Resilient Autonomous Energy Systems

NREL Workshop, Golden, CO (virtual)
September 8-9, 2021
*Agenda (**all times are in Mountain Time**)*

Wednesday, September 8

Introduction

8:15 – 8:20 am: Workshop Welcome and Agenda - **Andrey Bernstein, NREL**
8:20 – 8:30 am: Word from NREL's Director - **Martin Keller, NREL**

Distributed, event-triggered optimization and control (moderator: Guido Cavraro)

8:30 – 9:05: *Approximating Feasible Power Injection Regions of Radial AC Networks*
Changhong Zhao, The Chinese University of Hong Kong

9:05 – 9:40: *A Feedback-Optimization Approach to Resilient Power System Operation*
Saverio Bolognani, ETH Zurich

9:40 – 10:15: *Online Stochastic Optimization of Unknown Linear Systems: Data-Driven Controller Synthesis and Applications to Energy Systems*
Emiliano Dall'Anese, University of Colorado Boulder

10:15 – 10:30: Break

10:30 – 11:05: *Resource-Aware Network Optimization in Autonomous Energy Grids*
Jorge Cortes, University of California San Diego

11:05 – 11:40: *Emergency Voltage Regulation in Power Systems via Ripple-Type Control*
Guido Cavraro, NREL

11:40 – 12:00: Discussion

12:00 – 13:00: Break

Robust and chance-constrained optimization (moderator: Xinyang Zhou)

13:00 – 13:35: *Network-Cognizant Time-Coupled Aggregate Flexibility of Distribution Systems Under Uncertainties*
Bai Cui, NREL

13:35 – 14:10: *Stochastic Hybrid Approximation for Uncertainty Management in Gas-Electric Systems*
Line Roald, University of Wisconsin-Madison

14:10 – 14:45: *Impact of Market Timing on the Profit of a Risk-Averse Load Aggregator*
Johanna Mathieu, University of Michigan

14:45 – 15:00: Break

15:00 – 15:35: *Distributionally Robust Bootstrap Optimization*

Tyler Summers, University of Texas at Dallas

15:35 – 16:10: *Robust AC Optimal Power Flow with Robust Convex Restriction*

Daniel Molzahn, Georgia Tech

16:10 – 16:30: Discussion and closing remarks

Thursday, September 9

Introduction

8:25 – 8:30 am: Workshop Welcome and Agenda - **Andrey Bernstein, NREL**

Data-driven optimization and control (moderator: Ahmed Zamzam)

8:30 – 9:05: *Formulas for data-driven control*

Claudio De Persis, University of Groningen

9:05 – 9:40: Learning-Based Actuator Placement and Receding Horizon Control for Security against Actuation Attacks

Kyriakos Vamvoudakis, Georgia Tech

9:40 – 10:15: *Curriculum-based Reinforcement Learning for Distribution System Critical Load Restoration*

Xiangyu Zhang, NREL

10:15 – 10:30: Break

10:30 – 11:05: *Convergence and sample complexity of gradient methods for the model-free linear quadratic regulator problem*

Mihailo Jovanovic, University of Southern California

11:05 – 11:40: *Safe and Efficient Reinforcement Learning for Frequency Control*

Baosen Zhang, University of Washington

11:40 – 12:00: Discussion

12:00 – 13:00: Break

Solvability and stability of non-linear systems (moderator: Bai Cui)

13:00 – 13:35: *Next-generation grid frequency and voltage control using fast inverter-based resources*

John Simpson-Porco, University of Toronto

13:35 – 14:10: *Recent advances in small signal stability in power grids: New certificate, impact of damping, and Braess's Paradox*

Andy Sun, Georgia Tech

14:10 – 14:45: *Co-optimization of Distribution Network and DER Operations to Enhance Grid Resilience*

Fei Ding, NREL

14:45 – 15:00: Break

15:00 – 15:35: *Coherence and Concentration in Tightly Connected Networks*

Enrique Mallada, Johns Hopkins University

15:35 – 16:10: *Rethinking grid-forming control: a universal control paradigm for resilient converter-dominated power systems*

Dominic Gros, University of Wisconsin-Madison

16:10 – 16:30: Discussion and closing remarks

Speaker: Saverio Bolognani

Title: A Feedback-Optimization Approach to Resilient Power System Operation

Abstract: With the increase in solar and wind generation, the electric power system is going through an unprecedented transformation which render today's real-time control architecture ineffective. This calls for more elaborated control strategies for voltage regulation, line congestion control, and power curtailment. On the other hand, these distributed energy resources offer additional and unprecedented flexibility to counteract disturbances and make the grid more resilient. We propose a control design procedure that turns iterative optimization algorithms into output-feedback controllers. These controllers can naturally deal with plant constraints and are proven to be robust against model mismatch, both in theory and in experiments. We will show how these controllers can operate a power system very efficiently in normal operations, but also react quickly to disturbances and quickly restore safe operation.
In this workshop, we will present the theoretical foundation of this framework and present the results of a three-year collaboration with the French transmission grid operator, including numerical simulations on a real part of the French subtransmission grid.

