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Model Predictive Control of Energy Storage Systems for Combined Energy Arbitrage and Voltage Regulation

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Project Objective and Methodology

Objective

Maximize technical and economic benefits from energy storage systems (ESSs) by combining ancillary services and power quality applications in a single framework

Methodology

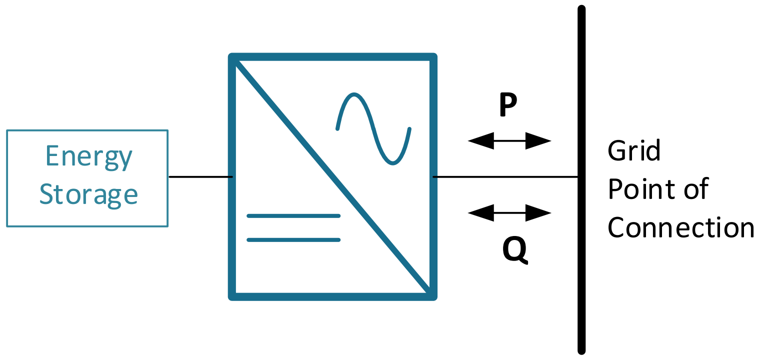
Developed a model predictive control (MPC)-based optimal dispatch strategy to combine energy arbitrage and voltage regulation applications

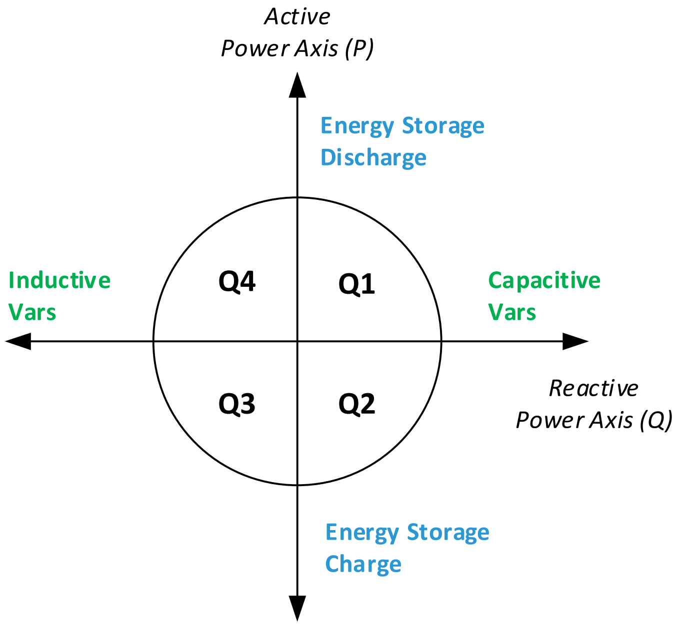
Outline of the Presentation

- Background
- Reactive Power Capability of Energy Storage Systems
- Model Predictive Control Framework
- Case Study
- Simulation Results and Analysis
- Outcomes and Future Work

Background

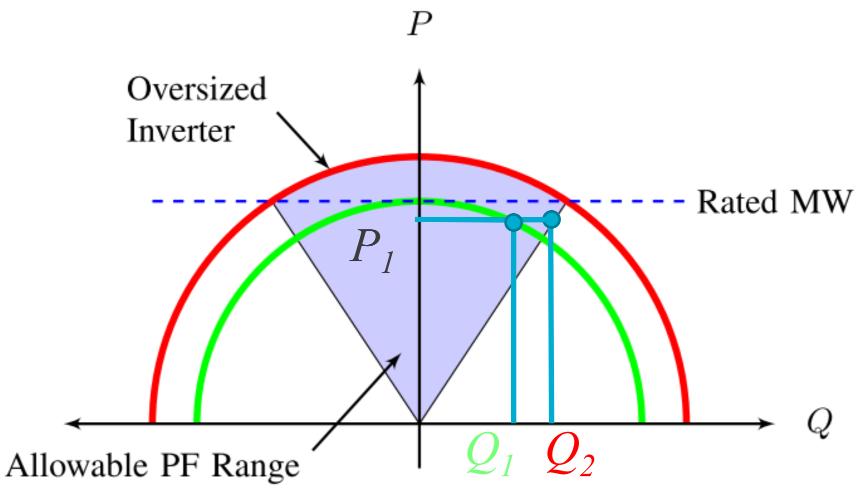
- ESSs have the potential to provide multiple unique services
  - Provides avenues for higher revenue streams
- ESSs can provide reactive power to grid on top of active power services
- A control framework is required to dispatch ESSs in real-time while maximizing benefits
  - Model predictive controls (MPCs) ideal for such applications





