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

Ujjwol Tamrakar, Tu A. Nguyen

2022 DOE Energy Storage Peer Review
Presentation Number: 906
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
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
  - Model predictive controls (MPCs) ideal for such applications

A control framework is required to dispatch ESSs in real-time while maximizing benefits
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
  • Except for small losses due to increased voltage and current ripple


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

**Energy Arbitrage (MPC)**
- Using active power from storage units

**Voltage Regulation (MPC)**
- Using reactive power from storage units

**Pricing Information**
**System Information**

**PV Forecasts**
**Load Forecasts**
**System Information**
MPC Framework for Combined Energy Arbitrage and Voltage Regulation from Energy Storage

Objective Function

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

System Dynamics and Constraints

$$x_k = Ax_{k-1} + K_p p_k^{net} + K_q q_k^{net}$$
$$x^{min} \leq x_k \leq x^{max}$$
$$S_k = \gamma_s S_{k-1} + \gamma_c p_k^c \tau - p_k^d \tau$$
$$S^{min} \leq S_k \leq S^{max}$$

Inverter Capability and Power Factor Limits

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

Decision Variables

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

Solar and Load Forecast

System Measurements (Voltage, SOE)

Centralized Model Predictive Control

- 5-min, 1-hour lookahead
- Optimization Constraints
- Cost Function
- Power System Model
- Dispatch / Control Signals
  - ESS Active and Reactive Power Commands

Real-Time Market Data

Decision Variables

Objective Function

System Dynamics and Constraints

Inverter Capability and Power Factor Limits
Simulation Case Study: Energy Arbitrage and Voltage Regulation

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

Inverter Capability Limits **NOT** Violated!
No need to oversize inverter

Inverter Power Factor Limits **NOT** Violated!
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.

<table>
<thead>
<tr>
<th>Prediction Horizon</th>
<th>Revenue Over Two Day Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>T = 6, 30 minutes look ahead</td>
<td>$205.68</td>
</tr>
<tr>
<td>T = 12, 1 hour look ahead</td>
<td>$294.25</td>
</tr>
<tr>
<td>T = 24, 2 hour look ahead</td>
<td>$376.09</td>
</tr>
<tr>
<td>T = 48, 4 hour look ahead</td>
<td>$418.75</td>
</tr>
<tr>
<td>T = 96, 8 hour look ahead</td>
<td>$456.60</td>
</tr>
</tbody>
</table>

- 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
THANK YOU!

Tu A. Nguyen
Alvaro F. Bastos

Contact Information:
Ujjwol Tamrakar, Ph.D.
Sandia National Laboratories
utamrak@sandia.gov

Funding provided by US DOE Energy Storage Program managed by Dr. Imre Gyuk of the DOE Office of Electricity.