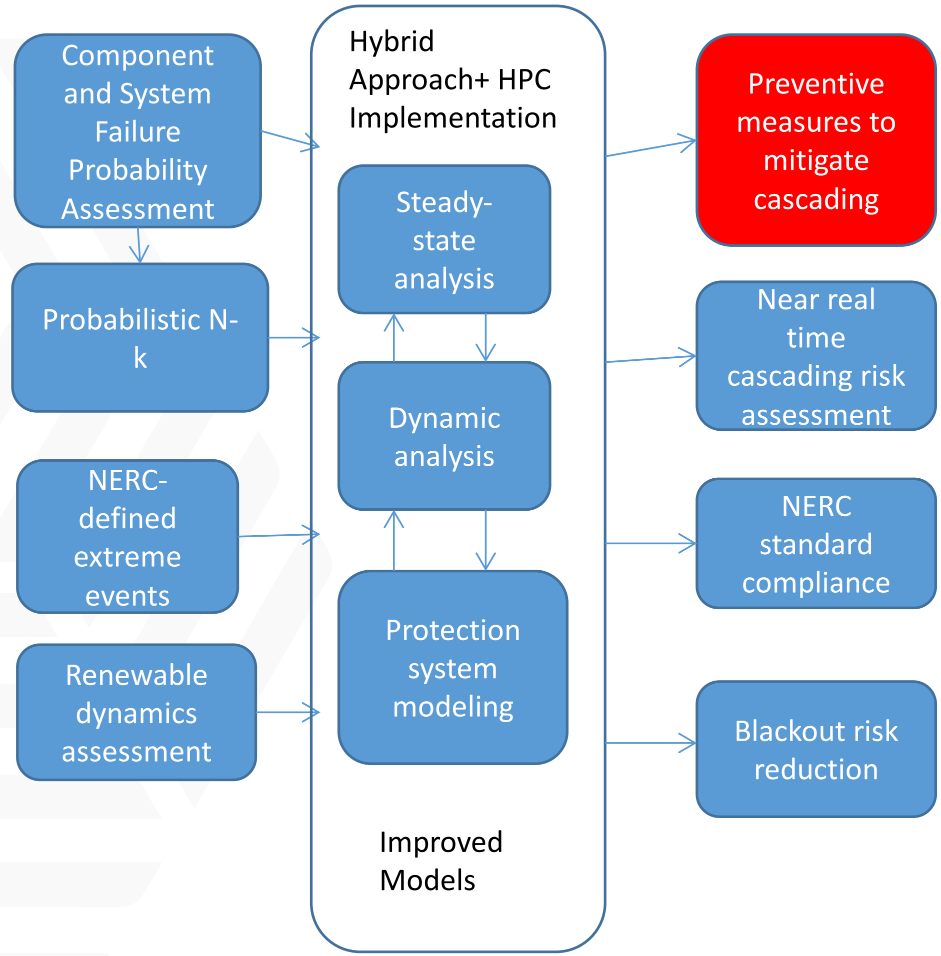
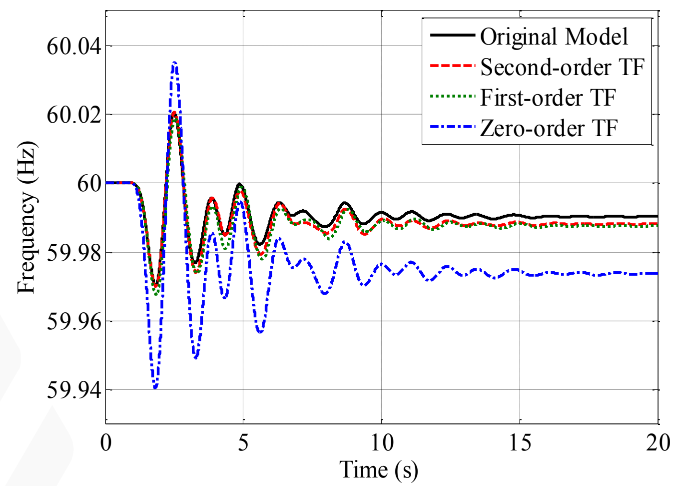
- April 2017 – April 2018 highlights
  - Comprehensive implementation of corrective actions through optimization
  - Develop a combined dynamic simulation/protection model for WECC coordinated with BPA and GE
  - Demonstrate 10x time speedup of dynamic contingency analysis (HPC)
    - Major milestone for meeting near real time analysis capabilities
  - 10x scalability of N-k approaches
    - Significantly larger k failures than state-of-the-art
- Extreme Event Modeling Follow ons
  - Strategy document outlines possible future activities
  - Mitigation capability development is significant
    - Required to meet MYPP goal: *10% reduction in the economic costs of power outages by 2025*
  - Resilience
  - Integrating ancillary services into cascading models of renewables
    - SOW sent to DOE PMs

