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Permalink

https://escholarship.org/uc/item/9kt923sh

ISBN

9781728131030

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Publication Date

2020-02-17

DOI

10.1109/isgt45199.2020.9087767

Peer reviewed

HIL-validation of an Extremum Seeking-based Controller for Advanced DER Management

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Abstract—**Paradigm shifts in electricity generation are leading to more renewable and distributed energy resources (DER) on the grid. There is a strong interest to utilize these resources for various grid services, but the practicality of commanding multiple DER is often an obstacle to such approaches. In this article, we seek to validate through Hardware-in-the-Loop (HIL) simulation an extremum seeking (ES) based control scheme proposed in previous work. The method aggregates and coordinates multiple distributed controllers to offer transmission grid level services. The HIL validation uses a prototype real-time implementation of the controller's logic on distributed devices and photovoltaic (PV) inverters operating on a simulated utility distribution feeder. Several grid services, including load following and voltage regulation, were validated to demonstrate the deployment feasibility of the ES control approach on equipment already installed on the grid.**

Index Terms—**Distributed energy resources, DERMS, Voltage regulation, Model-free control, Optimal control**

I. INTRODUCTION

DER are becoming more common in the electric power grid. Their share of the electricity generation is growing rapidly, as investment costs to build new plants are dropping. In current regulation, DER are only subject to grid codes mandating local control features, such as local voltage regulation, fault ride-through capability, etc. As DER are displacing more traditional dispatchable generation units, utilities look for alternative methods to operate the electric grid reliably. The interest is strong to include DER in the transmission and distribution system operator's tool-set, and investigate the feasibility of using them as resources to regulate both local state variables (i.e. distribution level) and transmission level state variables.

In previous work, the Authors have investigated the use ES control [1] to manage DER. Extremum Seeking control uses probing signals to find the minimizer(s) of a defined objective. In [2], a 2-Dimensional ES (2D-ES) approach was shown feasible to independently manage DER active and reactive power injections to reach desired active and reactive power targets at the distribution feeder head level. The work was carried out using offline simulations. A first implementation of ES control for managing PV inverters' reactive power injections was carried out by a group at Sandia National

Lab [3]. In their work, a single dimension ES controller was tested in power hardware-in-the-loop (P-HIL) experiments to validate the approach.

The work is part of a project for developing advanced DER management services (DERMS), and demonstrate their potential on smart-grid technologies readily available, using HIL simulations. In this paper, we focused on the validation of the 2D-ES control scheme using the LBNL test-bed, namely Flexgrid. The facility features a Real-Time Simulator and a microgrid equipped with a PV-battery system that is reconfigurable to be interfaced with the grid simulator in P-HIL setups. The Authors explored several cases to validate, where the Flexgrid PV inverters were managed by a 2D-ES controller implemented on a commercial smart-grid hardware platform.

The paper begins with an overview of the 2D-ES control approach and its configuration to satisfy the different objectives of the considered cases. The Flexgrid test-bed and hardware controller are presented in Section III, followed by details on the experimental protocol. Next, the experimental results are discussed, and concluding remarks are provided.

II. EXTREMUM SEEKING CONTROL

Extremum Seeking control is built in two parts: a centrally-computed objective function, and the distributed ES control logic. The ES logic operates on the global objective without exogenous information; it is based on probing signals (e.g. sinusoidal probe) injected in the active power (P) and / or reactive power (Q) of the DER. The perturbation propagates through the distribution system and impacts power system states, which are incorporated into the objective function as desired. Objective function gradient information is extracted from successive objective function evaluations received by the ES controllers. Each controller adjusts its setpoint to minimize the objective function via gradient search. Our earlier work demonstrated that conditions for objective function convexity (and therefore reaching global optimality via gradient search) include a broad range of power flow conditions [4].

Due to segregation between a common objective and the controlling entity(-ies), utilities can aggregate participating distributed units by broadcasting the scalar objective function to all controllers and allowing them to independently determine their control effort. The objective can be chosen as desired without interfering with the controllers' settings.

