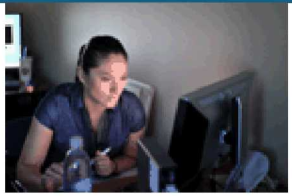
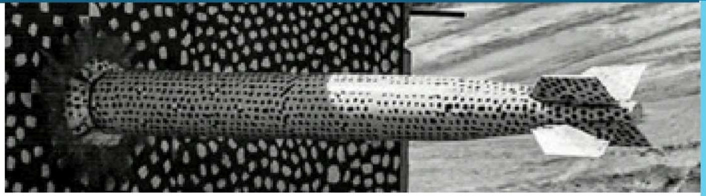
SAND2020-10003C

Fast Frequency Support in Low Inertia Power System Using Energy Storage





PRESENTED BY

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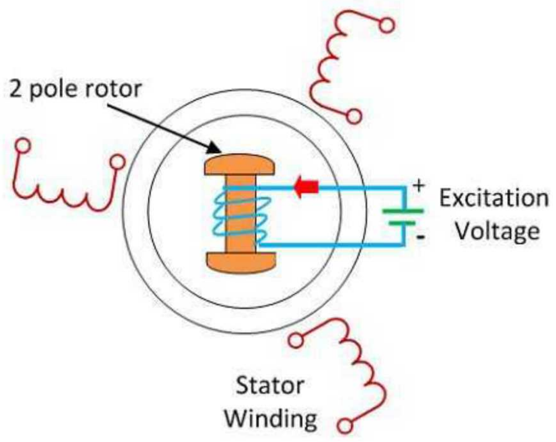
Inertia in Power Systems

- Synchronized operation
  - Largely depends on "***inertia***" from generators
- Rotational energy stored in the rotor



$$Rotational\ Energy(E_{rot}) = \frac{1}{2}M\omega^2$$

$$Rotational\ Energy(E_{rot}) = H_i S_{rated}$$

System "**Inertia**" (MWs)

Inertia Constant (s)

Power Rating (MW)

- Whenever power imbalance occurs
  - Rotational energy is released/absorbed
  - Prevents over-speeding/under-speeding of the generator
  - Keeps frequency within limits

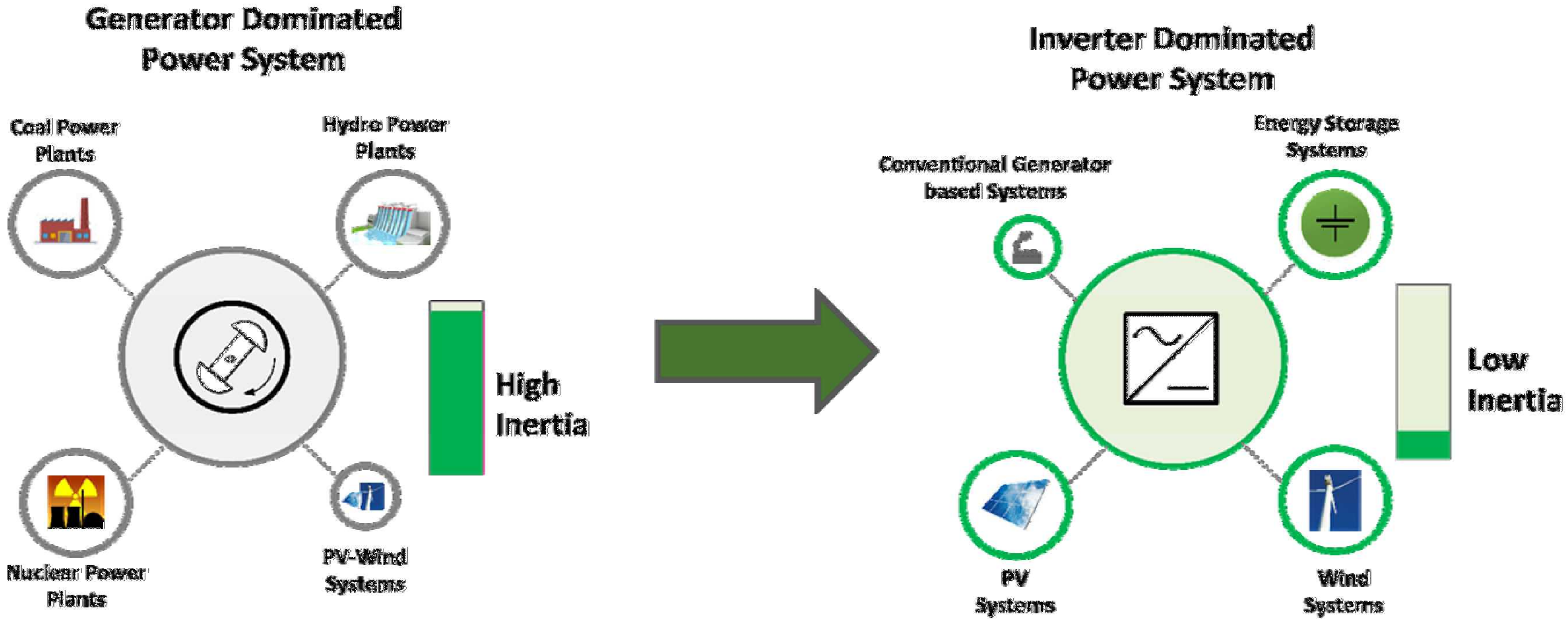
Effect of Renewables on Frequency Stability

Photovoltaic Power Plants
No Rotational Energy
No Inertia

Wind Power Plants
Coupled through power electronic converters
Limited Inertia

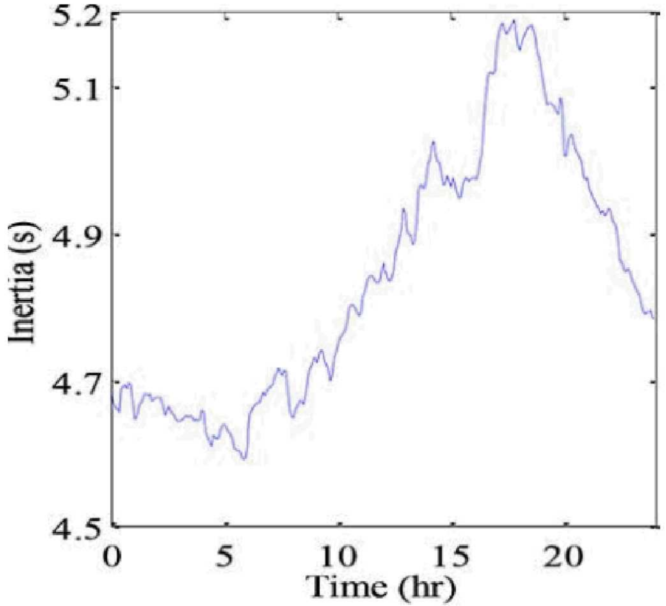
- Displacement of conventional generation leads to frequency stability issues
  - Large frequency deviations and Rate-of-Change-of- Frequency (ROCOF)
  - Under Frequency Load Shedding (UFLS) relays can be triggered
  - Causing cascaded tripping

