NC STATE UNIVERSITY

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# Infusing Autonomy and Resilience in Power Distribution Systems with Smart Transformers

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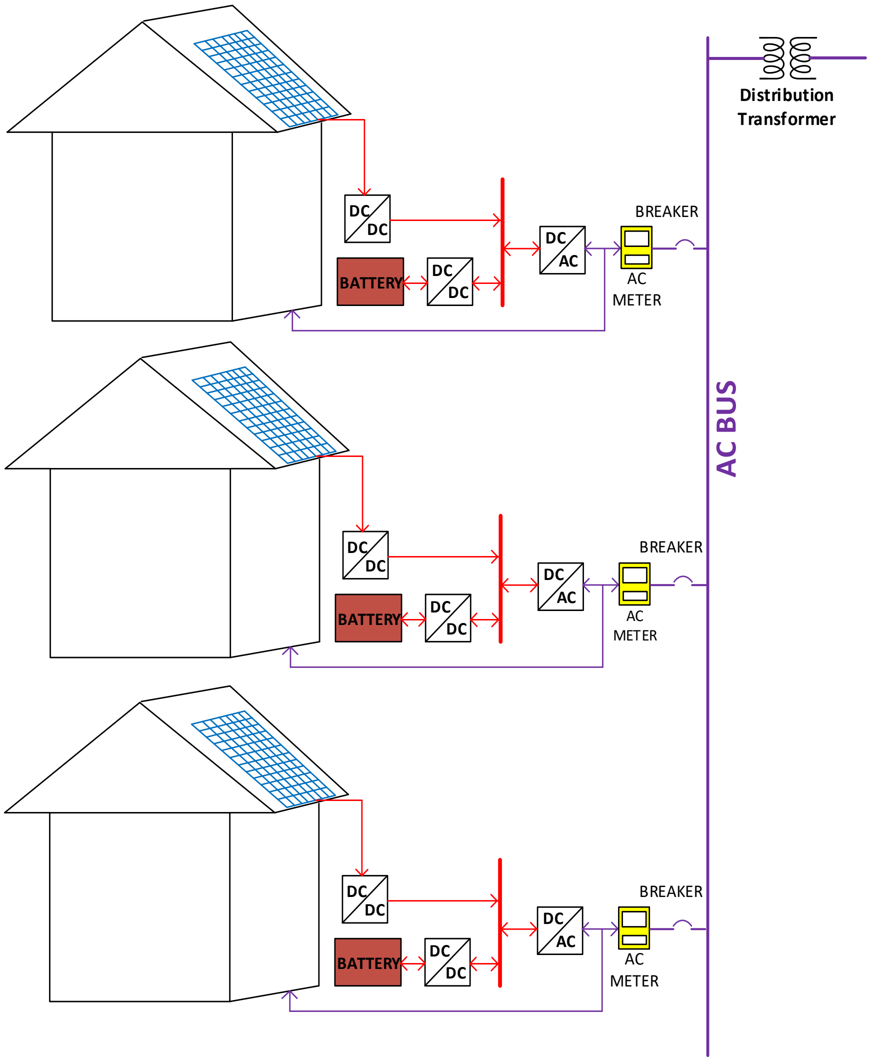
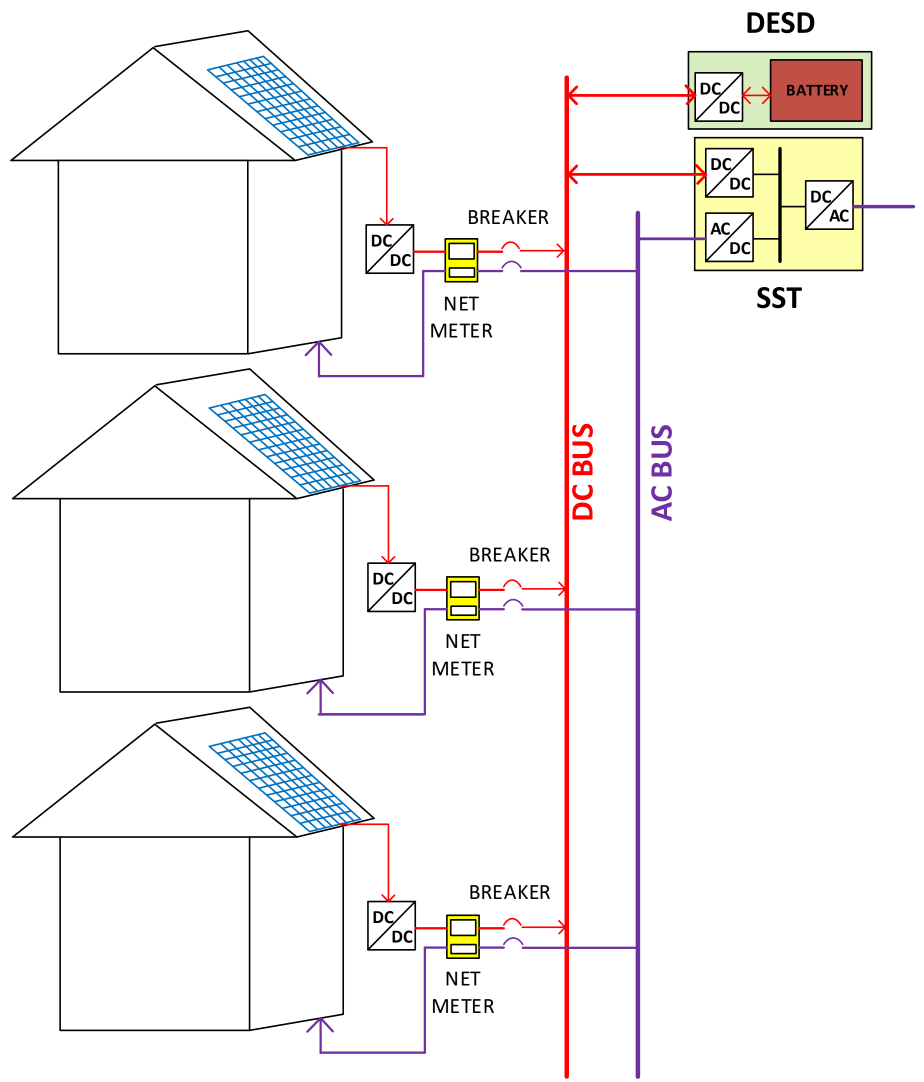
# Power Distribution Systems with Smart Transformers