In this work, our goal is to coordinate DER on a common distribution feeder network to provide these transmission level services:

- Active power target tracking at the feeder head
- Voltage regulation at the feeder head
- Voltage violation regulation at nodes within the feeder

These services can be included into a single objective function, formulated as the weighted sum of the terms associated with each service as:

$$J = \alpha_P F_P + \alpha_Y F_V + c_Y \left(F_{V_+} + F_{V_-} \right) + \alpha_C \left(C_P + C_Q \right) \quad (1)$$

where:

$$F_P = (P_0 - P_t)^2, \quad F_V = \sum_{\phi \in \{a,b,c\}} (V_{\phi,0} - V_t)^2$$

$$F_{V_+} = \sum_{\substack{m \in \mathcal{N} \\ \phi \in \{a,b,c\}}} \left(\max \left((V_{\phi,m})^2 - (1.05)^2, 0 \right) \right)^2$$

$$F_{V_-} = \sum_{\substack{m \in \mathcal{N} \\ \phi \in \{a,b,c\}}} \left(\min \left((V_{\phi,m})^2 - (0.95)^2, 0 \right) \right)^2$$

$$C_P = \sum_{n \in \mathcal{P}} P_n^2, \quad C_Q = \sum_{n \in \mathcal{P}} Q_n^2$$

F_P and F_V facilitate active power and voltage magnitude tracking by comparing the measurements P_0 and V_0 to targets (P_t, V_t). F_{V_+} and F_{V_-} enable regulating over and under voltage respectively, by including a set of network voltages $(V_m, m \in \mathcal{N})$ in a sum conditioned on the normal operation range $[0.95, 1.05]$. C_P and C_Q, the sum of the squared control efforts (P_n, Q_n), ensure the control effort is minimized, avoiding the situation where two controllers deliver opposing control actions.

The weights α_P, α_Y, c_Y, and α_C must be tuned for each configuration to obtain optimal results of the ES controllers; terms can be deactivated by setting weights to zero.

III. IMPLEMENTATION ENVIRONMENT

This paper seeks to validate ES control [2] in a P-HIL environment, Flexgrid, with production smart grid infrastructure.

A. Flexgrid Testing Environment

The key components of Flexgrid are: (1) a re-configurable three-phase micro-grid, (2) an Ametek 30kVA grid emulator, and (3) an Opal-RT grid simulator. The Opal-RT simulates a distribution network model using measurements from the microgrid as inputs, sets the Ametek voltage according to simulation outputs. The micro-grid is equipped, on each phase, with a PV and battery system connected through a common inverter that can be remotely controlled through a MODBUS connection. The inverter offers a range of control options that facilitate active and reactive power production.

The microgrid can interface with the simulation by *hard coupling* or *soft coupling*. In both cases the microgrid real and reactive power are used as inputs to the OpalRT simulator. However in hard coupling the microgrid is connected to the
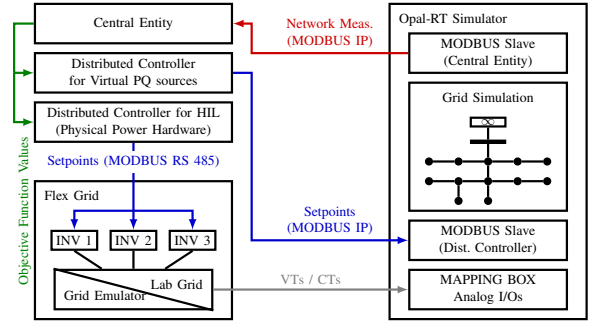

Fig. 1. HIL Setup at Flexlab

Ametek emulator and the voltage at the microgrid point of coupling can be adjusted to equal the output of the OpalRT simulation. In soft coupling, the emulator is taken out of the loop and the microgrid interfaces directly with the local distribution network. Hard coupling is needed for P-HIL experiments involving local voltage dependent control schemes. However, soft coupling is sufficient to examine whether control schemes generated from feeder head conditions can be correctly actuated by hardware inverters.

