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AGM FY20 Q4 progress report

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LLNL Advanced Grid Modeling Projects

Quarterly Update (FY20 Q4)

December 1, 2020

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- Grid Data Crossing Software (GriD-Xing) (AGM): Can Huang (huang38@llnl.gov)
- Adaptive Surrogate Modeling for Grid Risk and Reliability Quantification (AGM): Mert Korkali (korkali1@llnl.gov)
- Load Sculptor (AGM): Nan Duan (duan4@llnl.gov)
- Parallel in Time Algorithms for Solving Transient Stability Simulations for Power Systems (AGM): Rob Falgout (falgout2@llnl.gov)

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AGM Program
Steering Committee Meeting
Project Update (FY20 Q4)

Project Title:	**Stochastic Optimization for Grid Resilience (AGM05)**
Organization:	DOE OE Advanced Grid Modeling (AGM)
Team:	LLNL
FY 2020 Funding ($K):	$285k ($285k received)

Project Objectives

The goal of this project is to develop optimization techniques that can optimally allocate blackstart resources (pre-outage) and develop restoration sequences (post-outage) to improve the resiliency of the electrical grid. By building on a mathematical framework that models in detail power grid restrictions during restoration, our tool will enable planners to efficiently plan system upgrades to improve the ability of the system to recover from outages. Longer-term, the project will drive research in stochastic optimization-based planning tools to improve preparation for, emergency response to, and recovery from large-area, long-duration blackouts.

This project is currently in its third year, by end of which the team will have achieved the following:

1. Developed a stochastic model for simulating the uncertain and unobservable state of the grid after a major blackout.
2. Developed a dynamic programming (exact) approach to optimize power system restoration under uncertain grid state offline.
3. Study approximate policies, with demonstrable theoretical or practical results validated against exact approach, for optimizing power system restoration with uncertain state online.

4. Validate approximate policies using real system data and against existing restoration plans.

Summary of Major Activities in FY20 Q4:

Task 1: Develop a stochastic model for simulating and optimizing power grid restoration under unobservable system state.
FY20 Q4: No update since last quarterly report.

Task 2: Mathematical analysis, technical reports and papers
FY20 Q4: We have formalized our optimization problem under the unified framework for sequential decisions under uncertainty proposed by W. Powell. Using this framework, we have narrowed suitable policies for performing restoration to the class of deterministic look-ahead policies. Within this class of policies, we are currently developing a forward simulator, that will let us optimize parametrized policies and obtain lower bounds to assert the qualities of our policies. The parameters in our policy correspond to buffers in system constraints, with the net effect that deterministic look-ahead solutions are more conservative and similar to those obtained if we were to solve the stochastic program exactly. This work will continue in the next quarter, when we will test it with the ARPA-E data for which we developed parsers in Q1. In a parallel effort, we have submitted an abstract to a special issue of Operations Research on our specialized approach for optimal power system restoration. We continue to work towards our draft on restoration with communication induced delays.

Task 3: Develop a software tool for testing and validating our algorithms
FY20 Q4: We have developed, implemented and tested a greedy initialization heuristic, inspired by dynamic programming, which generates feasible joint communication repair and power restoration sequences in a fraction of the time than branch-and-bound does. The heuristic works, roughly speaking, in three stages: (1) we ignore communications restrictions and build a greedy power restoration plan, (2) we take the power restoration plan as fixed and build a greedy communications repair plan trying to allow the power restoration plan to realize, and (3) we take the communications repair plan as fixed and build a power restoration plan that respects the restrictions of the communications plan. We have tested this heuristic using the IEEE-39 and IEEE-118 test cases, with various levels of observable communications damage, where our heuristic produces solutions between 0.5% and 10% suboptimal. This heuristic will serve to provide an initial solution in our deterministic policy for restoration, as well as for our specialized algorithms finding bounds (offline) for benchmarking the performance of our policies.

Task 4: Test framework using real system data and against existing restoration plans
FY20 Q4: Task to begin in next quarter.

AGM Program
Steering Committee Meeting
Project Update (FY20 Q4)

Project Title:	**Grid Data Crossing Software (GriD-Xing)**
Organization:	Advanced Grid Modeling (AGM)
Team:	LLNL
FY20 Funding ($K):	$270K

Project Objectives

Grid Data Crossing (GriD-Xing) is an open-source data management and analytics tool that integrates data processing, storage, visualization, and analysis functionalities for users at industry (e.g., EMS and DMS) and universities. It can increase the applicability of large set of multi-source data from cross domains (e.g., power system, natural gas, and cyber data) and ultimately improve the resilience, reliability, and security of critical energy infrastructure. GriD-Xing is also a research platform to identify the usefulness of large multi-source data via case studies of interest to industry.

Major Accomplishments in FY18 (Funding $250k): Delivered data processing and storage software algorithms and a technical report. Specifically, 1) developed a set of data processing algorithms for single-source and multi-source measurements in both Python and MATLAB and applied them for data analytics through data-driven state estimation and event detection, and 2) designed a new shared, distributed data storage system named UPS for transmission and distribution PMUs (T+D PMUs) in Go language, and tested the prototype with the benchmark covering QoS, flexibility, and scalability. UPS's computing query speed is 10 times faster than the benchmark storage infrastructure. Successfully deployed GriD-Xing for assisting GMLC and LDRD projects and published three technical papers.

<u>Major Accomplishments in FY19 (Funding $133k):</u> Integrated the data processing and storage prototype algorithms into a software package with a user manual; Improved the data processing functionality, adding information fusion algorithms to address the time-skewness issue between synchronized and non-synchronized data (e.g., PMU/µPMU and SCADA/AMI data) for improving GriD-Xing usefulness. Specially, LLNL leveraged the GriD-Xing capability in several proposals, and successfully received a grant of $900k from the DoD ESTCP program, where GriD-Xing will be demonstrated at a military site.

Summary of Major Activities in FY20 Q4:

Plan: In FY 20, the team extends the scope from power grids to independent infrastructures and enhance GriD-Xing usability for enhancing critical infrastructure resilience under extreme events. <u>Specifically, the team will develop novel energy flow models for integrated power and gas systems and data integration approaches for interdependent infrastructure (e.g., electric, gas, and communication infrastructure), which is complement to NAERM.</u>

Task 1: Data collection: Collecting real-world data of interdependent Infrastructure, including power flow, gas movement, and communication traffic data

Completed in Q1.

LLNL utilized the data resources from both open-source databases and prior projects to build up a real-world data library covering power, natural gas, and communication systems. The current data library has 1) real-time gas movement, capacity, and price data from pipeline EBBs and EIA, 2) real-time power flow, consumption, and price data from NERC Tag and ISO/RTO, and 3) power outage records from utilities, extreme weather records from NOAA, etc. It also includes the topology information of the power distribution and AMI network, from CenterPoint Energy.