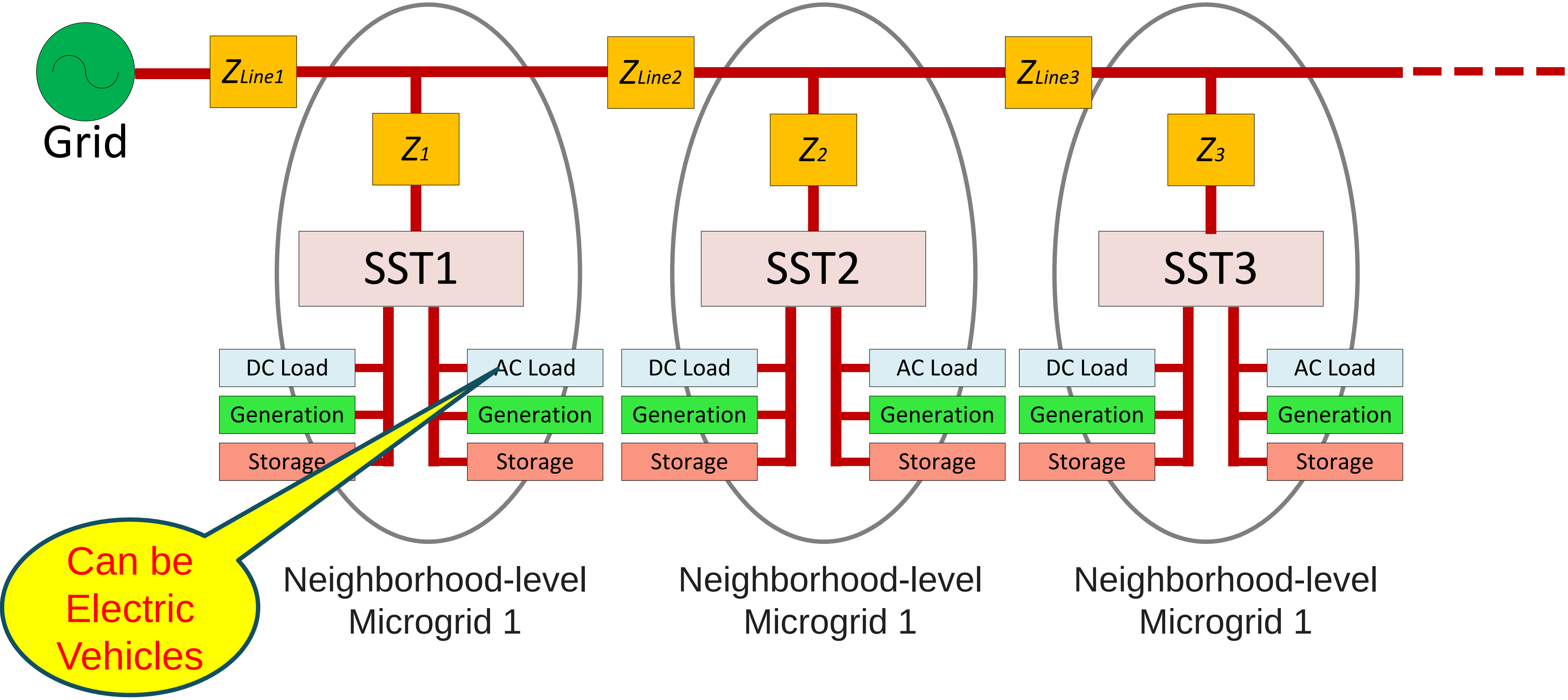
## Today, individual customers




## In 5 more years, shared autonomy



# Modeling of Distribution Grids




- SSTs are connected in single phases of a 7.2 KV (3 PH, L-N) distribution feeder.
- Each SST is rated for 20 KVA
- 400 V DC and 120 V AC

# Networked Microgrid Model

## State-variable models per microgrid:

- ✓ More than 70 state variables from physical dynamics of the components
- ✓ 23 state variables arising from the internal PI controllers.
- ✓ 17 excitation input, 4 set-points and 6 switching parameters.

Grid

### Rectifier

$\dot{X}_1 = f_1(X_1) + g_1(U_1)$

$Y_1 = [V_{dcHV}, I_{dcHV}]$

- $6^{th}$ order system
- Nonlinear due to product of states and sinusoidal terms.

$U_2 = f_7(Y_1)$

### DC/DC Converter

$\dot{X}_2 = f_2(X_2) + g_2(U_2)$

$Y_2 = [V_{dcLV}, I_{dcLV}]$

- $3^{rd}$ order system
- Nonlinear due to product of states

$U_3 = f_8(Y_2)$

### Inverter

$\dot{X}_3 = f_3(X_3) + g_3(U_3)$

$Y_3 = [V_{acrms}, I_{acrms}]$

- $6^{th}$ order system

$U_2 = f_9(Y_4)$
$U_4 = f_{10}(Y_2)$

$U_2 = f_{11}(Y_5)$
