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Distribution Voltage Regulation using Extremum Seeking Control with Power Hardware-in-the-Loop

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Abstract — **Interoperable distributed energy resources (DER), including photovoltaic inverters, are capable of providing a number of grid services by receiving commands from grid operators, aggregators, or other third parties. In many control scenarios, the grid operator must determine the operating mode and parameters for the devices to achieve a specific control objective. In this work, we experimentally validate a distributed technique to achieve optimal DER reactive power operating points for distribution circuit voltage regulation using extremum seeking control. The method is demonstrated with physical and virtual DER connected to multiple hardware-in-the-loop distribution circuit simulations. Results show photovoltaic inverters can adjust their reactive power output to minimize voltage deviations.**

Index Terms — **voltage regulation, DER control, power factor correction, extremum seeking control.**

I. Introduction

The challenges associated with distribution circuit voltage regulation increase as the penetration of variable, distributed renewable energy generation grows [1]. Typically, the source of the voltage perturbations is the changing distributed energy resource (DER) current injection magnitudes on high impedance lines at the ends of radial feeders. Historically, voltage swings were corrected by load tap changing (LTC) transformers, capacitor banks, and other voltage regulation equipment. However, new grid code requirements in California, Hawaii, and at the national level [2] are requiring newly installed DER to include voltage regulation capabilities. These new functions are either autonomous functions—e.g., the volt-var function—or commanded active or reactive power setpoints [3]. Using autonomous functionality (e.g., volt-var) to perform voltage regulations has many benefits including speed and simplicity, however, it does not achieve the global optimal operation for a DER fleet because each DER does not have visibility into the rest of the circuit [4]. To reach an optimal setpoint for DER equipment, more sophisticated techniques combining state estimation and central control are often proposed [5]. These methods rely on fast optimization algorithms, knowledge of the circuit state and topology, line ratings and distances, transformer and DER locations, and bidirectional communications from an advanced distribution management system (ADMS) or DER management system (DERMS) to set the power factor or reactive power contribution of each DER. Real-time grid simulations are necessary to produce optimal DER setpoints, but these are often infeasible in practice because distribution system operators do not have in-depth knowledge of their system or where DER equipment is interconnected.

Herein, we investigate a method that does not require knowledge of the feeder topology or real-time grid simulations or optimization routines. DER extremum seeking control (ESC) implementation enables coordinated operations of multiple DER to produce near-optimal system-wide control. By broadcasting real-time information on a pre-selected fitness function, each DER can adjust its output to move the system toward the global optimum. This does not depend on *a priori* knowledge of distribution system topology, DER sizes or locations, or renewable energy power generation or forecasts. ESC can enable behind-the-meter DER to provide distribution and bulk system services and expand the revenue streams for DER equipment through aggregated market participation [6]. In prior work, the algorithm was tuned in simulation to provide distribution voltage regulation [7] and experimentally demonstrated to maintain ANSI C84.1-2011 [8] Range A limits and reach near-optimal setpoints for multiple DER on a simple distribution circuit [4]. In this work, we demonstrate the ability of the ESC algorithm to operate with physical and virtual photovoltaic (PV) inverter connected to larger power hardware-in-the-loop distribution circuits simulations.

II. ESC Implementation

Extremum Seeking Control is a real-time optimization technique for multi-agent, nonlinear, and infinite-dimensional systems [7]. The decentralized, model-free control algorithm operates by adjusting system inputs (e.g., reactive power) to optimize measured outputs (e.g., feeder voltage). While there are many forms of ESC, the method discussed herein adjusts system inputs, u, via use of a sinusoidal perturbation, demodulates system outputs, *J(u)*, to extract approximate gradients, and finally performs a gradient descent. A block diagram of the approach is shown in Fig. 1. The parameters *k*, *l*, *h*, *a*, and ω are chosen by the designer. In addition to choosing unique probing frequencies for each controllable DER, one must ensure that *l*, *h* << ω thereby ensuring proper operation of the high and low pass filters in each ESC loop. The reader is invited to refer to [7] for more detail regarding the configuration of ESC for this activity.