Bio: Saverio Bolognani received the B.S. degree in Information Engineering, the M.S. degree in Automation Engineering, and the Ph.D. degree in Information Engineering from the University of Padova, Italy, in 2005, 2007, and 2011, respectively. In 2006-2007, he was a visiting graduate student at the University of California at San Diego. In 2013-2014 he was a Postdoctoral Associate at the Laboratory for Information and Decision Systems of the Massachusetts Institute of Technology in Cambridge (MA). He is currently a Senior Researcher at the Automatic Control Laboratory at ETH Zurich. His research interests include the application of networked control system theory to power systems, distributed control and optimization, and cyber-physical systems.

Speaker: Emiliano Dall'Anese

Title: Online Stochastic Optimization of Unknown Linear Systems: Data-Driven Controller Synthesis and Applications to Energy Systems

Abstract: This talk presents a data-driven control framework to steer an unknown, stochastic linear system towards the solution of a (stochastic) convex optimization problem. Despite the centrality of this problem in many modern engineering and scientific applications, most available methods critically rely on a precise knowledge of the system dynamics. We show that the transfer function of a linear system can be computed from control experiments without knowledge or estimation of the system model. Inspired by stochastic gradient descent methods, we then leverage this data-driven representation to design a controller that drives the system to the solution of a stochastic convex optimization problem (embedding performance metrics) without requiring any knowledge of the time-varying disturbance (and its probability distribution) affecting the model equation. Our technical analysis combines concepts and tools from behavioral theory, stochastic optimization with decision-dependent distributions, and stability of stochastic systems.

Bio: Emiliano Dall'Anese is an Assistant Professor in the Department of Electrical, Computer, and Energy Engineering at the University of Colorado Boulder, and an affiliate Faculty with the Department of Applied Mathematics. He received the Ph.D. in Information Engineering from the Department of Information Engineering, University of Padova, Italy, in 2011. From January 2011 to November 2014, he was a Postdoctoral Associate at the Department of Electrical and Computer Engineering of the University of Minnesota, and from December 2014 to July 2018 he was a Senior Researcher at the National Renewable Energy Laboratory. He received the National Science Foundation CAREER Award in 2020, and the IEEE PES Prize Paper Award in 2021.

Speaker: Jorge Cortes

Title: A Feedback-Optimization Approach to Resilient Power System Operation

Abstract: Trading computation and decision making for less communication, sensing, or actuator effort offers great promise for the autonomous operation of both individual and interconnected cyber physical systems. Resource-aware control seeks to prescribe, in a principled way, when to use the available resources efficiently while still guaranteeing a desired quality of service in performing the intended task. This talk describes our progress in the synthesis of decentralized resource-aware coordination mechanisms to solve network optimization problems defined by objective functions which combine locally evaluable costs with network-wide coupling components. Such problems arise in numerous examples of autonomous energy grids, including virtual power plants and heating, ventilation, and air conditioning systems in intelligent buildings. Our proposed coordination mechanisms are feedback-based, anytime, and asynchronous by design, and ensure the asymptotic convergence of the network to the desired optimizer. This is joint work with Priyank Srivastava and Guido Cavraro.

Bio: Jorge Cortes is Professor and Cymer Corporation Endowed Chair at the Department of Mechanical and Aerospace Engineering at the University of California, San Diego. He received the Licenciatura degree in mathematics from the Universidad de Zaragoza, Spain, in 1997, and the Ph.D. degree in engineering mathematics from the Universidad Carlos III de Madrid, Spain, in 2001. He held postdoctoral positions at the University of Twente, The Netherlands, and at the University of Illinois at Urbana-Champaign, USA. He was an Assistant Professor with the Department of Applied Mathematics and Statistics at the University of California, Santa Cruz from 2004 to 2007. He is the author of "Geometric, Control and Numerical Aspects of Nonholonomic Systems" (New York: Springer-Verlag, 2002) and co-author of "Distributed Control of Robotic Networks" (Princeton: Princeton University Press, 2009). His current research interests include distributed control and optimization, network science and complex systems, resource-aware control and coordination, distributed decision making and autonomy, and multi-agent coordination in robotics, transportation, power systems, and neuroscience.
url: http://carmenere.ucsd.edu/jorge

Speaker: Claudio De Persis
Title: Formulas for data-driven control

Abstract: We have recently introduced some methods to design controllers using finite-length data collected from dynamical systems excited by persistently exciting inputs. The design is based on the solution of formulas expressed via data-dependent Linear Matrix Inequalities and Sum-of-Squares programs. The methods provide formal guarantees on the correctness and robustness of the controllers. The talk will present some of these results.