$U_5 = f_{12}(Y_2)$

$U_2 = f_{13}(Y_6)$
$U_6 = f_{14}(Y_2)$

### Storage

$\dot{X}_4 = f_4(X_4) + g_4(U_4)$

$Y_4 = [V_{oc}, I_{batt}] = h_4(X_4) + l_4(U_4)$

- $8^{th}$ order system
- Nonlinear due to the electrochemical equations

### DRER (PV)

$\dot{X}_5 = f_5(X_5) + g_5(U_5)$

$Y_5 = [I_{PV}] = l_5(U_5)$

- $10^{th}$ order system
- Nonlinear due to product of states and sinusoidal terms

Solar

### DRER (Wind)

$\dot{X}_6 = f_6(X_6) + g_6(U_6)$

$Y_6 = [I_{wind}] = h_6(X_6)$

- $16^{th}$ order system
- Nonlinear due to the wind characteristics

Wind

# Equilibrium + Transient Stability

- Conventional synchronous generators:

$$M\ddot{\delta} = P_m - r\sin\delta$$

Two equilibria, one stable, one unstable
AGC ensures stable equilibrium despite load changes

- In distribution grids there is no AGC!

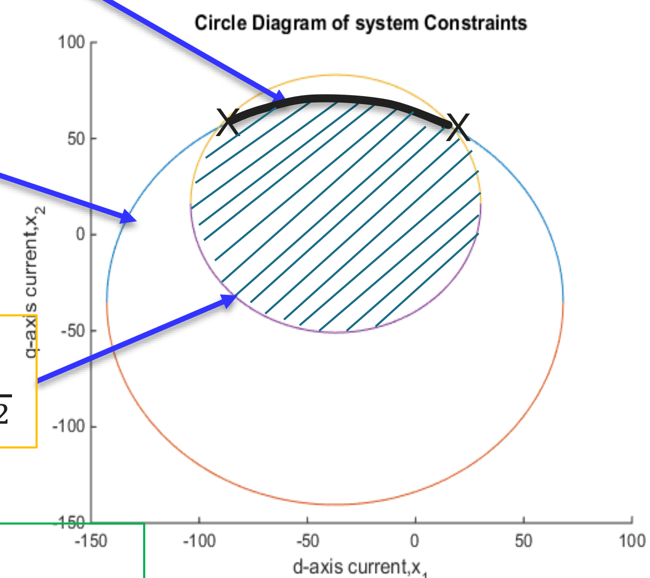
Feasible Operating Curve

## Rectifier steady-state equations

$$\left(x_1 + \frac{y_1}{2a_2}\right)^2 + \left(x_2 + \frac{y_2}{2a_2}\right)^2 = \frac{{y_1}^2 + {y_2}^2}{4{a_2}^2} - \frac{2P_{\text{rec}}}{a_2}$$