B. Smart-grid Infrastructure

We implemented ES on Smarter Grid Solutions (SGS)'s DERMS platform [5], comprising a central entity and distributed controllers:

1) Central Entity: The central entity collects the system's measurements from the grid simulator through a MODBUS connection, and communicates with distributed elements by a DNP3 link. The platform also provides a programming environment where scripts can be executed after each measurement poll. The scripting facility computes the objective function based on the system's measurements.

2) Distributed Controller: Distributed controllers are computers that feature a wide range of inputs and outputs (e.g. analog, digital, IP communication). The controllers have real-time execution, custom scripting facility, and various I/Os, that enable configuration of DERM services in the field. They execute ES by receiving objective function values from the central entity and communicating directly with the DER.

C. Full HIL Setup

The full setup shown in Fig. 1, includes the real-time simulator, simulating a feeder model configured with three additional resources: two virtual ES resources and the HIL ES resource. (For practicality we considered the microgrid's three separate systems as a single aggregated ES resource.) Having multiple ES resources enables the study of their interactions.

The simulator sends network measurements to the central entity of the smart-grid control system through a MODBUS connection. The central entity uses the measurements to compute the current value of the objective function and broadcasts it over a DNP3 channel to the distributed controllers.

We configured two separate distributed controllers. The first distributed controller runs the virtual ES instances and

communicates with the simulator directly over MODBUS to feed virtual DER. The second controller runs the ES dedicated to controlling the inverters, and features a special mapping to communicate with the inverters through MODBUS over a serial connection. This controller can also be configured to balance the control effort over several of the inverters, and compute the current power factor to control an inverter's reactive power setpoint. The P-HIL setup integrates the Flexgrid equipments into the simulation through analog I/Os.

IV. Models, Data and Scenarios

Our test setup to include a real distribution feeder model and load data. We obtained a three-phase 150 node distribution feeder model with a reported peak loading of 1.5 MW from Pacific Gas and Electric (PG&E). We prepared the model for simulation with OpalRTs ePhasorsim product.

We introduced a larger transmission impedance to facilitate feeder head voltage sensitivity to reactive power changes within the distribution system. We also modified the model to include three ES-controlled resources (two virtual and one HIL, as explained in the previous section). The output of each device was scaled by a constant factor such that its maximum power equaled 750kW. For the HIL resource, we took the output of the actual PV plus storage system and scaled it before passing its real and reactive values into the model. Using a scaled output that is greater than the physical resource assumes that the output and control response of the hardware in the lab and a larger system would be equivalent as a proportion of their maximum output. We treated the ES resources as three-phase balanced devices.

A. Load and Solar Data

We synthesized the simulation data using real measurements from the Pecan Street Dataport [6]. These were sampled once per minute from about 700 consumption nodes, with demand (i.e. load consumption) and generation (i.e. PV) identified.

The active power profile of each node was generated as the sum of a consumption and a generation (PV) profile. Consumption profiles were built by summing data for randomly drawn nodes from the Pecan Street data. The set is then scaled to achieve a total peak power of 1.5 MW. Reactive power data was generated from real power data by assuming 0.9 power factor. The PV data was scaled to 50% penetration, based on total peak power. We then linearly interpolated the data to increase its resolution to 10 samples per second (S/s).

Finally, we added "noise" to the data based on μPMU measurements from a local distribution feeder. To do so we first passed real and reactive power data from the μPMU through a high pass filter with a cut-off frequency of $1/60$ Hz. We then resampled at the desired final rate of 10 S/s, scaled based on the peak power ratio between the source (μPMU data) and destination (profile set), and added to the lower resolution data. The resulting low and high frequency variability in the data set provided realistic background variation against which the ES controllers would need to identify optimal setpoints.

B. Scenarios

Throughout the different experiments, the virtual ES devices operated at frequency of $\sqrt{3}/10$ Hz and $\sqrt{5}/10$ Hz, both with an integrator gain of 300. The probing amplitude was set to 5 kW, and 45 kVAR (after scaling). The HIL ES controller operated at a frequency of 0.05 Hz, with an integrator gain of 500, and amplitudes of 10 kW and 50 kVAR. We manually tuned the objective function weights for each scenario by running a few preliminary experiments.

