Technical Conference: Increasing Real-Time and Day-Ahead Market Efficiency and Enhancing Resilience through Improved Software

Agenda

AD10-12-010
June 25 – 27, 2019

Tuesday, June 25, 2019

9:00 AM	Introduction (Meeting Room 3M-2) **Richard O'Neill**, Federal Energy Regulatory Commission (*Washington, DC*)
9:15 AM	Session T1 (Meeting Room 3M-2) **A Multi-Period Market Design for Markets with Intertemporal Constraints** Jinye Zhao, ISO New England (*Holyoke, MA*) Tongxin Zheng, ISO New England (*Holyoke, MA*) Eugene Litvinov, ISO New England (*Holyoke, MA*) **Exploring The Impacts of Price Formation Enhancements in PJM's Wholesale Energy Markets** Anthony Giacomoni, PJM Interconnection (*Audubon, PA*) Amanda Long, PJM Interconnection (*Audubon, PA*) **MISO R&D on Improving the Efficiency of Market Clearing Software** Yonghong Chen, Midcontinent ISO (*Carmel, IN*)
10:45 AM	Break
11:00 AM	Session T2 (Meeting Room 3M-2) **Implementation of Fuel, Generator Contingency, and Remedial Action Scheme Constraints to Promote Electric System Resilience** Guillermo Bautista , California ISO (*Folsom, CA*) **Reserve Demand Curves in Real-time Market** Feng Zhao, ISO New England (*Holyoke, MA*) Eugene Litvinov, ISO New England (*Holyoke, MA*) Tongxin Zheng, ISO New England (*Holyoke, MA*) **Improving MISO Real-Time Market Efficiency and Reliability through Online Stability Assessment** Clayton Umlor, Midcontinent ISO (*Eagan, MN*) Raja Thappetaobula, Midcontinent ISO (*Eagan, MN*)
12:30 PM	Lunch
1:45 PM	Session T3 (Meeting Room 3M-2) **Managing Flexibility and Uncertainty in Markets and Operations - Including Near-Term Improvements to Manage Intra-Hour Flexibility** Congcong Wang, Midcontinent ISO (*Carmel, IN*) Stephen Rose, Midcontinent ISO (*Eagan, MN*) Long Zhao, Midcontinent ISO (*Carmel, IN*) **Reserve Deliverability with Application to Short-Term Reserve Product** Fengyu Wang, Midcontinent ISO (*Carmel, IN)* Akshay Korad, Midcontinent ISO (*Carmel, IN*) Yonghong Chen, Midcontinent ISO (*Carmel, IN*) Ryan Sutton, Midcontinent ISO (*Carmel, IN*) **Automatic Generation Control (AGC) Enhancement for Fast-Ramping Resources** Akshay Korad, Midcontinent ISO (*Carmel, IN*) Pavan Addepalle, Midcontinent ISO (*Carmel, IN*) Yaming Ma, Midcontinent ISO (*Carmel, IN*)
3:15 PM	Break

Tuesday, June 25, 2019

3:30 PM	Session T4 (Meeting Room 3M-2) **Impacts of Price Formation Efforts Considering High Renewable Penetration Levels and System Resource Adequacy Targets** Robin Hytowitz, Electric Power Research Institute (*Palo Alto, CA*) Bethany Frew, National Renewable Energy Laboratory (*Golden, CO*) Gord Stephen, National Renewable Energy Laboratory (*Golden, CO*) Erik Ela, Electric Power Research Institute (*Palo Alto, CA*) Jessica Lau, National Renewable Energy Laboratory (*Golden, CO*) Nikita Singhal, Electric Power Research Institute (*Palo Alto, CA*) Aaron Bloom, NextEra Analytics (*St. Paul, MN*) **Market-based Resource Adequacy Assessment Framework under High Wind Penetrations** Jonghwan Kwon, Argonne National Laboratory (*Lemont, IL*) Zhi Zhou, Argonne National Laboratory (*Lemont, IL*) Todd Levin, Argonne National Laboratory (*Lemont, IL*) Audun Botterud, Massachusetts Institute of Technology (*Cambridge, MA*) **An Efficient Algorithm for Convex Hull Pricing Problems in MISO Day-Ahead Market** Yongpei Guan, University of Florida (*Gainesville, FL*) Yanan Yu, University of Florida (*Gainesville, FL*) Yonghong Chen, Midcontinent ISO (*Carmel, IN*)
5:00 PM	Adjourn

Wednesday, June 26, 2019

8:45 AM	Arrive and welcome (Meeting Room 3M-2)
9:00 AM	Session W1-A (Meeting Room 3M-2) **Mixed Integer Programming Formulations for the Unit Commitment Problem** Bernard Knueven, Sandia National Laboratories (*Albuquerque, NM*) James Ostrowski, University of Tennessee (*Knoxville, TN*) Jean-Paul Watson, Sandia National Laboratories (*Albuquerque, NM*) **Value of Modelling Constraints in Generation Scheduling - Towards Computationally Efficient Scheduling Proxies** Miguel Ortega-Vazquez, Electric Power Research Institute (*Palo Alto, CA*) **New Formulation of Security Constraints for Power Systems Optimization and its Applications to Energy Exchange Pricing** Alinson Santos Xavier, Argonne National Laboratory (*Lemont, IL*) Feng Qiu, Argonne National Laboratory (*Lemont, IL*) Santanu S. Dey, Georgia Institute of Technology (*Atlanta, GA*) **Fast Evaluation of Security Constraints in a Security Constrained Unit Commitment Algorithm** Jesse Holzer, Pacific Northwest National Laboratory (*Richland, WA*) Yonghong Chen, Midcontinent ISO (*Carmel, IN*) Feng Pan, Pacific Northwest National Laboratory (*Richland, WA*) Edward Rothberg, Gurobi Optimization (*Beaverton, OR*) Arun Veeramany, Pacific Northwest National Laboratory (*Richland, WA*)
9:00 AM	Session W1-B (Meeting Room 3M-4) **Hybrid Storage Resources - Implications for Grid Services and Market Design** Mark Ahlstrom, NextEra Energy Resources (*St. Paul, MN*) **Incorporating Electric Storage Resources into Wholesale Electricity Markets While Considering State of Charge Management Options** Nikita Singhal, Electric Power Research Institute (*Palo Alto, CA*) Erik Ela, Electric Power Research Institute (*Palo Alto, CA*) **A Configuration Based Pumped-storage Hydro Model in MISO Day-ahead Market** Bing Huang, University of Texas Austin (*Austin, TX*) Yonghong Chen, Midcontinent ISO (*Carmel, MN*) Ross Baldick, University of Texas Austin (*Austin, TX*) **Unlocking the Market Value of Energy Storage via Improved Economic Dispatch and Storage Control** Bolun Xu, Massachusetts Institute of Technology (*Cambridge, MA*) Audun Botterud, Massachusetts Institute of Technology (*Cambridge, MA*) Magnus Korpas, Norwegian University of Science and Technology (*Trondheim, Norway*) Francis O’Sullivan, Massachusetts Institute of Technology (*Cambridge, MA*)
11:00 AM	Break
11:15 AM	Session W2 (Meeting Room 3M-2) **Ten Years Later: Rethinking Principles of Smart Architectures and Data-enabled Software** Marija Ilic, Carnegie Mellon University (*Pittsburgh, PA*) **Simulation Modeling of Coordinated Operation of Natural Gas and Electric Markets with GECO ENELYTIX** Aleksandr Rudkevich, Newton Energy Group LLC (*Boston, MA*) Anatoly Zlotnik, Los Alamos National Laboratory (*Los Alamos, NM*) John Goldis, Newton Energy Group LLC (*Boston, MA*) Russ Philbrick, Polaris Systems Optimization (*Seattle, WA*) Xindi Li, Tabors Carmanis Rudkevich (*Boston, MA*) Aleksandr Beylin, Newton Energy Group LLC (*Boston, MA*) Pablo A. Ruiz, Boston University (*Boston, MA*) Rafael Castro, Polaris System Optimization (*Seattle, WA*) Richard D. Tabors, Tabors Carmanis Rudkevich (*Boston, MA*)

