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Model-Free Optimal Voltage Phasor Regulation for Switching in Distribution Networks

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Introduction Through the proliferation of phasor measurement units (PMUs), utilities and system operators are gaining deeper insights in to grid operation. Additionally, with the increased ubiquity of PMUs comes the possibility of more advanced control schemes that control voltage magnitude and angle, and real and reactive power flows through mappings to voltage phasors.

In this work, we seek to leverage PMUs and distributed energy resources (DERs) to *directly control voltage phasors* on a distribution network in a model-free setting. Specifically, we seek to minimize the voltage phasor difference between two ends of a switch without an explicit network model.

We have two bodies of previous work in this area. In one, we developed a linearized model for unbalanced power flow to be incorporated into a convex optimal power flow (OPF) formulation, designed to minimize the voltage phasor difference across an open switch, [1], [2]. However, this method requires significant amounts of accurate network information, such as line connectivity, self and mutual impedances, and node load real power, reactive power, and model. Utilities may not have, or be able to obtain, all the data necessary to properly deploy the OPF in our previous work.

In another body of work, several of the authors of the present work consider optimal governance of DER in a model-free setting [3], for loss reduction and voltage regulation using an extremum-seeking (ES) algorithm.

In this work, we look to an ES algorithm, to achieve the objective of minimizing the voltage phasor difference across an open switch. The contributions of this work will be the investigation of ES for control of voltage phasors (and voltage phasor difference) on radial and mesh networks. We will investigate the network and loading conditions under which ES algorithm is stable. We will simulate the ES control scheme for several objectives, and explore its robustness in the face of network operations such as capacitor bank switching, changing loads, and network reconfiguration.

Preliminaries Extremum Seeking (ES) is a control method in which a perturbation added to a nominal control input is used to obtain an approximation of the gradient of an objective function. The gradient approximation is then used to direct the nominal control input to minimize the objective function.

In this work we employ multiple ES controllers, on a distribution network, that govern nodal real and reactive power dispatch to minimize the voltage phasor difference across an open switch. Fig. 1 shows an ES control loop for a single node dispatching real and reactive power. The real and reactive probing signals are offset in phase by $\pi/2$ so that the perturbations are orthogonal and thus can probe with the frequency without interacting.

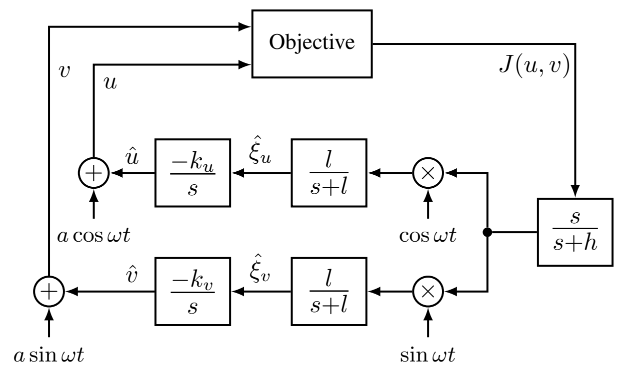

Fig. 1: *Extremum Seeking* control loop for real and reactive power.

The conservation of complex power at node m is given by (1):

$$s_m + w_m - jc_m + \sum_n S_{mn} = 0\,, \tag{1}$$

where $s_m = p_m + jq_m$ is the complex demand, $w_m = u_m + jv_m$ is the complex DER dispatch from the ES controller, and $S_{mn} = P_{mn}jQ_{mn}$ is the complex line power flow from node m to node n, and c_m is the capacitance. We define the squared voltage magnitude at a node, and the squared voltage magnitude difference between two nodes, as:

$$E_m = |V_m|^2\,, \quad E_{mn} = E_m - E_n\,. \tag{2}$$

The voltage angle at a node, and voltage angle difference between two nodes, are defined as:

$$\theta_m = \angle V_m, \quad \theta_{mn} = \theta_m - \theta_n\,. \tag{3}$$

The objective function $J(E(t), \theta(t), u(t), v(t))$ is defined as:

$$J(u(t), v(t)) = \left(E_{A3,A5}(t)\right)^2 + \beta\left(\theta_{A3,A5}(t)\right)^2\,. \tag{4}$$

Simulation Results We perform preliminary simulations on a simple single phase radial distribution network, shown in Fig. 2. We assume the network is connected to a transmission line that is unaffected by control actions on the network, and thus has a constant voltage profile. The transmission line is represented in Fig. 2 by node ∞. Nodes with DER dispatch by ES controllers are marked in blue. An open switch exists between nodes A3 and A5, that a utility operator would like to close. Therefore ES control is employed to minimize the phasor difference between the two nodes to prevent arcing or large system disturbances.

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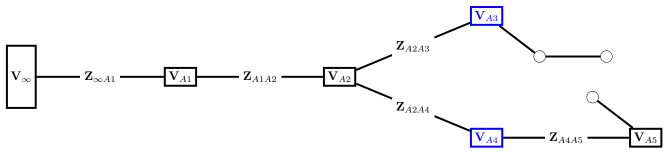


Fig. 2: Six node single phase network.

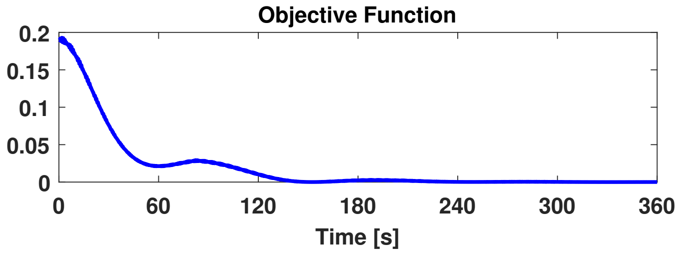


Fig. 3: Objective Function of ES Controller.