We designed the active power target tracking case with a feeder head target changing every 5 minutes. This scenario is configured to test whether ES control can coordinate an entire distribution system to consume (or deliver) real power in a way that mimics that of a conventional generator operating in a pooled transmission market. The performance of ES for this service will be assessed by computing two scores:

S_1: Average tracking error as a percentage of the P target
S_2: Average tracking error as a percentage of the used control range (here 350 kW)

Both scores were computed using all measurement samples and from 5 min average measurements.

The voltage tracking case studies how DER can regulate voltages in the transmission network as a generator would. The control loop uses reactive power to track the desired voltage at a chosen bus (in this case the feeder head), set at 1 p.u. in our tests. We tested voltage regulation with and without active power tracking to study the multi-objective capability of ES.

The voltage violation case seeks to keep a chosen set of network voltages within [0.95 p.u. 1.05 p.u.]. Provided that measurements are available, the formulation enables control of several bus voltages at the same time. We chose a set of various nodes throughout the feeder, including leaves, in all branches of the feeder, and forks in the feeder. We combined this case with active power reference tracking to show how real power control measures can be executed while respecting the voltage operating constraints of a distribution network.

Each experiment was nominally one hour, but configuration and booting sequences caused the experiments to vary in length. Insolation conditions also varied across experiments.

V. Experimental Results

A. Feeder Head Active Power Target Tracking

1) All ES case: Fig. 2 shows that as the target changes, the controllers are able to follow the new command, changing the total output of controllable resources by several hundred kilowatts within a few minutes. Small step changes are almost met in a few seconds; larger step changes take up to 2 minutes. The objective function is driven to zero very quickly after each step change. We computed scores of $S_1 = 3.06$ %, $S_{1,5\text{min}} = 1.77$ %, $S_2 = 9.34$ %, and $S_{2,5\text{min}} = 5.21$ %.

The controller connected to the HIL inverters is significantly slower in its response than the virtual resources. This is due to its lower probing frequency, which was imposed by physical constraints in the communication link with the inverters, which results in slower ES gradient estimation.
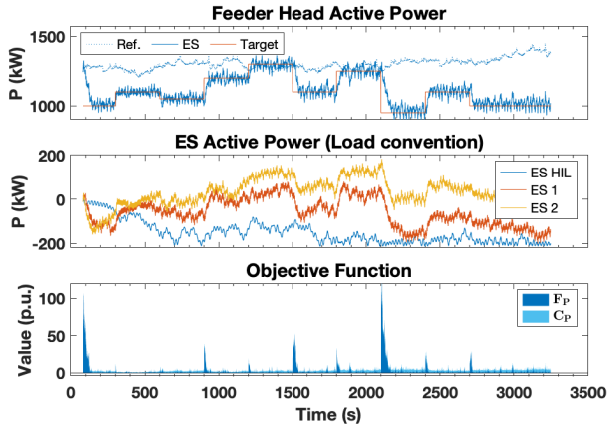
Fig. 2. Results of the Feeder Head Active Power Target Tracking Experiment

2) HIL ES only case: We then de-activated the virtual ES sources to study to performance of physical power devices in isolation. We restricted targets to update every 10 minutes (instead of 5 minutes) to test the slower controller.

Figure 3 shows that the controller is able to track a changing target, albeit at a slower rate. The performance scores are $S_1 = 4.77$ %, $S_{1,5min} = 3.08$ %, $S_2 = 14.59$ %, and $S_{2,5min} = 11.49$ % in this case. Because the controller is slower, the objective function takes on larger values than in the first case, but it is ultimately driven to zero.