Wednesday, June 26, 2019

12:15 PM	Lunch
2:00 PM	Session W3-A (Meeting Room 3M-2) **Learning to Solve Large-scale Security-constrained Unit Commitment Problems** Feng Qiu, Argonne National Laboratory (*Lemont, IL*) Alinson Santos Xavier, Argonne National Laboratory (*Lemont, IL*) Shabbir Ahmed, Georgia Institute of Technology (*Atlanta, GA*) **A Decomposition and Coordination Approach for Unit Commitment with Sequential and Parallel Implementations** Niranjan Raghunathan, University of Connecticut (*West Hartford, CT*) Mikhail Bragin, University of Connecticut (*Storrs, CT*) Bing Yan, University of Connecticut (*Storrs, CT*) Peter Luh, University of Connecticut (*Storrs, CT*) Khosrow Moslehi, ABB (*San Jose, CA*) **HIPPO: A Concurrent Optimizer for Solving Day-ahead Security Constrained Unit Commitment Problem** Feng Pan, Pacific Northwest National Laboratory (*Richland, WA*) Yonghong Chen, Midcontinent ISO (*Carmel, IN*) Jesse Holzer, Pacific Northwest National Laboratory (*Richland, WA*) **A GPU-based Contingency Analysis Tool** Evgeniy Goldis, Newton Energy Group LLC (*Boston, MA*) Andrei Kharchenko, University of Georgia (*Athens, GA*) Aleksandr Rudkevich, Newton Energy Group LLC (*Boston, MA*) Yonghong Chen, Midcontinent ISO (*Carmel, IN*) Fengyu Wang, Midcontinent ISO (*Carmel, IN*) Jessica Harrison, Midcontinent ISO (*Carmel, IN*)
	Session W3-B (Meeting Room 3M-4) **Quantifying the Amount of Installed Flexibility in the Resource Fleet: Case Study on CAISO** Erik Ela, Electric Power Research Insitute (*Palo Alto, CA*) Qin Wang, Electric Power Research Insitute (*Palo Alto, CA*) Clyde Loutan, California ISO (*Folsom, CA*) Eamonn Lannoye, Electric Power Research Institute (*Dublin, Ireland*) Karl Meeusen, California ISO (*Folsom, CA*) Mark Rothleder, California ISO (*Folsom, CA*) **Extending ISO Operational Software to Long-Term Production Cost Models** James David, PowerGEM LLC (*Clifton Park, NY*) Boris Gisin, PowerGEM LLC (*Clifton Park, NY*) Qun Gu, PowerGEM LLC (*Clifton Park, NY*) Brian Thomas, PowerGEM LLC (*Clifton Park, NY*) **Toward a Resilience-focused Production Cost Modeling Capability** Jean-Paul Watson, Sandia National Laboratories (*Albuquerque, NM*) Jessica Lau, National Renewable Energy Laboratory (*Golden, CA*) **Robust Solution of High Renewable Penetration Planning Cases in PS-SUGAR** David Bromberg, Pearl Street Technologies (*Pittsburgh, PA*) Amritanshu Pandey, Pearl Street Technologies (*Pittsburgh, PA*) Hui Zheng, Pearl Street Technologies (*Pittsburgh, PA*) Yifan Li, Midcontinent ISO (*Carmel, IN*)
4:00 PM	Adjourn

Thursday, June 27, 2019

8:45 AM	Arrive and welcome (Meeting Room 3M-2)
9:00 AM	Session H1-A (Meeting Room 3M-2) **GridPACK - An HPC Platform for Better Grid Efficiency and Resilience** Yousu Chen, Pacific Northwest National Laboratory (*Richland, WA*) Bruce Palmer, Pacific Northwest National Laboratory (*Richland, WA*) Zhenyu Huang, Pacific Northwest National Laboratory (*Richland, WA*) **Grid Mind: Data-driven Autonomous Grid Dispatch and Control Based on AI** Di Shi, GEIRINA (*San Jose, CA*) Zhiwei Wang, GEIRINA (*San Jose, CA*) **Period Optimal Power Flow Model in Power Systems with High Penetration of Intermittent Power Sources** Zongjie Wang, Cornell University (*Ithaca, NY*) Lindsay Anderson, Cornell University (*Ithaca, NY*)
9:00 AM	Session H1-B (Meeting Room 3M-3) **Scenario Generation for Two-Stage Stochastic Economic Dispatch** Ignas Satkauskas, National Renewable Energy Laboratory (*Golden, CO*) Matthew Reynolds, National Renewable Energy Laboratory (*Golden, CO*) Devon Sigler, National Renewable Energy Laboratory (*Golden, CO*) Jonathan Maack, National Renewable Energy Laboratory (*Golden, CO*) Wesley Jones, National Renewable Energy Laboratory (*Golden, CO*) **A Scalable Mixed-integer Decomposition Approach for Optimal Black-start and Restoration of Power Systems** Ignacio Aravena, Lawrence Livermore National Laboratory (*Livermore, CA*) Amelia Musselman, Lawrence Livermore National Laboratory (*Livermore, CA*) Georgios Patsakis, UC Berkeley (*Berkeley, CA*) Deepak Rajan, UC Berkeley (*Berkeley, CA*) Shmuel Oren, UC Berkeley (*Berkeley, CA*) **Scalable Preventive Unit Commitment for Operation during Extreme Weather** Mostafa Sahraei-Ardakani, University of Utah (*Salt Lake City, UT*) Farshad Mohammadi, University of Utah (*Salt Lake City, UT*) Ge Ou, University of Utah (*Salt Lake City, UT*) Zhaoxia Pu, University of Utah (*Salt Lake City, UT*)
10:30 AM	Break
10:45 AM	Session H2 (Meeting Room 3M-3) **The ARPA-E Grid Optimization (GO) Competition: Challenge 1 and Beyond** Kory Hedman, US Department of Energy, ARPA-E (*Tempe, AZ*) David Guarrera, Quantitative Scientific Solutions LLC (*Washington, DC*) Ashley Arigoni, Quantitative Scientific Solutions LLC (*Denver, CO*) Ray Duthu, Quantitative Scientific Solutions LLC (*Washington, DC*) **Performance-based Energy Resource Feedback, Optimization, and Risk Management: PERFORM** Kory Hedman, US Department of Energy, ARPA-E (*Tempe, AZ*) Joseph King, US Department of Energy, ARPA-E (*Washington, AZ*) Ashley Arigoni, Quantitative Scientific Solutions LLC (*Denver, CO*) David Guarrera, Quantitative Scientific Solutions LLC (*Washington, DC*) Ray Duthu, Quantitative Scientific Solutions LLC (*Washington, DC*) Mirjana Marden, US Department of Energy, ARPA-E (*Washington, DC*) **HELICS: Co-Simulation for Better Grid Efficiency and Resilience** Henry Huang, Pacific Northwest National Laboratory (*Richland, WA*) Liang Min, Lawrence Livermore National Laboratory (*Livermore, CA*) Jason Fuller, Pacific Northwest National Laboratory (*Richland, WA*) Bryan Palmintier, National Renewable Energy Laboratory (*Golden, CO*) Philip Top, Lawrence Livermore National Laboratory (*Livermore, CA*) Shri Abhyankar, Pacific Northwest National Laboratory (*Richland, WA*)
12:15 PM	Adjourn

Staff Technical Conference on Increasing Real-Time and Day-Ahead Market efficiency and Enhancing Resilience through Improved Software

Presenters' Abstracts

Tuesday, June 25

Opening (Tuesday, June 25, 9:00 AM, Meeting Room 3M-2)

INTRODUCTION

Dr. Richard O'Neill, Chief Economic Advisor, Federal Energy Regulatory Commission (*Washington, DC*)

Session T1 (Tuesday, June 25, 9:15 AM, Meeting Room 3M-2)

A MULTI-PERIOD MARKET DESIGN FOR MARKETS WITH INTERTEMPORAL CONSTRAINTS

Dr. Jinye Zhao, Lead Analyst, ISO New England (*Holyoke, MA*)
Dr. Tongxin Zheng, Technical Director, ISO New England (*Holyoke, MA*)
Dr. Eugene Litvinov, Chief Technologist, ISO New England (*Holyoke, MA*)

The participation of renewable, energy storage, and resources with limited fuel inventory in electricity markets has created the needs for optimal scheduling and pricing across multiple market intervals for resources with intertemporal constraints. In this presentation, a new two-tier multi-period market model is proposed to enhance the efficiency of markets with such types of resources. It is also the first market design model that considers the coordination between a forward market and a spot market under the multi-period paradigm, achieving reliability, economic efficiency and dispatch-following invectives simultaneously. The upper-tier market solves a multi-period model with a long look-ahead time horizon whereas the lower-tier market solves a series of multi-period dispatch and pricing problems with a shorter look-ahead time horizon on a rolling basis. By using the upper-tier schedules and opportunity costs of intertemporal constraints as a guideline, the lower-tier market model is able to produce economically efficient dispatch solutions as well as prices that incentivize dispatch following under the perfect forecast condition. The proposed scheme is applied to the

dispatch and pricing of energy storage resources. Numerical experiments show that the proposed scheme outperforms the traditional myopic method in terms of economic efficiency, dispatch following and reliability.

EXPLORING THE IMPACTS OF PRICE FORMATION ENHANCEMENTS IN PJM'S WHOLESALE ENERGY MARKETS

Dr. Anthony Giacomoni, Senior Market Strategist, PJM Interconnection (*Audubon, PA*)
Ms. Amanda Long, Analyst, PJM Interconnection (*Audubon, PA*)

The current locational marginal pricing (LMP) method was chosen because it was simple in both concept and implementation. However, under several circumstances, this method could fail to accurately reflect all costs needed to serve load. For example, it does not allow inflexible units to set price. When the cost of an inflexible unit that is needed to serve demand is precluded from setting price, the LMP does not accurately reflect the true incremental cost to serve load. This pricing limitation can suppress energy and reserve prices and inappropriately increase reliance on the capacity market.