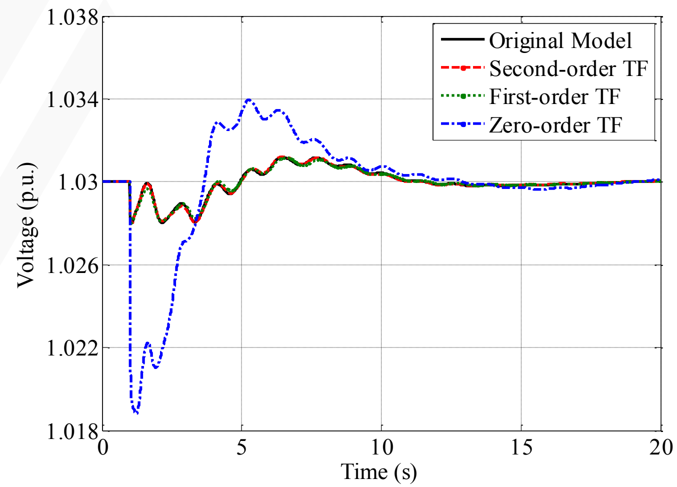


Extreme Event Modeling

Technical Details – Model Reduction

- Dynamic model reduction is required to meet both time-critical and accuracy requirements. Conventional methods in commercial software can only be used for offline system analysis and cannot cope with the fast-changing nature of dynamic grids.
- We develop measurement based model reduction approaches, which offer the advantages of highly accurate system dynamics of external behaviors in real time, and significantly increased simulation speed.
- Specifically, frequency-domain transfer function models with much reduced orders are derived and identified based on real-time phasor measurements. Performances have been tested on a 23-bus system, the NPCC system and the EI system.

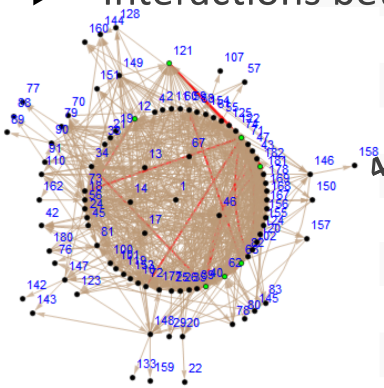




Extreme Event Modeling

Technical Details-Predicting critical cascading path

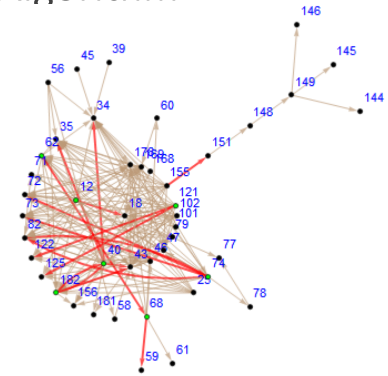
- Interactions between components estimated by Expectation Maximization Algorithm



41,000 cascades

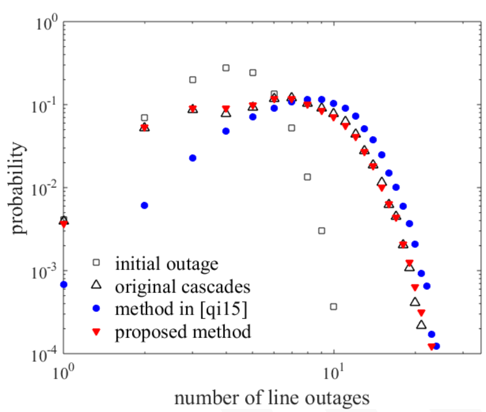
	generation 0	generation 1	generation 2	$\cdots$
cascade 1	$F_0^{(1)}$	$F_1^{(1)}$	$F_2^{(1)}$	$\cdots$
cascade 2	$F_0^{(2)}$	$F_1^{(2)}$	$F_2^{(2)}$	$\cdots$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
cascade M	$F_0^{(M)}$	$F_1^{(M)}$	$F_2^{(M)}$	$\cdots$

400 cascades

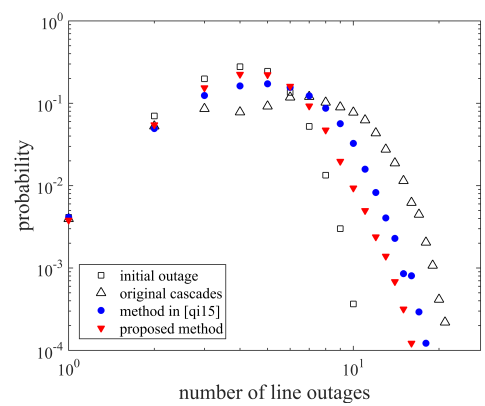


Identified **top 7 key components** and **top 13 key links** using 400 cascades are the same as those using 41,000 cascades