This experiment validated the implementation including all the hardware setup from the controller, down to the physical actuators. In the conclusions we will discuss strategies to improve the controller response time by resolving the communication constraints to the inverters.
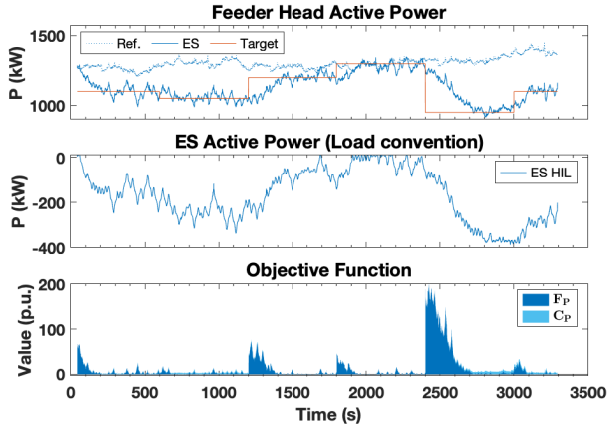

Fig. 3. Active Power Tracking Experiment with only the Physical Inverter

B. Feeder Head Voltage Target Tracking

In this case the voltage magnitudes of all three phases were used in the objective function. For practicality and due to limitations in the HIL inverters, we ran them as one balanced device, and did the same with the virtual resources for consistency. Therefore we could not control phases independently.

Fig. 4 shows that the controller quickly changes voltages in the beginning of the simulation. The controllers then regulate

voltages to roughly the same values as background demand and supply change continually. Note that the objective function is stabilizes near a low non zero value, reflecting the inability of the controller to impact the phases independently.
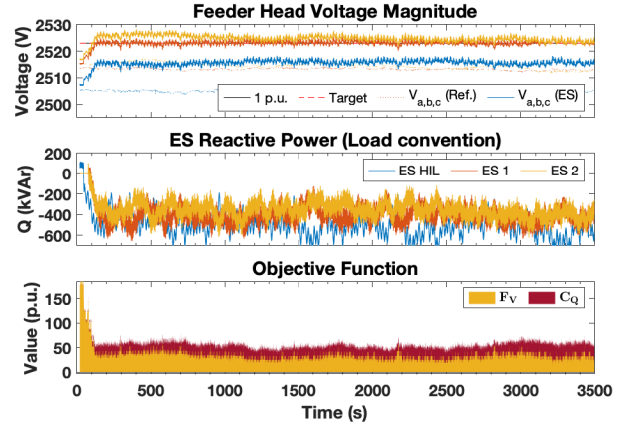

Fig. 4. Results of the Feeder Head Voltage Target Tracking Experiment

C. Feeder Head Active Power and Voltage Target Tracking

The 2D-ES formulation (operating on both P and Q channels simultaneously) works by introducing a phase shift of $\pi/2$ between the P and Q probes. This facilitates independent control of two output variables (e.g. voltage and real power) with one objective function if the inputs that influence one variable weakly influence the second.

We sought to control active power at the feeder head while maintaining voltage at 1 p.u. there as well. Fig. 5 shows that both targets were met with results similar the previous single objective experiments. Globally, the controllers are able to satisfy a combined objective.

The response of the controllers is slower than in the single objective case, which results in higher tracking performance scores at $S_1 = 4.9$ %, $S_{1,5min} = 2.94$ %, $S_2 = 14.93$ %, and $S_{2,5min} = 8.72$ %.. This is because the gradient extraction becomes more complex, as several components change at the same time. This slow down is prominent around $t = 1500$ s and $t = 2100$ s, when large transients occur.
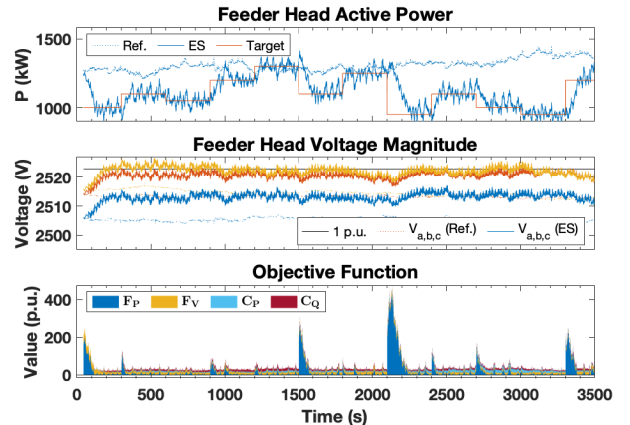