This presentation will explore the impacts from expanding the eligibility criteria for setting energy market prices in both PJM's day-ahead and real-time energy markets. The impacts on prices, revenues, congestion, and out-of-market uplift payments will be discussed.

MISO R&D ON IMPROVING THE EFFICIENCY OF MARKET CLEARING SOFTWARE

Dr. Yonghong Chen, Consulting Advisor, Midcontinent ISO (*Carmel, IN*)

This presentation discusses recent progresses at MISO to prepare for the portfolio evolution with increased uncertainty and variability. It includes computational research to improve commercial solver performance as well as the R&D to develop high performance computer based SCUC under the ARPA-E HIPPO project, enhancing resource modeling to better optimize storage and prepare for future DER integration, improving pricing through advanced resource modeling aiming to achieve full convex hull price, reserve deliverability and stochastic look ahead commitment.

Session T2 (Tuesday, June 25, 11:00 AM, Meeting Room 3M-2)

Implementation of Fuel, Generator Contingency, and Remedial Action Scheme Constraints to Promote Electric System Resilience

Dr. Guillermo Bautista, Director of Market Analysis & Forecasting, California ISO (*Folsom, CA*)

The CAISO has implemented constraints in its energy market software to manage operational conditions related to natural gas usage, generator contingencies and remedial action schemes. Natural gas constraints are used in both day-ahead and real-time markets to enforce minimum gas burn when there is limited natural gas available. This constraint allows the CAISO to optimally reduce natural gas usage across a pool of resources. The constraints for generator contingencies and remedial action schemes allow the market solution to reflect these contingencies, model the effect of generation pickup, and minimize the potential for transmission overloads.

Reserve Demand Curves in Real-time Market

Dr. Feng Zhao, Principal Analyst, ISO New England (*Holyoke, MA*)
Dr. Eugene Litvinov, Chief Technologist, ISO New England (*Holyoke, MA*)
Dr. Tongxin Zheng, Technical Director, ISO New England (*Holyoke, MA*)

Most US ISOs/RTOs use reserves in their Real-time Markets (RTM) for system operational reliability. However, due to the lack of reserve demand bids, the reserve markets are one-sided with ISOs/RTOs setting the requirements and penalty prices. This impedes the economic tradeoff between reliability and efficiency.

Conceptually, a Reserve Demand Curve (RDC) should reflect the diminishing marginal reliability benefit of reserve. The benefit can be measured by avoided Loss of Load (LOL). However, LOL depends on system state, a challenge to derive RDC as a single-variable function of reserve. Also, multiple reserve products and local reserves complicate RDCs.

This work extends our previous framework for Capacity Demand Curves (CDCs) to RTM with multiple reserve products and local reserves. To reduce computational burden of simulating system states, historical RT dispatch cases are used instead. Unlike existing approaches that assume the shape of RDC, we analyze each dispatch case to obtain a pair of available reserve and LOL level. These pairs, together with the scaling factor of Value of Lost Load (VOLL), form the RDC. Also, VOLL is derived from the short-term market equilibrium instead of being administratively set, and it connects to the similar parameter for CDCs, thus unifying both demand curves in a consistent framework. Our work also provides new perspectives on questions such as: Do the existing planning criteria and operational criteria imply the same reliability level?

IMPROVING MISO REAL-TIME MARKET EFFICIENCY AND RELIABILITY THROUGH ONLINE STABILITY ASSESSMENT

Mr. Clayton Umlor, Senior Reliability Engineer, Midcontinent ISO (*Eagan, MN*)
Mr. Raja Thappetaobula, Manager North Operations, Midcontinent ISO (*Eagan, MN*)

This presentation details development and implementation of an online stability assessment tool at MISO. The traditional manner of operating the system with conservative limits based on offline calculations, while effective, may prove to be inefficient for managing today's dynamic grid. Higher penetration of renewables introduces additional uncertainties. Ensuring system stability is critical as instability can quickly cause cascading failures resulting in widespread blackouts. MISO calculates system capability from a voltage/transient stability perspective in near real-time on key stability interfaces. Implementation of online stability assessment has the potential to improve market efficiency through reduction of real time congestion costs.

Session T3 (Tuesday, June 25, 1:45 PM, Meeting Room 3M-2)

MANAGING FLEXIBILITY AND UNCERTAINTY IN MARKETS AND OPERATIONS - INCLUDING NEAR-TERM IMPROVEMENTS TO MANAGE INTRA-HOUR FLEXIBILITY

Dr. Congcong Wang, Midcontinent ISO (*Carmel, IN*)
Dr. Stephen Rose, Midcontinent ISO (*Eagan, MN*)
Dr. Long Zhao, Midcontinent ISO (*Carmel, IN*)
Mr. Ryan Sutton, Market Innovation and Solutions Analyst, Midcontinent ISO (*Carmel, IN*)

MISO is exploring markets and operations solutions to manage increasing variability and uncertainty. A key element is defining the nature of variability and uncertainty, including system needs and how they will change. Several opportunities also exist for near term implementation to address known issues. This presentation first discusses recent enhancements that are built into Market Clearing Engines without increasing computational complexity. These include: improving headroom modeling in unit commitment to manage intra-hour ramping and unit starts/stops at the top of the hour; improving ramp capability products to better utilize ramp for load following in economic dispatch; and improving the Regulation selection process to maintain capacity and flexibility when varying Real-Time conditions require more units on Regulation. It then outlines our on-going work to quantify flexibility need for the MISO system as a function of variability and uncertainty and to quantify flexibility supply as a function of the characteristics of generation, load, and other supply.

RESERVE DELIVERABILITY WITH APPLICATION TO SHORT-TERM RESERVE PRODUCT

Dr. Fengyu Wang, Engineer, Midcontinent ISO (*Carmel, IN)*
Dr. Akshay Korad, Engineer, Midcontinent ISO (*Carmel, IN*)
Dr. Yonghong Chen, Engineer, Midcontinent ISO (*Carmel, IN*)

Midcontinent Independent System Operator (MISO) proposes a 30-minute Short Term Reserve (STR) product co-optimized along with other energy and ancillary service requirements in the market clearing processes. This new STR product mainly aims to improve market efficiency in the commitment processes and market re-dispatch related to 30 minutes operational needs for Regional Directional Transfer (RDT) and Reserve Zones with import limits. Furthermore, the STR product provides price signals, improves market transparency, and reduces uplift caused by out-of-market commitments. One STR product design challenge is to ensure deliverability of cleared STR without causing post-deployment violations. Market design with the consideration of post-deployment deliverability constrains are incorporated to achieve that goal. This presentation will discuss background of STR, preliminary market design of STR, and STR deliverability constraints. Future applications of deliverability approach may enhance other reserve products.

AUTOMATIC GENERATION CONTROL (AGC) ENHANCEMENT FOR FAST-RAMPING RESOURCES

Dr. Akshay Korad, Market Design Engineer, Midcontinent ISO (*Carmel, IN*)
Mr. Pavan Addepalle, Sr. Advisor Market Engineering, Midcontinent ISO (*Carmel, IN*)
Mr. Yaming Ma, Sr. Engineer Research and Development, Midcontinent ISO (*Carmel, IN*)

> MISO's Automatic Generation Control (AGC) deploys regulation at four-second intervals to operate the balancing area at scheduled interchange and regulate Eastern Interconnection frequency within operating range. Opportunities exist to better utilize available capabilities to improve efficiency and to meet continually changing regulation needs. With the increase in the renewable generation portfolio comes increased uncertainty for the system to control and an increased need for flexible regulation. In the redesigned Fast First AGC, AGC deploys a fast changing regulation signal on fast ramping resources and complements this changing regulation need via deployment on the other resources via a slower moving signal. This optimization and coordination of the two signals achieves the objectives of (i) meeting immediate system control needs via a fast changing regulation signal; and (ii) lengthening the aggregate availability (duration) of the fast ramping resources to the system; and (iii) maintaining system balance regardless of regulation net energy needs over time. This presentation explores some of these salient features of the Fast First AGC design.