Reactive Power Capability of ESS's Inverter

- Inverter of the ESS can be controlled to inject/absorb reactive power while providing real power (either during charging / discharging)
- ***Requirements***:
  - Oversizing of capacitor may be required to handle higher voltage ripples†
  - Inverter oversizing NOT required but may be beneficial in some cases
- Will cause minimal battery degradation
- Minimal impact on state of charge
  - Except for small losses due to increased voltage and current ripple

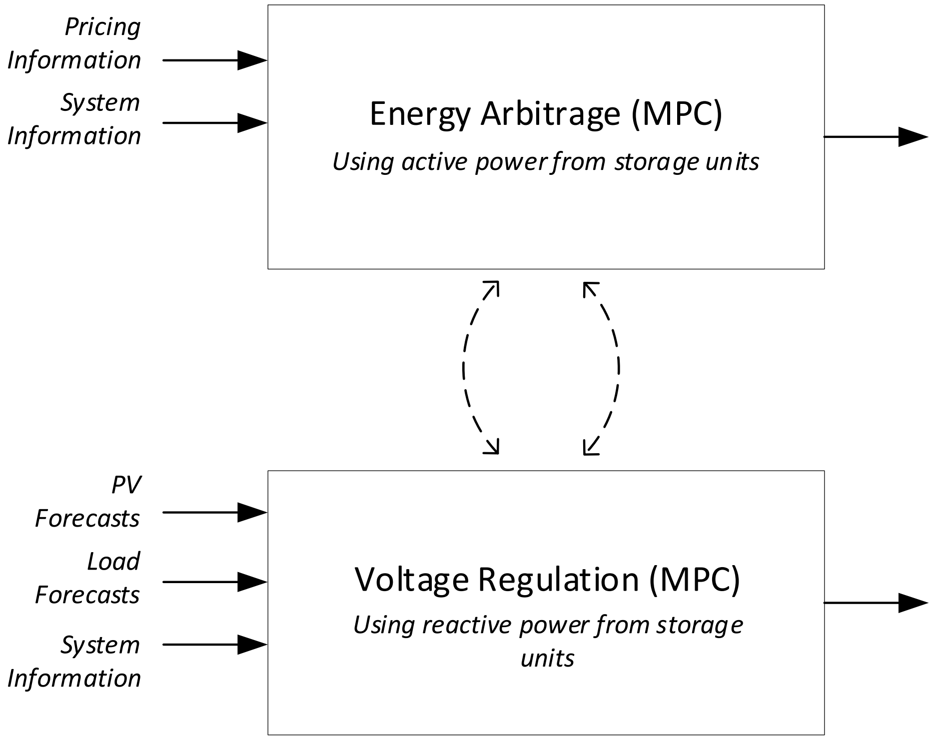


Source: *R. H. Byrne, T. A. Nguyen, D. A. Copp, B. R. Chalamala and I. Gyuk, "Energy Management and Optimization Methods for Grid Energy Storage Systems," in IEEE Access, vol. 6, pp. 13231-13260, 2018, doi: 10.1109/ACCESS.2017.2741578.*

- *† S. Gonzalez, J. Stein, A. Fresquez, M. Ropp and D. Schutz, "Performance of utility interconnected photovoltaic inverters operating beyond typical modes of operation," 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC), 2013, pp. 2879-2884, doi: 10.1109/PVSC.2013.6745071.*

MPC for Combined Ancillary Services and Power Quality Applications

- **Inputs**:
  - System measurements, forecasts, and real-time pricing data
- **Outputs**:
  - Optimal dispatch of active and reactive power
- **Objective**:
  - Maximize benefits from ancillary services
  - Either economic or technical
- Remaining inverter capability to provide power quality service
  - Minimal impact to benefit from ancillary service
  - May in fact provide opportunities for improved benefit



MPC Framework for Combined Energy Arbitrage and Voltage Regulation from Energy Storage

Objective Function

$$\max_{p_k^d, p_k^c, q_k^d, q_k^c} \quad J_{EA} := \sum_{k=1}^{T} \left(c_k p_k^d \tau - c_k p_k^c \tau \right)$$

System Dynamics and Constraints

$$\boldsymbol{x_k} = \boldsymbol{A x_{k-1}} + \boldsymbol{K_p p_k^{net}} + \boldsymbol{K_q q_k^{net}}$$
$$\boldsymbol{x^{min}} \leq \boldsymbol{x_k} \leq \boldsymbol{x^{max}}$$

