Field Demonstration of Inverter-based Voltage Management using Extremum Seeking Control

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***Abstract*—The influx of Distributed Energy Resources (DER) throughout the distribution system presents a challenge and an opportunity for maintaining power quality standards throughout the system. As such, DER Management systems have become a burgeoning field in both industry and academia. This work presents results from a field test of a model-free, distributed control approach, Extremum Seeking, applied to voltage management on a live feeder in Riverside, CA. The paper presents selected results to highlight the successes and challenges the control approach faced. The work shows that despite slow inverter response, extremum seeking control is able to drive voltage toward a target without knowledge of the system it is operating on.**

***Index Terms*—Voltage Support, DER, Model-Free Control, Field Demonstration**

I. Introduction

With the increasing penetration of distributed energy resources (DER) on the grid edge, there has been significant interest in DER management solutions in both industry and academia. A chief concern of DER management is in maintaining voltage within acceptable standard ranges. Many methods for managing this issue have been proposed [1]. Interconnection standards [2] provide a basis for local voltage management via droop-like control, but cannot maintain voltages across a system without significant penetration. Centralized optimization approaches [3], [4], distributed optimization [5] and combinations of optimization and droop [6], [7] show promise for managing voltage within distribution systems, but rely on significant point-to-point communication, measurement visibility, and accurate systems models. All of these requirements have historically been challenging for distribution utilities. However, another control approach that attempts to mitigate these issues, extremum seeking control, has emerged in the literature.

Extremum Seeking (ES) control is a distributed control approach that seeks to perturb a system by injecting a relatively slow sinusoidal probe in its controllable output. It uses the impact of that perturbation on a measured objective to calculate its gradient and drive the objective toward a minima [8]. If the objective is convex, ES can be proven to drive the system into a neighborhood of the global minimum [9]. The ES controller does not need to know anything about the composition of the objective in order to drive it towards a minima, and thus is considered a model-free control approach.

A block diagram of the ES control algorithm is shown in Fig. 1. The objective is passed through a high-pass filter, the result is demodulated and passed through a low-pass filter. The output of the low pass filter is functionally the gradient of the objective with respect to the sinusoidal probe. This is then passed through an integrator to mimic gradient descent. The output of the integrator then has the probe signal added back and the control command, u, is sent to the inverter.

The control is distributed in the sense that its logic resides at the actuator, and only requires a broadcast of the objective function in order to operate. As long as each ES controller operates on a distinct probing frequency, a collection of these devices can minimize the same objective function without communication between controllers or any large scale centralized optimization.

ES applications for distribution system management began with voltage through reactive power control [9]. The work was extended to show a two dimensional ES controller for simultaneous management of voltage and real power target tracking [10] at a distribution substation, and further to manage voltage phasors [11]. While all of these studies show promising results, they rely on assumptions of very fast communication between the local controller and the inverter, and operate in systems

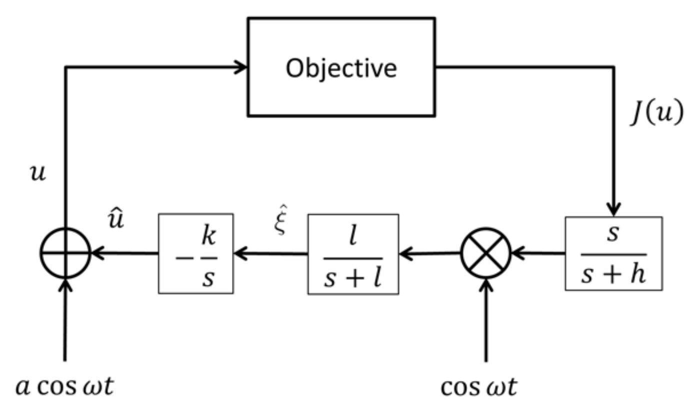

Fig. 1. ES control block diagram.

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with idealized conditions.