Transition Towards an Inverter Dominated Power System



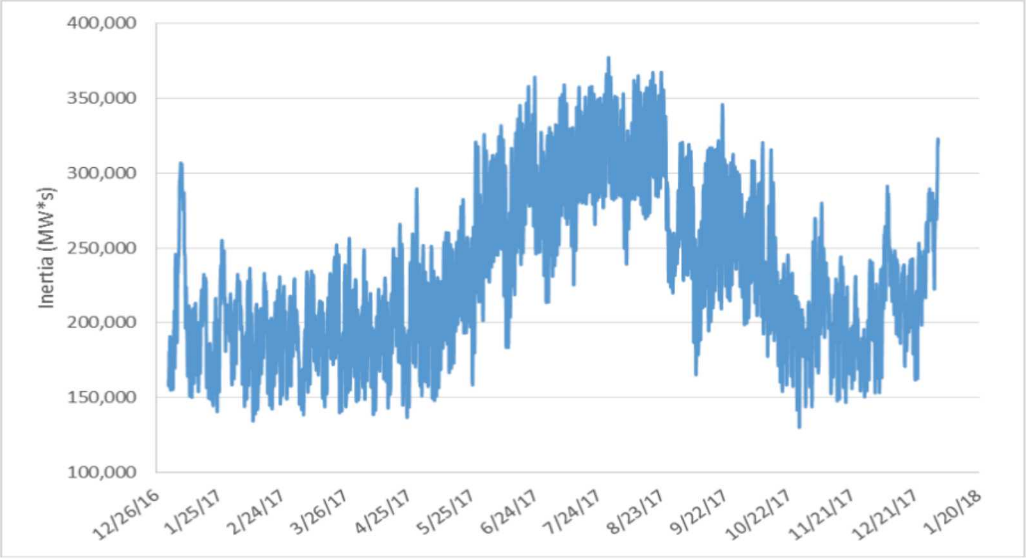
- Evolution towards inverter dominated power system
  - Typically non-dispatchable
- Inertia in power system getting reduced everyday
- Penetration of renewables is limited due to stability concerns

Uncertainty in Grid Inertia with Renewables



Daily inertia variations from the UK grid

Source: X. Cao, B. Stephen, I. F. Abdulhadi, C. D. Booth and G. M. Burt, ***"Switching Markov Gaussian Models for Dynamic Power System Inertia Estimation,"*** *IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 3394-3403, Sept. 2016.*

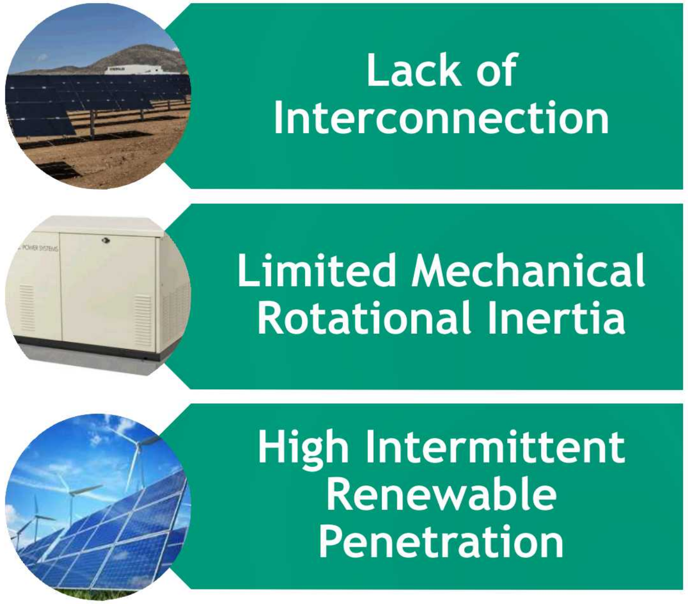


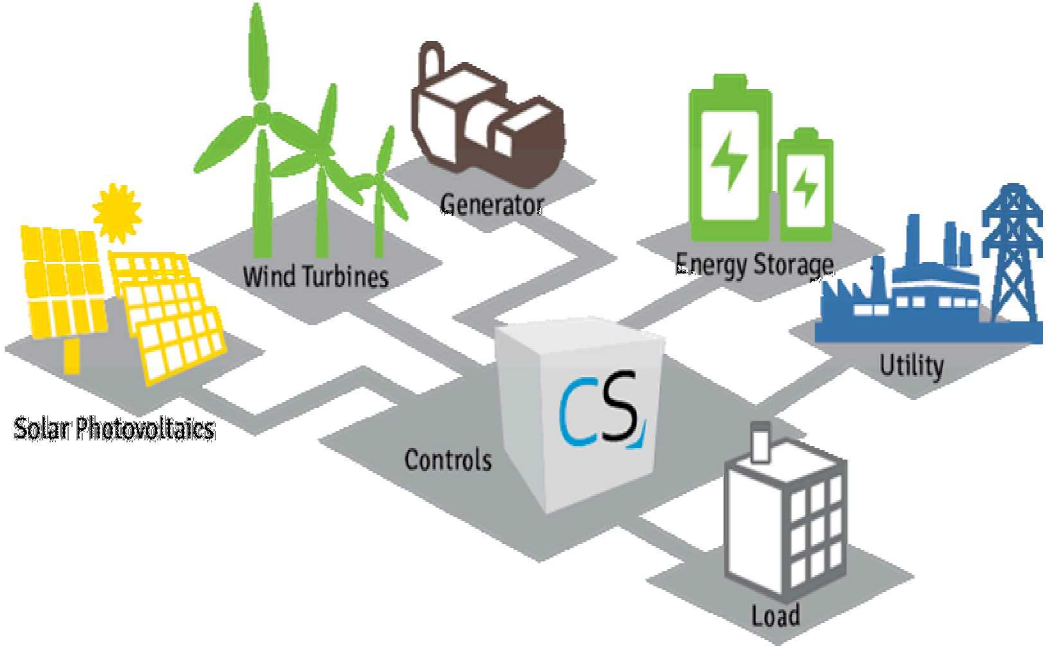
Seasonal variation in inertia of ERCOT

Source: ERCOT. (2018) ***Inertia: Basic Concepts and Impacts on the ERCOT Grid****. http://www.ercot.com/content/wcm/lists/144927/Inertia_Basic_Concepts_Impacts_On_ERCOT_v0.pdf*

- Inertia dependent on the number of synchronous generations at any given time
- Inertia variability more pronounced in microgrids
- Design of controllers and protection systems becoming challenging

Inertia in Microgrids



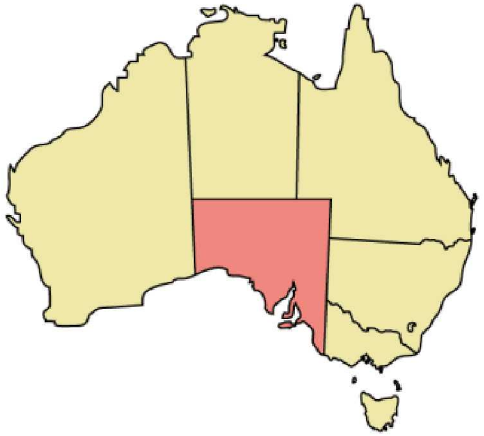


- Microgrid definition:
  - *"A small network of electricity users with a local source of supply that is usually attached to a centralized national grid but is able to function independently"*
- Lower inertia response - microgrids more prone to frequency stability problems

Real World Events Due to Low Inertia: South Australian Blackout

- South Australian Blackout
  - September 2018, 2016 – 850,000 people affected

- Multiple wind farms tripping due to a severe storm
  - Rapid voltage/frequency events – prevented wind turbines staying online
  - Output of wind turbines fell by 456 MW over less than 7s
  - Frequency plummeted – Cascaded Tripping

