SAND2021-6406C

IEEE ISIE 2021 – Kyoto, Japan
SS01: Energy Storage System Modeling and Monitoring System

Model Predictive Dispatch of Energy Storage for Voltage Regulation in Active Distribution Systems

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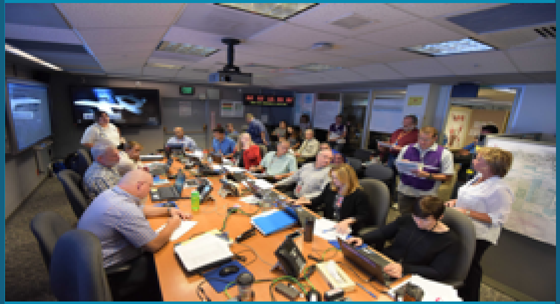

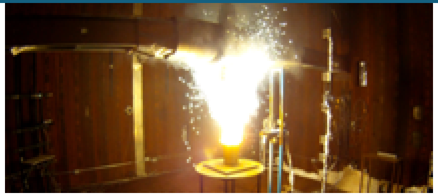

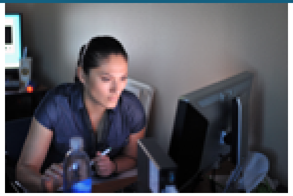

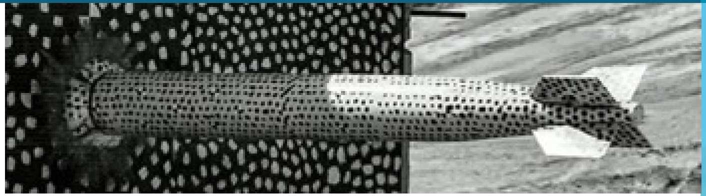

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Outline

- Introduction
- Existing Work on Voltage Regulation of Distribution Systems
- Objective of the Work
- Proposed Dispatch of Energy Storage Using Model Predictive Control
- Methodology / Simulation Setup
- Results and Analysis
- Conclusions and Future Work

Voltage Regulation in Systems with High Renewable Penetration

Issues in Power Distribution Systems with High Renewable Penetration

Imbalance between PV generation and load → Power quality issues: Poor Voltage Regulation, Over-voltages → Excessive operation of traditional devices

- Current practices using transformers, voltage regulators and switching capacitors sub-optimal
- System operators have to impose stringent operational limits
  - Traditionally 5-10% voltage deviation allowed
  - Hawaiian electric has proposed limiting voltage operation range to ±2.5% during day time due to excessive PV
- Reduces efficiency and utilization of renewables

Energy Storage and Voltage Regulation

- Existing solutions
  - Limit integration of renewables
  - Curtailment of power from renewables
- Energy storage a flexible asset for voltage regulation
- Voltage regulation can be provided either by active or reactive power support
  - Inverter of energy storage system (ESS) can provide reactive power support
  - Oversizing by 10% → Increase Q-capability of ±46%
  - Active power support also desirable when R/X ratio is higher
- Voltage regulation through substation installations or distributed energy storage

Existing Work on Voltage Regulation of Distribution Systems

Local Control Strategies

- Local voltage measurements
- No communication
- Control instability

Decentralized and Distributed Strategies

- Low-form of communication typically between neighboring nodes
- Improved control stability
- Does not guarantee optimality