Some work has been done to put ES control into more realistic conditions and test it with actual power hardware. Hardware-in-the-Loop tests have demonstrated successful operation of PV inverters for voltage management [12], [13] and real power tracking [14], [15]. These tests showed successful management in laboratory conditions despite challenges in communication delays and inverter response. However, these tests still do not represent how ES performs on a live system in the presence of real noise and system perturbations.

This work presents results of a deployment and testing of extremum seeking control for voltage management on a live system in the Riverside Public Utility territory. The aim was to see if ES will manage voltage successfully in real-world conditions and to further illuminate any technical gaps needed to make ES a viable control option in power systems. The work is part of a larger project, led by the University of California, Riverside, deploying an scalable DER management system capable for significant PV penetrations.

The remainder of the report will be presented as follows: Section II will discuss the test site and hardware. Section III will describe the tests performed. Section IV will present selected results and discuss their successes and failures. And finally Section V will conclude with thoughts on the overall field test outcomes, the challenges for extremum seeking, and express needs for future work.

II. Field Test Site and Hardware

The demonstration test sites included three PV arrays located at buildings on the University of California, Riverside (UCR) College of Engineering Center for Environmental Research and Technology (CE-CERT) campus. Each PV array was connected to an Advanced Energy inverter (models AE100TX/AE260TX) at a different CE-CERT building, their DC and AC capacities are shown in Table I. Additionally, a 100 kW, 1 MWh battery was connected at building 1200. All of the control logic for this, and other applications developed in this project, are performed on Smarter Grid Solutions' Active Network Management platform. The platform is comprised of a central server for operational control and visualization applications and data exchange, as well as distributed controllers connected at the inverters.

The three CE-CERT buildings reside on two feeders connected to the same substation in the Riverside Public Utility service territory. Building 1200 is on one feeder, while buildings 1084 and 1086 are on a different feeder. A microPMU was placed on the low-side of the transformer that fed building 1200. All other voltage measurements used in the control demonstrations were located at the PV inverters.

TABLE I
PV installation capacities at UCR CE-CERT buildings.

Building	PV Capacity [kW]	Inverter Capacity [kW]
1200	100	100
1084	180	100
1086	180	260

The AE100TX/AE260TX 3-phase inverters provide limited controllability of real and reactive power. They are capable of receiving a real power curtailment command that arrive no faster than every 30 seconds. This response is much slower than previous hardware-in-the-loop tests [14], [15] and forces the minimum period of the sinusoidal ES probe from less than 1 minute to 10 minutes. This slow probing significantly increases the neighborhood of the optimum voltage the algorithm guarantees [9].

These AE inverters also had very limited reactive power control, allowing for reliable operation between ± 0.95 power factor in increments of 0.01. The extremely small range and limited granularity of control meant that meaningful volt-var control is not possible with these resources, and so while ES can simultaneously manage both real and reactive power, only real power was controlled.

III. Test Description

Thirteen extremum seeking tests were performed on the PV inverters at the UCR CE-CERT buildings 1200, 1084, and 1086 from January to July 2020. The tests were 4-6 hours in length. Table II shows the test dates and resources used.

In every test, the majority of parameters that define the ES control remained the same and are listed in Table III. Most testing was performed at building 1200 with only the single ES controller, though tests at 1084 and 1086 were performed such that the two inverters operated together on the same objective, and so had differing probing frequencies and corresponding filter parameters.

One area in which the tests changed substantially is in the composition of the objective. Early tests managed the voltage of the inverter, where later tests managed voltage at the CE-CERT building microPMU or even at two locations. The voltage regulation setpoints were chosen such that we anticipated optimal PV output would be greater than full power. As voltage conditions at the CE-CERT buildings are typically high, these targets were typically between 284 and 290 volts line-to-neutral. These voltage objectives took the form: $J = \alpha_l * \sum_{\phi=1}^{3}(V_{target,l} - V_{\phi,l})^2$, where α_l is a weight and the equation would be repeated for each location, l included in the objective function.

TABLE II
Experiment date information, times in Pacific timezone.