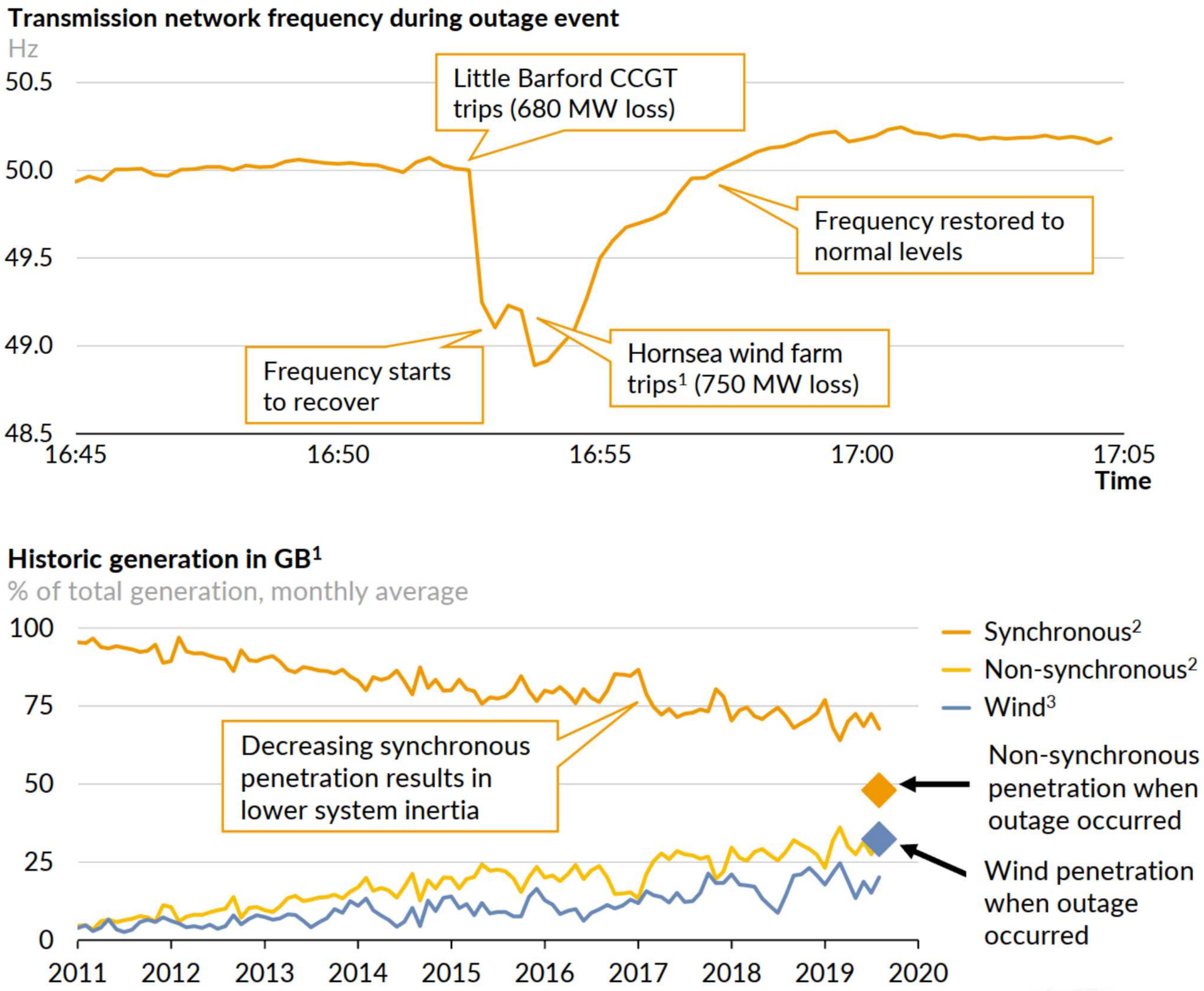


Source: ***Smart Power Electronic Converters May Help Stabilize the Grid.*** *Available: https://spectrum.ieee.org/energywise/energy/the-smarter-grid/can-power-electronic-converters-lead-to-grid-stability [Online]*
Source: **Wind Farms Settings to Blame for SA Blackout.** *http://www.abc.net.au/news/2017-03-28/wind-farm-settings-to-blame-for-sa-blackout-aemo-says/8389920 [Online].*

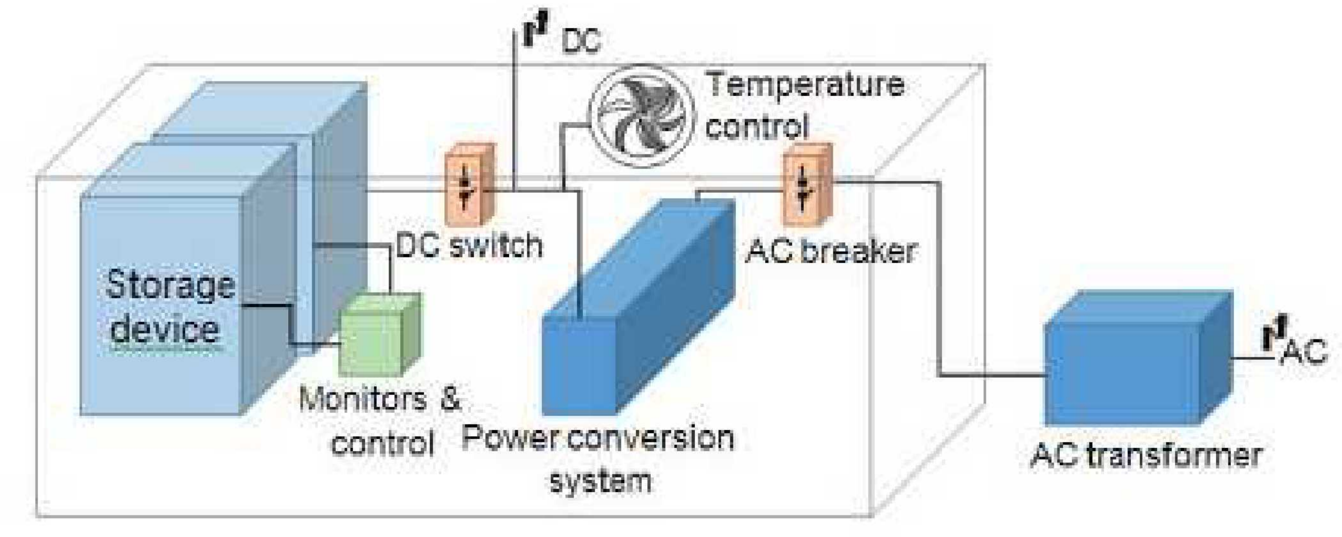
Real World Events Due to Low Inertia: UK Blackout

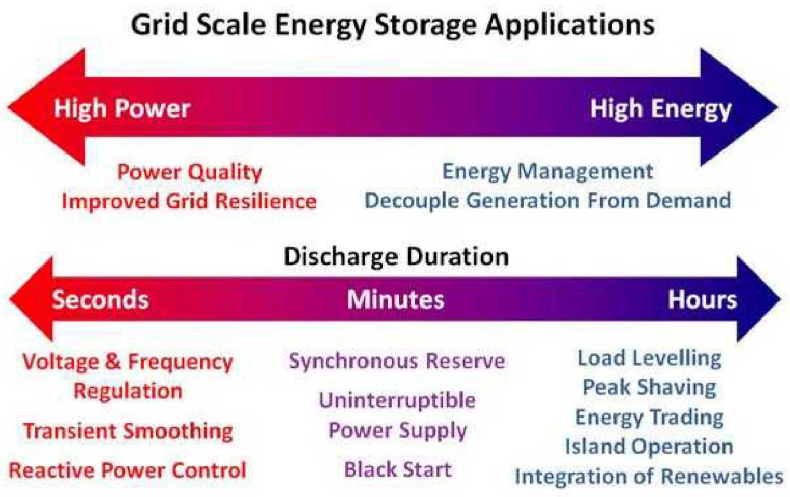
- Great Britain experienced a power outage – August 2019
  - 1 million people affected for 15 - 45min
  - Rail transit services and hospitals affected

- Low inertia the root cause
  - System did not have enough fast-frequency services procured



