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Dissipativity-based Voltage Control in Distribution Grids with Storage

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Joint work with
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Motivation

- Presence of large scale storage and other distributed energy resources (DERs) changes the operation of the distribution grid drastically

- A major challenge is that use of storage devices especially if coupled to solar and in feed-to-the-grid mode can cause rapid fluctuations in voltages that are beyond traditional techniques such as switching capacitor banks

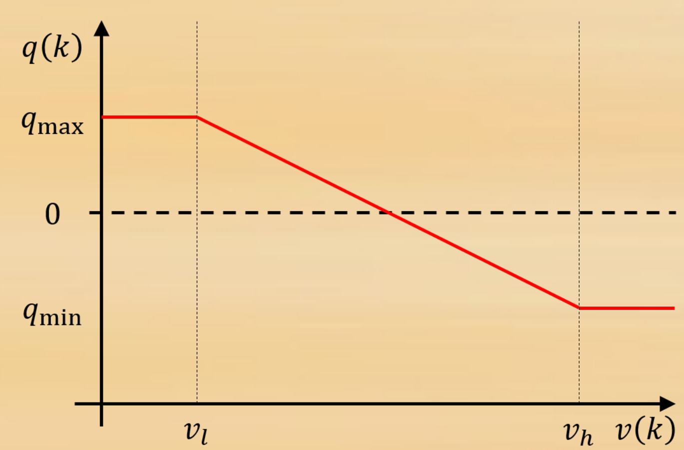
- This is also an opportunity: inverters at the storage devices can be used for reactive power support to stabilize voltage and meet power quality constraints

- We focus on decentralized control of these inverters which requires no communication among devices

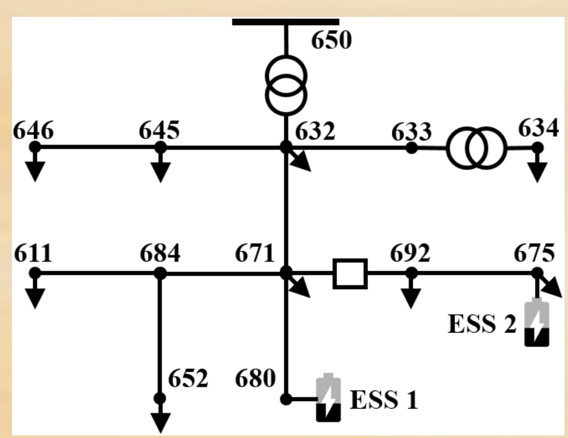
- A known issue with decentralized control using droop curves at each inverter is stability loss (leading to oscillations in voltage) when multiple devices are connected to a network

- We consider the problem of guaranteeing stability with decentralized control when susceptance matrix of grid is unknown and potentially time-varying

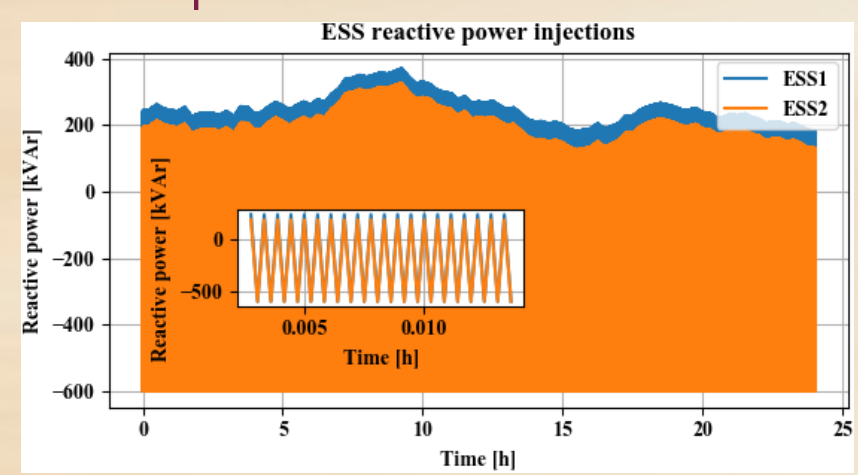
- We allow for heterogeneous droop curves (suitable for heterogeneous devices), include saturation at droop curves, and utilize dissipativity based and extremum seeking control to solve the problem



Droop controller



Sample 13-bus system to study effect of multiple droop controllers



Resulting oscillations (stability loss)

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Problem Formulation

- Consider a radial distribution grid in which the voltage v can be observed and the reactive power q can be controlled

- Assume a discrete time formulation with discretization time large enough so that inverter dynamics reach a steady state between the discrete time steps

- Thus, if $q(k)$ is specified at time k, actual reactive power injections (and corresponding voltages from linearized power flow equations) reach these values at time $k+1$.