Centralized Strategies

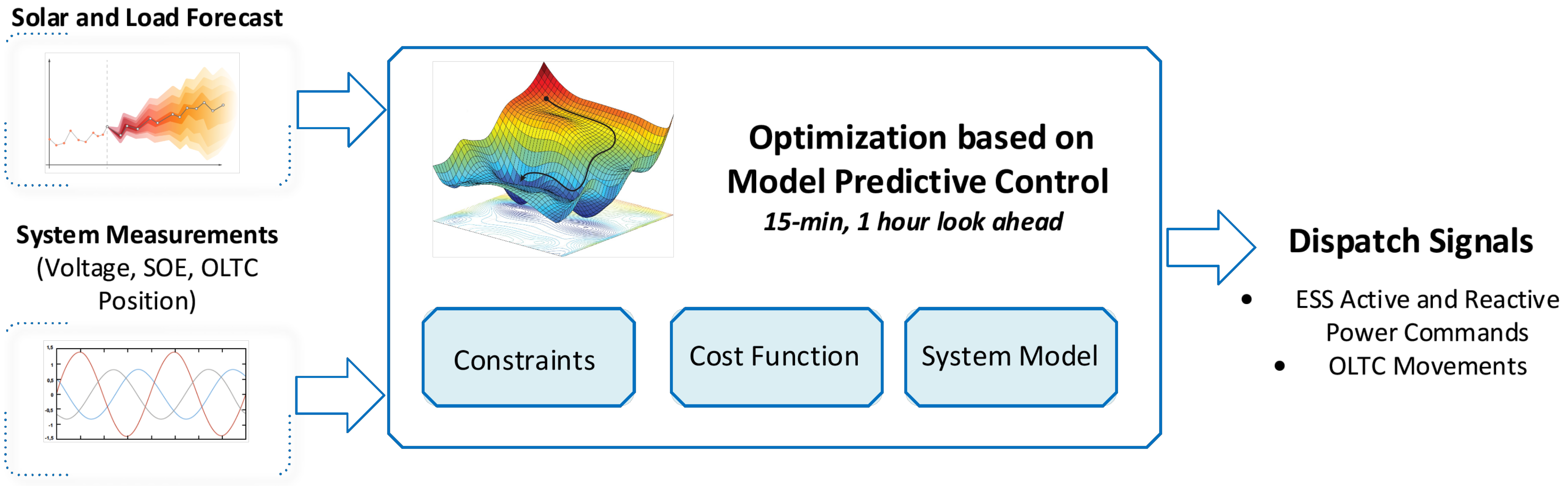
- Sophisticated communication
- Stability and optimality can be guaranteed

Control Strategies Utilizing
Model Predictive Control (MPC) Framework

Objective of the Work

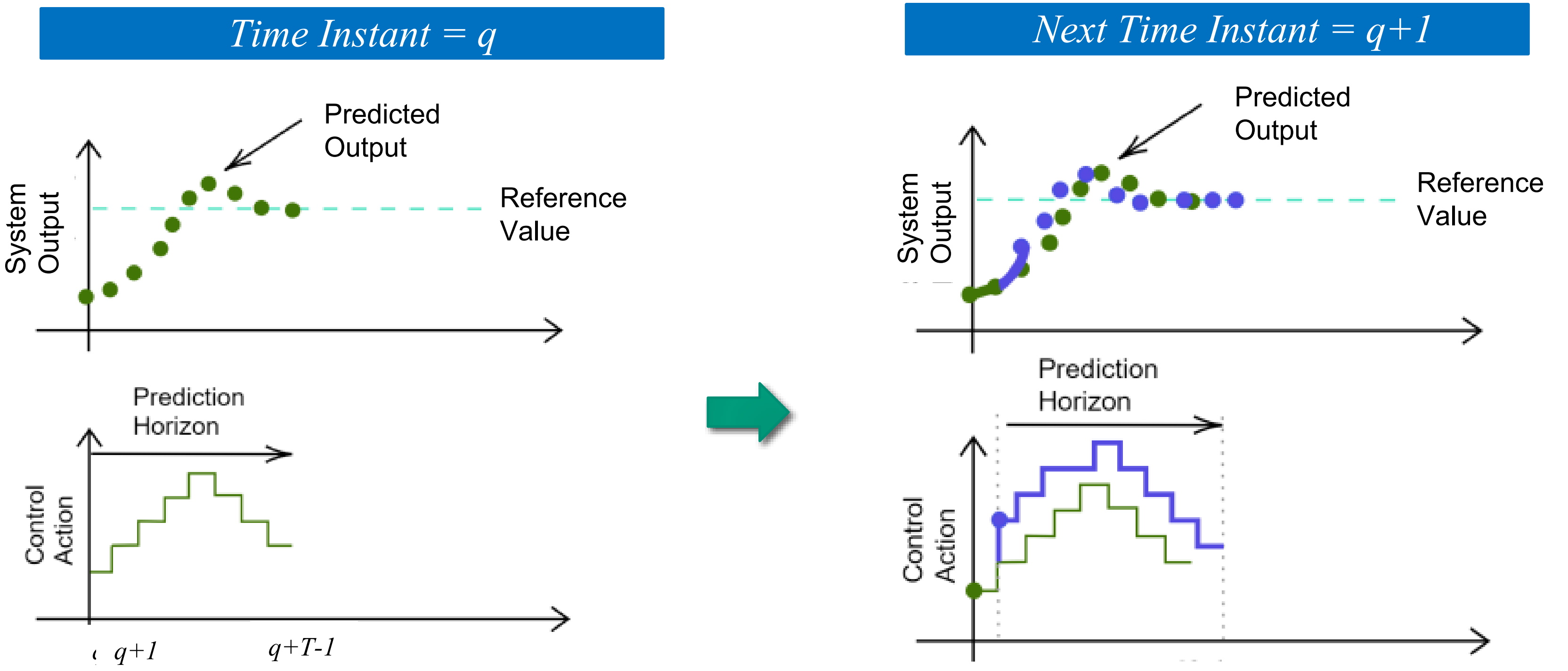
- Develop a dispatch framework using MPC to utilize energy storage for voltage regulation in distribution systems
- Minimize operation of traditional voltage regulators such as On Load Tap Changers (OLTCs)