Test Date	Resources	Location	Start Time	End Time
1/17/20	PV	1200	10:00	15:00
1/24/20	PV	1200	10:00	15:00
1/29/20	PV	1200	10:06	14:30
2/20/20	PV	1084 & 1086	12:34	15:37
3/20/20	PV	1084 & 1086	9:30	15:15
4/23/20	PV	1200	10:00	14:00
5/20/20	PV	1200	11:00	15:00
6/9/20	PV	1200	10:00	15:00
6/10/20	PV	1200	10:00	15:00
6/11/20	PV	1200	9:16	14:00
7/17/20	PV+Batt	1200	9:00	15:05
7/22/20	PV+Batt	1200	9:00	15:00
7/25/20	PV+Batt	1200	10:30	16:00

For each test, the system is initialized at near full PV curtailment. This provides visibility into whether the ES controller can identify the appropriate action, consistent with engineering intuition. Because the setpoint was chosen to be above the the voltages, we expect the ES controller to drive the system output toward full power. Correspondingly, if voltages are greater than the setpoint later in the test, we anticipate that the control would choose to curtail the PV system. When voltages are near the target voltage setpoint, we expect ES to move the output of the PV inverter very little.

IV. Selected Results and Discussion

Results from four of the thirteen field tests will be discussed here to highlight successes, failures, and features of the ES approach to volt-watt control. The evaluation of these results is limited based on the circumstances of the tests. Algorithm performance is assessed through observation of the trajectory of control and the internal states of the algorithm. While PV capacity, hardware limitations, and the sensitivity of voltage to network conditions make the prospect of maintaining a tight tolerance around a voltage target unrealistic, we can still show the ability of the algorithm to support voltage management of a feeder by evaluating if it is behaving in such a way that is consistent with engineering intuition.

The first test we will discuss was performed on January 29th, 2020. Fig. 2 displays experimental results in which the local inverter voltage was regulated with a target of 290V. The top plot shows the PV output, the setpoint that ES commanded with and without the probe, and an estimation of the maximum PV output given the solar radiation. The bottom plot shows both the average L-N voltage measured across the tthree phases of the inverter, the target voltage, and the value of the objective function. We see ES commanding the inverter to increase its output towards the maximum after initialization as the voltages are below their target. We see the average voltage driven towards its target and the objective function value fall. The internal gradient estimated by the ES controller is correctly identified negative while the system increases its power output. Lastly, the test had considerable cloud cover, which is evident in the PV max power curve in the second half of the experiment period. This ES control logic was able to successfully mitigate that impact by curtailing just below the unstable PV output power region so that it could continue to probe and monitor its impact on the system.

The experiment on February 20th, was performed on the inverters located at buildings 1084 and 1086. In this experiment, the objective is composed of the local voltages at both inverters with equal weighting, with target of 290V. Results are shown in Fig. 3, and a third plot is added to show the evolution

TABLE III
EXTREMUM SEEKING CONTROL PARAMETERS.

Building	Amp. [kW]	Frequency [Hz]	Filter Params.	Int. Gain
1200	8	1.667E-3	1.667E-4	-0.2
1084	8	1.515E-3	1.515E-4	-0.2
1086	8	1.667E-3	1.667E-4	-0.2

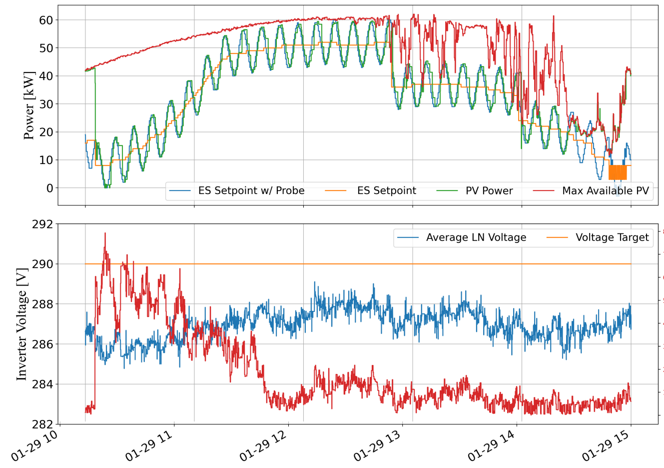

Fig. 2. Experimental results from January 29th Field Test.