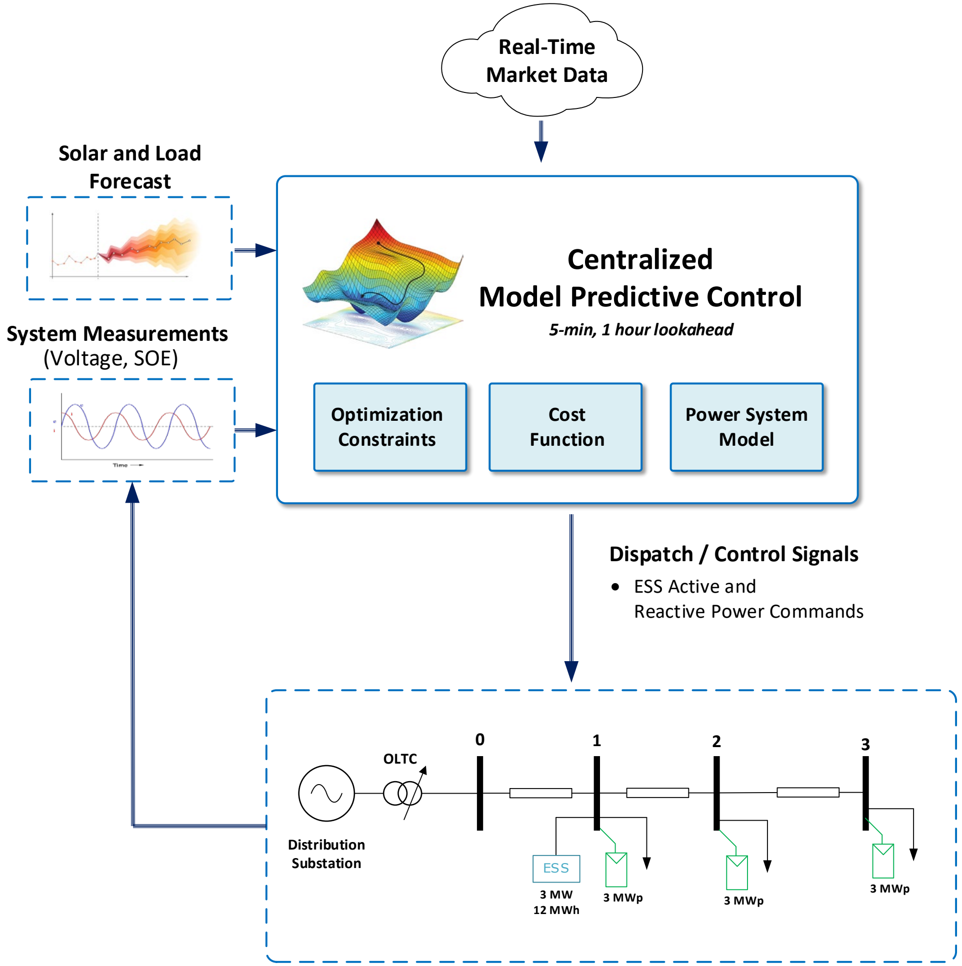
$$S_k = \gamma_s S_{k-1} + \gamma_c p_k^c \tau - p_k^d \tau$$
$$S^{min} \leq S_k \leq S^{max}$$

Inverter Capability and Power Factor Limits

$$-tan\left(\bar{\phi}\right) p_k^c \leq q_k^c \leq tan\left(\bar{\phi}\right) p_k^c$$
$$-tan\left(\bar{\phi}\right) p_k^d \leq q_k^d \leq tan\left(\bar{\phi}\right) p_k^d$$
$$\left(p_k^d\right)^2 + \left(q_k^d\right)^2 \leq \left(\bar{P}\right)^2$$
$$\left(p_k^c\right)^2 + \left(q_k^c\right)^2 \leq \left(\bar{P}\right)^2$$