Proposed Dispatch of Energy Storage Using Model Predictive Control



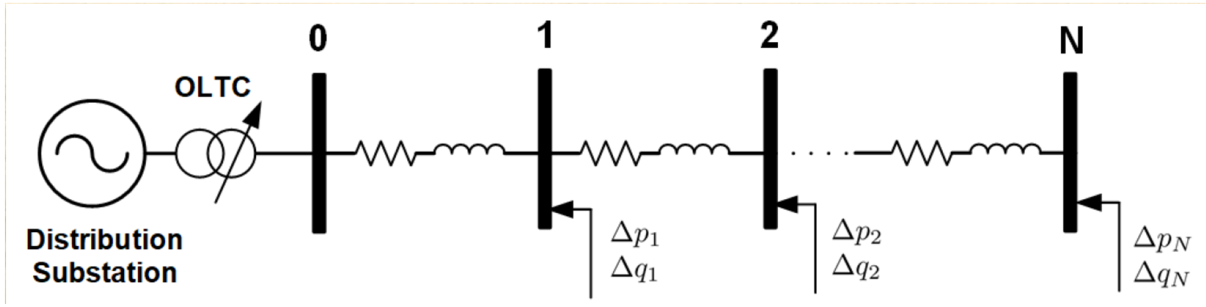
- Utilize renewable energy and load forecast information to optimally dispatch energy storage to:
  - Maintain system voltage within desired range
  - Limit operation of traditional devices such as OLTCs and capacitor banks

Basics of Model Predictive Control



- Optimal control action computed based on prediction from a system model
- Cost function is defined to optimize system (reduce deviation, reduced power usage)
- Prediction horizon moves one-time step
- Optimization re-runs to calculate new optimal control

Modeling of Distribution Systems



$$\boldsymbol{x}(k) = [v_1(k)\, v_2(k) \dots v_N(k)]^T$$

Set of Node Voltages

$$\boldsymbol{\Delta u}(k) = [\Delta p_1(k) \dots \Delta p_N(k)\ \Delta q_1(k) \dots \Delta q_N(k)\ \Delta n_{oltc}(k)]^T$$

Set of Active and Reactive Injections and OLTC movements

Predictive Model

$$\boldsymbol{x}(k+1) = \boldsymbol{A}x(k) + \boldsymbol{B\Delta u}(k) + \boldsymbol{D\Delta d}(k)$$

Sensitivity Matrix

Describes voltage sensitivity to Δp, Δq, and Δn_{oltc}

- Predict voltage at the next sampling instant
- This model can be used as the “predictive” model to implement MPC based dispatch of ESSs

Model Predictive Control Framework

Objective Function

Minimize control actions Δp, Δq, and Δn_{oltc}

$$\min \sum_{k=1}^{T} \{R_n \boldsymbol{U}_n(k) + R_p \boldsymbol{U}_p(k) + R_q \boldsymbol{U}_q(k)\}$$

$$\underbrace{\Delta \boldsymbol{n}^+(k) + \Delta \boldsymbol{n}^-(k)}_{\text{OLTC Movements}}$$

$$\underbrace{\Delta \boldsymbol{p}^+(k) + \Delta \boldsymbol{p}^-(k)}_{\text{ESS Charge/Discharge}}$$

$$\underbrace{\Delta \boldsymbol{q}^+(k) + \Delta \boldsymbol{q}^-(k)}_{\text{Inductive/Capacitive Reactive Power}}$$