of the gradients estimated by each ES controller. The inverter at 1084 has a larger impact on its voltage, and thus a larger gradient on the objective, so it begins to move first. We see that the ES controller at 1086 has some difficulty identifying it's gradient, but once 1084 can no longer contribute, 1086 begins to move in the direction of minimizing the objective function. While the test was successful, and the two inverters did drive toward their optimum power output, improvements in the slow responsiveness in the second inverter could be made. More work is needed to understand the conditions that caused the large fluctuations the gradient estimation at building 1086 which yielded the slower response.

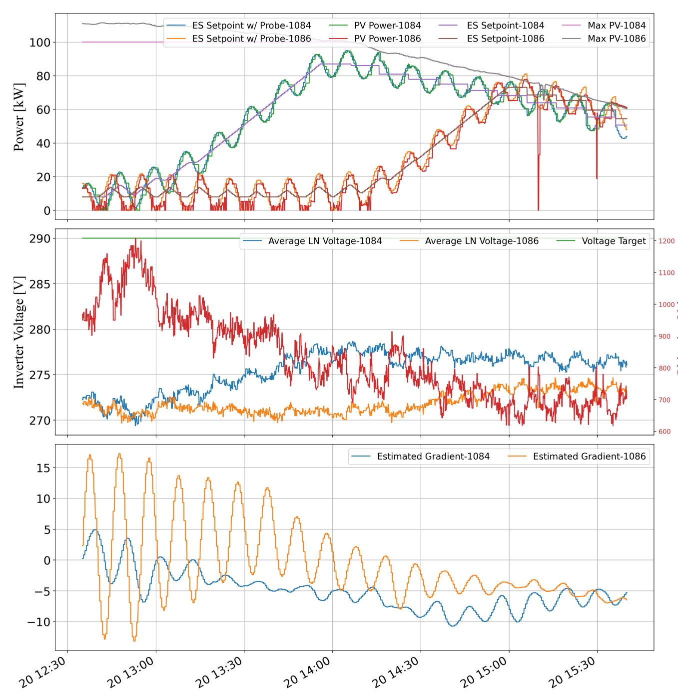

Fig. 3. Experimental results from the February 20th Field Test.

In the final successful test discussed, on July 22nd, the voltage was initially regulated to 288V L-N, measured at the microPMU located at low-side building 1200's utility transformer. In this test, the 100kW battery was connected to the building 1200's circuit and used to duplicate the output of the PV to effectively double the installed capacity managed in the test. Results are shown in Fig. 4. Like previous results, the voltage target begins above the measured building service voltage, the ES control identifies a negative gradient and begins to drive the system toward full power. The system saturates at full output just as external conditions on the feeder cause the voltage to jump near the target voltage. This presents an opportunity and the test operator chooses to reduce the target below the current voltage range to see if the system responds. Shortly after the change the system identifies a positive gradient and begins curtailing away from maximum power as the testing period ends. This behavior is consistent with successful operation of the extremum seeking control, and shows its ability to adjust to changing conditions and objectives.

