Final Scientific/Technical Report

Management of Risk and Uncertainty Through Optimized Co-Operation of Transmission Systems and Microgrids With Responsive Loads

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PRINCIPAL INVESTIGATORS

C. Lindsay Anderson, Associate Professor

Cornell University

cla28@cornell.edu

Judith B. Cardell, Professor

Smith College

jcardell@smith.edu

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LIST OF ACRONYMS AND ABBREVIATIONS

DER: Distributed energy resources

DL: Deferrable load

DR: Demand response

EL: Elastic load

IEEE: Institute of Electrical and Electronics Engineers

RTP: Real-time pricing

TCL: Thermostatically controlled load

I. Executive Summary

The evolution of the power system to the reliable, efficient and sustainable system of the future will involve development of both demand- and supply-side technology and operations. Ambitious national and state-level goals around the decarbonization of electricity relies on the integration of very high levels of renewable resources, most of which are variable and intermittent. The use of demand response is an ideal approach to counterbalance the intermittency of renewable generation and brings the consumer into the spotlight.

Though individual consumers are interconnected at the low-voltage distribution system, these resources are typically modeled as variables at the transmission network level. Demand-side participation cannot be leveraged effectively without explicitly including the distribution system dynamics in the optimization-based wholesale market operations. This project grew from a vision for co-optimized interaction of distribution systems, or microgrids, with the high-voltage transmission system. In this framework, microgrids encompass consumers, distributed renewables and storage. The energy management system of the lower voltage system (distribution or microgrid) can also sell (buy) excess (necessary) energy from the transmission system.

Until recently, very little research had been conducted on the co-optimization of these two systems due to computational limitations. However, advances in computational capabilities, and the judicious use of decomposition methods and innovative approximation methods for high-dimension dynamic programming made this goal a viable objective for this project, leading to a fundamental shift in the ability to integrate and fully utilize demand-side resources.

To this end, the modeling framework developed introduces a novel co-optimization framework, to include the operations of both the transmission and distribution systems (or microgrids) in operational decision making. This framework was used to analyze renewable and distributed generation along with responsive demand and to compare the capability of co-optimized systems to perform with higher levels of variable renewables.

An ideal microgrid is defined as an electric entity capable of operating in both interconnected (with the high-voltage grid) and islanded mode. As such, the microgrid should incorporate generating units (traditional units and intermittent) and if needed, exchange power with the high-voltage grid. The interplay between the microgrid and high-voltage grid motivated the development of the co-optimization approach to ensure efficient performance of the interconnected network.

As the level of renewable and distributed energy resources (DER) increases in power systems, there is a coincident effort to ensure ongoing reliability. Microgrids are likely to play a central role in this development globally. However, a counterpoint is the high cost of microgrid operations, and there exists a need to develop efficient tools to operate microgrids optimally and economically. This project investigated the potential of demand response (DR) to reduce microgrid operation cost, while supporting renewable integration.

Results show that the use of a bi-level optimization approach is an appropriate structure, capable of co-optimizing a transmission system with multiple distribution systems and microgrids. While increasing the number of connected systems provides increasing flexibility for renewables integration this can also the economic benefits to the low-voltage subsystems with each additional system connected. Comparison of a traditional single-level decision structure with the co-optimization approach illustrates a reduction in overall system cost under co-optimization, while specific cost allocations to transmission and distribution systems are changed.

II. Objectives

The objective of this project was the development of a comprehensive co-optimization framework to integrate the traditional and renewable generation within the transmission system, with distribution systems and microgrids that included responsive load and distributed generation.

Development of this framework included the following specific tasks:

i. A performance comparison of renewable output forecasting/scenario generation methods

ii. A comprehensive framework for the interplay between the micro and macro grids

iii. An analysis of the impacts of different demand response strategies on the power grid operation

iv. An analysis of the performance of co-optimization methods for solving the integrated problem.

III. Technical Approach

This project developed a bi-level optimization framework applied to optimize system performance with (i) increasing presence of distributed energy resources (DER) at the low-voltage level, and (ii) variable wind power generation at the high-voltage level. Various system configurations with increasing presence of microgrids, with active devices were analyzed.

Preliminary work explored price mechanisms to manage the microgrid and its interactions with the transmission system. Wholesale market operations are addressed through the development of scalable stochastic optimization methods that provide the ability to co-optimize interactions between the transmission and distribution systems. Modeling challenges of the co-optimization are addressed via solution methods for large-scale stochastic optimization.

