GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Category 1 (Foundational/Regional) Project Final Report

Report Completion Date:9/23/19

Section 1: Project Information

Project Information	
Control #: Title:	**1.4.10** **GMLC Control Theory**
Project Title:	**Control Theory**
Project PI Name and Lab Affiliation: Project Co-PI (plus-one) and Lab Affiliation:	**Sidhant Misra (LANL)** **Karanjit Kalsi (PNNL)**
DOE Project Manager(s):	**Eric Lightner, Lee Sleezak**
Period of Performance:	**4/1/16 – 9/30/19**
Date Closed:	**9/30/19**

Section 2: Project Assessment and Checklist

Project Assessment and Checklist	Y/N	Confirmation Date	Comments
Have all quarterly reports been submitted?	**Y**	**9/23/19**	
Have all milestones have been delivered?	**Y**	**9/23/19**	
Are all products finalized (e.g. technical reports, journal articles)?	**Y**	**9/23/19**	
Have all project products been finalized and presented/submitted to DOE Project Manager(s) and/or GMI Leadership?	**Y**	**9/23/19**	
Have all potential sensitivities been identified and addressed with DOE Project Managers and/or GMI Leadership?	**Y**	**9/23/19**	
Has the project team received feedback from Project Stakeholders (e.g. advisory group)?	**Y**	**9/23/19**	
Are there any open or pending costs?	**N**	**9/23/19**	

Section 3: Outcomes, Deliverables, Publications

Provide the following: **In addition to titles, provide links to any websites or other repositories where deliverables and/or other information will be available after the project has been completed* **Publications available for public release, URLs, etc. listed here should be uploaded to GMLC Open Point*

1. **List of Outcomes:**

Task 1.1 Architecture and Metrics: Develop Control System Architectures

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A hierarchical architecture that exploits separation of time scales between grid wide optimization and real-time control of DERs was developed to enable computational scalability of control methods in the presence of a large number of controllable DERs

Task 1.2 Architecture and Metrics: Develop Metrics

Metrics for evaluation control architectures must account for efficiency, scalability and resilience. Various metrics attempting to capture all three aspects were considered and summarized in the roadmap (https://openpoint.nrel.gov/sites/gmlc/Shared%20Documents/Road_Map_GMLC_1_4_10.pdf?Web=1.

Task 1.3 Architecture and Metrics: Evaluate Control methodologies using metrics

The architecture and control algorithms were tested on a numerical testbed and the results were analyzed and reported in (https://openpoint.nrel.gov/sites/gmlc/Shared%20Documents/Report%20on%20Co-Simulation%20Testbed.pdf?Web=1).

Task 2.1 Control Theory: Develop Physics-Based DER and Load Models

Models for Air conditioners, water heaters, solar photovoltaic systems and batteries, were implemented in GridLAB-D. A primary challenge in leveraging the contribution of aggregated distributed energy resources is assessing the ***combined flexibility region.*** This amounts to understanding within what limits of active and reactive power can the aggregated DERs of different types can be dispatched within a given time period. Towards this, algorithms were developed for computing the combined flexibility region, and representing the resulting domain with a convex set that is suitable for efficient optimization [20]. An algorithm for aggregation of bid curves was developed to assess the cost of dispatching an aggregated set of controllable DERs away from their default/desired operating point. The aggregation algorithm also provides a corresponding disaggregation strategy that takes as input an aggregated set point prescribed by the power flow optimizer (PFO) and computes individual DER set points to be used by the real-time controller.

Task 2.2 Control Theory: Develop Power Flow Relaxations and Approximations

Incorporation of power flow physics are critical for distribution grid control in order to ensure that the set points and power flows remain within technical and safety limits at all times. Traditionally, especially in the context of transmission systems, this problem was handled by power flow aware optimization algorithms (such as optimal power flow solvers). The main challenge in porting these techniques over to distribution grid optimization in the presence of a large number of DERs is the resulting intractability of the optimization problem. To address this, several methods were developed based on two broad approaches:

(i) Decomposition: A strategic middle ground was adopted based on the spatio-temporal decomposition discussed under Task 1. Optimization based techniques were developed to compute locations of the aggregated device controllers (ADCs) such that the voltage limits underneath each ADC control area are guaranteed to be feasible. This allows for safely ignoring the power flow physics within each ADC control area, thus eliminating the need to model each DER response within the PFO optimization problem. It also allows for the abstraction of each ADC as a load/generation bus.

