Final Report for ARPA-E NODES "Real-Time Optimization and Control of Next-Generation Distribution Infrastructure" Project

Andrey Bernstein

National Renewable Energy Laboratory

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5D00-78531
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Suggested Citation
Bernstein, Andrey. 2021. *Final Report for ARPA-E NODES "Real-Time Optimization and Control of Next-Generation Distribution Infrastructure" Project*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-78531. https://www.nrel.gov/docs/fy21osti/78531.pdf.

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National Renewable Energy Laboratory
Final Scientific/Technical Report
Real-Time Optimization and Control of Next-Generation Distribution Infrastructure
ARPA-E Award No.15/CJ000/07/07

Award:	15/CJ000/07/07
Sponsoring Agency	USDOE, Advanced Research Project Agency – Energy (ARPA-E)
Lead Recipient:	National Renewable Energy Laboratory
Project Team Members	Caltech, Harvard, University of Minnesota, Southern California Edison
Project Title:	Real-Time Optimization and Control of Next-Generation Distribution Infrastructure
Program Director:	Dr. Sonja Glavaski, Dr. Kory Hedman
Principal Investigator:	Dr. Emiliano Dall'Anese, Dr. Andrey Bernstein
Contract Administrator:	Dr. Mirjana Marden
Date of Report:	04/17/2020
Reporting Period:	07/19/2016 – 01/18/2020

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number 15/CJ000/07/07. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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Public Executive Summary

The project examined next-generation power distribution systems with high levels of power electronics-interfaced distributed energy resources (DERs) that include renewable energy systems (RESs), energy storage devices, electric vehicles, fuel cells, small-scale diesel generators, and controllable loads. The project developed a comprehensive distribution network management framework that unifies real-time voltage and frequency control with network-wide energy management under an integrated framework. The aim of the project was to: (1) systematically optimize network-wide operation and congruently regulate voltages and frequency in the face of high volatility induced by rapidly varying RES and uncontrolled loads; (2) facilitate high renewable integration beyond 50% on an energy basis; (3) meet power quality requirements and operational constraints; and (4) respect response, ramp time, and hold time requirements for synthetic frequency and regulating reserves via fast- and longer term dynamic energy management.

The developed distributed control architecture continuously steers operating points of DERs toward optimal solutions of pertinent optimization problems while dynamically procuring and dispatching synthetic reserves based on current system state and forecasts of ambient and load conditions. The control algorithms invoke simple mathematical operations that can be embedded on low-cost microcontrollers and enable distributed decision making on timescales that match the dynamics of distribution systems with high renewable integration.

The developed framework was tested and validated using (1) extensive software-only simulation; (2) closed-loop experiments with large-scale, real-time power systems models via

hardware-in-the-loop techniques; and (3) actual field deployments.

To translate algorithms to marketable products, the project principal investigators took part in the U.S. Department of Energy Energy I-Corps program to define the business model, customer segments, and potential revenue streams. Several patent applications were filed, and the technology was recently licensed by an industry company to explore the commercialization path using smart meter platforms.

The developed platform would help the U.S. grid assimilate at least 50% of renewable generation and provide system reliability and resilience while managing emerging energy generation and consumption patterns. The addition of flexible loads and DERs into the U.S. grid could offset 3.3 quads of thermal generation and displace 290 million tons of carbon dioxide emissions.

If this platform is adopted by industry, it will potentially help to replace 4.5 GW of spinning reserves (i.e., generation capacity on standby in case of outages and unforeseen intermittency), a value of $3.3 billion per year. A more efficient and reliable grid would help protect U.S. businesses from costly power outages and brownouts.

Acknowledgments

We thank ARPA-E for financially supporting the project and for guiding our progress throughout its execution. In particular, we thank the program directors, Dr. Sonja Glavaski and Dr. Kory Hedman, as well as the program coordinator, Dr. Mirjana Marden, for their leadership of the Network Optimized Distributed Energy Systems (NODES) program. We thank Steven Low (California Institute of Technology), Na Li (Harvard University), Sairaj Dhople (University of Minnesota), and Vahid Salehi (Southern California Edison), as well as other team members, for making this project a success.

Accomplishments and Objectives

The National Renewable Energy Laboratory (NREL), California Institute of Technology, University of Minnesota, Harvard University, and Southern California Edison (SCE) developed an innovative control architecture for distributed energy resource (DER) systems that addresses the unique needs of utility companies, DER aggregators, and end customers who own grid assets.

The new architecture is applicable to distribution systems, microgrids, and soft microgrids. It unifies real-time voltage and frequency control at the level of the home, building, or energy resource, with network-wide power management at the level of the utility or aggregator. This real-time distributed control architecture allows unprecedented flexibility, reliability, and efficiency of DER operations.

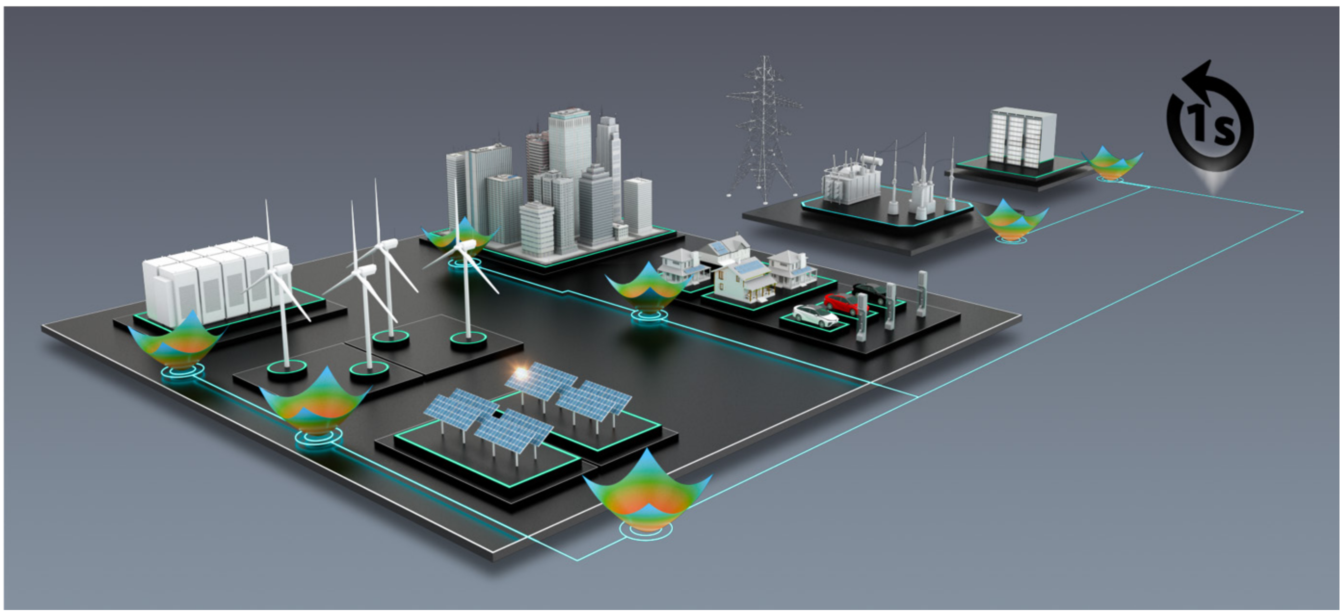

Figure 1: Real-time distributed optimization platform

The real-time optimization architecture enables:

- Optimization of an entire distribution grid in real time to increase system efficiency and reliability
- The ability for feeders, neighborhoods, and communities to emulate virtual power plants providing services to the grid (such as frequency support, regulating services, or capacity reserves) while concurrently addressing unique operational objectives
- Reliable integration and seamless, large-scale coordination of DERs
- 100% integration of renewable energy resources
- Interoperability with legacy grid components and advanced distribution management systems.