## Duty cycle constraints of the rectifier

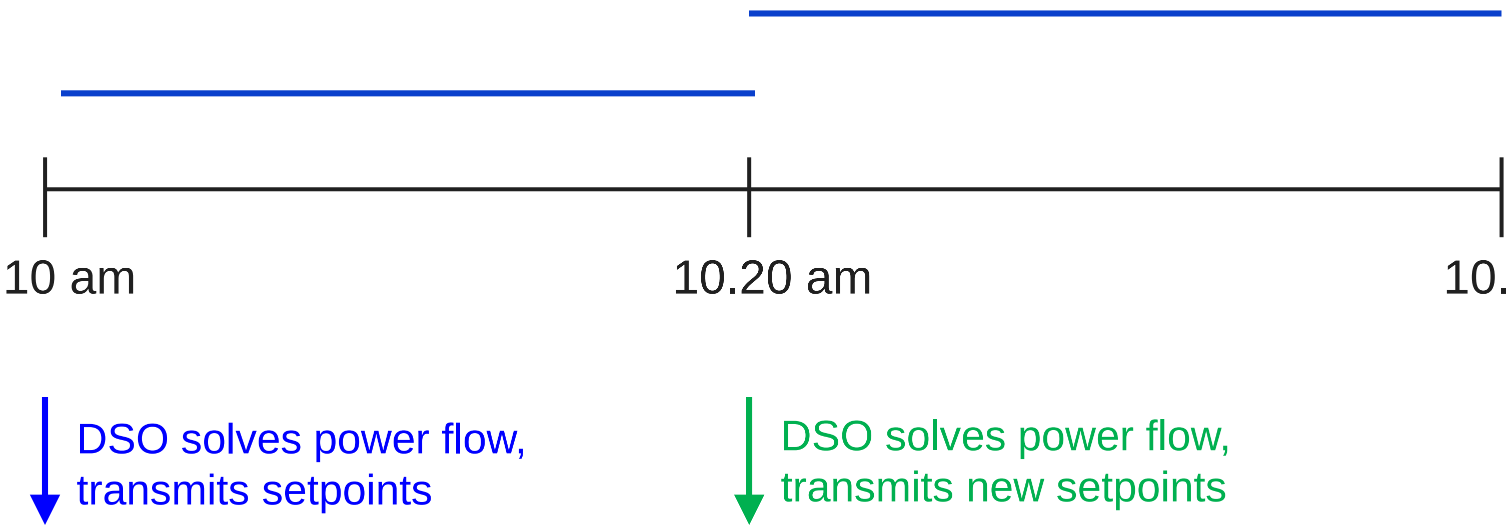
$$\left(x_1 + \frac{a_2 y_1 + a_1 y_2 w_1}{{a_2}^2 + {a_1}^2{w_1}^2}\right)^2 + \left(x_2 + \frac{a_2 y_2 - a_1 y_1 w_1}{{a_2}^2 + {a_1}^2{w_1}^2}\right)^2 \leq \frac{{r_1}^2}{{a_2}^2 + {a_1}^2{w_1}^2}$$