Task 2: Grid-Gas interdependence modeling: Observe and detect the probabilistic pattern of power and gas flows based on the historical grid-gas flow records and apply the results for grid-gas flow modeling

Completed in Q3.

Power and gas flow calculation is a fundamental problem in the operation and planning of integrated power and gas systems (IPGS). However, the nonlinear gas flow model introduces major challenges to the energy flow calculation. In Q1, the team completed the design of the framework and energy flow model. In Q2, the team completed the development of a tractably convex optimization algorithm to solve the energy flow problem. In Q3, we completed the testing of the proposed models and algorithms and submitted a journal paper.

Task 3: GriD-Xing demonstration with resilience-oriented use cases: Deployed Grid-Xing, especially the data integration, data analytics, and visual analytics functionalities, on use cases covering power and natural gas systems.

Completed in Q4.

<u>Use Case 1: GriD-Xing for topology reconfiguration (Completed in Q3)</u>. Topology reconfiguration is highly needed to improve the grid resilience and reliability. Existing optimization models for topology reconfiguration require a large number of integer variables to model the topology changes and may be computationally inefficient. Towards this end, a novel machine learning-based approach using recursive Adaptive Boosting (AdaBoost) is developed and tested in the

topology reconfiguration problem. Numerical simulations on the modified IEEE 123-node distribution system validate the effectiveness of the proposed recursive AdaBoost. Also, the proposed recursive AdaBoost can be robust to the ambient noise of measurements. More details can be found in the following paper.

M. Cui, C. Huang, J. Wang, "A Recursive AdaBoost Approach for Topology Reconfiguration in Unbalanced Distribution Systems", IEEE Trans. Power Systems, submitted.

<u>Use Case 2: GriD-Xing for power and gas cascading failure studies (Completed in Q4)</u>. We present the preliminary results from simulating a combined cascading failure and restoration process in an interdependent power and natural gas system. The interdependent system for simulation is generated using a directed graph object, which is the approach of choice these days for investigating interconnected infrastructure systems. For investigating the robustness and resilience of the combined system, we study both random, operational failures and targeted, preferential failures. The targeted failure simulations are performed by failing the most important connections in both the underlying systems. These important connections are the targets of choice for any adversary. We illustrate the response of the connected network is significant different when the mode of attack is targeted compared to when it is entirely random operational failures. We also show that failure in one of the underlying systems quickly propagates to the other system and has a significant impact on not only its own network but on the other network. The impact of failure is quantified through what percentage of the facilities in individual networks becomes non-functional because of the failures in the other system. Impact is also quantified in terms of the additional distance over which power or gas has to be transported because of disruptions in the transmission networks.

The extent of economic loss resulting from failures in an interconnected infrastructure system is a strong function of the restoration strategy including the time required to complete the restoration work. In this preliminary work, restoration is simulated using a simple rule-based process. In actuality, restoration is a complex exercise in scheduling and optimization, the main objective of which is to minimize the total economic loss from the failure events. This economic loss consists both of loss due to service disruptions (e.g, power and/or gas cannot be delivered to customers which results in revenue loss) and loss due to repairing and restoration. In the next step of the model development, we intend to incorporate this cost calculation and loss minimization scheme. Our development goal also includes coupling of the present graph-based simulator with a flow calculation simulator.

More details can be found in the report in Appendix II.

Appendix I: Summary of Major of Accomplishments

Software delivered

[1] Grid Data Crossing Software, released on LLNL Lab Network - LC, to be open source. It is now being utilized and tuned by two projects (A) Signature Library Framework Development, sponsored by DOE OE, and (B) Facility Energy Saving and Securing Technology Using Multi-Source Data, sponsored by DoD ESTCP.
[2] Single and Multiple Grid Events Generation Tool, to be open source. It is now being tested by CURENT/UTK Large-Scale Testbed.

Publications

I) Data Processing task

[1] Y. Xu, C. Huang, X. Chen, L. Mili, C. Tong, M. Korkali, L. Min, "Response-Surface-Based Bayesian Inference for Power System Dynamic Parameter Estimation," IEEE Transactions on Smart Grid, vol. 10, no. 6, pp. 5899-5909, Nov. 2019.
[2] C. Huang, et al, "Power Distribution System Synchrophasors with Non-Gaussian Errors: Real-World Data Testing and Analysis," IEEE Open Access Journal of Power and Energy, under review.

II) Data Storage task

[3] I. Kosen, C. Huang, Z. Chen, X. Zhang, L. Min, and Y. Liu, "UPS: Unified PMU-Data Storage System to Enhance T+D PMU Data Usability," IEEE Transactions on Smart Grid, vol. 11, no. 1, pp. 739-748, Jan. 2020.

III) Data Integration task

[4] J. Zhao, C. Huang, L. Mili, Y. Zhang, and L. Min, "Robust Medium-Voltage Distribution System State Estimation using Multi-Source Data," IEEE PES ISGT, Washington, DC, USA, pp. 1-5, 2020.
[5] J. Zhao, C. Huang, L. Mili, Y. Zhang, and L. Min, " Multi-source Multi-fidelity Data Fusion for Enhancing Power Grid Edge Situational-Awareness," IEEE Transactions on Smart Grid, under review.
[6] M. Cui, C. Huang, and J. Wang, "Topology Reconfiguration for Unbalanced Distribution Systems via Recursive AdaBoost", IEEE Transactions on Power Systems, under review.

IV) Data and Modeling for Energy Resilience and Interdependence

[7] Z. Chen, C. Huang, M. Nygaard, and L. Min, "Interdependent Expansion Planning for the Resilient Electricity and Natural Gas Networks", IEEE Transactions on Power Systems, under review.
[8] W. Jia, T. Ding, C. Huang, Z. Wang, Q. Zhou, and M. Shahidehpour, "Convex Optimization of Integrated Power-Gas Energy Flow Model and Application to Probabilistic Energy Flow", IEEE Transactions on Power Systems, accepted.
[9] T. Ding, S. Li, M. Qu, C. Huang, and M. Shahidehpour, "Hybrid Machine Learning Approach for Analyzing the Vulnerability to Random Cascading Outages in Power Systems", IEEE Transactions on Power Systems, under review.

[10] C. Huang, and M. Shahidehpour, “Modeling of Cascading Failures and Subsequent Restoration in Interdependent Power and Natural Gas Systems”, IEEE Transactions on Power Systems, to be submitted.

Outreach

[1] Contributed to IEEE Task Force on Synchrophasor Applications in Power System Operation and Control White Paper, where Grid Data Crossing work was presented and discussed, February 2020.

[2] Contributed to NASPI Tech. Report - Synchronized Measurements and their Applications in Distribution Systems, where Grid Data Crossing work was reported and cited, April 2020.