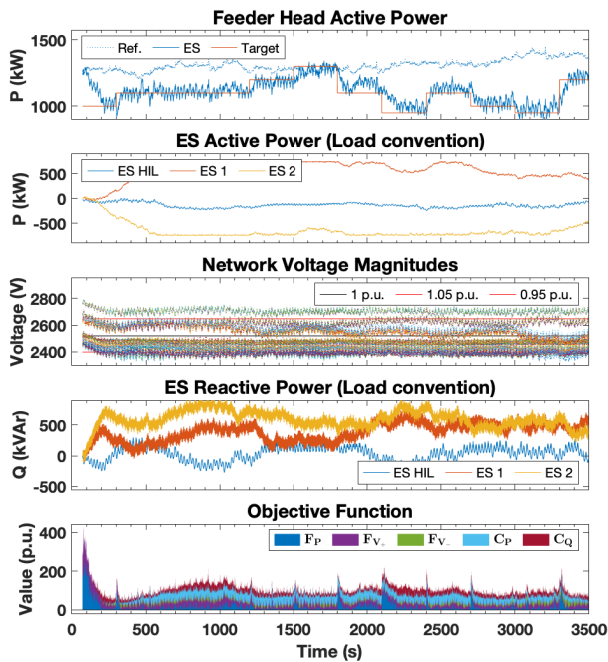Fig. 5. Feeder Head Active Power and Voltage Target Tracking

Fig. 6. Active Power Tracking and Network Voltage Regulation

D. Active Power Tracking with Network Voltage Regulation

In the last experiment, we tested nodal voltage regulation with feeder head active power target tracking. This constitutes a full test of the question set out at the beginning of the paper, namely whether DER can regulate transmission state variables while simultaneously ensuring local constraints are met.

Figure 6 shows that some of the network voltages were greatly above the 1.05 p.u. limit at the start of the experiment but were quickly brought closer to the limit. Some voltages remain outside the desired operating range because network does not have sufficient control resolution to bring high voltages into range without causing low voltages elsewhere.

The active power channels of the virtual ES controllers diverged near the end of the experiment due to inadequate tuning of the weights in the objective function. Despite several iterations, we could not find adequate weights for this experiment. Note that despite divergence, the objectives were still satisfied (including tracking performance scores of $S_1 = 4.51$ %, $S_{1,5\text{min}} = 3.55$ %, $S_2 = 13.68$ %, and $S_{2,5\text{min}} = 10.59$ %.).

VI. CONCLUSIONS

Some of the appealing characteristics of ES are that it does not require information about the grid where it operates, and it can easily be deployed using a central entity communicating with multiple distributed entities managing the DERs. Hence, it was possible to implement and deploy the control scheme using readily available smart grid equipment, and integrate it with commercial inverters to test and validate the approach.

Our previous research focused on deriving conditions for optimality and convergence of the ES control approach. This paper demonstrates that the control scheme works in practice,

with a real network model implemented in a real time simulator and real control hardware, power hardware and input load and solar data. Each experiment tested different grid services that could improve grid operations and generate revenue for DERs. The experiments showed promising results, validating not only our implementation of the control scheme, but also the feasibility of deploying an ES-based approach to enable new services in existing grids. The experiments showed that several units could be integrated into a single control scheme.

These results demonstrate that elevating load buses to the status of generators from the perspective of a transmission system operator is viable with real hardware. Though the data required to execute the validation experiments is extensive, the data requirements for real time control are very low.

A. Future Work

In the current implementation of the 2D-ES using the commercial platform delivered by SGS, and the PV-battery inverter setup, we faced several limitations. These stem principally from the communication channels used in the experimental setup. An alternative formulation, proposed in [7], alleviates the encountered issues by considering batches of measurements transmitted at slower intervals. Timestamped measurements also contribute to a better gradient estimation by facilitating the demodulation in the ES algorithm. Future work will include the implementation of the batch version of ES control. This work also highlights the need for a systematic process to tune the weights in the objective function, in particular in the case of combining several objective into the objective function. For the experiments presented here, the process was carried out as an iterative trial and error process. Further research is needed to investigate the feasibility of an entirely automated calibration process.

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