The publications from this project present analyses considering the impact of a grid-connected microgrid on network transmission of the power system. The locational marginal prices of the power system are used to strategically locate microgrids so as to avoid transmission system congestion. In addition, a Monte Carlo simulation approach is implemented to confirm that network congestion can be attenuated if appropriate price-based signals are set to define the import and export dynamic between the two systems [1].

Empirical studies were undertaken to explore interaction between the transmission system and a microgrid. Of primary interest is the effect of this interplay on the congestion conditions in the main network. This analysis used a coupled model between the unit commitment and dispatch of the transmission system, and the energy management solution for the microgrid. A case study of the IEEE 30-bus system was implemented to explore this approach.

In addition to system-based analysis, we also explored state-of-the-art in scenario reduction for renewable resources. One of the challenges of developing representative scenarios for spatially distributed renewables, is developing a low-cardinality set that represents the diversity and spatio-temporal correlation of the diverse locations on the grid. To address this issue, a new method was developed which is best described as "band-depth" clustering. In this approach, spatio-temporal data is clustered into *bands* that are used to classify similar scenarios in two dimensions. The details of this research is described in [2]

Three types of DR, namely thermostatically controlled load (TCL), deferrable load (DL) and elastic load (EL), are explored in the context of various system conditions. Since systems with significant renewables and DER are subject to high levels of uncertainty, the investigation is conducted under a stochastic rolling horizon optimization framework that leverages the update of renewable generation forecast and the energy market real-time prices (RTP). A case study illustrates that certain system conditions, such as price peaks and moderate temperatures, facilitate best demand response performance. Conversely, inaccurate price forecast information is seen to lead to ineffectual operation of microgrids that results in higher cost. The insights provided by the study of various types of DR are helpful for microgrid design with consumers' preferences taken into consideration [3]. Additional work on the leveraging of data centers in the provision of demand response is described in [4]

The incorporation of spatially distributed storage in operational decision making brings additional complexity. Because of their sequential nature, in theory, power scheduling problems with storage may be solved via stochastic dynamic programming. However, this scheme is limited to small networks by the so-called curse of dimensionality. The work described in [5] describes the management of a network composed of conventional power units and wind turbines through stochastic dual dynamic programming, showing that this approach allows solution of these complex problems in reasonable computational time.

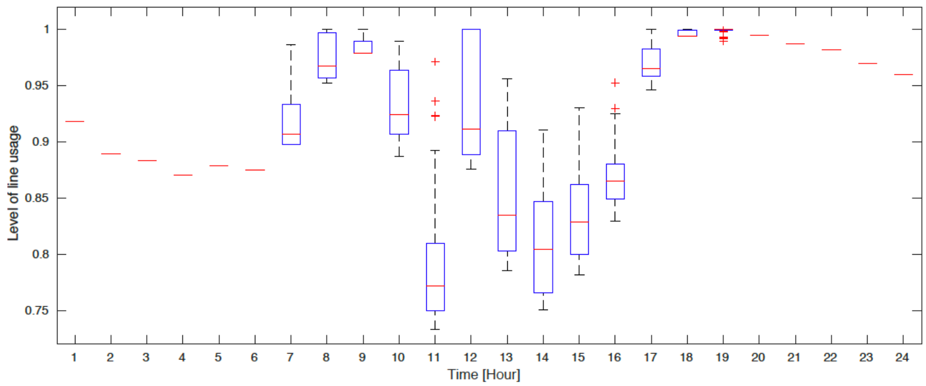
The culmination of this effort was the development of a co-optimization method to include the high- and low-voltage systems in a single framework, as illustrated in Figure 3. To achieve this objective, a bi-level optimization approach was selected from candidate methods. Initial framing and analysis of this problem was described in [6]. The scalability of bi-level optimization to manage increasing numbers of distribution systems within a transmission system is explored in [7], including comparing the performance of co-optimization of these systems, relative to the traditional single-level approach.