Bio: Claudio De Persis received the Laurea degree in electronic engineering in 1996 and the Ph.D. degree in system engineering in 2000 both from the University of Rome “La Sapienza,” Rome, Italy. Since 2011 he has been a Professor with the Engineering and Technology Institute, University of Groningen, Netherlands. Previously, he held faculty positions with the Department of Mechanical Automation and Mechatronics, University of Twente, Netherlands (2009-2011) and the Department of Computer, Control, and Management Engineering, University of Rome “La Sapienza” (2002-2009). He was a Research Associate with the Department of Systems Science and Mathematics, Washington University, St. Louis, MO, (2000–2001), and with the Department of Electrical Engineering, Yale University, New Haven, CT (2001–2002). His main research interest focuses on automatic control and its applications.

Speaker: Kyriakos Vamvoudakis
Title: Learning-Based Actuator Placement and Receding Horizon Control for Security against Actuation Attacks

Abstract: Cyber-physical systems (CPS) comprise interacting digital, analog, physical, and human components engineered for function through integrated physics and logic. Incorporating intelligence in CPS, however, makes their physical components more exposed to adversaries that can potentially cause failure or malfunction through actuation attacks. As a result, augmenting CPS with resilient control and design methods is of grave significance, especially if an actuation attack is stealthy. Towards this end, in the first part of the talk, I will present a receding horizon controller, which can deal with undetectable actuation attacks by solving a game in a moving horizon fashion. In fact, this controller can guarantee stability of the equilibrium point of the CPS, even if the attackers have an information advantage. The case where the attackers are not aware of the decision-making mechanism of one another is also considered, by exploiting the theory of bounded rationality. In the second part of the talk, and for CPS that have partially unknown dynamics, I will present an online actuator placement algorithm, which chooses the actuators of the CPS that maximize an attack security metric. It can be proved that the maximizing set of actuators is found in finite time, despite the CPS having uncertain dynamics.

Bio: Kyriakos G. Vamvoudakis was born in Athens, Greece. He received the Diploma (a 5 year degree, equivalent to a Master of Science) in Electronic and Computer Engineering from the Technical University of Crete, Greece in 2006 with highest honors. After moving to the United States of America, he studied at The University of Texas and he received his

M.S. and Ph.D. in Electrical Engineering in 2008 and 2011 respectively. From May 2011 to January 2012, he was working as an Adjunct Professor and Faculty Research Associate at the University of Texas at Arlington and at the Automation and Robotics Research Institute. During the period from 2012 to 2016 he was a project research scientist at the Center for Control, Dynamical Systems and Computation at the University of California, Santa Barbara. He was an assistant professor at the Kevin T. Crofton Department of Aerospace and Ocean Engineering at Virginia Tech until 2018. He currently serves as an Assistant Professor at The Daniel Guggenheim School of Aerospace Engineering at Georgia Tech. He holds a secondary appointment in the School of Electrical and Computer Engineering. His research interests include approximate dynamic programming, game theory, cyber-physical security, networked control, smart grid, and safe autonomy.
Dr. Vamvoudakis is the recipient of a 2021 GT Chapter Sigma Xi Young Faculty Award, a 2019 ARO YIP award, a 2018 NSF CAREER award, and of several international awards including the 2016 International Neural Network Society Young Investigator (INNS) Award, and the Best Paper Award for Autonomous/Unmanned Vehicles at the 27th Army Science Conference in 2010. He has also served on various international program committees and has organized special sessions, workshops, and tutorials for several international conferences. He currently is a member of the IEEE Control Systems Society Conference Editorial Board, an Associate Editor of: Automatica; IEEE Computational Intelligence Magazine; IEEE Transactions on Systems, Man, and Cybernetics: Systems; IEEE Transactions on Artificial Intelligence; Neurocomputing; Journal of Optimization Theory and Applications; IEEE Control Systems Letters; and of Frontiers in Control Engineering-Adaptive, Robust and Fault Tolerant Control, a registered Electrical/Computer engineer (PE), and a member of the Technical Chamber of Greece.