- With the control input as the prescribed values of reactive power injections, the system dynamics are

$$\begin{aligned} q(k+1) &= u(k) \\ y(k) &= v(k), \end{aligned}$$

where voltage and reactive power satisfy $v(k) = Xq(k) + \bar{v}$

- X is a positive definite matrix (usually unknown and possibly time-varying) that characterizes the susceptance of the grid

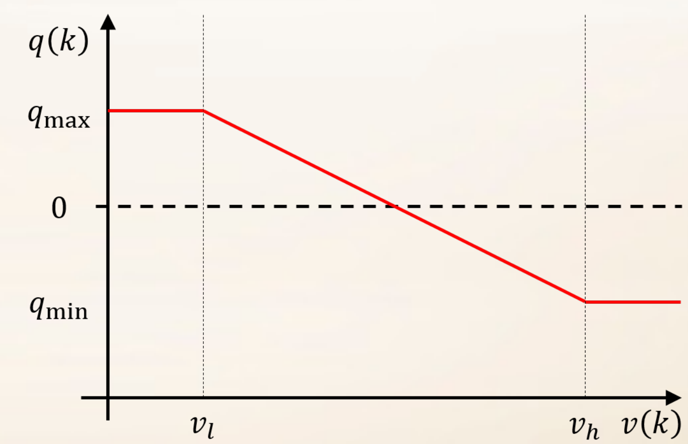
- Objective: Design $u(k)$ as a causal, bounded, and decentralized function of $y(.)$ such that the voltage $v(k)$ locally asymptotically stabilizes to a desired set point.

Proposed Solution

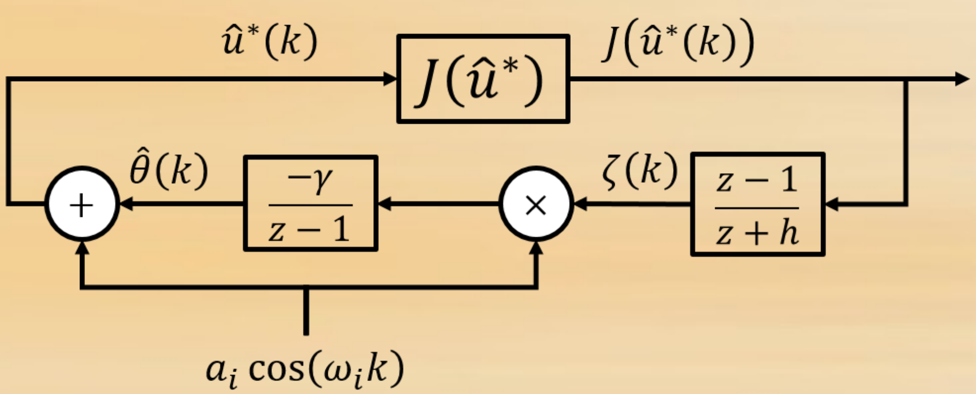
- *Step 1:* Show that the system is locally dissipative (i.e., dissipates energy supplied by external input).
- A technical challenge here is the presence of delay in the system from the input to the output.
- *Step 2:* Design controller to move from dissipativity to stability.

$$\begin{aligned} q(k+1) &= u(k) \\ y(k) &= v(k), \end{aligned}$$

$$u(k) = \begin{cases} q_{\max} & v(k) < v_l \\ u^\star - \overline{K}\,(v(k) - v^\star) & v_l \le v(k) \le v_h \\ q_{\min} & v(k) > v_h, \end{cases}$$