Targeted Applications and Customer Segments

The real-time optimization architecture offers:

- A solution for investor-owned utility companies, cooperatives, and municipalities, providing control modules located at the utility and at the DER level, synergistically coordinating in real time through the developed technology
- A solution for urban and rural microgrids for real-time distributed optimization of DERs
- A solution for urban soft microgrids (community-, campus-, and neighborhood-level systems connected to the rest of the grid through one point of interconnection) and community choice aggregations

Hardware-in-the-Loop Validation

The project team built a hardware-in-the-loop (HIL) research platform where the proposed technology has been validated using realistic distribution feeder models with hundreds of controllable assets. The team performed **the first-of-its-kind power HIL experiment with at least 100 DERs at power, controlled in real time and operated as if connected to the feeder**. The experiments were performed at the National Renewable Energy Laboratory's (NREL's) Energy Systems Integration Facility (ESIF) (see www.nrel.gov/esif).

Field Deployments

The technology has been tested at the Stone Edge Farm Microgrid in Sonoma Valley, California, and deployed in the territory of the electric cooperative Holy Cross Energy in Colorado.
The Stone Edge Farm Microgrid in Sonoma Valley is a unique test bed extending more than 16 acres in Sonoma, California—see Figure 2. It includes various controllable assets, such as photovoltaic (PV) systems, energy storage systems, a hydrogen electrolyzer, gas turbines, and controllable loads. The microgrid is operated by Heila Technologies.

Holy Cross Energy electric co-op in Colorado is based in Glenwood Springs, Colorado, and serves neighboring municipalities (see Figure 3), including the famous ski resorts Aspen and Vail. The developed technology was tested in the Basalt Vista affordable housing community, build by Habitat for Humanity. The community includes 27 homes for teachers and members of the local workforce; 4 homes were selected for the field deployment. The houses are designed as zero net energy buildings with all electric construction. Each of the four homes had five controllable DERs, including a solar panel system that ties to the grid through an inverter; a battery system that also ties to the grid using an inverter; an electric vehicle (EV) charger; and a heating, ventilating, and air-conditioning system. A Heila EDGE device was installed next to each asset to run the algorithms.

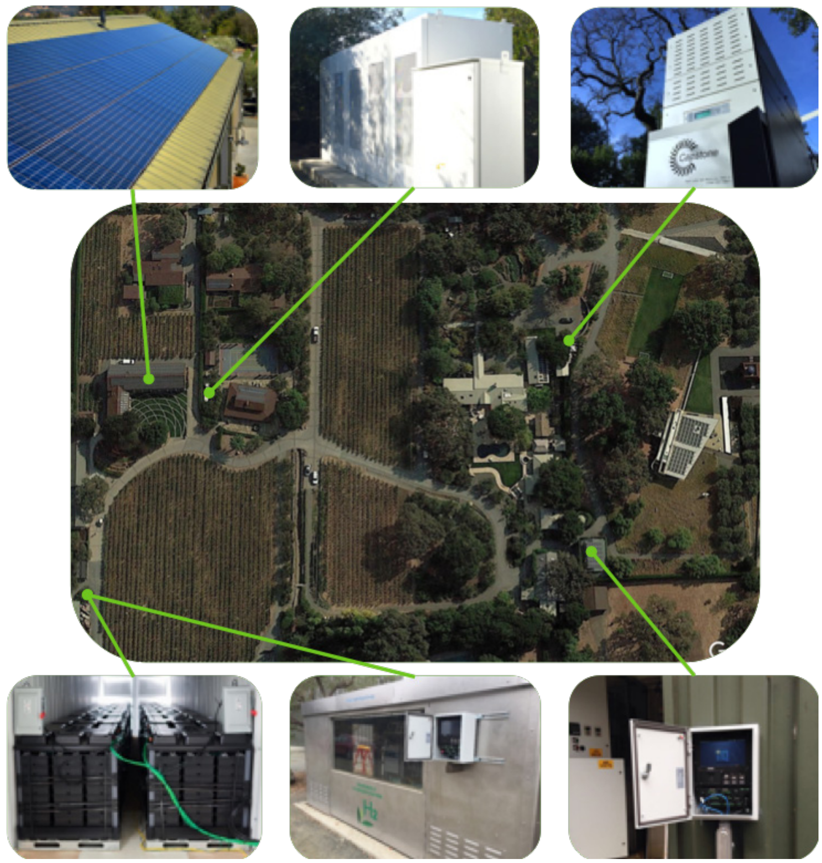

Figure 2: Stone Edge Farm Microgrid. *Photos courtesy of Stone Edge Farm Microgrid*