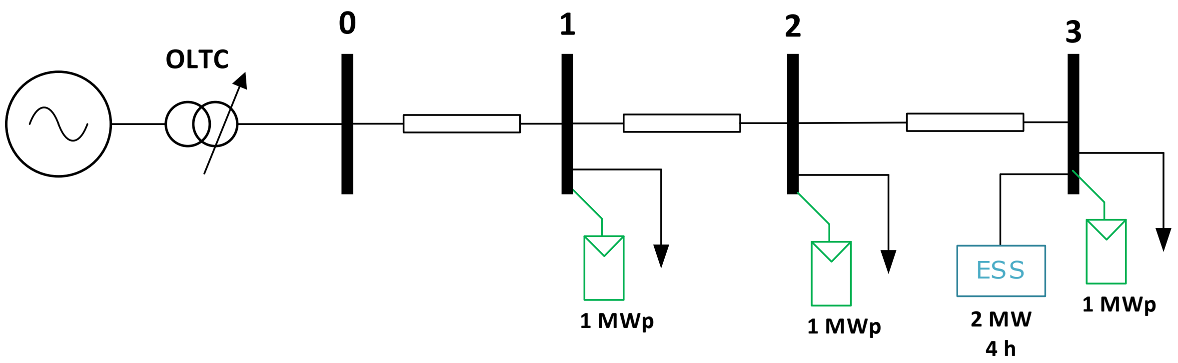
Decision Variables

$$p_k^{net} = p_k^d - p_k^c$$
$$q_k^{net} = q_k^d + q_k^c$$
$$p_k^d \leq \beta_k^d P^{max}$$
$$p_k^c \leq \beta_k^c P^{max}$$
$$-\beta_k^d Q^{max} \leq q_k^d \leq \beta_k^d Q^{max}$$
$$-\beta_k^c Q^{max} \leq q_k^c \leq \beta_k^c Q^{max}$$
$$\beta_k^d + \beta_k^c \leq 1$$

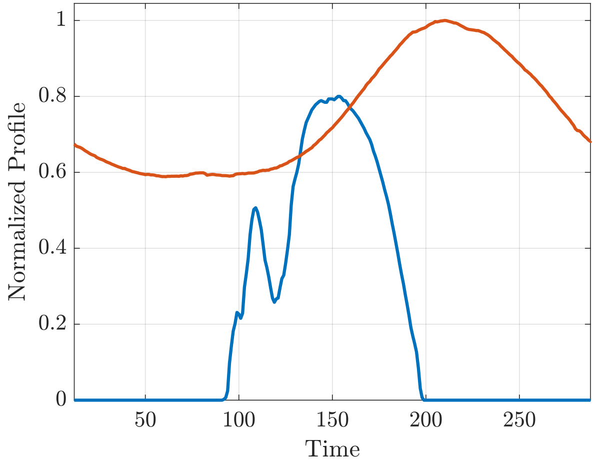


Simulation Case Study: Energy Arbitrage and Voltage Regulation

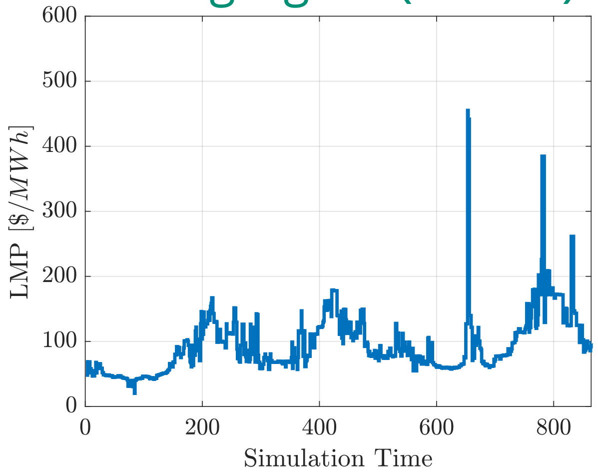
IEEE 4 – Bus Test Case



PV Irradiance and Load Profile



Pricing Signal (ISO-NE)



- Proposed framework tested in IEEE 4-bus distribution network
- 1 MWp PV along with a time varying load at each node
- Pricing signal obtained from ISO-NE
- 2 MW, 4h energy storage placed at end of feeder for energy arbitrage
    - Inverter rating 2 MVA