Benefits to NAERM

Ongoing work:

1) GriD-Xing provides a data management and analysis platform for archiving, sharing, and analyzing data collected from cross energy sectors in NAERM

2) GriD-Xing proposes a linearized energy flow model that can help NAERM tightly link nonlinear gas flow equations with linear power flow equations in NAERM Grid-Gas Use Case.

Appendix II: Report of Use Case 2

(Attached)

FY20 Q4 Project Update-AGM Data

Project Quarterly Update

OE AGM Program

Project Update (FY20 Q4)

Project Title:	**Adaptive Surrogate Modeling for Grid Risk and Reliability Quantification**
Organization:	DOE OE Advanced Grid Modeling (AGM)
Team:	LLNL, Virginia Tech
FY 2020 Funding ($K):	$285K

Project Objectives

The goal of this project is to create an **uncertainty quantification (UQ) framework** for grid planning under uncertainty in several input data/parameters (load profiles, spatiotemporally correlated renewable power generation, transmission-grid topology changes, contingencies, etc.), accompanied with high-impact, low-frequency extreme events. The outcome of this research will lead to a better understanding of bulk power grid responses to severe perturbations in order to assess system reliability, resiliency, and security. By the end of the project duration, the team will successfully:

- advance the state-of-the-art of UQ methods for grid operations, control, and planning to arrive at timely and credible risk-informed decisions in complex setting, including stochasticity, large system scale, high-dimensional correlated inputs; and
- facilitate robust and efficient risk, reliability, and security assessment to ensure safe and stable grid operation.

Summary of Major Activities in FY20 Q4:

- In this quarter, we have developed a computationally efficient data-driven framework for decision making under uncertainty in joint chance-constrained (JCC)-AC-optimal power-flow (OPF) problem that can characterize the security of an overall system performance by satisfying multiple constraints simultaneously for a predefined probability. Specifically, learning from the historical data, we have started by accurately estimating an uncertainty model of the renewable energy generation units and infer their marginal density functions using a kernel density estimator, which is a nonparametric method. Then, we have simulated the multidimensional dependence of these generation units using a vine-copula multivariate distribution estimate to model the asymmetric, tail-dependent samples. To reduce the prohibitive computational time required in the traditional Monte-Carlo (MC) method while achieving uncertainty propagation, we have applied a response-surface strategy that allows us to evaluate the time-consuming power-system model at arbitrary distributed sampled values with a negligible computational cost. Learning from the propagated samples, we have finally developed and applied a hybrid adaptive procedure to decompose the joint chance-constrained problem into an individual chance-constrained one that yields a less conservative and less costly solution compared with that obtained by the traditional Boole's inequality. Simulations conducted on a modified Illinois 200-bus test system demonstrate the excellent performance of the proposed method.

  Our quarterly contributions can be summarized as follows:

  - Starting from the **uncertainty modeling** that infers from the actual data, a kernel density estimator (KDE) is adopted to avoid the inaccuracy brought by the parametric marginal functions. Furthermore, using the vine-copula technique, high-dimensional, asymmetric, dependent multivariate with a variety of bivariate Archimedean copulas are accurately simulated.
  - In the **uncertainty-propagation stage**, the response surfaces of the nonlinear AC power-flow model based on polynomial chaos expansion (PCE) is proposed to improve the computing efficiency within the MC framework as well as to solve a JCC-AC-OPF problem. This response surface has no linear assumption and is further merged into the KDE framework to address arbitrary distributed marginals and combined with the vine copula to propagate complicated dependent uncertainties.
  - Finally, in the **decision-making period**, to overcome the conservativeness of the Boole's inequality, a hybrid adaptive approach is proposed to decompose the joint chance constraint (JCC) into individual chance constraints (ICCs) by first properly detecting the statistical active constraints and then by allocating the joint chance

constraints into individual ones using the correlation information analyzed from the PCE-propagated samples. The quantile of each system state is further adopted to better design the tightened bounds without using any Gaussian or symmetric assumption.

A flowchart that shows the components of the proposed hybrid adaptive framework is provided in Figure 1.

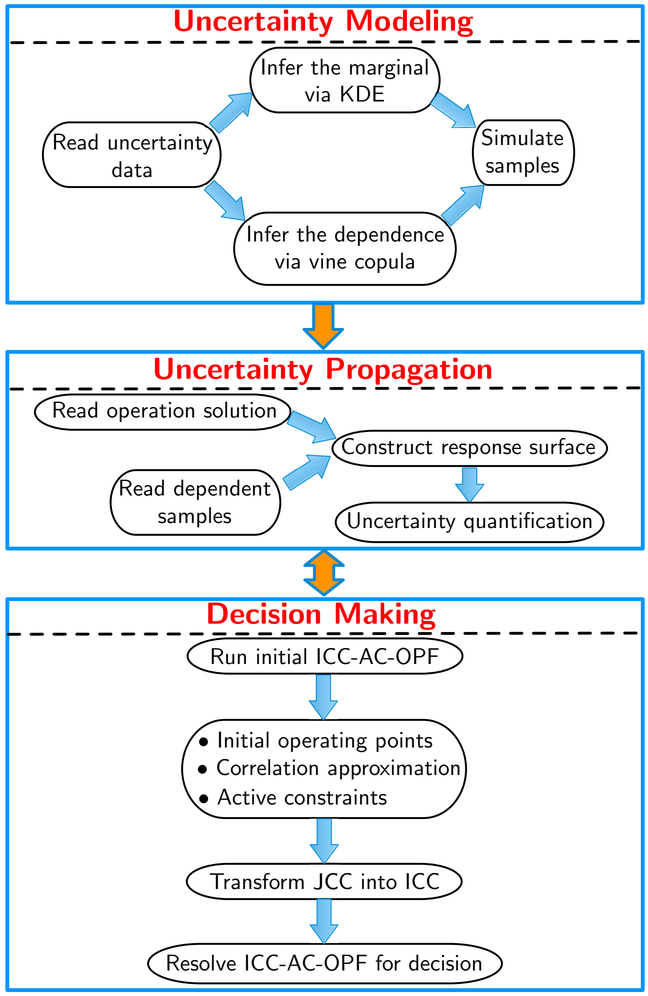

Figure 1. Flowchart of the proposed framework.

Simulation Results

Using the proposed method, various case studies are conducted on a modified 200-bus power system (i.e., the ACTIVSg200 case), geographically situated in the central part of the U.S. state of Illinois. The algorithms are tested with the MATLAB® R2018a version on a laptop with 2.60-GHz Intel® Core™ i7-6600U processors and a 16 GB of main memory. Four wind farms, each with a rated power of 50 MW, are added at Buses 5, 15, 100, and 140, respectively, to introduce the randomness. The data for their uncertainty are obtained via the NREL's Wind Data Set, within which, the real-world data are collected from Sites #1116, #9246, #9435, and #9386, from the first season of 2004, respectively. Their dependence is addressed via the vine copula. It is further assumed that the loads follow a Gaussian distribution with mean equal to the original bus loads and standard deviation equal to 5% of their mean. The capacity of transmission line between Buses 29 and 30 are increased from 100 MVA to 102 MVA, and unit commitment is not considered. In addition, we have utilized CPU-based parallel computing in evaluating collocation points.