Session T4 (Tuesday, June 25, 3:30 PM, Meeting Room 3M-2)

IMPACTS OF PRICE FORMATION EFFORTS CONSIDERING HIGH RENEWABLE PENETRATION LEVELS AND SYSTEM RESOURCE ADEQUACY TARGETS

Dr. Robin Hytowitz, Senior Engineer, Electric Power Research Institute (*Palo Alto, CA*)
Dr. Bethany Frew, Grid Systems Research Engineer, National Renewable Energy Laboratory (*Golden, CO*)
Mr. Gord Stephen, Grid Systems Research Engineer, National Renewable Energy Laboratory (*Golden, CO*)
Dr. Erik Ela, Principal Technical Leader, Electric Power Research Institute (*Palo Alto, CA*)
Ms. Jessica Lau, Senior Project Manager, National Renewable Energy Laboratory (*Golden, CO*)

Dr. Nikita Singhal, Senior Engineer, Electric Power Research Institute (*Palo Alto, CA*)
Dr. Aaron Bloom, Director of Product Research & Development, NextEra Analytics (*St. Paul, MN*)

> Future markets with very high penetrations of renewable energy could have many low- to zero-cost periods, which would reduce energy revenues for the generation fleet. This can impact the ability of resources that are needed for long-term reliability to recover operating and capital costs. This presentation explores the impact of an alternative pricing mechanism, relaxed minimum pricing, on revenue sufficiency on existing and future resource mixes, including those with high penetrations of wind and solar. The presentation will discuss results of a recent study that evaluated eight scenarios encompassing three different sensitivity categories: (1) one alternative pricing mechanism versus traditional LMP pricing, (2) high versus low renewable penetration levels, and (3) using a resource mix that has been adjusted to a preset resource adequacy target versus one that contains a full set of resources.
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> Results show renewable penetration has a greater impact on pricing and resulting profits than does the adjusted resource mix, the two pricing methods have modest variations in profits, and prices under the higher renewable penetration case were higher than under low renewable penetration. These conclusions are not intended to be direct predictions for future outcomes but rather to lead to additional research on the impacts of pricing on investment incentives and future resource adequacy targets.

MARKET-BASED RESOURCE ADEQUACY ASSESSMENT FRAMEWORK UNDER HIGH WIND PENETRATIONS

Dr. Jonghwan Kwon, Postdoctoral Appointee, Argonne National Laboratory (*Lemont, IL*)
Dr. Zhi Zhou, Principal Computational Scientist, Argonne National Laboratory (*Lemont, IL*)
Dr. Todd Levin, Energy Systems Engineer, Argonne National Laboratory (*Lemont, IL*)
Dr. Audun Botterud, Energy Systems Engineer, Massachusetts Institute of Technology (*Cambridge, MA*)

> In this talk, we will present an overview of a market-based resource adequacy assessment framework that analyzes the system generation portfolio and resource adequacy that results in a competitive market framework with markets for capacity, energy, and reserve products. The

model allows an improved analysis of generation portfolio and resource adequacy by capturing the strategic capacity investment and retirement decision-making of profit-maximizing generation companies. The model is based on Stackelberg leader-follower games and is formulated as a bi-level optimization problem, which is then transformed into a mathematical program with equilibrium constraints. Furthermore, we employ a Lagrangian decomposition algorithm and parallel computing to enhance computational performance. We will demonstrate the value and the potential application of the modeling framework by investigating how increasing wind penetration levels impact system resource adequacy with a case study of the ERCOT system in Texas. The case study will show how different market designs, including scarcity pricing schemes and capacity remuneration mechanisms, affect the generation portfolio. In addition, we will compare the results from the presented model with those obtained from a traditional centralized least-cost planning model. Our study will show that proper market designs can promote sufficient investment through market signals and can help the system to maintain socially optimal resource adequacy.

AN EFFICIENT ALGORITHM FOR CONVEX HULL PRICING PROBLEMS IN MISO DAY-AHEAD MARKET

Dr. Yongpei Guan, Professor, University of Florida (*Gainesville, FL*)
Ms. Yanan Yu, Ph.D. Student, University of Florida (*Gainesville, FL*)
Dr. Yonghong Chen, Principal Advisor, Midcontinent ISO (*Carmel, IN*)

To increase the market transparency, the independent system operators (ISOs) have been working on minimizing the uplift payments based on the convex hull pricing theorem. However, the large-scale complex system brings computational challenges to the existing convex hull pricing algorithms. In this paper, based on the analysis of generator features in the Midcontinent ISO (MISO) system, we presented several new results and refined the current problem formulations. Considering these results, we built a compact convex hull pricing formulation. To improve the computational efficiency, we proposed two algorithms and a parallel complementary approach, which can provide a good approximation of the original formulation. We tested these algorithms on 10 MISO instances and derived the optimal solutions within 13 minutes.

Wednesday, June 26

Session W1-A (Wednesday, June 26, 9:00 AM, Meeting Room 3M-2)

MIXED INTEGER PROGRAMMING FORMULATIONS FOR THE UNIT COMMITMENT PROBLEM

Mr. Bernard Knueven, Senior Member of Technical Staff, Sandia National Laboratories (*Albuquerque, NM*)
Dr. James Ostrowski, Associate Professor, University of Tennessee (*Knoxville, TN*)
Dr. Jean-Paul Watson, Distinguished Member of Technical Staff, Sandia National Laboratories (*Albuquerque, NM*)

We provide a comprehensive overview of mixed integer programming formulations for the unit commitment problem (UC). UC formulations have been an especially active area of research over the past twelve years, due to their practical importance in power grid operations, and this paper serves as a capstone for this line of work. We additionally provide reference implementations of all formulations examined as part of the EGRET software package, publically available on GitHub. We computationally test existing and novel UC formulations on a suite of instances drawn from both academic and real-world data sources. Driven by our computational experience from this and previous work, we contribute some additional formulations for both production upper bound and piecewise linear production costs. By composing new UC formulations using existing components found in the literature and new components introduced in this paper, we demonstrate that performance can be significantly improved - and in the process, we identify a new state-of-the-art UC formulation.

VALUE OF MODELLING CONSTRAINTS IN GENERATION SCHEDULING - TOWARDS COMPUTATIONALLY EFFICIENT SCHEDULING PROXIES

Dr. Miguel Ortega-Vazquez, Senior Technical Leader, Electric Power Research Institute (*Palo Alto, CA*)

Power system tools based on unit commitment (UC) formulations (e.g., planning tools) follow a top-down approach. That is, these models concentrate on the top decision-making process (e.g., investment decisions) and little details are given to operating aspects of the system (e.g., UC represented via over-simplified proxies, the load is modeled via load duration curves, etc.) in order to gain computational speed. However, as the penetrations of renewable energy sources deepen, the time-dependent

variability and uncertainty of the net-load increases requiring different commitment and dispatch patterns of the available generation resources. Similarly, as emerging technologies such as storage are integrated, the need to explicitly represent inter-temporal couplings in the scheduling process becomes necessary. These characteristics are either ignored, or indirectly accommodated (e.g., via some reserve constraints), but this does not guarantee that the scheduling patterns would be realistic or even feasible; additionally, the upper layer decisions (e.g. investments) would be distorted or incorrectly chosen.
This work studies the UC problem from a bottom-up perspective, in which the objective is to obtain fairly accurate scheduling patters in a short amount of time. To do so, the impact of different constraints and costs in the UC formulation is assessed in terms of 1) solution cost; 2) solution reliability; and 3) computational burden of the solve.

New Formulation of Security Constraints for Power Systems Optimization and its Applications to Energy Exchange Pricing

Dr. Alinson Santos Xavier, Postdoctoral Appointee, Argonne National Laboratory (*Lemont, IL*)
Dr. Feng Qiu, Principal Computational Scientist, Argonne National Laboratory (*Lemont, IL*)
Dr. Santanu S. Dey, Associate Professor, Georgia Institute of Technology (*Atlanta, GA*)

When solving large-scale power systems optimization problems, such as the Day-Ahead Security-Constrained Unit Commitment Problem (DA SCUC), one of the most complicating factors is modeling transmission and security constraints. The most common formulation used in the industry, based on Injection Shift Factors (ISF), yields very dense and unstructured constraints, which not only may cause performance issues, but also makes it unsuitable for decentralized studies, such as optimal energy exchange pricing. In this work, we present a novel DC power flow formulation which has a decomposable block-diagonal structure, scales well for large systems, and can efficiently handle N-1 security requirements. The formulation also provides interpretable shadow prices, which can be used to determine optimal energy exchange prices between neighboring zones. Benchmarks on Multi-Zonal Security-Constrained Unit Commitment problems show that the proposed formulation can reliably and efficiently solve instances with up to 6,515 buses, with no convergence or numerical issues.

FAST EVALUATION OF SECURITY CONSTRAINTS IN A SECURITY CONSTRAINED UNIT COMMITMENT ALGORITHM

Dr. Jesse Holzer, Research Engineer, Pacific Northwest National Laboratory (*Richland, WA*)
Dr. Yonghong Chen, Principal Advisor, Midcontinent ISO (*Carmel, IN*)
Dr. Feng Pan, Computer Scientist, Pacific Northwest National Laboratory (*Richland, WA*)
Dr. Edward Rothberg, CEO and Co-founder, Gurobi Optimization (*Beaverton, OR*)
Dr. Arun Veeramany, Scientist, Pacific Northwest National Laboratory (*Richland, WA*)

We present a new fast security constraint evaluation (SCE) method and show how it facilitates algorithms for security constrained unit commitment (SCUC). This SCE method is developed in the HIPPO project on algorithms for SCUC for the computational engine of large scale day ahead electricity markets. Our SCE method achieves speedup on the order of 10x to 100x relative to existing commercial methods currently used in this context. This speedup permits the use of SCE as an integrated part of an algorithm for SCUC rather than in alternation with an SCUC algorithm, giving greater flexibility in the design of SCUC algorithms. This algorithmic flexibility enables the HIPPO suite of SCUC algorithms to achieve further speedup relative to existing algorithms.