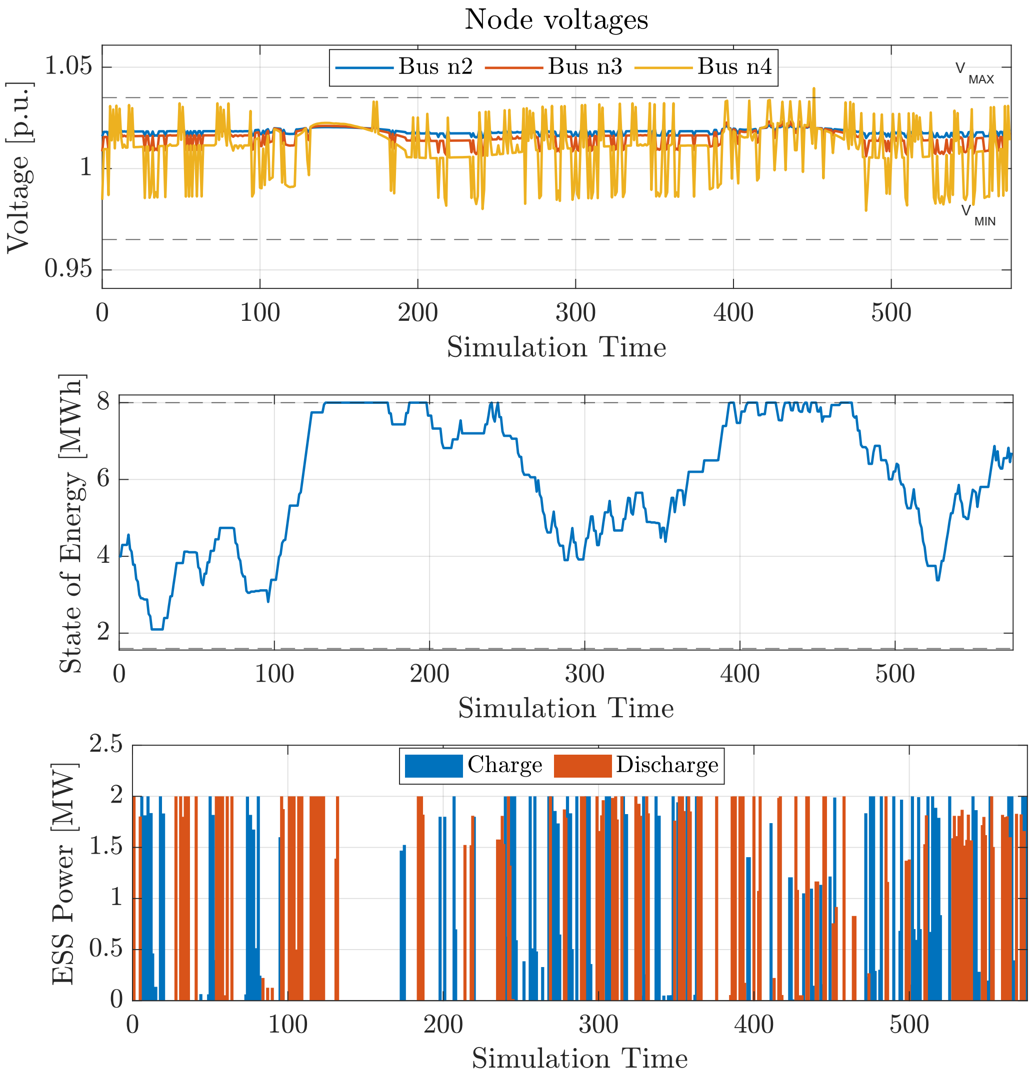
Energy Arbitrage without Voltage Regulation

- MPC implemented such that the ESS only provides energy arbitrage
- **No reactive power support** for voltage regulation
- Voltage limit = 0.965 – 1.035 p.u.

Revenue = $38.71 over two days

Limited due to voltage violations!

Can reactive power support from ESS help to provide voltage regulation and thus allow for better energy arbitrage revenue?