Optimization Constraints

$$\boldsymbol{x}_{min} \leq \boldsymbol{x}(k) \leq \boldsymbol{x}_{max}$$

$$\boldsymbol{SOC}(k) = \boldsymbol{SOC}(k-1) + \frac{\tau}{T_{ess}}(\boldsymbol{\eta}^{\boldsymbol{cd}} \boldsymbol{p}^+(k) - \boldsymbol{p}^-(k))$$

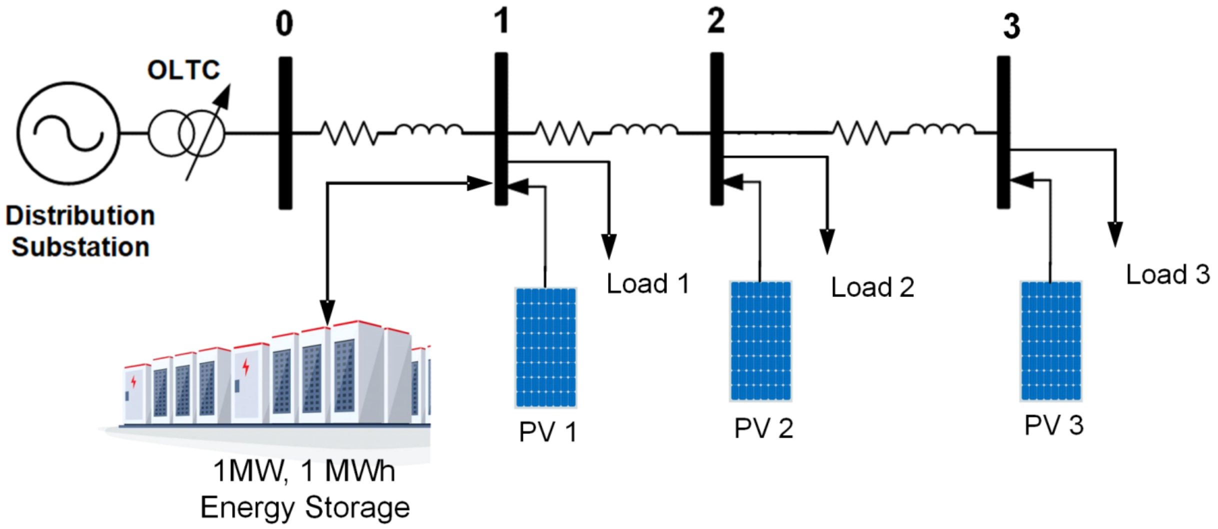
$$\boldsymbol{SOC}_{min} \leq \boldsymbol{SOC}(k) \leq \boldsymbol{SOC}_{max}$$

Other Charge/discharge constraints, inverter capability constraints (listed in paper)

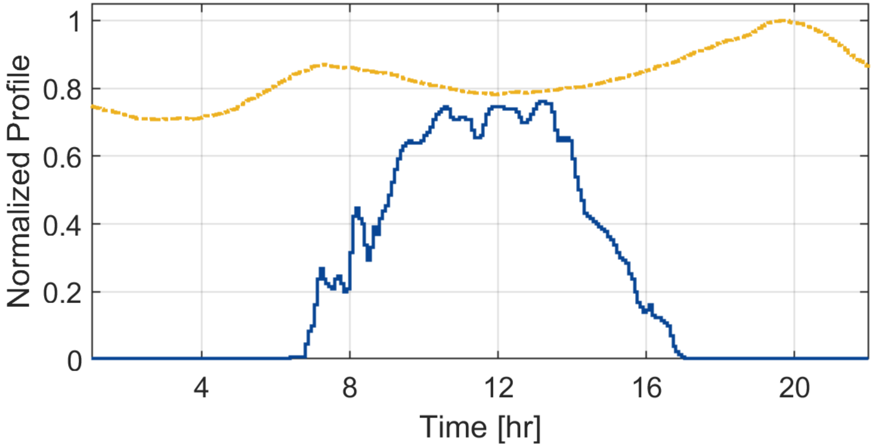
- Prediction horizon (T) = 60 mins, optimal values for the control actions computed every 5 mins