Basics of Energy Storage System





- Components of Energy Storage Systems:
  - Storage device (battery)
  - Monitors and controls (Battery Management System – BMS)
  - Power Conversion System (DC-AC conversion)
- Applications can range from high power to high energy
- Flexibility resource to improve grid reliability and resiliency

Basic Concepts of Virtual Inertia

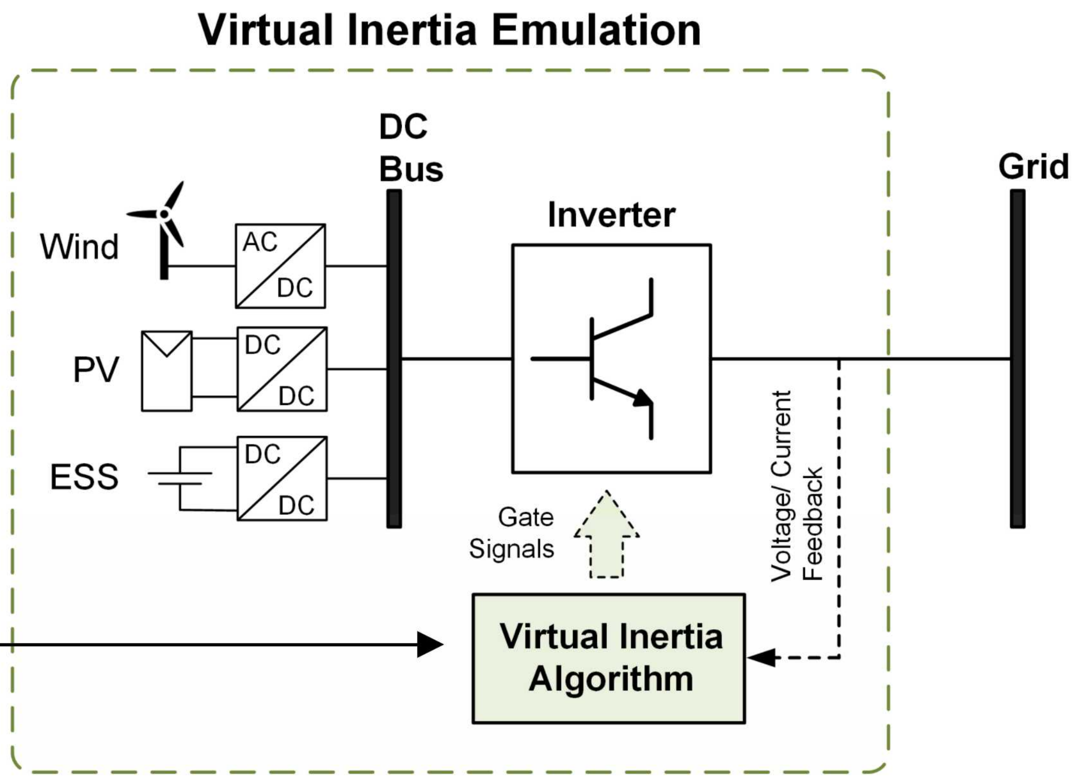
- Combination of control algorithms, energy storage systems, RESs and power electronics that emulates inertia

Equation to emulate synchronous generator behavior

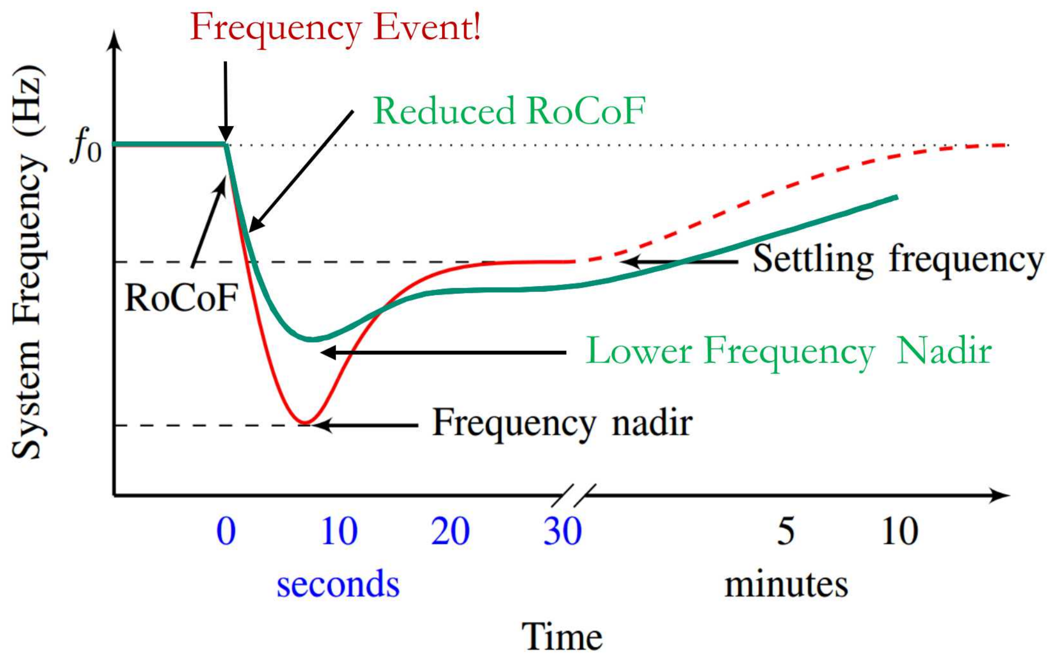
$$P_{SI} = K_p \Delta f + K_i \frac{d\,\Delta f}{dt}$$

1. **Damping Constant**
   - Similar to frequency droop
   - Returns frequency to steady state value

2. **Inertial Constant**
   - Tries to arrest the rate of change of frequency
   - Injects/absorbs power only during transient



Fast-Frequency Support through Virtual Inertia Using Energy Storage



- In initial few seconds, no governor response
  - Inertial response responsible to maintain power balance
  - Decreased inertia means frequency changes and a large rate of change frequency (ROCOF)
  - Trigger frequency relays → Cascade outage → Frequency instability
- Emulation of virtual inertia through power electronic converters
  - Ensures the ROCOF is minimized
  - Ensures frequency does not dip to low (or high)

Generations of Virtual Inertia Development

Third Generation

System Level Coordination and Optimization

- Inertia estimation
- Coordination of multiple units with virtual inertia
- Optimal placement

First Generation

Development of novel topologies

- **Frequency derivate-based**: Virtual Synchronous Generators
- **Dynamic model-based**: Synchronous power controller, Synchronverters