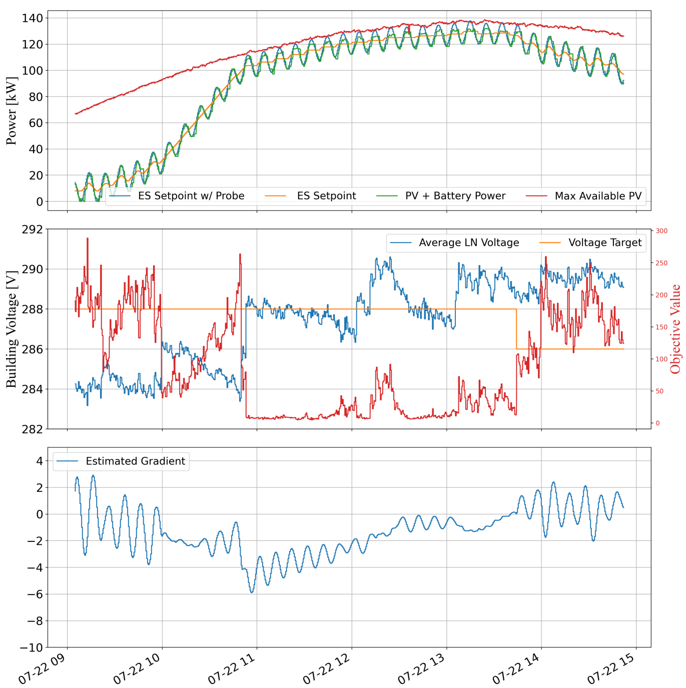

Fig. 4. Experimental results from the July 22nd Field Test.

While most of the thirteen experiments performed showed results consistent with successful ES control, there were two that failed to operate successfully. The first failure was due to a software bug, however the second, on our last test on July 25th, was caused by a failure of the algorithm to determine its gradient in real world conditions. July 25th was the only test that was performed on a weekend, in an attempt to maximize the effective PV penetration on the feeder lateral. ES control was configured to manage the three phase service voltage for building 1200 measured by microPMU. Results are shown in Fig. 5. We can see that despite the low voltage relative to the target, the power output fails to increase. The gradient estimation is incorrectly identified as positive, resulting in the system remaining curtailed during the entire test. This is despite the operator attempting to increase the voltage target and thus the objective function value.

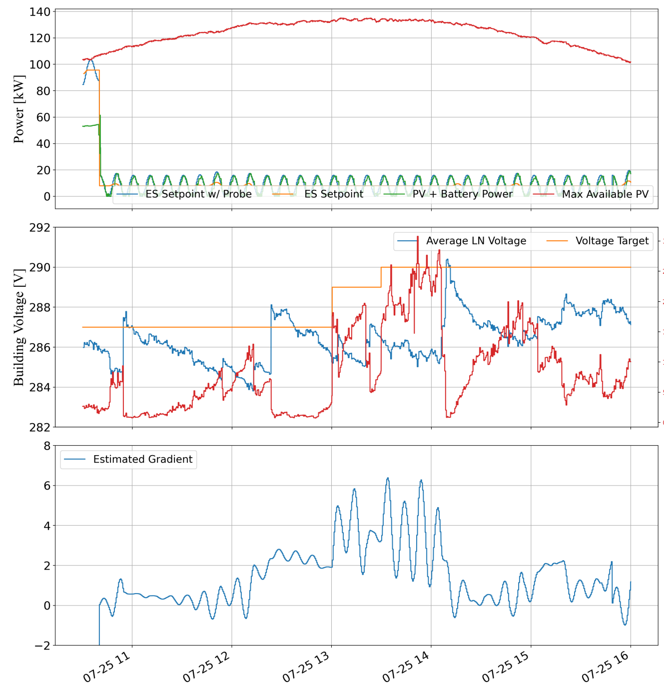

Fig. 5. Experimental results from the July 25th Field Test.

A power spectral density (PSD) analysis was performed on the microPMU and objective data to understand the visibility of the sinusoidal probing signal during the test. Fig. 6 shows PSD plots for the failed test and another testing day in which the ES was able to determine its gradient. The top plot shows the PSD performed on the voltage plot, the vertical lines indicate the probing frequency and its first harmonic. We can see that in the successful test, there is a corresponding spike at the probing frequency in the voltage PSD plot relative to its nearest neighbors, which is absent in the failed test's plot. When we look at the power measured at the microPMU, the plot suggests that meter was reading similarly for both tests, indicating that the probing signal in real power was in fact active and visible in power. The bottom PSD plot further indicates that the absence of the probe signal in the voltage is more conspicuous when the analysis is run on the objective function. When we consider the results, the surrounding background noise coupled with a potential stiffness in the voltage response to power changes may have prevented the ES control from being able to observe its probe's impact. This stiffness may be caused by low weekend loading conditions, but require further study in similar conditions to be sure.