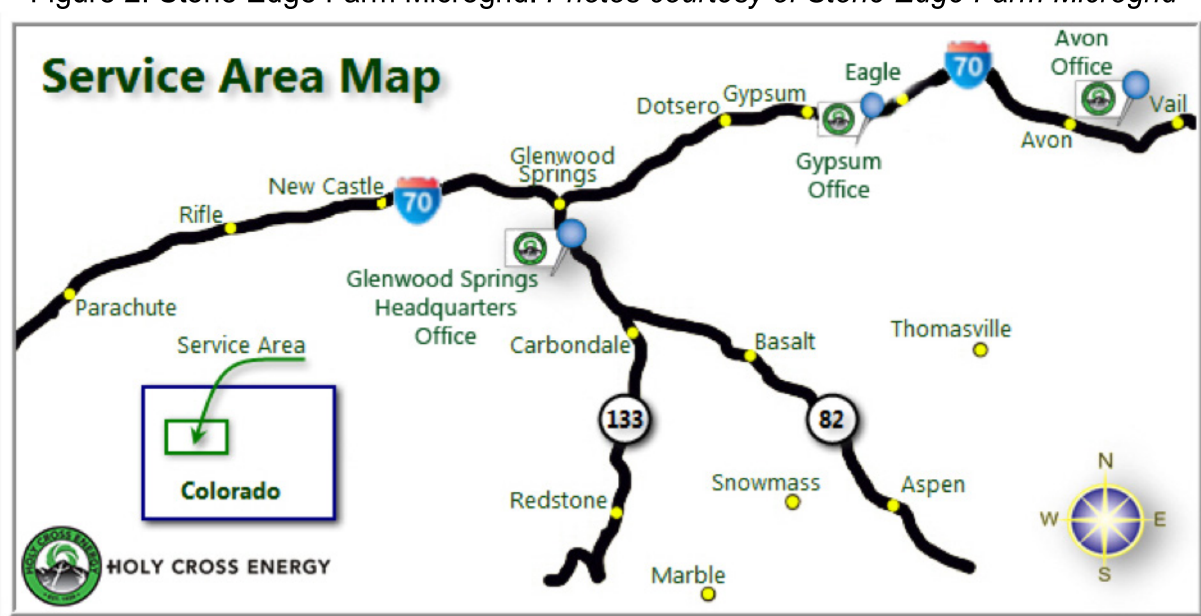

Figure 3: Holy Cross Energy service map. *Image courtesy of Holy Cross Energy*

Addressing Customer and Utility Needs

The real-time architecture provides unique coordination and feedback-based optimization capabilities to enable large-scale integrations of DERs by:

1. Leveraging real-time network-wide coordination to ensure reliable system operation during fast-changing ambient conditions and loads and to enable fast response to disturbances precipitating from the main grid, sudden loss of load, and network failures
2. Ensuring voltage regulation and ampacity limits for any integration level of DERs
3. Automatically managing a large number of DERs without requiring the utility to run extensive feasibility studies and track their usage patterns
4. Enabling behind-the-meter DER management based on local objectives that are flexibly defined by end users while partaking in grid operations to enhance reliability.

Enabling Virtual Power Plants

Traditional approaches to regulating frequency and maintaining reliable operation of transmission systems use primary frequency response, automatic generation control, and regulation services provided by large-scale synchronous generators. In the future, dispatchable DERs could supplement generation-side capabilities by providing additional flexibility in regulating frequency and maintaining reliable system operation. Toward realizing this vision, the project team leveraged real-time coordination and feedback-based optimization to develop an algorithmic framework for DER aggregations in distribution feeders to emulate a virtual power plant that can effectively provide regulation services to the bulk system and guarantee power quality across the distribution network.

To provide primary frequency support, the team synthesized controllers for DERs located throughout a feeder so that the active power injected at the feeder head could collectively adjust in response to frequency deviations. This framework enables analysis at the transmission level, where distribution-level DER aggregations can effectively be modeled as virtual power plants that provide primary frequency response needs at the feeder head.

To provide secondary frequency support and regulating services at multiple temporal scales, the team developed a distributed control architecture that manages active power at the feeder head in real time to track given set points. For example, a set point could be an automatic generation control signal, a ramping signal, or a 5-minute dispatch commanded by the transmission system operator. Controllers are designed to track the set point at the feeder head, concurrently maximize customer and utility performance objectives, and ensure that electrical limits are enforced throughout the feeder.

Several tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized here.

Table 1. Key Milestones and Deliverables

Tasks	Milestones and Deliverables
Task 1: Development of distributed network-optimal controllers for synthetic regulating reserves (Category 2)	M1.1.1: Model presented to ARPA-E (Q2). **Actual Performance:** (Q2) The developed model for synthetic regulating reserves was presented to ARPA-E. The model specified convex constraints in the optimization problem for the RMT command for synthetic regulating reserves.
1.1 Develop model and constraints for synthetic regulating reserves (Category 2)	M1.2.1: Test controllers for synthetic regulating reserves for single-phase systems (Q3). **Actual Performance:** (Q3) The distributed controllers for synthetic regulating reserves were tested in MATLAB using Test Case I (defined in Task 4). The simulated power at the substation reaches a level within 5% of the required RMT less than 5 minutes (simulation time). The required RMT is at least 5% of the net feeder load.
1.2 Design controllers for synthetic regulating reserves (Category 2) for single-phase systems	M1.3.1: Design documentation of controllers for synthetic regulating reserves for multi-phase systems (Q4). **Actual Performance:** (Q4) Completed the design of the distributed controllers' model and algorithms to achieve the required RMT target (5% of the net feeder load) and convergence rate for *multiphase unbalanced* optimal power flow
1.3 Design controllers for synthetic regulating reserves (Category 2) for multi-phase systems	M1.4.1: Go/No-Go checkpoint: Validation of simulated distributed controllers' ability to satisfy RT, RMT and RMVT performance requirements for Category 2 (Q5). **Actual Performance:** (Q5) The distributed controllers for synthetic regulating reserves were tested in MATLAB using Test Case II (defined in Task 4). The simulated power at the substation reaches a level within 5% of the Funding Opportunity Announcement Category 2 required RMT in ramp time less than 5 minutes (time computed by post-processing simulation results, based on emulated communication delay and actuation time).
1.4 Test controllers for synthetic regulating reserves (Category 2)	
1.5 Embed controllers for synthetic regulating reserves in microcontroller board	M1.5.1: Setpoint update in less than 5 seconds for regulating reserves (Q6). **Actual Performance:** (Q6) The distributed control algorithm was implemented in the microcontroller, and it was interfaced with a PV inverter. The time required for the selected microcontroller to update the set point and for the inverter to update the output power was less than 5 seconds.

Tasks	Milestones and Deliverables
Task 2: Development of controllers for synthetic frequency response reserves (Category 1) 2.1 Develop model for synthetic frequency response reserves (Category 1) 2.2 Develop controllers for synthetic frequency response (Category 1) for single-phase balanced systems 2.3 Test controllers for synthetic frequency response (Category 1) for single-phase balanced systems	M2.1.1: Model presented to ARPA-E (Q2) **Actual Performance:** (Q2) The developed model for distributed synthetic frequency response reserves was presented to ARPA-E. M2.2.1: Model and controllers presented to ARPA-E (Q3) **Actual Performance:** (Q3) The developed distributed synthetic frequency response controllers were presented to ARPA-E. Preliminary validation test results showed the feasibility and convergence of the developed decentralized control algorithms. M2.3.1: Controllers presented to ARPA-E (Q4) **Actual Performance:** (Q4) The controllers were shown to be able to regulate the net power drawn/up at the substation by at least 5% with a ramp time less than 15 seconds. M2.4.1: Controllers presented to ARPA-E (Q5) **Actual Performance:** (Q5) The developed distributed controllers for synthetic frequency response reserves for *multiphase unbalanced* systems were presented to ARPA-E. Preliminary validation test results showed the feasibility and convergence of the developed multiphase unbalanced decentralized control algorithms. M2.5.1: Ramp time for controllers for synthetic frequency response (Q7) **Actual Performance:** (Q7) The simulation results showed that the synthetic frequency reserve provided to the grid reaches a level within 5% of the required RMT in less than 8 seconds. The controllers are able to maintain the RMT and stay within the 5% RMVT for 30 seconds. The required RMT level is at least 2% of the net feeder load. M2.5.2: Response time less than 2 seconds for frequency regulating reserves (Q8) **Actual Performance:** (Q8) The simulation results showed that the response time of the selected microcontroller coupled with a PV system is less than 2 seconds.