Second Generation

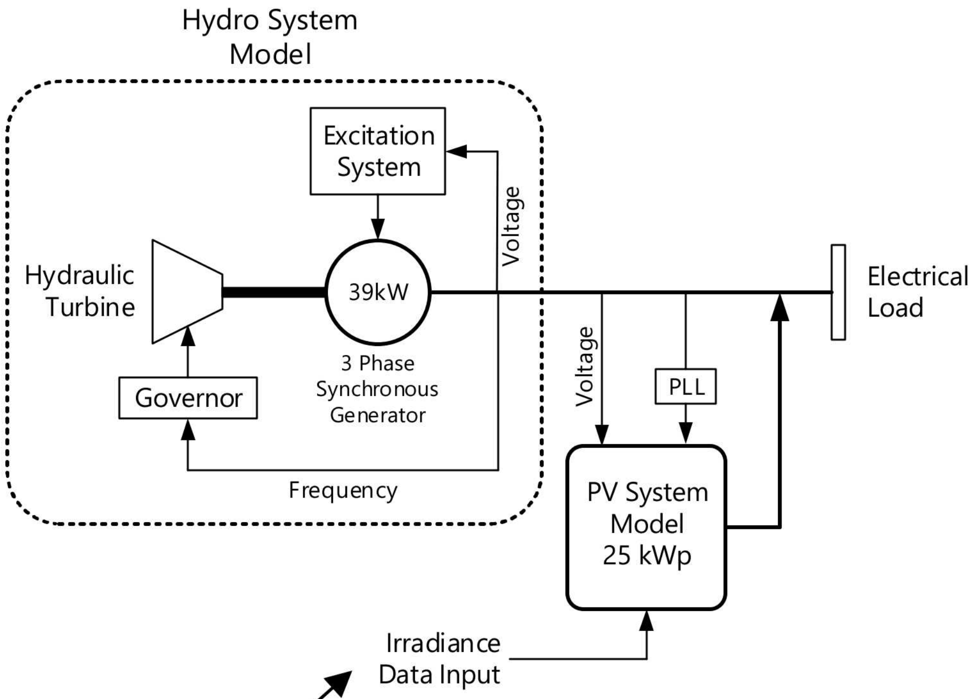
Optimization Techniques

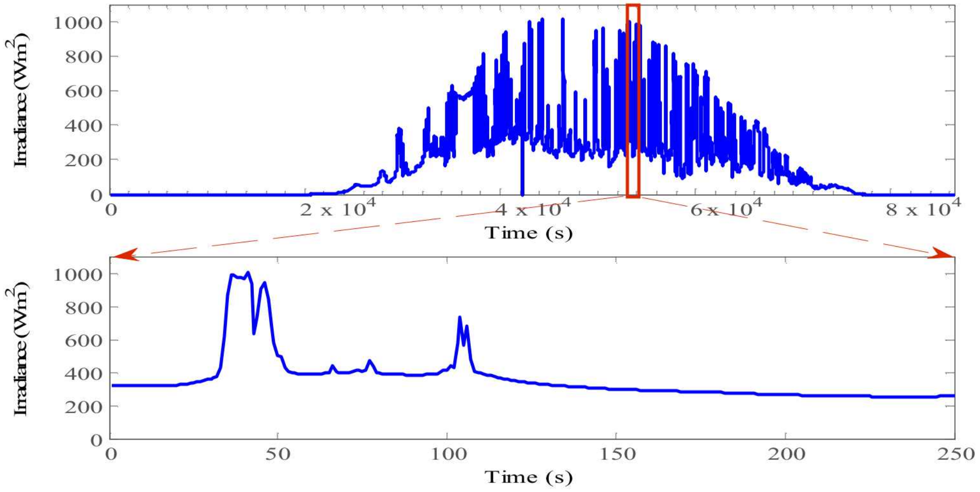
- Model-free or model-based optimization
- Reduce energy/power requirements
- Reduce cost of deployment

__U. Tamrakar,__ D. Shrestha, M. Maharjan, B.P. Bhattarai, T.M. Hansen, and R. Tonkoski, "__Virtual inertia: Current trends and future directions__," Applied Sciences: Advances in Integrated Energy Systems Design, Control and Optimization, vol. 7, no. 7, pp. 654, June 2017.

Virtual Inertia: Case Study of a PV-Hydro Microgrid System

- 64 kW PV-hydro microgrid benchmark
  - 39 kW hydro system with a 25 kWp PV system
- Hydro master unit which controls system frequency
- Inertia constant set to 2 s
- PV system model as current sources
- Power output depends on irradiance data input



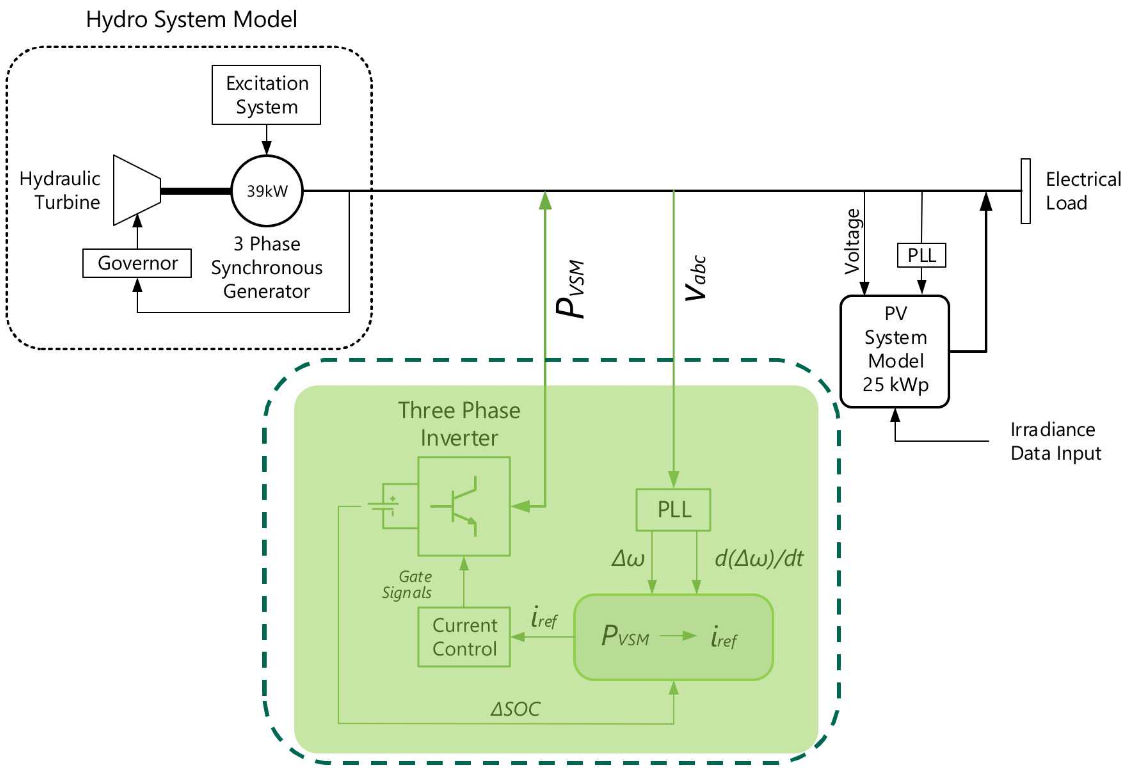


Virtual Inertia: Case Study of a PV-Hydro Microgrid System

- Power to be injected/ absorbed calculated based on:

$$P_{VSM} = K_i \frac{d(\Delta\omega)}{dt} + K_p(\Delta\omega) + K_{soc}(\Delta SOC)$$

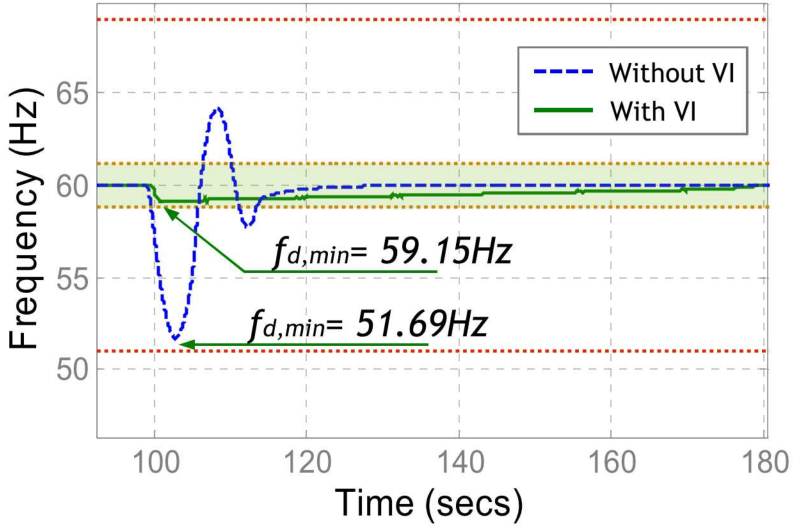
- SOC (State of Charge) of battery maintained at 50% with the control loop so that ESS unit is always ready charge or discharge power
- Current controller then generates gate signals for three phase inverter
- Transient analysis performed in OPAL-RT real time digital simulator through software in the loop simulations