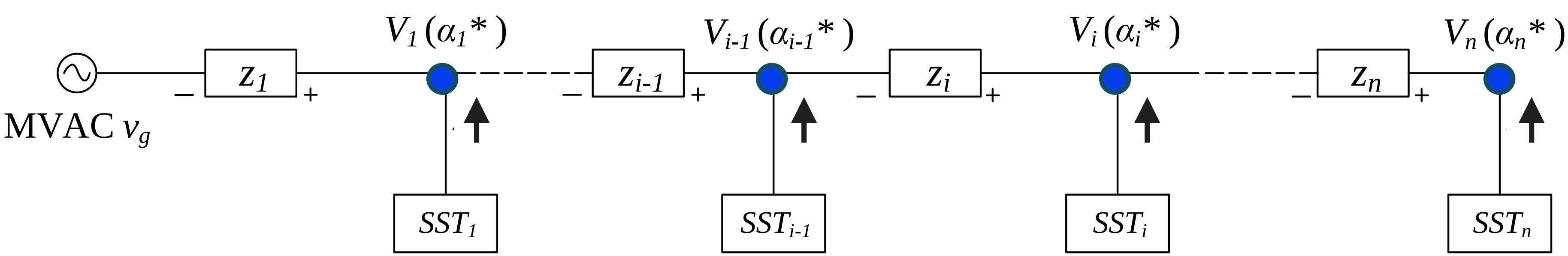



- Careful choice of system parameters & setpoints
- Careful choice of loads (electric vehicles)
- Infinite feasible equilibria, which one is optimal?
- What if transmission grid is not *an infinite source* of current?