ES controllers are placed at nodes A3 and A4. Both are able to source and sink real power, and source and sink reactive power independently. Each controllers probes with real and reactive power, offset by $\pi/2$. Both controllers have a maximum apparent power limit of 0.15 p.u.

Fig. 3 shows the objective function, as defined by (4), being driven to zero.

Fig. 4a gives the magnitude difference, as defined by (2), Fig. 4b gives the voltage angle difference, as defined by (3), and Fig. 4c gives the voltage phasor difference, defines as $V_m - V_n$ with $m = A3$ and $n = A5$. The trajectory toward zero for all three quantities is clearly shown.

Fig. 5a shows the DER dispatch from the ES controller at node A3, and Fig. 5b shows the DER dispatch form the ES controller at node A4. It can be seen that the apparent power limit of node A4 is reached.

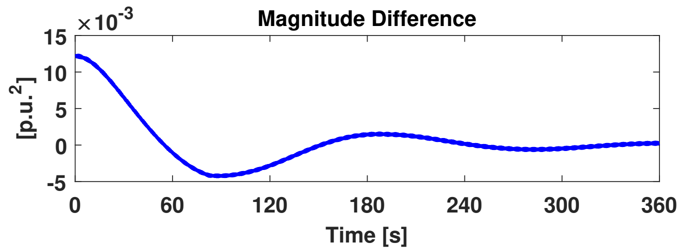
Conclusions Preliminary simulations show great promise of using ES control for governing both voltage phasors, and voltage phasor difference. The main contribution of our work will be an investigation into the network conditions under which the mapping from control input to objective function is convex for a radial network, which will dictate the conditions for stability of the ES method. The second contribution is to extend this for meshed networks. Finally, we plan to perform simulations on more complex networks, with realistic daily loading conditions to explore ES control performance.

References

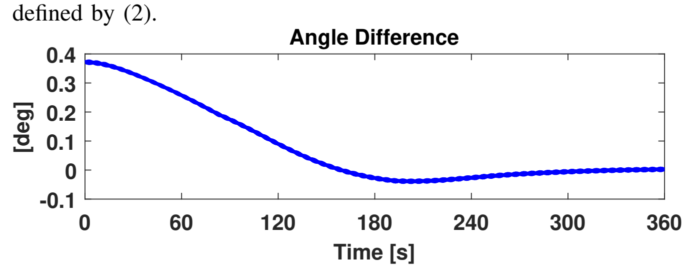
[1] D. B. Arnold, M. D. Sankur, R. Dobbe, K. Brady, D. S. Callaway, and A. Von Meier, "Optimal dispatch of reactive power for voltage regulation and balancing in unbalanced distribution systems," *IEEE Power and Energy Society General Meeting (PESGM), 2016*, 2016.

[2] M. D. Sankur, R. Dobbe, A. von Meier, S. E. M, and D. B. Arnold, "Optimal voltage phasor regulation for switching actions in unbalanced distribution systems," *Submitted for review, IEEE Transactions on Smart Grid*, 2018.

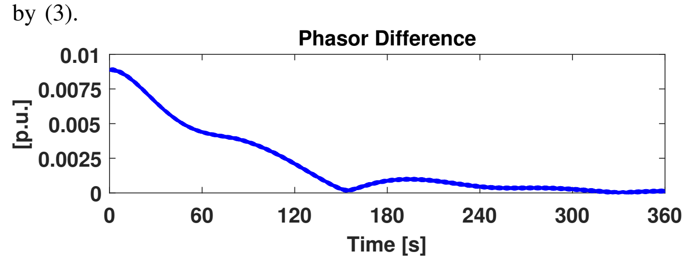
[3] D. B. Arnold, M. D. Sankur, M. Negrete-Pincetic, and D. Callaway, "Model-free optimal coordination of distributed energy resources for provisioning transmission-level services," *IEEE Trans. Power Syst.*, vol. 33, no. 1, pp. 817–829, Jan. 2018.



(a) Voltage magnitude difference between nodes A3 and A5, as defined by (2).

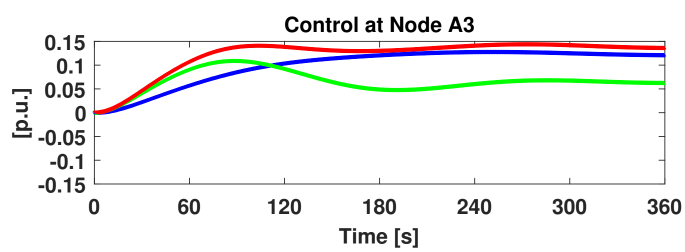


(b) Voltage angle difference between nodes A3 and A5, , as defined by (3).

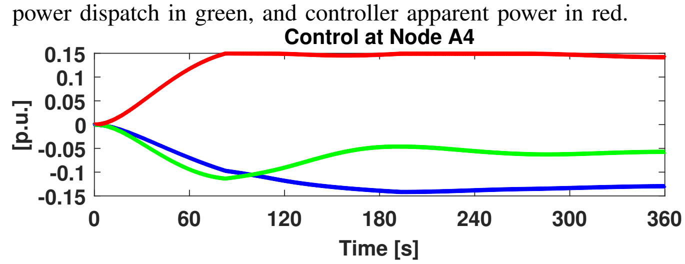


(c) Voltage phasor difference between nodes A3 and A5, defined by $|V_{A3} - V_{A5}|$.

Fig. 4: Magnitude, angle, and phasor differences.



(a) Control at node A3, with real power dispatch in blue, reactive power dispatch in green, and controller apparent power in red.



(b) Control at node A4, with real power dispatch in blue, reactive power dispatch in green, and controller apparent power in red.

Fig. 5: Control at nodes A3 and A4.