Speaker: Mihailo Jovanovic

Title: Convergence and sample complexity of gradient methods for the model-free linear quadratic regulator problem

Abstract: Model-free reinforcement learning attempts to find an optimal control action for an unknown dynamical system by directly searching over the parameter space of controllers. The convergence behavior and statistical properties of these approaches are often poorly understood because of the nonconvex nature of the underlying optimization problems and the lack of exact gradient computation. In this talk, we discuss performance and efficiency of such methods by focusing on the standard infinite-horizon linear quadratic regulator problem for continuous-time systems with unknown state-space parameters. We establish exponential stability for the ordinary differential equation (ODE) that governs the gradient-flow dynamics over the set of stabilizing feedback gains and show that a similar result holds for the gradient descent method that arises from the forward Euler discretization of the corresponding ODE. We also provide theoretical bounds on the convergence rate and sample complexity of the random search method with two-point gradient estimates. We prove that the required simulation time for achieving ϵ-accuracy in the model-free setup and the total number of function evaluations both scale as $\log (1/\epsilon)$.

Bio: Mihailo R. Jovanovic is a professor in the Ming Hsieh Department of Electrical and Computer Engineering and the founding director of the Center for Systems and Control at the University of Southern California. He was a faculty member in the Department of Electrical and Computer Engineering at the University of Minnesota, Minneapolis, from December 2004 until January 2017, and has held visiting positions with Stanford University and the Institute for Mathematics and its Applications. His current research focuses on large-scale and distributed optimization, design of controller architectures, dynamics and control of fluid flows, and fundamental limitations in the control of large networks of dynamical systems. He had served as a Guest Editor (of the Special Issue on Analysis, Control and Optimization of Energy System Networks in the IEEE Transactions on Control of Network Systems), the Chair of the APS External Affairs Committee, a Program Vice-Chair of the 55th IEEE Conference on Decision and Control, an Associate Editor of the SIAM Journal on Control and Optimization, an Associate Editor of the IEEE Transactions on Control of Network Systems, and an Associate Editor of the IEEE Control Systems Society Conference Editorial Board. Prof. Jovanovic is a fellow of APS and IEEE. He received a CAREER Award from the National Science Foundation in 2007, the George S. Axelby Outstanding Paper Award from the IEEE Control Systems Society in 2013, and the Distinguished Alumnus Award from UC Santa Barbara in 2014.

Speaker: Baosen Zhang

Title: Safe and Efficient Reinforcement Learning for Frequency Control

Abstract: Inverter-based resources such as solar and storage provide us with more flexibility in the control of power systems. Through their power electronic interfaces, complex control functions can be implemented to quickly respond to changes in the system. Recently, reinforcement learning has emerged as a popular method to find these nonlinear

controllers. The key challenge with a learning-based approach is that stability and safety constraints are difficult to enforce on the learned controllers. Using a Lyapunov theory-based approach, we show how to explicitly engineer the structure of neural network controllers such that they guarantee system stability. The resulting controllers only use local information and outperform conventional droop as well as strategies learned purely by using reinforcement learning.

Bio: Baosen Zhang is the Keith & Nancy Rattie Endowed Career Development Professor in the Department of Electrical and Computer Engineering at the University of Washington. He received his undergraduate degree in engineering science from the University of Toronto in 2008; and the Ph.D. degree in Electrical Engineering and Computer Science from the University of California at Berkeley in 2013. Before joining UW, he was a postdoctoral scholar at Stanford University. He has received the NSF CAREER Award, as well as a number of best paper awards.

Speaker: John Simpson-Porco

Title: Next-Generation Grid Frequency and Voltage Control using Fast Inverter-Based Resources

Abstract: The ongoing deployment of DERs is changing the way the grid is operated and controlled; classical power system control architectures are presently being re-examined and revised to meet new challenges and objectives. With the goal of improving system reliability and security, we focus here on how fast inverter-based resources (IBRs) and hierarchical/distributed control loops can be leveraged to mitigate frequency and voltage events in the bulk grid. The frequency and voltage control strategies we describe are high-bandwidth feedback controllers, which operate based only on local measurements and local model information available within small local control areas (LCAs) of the bulk grid; both controllers can be retrofit onto existing grid control systems. The frequency controller dynamically estimates the local power imbalance within the LCA, and quickly re-dispatches local IBRs to correct the imbalance. When sufficient active power is unavailable locally, additional power is sourced from IBRs in adjacent LCAs. The voltage controller instead optimally coordinates traditional voltage control devices (synchronous machines, SVCs) with IBRs to maintain bus voltages and device reactive powers within specified design limits. Extensive simulation results illustrate that the strategies provide fast and localized frequency and voltage control across a variety of scenarios and grid contingencies.