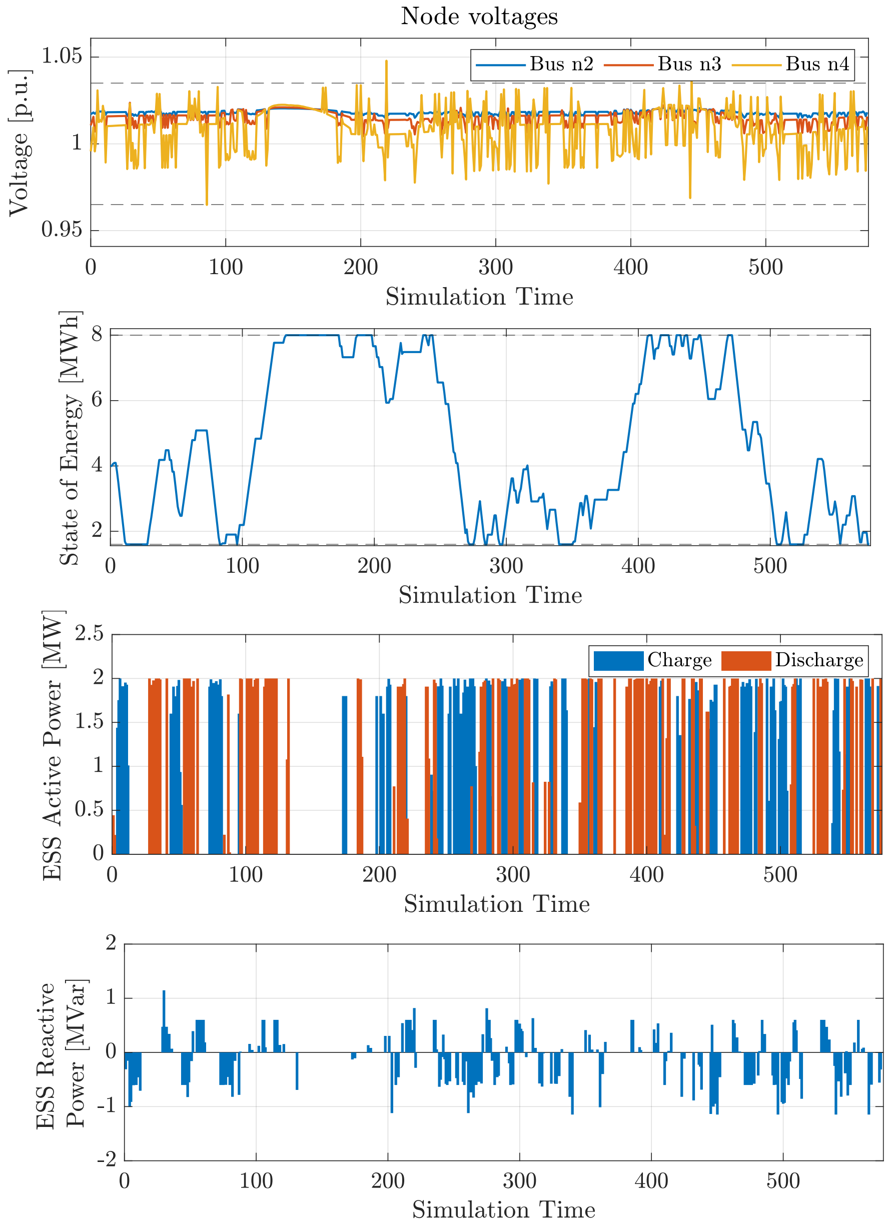


Energy Arbitrage with Voltage Regulation

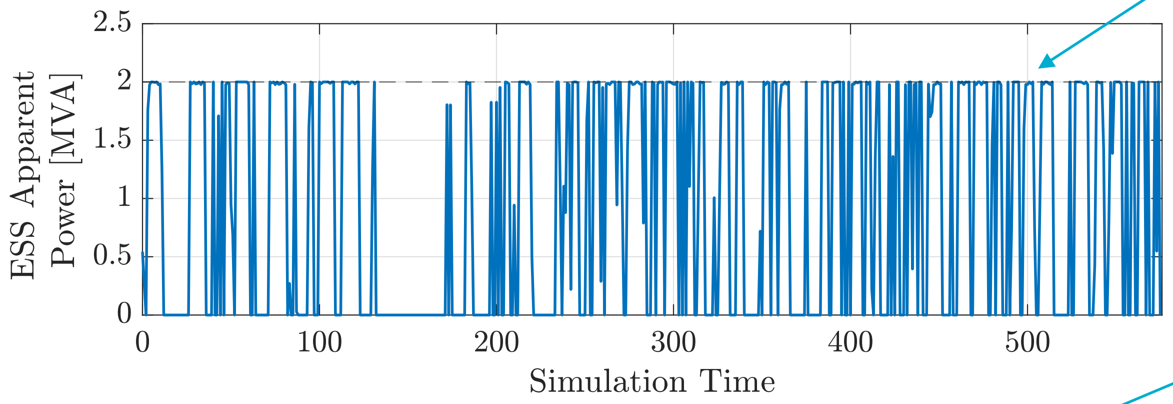
- Same inverter – 2 MVA rated and same pricing signal
- **Reactive power support provided from ESS's inverter**
- Reactive power support maintains voltage at all nodes within limits
- Allows more charge and discharge opportunities

Revenue = $292.28 over two days

Higher revenue from energy arbitrage!