Simulation Setup

IEEE 4-bus Distribution Test Case



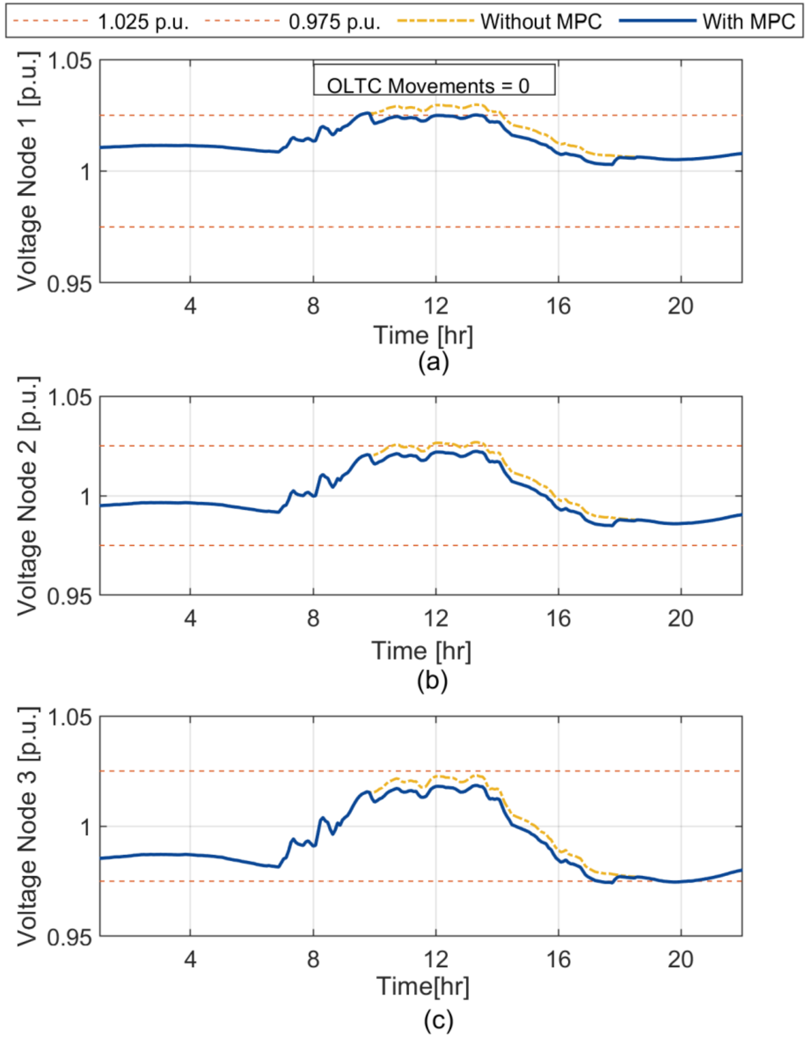
PV and Load Profiles for Month of May



- Proposed method tested in 4-bus distribution system
- OLTC installed at the substation
- 3 MWp PV installed at each distribution node
- A 1 MW, 1 MWh energy storage unit assumed to be installed at the substation for voltage regulation

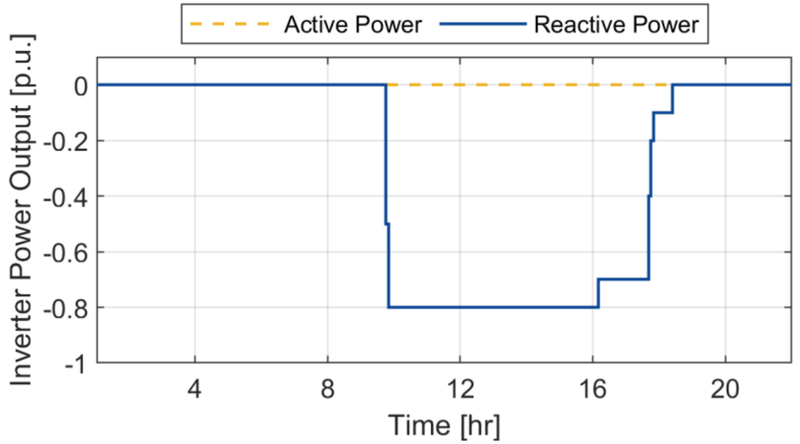
Results and Analysis: Voltage without MPC