1) **Uncertainty Modeling:** Starting from uncertainty modeling, apart from using KDE for marginal modeling, we need to select a vine structure for dependence modeling. To conduct a quantitative comparison studies among different copula regarding their corresponding modeling accuracy, we have used the index of log-likelihood (LL) as suggested in the literature. Within each vine structure, the inference choices for the bivariate copula families include the Gaussian copula, the Student's *t*-copula, the Clayton copula, the Gumbel copula, and the Frank copula as well as the rotated version of the Archimedean copulas. We obtain the simulation results as shown in Table I. From the quantitative test, it can be inferred that both the D- and C-vine copulae exhibit very high accuracy, whereas the traditional Gaussian copula exhibits the lowest accuracy. Therefore, we select D-vine copula in this article to simulate the dependence among wind uncertainty.

Table I. Quantitative Test for Different Copulae

Copula	D-Vine	C-Vine	Gaussian
LL	4.215×10^3	4.214×10^3	3.892×10^3

2) **Validation of the Proposed Method:** Here, we test the performance of the proposed method under different acceptable violation probabilities, $\boldsymbol{\epsilon}$, using 10,000 as the sample size. The simulation results of the proposed method are validated with the MC method with 10,000 samples to measure its joint violation probability. The traditional method based on the Boole's inequality is also taken as a comparison. The simulation results are provided in Table II. It can be seen that the proposed method can provide a solution with a joint violation probability within the JCC's setting limits while showing less conservative solutions compared with those obtained from the traditional Boole's method. This demonstrates the improved performance of the proposed method.

Table II. Validation on the Modified 200-bus System

	Boole's	Proposed method
$\epsilon = 2\%$	0.96%	1.88%
$\epsilon = 5\%$	1.28%	2.71%

3) **Tradeoff between Security and Economy:** The CC-OPF is flexible in balancing the security and the economy. As shown in Table III, with the increase in ϵ, the cost can be further reduced at the risk of some security. Furthermore, the proposed method achieves a less conservative decision that yields more economic benefits compared with the Boole's method. Although the deterministic method has the lowest operational cost, but has no security guarantee at all. Here, let us select the voltage magnitude at Buses 11 to 20 with an upper limit of 1.1 pu as an example (all are PQ buses), their boxplots for the proposed method and the deterministic method are provided in Figure 2. It shows a significant improvement in the security using the proposed method with a few violations. Further, as shown in Buses 15 and 16, the system states show obvious asymmetric distributions on the tails. This further validates the rationality of using the quantile rule to update bounds instead of using symmetric assumptions.

Table III. Cost Comparison for the Proposed Method ($/hr)

	Deterministic	Boole's	Proposed method
$f(\epsilon = 2\%)$	3.604×10^4	4.021×10^4	3.926×10^4
$f(\epsilon = 5\%)$	3.604×10^4	3.958×10^4	3.906×10^4

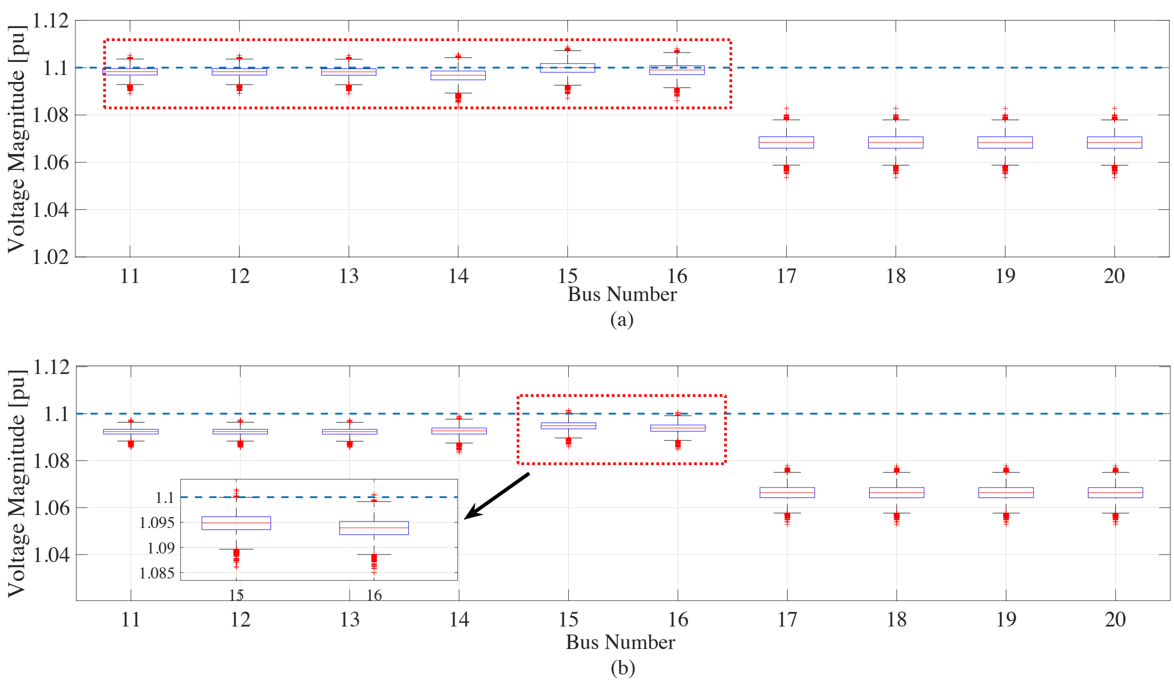

Figure 2. Boxplots of bus-voltage magnitude at Buses 11 through 20 with the **(a)** deterministic method and **(b)** proposed method.

4) **Computing Efficiency:** Finally, we would like to mention that the response-surface technique brings significant improvement in the computing time since the proposed

method can finish the simulation in **10 s** while the traditional MC method spends around **1 h**. The two-order-of-magnitude speedup factor shows its capability for online applications.

Plans for Future Work

Our future work will focus on enabling the proposed method to be scalable to larger-scale power systems and extend this framework to other decision-making-related applications such as optimal renewable curtailment and load shedding.