- Probabilistic interaction model simulation based on estimated interactions



Probability distribution of line outages from the interaction model simulation matches well with that from detailed cascading failure model simulation



Good mitigation effect (greatly reduced probability for large-scale cascading failures) by removing the top 10 key links

- Efficiency improvement: a speedup of **100.61x** by interaction model

[qi15] J. Qi, K. Sun, and S. Mei, “An interaction model for simulation and mitigation of cascading failures,” *IEEE Trans. Power Syst.*, vol. 30, no. 2, pp. 804-819, Mar. 2015.

Extreme Event Modeling

Technical Details-Data collection and probabilistic modeling of component and system failures

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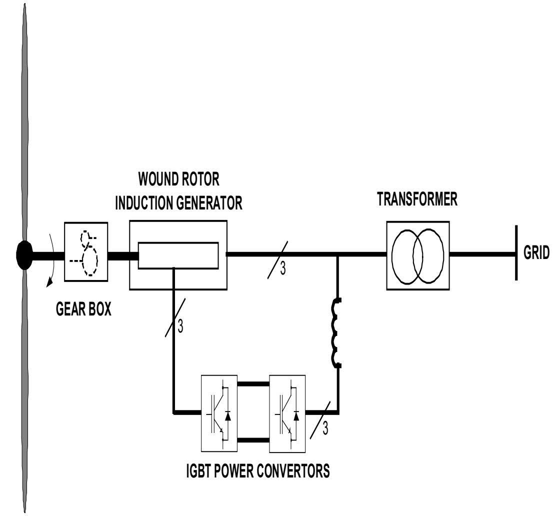
- **System Failures**
  - **Overview:** Analyzing historical extreme event data and developing tools and methods to identify predictors leading to extreme events.
  - **Significance:** Tool developed will aid utilities in their efforts to predict and plan for extreme events in an operational context.
  - **Existing Efforts:** Probabilistic N-k event analysis and cascade modeling, with two sub-foci:
    - *Causal Impact Simulation*: Wind ramping extreme events simulated for the Western Interconnection to produce test dataset.
    - *Response Analysis*: Probability modeling of frequency events obtained at NREL for the Western Interconnection; validated (or not) with NERC records of extreme (frequency) events.
  - **Success:** A priori probability models leading to accurate predictions of extreme events relative to a posteriori realizations.
  - **Suggested R&D:** Energy policy / investment model for the appropriate level of grid robustness in the face of extreme events.
- **Component Failures**
  - Development of a compendious and expandable repository for outage data for transmission circuits, transformers, generators, and common mode outages from many disparate sources
  - Investigation of data poolability issues
  - Development of statistical distributions and a tool for outages of different grid components.

Extreme Event Modeling

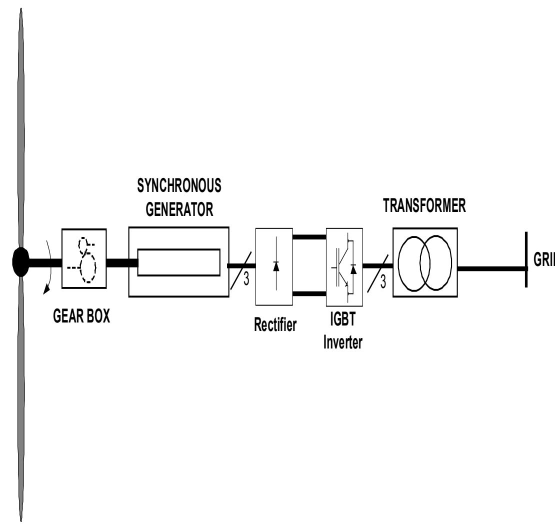
Technical Details-Renewable Energy Modeling

- Survey of studies and models that are linked to slowly varying dynamics of renewables
- Extended-term dynamic simulations to be used in cascading analysis using LLNL's open-source power transmission system simulator *GridDyn*
- Simulation of representative renewable variability and ramp events
- Implementation of WECC Type-3 and Type-4 generic wind turbine generator (WTG) models on GridDyn, along their with generator/converter, converter control, and pitch control models
- Analysis of the impact of the two WTG models on dynamic performance of power systems

Type-3 Wind Turbine Generator: Double-Fed Asynchronous Generator



Type-4 Wind Turbine Generator: Full Power Conversion



Extreme Event Modeling

Technical Details—Deterministic N-k

Key assumption: Intentional adversary, with full knowledge of the system structure/parameters