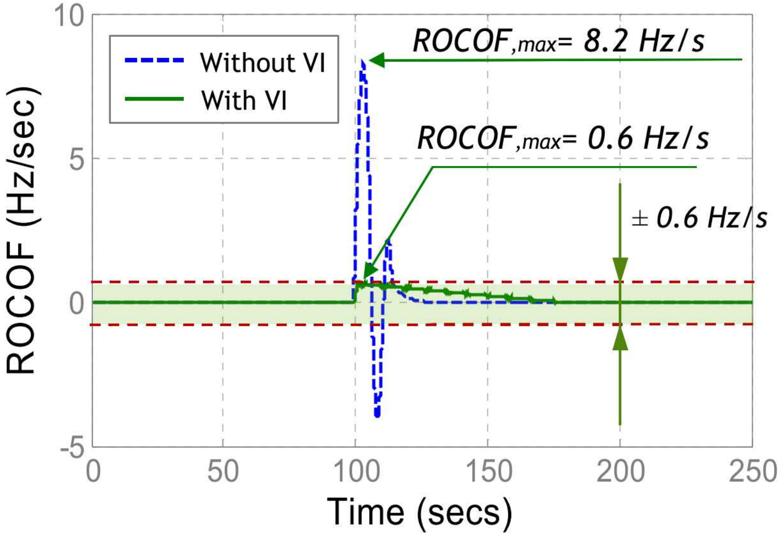


ESS Unit with Virtual Inertia

U. Tamrakar, *D. Galipeau, R. Tonkoski and I. Tamrakar, "Improving transient stability of photovoltaic-hydro microgrids using virtual synchronous machines," in IEEE Eindhoven PowerTech, Eindhoven, 2015, pp. 1-6, doi: 10.1109/PTC.2015.7232663.*

Frequency Variations and ROCOF due to Step Change in Irradiance



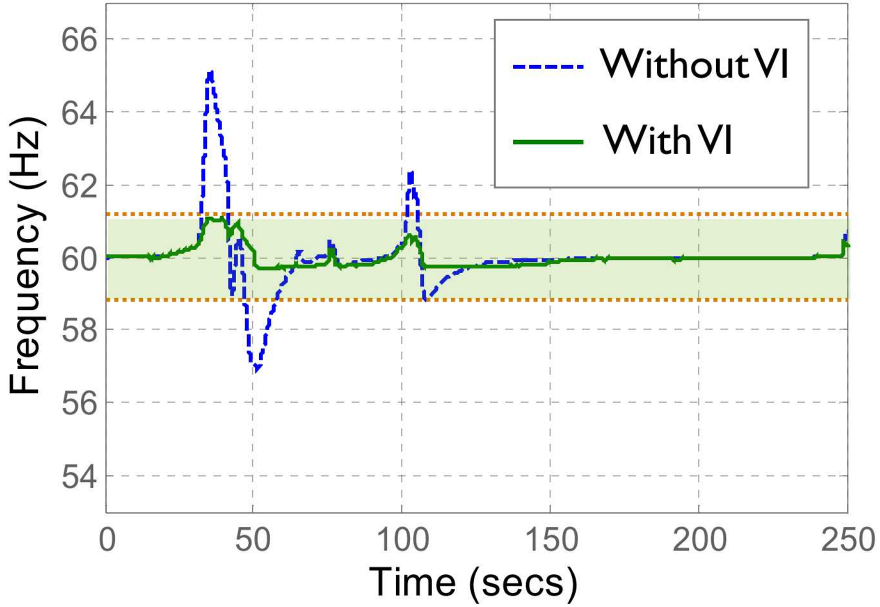


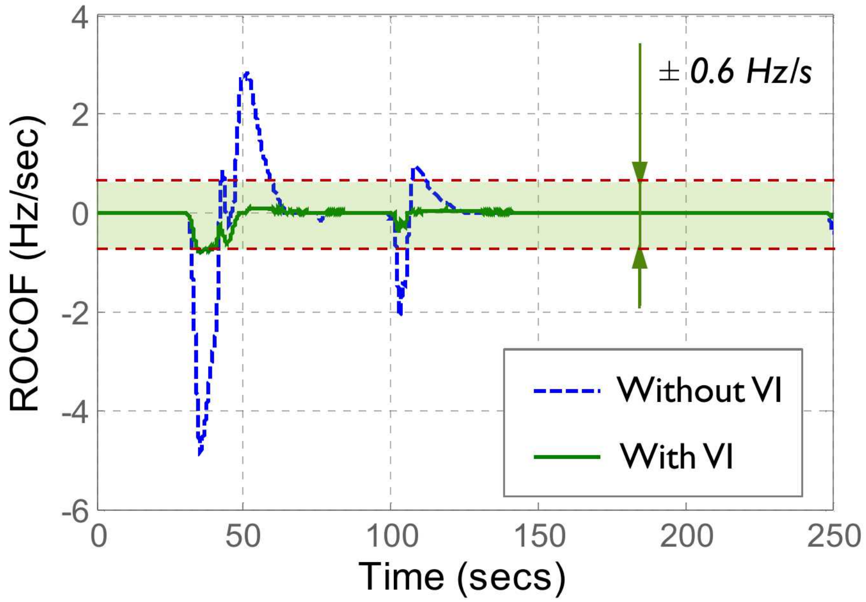
ISO 8528-5 Recommendations for Gensets

Normal frequency range = ±2.5%
Critical frequency range = ±15%
Recovery time = 10 s
Max. ROCOF = 0.6 Hz/s
(Ref.: ISO Standard 8528-5)

- Step change in irradiance from 750 W/m^2 to 250 W/m^2 @ 100 s
- Minimum frequency deviation reduced from 51.6 Hz to 59.1 Hz.
- Maximum frequency deviation reduced from 64.2 Hz to 60.1 Hz .
- Peak ROCOF reduced from 8.2 Hz/s to 0.6 Hz/s.
- Reductions within recommended levels, prevents unnecessary frequency relay tripping.