FY20 Publications (Accepted or Published)

[P1] Z. Hu, Y. Xu, M. Korkali, X. Chen, L. Mili, and J. Valinejad, "A Bayesian Approach for Estimating Uncertainty in Stochastic Economic Dispatch considering Wind Power Penetration," *IEEE Transactions on Sustainable Energy* (**accepted**). Available online at: https://doi.org/10.1109/TSTE.2020.3015353

[P2] Y. Xu, L. Mili, M. Korkali, K. Karra, Z. Zheng, and X. Chen, "A Data-Driven Nonparametric Approach for Probabilistic Load-Margin Assessment considering Wind Power Penetration," *IEEE Transactions on Power Systems*, vol. 35, no. 6, pp. 4756-4768, Nov. 2020. (**published**). Available online at: https://doi.org/10.1109/TPWRS.2020.2987900

[P3] Y. Xu, K. Karra, L. Mili, M. Korkali, X. Chen and Z. Hu, "Probabilistic Load-Margin Assessment using Vine Copula and Gaussian Process Emulation," *Proceedings of the 2020 IEEE PES General Meeting (PESGM)*, Aug. 2–6, 2020, Montreal, Canada (**accepted**). Preprint available at: https://arxiv.org/pdf/2004.05771.pdf

[P4] Y. Xu, Z. Hu, L. Mili, M. Korkali, and X. Chen, "Probabilistic Power Flow Based on a Gaussian Process Emulator," *IEEE Transactions on Power Systems*, vol. 35, no. 4, pp. 3278-3281, July 2020 (**published**). Available online at: https://doi.org/10.1109/TPWRS.2020.2983603

[P5] Z. Hu, Y. Xu, M. Korkali, X. Chen, L. Mili, and C. H. Tong, "Uncertainty Quantification in Stochastic Economic Dispatch using Gaussian Process Emulation," *Proceedings of the Innovative Smart Grid Technologies (ISGT) 2020*, Feb. 17-20, 2020, Washington, D.C. (**published**). Available online at: https://doi.org/10.1109/ISGT45199.2020.9087714

[P6] Y. Xu, M. Korkali, L. Mili, and X. Chen, "An Efficient Multifidelity Model for Assessing Risk Probabilities in Power Systems under Rare Events," *Proceedings of the 53rd Hawaii International Conference on System Sciences (HICSS) 2020*, Maui, HI (**published**). Available online at: https://scholarspace.manoa.hawaii.edu/bitstream/handle/10125/64123/1/0308.pdf

FY20 Publications (Under Review)

[P7] Y. Xu, M. Korkali, L. Mili, J. Valinejad, T. Chen, and X. Chen, "An Iterative Response-

Surface-Based Approach for Chance-Constrained AC Optimal Power Flow Considering Dependent Uncertainty," *IEEE Transactions on Smart Grid* (**under second-round review**).

[P8] Y. Xu, M. Korkali, L. Mili, K. Karra, J. Valinejad, L. Peng, and X. Chen, "An Efficient Data-Driven Framework for Decision Making under Uncertainty in Joint Chance-Constrained Optimal Power Flow," *IEEE Transactions on Industrial Informatics* (**under review**).

[P9] Y. Xu, L. Mili, M. Korkali, X. Chen, J. Valinejad, and L. Peng, "A Surrogate-Enhanced Scheme in Decision Making under Uncertainty in Power Systems," *2021 IEEE PES General Meeting (PESGM)*, (**under review)**

AGM Program
Steering Committee Meeting
Project Update (FY20 Q4)

Project Title:	**Load Sculptor**
Organization:	Advanced Grid Modeling (AGM)
Team:	LLNL, Mississippi State University
FY 2020 Funding ($K):	$250K

Project Objectives

The goal of this project is to develop a data-driven multi-fidelity robust **dynamic load modeling** and **uncertainty quantification** tool called **Load Sculptor** that enhances utilities' ability to perform planning, stability assessment and control tasks. This project's technical approach is to integrate deep neural networks and uncertainty quantification for deriving reliable and flexible dynamic load models, saving computational costs and enhancing operators' situational awareness to uncertainties.

The project objectives are:

- Develop computationally **cheap surrogate load models** for dynamic simulation and security assessment without sacrificing the accuracy requirements.
- Derive **robust load model parameter sets** that are able to capture a wide range of operating conditions while quantifying the influences of parameter uncertainties on the simulation results.

The project tasks are:

- Task 1: NDA and contract with utility partners for acquiring field data and system models. (Done)
- Task 2: Pattern recognition and dimension reduction submodules for load

characteristic clustering. (Done)

- Task 3: Dynamic load model reduction via multi-fidelity DNN surrogate models to significantly speed up time-domain simulations without loss of accuracy (statistically less than 3% RMS error). (Ongoing)
- Task 4: Model validation and uncertainty assessment using simulations and field data.

Summary of Major Activities in FY20 Q4:

During this performance period, the team has established collaboration with PacifiCorp and is expecting the data from their proposed PMU installation locations. The team has also developed a dimension reduction technique that considers the nonlinear functions in dynamic load models. For the next performance period, the team will implement the WECC composite load model in the time-domain simulation platform to provide training data for surrogate models.

Dimension Reduction for Dynamic Load Models:

In this quarter, we have developed a novel model reduction approach using the discrete empirical interpolation method enhanced proper orthogonal decomposition (DEIM-POD)[1]. DEIM introduces an optimal selection procedure for the observation points in the state space so that the projection error of the nonlinear functions is minimized. DEIM provides a great solution for dynamic load model reduction because it not only effectively reduces the number of nonlinear function evaluations but also identifies the critical load locations where the parameters are important for the accuracy of dynamic load reduced-order models (ROMs). The contributions of this approach are:

- DEIM is applied to the nonlinear functions of the dynamic load models of 3 systems with different scales.
- This approach uses the observation points selected by DEIM to identify the critical locations for maintaining dynamic load parameter accuracy.

The observation points of the nonlinear functions in the dynamic load models are sparsely selected using DEIM as shown in Algorithm 1:

Algorithm 1: DEIM

Input: $\mathbf{U} = [\mathbf{u}_1, ..., \mathbf{u}_m] \in \mathbb{R}^{n \times m}$
Output: $\mathbf{P} = [\mathbf{e}_{p_1}, ..., \mathbf{e}_{p_m}] \in \mathbb{R}^{n \times m}$
$[\rho, p_1] = \max|\mathbf{u}_1|$;
$\mathbf{P} = [\mathbf{e}_{p_1}]$;
for $i = 2$ *to* m **do**
  solve $\mathbf{P}^T \mathbf{U}(1 : i-1, :)\mathbf{c} = \mathbf{P}^T \mathbf{u}_i$ for $\mathbf{c}$;
  $\mathbf{r} = \mathbf{u}_i - \mathbf{U}(1 : i-1, :)\mathbf{c}$;
  $[\rho, p_i] = \max|\mathbf{r}|$;
  $\mathbf{P} \leftarrow [\mathbf{P}, \mathbf{e}_{p_i}]$
end

IEEE 9-bus system

[1] S. Chaturantabut and D. C. Sorensen, "Nonlinear model reduction via discrete empirical interpolation," SIAM J. Sci. Comput., vol. 32, no. 5, pp. 2737–2764, 2010.