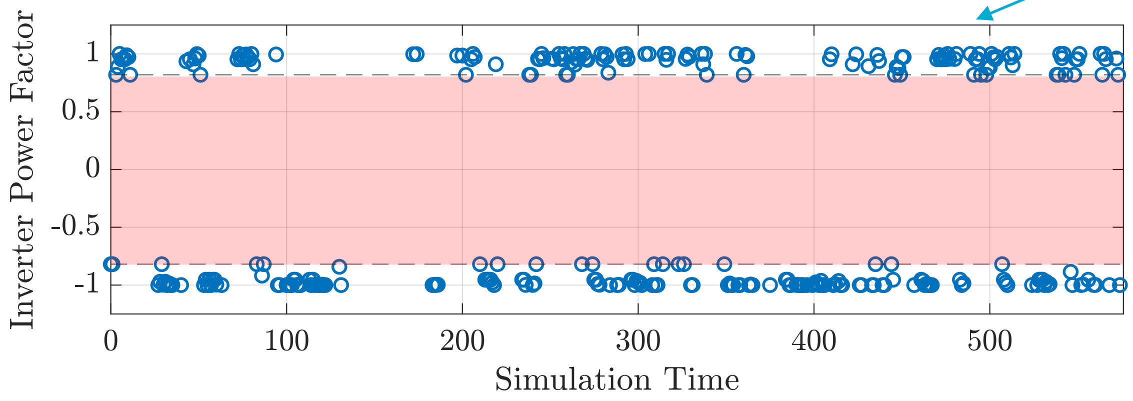


Energy Arbitrage with Voltage Regulation



Inverter Capability Limits NOT Violated!

No need to oversize inverter



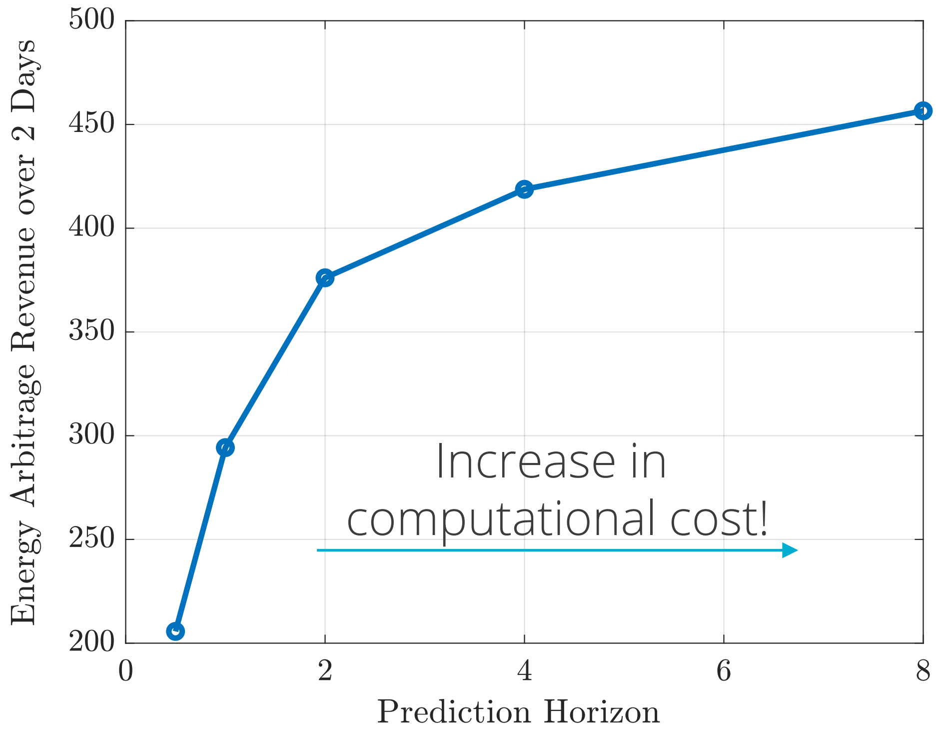
Inverter Power Factor Limits NOT Violated!

- Inverter constraints are not violated when employing ESS for the combined applications

Impact of Prediction Horizon on Energy Arbitrage Revenue

- IEEE 4 Bus Test Case
- 2 MW, 4h energy storage
- Voltage limits: 0.965 – 1.035 p.u.

Prediction Horizon	Revenue Over Two Day Simulation
T = 6, 30 minutes look ahead	$205.68
T = 12 , 1 hour look ahead	$294.25
T = 24, 2 hour look ahead	$376.09
T = 48, 4 hour look ahead	$418.75
T = 96, 8 hour look ahead	$456.60