Biography: John W. Simpson-Porco is an Assistant Professor of Electrical and Computer Engineering at the University of Toronto. His research focuses on feedback control theory and applications of control to power and energy systems. John received his B.Sc. degree in Engineering Physics from Queen's University in 2010, and his Ph.D. degree in Mechanical Engineering from the University of California, Santa Barbara in 2015. From 2016 to 2020 he was an Assistant Professor at the University of Waterloo. Professor Simpson-Porco is a recipient of the Automatica Best Paper Prize and the IEEE PES Technical Committee Award for Outstanding Technical Report. He is currently an Associate Editor for the IEEE Transactions on Smart Grid.

Speaker: Andy Sun

Title: Recent advances in small signal stability in power grids: New certificate, impact of damping, and Braess's Paradox

Abstract: In this talk, we will discuss some recent advances in the understanding of small signal stability in power grids and new development of stability certificate and distributed control methods. In particular, we provide exact conditions and theoretical justification for the intuitive notion that damping increases stability. Then we propose a new certificate of small signal stability in power grid that only requires local information, which leads to a fully distributed control scheme. Finally, we will show the existence of Braess's paradox in the context of multi-microgrids stability using structure-preserving network analysis. This is joint work with my doctoral student Amin Gholami.

Biography: Dr. Andy Sun is the McKenney Family Associate Professor in the H. Milton Stewart School of Industrial and Systems Engineering at Georgia Tech. Dr. Sun has a broad research interest in optimization and control of large-scale power grids. Dr. Sun's research has won several awards, including the INFORMS George B. Dantzig Dissertation Award, the NSF CAREER Award, the INFORMS ENRE Best Publication in Energy in 2017 and 2019, the Best paper Published in IEEE Trans. Power System in 2017-2019, among others. Dr. Sun's work in robust optimization for renewable resource integration has been implemented in some major electricity markets in the US. Dr. Sun obtained his PhD degree in Operations Research from MIT, and was a postdoctoral researcher at the IBM Watson Research Center, before joining Georgia Tech.

Speaker: Enrique Mallada

Title: Coherence and Concentration in Tightly Connected Networks

Abstract: Achieving coordinated behavior—engineered or emergent—on networked systems has attracted widespread interest in several fields. This interest has led to remarkable advances in developing a theoretical understanding of the conditions under which agents within a network can reach an agreement (consensus) or develop coordinated behavior, such as synchronization. However, much less understood is the phenomenon of network coherence. Network coherence generally refers to nodes' ability in a network to have a similar dynamic response despite heterogeneity in their behavior. In this talk, we present a general framework to analyze and quantify the level of network coherence that a system exhibits by relating coherence with a low-rank property. More precisely, for a networked system with linear dynamics and coupling, we show that the system transfer matrix converges to a rank-one transfer matrix representing the coherent behavior as the network connectivity grows. Interestingly, the non-zero eigenvalue of such a rank-one matrix is given by the harmonic mean of individual nodal dynamics, and we refer to it as the coherent dynamics. Our analysis unveils the frequency-dependent nature of coherence and a non-trivial interplay between dynamics and network topology. We further illustrate how this framework can be leveraged for obtaining accurate reduced-order models of coherent generators and tuning grid forming inverters to shape the (coherent) frequency response in power grids.

Biography: Enrique Mallada is an assistant professor of electrical and computer engineering at Johns Hopkins University (JHU) since 2016. Before joining Hopkins, he was a post-doctoral fellow at the Center for the Mathematics of Information at the California Institute of Technology from 2014 to 2016. He received his ingeniero en telecomunicaciones (telecommunications engineering) degree from Universidad ORT, Uruguay, in 2005 and his Ph.D. degree in electrical and computer engineering with a minor in applied mathematics from Cornell University in 2014. Dr. Mallada was awarded the Johns Hopkins Alumni Association Excellence in Teaching Award in 2021, the Johns Hopkins Catalyst Award and Discovery Award in 2020 and 2019, the NSF CAREER award in 2018, the ECE Director's Ph.D. Thesis Research Award for his dissertation in 2014, the Cornell University's Jacobs Fellowship in 2011, and the Organization of American States scholarship from 2008 to 2010. His research interests lie in the areas of control, dynamical systems, and optimization, with applications to engineering networks, including power grids, and the Internet.

Speaker: Dominic Groß

Title: Rethinking grid-forming control: a universal control paradigm for resilient converter-dominated power systems

Abstract: At the heart of the transition to a zero-carbon power system is a technological paradigm shift from conventional bulk generation to distributed renewable generation connected to the grid via power electronics. Control strategies for grid-connected power converters can be broadly categorized into grid-following (GFL) controls that assume a stable grid and are often fragile, and grid-forming (GFM) controls commonly seen as more resilient solution. However, the requirements of GFM controls pose significant obstacles in several application scenarios such as integration of renewables and high-voltage DC transmission. Moreover, operating a mix of machines, GFL converters, and GFM converters can result in a wide range of adverse interactions that are difficult to predict and jeopardize grid stability. This talk will discuss recent results on universal controls that can be used independently of the converter power source or network configuration, subsumes GFL and GFM operation, and are compatible with machine-based generation.