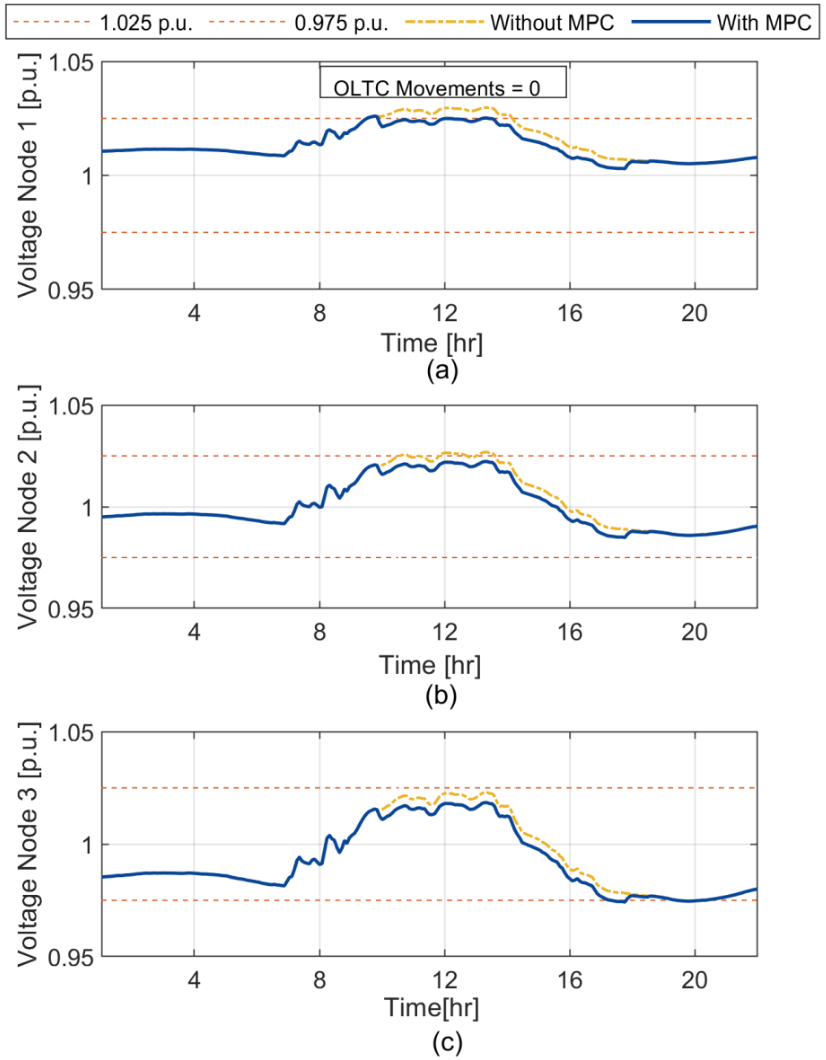
- Analysis for month of May for single day of operation
- 3 MW PV at each node along with a load
- Without MPC voltage exceeds range
  - Overvoltage at nodes 1 and 2
  - Middle of the day
  - High generation and low load causing reverse power flow
  - Drastic drop in PV generation at night causing undervoltage



Results and Analysis: Voltage with MPC (Priotorizing ESS Operation)