IV. Results

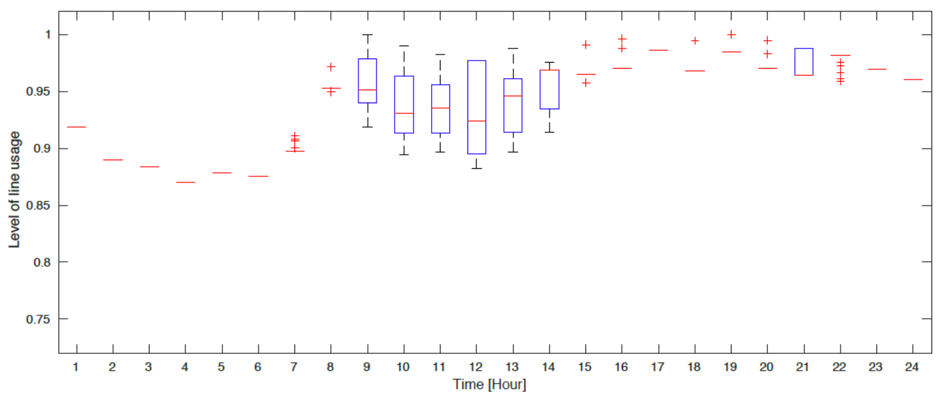
This project proposed and developed the use of a bi-level optimization algorithm to replace the traditional single-level optimization currently used for the analysis of power system costs and generator dispatch, as shown in Figure 1. Though the existing single-level framework adequately determines system performance at low levels of DER and microgrid penetration, as the use of new technologies and active devices becomes more widespread, the traditional single-level framework will become inadequate. The project developed a bi-level optimization framework and demonstrates its use with the IEEE 30 bus test system and an increasing number of active microgrids. The system simulations presented demonstrate that as DER use increases a bi-level optimization framework more accurately determines power system operating costs than does the traditional single-level optimization algorithm.

The results show that in a congested system the most effective location for the microgrid is the load-bus with the highest nodal price for power. The effect of this placement shows positive performance outcomes for the transmission system through elimination of transmission congestion. Placement at locations with lower nodal prices has no effect on congestion in the best case, and exacerbates congestion problems in the worst case of placement at the source node of a congested line.

Given the placement of a microgrid in a congested network, pricing strategies are important to induce the microgrid to behave in a manner that attenuates congestion in the transmission system, while optimizing energy management within the microgrid. The results from this project show that fixed prices for power injections/withdrawals from the transmission system send ineffective signals to the microgrid, regardless of the level of those prices. Conversely, the piecewise linear cost function, obtained from sensitivity analysis within the transmission system, is highly effective in ensuring that microgrid develops a strategy that is effective for both its consumers and the transmission system as a whole. As shown in Figure 1, a piecewise linear cost function for exchange between transmission and microgrid can mitigate congestion costs on the transmission network.



(a)



(b)

Figure 1: Comparison of Line Use under Exchange Pricing Schemes. Comparison of transmission line between nodes 6 and 8 (a potentially congested segment) on the IEEE 30-bus system, under two pricing schemes: (a) is a fixed locational marginal price, and (b) is a dynamic piecewise linear function of energy exchange, showing less variability under piecewise linear pricing function.

A stochastic rolling horizon model is used to simulate the decision process of a microgrid energy management system to manage loads, generation, and purchases from the main grid. The rolling horizon scheme allows exploitation of the forecast updates for the prices and renewables in the real time market. Therefore, this load categorization and the

corresponding DR designs enable the best utilization of DR potential. Insights from the analysis of different DR provides microgrid operators and designers with the knowledge to incorporate the various types of DR that are suitable for the given system conditions. In general, TCL achieves fine performance based on provision of load reduction during peak price periods. Accurate deferral of loads to off-peak periods, in conjunction with good price forecasts, is the basis for cost savings from DL. In contrast, EL accomplishes energy saving primarily from energy conservation under high price periods. However, lower operational cost is possible for increased consumption as a result of the reduced average energy price. Last, it is shown that DR in a microgrid has the potential to provide more cost savings than in a distribution network, since a microgrid provides more flexibility for DR to arbitrage. As an example, Figure 2 highlights the potential cost savings to the microgrid operator, under peak summer conditions from each of TCL, while Figure 4 shows the combined savings from TCL, DL and EL over the same time period.