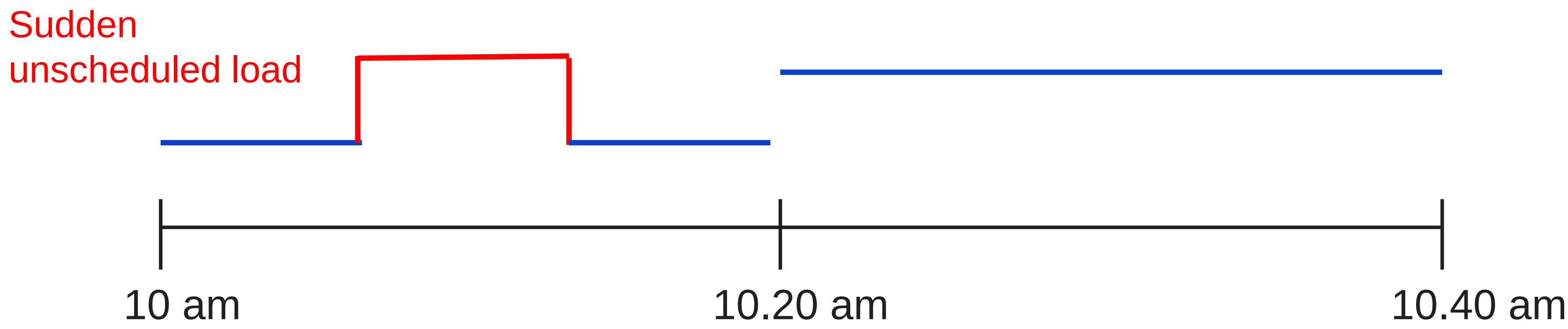
# Resilience via Control of Storage

- Load (including electric vehicles) Forecasting



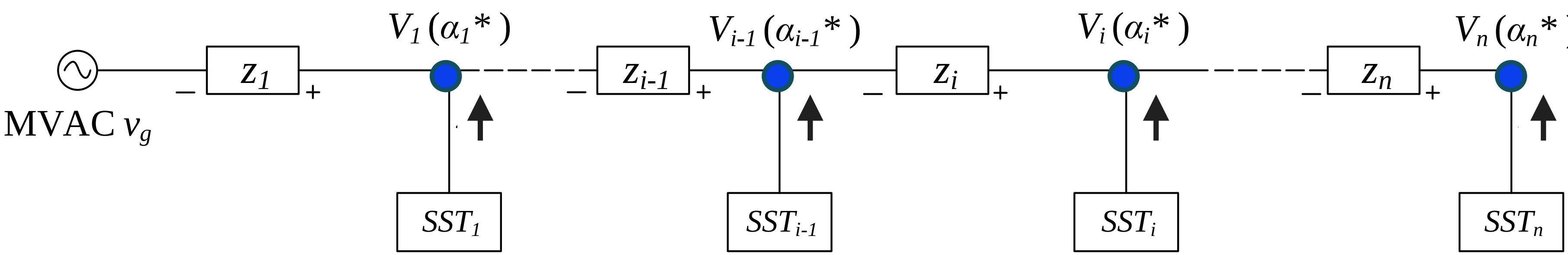



# Control of Storage




DSO solves power flow, transmits setpoints

DSO solves power flow, transmits new setpoints



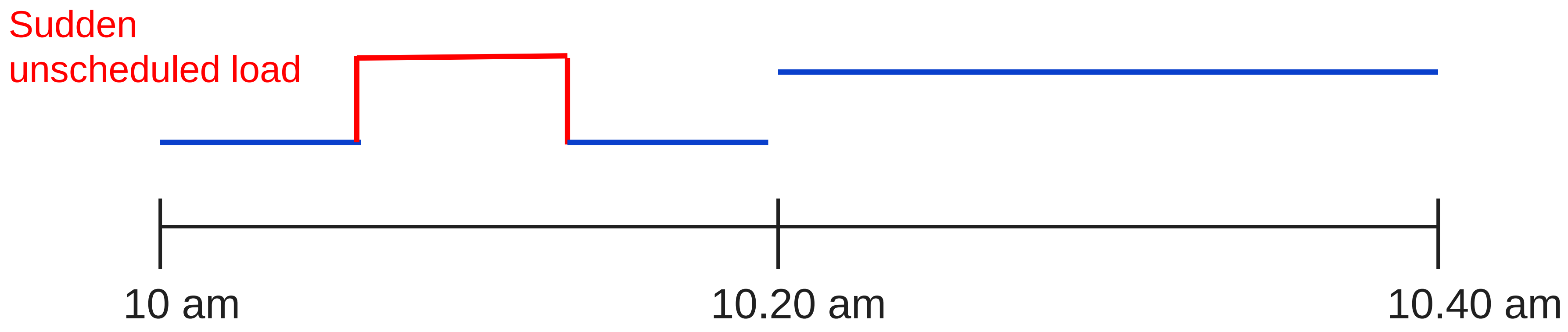

SST $\quad \dot{x}_i = f_i(x_i, \zeta_i, x_j, \alpha_i)$

Storage $\quad \dot{\zeta}_i = g_i(x_i, \zeta_i, u_i)$

Note: every storage need to participate

Interesting applications of Passivity, Backstepping control, Adaptive backstepping

# Control of Storage




Much more accurate short-term load forecasting (including electric vehicles) is needed!

Load demands depend on various factors:

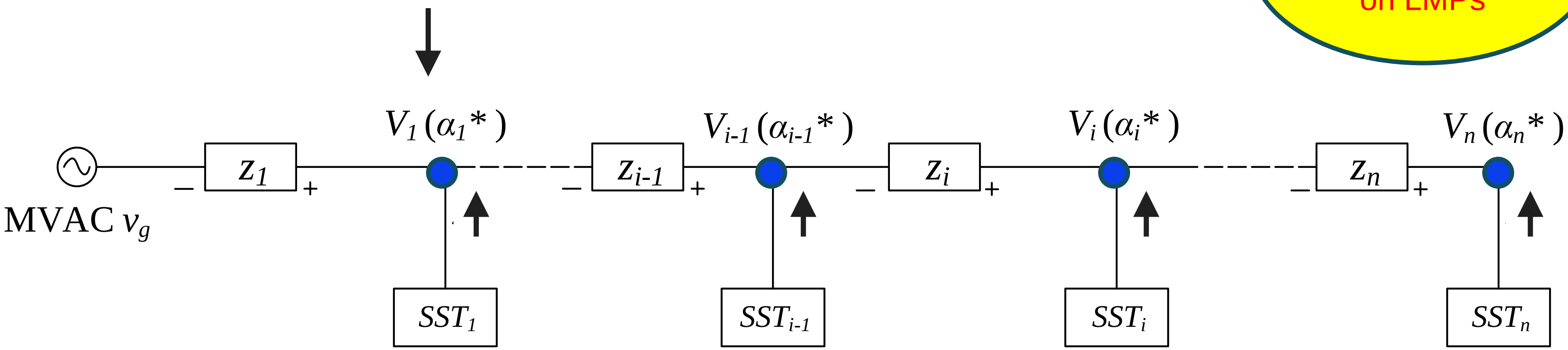
- Number of customers
- Number of electric vehicles
- Residential, industrial, banks, malls, hospitals, data centers
- Weather
- Social factors, income levels
- Demand response

Reinforcement learning is being studied as a potential tool for DR-advisor (Behl & Mangharam, 2016)