(ii) Relaxations and Approximations: A comprehensive survey of relaxations and approximations of the power flow physics that allow for appropriate trade-off between accuracy and tractability was conducted and the results were published in [11]. Optimized adaptive system-specific power flow approximations were developed [14].

Task 2.3 Control Theory: Integrate Closed Loop Control and Optimization

Network wide model and power flow physics must be incorporated in decision making in order to accurately quantify the effect of altering set-points of aggregated DERs and controllable network elements. Non-linear optimization algorithms were developed that incorporate full three phase power flow physics and enforce voltage and device limits. A Julia package ***PowerModelsDistribution.jl*** was released that supports full three phase power flow model, multiple load models and multiple power flow approximations. The algorithm for the power flow optimizer (PFO) was developed and implemented in order to ingest combined flexibility region information gathered from each ADC and dispatch min-cost set-points for the aggregated DERs to the real-time controllers.

Task 2.4 Control Theory: Theory for Hierarchical, Decentralized and Distributed Control

Real-time control algorithms to manage the output of controllable DERs are required in order to maintain desired aggregated power set points. Real-time control algorithms were developed for different category of DERs – batteries, solar PVs and water heaters. The methods were tested and documented in multiple publications [22,23]**.** These algorithms are able to accept ADC set points from the PFO that are disaggregated by DER type and perform real-time control on the corresponding DER type to match the prescribed set-point.

Task 3.1 Testing and Validation: Specify and Develop Numerical Test Beds

A co-simulation platform was set up for the IEEE 123 bus test feeder using GridLAB-D, FNCS interface and a Python Cosim manager. The details of the test bed are documented in https://openpoint.nrel.gov/sites/gmlc/Shared%20Documents/Report%20on%20Co-Simulation%20Testbed.pdf?Web=1

Task 3.2 Testing and Validation: Testing of Control Architectures and Methods

ADC modules were implemented as MATLAB functions and are invoked by the Cosim Manager using the MATLAB Engine API. The ADC modules are designed to perform the following functions: (i) Aggregate the flexibility of all DERs in an ADC to produce an ADC-level flexibility region, (ii) Disaggregate the control setpoints produced by the PFO into device-specific setpoints using the latest relative flexibility (iii) Dispatch and control air conditioners, PV and battery systems, and water heaters.

The PFO implementation in Julia was integrated into the testbed and can be invoked using a system call from the Cosim Manager. ADC-level flexibility regions are then passed to the PFO and ADC control setpoints are returned. The PFO references a static model of the power system.

The overall control strategy was tested and the tracking performance of the ADCs and the overall reduction in energy cost was analyzed. The results are reported in https://openpoint.nrel.gov/sites/gmlc/Shared%20Documents/Report%20on%20Co-Simulation%20Testbed.pdf?Web=1

2. **List of Deliverables:**

Roadmap

Comprehensive roadmap document describing overall DER integration and control strategy. Available on openpoint at https://openpoint.nrel.gov/sites/gmlc/Shared%20Documents/Road_Map_GMLC_1_4_10.pdf?Web=1

Task 1.1 Architecture and Metrics

- Modern distribution system resilient control system metrics and planning tool prototype. (PowDDeR). Available on openpoint at https://openpoint.nrel.gov/sites/gmlc/Shared%20Documents/PowDDERMetricsPresentation2018-June.pdf?Web=1

Task 2.1 Control Theory: Develop Physics-Based DER and Load Models

- MATLAB code for constructing aggregated flexibility regions DERs.
- A peer reviewed journal paper describing the aggregation strategy

Task 2.2 Control Theory: Develop Power Flow Relaxations and Approximations

- Survey article on various power flow relaxations and approximations
- Journal article on ADC placement.
- Peer reviewed articles on optimized adaptive power flow linearized approximations.