The ESC optimization function was based on the voltage regulation problem in [4] and [7]. The optimization objective function for these simulations is given by:

$$J = \sum_i C_i \left(V_i - V_n\right)^2 \tag{1}$$

where, V_i is the voltage measurement at Bus *i* and V_n is the nominal voltage (240 Vac), and C_i is the bus *i* voltage deviation weightings. For the experiments in this paper, *Ci* values were all set to unity so that all buses were weighted evenly. We assume there are measurements on all the feeder buses in these experiments, but any subset of the buses could be measured to construct the objective function. One of the benefits of the ESC is that all DER can independently optimize their behavior by the selection of different probing frequencies. In these experiments, the physical DER on Bus 31 probed at 0.07 Hz. *Simulated DER on Buses 32, 33, and 34 will be included in the final paper.*

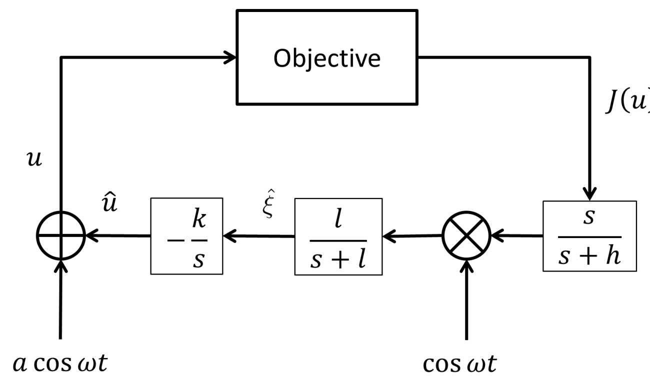

Fig. 1. Block diagram of ESC. Consult [7] for a description.

III. PHIL TESTBED

The power hardware-in-the-loop simulations were conducted with an Opal-RT OP5600 real-time digital simulator running a 7-bus feeder model in RT-Lab. The model is depicted in Fig.2. A physical 3.0 kW inverter was interfaced to the power simulation via a 180 kVA Ametek RS180 grid simulator. The current waveform was measured by a Pearson CT110 and returned to the power simulation via an analog input. The DC side of the inverter was connected to an Ametek PV simulator configured to represent a 3.2 kWp silicon PV system. The objective function is calculated in the Opal-RT simulation in real-time and exported as an analog