The time evolution of the induction motor (IM) loads' state variables of the IEEE 9-bus system with 3 load buses after a 1-cycle 3-phase fault at bus 1 is shown in Fig. 1. The repetitive pattern across different IMs shows that a low-dimensional basis may exist to represent the full dynamic of all IM loads. This observation is verified by the singular value decomposition (SVD) of the state variables. As shown in Fig. 2, the time evolution of the full state space of dynamic loads can be represented by 6 dominant modes.

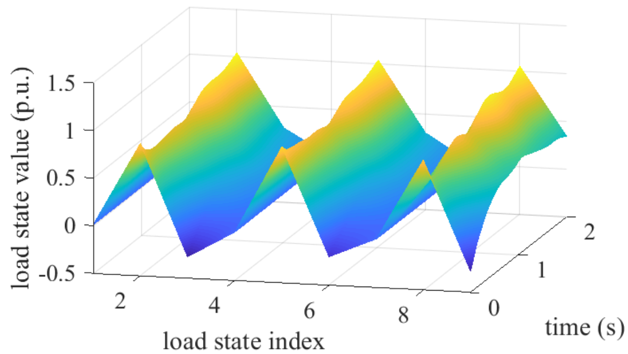

Fig. 1. Manifold of the state variables of IMs defined by d**x**/dt = **Ax**+**F**(**x**, **u**) at 3 load buses of the IEEE 9-bus system.

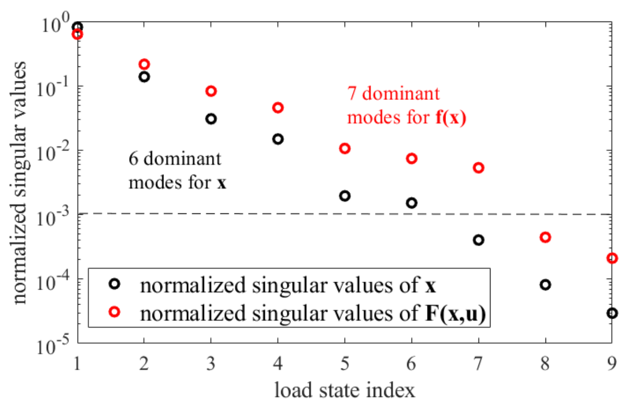

Fig. 2. Normalized singular values of **x** and **F**(**x, u**) for the IMs of the IEEE 9-bus system.

However, the SVD of state space only provides a linear approximation of the dynamic loads. To acquire an accurate approximation for the nonlinear components, a separate SVD needs to be applied to the nonlinear functions **F**(**x**,**u**) of the dynamic load model. The time evolution of the nonlinear functions is shown in Fig. 3. Its dominant modes are shown in Fig. 2 alongside those of the state variables. With the same truncation threshold, the nonlinear functions have 7 dominant modes, which suggests that the nonlinear functions have a richer dynamic behavior than the state variables.

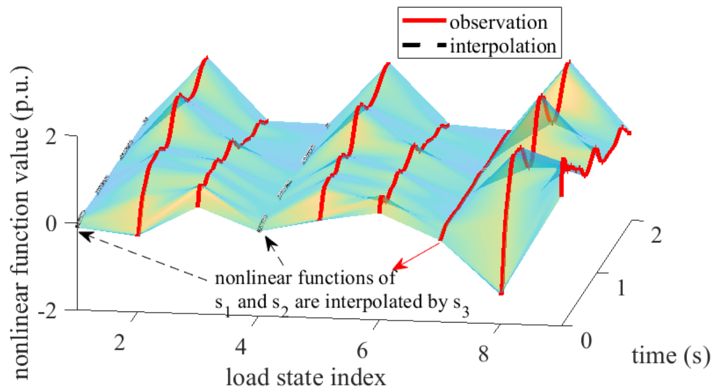

Fig. 3. Apply DEIM to the nonlinear functions **F**(**x, u**) representing IMs at 3 load buses of the IEEE 9-bus system.

After applying Algorithm 1 to the basis acquired from the SVD of the nonlinear functions, the observation points that minimize the projection error of the nonlinear functions onto their basis are selected and highlighted in Fig. 3. It shows that the time evolution of s_1 and s_2 nonlinear functions can be interpolated by the nonlinear function of s_3. Therefore only 7 out of 9 nonlinear functions need to be evaluated for the ROM.

Another insight provided by DEIM is the location of those observation points. For a larger power grid where fine turning all dynamic load models is prohibitively labor-intensive, DEIM observation points can be utilized as suggestions for critical locations for maintaining parameter accuracy. Although for a small system like the IEEE 9-bus system, the observation points cover all three load buses, for a larger system, it is possible to limit the number of observation points to a small number across multiple contingencies. This helps utilities to focus on tuning the critical dynamic load models that contribute the most to the accuracy of ROM.

As suggested by Fig. 3, there are 7 state variables whose nonlinear functions need to be evaluated for the IEEE 9-bus system. The simulation result of these state variables using DEIM-POD is compared to the result of using the full model in Fig. 4. It demonstrates a good match for these 7 state variables.

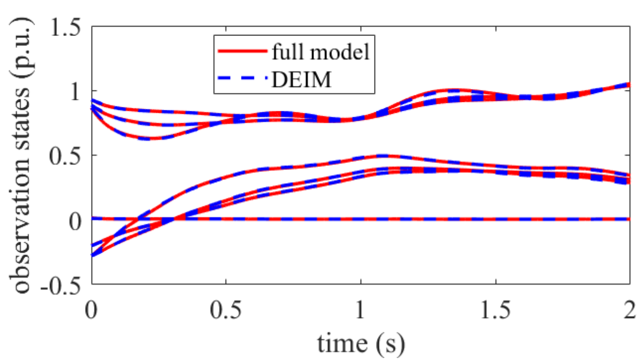

Fig. 4. Observation states comparison of the IEEE 9-bus system's full model and DEIM ROM.

The 2-norm percentage errors of the entire 2-second simulation period for all 9 state variables of the 3 dynamic loads are shown in Fig. 5. It shows that the observation state variables' errors are minimized comparing to the interpolated states. Note that state 7 (i.e. s_3) has the highest error among all observation states, because it is the last one chosen among all 7 observation states.

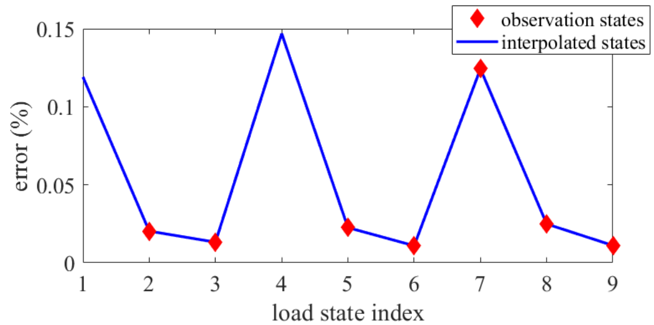

Fig. 5. Normalized error of the IEEE 9-bus system load states simulated using DEIM.