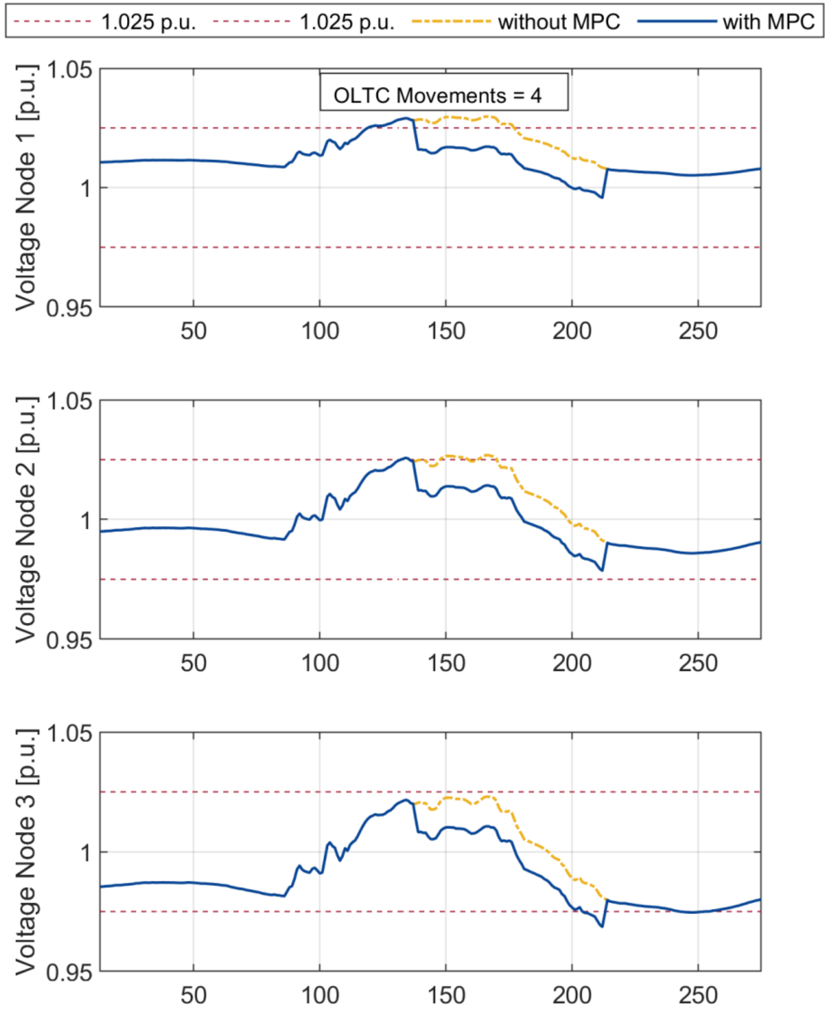
- MPC weight settings
  - $R_n = 1.0$
  - $R_p = 0.001$
  - $R_q = 0.00001$
- Perfect forecast information assumed
- MPC-based dispatch with ESS priority over OLTC
  - Voltage of all three node within specified limits
  - No OLTC movements observed





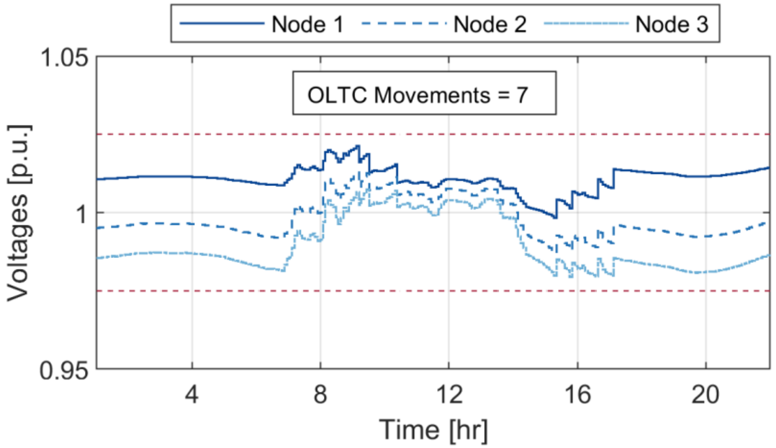
Results and Analysis: Voltage with MPC (Priotorizing OLTC Movements)

- MPC weight settings
  - R_n = 0.00001s
  - R_p = 1.0
  - R_q = 1.0
- MPC-based dispatch with OLTC priority over ESS
  - Voltage of all three node within specified limits
  - Four OLTC movements observed
  - No active/reactive power support provided by ESS



Results and Analysis: Voltage with OLTC only (no MPC dispatch)

Voltage Profiles for a day in month of May



Month of the year	with MPC dispatch	with traditional OLTC (no MPC dispatch)
May	0	7
July	0	4
September	0	2
December	0	0

- No MPC, but OLTC enabled to compare reduction in movements
- OLTC Settings:
  - Set-point = 0.99 p.u.
  - Deadband = ± 2%
  - Percent regulation = 0.00625 p.u.
  - Measurement point = Node 3 (No line drop compensation)
- High number of OLTC movements without MPC
  - May have negative impacts on OLTC lifetime

Conclusions and Future Work

- MPC-based dispatch strategy for ESSs to provide voltage regulation formulated
- Provide active and reactive power support utilizing 1-hour ahead PV and load forecast
- Minimize OLTC operation
  - Keeping voltage within desired range
  - Increase lifetime of mechanical OLTC devices
- Future work will include incorporating uncertainties in forecasts and ESS degradation aspects

Acknowledgements

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