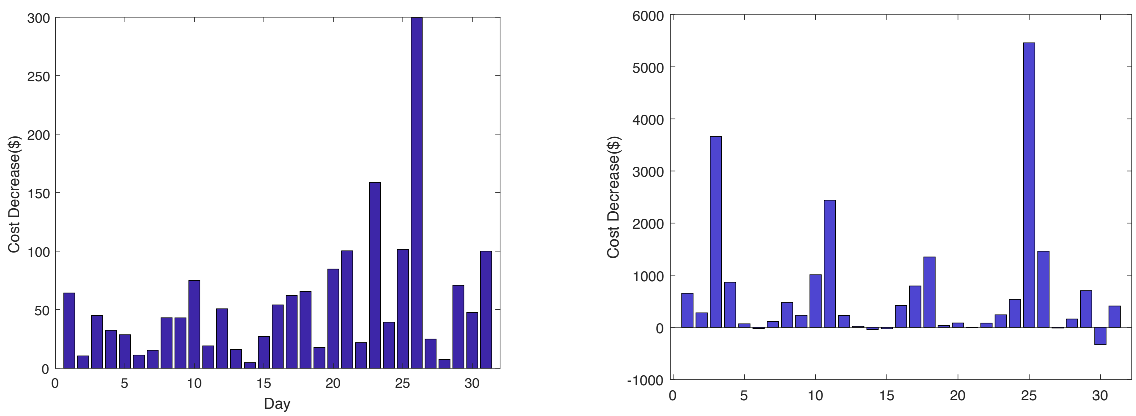


Figure 2: Microgrid Cost Savings for Flexible Load Types: Cost savings to an example microgrid in peak summer conditions; panel (a) shows savings through TCL use, and (b) shows total of TCL, DL and EL.

In the final phases of the project the co-optimization framework, shown in Figure 3, is used to analyze a grid-connected microgrid or distribution system with DR and distributed generation.

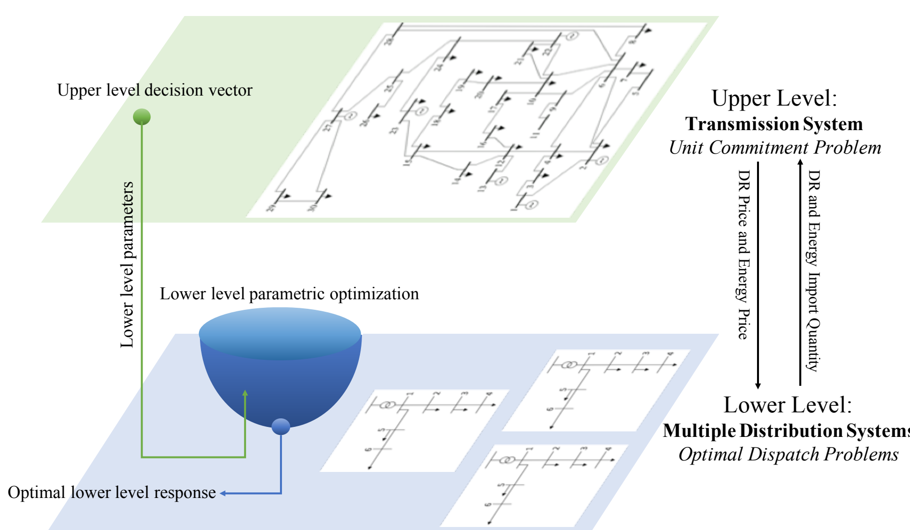
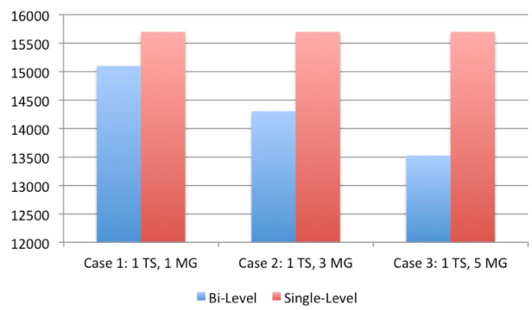
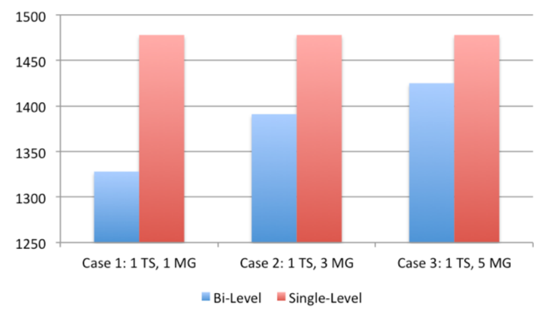


Figure 3: Overview of Bi-level framework for Transmission-Distribution Co-optimization

Results of the co-optimization framework can be used to explore the benefit of considering transmission and distribution decisions simultaneously. The framework is also capable of exploring the impact of coordinated decision making on the distribution of costs across transmission and distribution systems. For example, Figure 4 shows the distribution of system costs as the number of connected microgrids are increased in the coordinated decision making. This result highlights that bi-level optimization is able to leverage microgrid flexibility to reduce overall system costs. In Figure 4(b), it is clear that increasing number of connected microgrids leads to reduced cost savings for each individual microgrid in the system.