# Control of Storage

Setpoint decided by Locational Marginal Pricing

Impact of transportation on LMPs



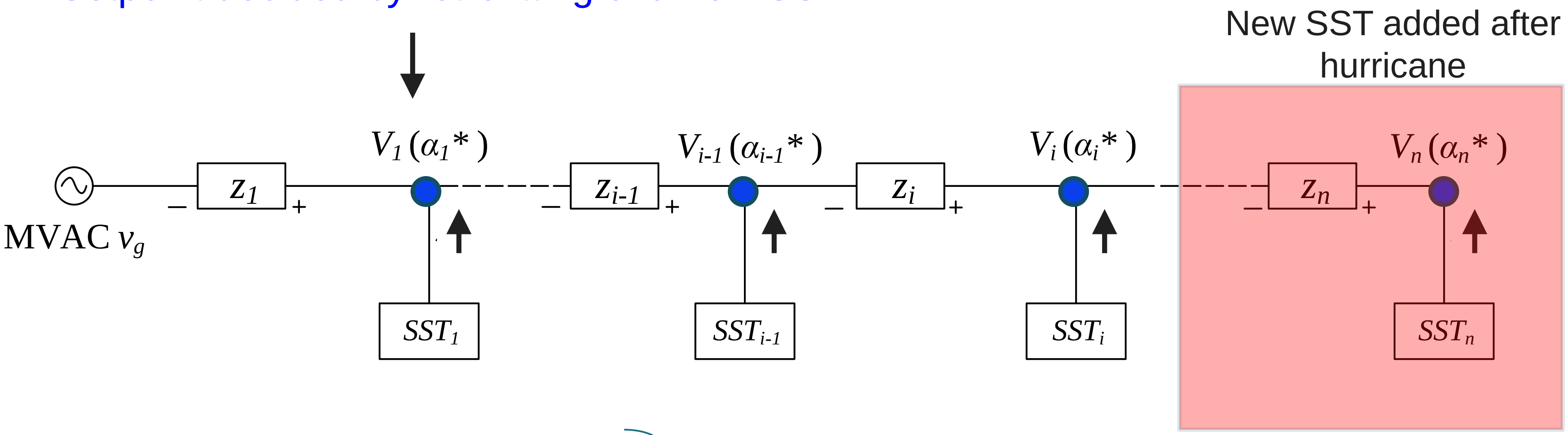

SST $\quad \dot{x}_i = f_i(x_i, \zeta_i, x_j, \alpha_i)$

Storage $\quad \dot{\zeta}_i = g_i(x_i, \zeta_i, u_i)$

Can be an interesting application of Backstepping control, Adaptive backstepping

# Control of Storage

Setpoint decided by retrofitting of a new SST




SST $\dot{x}_i = f_i(x_i, \zeta_i, x_j, \alpha_i)$

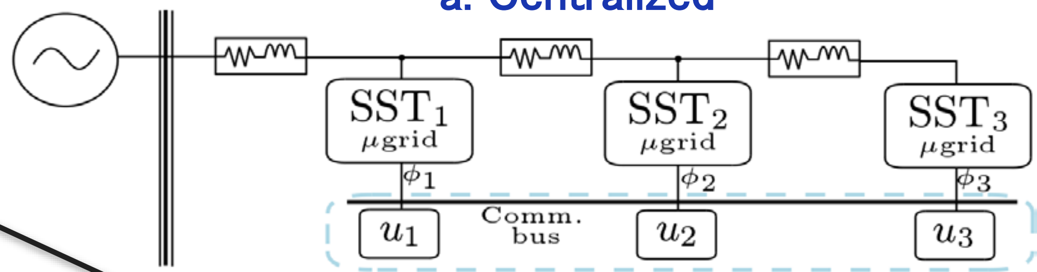
Storage $\dot{\zeta}_i = g_i(x_i, \zeta_i, u_i)$

Can be an interesting application of Retrofit Control

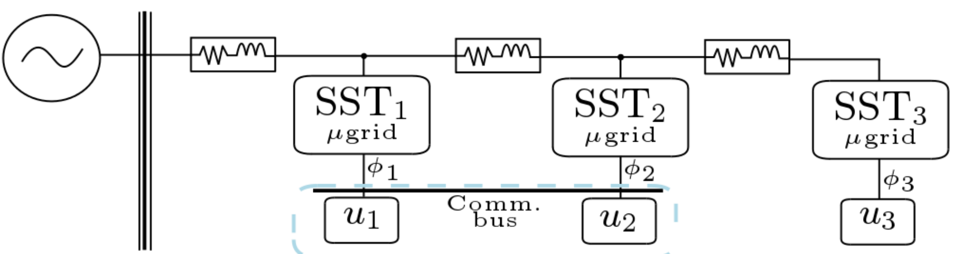
Proximity effect: Whether load changes or a new SST is added, setpoints of neighboring SSTs are going to see maximum change