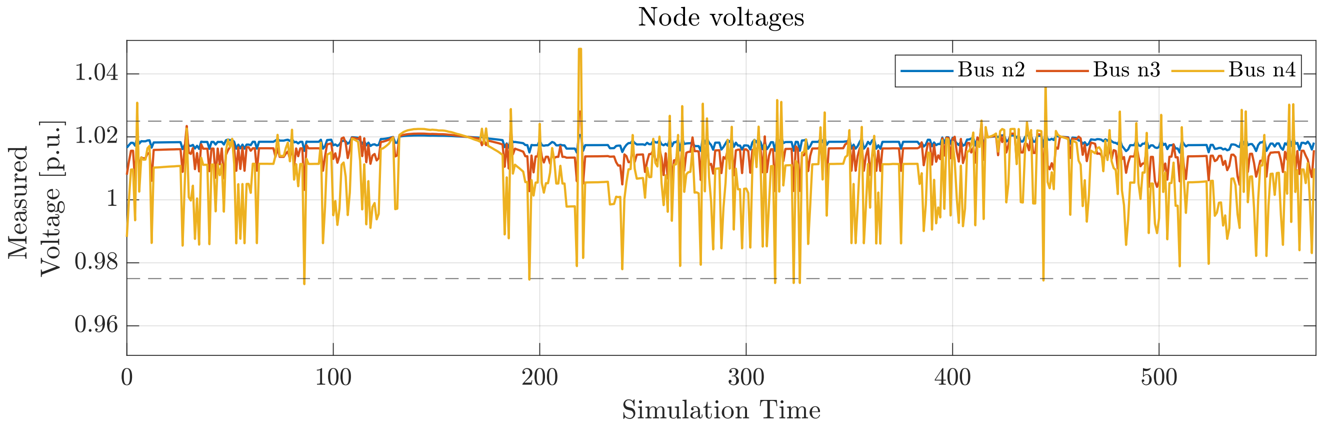


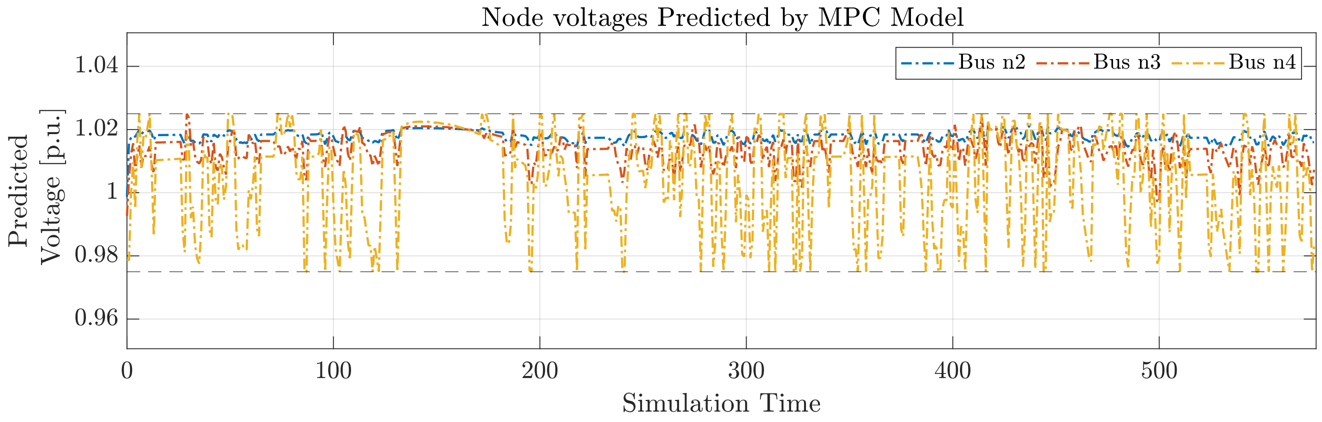
- Higher prediction horizons provided improved benefits
- Computational cost increases with longer prediction horizons
  - More critical when implementing in larger distribution networks

Tighter Voltage Limits of ±2.5%

- IEEE 4 Bus Test Case
- 2 MW, 4h energy storage
- Voltage limits: 0.975 – 1.025 pu

- Voltage limits are violated
- However, MPC is working as expected
  - Predicted voltages are within limits
- Possible sources of error
  - P,Q dispatch commands are NOT exactly implemented by OpenDSS
  - Error in voltage prediction model
  - Error in sensitivity matrix used to predict voltages





Outcomes and Next Steps

Outcomes

- Initial MPC formulation for voltage regulation was presented in an invited technical talk at IEEE Siouxland Section Speaking Event (Feb 2022)
- Journal paper which will generalize the formulation along with an example of EA and power factor correction example is under preparation

Next Steps

- Test for larger distribution networks
- Demonstrate feasibility of this framework using real-time digital simulation and power-hardware-in-the-loop techniques

Acknowledgements

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