In the considered existing SCE methods, the pre-contingency admittance matrix is factored in a startup phase, and then given an SCUC solution, changes occurring in contingencies are handled by partial re-factorization, with significant computation in this evaluation phase. Our SCE method uses the Sherman-Morrison-Woodbury formula to handle contingencies. We perform as much computation as is practically possible in the startup phase, minimizing computation in evaluation. Our method is implemented with widely used open source high performance linear algebra software. Substantial parallelism is already achieved within this linear algebra software, but our method is also parallelized with respect to time periods in the SCUC problem.

Session W1-B (Wednesday, June 26, 9:00 AM, Meeting Room 3M-4)

HYBRID STORAGE RESOURCES - IMPLICATIONS FOR GRID SERVICES AND MARKET DESIGN

Mr. Mark Ahlstrom, VP of Renewable Energy Policy, NextEra Energy Resources (*St. Paul, MN*)

> Hybrid solar+storage projects have altered our thinking about resources and may change how we think about market design, too. Solar hybrids are financially viable today and will soon dominate interconnection queues. Software backed by energy and electronics can emulate more ideal resources and innovate them quickly.
>
> This raises big questions for market design. How should such resources offer their capabilities? Is it a price formation failure if all capabilities are not considered? If resources can reduce their less ideal and non-convex characteristics through physically or virtually hybridizing, how does this compare with our current approach of having the market accommodate the less-than-ideal resource characteristics? Indeed, should markets become simpler - demanding the grid services that they truly want to operate a balanced, reliable system - and expect market participants to innovate on how to best provide them?
>
> Our pace of change will accelerate, as it has for all other industries once the digital revolution found its roots in them. Our industry has been a laggard, but today's software, communications and computing will make change happen all that much faster - or allow customers to move around us to get what they want.

INCORPORATING ELECTRIC STORAGE RESOURCES INTO WHOLESALE ELECTRICITY MARKETS WHILE CONSIDERING STATE OF CHARGE MANAGEMENT OPTIONS

Dr. Nikita Singhal, Senior Engineer, Electric Power Research Institute (*Palo Alto, CA*)
Dr. Erik Ela, Principal, Electric Power Research Institute (*Palo Alto, CA*)

> FERC Order 841 directs the U.S. ISOs and RTOs to incorporate appropriate modifications to their market design rules and market clearing software to enable an enhanced participation of electric storage resources (ESRs) in energy, ancillary services, and capacity markets. One specific requirement within Order 841 necessitates that each ISO/RTO provide

ESRs with the option to self-manage their state of charge (SOC) and not impose ISO management of SOC as a requirement. This study focuses on incorporating ESRs into wholesale electricity markets and evaluating the potential implications of greater penetration levels of ESRs on the operation of wholesale electricity markets. To this end, the study conducted detailed simulations and analyses to understand the implications of higher penetration levels of ESRs participating in wholesale electricity markets with different options to manage and optimize ESR schedules given their unique SOC constraints. Furthermore, the study provides both formulaic and quantitative insights into the ways in which the different SOC management options can be implemented. Results provide key insights on the potential outcomes, e.g., economic efficiency, price setting, SOC feasibility and reliability outcomes, for different penetration levels of ESRs, different penetration levels of variable energy resources, different SOC management options, and different SOC duration capacities.

A CONFIGURATION BASED PUMPED-STORAGE HYDRO MODEL IN MISO DAY-AHEAD MARKET

Mr. Bing Huang, Graduate Student, University of Texas Austin (*Austin, TX*)
Dr. Yonghong Chen, Consulting Advisor, Midcontinent ISO (*Carmel, MN*)
Dr. Ross Baldick, Professor, University of Texas Austin (*Austin, TX*)

This presentation proposes a configuration based pumped-storage hydro (PSH) model for the day-ahead market, in order to enhance the use of pumped-storage hydro resources in the system. By introducing three configurations (namely pumping, generating and all-off or off-line) for a pumped-storage hydro unit, the proposed model can more accurately reflect the practical operations of pumped-storage hydro units in the day-ahead market. A comprehensive review of the existing pumped-storage hydro models and industry practices is presented. The definition of configurations of a pumped-storage hydro unit and the transitions between the configurations during operation are revealed and discussed in detail to describe the proposed model. A numerical study is presented with two identical PSH units in a PSH plant sharing a reservoir. The effectiveness of the pumped-storage hydro units in the proposed model are demonstrated with examples. The disadvantages of including positive bid prices for pump loads and their negative effects on social welfare are discussed with quantified simulation results.

UNLOCKING THE MARKET VALUE OF ENERGY STORAGE VIA IMPROVED ECONOMIC DISPATCH AND STORAGE CONTROL

Dr. Bolun Xu, Postdoc Associate, Massachusetts Institute of Technology (*Cambridge, MA*)
Dr. Audun Botterud, Principal Research Scientist, Massachusetts Institute of Technology (*Cambridge, MA*)
Dr. Magnus Korpas, Research Director, Norwegian University of Science and Technology (*Trondheim, Norway*)
Dr. Francis O'Sullivan, Research Director, Massachusetts Institute of Technology (*Cambridge, MA*)

Energy storage devices are becoming key flexible resources in power systems, especially in real-time markets as they can respond to system deviations instantaneously. But operating large amounts of storage devices economically and efficiently requires solving multi-period economic dispatch with day-long duration and high time resolution (e.g. 5 min), which is is extremely difficult to solve over the size of a realistic power system.

We present a novel dual decomposition method that decomposes a multi-period economic dispatch problem into parallel single-period economic dispatch sub-problems, based on theoretical insights into the Karush-Kuhn-Tucker (KKT) conditions. By parallelizing all sub-problems, our method can solve large-scale multi-period economic dispatch problems in a few seconds, while solving the problem as a single optimization can take several minutes. Computation experiments show that our method converges within 50 iterations with dual objective errors less than 0.1%.

Our work makes it possible for system operators to dispatch energy storage devices optimally based on their physical parameters only, instead of the current market proposals in which storage participants must design strategical bids based on their own future insights (e.g. price forecast). The dual decomposition approach also provides insights into designing future pricing schemes in electricity markets with high shares of energy storage and renewable energy.

Session W2 (Wednesday, June 26, 11:15 AM, Meeting Room 3M-2)

TEN YEARS LATER: RETHINKING PRINCIPLES OF SMART ARCHITECTURES AND DATA-ENABLED SOFTWARE

Dr. Marija Ilic, Professor Emeritus, Massachusetts Institute of Technology/Carnegie Mellon University (*Pittsburgh, PA*)

> After starting with a "wicked" problem of electricity services in the changing electric energy systems we offer rethinking of basic objectives, modeling the relevant characteristics of components and their interactions using common variables understandable across disciplines and stakeholders. We propose to consider protocols which support three basic principles; these can be shown to be direct extensions of today's automatic generation control principles, and, as such, can be observed when designing DERMS and their integration with the TSOs and ISOs. The extensions require more granularity over time and stakeholders. Once these are understood, we begin to overcome the problem of technology biases and open the industry to previously unexplored solutions. Each of the tradeoff and synergies can be understood in light of these principles. In particular, in this talk we consider the role of data-enabled software in reconciling trade-off and building synergies needed to re-integrate distributed stakeholders in the changing electric energy systems. Both trade-off and synergies issues are many and they have tremendous implications on system performance. We make the point that an IT-enabled interactive end-to-end framework based on transparent protocols is essential for managing these tradeoff and synergies. This calls for enhanced SCADA interfacing across DERs/microgrids – DSOs-TSOs-ISOs and exchanging information defined by the protocols.