Tasks	Milestones and Deliverables
Task 3: Development of dynamic synthetic reserve optimization algorithms 3.1 Formalize multi-period optimization problem encapsulating RMT and Duration targets 3.2 Distributed solution of the multi-period optimization problem encapsulating RMT and Duration targets 3.3 Test distributed solution of the multi-period optimization problem 3.4 Embed distributed solution of the multi-period optimization problem in a microcontroller board	M3.1.1: Formulation accepted (Q4) **Actual Performance:** (Q4) The formulated multi-period AC optimal power flow (ACOPF) problem was presented and accepted by ARPA-E. The problem models constraints specifying that the RMT can be maintained during a given temporal window of at least 30 minutes for synthetic regulating reserves. M3.2.1: Distributed solution presented to ARPA-E (Q6) **Actual Performance:** (Q6) The distributed solution methods for the multi-period ACOPF optimization problem encapsulating RMT and duration targets were presented to ARPA-E. The preliminary validation test results showed the feasibility and convergence of the developed multi-period ACOPF optimization solution methods. M3.3.1: Performance validation of distributed multi-period ACOPF solver (Q7) **Actual Performance:** (Q7) Validation tests were performed using software-only simulations of Test Case III to show that the distributed controllers using the multiperiod ACOPF solution method can maintain an RMT larger than 5% of the feeder net load for regulating reserves within ±5% at least 70% of time during an interval of 30 minutes. M3.4.1: Solution of subproblem in microcontrollers reached in less than 5 seconds (Q8) **Actual Performance:** (Q9) The milestone was delayed by one quarter due to implementation problems when using Embotech software to develop solvers for microcontrollers. The algorithms were implemented in a BeagleBone microcontroller, and the solution of the subproblem of the distributed solver reaches 99% of optimal value within 1 second on average.
Task 4: Testing and validation plan 4.1 Identify controllable DERs 4.2 Develop HIL test plan at NREL 4.3 Develop HIL test plan at SCE 4.4 Development of "Test Case I"	M4.1.1: List of controllable DERs (Q1) **Actual Performance:** (Q1) The list of controllable DERs was presented to ARPA-E. The proposed list contains PV inverters, energy storage systems, EVs, and controllable loads. M4.2.1: HIL test plan presented to ARPA-E (Q2) **Actual Performance:** (Q2) The HIL test plan for power-HIL demonstration at NREL's ESIF was presented to ARPA-E. The test includes a minimum of 100 devices at power. The demonstration will take place in the third year of the project. The final demo will include at least the following types of DERs: PV inverter, microinverter, energy storage system, EV, and single-phase controllable RLC load. Tests will use either OPAL-RT platform. M4.3.1: Test plan at SCE presented to ARPA-E (Q3)

Tasks	Milestones and Deliverables
4.5 Development of "Test Case II" 4.6 Development of "Test Case III" 4.7 Development of "Test Case IV" 4.8 Finalize of "Test Case V" for experiments at SCE	**Actual Performance:** (Q3) The test plan for the controller-HIL demonstration at SCE was presented to ARPA-E. The demonstration includes a minimum of 100 controllable devices emulated in PowerFactory or an equivalent real-time computing platform. A minimum of 10 microcontroller boards embedding the control algorithms for Category 2 are interfaced with PowerFactory or an equivalent real-time computing platform. M4.4.1: "Test Case I" presented to ARPA-E (Q2) **Actual Performance:** (Q2) Update on the development of Test Case I was presented to ARPA-E. M4.5.1: "Test Case II" presented to ARPA-E (Q3) **Actual Performance:** (Q3) Update on the development of Test Case II was presented to ARPA-E. M4.6.1: "Test Case III" presented to ARPA-E (Q6) **Actual Performance:** (Q6) Update on the development of Test Case III was presented to ARPA-E. M4.7.1: "Test Case IV" presented to ARPA-E (Q7) **Actual Performance:** (Q7) Test Case IV was presented to ARPA-E. Test cases I, II, III, and IV are cumulative in nature. The final test case is based on a titanium feeder from SCE territory, with 366 single-phase points of connection serving residential, commercial, and industrial customers. The peak load of the feeder is ~7 MW, and it contains a mix of delta and wye connections. Total DER capacity is ~8.5 MW for PV and ~1 MW for batteries. This results in a renewable energy penetration (annual energy basis) of ~51%. M4.8.1: "Test Case V" presented to ARPA-E (Q9) **Actual Performance:** (Q9) Test Case V was presented to ARPA-E. It is based on the Camden substation model from the SCE territory, with seven feeders. The model has more than 1,500 single-phase points of interconnection, representing approximately 2,000 customers. The peak load of the feeder is ~40 MW. The model was extended to include a high penetration of DERs, with ~70 MW for PV and ~10 MW for batteries. The total number of DERs is 514, emulated in the PowerFactory platform.

Tasks	Milestones and Deliverables
Task 5: HIL testing 5.1 Test algorithms using power-HIL at NREL and SCE	M5.1.1: Power-HIL Testbed setup and demonstration at NREL (Q7) **Actual Performance:** (Q7) The power-HIL test bed was set up at NREL. This includes setting up the input/output for the communications among microcontrollers and inverters, batteries, and EVs and enabling communications among microcontrollers. The initial demonstration showed bidirectional communications from the lab central management system to controllers and between controllers and their controlled devices. The test bed capability to command the PQ set points to devices was shown. M5.1.2: Go/No-Go checkpoint: Validation of controllers' ability to satisfy Category 2 performance requirements (Q8) **Actual Performance:** (Q8) HIL experiments using Test Case III were performed to show the proof of concept of the HIL test bed. The setup included five actual controllable devices at power: two SMA inverters, one Fronius inverter, 12 SunPower microinverters (controlled as one), and one LG battery inverter. Overall, 10 BeagleBone microcontroller boards were used (for 5 actual and 5 simulated devices). The test on Category 2 algorithms showed: a) The initial response time of PV inverters is less than 5 seconds. b) The simulated power at the substation reaches a level within 5% of the required RMT in less than 5 minutes. The RMT level is at least 5% of the net load of the distribution system. c) The RMT can be maintained within ±5% at least 70% of time during an interval of 30 minutes. M5.1.3: Validation of controllers' ability to satisfy Category 1 performance requirements (Q10) **Actual Performance:** (Q11) HIL experiments using Test Case III were performed, 5 actual controllable devices at power, and 10 microcontroller boards, as in M5.1.2. Two scenarios were demonstrated: (1) Category I response only—in response to system frequency deviation; and (2) Category II + Category I response—system frequency deviation occurs during substation power set point tracking. The tests showed: a) The initial response time of PV inverters is less than 2 seconds. b) The simulated power at the substation reaches a level within 5% of the required RMT in less than 8 seconds. M5.1.4: HIL tests with 100 devices (Q12) **Actual Performance:** (Q12) The final HIL experiment using Test Case