Task 2.3 Control Theory: Integrate Closed Loop Control and Optimization

- Open source Julia package PowerModelsDistribution.jl for distribution grid optimization with full three phase power flow modeling.

Task 2.4 Control Theory: Theory for Hierarchical, Decentralized and Distributed Control

- Peer reviewed articles describing the real-time control strategies

Task 3 Testing and Validation

- Report on test results from the numerical testbed on the IEEE 123 bus distribution feeder. Available on openpoint at https://openpoint.nrel.gov/sites/gmlc/Shared%20Documents/Report%20on%20Co-Simulation%20Testbed.pdf?Web=1

3. List of Publications:

1 K. Dvijotham, P. Van Hentenryck, M. Chertkov, M. Vuffray, S. Misra, Graphical Models for Optimal Power Flow,
Proceedings of 22nd International Conference on Principles and Practice of Constraint Programming (CP 2016) [best paper award],
extended version is published in Constraints, p. 1-26 (2016), arxiv:1606.06512;
Completed/Nov 2016

2 D.K. Molzahn, C. Josz, and I.A. Hiskens, "Moment Relaxations of Optimal Power Flow Problems: Beyond the Convex Hull," IEEE Global Conference on Signal and Information Processing (GlobalSIP), December 2016.
Completed/December 2016

3 K. Dvijotham and D.K. Molzahn, "Error Bounds on the DC Power Flow Approximation: A Convex Relaxation Approach," IEEE 55th Annual Conference on Decision and Control (CDC), December 2016.
Completed/December 2016

4 D.K. Molzahn, "Incorporating Squirrel-Cage Induction Machine Models in Convex Relaxations of OPF Problems," IEEE Transactions on Power Systems (Letters), 2017.Completed/February 2017

5 X. Zhou, E. Dall'Anese, L. Chen, and K. Baker, "Incentive-based Voltage Regulation in distribution Systems," American Control Conference, Seattle, WA, May 2017.
Completed/May 2017

6 M. Chertkov and V. Chernyak, "Ensemble of Thermostatically Controlled Loads: Statistical Physics Approach" arxiv:1701.04939,
to appear (accepted) in Scientific Reports (Nature Group).
Completed/June 2017

7 M. Chertkov and V. Chernyak, Ensemble Control of Cycling Energy Loads: Markov Decision Approach, arxiv:1701.04941,
to appear (accepted) by Springer, Series: Institute of Mathematics and Applications, Title of book: Energy Markets and Responsive Grids: Modeling, Control and Optimization, editors: S. Meyn, T. Samad, S. Glavaski, I. Hiskens, J. Stoustrup.
Completed June 2017

8 J. Lian, D. Wu, K. Kalsi and H. Chen, "Theoretical framework for integrating distributed energy resources into distribution systems," accepted by 2017 IEEE PES General Meeting, Chicago, IL, July 2017.
Completed, July 2017

9 Stavros Karagiannapoulous, Line Roald, Petros Aristidou, Gabriela Hug, "Operational Planning of Active Distribution Grids under Uncertainty", IREP Conference, August 2017
Completed/August 2017

10 L.A. Roald, D.K. Molzahn, and A.F. Tobler, "Power System Optimization with Uncertainty and AC Power Flow: Analysis of an Iterative Algorithm," to appear in IREP Symposium on Bulk Power System Dynamics and Control-X. The Power System of the Future: Global Dynamics arising from Distributed Actions, August 27 - September 1, 2017.