Biography: Dominic is an Assistant Professor with the Department of Electrical and Computer Engineering at the University of Wisconsin-Madison, USA. From 2016 to 2019 he was a postdoctoral researcher at the Automatic Control Laboratory of ETH Zürich, Switzerland. From 2014 to 2015 he was with Volkswagen Group's Research Division in Wolfsburg, Germany. He received a Dipl.-Ing. degree in Mechatronics from the University of Kassel, Germany, in 2010, and a Ph.D. degree in Electrical Engineering from the same university in 2014. His research interests include distributed control and optimization of complex networked systems with applications in converter-dominated power systems.

Speaker: Changhong Zhao, Chinese University of Hong Kong
Title: Approximating Feasible Power Injection Regions of Radial AC Networks

Abstract: We develop an optimization method to approximate the region of feasible net power injections, which serves as a basis to analyze the generation and demand capacities that can be accommodated by a distribution network, or for fast and safe control of power-dispatch resources. Based on the nonlinear Dist-Flow model of an alternating-current (AC) network with a radial structure, we first formulate a power-injection feasibility problem considering voltage and current limits. The feasibility problem is then relaxed to a convex second-order cone program (SOCP). We utilize the strong dual problem of the SOCP to express (or approximate) the SOCP-relaxed feasible power injection region with a convex polyhedron. Finally, we apply a heuristic to remove power injections that make the SOCP relaxation inexact. As a result, we obtain an approximate polyhedron of solvable and safe power injections. Preliminary numerical results validate efficacy of the proposed method.

Bio: Changhong Zhao is an Assistant Professor with the Department of Information Engineering, the Chinese University of Hong Kong. He received BE ('10) in Automation from Tsinghua University and MS ('12) and PhD ('16) in EE from Caltech. From 2016 to 2019, he worked with the US National Renewable Energy Laboratory. His research is on control and optimization of networked systems such as smart grid. He received Wilts Prize from Caltech EE Department and Demetriades Prize from Caltech EAS Division for best PhD thesis, the 2020/21 Early Career Award from Hong Kong Research Grants Council, the 2021 IEEE PES Prize Paper Award, and a 2021 Best Paper of IEEE Transactions on Power Systems.

Speaker: Johanna Mathieu, University of Michigan
Title: Impact of Market Timing on the Profit of a Risk-Averse Load Aggregator

Abstract: Non-generating resources such as thermostatically controlled loads (TCLs) can arbitrage energy prices and provide balancing reserves when aggregated due to their thermal energy storage capacity. This talk will explore the impact of market timing, quantified by lead time and contract period, on optimal TCL aggregate power consumption and reserve capacity bids and quantify trade-offs between market timing and TCL aggregate flexibility. We do this by optimizing the power consumption and reserve capacity offers at given lead times and contract periods, varying from 24 hours ahead to real-time. We introduce uncertainty in prices and TCL availability, formulate a two-stage chance-constrained optimization problem of a risk-averse aggregator, implement it on a rolling horizon basis, and evaluate how the trade-offs change. The results show that shorter lead times and contract periods positively impact TCL profit as well as flexibility if the prediction horizon is sufficiently long. The proposed method can be used by aggregators to decide on optimal bids and incentive payments to consumers to reward flexibility. This is joint work with Lars Herre of DTU and Lennart Soder of KTH.

Bio: Johanna Mathieu is an associate professor of Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor. Prior to joining Michigan, she was a postdoctoral researcher at ETH Zurich, Switzerland. She completed her PhD at the University of California at Berkeley in 2012. She is the recipient of an NSF CAREER Award and the Ernest and Bettine Kuh Distinguished Faculty Award. Her research focuses on ways to reduce the environmental impact, cost, and inefficiency of electric power systems via new operational and control strategies. She is particularly interested in developing new methods to actively engage distributed flexible resources such as energy storage, electric loads, and distributed renewable resources in power system operation, which are especially important in power systems with high penetrations of intermittent renewable energy resources such as wind and solar.