V. Concluding Remarks

The work presented showed results from a series of field tests of extremum seeking control for management of observable local voltages. The tests were performed on commercial-

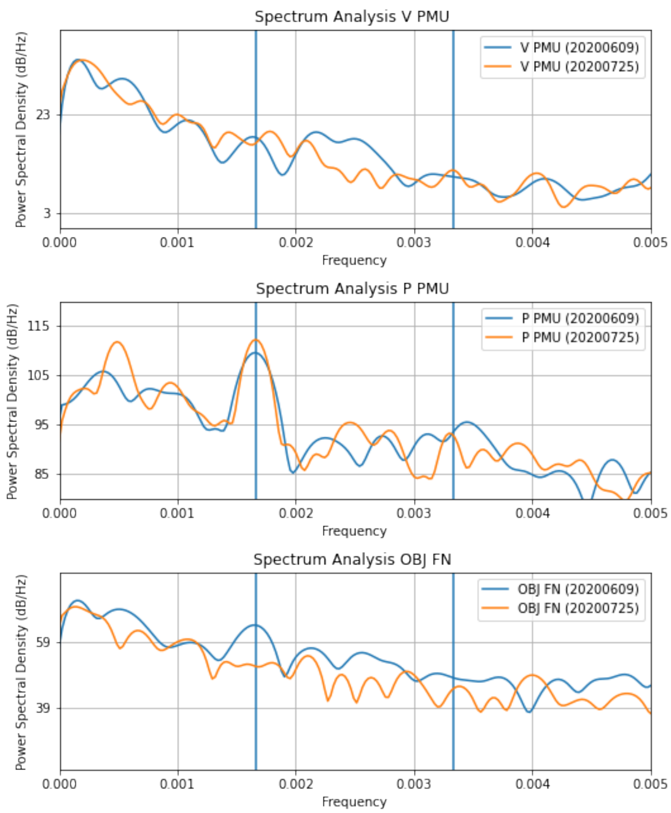

Fig. 6. Power spectral density plots for voltage, power, and objective values during the July 25th Test.

scale PV installations at three buildings on the University of California, Riverside's CE-CERT campus. Thirteen tests were performed, of which four are presented here. Three test show results consistent with successful actuation of volt-watt control by the extremum seeking controllers, despite a very slow response capability of the inverters installed at the site and the relatively small impact on voltage that the installed systems had across their full output range. The final test result selected presented a case in which the ES controller was unable to respond in a way consistent with expectations, and spectral analysis on the results data suggest the light loading conditions of the system may have diminished the ES probes impact on the voltage objective.

While the goals of the field trial were successfully met, the team believes that more work is needed before ES control can be deployed at scale:

- Further demonstrations are needed with inverters capable of faster probing signals (periods less than one second) in order to observe a tighter convergence on a minima.
- Additionally, simulation and demonstration studies to identify the conditions that impact the ability of ES to identify an appropriate gradient are needed to help.
- Refinement of the ES approach to adaptively determine probing signal parameters based on conditions could significantly improve the algorithm's performance across a wide variety of conditions and may speed deployment by eliminating the need for manual parameter tuning.
- Finally, ES control offers a single control algorithm capable of managing a diverse set of power systems objectives, but may not be suitable for all applications if the inverters simply meet the minimum performance requirements of current interconnection standards. Interconnection standards with higher performance specifications may be needed to support ES and other innovative control approaches.

Acknowledgments

References

[1] K. Turitsyn, P. Sulc, S. Backhaus, and M. Chertkov, "Options for control of reactive power by distributed photovoltaic generators," *Proceedings of the IEEE*, vol. 99, no. 6, pp. 1063–1073, 2011.