Completed/August 2017

11 D.K. Molzahn and I.A. Hiskens, "A Survey of Relaxations and Approximations of the Power Flow Equations," Accepted to Foundation and Trends in Electric Power Systems, 2018.
Completed/August 2018

12 "Identifying Critical Resiliency of Modern Distribution Systems with Open Source Modeling," Resilience Week 2017 (IEEE xPlore).
Completed/September 2017

13 "Electricity Distribution System Resilient Control System Metrics," Resilience Week 2017 (IEEE xPlore).
Completed/September 2017

14 K. Dvijotham, S. Misra, and D.K. Molzahn, "Optimal Adaptive Approximations of the AC Power Flow Equations," accepted to 20th Power Systems Computation Conference (PSCC), June 11-15, 2018.
Completed/October 2017

15 D.K. Molzahn and L.A. Roald, "AC Optimal Power Flow with Robust Feasibility Guarantees," accepted to 20th Power Systems Computation Conference (PSCC), June 11-15, 2018.
Completed/October, 2017

16 M. Chertkov, D. Deka, Voltage aware, stochastic optimal control of a complex distribution feeder, PSSC 2018 abstract (accepted)
Completed/October, 2017

17 A. Bernstein, C. Wang, E. Dall'Anese, and J.-Y. Le Boudec. "Multiphase Optimal and Non-Singular Power Flow by Successive Linear Approximations."
In Preparation/October, 2017

18 J. Lian, J. Fuller and K. Kalsi, "Transactive control of thermostatically controlled loads for frequency regulation," to be submitted to IEEE Transactions on Power Systems, 2017.
In Preparation/October, 2017

19 J. Lian, H. Chen, D. Wu and W. Zhang, "Multi-layer Market-based Approach for Seamless Integration of Distributed Energy Resources," to be submitted to IEEE Transactions on Power Systems, 2017
In Preparation/October, 2017

20 S. Kundu, J. Hansen, J. Lian, and K. Kalsi, "Assessment of optimal flexibility in ensemble of frequency responsive loads," submitted to IEEE International Conference on Smart Grid Communications, October, 2017
Completed, October 2017

21 H. Chen, W. Zhang, J. Lian and A. Conejo, "Robust distributed Volt/VAR control of power distribution systems," accepted by 56th IEEE Conference on Decision and Control, Melbourne, Australia, December, 2017.
Completed, December 2017

22 A. Bernstein, N. J. Bouman, and J.-Y. Le Boudec. "Real-Time Control of an Ensemble of Heterogeneous Resources," submitted to CDC 2017.
Accepted, December 2017

23 X. Zhou, E. Dall'Anese, L. Chen, and A. Simonetto, "An Incentive-based Online Optimization Framework for Distribution Grids," IEEE Trans. on Automatic Control, submitted Mar. 2017; under review.
Submitted, conditionally accepted

24 X. Zhou, Z. Liu, E. Dall'Anese, and L. Chen, "Stochastic Dual Algorithm for Voltage Regulation in Distribution
Networks with Discrete Loads", IEEE SmartGridComm, 2017
Submitted, under review

25 C. Josz and D.K. Molzahn, "Lasserre Hierarchy for Large Scale Polynomial Optimization in Real and Complex Variables," SIAM Journal on Optimization, vol. 28, no. 2, pp. 1017-1048, 2018.
Accepted

26 D.K. Molzahn, "Identifying Redundant Flow Limits on Parallel Lines," IEEE Transactions on Power Systems (Letters), vol. 33, no. 3, pp. 3210-3212, 2018.
Accepted

27 M.R. Narimani, D.K. Molzahn, and M.L. Crow, "Improving QC Relaxations of OPF Problems via Voltage Magnitude Difference Constraints and Envelopes for Trilinear

Monomials," 20th Power Systems Computation Conference (PSCC), June 11-15, 2018.
Accepted

28 A. Barzegar, D.K. Molzahn, and R. Su, "A Method for Quickly Bounding the Optimal Objective Value of an OPF Problem using a Semidenite Relaxation and a Local Solution," submitted to IEEE Transactions on Power Systems.
Submitted

29 D.K. Molzahn and L.A. Roald, "Grid-Aware versus Grid-Agnostic Distribution System Control: A Method for Certifying Engineering Constraint Satisfaction," accepted to 52nd Hawaii International Conference on System Sciences (HICSS), January 8-11, 2019.
Accepted