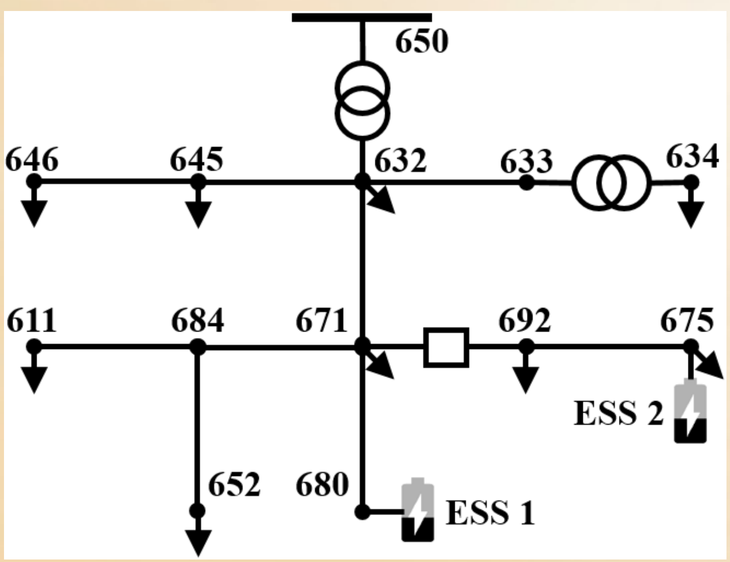
- Can prove stability under a technical condition on the controller gain $(I + X\bar{K})^{-1}(X\bar{K} - 1) < 0$ which relates the controller gain to susceptance (and hence coupling) in the grid.
- *Step 3:* Utilize adaptive extremum seeking controller that does not require knowledge of X or $u^\star$.



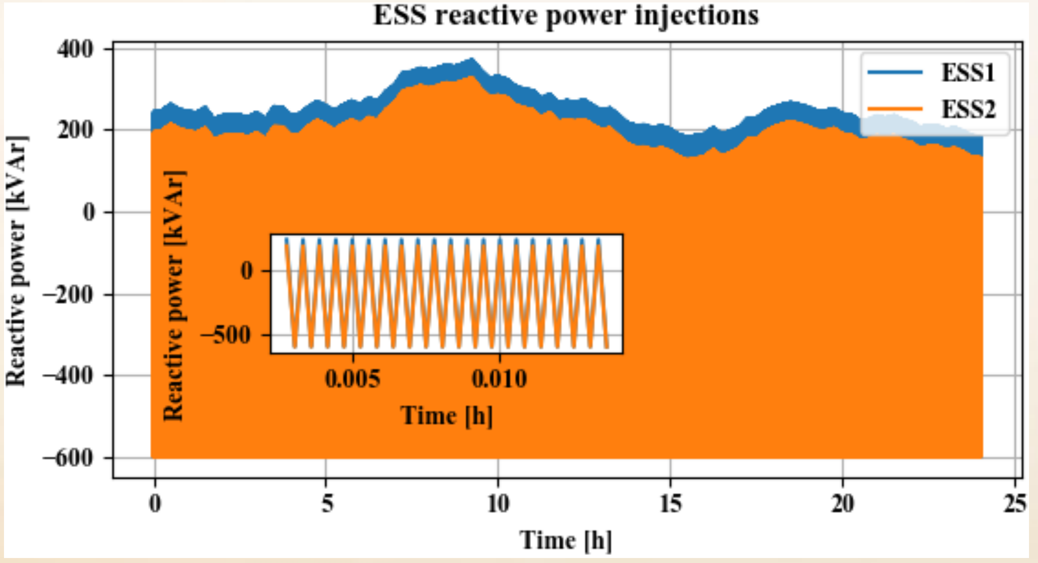
- Can show local exponential convergence to an $O(a_i)$ neighborhood of the correct value $u^\star$
- *Step 4:* Obtain condition for time-varying X as an upper bound on the rate at which the stability condition is violated.

Numerical Example

- Proposed controller was validated in an openDSS simulation with a time step of 1 second over 24 hours
- Two three phase 600kW/600kWh energy storage systems (ESS) were added to the unbalanced IEEE 13-bus test feeder buses 675 and 680.
- Volt-var control based on standard IEEE 1547-2018 led to oscillations