WECC 179-bus system

The result from the WECC 179-bus system demonstrates a significant reduction of nonlinear functions. As shown in Fig. 6, only 7 states' nonlinear functions need to be evaluated to represent the dynamic after a 1-cycle 3-phase fault at bus 1. The 2-norm percentage errors of all 312 load states are shown in Fig. 7.

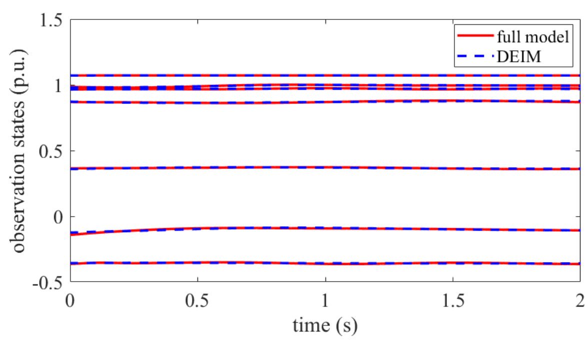

Fig. 6. Observation states comparison of the WECC 179-bus system's full model and DEIM ROM.

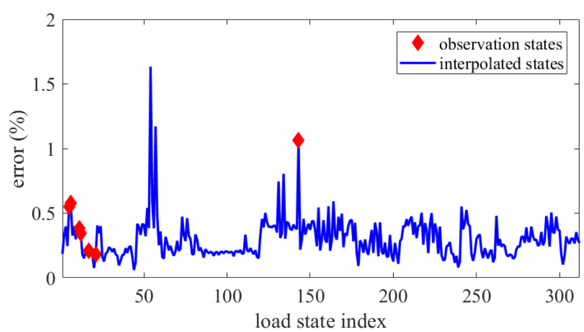

Fig. 7. Normalized error of the WECC 179-bus system load states simulated using DEIM.

To show the selected observation points for different contingencies, a total of 179 simulations with 1-cycle 3-phase bus faults applied to each bus in the system are performed. As shown in Fig. 8, only a small number of load buses have states that are frequently selected by DEIM across all contingencies. The load buses that have states selected for at least 40 contingencies are highlighted in Fig. 9. The selected locations provide a comprehensive coverage of the system. It shows that DEIM can indeed be utilized as a means of selecting critical locations for maintaining dynamic load model accuracy.

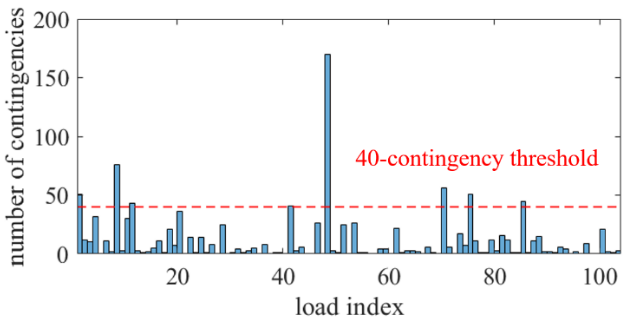

Fig. 8. Number of contingencies for which each load is chosen as observation point in WECC 179-bus system.

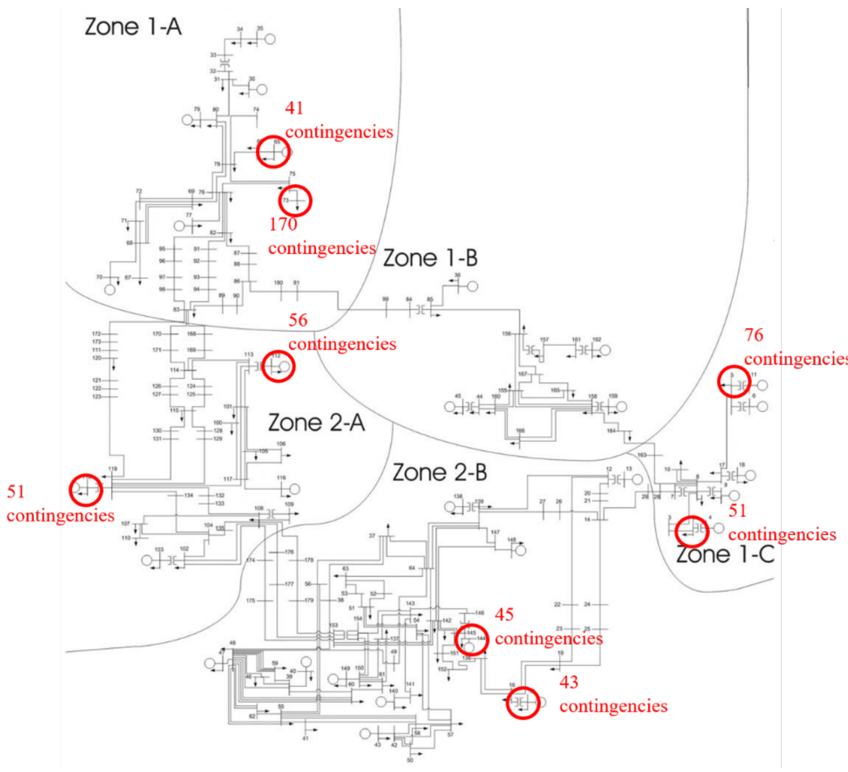

Fig. 9. Locations of load bus most frequently chosen as observation point in WECC 179-bus system.

IEEE 2384-bus system

For the IEEE 2384-bus system, there are 3 selected observation states as shown in Fig. 10 after a 1-cycle 3-phase fault at bus 1. The 2-norm percentage errors of all 5478 load states are shown in Fig. 11 and all of them are maintained under 0.6%.

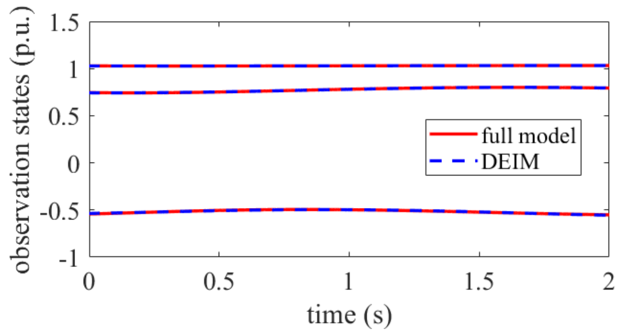

Fig. 10. Observation states comparison of the IEEE 2384-bus Polish system's full model and DEIM ROM.