Tasks	Milestones and Deliverables
	IV was performed, with 104 actual devices at power and 10 microcontroller boards. For Category 2, tests showed: a) The initial response time for controllers is less than 5 seconds. b) The simulated power at the substation reaches a level within 5% of the required RMT less than 5 minutes after receiving an RMT command. c) The RMT can be maintained within ±5% during an interval of 30 minutes. For Category 1, tests showed: a) The initial response time for controllers is less than 2 seconds. b) The simulated power at the substation reaches a level within 5% of the required RMT less than 8 seconds after a frequency drop. The RMT level is at least 2% of the net load of the distribution system. c) The RMT can be maintained within ±5% during an interval of 30 seconds. M5.1.5: Tests at SCE (Q14) **Actual Performance:** (Q14) Controller-HIL experiments at SCE using Test Case V were performed, with total of 160 DERs and 10 microcontroller BeagleBone boards interfaced with the PowerFactory platform. The tests showed: a) The initial response time for controllers is less than 5 seconds. b) The simulated power at the substation reaches a level within 5% of the required RMT less than 5 minutes after receiving an RMT command. c) The RMT can be maintained within ±5% during an interval of 30 minutes
Task 6: Technology-to-market 6.1 Technology to Market plan development and updates 6.2 Develop IPMP 6.3 IAB engagement	M6.1.1: Technology to Market plan: Preliminary T2M plan (Q1) **Actual Performance:** (Q1) Preliminary high-level technology-to-market plan was developed with a high-level view of the team's plans for technology dissemination and commercialization. M6.1.2: Technology to Market plan: (1) Novel Capabilities, (2) Pathways to adoption (Q4) **Actual Performance:** (Q4) Revised technology-to-market plan was presented, based on discussion with IAB members. Participation in

Tasks	Milestones and Deliverables
6.4 Technology Dissemination and Demonstration	the DOE Energy I-Corp program was scheduled to refine the plan. M6.1.3: Technology to Market plan: Stakeholder analysis (Q6) **Actual Performance:** (Q6) The principal investigators participated in the DOE Energy I-Corp program. The program is comprehensive training to develop the business model for the technology. During the program, approximately 90 customer discovery interviews were conducted with industry. This enabled us to secure the necessary industry connections and insights to ready the technology for the market and gain an industry engagement framework to apply to future research and share with fellow researchers. M6.1.4: Technology to Market plan: Competitive analysis (Q8) **Actual Performance:** (Q6) Developed as part of the DOE Energy I-Corp program M6.1.5: Technology to Market plan: Business model (Q10) **Actual Performance:** (Q6) Developed as part of the DOE Energy I-Corp program M6.1.6: Technology to Market plan: Post ARPA-E funding (A) (Q11) **Actual Performance:** (Q6) Developed as part of the DOE Energy I-Corp program M6.2.1: Submission of IPMP (Q3) **Actual Performance:** (Q3) The finalized IPMP was submitted to ARPA-E. M6.3.1: IAB engagement: Industrial advisory board (Q1) **Actual Performance:** (Q1) The IAB was extended to include additional personnel. M6.3.2: IAB engagement: IAB activity finalized (Q2) **Actual Performance:** (Q2) Selected and committed industry advisors to participate in the activities of the board, defined IAB engagement plan and schedule, and got IAB commitment to the planned meetings and reviews schedule. M6.3.3: IAB engagement: feedback for Category 2 (Q2) **Actual Performance:** (Q2) Outlined proposed Category 2 controllers to the IAB and obtained feedback. The main feedback was that the "star" communications topology is preferable for current industry practice. M6.3.4: IAB engagement: feedback for Category 1 (Q4) **Actual Performance:** (Q4) Outlined proposed Category 1 controllers to the IAB and obtained feedback.

Tasks	Milestones and Deliverables
	M6.3.5: IAB engagement: multi-period ACOPF problem formulation presented to IAB (Q4) **Actual Performance:** (Q4) The formulated multiperiod ACOPF problem was presented to the IAB for review and feedback. M6.3.6: IAB engagement: feedback for HIL setup (Q6) **Actual Performance:** (Q6) The proposed test plan at NREL was presented to the IAB for review and feedback. M6.3.7: IAB engagement: present finalized HIL test setup and test case (Q8) **Actual Performance:** (Q8) The finalized HIL test plan at NREL was presented to the IAB for review and feedback. M6.3.8: IAB engagement: Showcase first demo (Q9) M6.3.9: IAB engagement: Showcase demo (Q11) M6.3.10: IAB engagement: Showcase results from SCE experiments (Q12) M6.3.11: IAB engagement: follow up opportunities (Q12) **Actual Performance:** (Q14) These milestones were combined with M6.4.7. M6.4.1: Technology Dissemination and Demonstration: Publications and workshop demonstrations (Q4) **Actual Performance:** (Q4) Presented update on publications submitted or in progress and plans for workshop/conference sessions for technology presentation. M6.4.2: Technology Dissemination and Demonstration: Finalize demo setup (Q7) **Actual Performance:** (Q7) Update on Test Case IV and on the architecture and hardware setup used in the smaller scale demo and larger scale demo at NREL was presented. M6.4.3: Technology Dissemination and Demonstration: Publications and workshop demonstrations (Q8) **Actual Performance:** (Q8) Presented update on publications submitted or in progress and plans for workshop/conference sessions for technology presentation. M6.4.4: Technology Dissemination and Demonstration: Small-scale demo at NREL (Q8) **Actual Performance:** (Q8) Small-scale demo with five actual controllable devices using Test Case III was performed in a conference call with ARPA-E. M6.4.5: Technology Dissemination and Demonstration: large-

Tasks	Milestones and Deliverables
	scale demo at NREL (Q11) M6.4.6: Technology Dissemination and Demonstration: large-scale demo at SCE (Q12) M6.4.7: Tech-to-market workshop (Q12) **Actual Performance:** (Q14) These milestones were combined with M6.4.7. A workshop was held at NREL on January 16, 2020. The workshop consisted of project innovation presentations (including framework, validation at NREL, SCE, and demonstrations), invited talks, and live demonstration at NREL's HIL test bed. We got overwhelming positive feedback from the participants, who were very impressed with the work done in this project. As a result of the workshop, we received requests from several companies that are potentially interested in licensing our technology. The workshop material is available via the following link: https://www.nrel.gov/grid/rto-workshop.html.
Task 7: Demonstration at the Stone Edge Farm Microgrid (SEFM) 7.1 Test plan 7.2 Phase 1 of testing 7.3 Phase 2 of testing	M7.1.1: Test plan at SEFM presented to ARPA-E (Q7) **Actual Performance:** (Q7) The test plan was presented to ARPA-E. The test plan includes two phases: In Phase 1, the real-time algorithm developed under Task 1 is tested with at least four (4) controllable assets. In Phase 2, the real-time algorithm is tested with at least twenty (20) controllable assets. The test plan identified the type of devices to be used in the demonstration and the performance metrics. M7.2.1: Documentation for Phase 1 demonstration (Q8) **Actual Performance:** (Q8) Phase 1 demonstration was successfully conducted. The results show successful voltage regulation and virtual power plant capabilities. M7.3.1: Documentation for Phase 2 demonstration (Q9) **Actual Performance:** (Q10) Phase 2 demonstration was conducted, showing successful virtual power plant capabilities. Unfortunately, voltage regulation capabilities were not shown due to unforeseen events—an unexpected change in personnel at Stone Edge Farm Microgrid as well as wildfires in California.
Task 8: Demonstration on a utility circuit 8.1 Identify utility/cooperative/municipality partners	M8.1.1: Present partner and demonstration site to ARPA-e (Q9) **Actual Performance:** (Q9) The chosen partner is Holy Cross Energy coop in Colorado. The demonstration site is the Basalt Vista neighborhood built by Habitat for Humanity. M8.2.1: Present test plan for demonstration (Q10) **Actual Performance:** (Q10) The finalized plan for the field