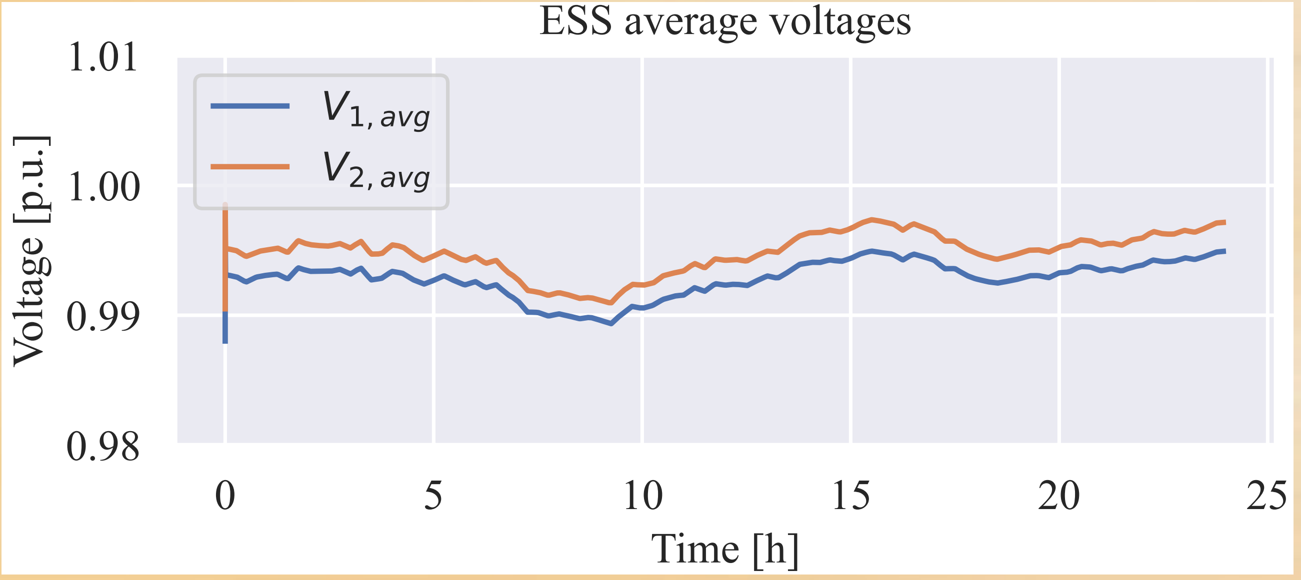


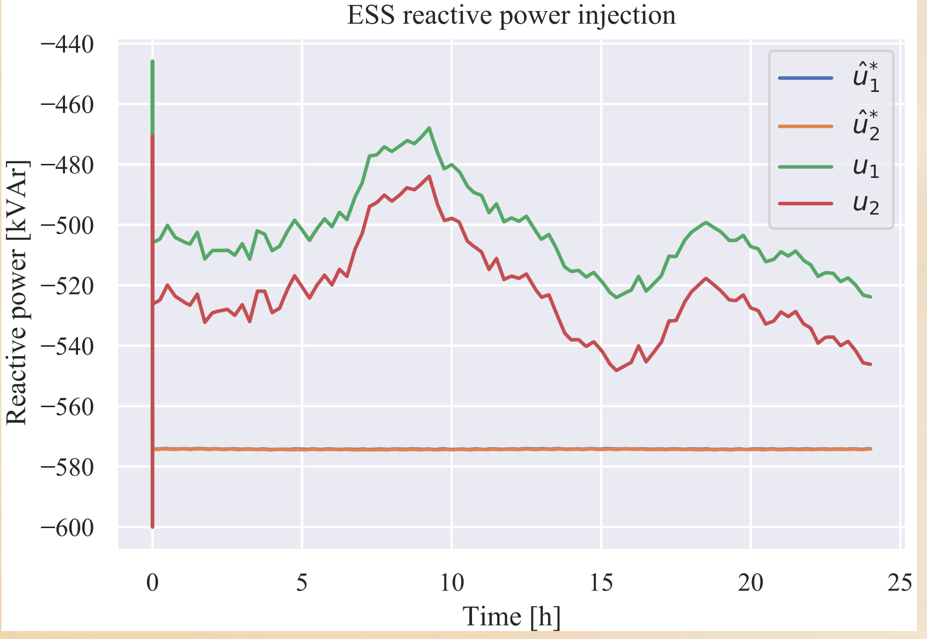
Sample 13-bus system



Resulting oscillations (stability loss) from volt-var control based on IEEE 1547-2018

- Stability was maintained with proposed controller





Conclusions

- We provide a decentralized control method of inverters that guarantees stability when multiple devices are connected to a network even when susceptance matrix of grid is unknown and potentially time-varying