Speaker: Daniel Molzahn, Georgia Institute of Technology
TItle: Robust AC Optimal Power Flow with Robust Convex Restriction

Abstract: The robust optimal power flow (OPF) problem seeks an operating point for an electric power grid that minimizes operating costs while ensuring that all power injection fluctuations within a specified uncertainty set do not result in constraint violations. This presentation considers the robust AC OPF problem which models the AC power flow equations. Guaranteeing robustness is particularly challenging in this context due to the nonconvexities induced by the nonlinear AC power flow equations. So-called convex restrictions provide a mechanism for overcoming these challenges in order to provide rigorous guarantees regarding robust feasibility. A convex restriction is a convex sufficient condition

which ensures that all power injections within a specified set have corresponding power flow solutions that satisfy specified operational limits. The work described in this presentation extends a previously developed convex restriction to a robust convex restriction, which is a convex inner approximation of the nonconvex feasible region of the AC OPF problem that accounts for uncertainty in the power injections. This robust convex restriction is integrated in an algorithm that solves the robust AC OPF problem by evaluating a sequence of convex optimization problems. This presentation demonstrates this algorithm and its ability to control robustness versus operating cost trade-offs using several test cases. This is joint work with Dongchan Lee, Line Roald, and Kostya Turitsyn.

Bio: Dr. Daniel Molzahn is an assistant professor in the School of Electrical and Computer Engineering at the Georgia Institute of Technology. He also holds an appointment as a computational engineer in the Energy Systems Division at Argonne National Laboratory. Dr. Molzahn was a Dow postdoctoral fellow at the University of Michigan. He completed the B.S., M.S., and Ph.D. degrees in Electrical Engineering and the Masters of Public Affairs degree from the University of Wisconsin–Madison, where he was a National Science Foundation Graduate Research Fellow. Dr. Molzahn received the IEEE Power and Energy Society's 2021 Outstanding Young Engineer Award for his contributions to the theory and practical application of nonlinear optimization algorithms for electric power systems.

Speaker: Line Roald

Title: Stochastic Hybrid Approximation for Uncertainty Management in Gas-Electric Systems

Abstract: Flexibility from gas-fired generation plays an important role in managing renewable energy variability. However, frequent changes in gas generation output translate into variability in natural gas consumption, and propagates of uncertainty from the electric grid to the natural gas system. To ensure that both systems are operating safely, there is an increasing need for coordination and uncertainty management among the electricity and gas networks. A challenging aspect of this coordination is the consideration of natural gas dynamics, which play an important role in intra-day operation, but give rise to a set of non-linear and non-convex equations. This problem is hard to optimize even in the deterministic case, and quickly becomes intractable when considering multiple scenarios for stochastic optimization. To address this challenge, we propose using a Stochastic Hybrid Approximation algorithm, and investigate the efficacy of several different variants of this algorithm. Our case study demonstrates that the proposed technique is able to quickly obtain high quality solutions and outperforms existing benchmarks such as Generalized Benders Decomposition. We also show that coordinated uncertainty management and consideration of a dynamic gas model can significantly reduce both electric and gas system load shed in stressed conditions.

Bio: Line Roald is an Assistant Professor and Grainger Institute Fellow in the Department of Electrical and Computer Engineering in University of Wisconsin—Madison. She received her Ph.D. degree in Electrical Engineering (2016) from ETH Zurich, Switzerland. Prior to joining UW Madison, she was a postdoctoral research fellow with the Center of Non-Linear Studies at Los Alamos National Laboratory and she is a recipient of an NSF CAREER award and the UW Madison ECE Outstanding Mentoring Award. Her research interests center around modeling and optimization of energy systems, with a particular focus on managing uncertainty and risk from renewable energy variability and component failures.

Speaker: Tyler Summers

Title: Distributionally Robust Bootstrap Optimization

Abstract: Control architectures and autonomy stacks for complex engineering systems are often divided into layers to decompose a complex problem and solution into distinct, manageable sub-problems. To simplify designs, uncertainties are often ignored across layers in the stack, an approach with deep roots in classical notions of separation and certainty equivalence. But to develop resilient architectures for complex energy systems, especially as interactions between data-driven learning layers and model-based decision-making layers grow more intricate, much more sophisticated interfaces between layers are required. In this talk I will discuss a basic architecture that couples a statistical parameter estimation layer with a constrained optimization layer. I will show how the layers can be tightly integrated by combining a bootstrap resampling technique with distributionally robust optimization. The approach allows a finite-data out-of-sample safety guarantee and an exact reformulation as a tractable finite-dimensional convex optimization problem.

Bio: Tyler Summers is an associate professor at the University of Texas at Dallas. Prior to joining UT Dallas, he was an ETH Postdoctoral Fellow at the Automatic Control Laboratory at ETH Zurich from 2011 to 2015. He received a PhD degree in Aerospace Engineering at the University of Texas at Austin in 2010. He was a Fulbright Postgraduate Scholar at the Australian National University in Canberra, Australia in 2007-2008. He received the National Science Foundation CAREER Award in 2021 and a Young Investigator Program award from the Army Research Office in 2017. His research interests are in feedback control, optimization, and learning in complex dynamical networks, with applications in robotics and electric power networks.