# Cyber-Physical Architecture

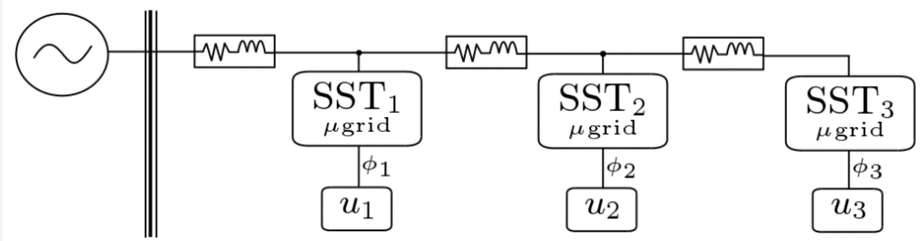
## a. Centralized




## c. Sparse

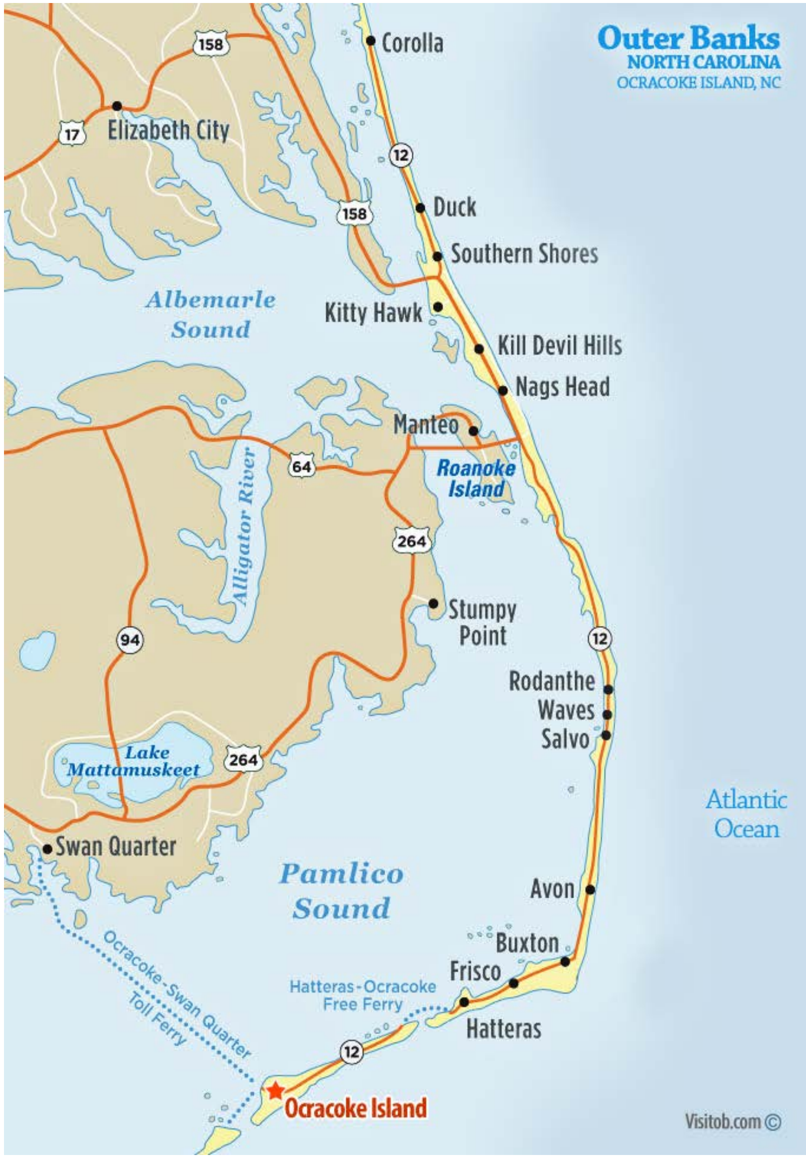



## b. Decentralized




**Three Different Communication Topologies**

# Coastal Microgrid Community




- Ocracoke Island Microgrid – 250 miles from Raleigh, in the outer banks of NC
- 1000 residents
- Took two weeks for full power restoration after Hurricane Sandy (currently closed after Dorian)
- We are working with NC Electricity Cooperative on medium-voltage SSTs, future plans at Ocracoke

# Open Topics of Research

- Control of networked microgrids with SSTs respecting coupling with transportation infrastructure
- Transient Stability
- Power sharing methods in multi-SST system
- Cyber-Physical architecture for control (Use of 5G networks, SDN)
- Plug-and-play operation via retrofitting
- Storage optimization, control, and placement
- Machine learning methods for DR & forecasting of vehicle loads
- Cost-Benefit Analysis and Economics of SSTs

Reference:
A. Milani, M. Khan, A. Chakrabortty, and I. Husain, "Equilibrium Point Analysis & Power Sharing Methods in Distribution Systems Driven by Solid-State Transformers," *IEEE Transactions on Power Systems*, 2018.

# Thank You

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