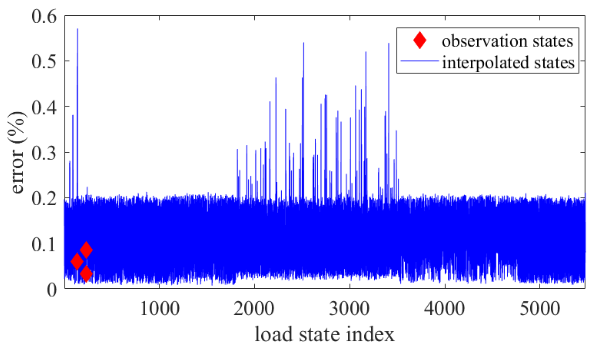

Fig. 11. Normalized error of the IEEE 2384-bus Polish system load states simulated using DEIM.

For 300 1-cycle 3-phase bus faults applied at different locations in the system, the top 3 most frequently selected observation locations are load 45 (300 times), load 247 (30 times) and load 46 (16 times).

ROM Characteristics

The characteristics of the ROMs constructed for the dynamics after the 1-cycle 3-phase fault at bus 1 of the 3 studied systems are shown in Table I. Although for the IEEE 9-bus system, the number of avoided nonlinear function evaluation is only 2, for the IEEE 2384-bus system, the number reaches 5475, which suggests the potential of this approach to large systems.

Table I

ROM Characteristics of Studied Systems

	9-bus	179-bus	2384-bus
load state modes	6	3	3
nonlinear function modes	7	7	3
s observation	1	0	0
v'_{d1} observation	3	4	2
v'_{q1} observation	3	3	1
observation load buses	3	5	2
avoided nonlinear evaluations	2	305	5475

List of Publications and Presentations:

Publication:

- N. Duan, J. Zhao, X. Chen, B. Wang, S. Wang, “Discrete empirical interpolation method based dynamic load model reduction”, to be submitted to IEEE PES General Meeting 2021.

Presentation:

- “Development update on Load Sculptor: a robust dynamic load modeling and uncertainty quantification tool”, WECC Modeling and Validation Subcommittee Meeting, Aug. 2020.

AGM Program
Steering Committee Meeting
Project Update (FY20 Q4)

Project Title:	**Parallel in Time Algorithms for Solving Transient Stability Simulations for Power Systems**
Organization:	Advanced Grid Modeling (AGM)
Team:	LLNL
FY2020 Funding ($K):	$90K ($488k with carryover)

Project Purpose. Sequential time stepping in transmission systems can pose a bottleneck for simulations in which a larger number of time steps is required, especially for renewable systems with longer time horizons (e.g., wind ramping). In addition, computer systems now advance speed through concurrency rather than processor clock rates. Simulations can be accelerated through use of concurrency, although parallelizing over buses often leads to inefficient simulations due to poor linear solvers. Moreover, a full restructuring of the code is often needed to incorporate such concurrency. This project investigates computationally efficient solutions of long-term dynamic simulations through incorporation of computational parallelism and development of a novel multigrid reduction in time (MGRIT) integration scheme for transmission power grid simulation.

Technical Approach. The MGRIT method pursued in this project makes use of current simulation time integrators by wrapping them into a multilevel time integration approach. The method leverages significant advances in parallel multilevel algorithms that have been developed in both theory and software over the last two decades. The MGRIT approach has been matured in the XBraid software developed at LLNL which was designed to use existing time integration code and thus requires only modest code modification for its use. MGRIT has mostly been applied to problems with continuous behaviors, so a key part of this project's work is adapting the MGRIT method to handling discontinuities in power grid systems, such as occur in equipment limit adjustments or load changes. Methods must be tested in software on high concurrency machines to understand potential benefits and weaknesses, so our approach also includes implementation of the MGRIT algorithms and capabilities into the GridDyn transmission code at LLNL and assessing performance on LLNL's high concurrency systems.

Summary of previous progress. An important component of this project has been the question of handling discontinuities. We completed an initial integration of the MGRIT algorithm into GridDyn, and within GridDyn, we formulated both fixed and variable step MGRIT methods for handling systems with scheduled discontinuities. We applied these methods to a version of the reduced WECC system with a discontinuous square load applied every 2 seconds and demonstrated uniform convergence of the MGRIT algorithm independent of the number of discontinuities. The largest problem had 460 discontinuities yet MGRIT's coarsest grid only had 4 time points. We observed speedups of up to 53x with uniform time steps and up to 47x speedup with variable step methods. Convergence was insensitive to the load size, which ranged from 50MW to 200MW. We presented these results at the PES 2018 General Meeting. The paper is the first work we know of to present significant speedups with a parallel in time method on a power grid problem with discontinuous loads.

More recently, we have focused on the unscheduled discontinuity problem. In serial, the locations of these discontinuities are computed in a sequential procedural way, which does not immediately translate to the parallel-in-time setting where they must be computed simultaneously. To address this, we first worked on the mathematical formulation of the problem. One approach we explored was an optimal control formulation designed to optimize the location of the discontinuities based on a certain objective function. Although successful, the approach is expensive and is unlikely to yield appreciable speedups. We instead directed our research to a nonlinear ODE formulation of the problem, using an exciter model problem as a first test example.

For a problem with unscheduled events, the grid locations of the events must also be computed in parallel. This means that the temporal grid must adapt as the problem is being solved. In the scheduled event case, our adaptive algorithm added new time points where needed to achieve the desired simulation accuracy. For unscheduled events, we use the same strategy, but we also need a procedure for computing the event points themselves. We developed a double-step approach that allows the event points to "float" while the method is iterating. This allows us to refine temporally to achieve accuracy, while not adding too many time points to the grid. For the exciter model problem, we achieved speedups of up to 15x in parallel. To our knowledge, the resulting paper is the first to demonstrate significant speedups of a parallel-in-time algorithm for a model power grid problem with unscheduled events.

FY2020-Q4 Progress and plans.

To extend our results to more relevant and complex test problems that involve equipment limits and possibly deadbands, we are implementing our new unscheduled-event algorithm in GridDyn. This will allow us to easily test the two-bus regulation study model problem previously identified, but also a host of other more difficult model problems. It will also make it easy to compare the simulation time of our parallel-in-time method with traditional time-stepping approaches, using temporal adaptivity in both cases. In our Q4 efforts, we finished a first implementation of the code that couples GridDyn, ParaDAE, and XBraid, allowing us to run our double-step unscheduled-event algorithm in GridDyn (this algorithm had previously been implemented outside of GridDyn). We are now going through the testing phase. Our paper on this double-step algorithm was published and presented at the PESGM virtual meeting.

List of Publications and Presentations during this quarter.

Papers:

- Stefanie Günther, Robert D. Falgout, Philip Top, Carol S. Woodward, and Jacob B. Schroder, "Parallel-in-time solution of power systems with unscheduled events," IEEE Power and Energy Society General Meeting (PESGM) 2020.

Presentations:

- Stefanie Günther, Robert D. Falgout, Philip Top, Carol S. Woodward, and Jacob B. Schroder, "Parallel-in-time solution of power systems with unscheduled events," a recorded presentation to the IEEE Power and Energy Society General Meeting (PESGM), August 2020.