Frequency Variations and ROCOF due to a Real Irradiance Pattern

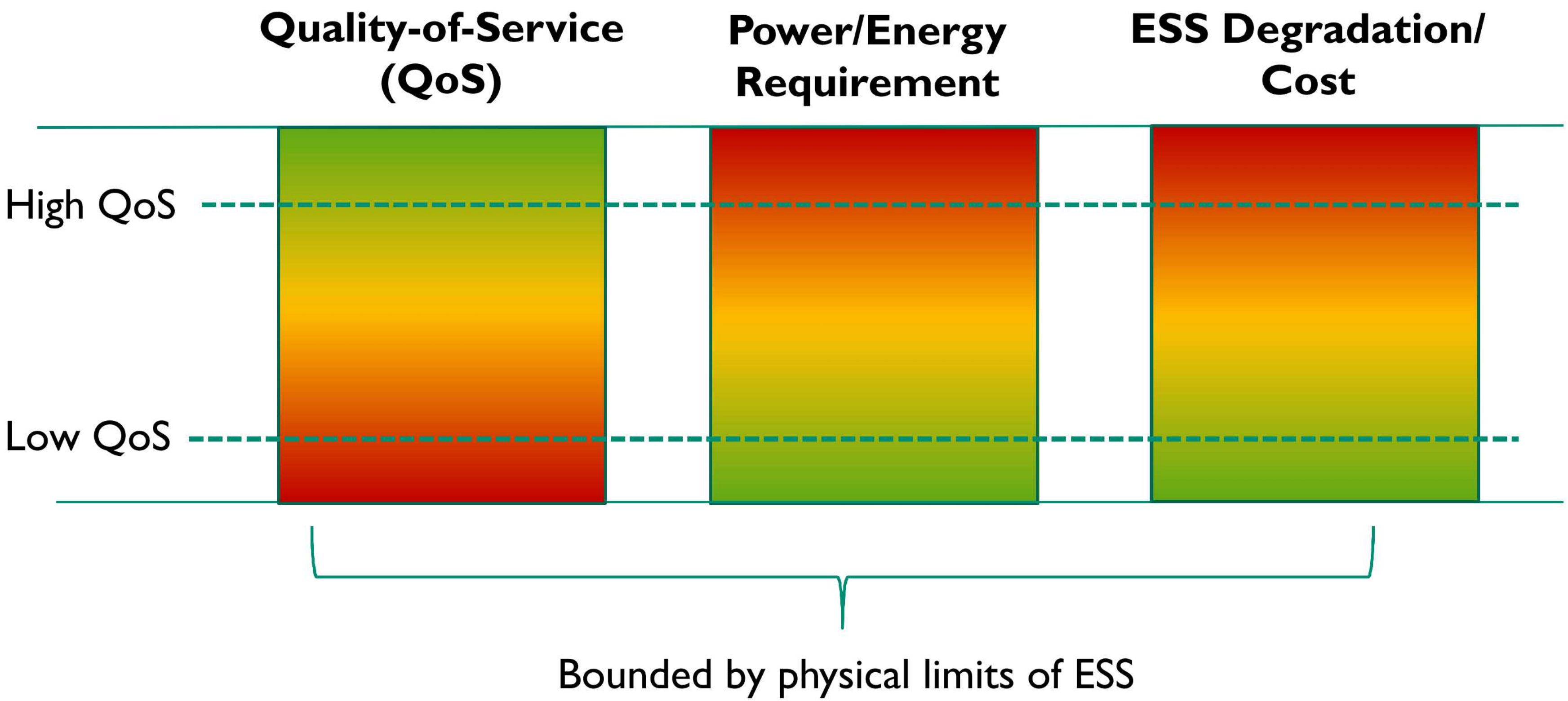




- Frequency variations due the real irradiance changes reduced to within recommend limits
- Peak ROCOF reduced from 4.8 Hz/s to 0.7 Hz/s slightly above the recommended limit
- Sufficient to prevent relays from tripping

Need for Model Predictive Fast Frequency Support

QoS → Reduction in frequency deviation and ROCOF



Model Predictive Fast Frequency Support Using Energy Storage

- Objective: Design a control framework to provide near-optimal fast frequency support using ESSs

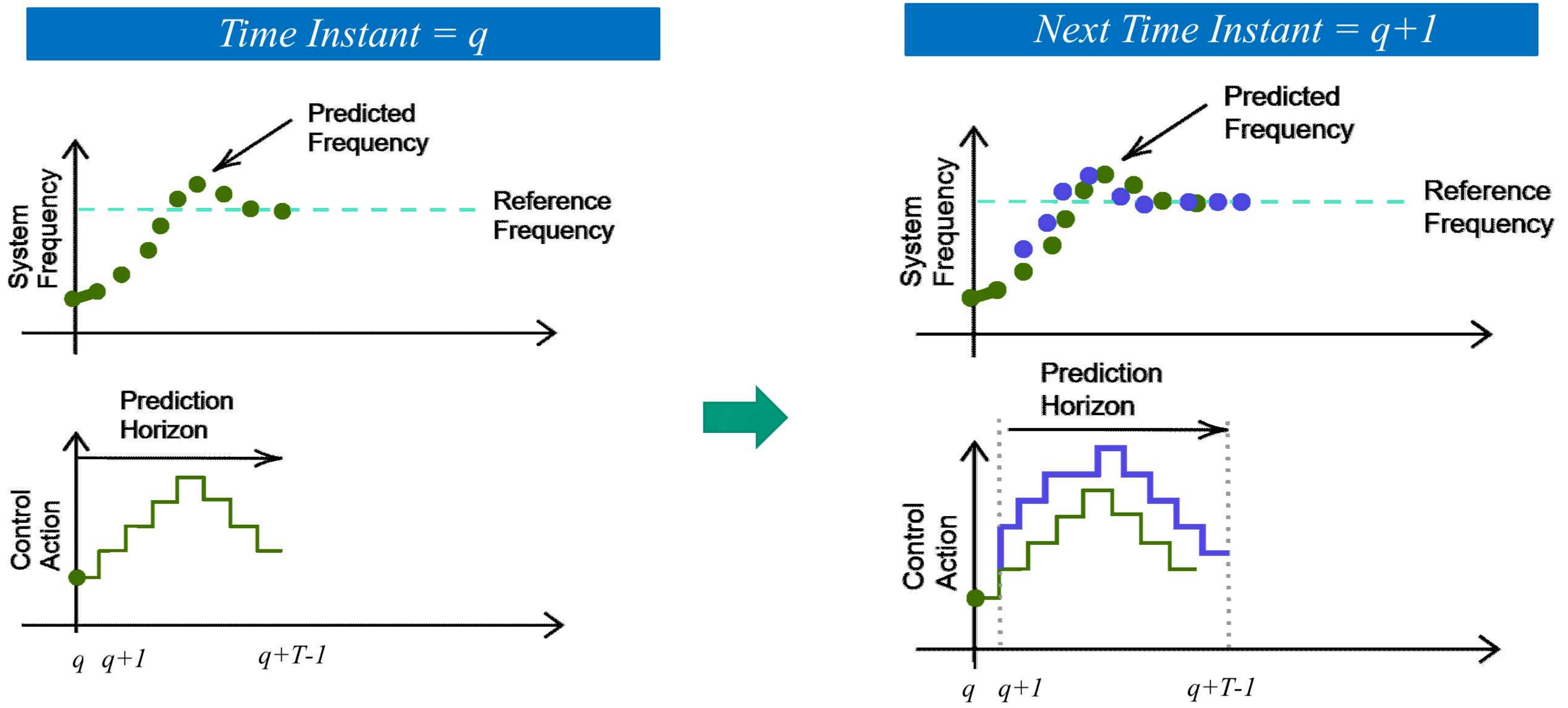
Desired Features

Flexible to change performance based on resource availability and/or desired quality of service (QoS)

Able to *incorporate physical constraints* of the ESS (Power , Ramp-Rate Limits)

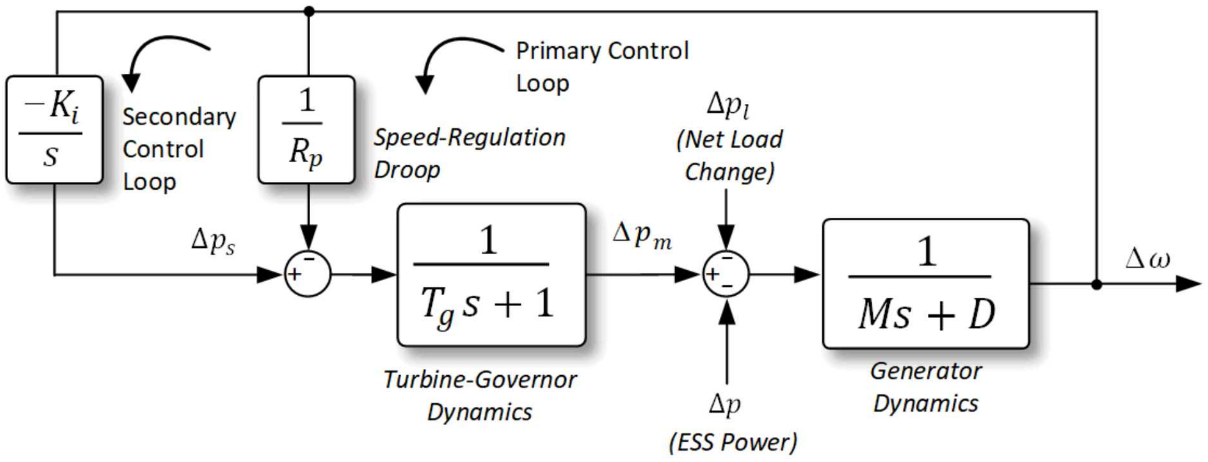
Adapt to changing system parameters

Basic Concepts 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 reruns to calculate new optimal control