Tasks	Milestones and Deliverables
8.2 Test plan for demonstration 8.3 Conduct demonstration	demonstration was presented. It includes four houses in the Basalt Vista community, with five controllable devices in each house: a solar panel; a battery system; an EV charger; an electric water heater; and a heating, ventilating, and air-conditioning system. A Heila EDGE device will be colocated next to each asset and will run algorithms. M8.3.1: Interim reporting on field testing (Q11) **Actual Performance:** (Q11) The interim report on field-testing was presented. Due to delayed construction and deployment, the actual field test is delayed. M8.3.2: Documentation for utility demonstration (Q12) **Actual Performance:** (Q14) The field demonstration was successfully conducted. The experiment showed how our algorithms can perform: (1) peak load management: charging battery during off-peak time and then discharging battery during peak time (4 p.m.–9 p.m.) to offset net load consumption; and (2) real-time optimization, with the objective of zero power flow at the transformer.

Project Activities

The project developed a comprehensive distribution network management framework that unifies real-time voltage and frequency control with network-wide energy management under an integrated framework. The aim of the project was to: (1) systematically optimize network-wide operation and congruently regulate voltages and frequency in the face of high volatility induced by rapidly varying RES and uncontrolled loads; (2) facilitate high renewable integration beyond 50% on an energy basis; (3) meet power quality requirements and operational constraints; and (4) respect response, ramp time, and hold time requirements for synthetic frequency and regulating reserves via fast- and longer term dynamic energy management. The developed distributed control architecture continuously steers operating points of DERs toward optimal solutions of pertinent optimization problems while dynamically procuring and dispatching synthetic reserves based on current system state and forecasts of ambient and load conditions. The control algorithms invoke simple mathematical operations that can be embedded on low-cost microcontrollers and enable distributed decision making on timescales that match the dynamics of distribution systems with high renewable integration. The developed framework was tested and validated using (1) extensive software-only simulation; (2) closed-loop experiments with large-scale, real-time power systems models via HIL techniques; and (3) actual field deployments.

Project Outputs

A. Journal Articles

1 Enrique Mallada, Changhong Zhao, and S. H. Low, "Optimal Load-Side Control for Frequency Regulation in Smart Grids," *IEEE Transactions on Automatic Control* 62, no. 12 (Dec 2017).

2 Yujie Tang, Krishnamurthy Dvijotham, and Steven Low, "Real-Time Optimal Power Flow," *IEEE Transactions on Smart Grid* 8, no. 6 (Nov. 2017).

3 Qiuyu Peng and Steven H. Low, "Distributed Optimal Power Flow Algorithm for Radial Networks, I: Balanced Single Phase Case," *IEEE Transactions on Smart Grid* 9, no. 1 (Jan. 2018).

4 Yujie Tang and Steven H. Low, "Optimal Placement of Energy Storage in Distribution Networks," *IEEE Transactions on Smart Grid: Special Issue on Distributed Control and Efficient Optimization Methods for Smart Grid* 8, no. 6 (Nov. 2017): 3,094–3,103.

5 Yujie Tang, Krishnamurthy Dvijotham, and Steven H. Low, "Real-Time Optimal Power Flow," *IEEE Transactions on Smart Grid, Special Issue on Distributed Control and Efficient Optimization Methods for Smart Grid* 8, no. 6 (Nov. 2017): 2,963–2,973.

6 Changhong Zhao, Enrique Mallada, S. H. Low, and Janusz Bialek, "Distributed Plug-and-Play Optimal Generator and Load Control for Power System Frequency Regulation," *International Journal of Electrical Power & Energy Systems* 101 (Oct. 2018): 1–12.

7 S. S. Guggilam, C. Zhao, E. Dall'Anese, Y. C. Chen, and S. V. Dhople, "Optimizing Power-Frequency Droop Characteristics of Distributed Energy Resources," *IEEE Transactions on Power Systems* 33, no. 3 (May 2018): 3,076–3,086.

8 S. S. Guggilam, C. Zhao, E. Dall'Anese, Y. C. Chen, and S. V. Dhople, "Optimizing DER Participation in Inertial and Primary-Frequency Response," *IEEE Transactions on Power Systems* 33, no. 5 (Sept. 2018): 5,194–5,205.

9 E. Dall'Anese, S. S. Guggilam, A. Simonetto, Y. C. Chen, and S. V. Dhople, "Optimal Regulation of Virtual Power Plants," *IEEE Transactions on Power Systems* 33, no. 2 (March 2018): 1,868–1,881.
10 Zhaojian Wang, Feng Liu, John Z. F. Pang, S. H. Low, and Shengwei Mei, "Distributed Optimal Frequency Control Considering a Nonlinear Network-Preserving Model," *IEEE Transactions on Power Systems* 34, no. 1 (Jan. 2019): 76–86.
11 Zhaojian Wang, Feng Liu, S. H. Low, Changhong Zhao, and Shengwei Mei, "Distributed Frequency Control with Operational Constraints, Part I: Per-Node Power Balance," *IEEE Transactions on Smart Grid* 10, no. 1 (Jan. 2019): 40–52.
12 Zhaojian Wang, Feng Liu, S. H. Low, Changhong Zhao, and Shengwei Mei, "Distributed Frequency Control with Operational Constraints, Part II: Network Power Balance," *IEEE Transactions on Smart Grid* 10, no. 1 (Jan. 2019): 53–64.
13 Zhaojian Wang, Shengwei Mei, Feng Liu, Steven H. Low, and Peng Yang, "Distributed Load-Side Control: Coping with Variation of Renewable Generations", *Automatica* 109 (Nov. 2019).
14 Andrey Bernstein and Emiliano Dall'Anese, "Real-Time Feedback-Based Optimization of Distribution Grids: A Unified Approach," *IEEE Transactions on Control of Network Systems* (2019).
15 E. Weitenberg, Y. Jiang, C. Zhao, E. Mallada, C. De Persis, and F. Dorfler, "Robust Decentralized Secondary Frequency Control in Power Systems: Merits and Trade-Offs," *IEEE Transactions on Automatic Control* 64, no. 10 (Oct. 2019).
16 Sindri Magnusson, Guannan Qu, Na Li, and Carlo Fischione, "Voltage Control Using Limited Communication," *IEEE Transactions on Control of Network Systems* 6, no 3 (2019): 993–1003.
17 Xin Chen, Emiliano Dall'Anese, Changhong Zhao, and Na Li, "Aggregate Power Flexibility in Unbalanced Distribution Systems," *IEEE Transactions on Smart Grids*, 11, no. 1 (2020): 258–.
18 Guannan Qu and Na Li, "An Optimal and Distributed Feedback Voltage Control under Limited Reactive Power," *IEEE Transactions on Power Systems* 35, no. 1 (2020): 315–331.
19 Sindri Magnusson, Guannan Qu, and Na Li, "Distributed Optimal Voltage Control with Asynchronous and Delayed Communication," accepted to *IEEE Transactions on Smart Grid*, ArXiv:1903.01065.