NREL Speakers:

Speaker: Guido Cavraro

Title: Ripple-Type Control for Enhancing Resilience of Networked Physical Systems.

Abstract: With increasing penetration of volatile renewable generation and cyber-physical disruptions, ensuring safe operation of bulk power systems has become unprecedentedly challenging. Since communication and computational costs restrict centralized system dispatch to be called upon every few minutes; and purely local schemes are shown to be insufficient, distributed controls have been advocated for handling unanticipated system conditions in real time. However, the applicability of distributed control schemes is fundamentally limited by their need for widespread communication and model cognizance. In this context, we put forth a hybrid low-communication saturation-driven protocol for the coordination of control agents that are distributed over a physical system and are allowed to communicate with peers over a 'hotline' communication network. Under this protocol, when agents observe a constraint violation based on local measurements, they respond locally until their control resources saturate, in which case they send a beacon for assistance to peer agents. The scheme ensures that minor violations are efficiently mitigated via fast local controls, while severe violations may be handled by a collaboration of a relatively small set of agents. We evaluate the performance of this scheme via extensive numerical tests on the IEEE 14-bus test feeder, where agents act upon noisy measurements under diverse scenarios of random load variations and severe low voltage events.

Biography: Guido Cavraro received the B.Sc. degree in Information Engineering, the M.Sc. degree in Automation Engineering, and the Ph.D. degree in Information Engineering from the University of Padova, Italy, in 2008, 2011, and 2015, respectively. He has been a Visiting Scholar with the California Institute for Energy and Environment, UC Berkeley. From 2015 to 2016, he was a Postdoctoral Associate with the Department of Information Engineering, University of Padova. From 2016 to 2018, he was a Postdoctoral Associate with the Bradley Department of Electrical and Computer Engineering, Virginia Tech, USA. He is currently a Research Engineer with the Power Systems Engineering Center, National Renewable Energy Laboratory, USA. His research interests include control, optimization, and identification applied to power systems and smart grids.

Speaker: Xiangyu Zhang

Title: Curriculum-based Reinforcement Learning for Distribution System Critical Load Restoration

Abstract: In this study, we propose a curriculum learned deep reinforcement learning (RL) controller to facilitate distribution system critical load restoration (CLR) using DERs after a substation outage. Due to the intermittent generation from renewable DERs, we investigate how our developed RL controller can hedge against such uncertainty and evaluate its performance under renewable generation forecasts with different error levels. Like many grid control problems, CLR is complex due to the large control action space and renewable uncertainty in a heavily constrained non-linear environment with strong intertemporal dependency. To train the controller, we design a learning curriculum in which the RL agent progressively learns generation control and load restoration decisions under different scenarios. Via curriculum learning, the trained RL controller is expected to achieve a better control performance, with critical loads restored as rapidly and reliably as possible. In the case study, we demonstrate the effectiveness of the proposed curriculum

learning framework and show that the developed RL controller is less susceptible to renewables forecast error as compared with two model predictive controller baselines.

Biography: Xiangyu Zhang is a researcher from the Computational Science Center at the National Renewable Energy Laboratory. He received his Ph.D. degree in Electrical Engineering from Virginia Tech. Currently, he is interested in solving energy system related control problems with deep reinforcement learning and other optimal control techniques on high-performance computing systems.

Speaker: Bai Cui

Title: Network-Cognizant Time-Coupled Aggregate Flexibility of Distribution Systems Under Uncertainties

Abstract: Increasing integration of distributed energy resources (DERs) within distribution feeders provides unprecedented flexibility at the distribution-transmission interconnection. To exploit this flexibility and to use the capacity potential of aggregate DERs, feasible substation power injection trajectories need to be efficiently characterized.
In this talk, we describe an approach to construct an ellipsoidal inner approximation of the set of feasible power injection trajectories at the substation such that for any point in the set, there exists a feasible disaggregation strategy of DERs for any load uncertainty realization. The problem is formulated as one of finding the robust maximum volume ellipsoid inside the flexibility region under uncertainty. Since the problem is NP-hard even in the deterministic case, we derive computationally tractable approximations of the resulting adaptive robust optimization problem based on optimal second-stage policies. The proposed approach yields less conservative flexibility characterization than existing flexibility region approximation formulations. The efficacy of the proposed method is demonstrated on a realistic distribution feeder.

Biography: Bai Cui is a researcher from the Power Systems Engineering Center at the National Renewable Energy Laboratory (NREL). He received his Ph.D. degree in Electrical Engineering from Georgia Tech in 2018. Prior to joining NREL, he was a postdoctoral appointee at Argonne National Laboratory. His research interests are in optimization and stability analysis of power systems with applications in power system resilience and renewable integration.