SIMULATION MODELING OF COORDINATED OPERATION OF NATURAL GAS AND ELECTRIC MARKETS WITH GECO ENELYTIX

Dr. Aleksandr Rudkevich, President, Newton Energy Group LLC (*Boston, MA*)
Dr. Anatoly Zlotnik, Staff Scientist, Los Alamos National Laboratory (*Los Alamos, NM*)
Dr. Evgeny (John) Goldis, CTO, Newton Energy Group LLC (*Boston, MA*)
Dr. Russ Philbrick, President, Polaris Systems Optimization (*Seattle, WA*)
Ms. Xindi Li, Senior Analyst, Tabors Carmanis Rudkevich (*Boston, MA*)
Dr. Aleksandr Beylin, Senior Developer, Newton Energy Group LLC (*Boston, MA*)
Dr. Pablo A. Ruiz, Research Professor, Boston University (*Boston, MA*)
Dr. Rafael Castro, Vice President, Polaris System Optimization (*Seattle, WA*)

Dr. Richard D. Tabors, President, Tabors Carmanis Rudkevich (*Boston, MA*)

Funded by ARPA-E under the Gas-Electric Co-Optimization (GECO) project, our team developed novel market designs to coordinate gas and electricity markets based on SCUC and SCED methods on the electric side, transient optimization of pipeline network on the natural gas side, and on the price based coordination of intra-day operation of these networks. The supporting algorithms and software are part of the GECO ENELYTIX modeling environment securely implemented within AWS cloud. GECO ENELYTIX is designed for scalable parallel execution of a large number of modeling scenarios partitioned into independently processed segment representing a scenario dynamics of two networks over a specific time interval. Each segment is processed by the Gas Electric Coordination (GECO) application, *GECO machine*. The GECO machine combines three principal modules – Power System Optimizer (*PSO*) provided by Polaris Systems Optimization, Gas System Optimizer (*GSO*) provided by Los Alamos National Laboratory and *Kordinator*, a coordination processor provided by Newton Energy Group as a part of ENELYTIX SaaS.
In this presentation, we summarize results of simulated coordinated operation of real electric and natural gas networks under different scenarios.

Session W3-A (Wednesday, June 26, 2:00 PM, Meeting Room 3M-2)

LEARNING TO SOLVE LARGE-SCALE SECURITY-CONSTRAINED UNIT COMMITMENT PROBLEMS

Dr. Feng Qiu, Principal Computational Scientist, Argonne National Laboratory (*Lemont, IL*)
Dr. Alinson Santos Xavier, Postdoctoral Appointee, Argonne National Laboratory (*Lemont, IL*)
Dr. Shabbir Ahmed, Professor, Georgia Institute of Technology (*Atlanta, GA*)

Security-Constrained Unit Commitment (SCUC) is a fundamental problem in power systems and electricity markets. In practical settings, SCUC is repeatedly solved via Mixed-Integer Linear Programming, sometimes multiple times per day, with only minor changes in input data. In this work, we propose a number of machine learning (ML) techniques to effectively extract information from previously solved instances in order to significantly improve the computational performance of MIP solvers when solving similar instances in the future. Based on statistical data, we predict redundant constraints in the formulation, good initial feasible solutions and affine subspaces where the optimal solution is likely to lie, leading to significant reduction in problem size. Computational results on a diverse set of realistic and large-scale instances show that, using the proposed techniques, SCUC can be solved on average 12 times faster than conventional methods, with no negative impact on solution quality.

A DECOMPOSITION AND COORDINATION APPROACH FOR UNIT COMMITMENT WITH SEQUENTIAL AND PARALLEL IMPLEMENTATIONS

Mr. Niranjan Raghunathan, Research Assistant, University of Connecticut (*West Hartford, CT*)
Dr. Mikhail Bragin, Assistant Research Professor, University of Connecticut (*Storrs, CT*)
Dr. Bing Yan, Assistant Research Professor, University of Connecticut (*Storrs, CT*)
Dr. Peter Luh, Professor, University of Connecticut (*Storrs, CT*)
Dr. Khosrow Moslehi, Director of Product Management, ABB (*San Jose, CA*)
Dr. Chien-Ning Yu, Senior Principal Technical Consultant, ABB (*San Jose, CA*)
Dr. Chia-Chun Tsai, Senior Software Engineer, ABB (*San Jose, CA*)
Dr. Yaowen Yu, Senior Application Engineer, ABB (*San Jose, CA*)
Dr. Xiaoming Feng, Corporate Research Fellow, ABB (*Raleigh-Durham, NC*)

The unit commitment problem with system- and area-level constraints is considered and formulated as a mixed-integer linear programming problem. To overcome the exponential growth of complexity as the problem size increases, it is solved within the Surrogate Absolute Value Lagrangian Relaxation (SAVLR) framework. This approach overcomes convergence issues of traditional Lagrangian relaxation methods. System demand constraints are relaxed and penalized by using absolute value functions to accelerate convergence. Transmission capacity and system reserve violations are handled through predetermined penalties without relaxation to avoid too many multipliers. The relaxed problem is decomposed into area-level sub-problems by fixing decision variables of other areas, and each sub-problem is solved by using Branch-and-Cut (B&C). The combination of SAVLR with B&C is shown to obtain near-optimal solutions in a computationally efficient manner for a sizeable test system. Parallel implementation of the method is also developed to speed up computations via parallel sub-problem solving by using B&C, and sub-problem model/data is loaded in a more efficient way. Parallelization of SAVLR presents challenges because slack variables associated with system-level constraints do not belong to any sub-problems. To avoid infeasibility, all slack variables are optimized in all sub-problems. Initial testing results demonstrate potential computational benefits. Parallel algorithm implementation is ongoing.

HIPPO: A CONCURRENT OPTIMIZER FOR SOLVING DAY-AHEAD SECURITY CONSTRAINED UNIT COMMITMENT PROBLEM

Dr. Feng Pan, Computer Scientist, Pacific Northwest National Laboratory (*Richland, WA*)
Dr. Yonghong Chen, Consulting Advisor, Midcontinent ISO (*Carmel, IN*)
Dr. Jesse Holzer, Mathematician, Pacific Northwest National Laboratory (*Richland, WA*)

HIPPO is an ARPA-E funded project aiming to develop efficient algorithmic techniques to solve security constrained unit commitment (SCUC). Over the last two years, the team developed a suit of enhanced models and distributed algorithms with multithread and high-performance computing cluster support. The core of the HIPPO software is a concurrent optimizer which orchestrate execution and communication among individual algorithms. The concurrent optimizer was validated with GE SCUC solver on MISO's market cases. In this talk, we will introduce the HIPPO software and the underlying solution approaches and present its performance on a set of MISO market cases.

A GPU-BASED CONTINGENCY ANALYSIS TOOL

Dr. Evgeniy Goldis, Chief Technology Officer, Newton Energy Group LLC (*Boston, MA*)
Dr. Andrei Kharchenko, Researcher, University of Georgia (*Athens, GA*)
Dr. Aleksandr Rudkevich, President, Newton Energy Group LLC (*Boston, MA*)
Dr. Yonghong Chen, Consulting Advisor for Market R&D, Midcontinent ISO (*Carmel, IN*)
Dr. Fengyu Wang, Market Engineer, Midcontinent ISO (*Carmel, IN*)
Ms. Jessica Harrison, Director of Research and Development, Midcontinent ISO (*Carmel, IN*)

Partially funded by the Midcontinent Independent System Operator, our team developed a GPU-based Contingency Analysis application with the goal of improving the turn-around-time of Day-Ahead market clearing processes and production cost simulations.

Contingency Analysis (CA) evaluates potential events on the electric grid to ensure the reliable system operations. Because most of the potential events will never occur, CA is run iteratively with SCUC and SCED algorithms. Even with this iterative process, however, CA can become a bottleneck and, often, only a subset of all contingency constraints are included.

GPU cards provide an array of independent multi-processors that can be used to massively parallelize linear algebra operations via the graphics pipeline, independent of the central processor (CPU). Leveraging this technology our team developed a linearized, DC-based contingency analysis tool capable of analyzing tens of millions of contingency constraints within a single iteration of SCUC/SCED and CA.

In this presentation, we summarize performance statistics for GPU-based Contingency Analysis under various scenarios and compare the performance to traditional CPU-based algorithms

Session W3-B (Wednesday, June 26, 2:00 PM, Meeting Room 3M-4)

QUANTIFYING THE AMOUNT OF INSTALLED FLEXIBILITY IN THE RESOURCE FLEET: CASE STUDY ON CAISO

Dr. Erik Ela, Principal, Electric Power Research Insitute (*Palo Alto, CA*)
Dr. Qin Wang, Senior Engineer/Scientist, Electric Power Research Insitute (*Palo Alto, CA*)
Mr. Clyde Loutan, Principal for Renewable Energy Integration, California ISO (*Folsom, CA*)
Dr. Eamonn Lannoye, Senior Project Manager, Electric Power Research Institute (*Dublin, Ireland*)
Dr. Karl Meeusen, Senior Advisor for Infrastructure and Regulatory Policy, California ISO (*Folsom, CA*)
Dr. Mark Rothleder, VP of Market Quality and Renewable Integration, California ISO (*Folsom, CA*)

The California Independent System Operator has some of the largest variable renewable resource penetrations nationwide and in the world. As a result, the resource fleet needs to be able to modify output to meet the increased system variability introduced by variable renewable resources. This study examined the existing and anticipated flexibility needs and flexibility available from the resource fleet within CAISO. To do so, the study evaluated the quantity of feasible flexible capacity using a new technique that measured the maximum installed flexibility (IFLEX) given temporal constraints. This was compared to the existing methods (such as effective flexible capacity (EFC)) to show what challenges the system may face in the future for flexible capacity needs. The IFLEX method shows the maximum amount of flexibility installed, analogous to installed capacity (and different from flexible ramping). While IFLEX is assessed such that it is independent of operating policies, it is actually dependent on conditions. Thus, unlike ICAP, it is a function of time. The presentation will show key findings of the study and several sensitivities and show how the method could be applied in other regions.