30 M.R. Narimani, D.K. Molzahn, H. Nagarajan, and M.L. Crow, "Comparison of Various Trilinear Monomial Envelopes for Convex Relaxations of Optimal Power Flow Problems," invited submitted to IEEE Global Conference on Signal and Information Processing (GlobalSIP), November 26-28, 2018.
Submitted

31 Bernstein et al, "Multiphase Optimal and Non-Singular Power Flow by Successive Linear Approximations,", in PSCC 2018.
Accepted

32 S. Kundu, K. Kalsi and S. Backhaus, "Approximating Flexibility in Distributed Energy Resources: A Geometric Approach," 2018 Power Systems Computation Conference (PSCC), Dublin, 2018, pp. 1-7.
Accepted

33 S. Kundu, V. Chandan and K. Kalsi, "Scalable Computation of 2D-Minkowski Sum of Arbitrary Non-Convex Domains: Modeling Flexibility in Energy Resources," 52nd Hawaii International Conference on System Sciences (HICSS), Maui, HI, USA, 2019.
Accepted

34 I. Chakraborty, S. Kundu, and K. Kalsi. 2019. Modeling Flexibility in Uncertain Distributed Energy Resources. In Proceedings of the Tenth ACM International Conference on Future Energy Systems (e-Energy '19). Association for Computing Machinery, New York, NY, USA, 398–399.
Accepted

35 S. Kundu, S. P. Nandanoori, K. Kalsi, S. Geng and I. A. Hiskens, "Distributed Barrier Certificates for Safe Operation of Inverter-Based Microgrids," 2019 American Control Conference (ACC), Philadelphia, PA, USA, 2019, pp. 1042-1047
Accepted

S. Kundu and K. Kalsi, " Transient Safety Filter Design for Grid-Forming Inverters with Sector-Like Bounds.," 2020 American Control Conference (ACC), Denver, CO, USA, 2019.
Accepted

Section 4: Final Costing

Each Lab Financial POC Completes Final Costing of GMLC Projects for their lab. PIs, Lab Leads will need to assist but not required to report financials with this final report.

Section 5: Final Thoughts/Comments

Final Thoughts	Comments
Lessons Learned	**Task 1 Architecture and Metrics** A hierarchical spatio-temporal decomposition strategy that allows real-time aggregate controllers to ignore power flow physics and network-wide power flow optimizer to ignore device level details achieves excellent performance in terms of scalability while maintaining sufficient accuracy and security. **Task 2.1 DER aggregate modeling** Device flexibility is not memoryless for batteries and thermostatically controlled appliances, and it is necessary to take state of charge into account in order to anticipate future shortage of capacity. **Task 2.2 Power Flow relaxations and approximations** Full non-linear power flow physics are required for accurate computation of power flows and voltages in the system, but linear

	approximations are sufficiently accurate to model the effect of uncertainty. **Task 2.3 Integrate Closed Loop Control and Optimization** It was a surprisingly difficult task to have easy access to three phase distribution system models with all features required for a full optimization based dispatch. In addition, there was no readily available non-proprietary parsers for several distribution system models. **Task 2.4 Theory for real-time control of DERs** Incentive based control of DERs can be formulated as a Stackerberg game, which is non-convex and bi-level. However this can be solved exactly through convex relaxation. **Task 3 Numerical testbed** System level design is necessary for a co-simulation testbed to ensure that there are no scoping or interface gaps between components. Starting the system level design as early as possible in a project and allowing decisions to inform controller design decisions in addition to testbed design decisions can significantly streamline the process.
Opportunities for Improvement	It was a significantly time consuming process to have all team members on the same page regarding the path forward in the project. Developing the roadmap served as a very useful way of achieving this. It would be highly beneficial to have time allocated in future projects for building a comprehensive roadmap.

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Future Projects: Ideas for future work? Possible next steps and research direction?	1. Moving from centralized to decentralized control methods within each aggregator's control area 2. Using machine learning techniques to support design of control protocols to maximize utilization of system specific features that are difficult to conceptualize from a human point of view. 3. Exploring multiple communication architectures from and their implications on control performance
Other:	