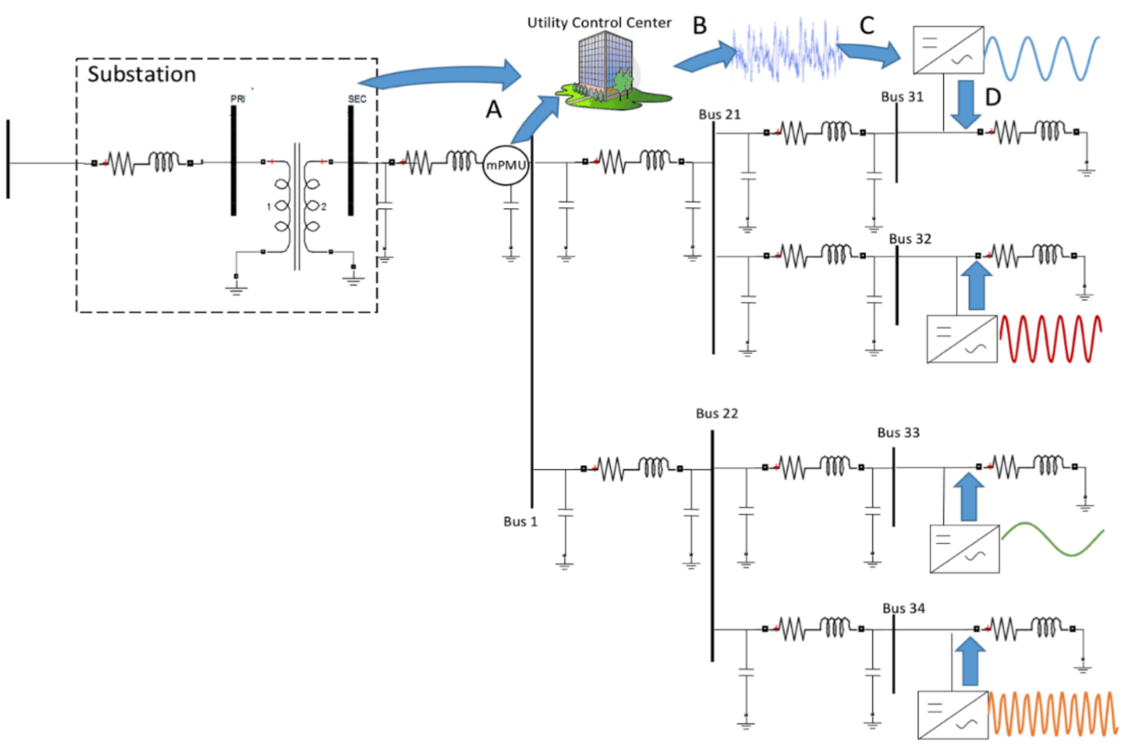

Fig. 2. 7-bus distribution circuit model with multiple PV inverters demonstrating ESC. A centralized control center collects data from the circuit (A), calculates the objective function (B), and sends it to all inverters (C) where individual inverters extract their frequency-specific effect on the objective function and adjust output to trend toward the global optimum (D).

output. This signal is measured with a National Instruments LabVIEW data acquisition system and imported into the ESC controller running on the SunSpec System Validation Platform (SVP). The SVP calculates the reactive power setpoint for the inverter and sends a power factor setpoint to the inverter via a SunSpec Modbus RTU connection.

III. Experimental results

The results of the PHIL experiments are shown in Fig. 3. The objective function is minimized to decrease the voltage deviation from nominal (240 V) on all the buses.

In the final paper, multiple inverters will be simulated with a larger distribution circuit model. Scenarios in which the PV irradiance is changing will also be studied.

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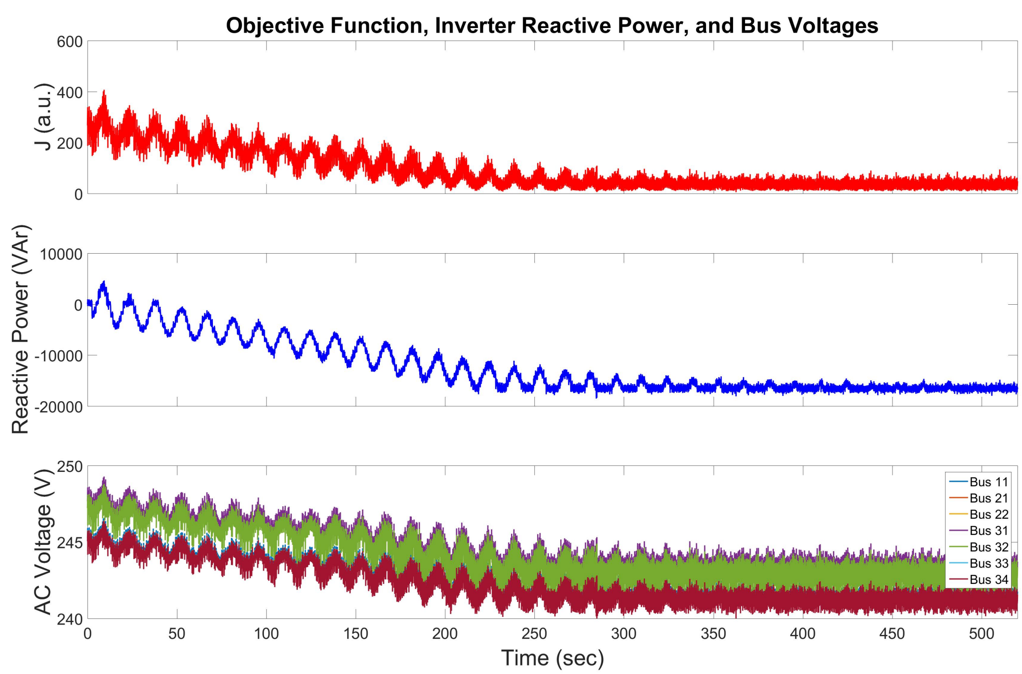

Fig. 3. ESC results for the 7-bus distribution model with the objective function (J), inverter reactive power, and bus voltages plotted for the simulation run. Note the reactive power probing signal affects the bus voltages and objective function so the gradient can be determined and move the inverter to the maximum absorptive power factor