EXTENDING ISO OPERATIONAL SOFTWARE TO LONG-TERM PRODUCTION COST MODELS

Mr. James David, Product Manager, PowerGEM LLC (*Clifton Park, NY*)
Mr. Boris Gisin, President, PowerGEM LLC (*Clifton Park, NY*)
Mr. Qun Gu, Principal Consultant, PowerGEM LLC (*Clifton Park, NY*)
Mr. Brian Thomas, Lead Consultant, PowerGEM LLC (*Clifton Park, NY*)

Long-term production cost modeling (PCM) software traditionally utilizes different underlying models than ISO day-ahead and real-time software, due to data availability, solution time horizons, software modeling details, vendor-specific approaches, and other factors. While long term PCM tools share similar objective functions and high-level solution methodologies as shorter-term software, they often contain many simplifications. As markets evolve and new types of resources are introduced at a rapid pace, planners and developers are required to model these resources in PCM models that are increasingly disconnected from short-term markets and operations, and therefore risk producing results that will not work upon actual implementation. Also, there is a growing need for mid-term (one-month to one-year ahead) simulation functionality that is closely aligned with ISO market rules. Over the past ten years, PowerGEM has extended the high-performance PROBE day-ahead and real-time market software - developed for ISOs - to PCM applications. This presentation will discuss the benefits of this approach compared to traditional PCM products, the computational advances that enable handing more constraints including transmission and ancillary services, advanced modeling of energy storage resources, and additional modeling elements implemented to better align long-term PCM study capabilities with the challenges of evolving markets.

TOWARD A RESILIENCE-FOCUSED PRODUCTION COST MODELING CAPABILITY

Dr. Jean-Paul Watson, Distinguished Member of Technical Staff, Sandia National Laboratories (*Albuquerque, NM*)
Ms. Jessica Lau, Senior Technical Project Manager, National Renewable Energy Laboratory (*Golden, CA*)

> Standard production cost models (PCMs) simulate power systems operations over extended time horizons. Traditional PCMs focus on analyzing reliability and economics of future planning scenarios. Such reliability and supporting economic analyses explicitly focus on high-probability, low-consequence power system failure events. Resilience to extreme events - low-probability, but with high consequence - is explicitly not considered by standard PCMs. Despite this lack of capability, standard PCMs can effectively serve as the basis for development of a resilience PCM - which we describe subsequently. The key observation underlying development of a resilience PCM is as follows: any power system operations simulation will involve a common set of models - including commitment, dispatch, and power flow - that capture critical operational constraints and behaviors. Given a common set of models, different operational objectives can be captured and analyzed. A resilience PCM provides three key capabilities above and beyond what is available in a standard PCM. The introduction of these three capabilities is necessary to express and analyze power system resilience, as opposed to reliability. These three capabilities are: threat models, restoration and recovery models, and resilience metrics. This talk will present on-going efforts to develop an open source and scalable resilience PCM.

ROBUST SOLUTION OF HIGH RENEWABLE PENETRATION PLANNING CASES IN PS-SUGAR

Dr. David Bromberg, CEO, Pearl Street Technologies (*Pittsburgh, PA*)
Dr. Amritanshu Pandey, Senior Research Scientist, Pearl Street Technologies (*Pittsburgh, PA*)
Dr. Hui Zheng, Co-founder, Pearl Street Technologies (*Pittsburgh, PA*)
Dr. Yifan Li, Policy Studies Engineer, Midcontinent ISO (*Carmel, IN*)

> Planning for a future grid with high penetration of renewables at the transmission- and distribution-levels is a challenging problem with high uncertainty. As large amounts of renewables are deployed, older plants decommissioned, and loads adjusted, planning engineers are tasked with simulating future grid scenarios where the operating points are inevitably far away from the current grid state. Solving a planning scenario such as

this by locating and resolving area real and reactive power deficiencies can be time-consuming, as standard planning software is ill-suited to simulating massive changes throughout the system - especially those resulting in an infeasible grid state. In this presentation, we will describe a case study using new grid planning software, Pearl Street's Suite of Unified Grid Analyses and Renewables (PS-SUGAR). PS-SUGAR takes a highly-modified, infeasible model of a future grid that is unsolvable in other tools, automatically identifies infeasible areas in the system, and re-dispatches user-specified resources to create a solved, feasible planning model. We will describe the solution engine and technology that drives the tool and present results for real transmission system models, demonstrating PS-SUGAR's ability to solve planning cases in minutes that might otherwise take weeks of an engineer's manual effort to solve.

Thursday, June 27

Session H1-A (Thursday, June 27, 9:00 AM, Meeting Room 3M-2)

GRIDPACK - AN HPC PLATFORM FOR BETTER GRID EFFICIENCY AND RESILIENCE

Mr. Yousu Chen, Electrical Engineer, Pacific Northwest National Laboratory (*Richland, WA*)
Dr. Bruce Palmer, Scientist, Pacific Northwest National Laboratory (*Richland, WA*)
Dr. Zhenyu Huang, Lab Fellow, Pacific Northwest National Laboratory (*Richland, WA*)

This presentation introduces GridPACK (Parallel Advanced Computing Kernels for Power Grid), an open source platform for developing power grid applications designed to run on high performance computing architectures. The GridPACK framework provides strong support for a wide variety of solvers and parallel linear algebra that can be tailored for different simulation problems, with a low threshold for HPC development. The framework can be used to develop new power grid applications with prebuilt modules. Multiple case studies will be discussed to show that GridPACK can significantly increase computational speed for applications such as transient analysis, contingency analysis, dynamic security assessment, and real-time path rating. Improved computational performance can enable larger and more comprehensive calculations that can improve grid efficiency and resilience.

GRID MIND: DATA-DRIVEN AUTONOMOUS GRID DISPATCH AND CONTROL BASED ON AI

Dr. Di Shi, Department Head, GEIRINA (*San Jose, CA*)
Mr. Zhiwei Wang, President, GEIRINA (*San Jose, CA*)

Power systems are facing grand challenges from increasing dynamics and stochastics from both the generation and the demand sides. This has caused great difficulty in designing and implementing optimal control in real time. Tremendous efforts have been spent in the past on computational methods and advanced modeling techniques that provide faster and better situational awareness, based on measurements from advanced grid sensors, PMU as an example. However, as grid operators are heavily involved in the decision-making procedure, the entire process has not been made fully automated, limiting the potential of such applications. That is, not only does the grid need to perceive faster, it also needs to think and act faster. Towards this end, sub-second autonomous control schemes need to be developed. The recent announcement made by US DOE on Sept. 25 regarding investment in developing AI based sub-second controller using PMU measurements confirms and consolidates this strong need. Over the past year, the PMU & System Analytics Group at GEIRI North America has built up an autonomous grid controller using deep reinforcement learning, the Grid Mind. Combined with Grid Eye, the grid monitoring and situational awareness platform, Grid Mind has demonstrated promise in helping address the pressing issues modern power systems faces and boost the grid resilience. This talk will summarize the major AI technology used in the Grid Mind framework.

PERIOD OPTIMAL POWER FLOW MODEL IN POWER SYSTEMS WITH HIGH PENETRATION OF INTERMITTENT POWER SOURCES

Dr. Zongjie Wang, Postdoctoral Associate, Cornell University (*Ithaca, NY*)
Dr. Lindsay Anderson, Associate Professor, Cornell University (*Ithaca, NY*)

Traditional optimal power flow (OPF) optimizes the system performance only in a single snapshot while applying the result to a certain time period. Therefore, how well the selected snapshot can represent such a time period is crucial for the effectiveness of OPF. We first propose period OPF over a time period that partitioned into consecutive linear time intervals, in which power injections are modeled and as a result, node voltages are proved as linear mapping of time. The optimality and operational limits in each time interval are respectively represented by its median and two end snapshots. Thus the overall system performance with the OPF application in a time period is significantly improved. From the perspective of power balancing, we also consider real-time dispatch timescale in power systems with high penetration of intermittent power sources (IPSs). AGC is the last-level defense of the system-wide power balancing, which has limited power adjustment capability. Hence real-time dispatch must eliminate as much power imbalance as possible, and its capability of doing so depends on its timescale. Based on the statistical forecast uncertainty functions, a theoretical formula between the uncertainty level of the power system and the critical timescale for real-time dispatch is proposed. By applying period OPF into real-time dispatch timescale, simulations on a modified IEEE 118-bus system have demonstrated the simplicity and effectiveness of the proposed model and formula.