[2] "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," tech. rep., IEEE. ISBN: 9781504446396.

[3] M. Farivar, C. R. Clarke, S. H. Low, and K. M. Chandy, "Inverter VAR control for distribution systems with renewables," in *IEEE International Conference on Smart Grid Communications (SmartGridComm)*, pp. 457–462, IEEE, 2011.

[4] E. Dall'Anese, G. B. Giannakis, and B. F. Wollenberg, "Optimization of unbalanced power distribution networks via semidefinite relaxation," in *North American Power Symposium (NAPS), 2012*, pp. 1–6, IEEE, 2012.

[5] S. Bolognani and S. Zampieri, "A distributed control strategy for reactive power compensation in smart microgrids," *IEEE Transactions on Automatic Control*, vol. 58, no. 11, pp. 2818–2833, 2013.

[6] K. Baker, A. Bernstein, E. Dall'Anese, and C. Zhao, "Network-Cognizant Voltage Droop Control for Distribution Grids," *IEEE Transactions on Power Systems*, vol. 33, pp. 2098–2108, Mar. 2018.

[7] B. A. Robbins, C. N. Hadjicostis, and A. D. Dominguez-Garcia, "A Two-Stage Distributed Architecture for Voltage Control in Power Distribution Systems," *IEEE Transactions on Power Systems*, vol. 28, pp. 1470–1482, May 2013.

[8] M. Krstic and Hsin-Hsiung Wang, "Design and stability analysis of extremum seeking feedback for general nonlinear systems," in *Proceedings of the 36th IEEE Conference on Decision and Control*, vol. 2, (San Diego, CA, USA), pp. 1743–1748, IEEE, 1997.

[9] D. B. Arnold, M. Negrete-Pincetic, M. D. Sankur, D. M. Auslander, and D. S. Callaway, "Model-Free Optimal Control of VAR Resources in Distribution Systems: An Extremum Seeking Approach," *IEEE Transactions on Power Systems*, vol. 31, pp. 3583–3593, Sept. 2016.

[10] D. B. Arnold, M. D. Sankur, M. Negrete-Pincetic, and D. S. Callaway, "Model-Free Optimal Coordination of Distributed Energy Resources for Provisioning Transmission-Level Services," *IEEE Transactions on Power Systems*, vol. 33, pp. 817–828, Jan. 2018.

[11] M. D. Sankur, R. Dobbe, A. von Meier, and D. B. Arnold, "Model-Free Optimal Voltage Phasor Regulation in Unbalanced Distribution Systems," *IEEE Transactions on Smart Grid*, vol. 11, pp. 884–894, Jan. 2020.

[12] J. Johnson, A. Summers, R. Darbali-Zamora, J. Hernandez-Alvidrez, J. Quiroz, D. Arnold, and J. Anandan, "Distribution Voltage Regulation Using Extremum Seeking Control With Power Hardware-in-the-Loop," *IEEE Journal of Photovoltaics*, vol. 8, pp. 1824–1832, Nov. 2018.

[13] J. Johnson, S. Gonzalez, and D. B. Arnold, "Experimental Distribution Circuit Voltage Regulation using DER Power Factor, Volt-Var, and Extremum Seeking Control Methods," in *2017 IEEE 44th Photovoltaic Specialist Conference (PVSC)*, (Washington, DC), pp. 3002–3007, IEEE, June 2017.

[14] M. Baudette, D. Arnold, C. Breaden, M. D. Sankur, D. S. Callaway, and J. S. MacDonald, "HIL-validation of an Extremum Seeking-based Controller for Advanced DER Management," in *2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, (Washington, DC, USA), pp. 1–5, IEEE, Feb. 2020.

[15] M. Baudette, M. D. Sankur, C. Breaden, D. Arnold, D. S. Callaway, and J. S. MacDonald, "Implementation of an Extremum Seeking Controllerfor Distributed Energy Resources:Practical Considerations," Aug. 2020.