Deterministic model: Adversary can disable k components (generators or lines) in the system

Severity measure: *Worst-case* load shed given k concurrent disablements of components

Power flow physics: Linearized (aka "DC") power flow, due to presence of binary decision variables

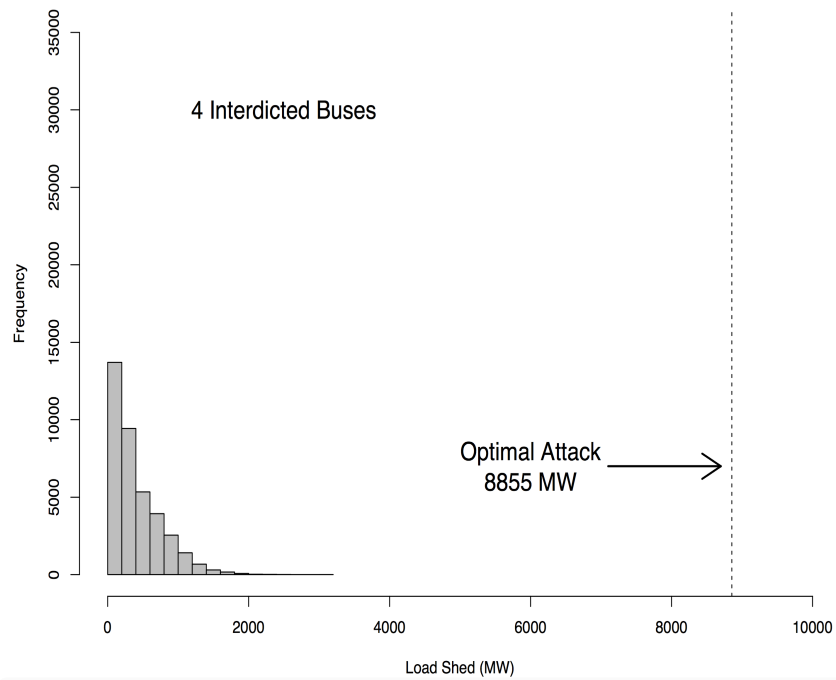
Key findings:

- (Exact) Worst-case algorithms enable quantification of relative costs of protecting against intentional vs. natural / probabilistic adversaries
- Heuristic algorithms fail to identify optimal solutions, often by large margins

Test cases

Small / Medium: IEEE 30 / IEEE 300

Large: American Electric Power (proprietary)



Loss of load when randomly disabling 4 buses in the IEEE 300-bus system, versus the optimal (worst-case) attack

Extreme Event Modeling

Technical Details—Probabilistic N-k

Probabilistic model: each component has a line failure probability

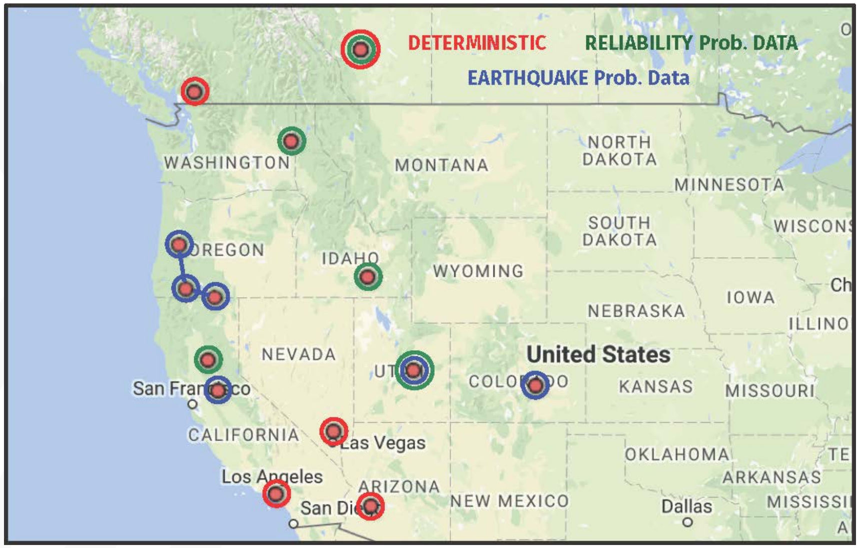
Severity measure: Probability of N-k scenario x Load shed

Power flow physics: Convex relaxation—second order cone (SOC), DC approximation and Network flow approximation

Key findings:

- SOC and DC approximation produce similar results
- AC feasibility test for all models indicate same level of severity
- Better power-flow physics (SOC) yields better computation time
- Probabilistic N-k will deliver analysis that compliments deterministic N-k

Impact regions produced by the N-k for different scenarios when k=5



WECC 240

The worst k failures in a power system change depending on the probabilistic model of failure