Session H1-B (Thursday, June 27, 9:00 AM, Meeting Room 3M-3)

SCENARIO GENERATION FOR TWO-STAGE STOCHASTIC ECONOMIC DISPATCH

Dr. Ignas Satkauskas, Posdoctoral Researcher, National Renewable Energy Laboratory (*Boulder, CO*)
Matthew Reynolds, Researcher, National Renewable Energy Laboratory (*Golden, CO*)
Devon Sigler, Researcher, National Renewable Energy Laboratory (*Golden, CO*)
Jonathan Maack, Postdoctoral Researcher, National Renewable Energy Laboratory (*Golden, CO*)
Wesley Jones, Senior Scientist, National Renewable Energy Laboratory (*Golden, CO*)

Stochastic models of power grid operations are important elements in the development of economic dispatch models under the presence of high penetrations of renewable energy, e.g. wind and solar. The need for stochastic modelling is induced by the presence of uncertainty in energy generation. While this uncertainty is currently addressed using reserves, such an approach will need review as the amounts energy generation that is uncertain grows: it is inefficient to maintain large quantities of excess generation which are not guided by spatiotemporal data. In this talk, we review the two-stage stochastic programming approach used to solve a 5-minute economic dispatch problem under short term wind uncertainty. We introduce a method of uncertainty scenario generation that uses data obtained from high-fidelity numerical weather prediction simulation, and hence, produces scenarios that preserve system physics and spatiotemporal dynamics. Finally, we compare the results of numerical experiments performed on synthetic test grids using standard Monte Carlo and novel importance sampling approaches.

A SCALABLE MIXED-INTEGER DECOMPOSITION APPROACH FOR OPTIMAL BLACK-START AND RESTORATION OF POWER SYSTEMS

Dr. Ignacio Aravena, Postdoctoral Researcher, Lawrence Livermore National Laboratory (*Livermore, CA*)
Dr. Amelia Musselman, Postdoctoral Researcher, Lawrence Livermore National Laboratory (*Livermore, CA*)
Mr. Georgios Patsakis, Ph.D. Student, UC Berkeley (*Berkeley, CA*)
Dr. Deepak Rajan, Adjunct Professor, UC Berkeley (*Berkeley, CA*)
Dr. Shmuel Oren, Professor, UC Berkeley (*Berkeley, CA*)

We present a scalable decomposition algorithm, based on the integer L-shaped method, for solving the optimal black-start and restoration problem for realistic power systems. The algorithm partitions the problem into master and slave problems. The master problem optimizes energization sequences of generators, buses, and branches, for the entire restoration horizon, while respecting stylized energization requirements. The slave problem verifies that there exist power flow solutions supporting the energization sequences proposed by the master problem, adding cuts to the master problem if the power flow problem is determined to be infeasible for a given energization sequence. The power flow verification is carried out using a piece-wise linear approximation of the power flow equations that is capable of capturing overvoltage situations common in restoration procedures. We develop strengthening inequalities, specialized binary cuts, and hybrid Benders-binary cuts for separating infeasible islands, as well as heuristics for obtaining feasible solutions. We present numerical results for the IEEE 39- and 118-bus systems, the Chilean 1500-bus grid, and the PG&E 1800-bus grid, as well as preliminary results for these same systems but with additional security considerations for restoration after cyber-attacks.

SCALABLE PREVENTIVE UNIT COMMITMENT FOR OPERATION DURING EXTREME WEATHER

Dr. Mostafa Sahraei-Ardakani, Assistant Professor, University of Utah (*Salt Lake City, UT*)
Mr. Farshad Mohammadi, Ph.D. Candidate, University of Utah (*Salt Lake City, UT*)
Ge Ou, Assistant Professor, University of Utah (*Salt Lake City, UT*)
Zhaoxia Pu, Professor, University of Utah (*Salt Lake City, UT*)

Extreme weather is the primary cause of power outages in the United States. Although weather forecast data is available to the system operators, there is no existing software tool for preventive power system operation during extreme weather. This is due to a variety of challenges, including the computational burden associated with handling weather forecast data and stochastic unit commitment. This talk presents a scalable modeling approach to solve the preventive unit commitment problem for large-scale networks. The model takes advantage of high-resolution weather forecast data, fast and accurate transmission fragility analysis, and a computationally-efficient stochastic unit commitment solver. The results show that our model can effectively solve the problem within an acceptable time and significantly reduce the power outages, through finding a preventive commitment.

Session H2 (Thursday, June 27, 10:45 AM, Meeting Room 3M-3)

THE ARPA-E GRID OPTIMIZATION (GO) COMPETITION: CHALLENGE 1 AND BEYOND

Dr. Kory Hedman, Program Director, US Department of Energy, ARPA-E (*Tempe, AZ*)
Dr. David Guarrera, Director of Analytics and Founding Partner, Quantitative Scientific Solutions LLC (*Washington, DC*)
Dr. Ashley Arigoni, Lead Scientist, Quantitative Scientific Solutions LLC (*Denver, CO*)
Dr. Ray Duthu, Lead Scientist, Quantitative Scientific Solutions LLC (*Washington, DC*)

This presentation will discuss the ongoing ARPA-E GO (Grid Optimization) Competition.

On October 31, 2018, the US Department of Energy Advanced Research Projects Agency-Energy (ARPA-E) launched Challenge 1 of the GO Competition. The GO Competition will be a series of challenges, with prize money, focused on complex problems within the electric power sector. If successful, the GO Competition will accelerate the development of transformational and disruptive methods for solving problems related to the electric power grid by providing a transparent, fair, and comprehensive evaluation of new solution methods. The GO Competition is aimed at overhauling and modernizing grid management systems and decision support software tools.

Challenge 1 of the GO Competition focuses on security-constrained optimal power flow (SCOPF), a non-convex mixed integer programming problem. The winners of Challenge 1 will be announced in the Fall of 2019. Challenge 2, which is an extension of Challenge 1, will focus on a more complex SCOPF problem; Challenge 2 will introduce advanced modeling of post-contingency corrective response and will include more detailed modeling approaches for transmission devices and power flow control technologies. Future challenges are expected to focus on stochastic optimization to manage stochastic resources (intermittent bulk renewables and distributed energy resources), grid resilience, and potentially cyber-security challenges.

PERFORMANCE-BASED ENERGY RESOURCE FEEDBACK, OPTIMIZATION, AND RISK MANAGEMENT: PERFORM

Dr. Kory Hedman, Program Director, US Department of Energy, ARPA-E (*Tempe, AZ*)
Dr. Joseph King, Program Director, US Department of Energy, ARPA-E (*Washington, AZ*)
Dr. Ashley Arigoni, Lead Scientist, Quantitative Scientific Solutions LLC (*Denver, CO*)
Dr. David Guarrera, Director of Analytics and Founding Partner, Quantitative Scientific Solutions LLC (*Washington, DC*)
Dr. Ray Duthu, Lead Scientist, Quantitative Scientific Solutions LLC (*Washington, DC*)
Dr. Mirjana Marden, Power System Research Engineer, US Department of Energy, ARPA-E (*Washington, DC*)

Emerging resources (wind, solar, and distributed energy resources) pose new challenges to grid planning and operations, challenges not acknowledged by antiquated grid management systems that were designed around conventional generation technologies. New management systems and decision support tools need to capture uncertainty and account for the correlation of stochastic resources. The PERFORM program aims to shift the operations and planning to a risk-driven paradigm. This shift would lead to a more accurate value proposition of emerging technologies. This program will provide grid operators a transparent quantification of their system position and overall risk exposure, which does not exist today. The PERFORM program goals are to: 1) balance the tradeoff between minimizing costs versus delivery risk while providing the foundation for an incentive compatible environment that efficiently mitigates risk; 2) design planning and operational practices built upon risk management and performance evaluation of all players in the electric power sector, from behind the meter to bulk resources; 3) develop transparent risk assessment methodologies that are well understood and widely adopted; 4) leverage finance, actuarial science, and operations research approaches to quantify risk, mitigate risk, and achieve a risk-driven resource value proposition based on portfolio management; and 5) translate financial and actuarial concepts to grid resource performance metrics.

HELICS: CO-SIMULATION FOR BETTER GRID EFFICIENCY AND RESILIENCE

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The accelerated adoption of distributed energy resources (DERs) - solar, wind, electric vehicles, energy storage and intelligent loads - coupled with the uncertainties of some of these resources, is creating profound challenges for bulk power system efficiency and resilience. Furthermore, market reforms are redefining the rules and roles of transmission operators, distribution utilities and consumers. Data communications play a more critical role than ever in power grid control and management, posing unprecedented cyber risks. Such complex challenges require an analytical platform that supports the simulation and assessment of interdependency in the grid holistically and at scale, across transmission and distribution systems, including its interactions with ubiquitous data communication systems. HELICS is such a platform built on co-simulation concepts, with open-source software principles, modular design and standardized interfacing techniques for easy adoption. As a result of efforts by multiple DOE National Labs, open-source HELICS software is now available at https://www.github.com/GMLC-TDC/HELICS-src for users to download and apply to their interdependency studies and applications. This talk will present the design of HELICS and demonstrate it with selected use cases. With thousands of downloads so far and users at leading smart grid sites, HELICS is a highly innovative and accessible software package for building a more efficient and resilient future power grid.