(a)



(b)

Figure 4 Comparison of Cost to (a) transmission system and (b) microgrids, under single- and bi-level optimization, with increasing number of connected microgrids.

Additional results and findings are detailed in the publications cited at the end of this report.

Accomplishments and Conclusions

System simulations quantify system performance in terms of cost, first using the traditional single-level optimization framework, and second using the proposed bi-level framework. Comparisons between the system with traditional, passive distribution systems and with microgrids are also presented, with results again quantified via the interconnected system operating costs. Results show that at low levels of DER and microgrid penetration, traditional (single-level) system optimization algorithms perform adequately as compared to the proposed bi-level optimization framework. However, as DER and microgrid penetration increase, the traditional single-level framework does not accurately capture the full system benefits of distributed technologies. The results demonstrate that new optimization algorithms, such as the proposed bi-level framework, will be required if the benefits of DER are to be accurately quantified in the evolving power system.

An important future direction is to model the microgrid interconnection with the transmission network and explore how DR in the microgrid benefits the main system.

Such a study will likely reveal new benefits of the microgrid DR programs. One crucial area is to investigate the DR's ability to shape the load profile at the connecting bus, which could impact the congestion likelihood in the main system, assist in the management of variability, and reduce locational marginal prices. In addition, incorporating the outside temperature uncertainty and more detailed physical constraints such as voltage magnitude and power losses is also a promising direction.

V. Accomplishments

The objective of this project was the development of a comprehensive co-optimization framework to incorporate the generation and transmission system with microgrids that may include responsive loads and distributed generation.

The objective was achieved through four primary elements:

1. Development of multi-area renewable resources modeling methods that preserve both spatial and serial correlations. The methods build on statistical- and optimization-based techniques to generate scenarios for various classes of renewables that are accurately correlated in space and time;
2. Investigation of demand response (DR) strategies to mitigate the impacts of renewables intermittency on system operation costs through microgrid modeling that integrates the energy management of the microgrid with the DR strategies;
3. Analysis of the interaction between the micro- and macro-grids to manage congestion in the transmission network and alleviate the burden of intermittent renewables through incorporating micro grid dynamics with the operational models of the transmission grid,
4. Development of a comprehensive stochastic optimization framework that incorporates renewables, DR and storage with judicious decomposition methods that ensure reliable solutions that are scalable to large networks.

This project addressed risk and uncertainty of the future power system by participating in the solicited research areas of a) Wholesale market operations through the integration of responsive demand in the unit commitment and economic dispatch process of the wholesale market, and c) Demand-side participation through comprehensive models that incorporate consumers and distributed generation in participatory micro grids.

The goals were achieved through the tasks/milestones delineated in Table 1.

Table 2: Milestone Status Report

Milestone	Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments on progress and/or deviations
Milestone 1	Development and Release of Project Website	12/1/16	12/1/16	Public release https://blogs.cornell.edu/sidr/	n/a
Data collection Task 2	Sufficient data is collected to develop and validate models	6/30/17	6/1/17	Minimum 3 characteristic regions are collected	Complete
Publication Year 1	Peer-reviewed conference proceeding, comparing current and alternative methods for characterizing uncertainty and correlations of renewables	9/30/17	9/15/17	Accepted for presentation	Completed, presented at SIAM conference October 2017.

Completion of Task 2	Investigation of DR strategies to mitigate the impacts of the intermittency of renewables on transmission system	9/30/17	9/30/17	Results disseminated	Complete
Milestone 2	Project website updated with models, data and publications from Task/Subtasks 2	9/30/17	10/15/17	Materials updated online	Complete
Data collection Task 3	Sufficient data is collected to develop and validate models	10/31/17	12/31/19	Performance data for minimum 2 different DR strategies	Completed
Presentation Year 1	Presentation at technical conference detailing performance of alternative renewables modeling approach	12/30/17	10/25/17	Accepted for Presentation	Complete

Publication Year 2	Technical publication submitted, illustrating DR/microgrid model with test case	3/30/18	09/22/19	Accepted for publication	Complete[1]
Completion Phases 1 & 2		1/30/18	10/01/18	Results disseminated	Complete
Data collection Task 4	Sufficient data and network samples collected to develop and validate models	1/30/18	12/31/18	Materials updated online	Complete
Milestone 3	Project website updated with models, data and publications from Task/Subtasks 4	10/30/18	04/01/19	Task 4 results available online	Complete