B. Conference Papers

1 Zhaojian Wang, Feng Liu, S. H. Low, Changhong Zhao, and Shengwei Mei, "Decentralized Optimal Frequency Control of Interconnected Power Systems with Transient Constraints," Presented at the 55th IEEE Conference on Decision and Control, December 2016.
2 Yujie Tang and S. H. Low, "Optimal Placement of Energy Storage in Distribution Networks," Presented at the 55th IEEE Conference on Decision and Control, December 2016.
3 Y. Nakahira, N. Chen, L. Chen, and S. H. Low, "Smoothed Least-laxity-first Algorithm for EV Charging," *Proceedings of 8th International Conference on Future Energy Systems (ACM e-Energy)*.
4 Linqi Guo, Karl F. Erliksson, and Steven H. Low, "Optimal Online Adaptive Electric Vehicle Charging," *Proceedings of the IEEE Power and Energy Society General Meeting*.
5 Changhong Zhao, Emiliano Dall'Anese, and Steven H. Low, "Convex Relaxation of OPF in Multiphase Radial Networks with Delta Connection," *Proceedings of the 10th Bulk Power Systems Dynamics and Control Symposium*, 2017.
6 Linqi Guo, Chen Liang, and Steven H. Low, "Monotonicity Properties and Spectral Characterization of Power Redistribution in Cascading Failures," Presented at the 55th Annual Allerton Conference on Communication, Control, and Computing, October 2017.
7 John C. Doyle, Nikolai Matni, Yuh-Shyang Wang, James Anderson, and Steven H. Low, "System Level Synthesis: A tutorial," Presented at the 56th IEEE Conference on Decision and Control, December 2017.

8 Pengcheng You, John Pang, Minghua Chen, Steven H. Low, and Youxian Sun, "Battery Swapping Assignment for Electric Vehicles: A Bipartite Matching Approach," Presented at the 56th IEEE Conference on Decision and Control, December 2017.
9 Linqi Guo and Steven H. Low, "Special Characterization of Controllability and Observability for Frequency Regulation Dynamics," Presented at the 56th IEEE Conference on Decision and Control, December 2017.
10 S. S. Guggilam, C. Zhao, E. Dall'Anese, Y. C. Chen, and S. V. Dhople, "Engineering Inertial and Primary-Frequency Response for Distributed Energy Resources," Presented at the 2017 IEEE 56th Annual Conference on Decision and Control (CDC), Melbourne, VIC, 2017, pp. 5112–5118.
11 Yujie Tang and Steven H. Low, "Distributed Algorithm for Time-Varying Optimal Power Flow," Presented at the 56th IEEE Conference on Decision and Control, December 2017.
12 S. S. Guggilam, C. Zhao, E. Dall'Anese, Y. C. Chen, and S. V. Dhople, "Primary Frequency Response with Aggregated DERs," Presented at the 2017 American Control Conference (ACC), Seattle, WA, 2017, pp. 3386–3393.
13 Linqi Guo, Changhong Zhao, and Steven H. Low, "Cyber Network Design for Secondary Frequency Regulation: A Spectral Approach," Presented at the 2018 Power Systems Computation Conference (PSCC).
14 James Anderson, Fengyu Zhou, and Steven H. Low, "Disaggregation for Networked Power System," Presented at the 2018 Power Systems Computation Conference (PSCC).
15 E. Weitenberg, Y. Jiang, C. Zhao, E. Mallada, F. Dorfler, and C. De Persis, "Robust Decentralized Frequency Control: A Leaky Integrator Approach," Presented at the European Control Conference, Limassol, Cyprus, June 2018.
16 X. Chen, C. Zhao, and N. Li, "Distributed Automatic Load-Frequency Control with Optimality in Power Systems," Presented at the IEEE Conference on Control Technology and Applications, Copenhagen, Denmark, August 2018.
17 Yujie Tang, Emiliano Dall'Anese, Andrey Bernstein, and S. H. Low, "A Feedback-Based Regularized Primal-Dual Gradient Method for Time-Varying Nonconvex Optimization," Presented at the IEEE Conference on Decision and Control, December 2018.
18 M.S. Nazir, I. Hiskens, A. Bernstein, and E. Dall'Anese, "Union-Based Approach and Applications to Aggregated Energy Resources," Presented at the IEEE Conference on Decision and Control, December 2018.
19 Linqi Guo, Chen Liang, Alessandro Zocca, S. H. Low, and Adam Wierman, "Failure Localization in Power Systems via Tree Partitions," Presented at the IEEE Conference on Decision and Control, December 2018.
20 Linqi Guo, Changhong Zhao, and S. H. Low, "Graph Laplacian Spectrum and Primary Frequency Regulation," Presented at the IEEE Conference on Decision and Control, December 2018.
21 Tianyi Chen, Na Li, and Georgios B. Giannakis, "Aggregating Flexibility of Heterogeneous Energy Resources in Distribution Networks," Presented at the American Control Conference (ACC), 2018.
22 Xin Chen, Changhong Zhao, and Na Li, "Distributed Automatic Load-Frequency Control with Optimality in Power Systems," Presented at the IEEE Conference on Control Technology and Applications (CCTA), 2018.
23 Fengyu Zhou, James Anderson, and Steven H. Low, "Differential Privacy of Aggregated DC Optimal Power Flow Data," Presented at the 2019 American Control Conference (ACC).
24 Sindri Magnusson, Guannan Qu, and Na Li, "Distributed Voltage Control with Communication Delays," Presented at the American Control Conference, 2019.
25 Sindri Magnusson, Carlo Fishione, and Na Li, "Optimal Voltage Control Using Event Triggered Communication," Presented at ACM E-Energy, 2019.
26 R. Khatami, S. S. Guggilam, Y. C. Chen, S. V. Dhople, and M. Parvania, "Dynamics-Aware

Continuous-time Economic Dispatch: A Solution for Optimal Frequency Regulation," *Proceedings of the 53rd Hawaii International Conference on System Sciences*, 2020.