- We allow for heterogeneous droop curves (suitable for heterogeneous devices), include saturation at droop curves, and utilize dissipativity based and extremum seeking control to solve the problem

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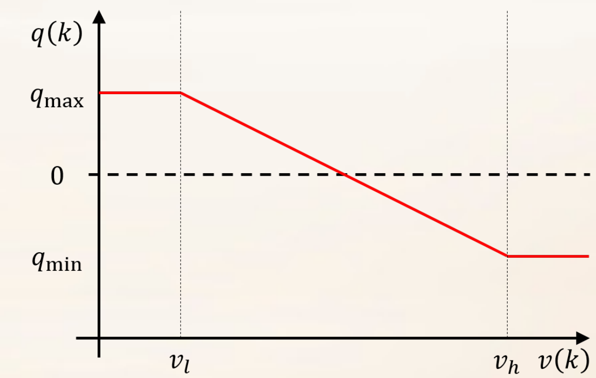

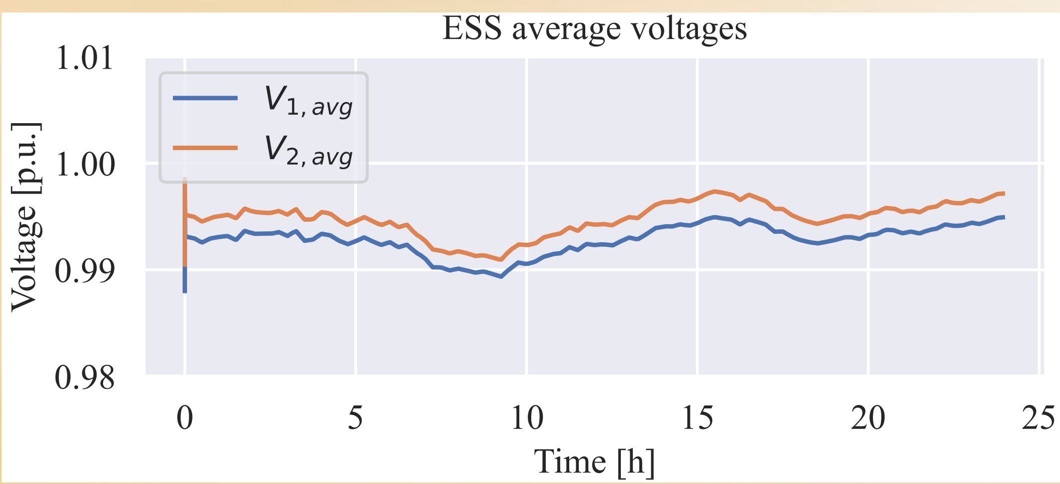

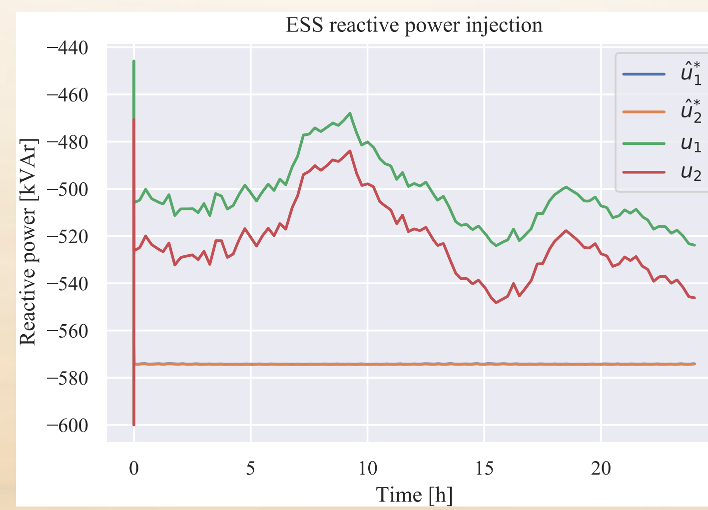

- Current work: identification of faulty devices and their compensation (based on Koopman operator based methods from year 2019-20).

- Products so far: Papers (IEEE PES GM 2021, IEEE PES ISGT 2022 submitted), Software released on github

- We thank Dr Imre Gyuk, Director for Energy Storage Research, Office of Electricity for funding and guidance for this research