[1] *Editor indicated the minor revisions would be acceptable, but has not been officially processed at time of reporting*

Presentation Year 3	Presentation at technical conference, detailing potential transactive energy framework for microgrid/distribution systems	11/1/18	01/10/19	Accepted for Presentation	Complete, presented at HICSS 52, January 2019
Presentation Year 3	Presentation at technical conference detailing results of DR/microgrid and optimal locations	11/1/18	07/22/19	Accepted for Publication	Complete, presented at PSERC Summer Workshop
PhD Awarded	PhD Student completes dissertation at completion of Task 4	1/1/19	06/13/19	Dissertation defense completed.	Complete
Publication Year 3	Technical publication submitted, (initial co-optimization model between microgrid with DR, and transmission)	9/30/19	09/15/19	Accepted for publication	One paper accepted for publication, also presented at HICSS Conference (Cardell) Second paper, under revision

Milestone 4	Project website updated with models, data and publications from Task/Subtasks 5	9/30/19	12/31/19	Task 4 results available online	Complete
Phase 4 & Project Completion		12/31/19	12/31/19	Project deliverables complete	Complete

APPENDIX A: Product or Technology Production

Publications and Presentations

- J. Liu, M.G. Martínez, C.L. Anderson (2016) Quantifying the Impact of Microgrid Location and Behavior on Transmission Network Congestion. Proceedings of the 2016 Winter Simulation Conference. Washington DC.
- L. Zéphyr, J. Cardell, C.L. Anderson (2017) A Vision for Co-optimized T&D System Interaction with Renewables and Demand Response. Proceedings of the 50th Hawaii International Conference on System Sciences. Kona, HI. January 4-7, 2017
- Zephyr, L., Liu, J., and Anderson, C. L. (2017) Stochastic Co-Optimization of Transmission and Distribution-as-Microgrids Networks with Renewables and Energy Storage. SIAM Conference on Optimization, Vancouver, Canada, May 22, 2017.
- L. Zéphyr (2017). Co-optimizing the Interplay Between Micro and Macro Grids. Presented at the INFORMS Annual Meeting, Phoenix Arizona. October 2017.
- Anderson, C.L. Incorporating Wind and Distributed Storage into Stochastic Economic Dispatch Solutions. Power Engineering Research Center (PSERC) Webinar. November 21, 2017.
- Aravinthan, V., Anderson, C.L., Cardell, J.B., and Jewell, W. (2017) Investigating Optimal Model Coordination for Integrated Transmission and Distribution Systems. Power Engineering Research Center (PSERC) Industrial Advisory Board Meeting, Phoenix AZ. December 3, 2017.
- Zéphyr, L., Anderson, C. L. (2017) Stochastic dynamic programming approach to managing power system uncertainty with distributed storage. Computational Management Science, 15, 87–110. http://doi.org/10.1007/s10287-017-0297-2
- Anderson, C.L. Research Needs for Co-optimization of Multi-level Integrated Electricity Systems. Closing Plenary Panelist. Utilities Variable Integration Group Spring Technical Meeting. March 13-15, 2018. Tuscon, AZ.
- Gupta, A., & Anderson, C. L. (2018). Statistical Bus Ranking for Flexible Robust Unit Commitment. IEEE Transactions on Power Systems. https://doi.org/10.1109/TPWRS.2018.2864131
- Angela Upreti, Judith Cardell, Dominique Thiebaut, (2019) "Data Privacy in the Smart Grid: A Decentralized Approach," Proceedings of the 52nd Hawaii International Conference on System Sciences http://hdl.handle.net/10125/59786.
- Liu, J., Zephyr, L. and Cardell, J., 2020, January. Co-optimizing High and Low Voltage Systems: Bi-Level vs. Single-Level Approach. In Proceedings of the 53rd

Hawaii International Conference on System Sciences. http://hdl.handle.net/10125/64107

- Liu, J., Zéphyr, L., & Anderson, C.L. “Optimal Operation of Microgrids with Load-differentiated Demand Response and Renewable Resources,” Journal of Energy Engineering (in press).

Website(s) or other Internet site(s)

The project website is located at https://blogs.cornell.edu/sidr/, with the purpose of describing the project and disseminating data and from the project. This website is updated as results and information become available.