C. Status Reports

Quarterly reports to DOE.

D. Media Reports

4/10/20	*GreenTech Media*: "NREL and Utilidata Bring Smart Inverter Optimization From the Lab to the Real World" Link
4/7/2020	*WIRED*: "The Power Plant of the Future Is Right in Your Home" Link
3/18/2020	*Smart Grid Observer*: "Utilidata Secures Rights to Technology for Bringing Real-Time Operational Controls to the Grid Edge" Link
1/10/2020	*GreenBiz*: "This Is What Energy Resilience Could Look Like" Link
12/12/2019	*Electric Energy Online*: "Small Colorado Utility Sets National Renewable Electricity Example Using NREL Algorithms" Link
7/9/2019	*PowerGrid International*: "ARPA-E Funds High-Risk, High-Reward Energy Technology for Grid Control and More" Link
4/22/2019	*Post Independent*: "Energy Wonks Hope to Achieve Breakthrough at Basalt Vista Project" Link

E. Invention Disclosures

NREL Record of Invention, ROI-16-124, "Design of Controllers Realizing Distribution-level Virtual Power Plant," received by NREL's technology transfer office on August 29, 2016.

F. Patent Applications/Issued Patents

1. NREL-16-124, "Real-Time Feedback-Based Optimization of Distributed Energy Resources," U.S. Issued Patent No. 10,516,269.
2. NREL-16-124A, "Real-Time Feedback-Based Optimization of Distributed Energy Resources," U.S Patent Application No. 16/681,054.
3. NREL-16-124 PCT, "Real-Time Feedback-Based Optimization of Distributed Energy Resources," PCT Patent Application No. PCT/US2017/061911 (completed).

This patent portfolio is jointly owned between NREL and Universite Catholique de Louvain

(UCL) (NREL-16-126/UCL-118) because of the inventorship contributions (Dall'Anese and Bernstein from NREL and Simonetto from UCL). NREL and UCL have executed an inter-institutional agreement designating NREL/The Alliance for Sustainable Energy as the lead institution for licensing and patent prosecution associated with the joint patent portfolio.

G. Licensed Technologies

Previously, NREL partnered with IP Group, Inc. (f.k.a FedIMPACT, LLC) under a field-limited 12-month option to an exclusive license for the NODES patent portfolio. IP Group is an investment entity that seeks early-stage commercialization opportunities viable for start-up company formation that are based on university and national laboratory technology. IP Group executed the option agreement for the technology, funded Emiliano Dall'Anese and Andrey Bernstein to go through the DOE Energy I-Corps, which is a 7-week dedicated entrepreneurial training program (cohort 6),and funded a cooperative research-and-development agreement (CRADA) at NREL to evaluate commercialization-related activities for taking the NODES IP portfolio to market. In December 2019, IP Group decided that they did not want to proceed with this opportunity nor start-up company formation due to lack of expertise within IP Group and certainty in the market. The IP Group CRADA and option were completed and allowed to go abandoned.

In February 2020, NREL began a partnership with another commercialization entity, Utilidata, Inc., that we believe is more suitable for taking such technology opportunities to market. Utilidata has executed a 6- to 12-month option to an exclusive field-limited license to patentable subject matter. Included in the option agreement is the ability to pursue nonexclusive rights to copyrightable subject matter (NREL software record SWR-18-27, see more information below) created under the NODES project. Currently, Utilidata is working with NREL to establish a multiproject CRADA and is seeking joint funding efforts to proceed with commercialization of a NODES-integrated smart meter product. More information is available here: https://utilidata.com/press/utilidata-secures-rights-to-technology-for-bringing-real-time-operational-controls-to-the-grid-edge/.

If the collaboration goes well and Utilidata meets the diligence milestones under their option agreement during the next 6 months to 1 year, NREL may proceed to negotiate and place a field-limited exclusive license.

NREL marketing summary for Real-Time Optimization of Distribution-level Energy Resources available on DOE's Lab Partnering Service: https://www.labpartnering.org/lab-technologies/ce8d218e-4826-497d-aa9b-af23282648ec.

H. Networks/Collaborations Fostered

- Established collaboration with leading groups in academia working on the topic of real-time optimization of power systems:
    - Florian Dorfler (ETH, Zurich)
    - Josh Taylor (University of Toronto)
    - John Simpson-Porco (University of Waterloo)
    - Sean Meyn (University of Florida)

- Ian Hiskens (University of Michigan).

- Fostered collaboration with industry and utilities:
  - Siemens
  - Holy Cross Energy
  - Utilidata
  - Heila Technologies.

I. *Websites Featuring Project Work Results*

Feature article:
https://www.nrel.gov/news/features/2019/small-colorado-utility-sets-national-renewable-electricity-example-using-nrel-algorithms.html
Newsletter story in November 2019 NREL *Energy Systems Integration Newsletter* (scroll to "ARPA-E Success Story: NODES Goes from Theory, to Lab, to Live"):
https://www.nrel.gov/esif/esi-news-201911.html

NREL + Holy Cross Energy fact sheet:
https://www.nrel.gov/docs/fy19osti/72335.pdf

Final workshop website:
https://www.nrel.gov/grid/rto-workshop.html

Newsletter story in March 2020 NREL *Energy Systems Integration Newsletter*:
https://www.nrel.gov/esif/esi-news-202003.html?utm_source=NREL+Energy+Systems+Integration+News&utm_campaign=428cabf856-EMAIL_CAMPAIGN_2019_04_23_09_39_COPY_01&utm_medium=email&utm_term=0_e50a8e7330-428cabf856-289558975#impact

J. *Other Products (e.g., Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)*

NREL software record SWR-18-27, "Real-Time Feedback-Based Optimization of Distribution Grids" (closed-source copyright assertion, MATLAB-based code)

This software enables (groups of) DERs to pursue given performance objectives while adjusting their (aggregate) powers to respond to services requested by grid operators and to maintain electrical quantities within engineering limits. The design of the algorithm leverages a time-varying bilevel problem formulation capturing various performance objectives and engineering constraints and an online implementation of primal-dual projected-gradient methods. The gradient steps are suitably modified to accommodate appropriate measurements from the distribution network and the DERs. By virtue of this approach, the resultant algorithm can cope with inaccuracies in the distribution system modeling, it avoids pervasive metering to gather the state of noncontrollable resources, and it naturally lends itself to a distributed implementation.

K. Awards, Prizes, and Recognition

R&D 100 Nomination for 2020, in process.

Follow-On Funding

Additional funding committed or received from other sources (e.g., private investors, government agencies, nonprofits) after effective date of ARPA-E award.

Table 2. Follow-On Funding Received

Source	Funds Committed or Received
DOE High Impact Projects	$250k (DOE) + $250k (Holy Cross Energy)
FedImpact (IP Group)	$191k
NREL LDRD “Autonomous Energy Systems”	$4.9M
Utilidata (in negotiation)	$400k