A Predictive Model Representing Power System Frequency Dynamics



- Approximate model for an isolated microgrid:

$$\dot{x} = A\Delta x + B\Delta u$$

$$y = C\Delta x + \eta$$

$$\dot{x} = \left[\Delta\dot{\delta}\ \Delta\dot{\omega}\ \Delta\ddot{\omega}\right]^\top, \Delta u = \Delta P$$

$$\longrightarrow$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -\frac{K_i}{MT_g} & -\left(\frac{D}{MT_g} + \frac{1}{R_p M T_g}\right) & -\left(\frac{D}{M} + \frac{1}{T_g}\right) \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \frac{-1}{MT_g} \end{bmatrix} \quad C = diag(1, 1, 1)$$

*A. Ingalalli, **U. Tamrakar**, T. M. Hansen and R. Tonkoski, "**Modeling Hydro Power System Frequency Dynamics for Virtual Inertia Emulation**," in IEEE 28th International Symposium on Industrial Electronics (ISIE), Vancouver, BC, Canada, 2019, pp. 2565-2570. (Best Presentation Award)*

Formulation of Model Predictive Controller

Predictive Model

$$\begin{bmatrix}\dot{\Delta\omega}\\ \ddot{\Delta\omega}\end{bmatrix} = \begin{bmatrix}0 & 1\\ -\left(\frac{D}{M}+\frac{1}{T_g}\right) & -\left(\frac{D}{MT_g}+\frac{1}{R_pMT_g}\right)\end{bmatrix}\begin{bmatrix}\Delta\omega\\ \dot{\Delta\omega}\end{bmatrix} + \begin{bmatrix}0\\ \frac{-1}{MT_g}\end{bmatrix}(\Delta P\ )$$

MPC Formulation

$$\min_{\Delta p}\ J_T := \sum_{k=q}^{q+T-1}\left(x_k^\top Q x_k + \Delta p_k^\top R \Delta p_k\right)$$

*Penalize frequency and ROCOF deviations using **Q*** — *Penalize ESS control signal using **R***

subject to

$$x_{k+1} = A_d x_k + B_d \Delta p_k \quad \forall k \in \{q,\dots,q+T-1\}$$ *System Dynamics*

$$|\Delta p_k| \le P_{max} \quad \forall k \in \{q,\dots,q+T-1\}$$ *Peak-Power Constraint*

$$\|\Delta p_{k+1} - \Delta p_k\|_\infty \le E \quad \forall k \in \{q,\dots,q+T-1\}$$ *Ramp-Rate Constraint*

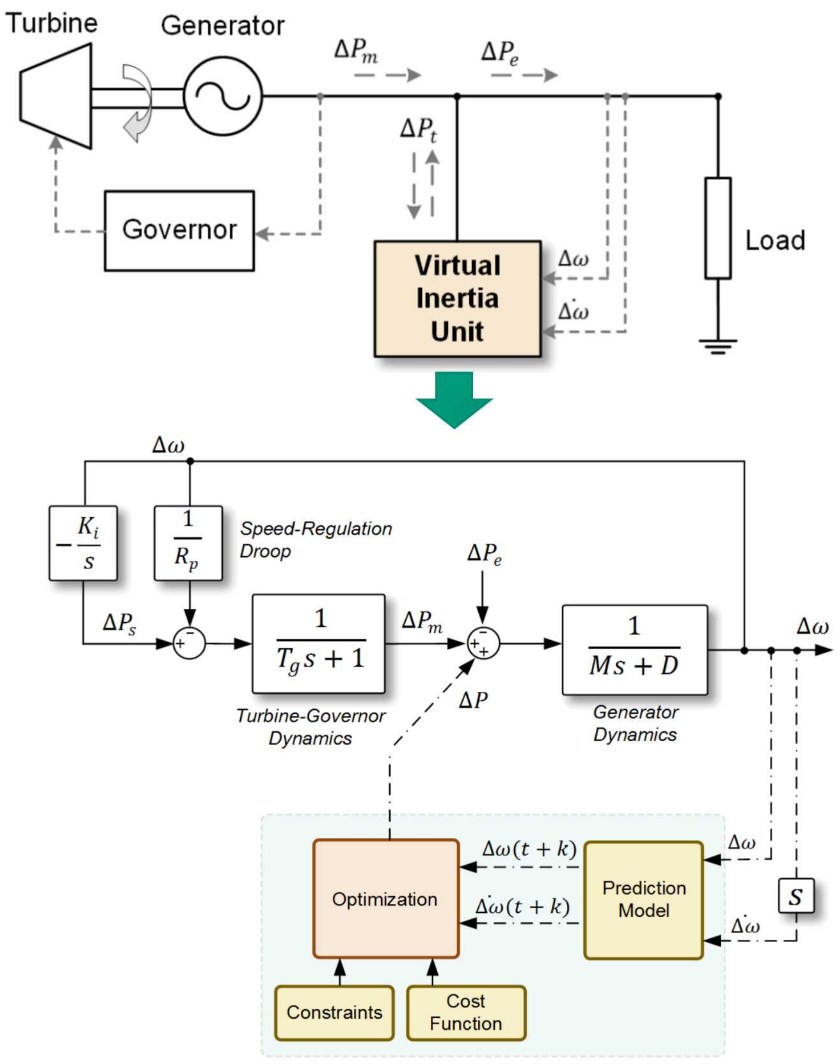
Optimal Control Action

$$\Delta p$$

Next sampling instant

Simulation Study : Model Predictive Fast Frequency Support

- Power system model implemented in MATLAB\Simulink
- MPC implemented using:
  - ACADO Code-generation Toolkit



Model Predictive Controller

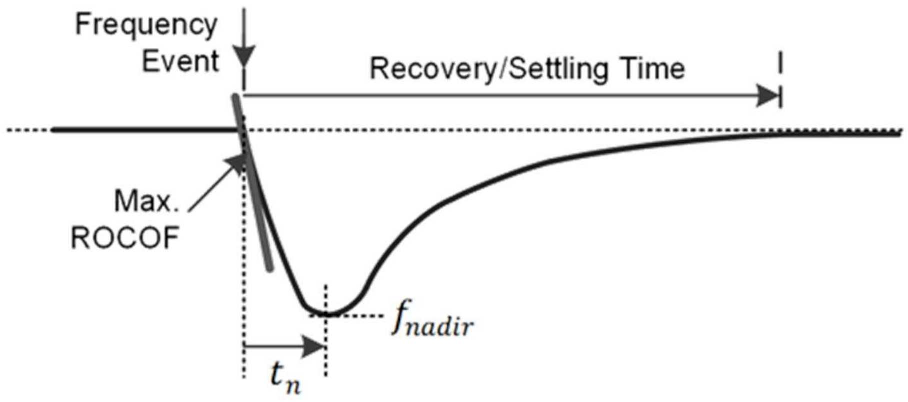
Simulation Parameters

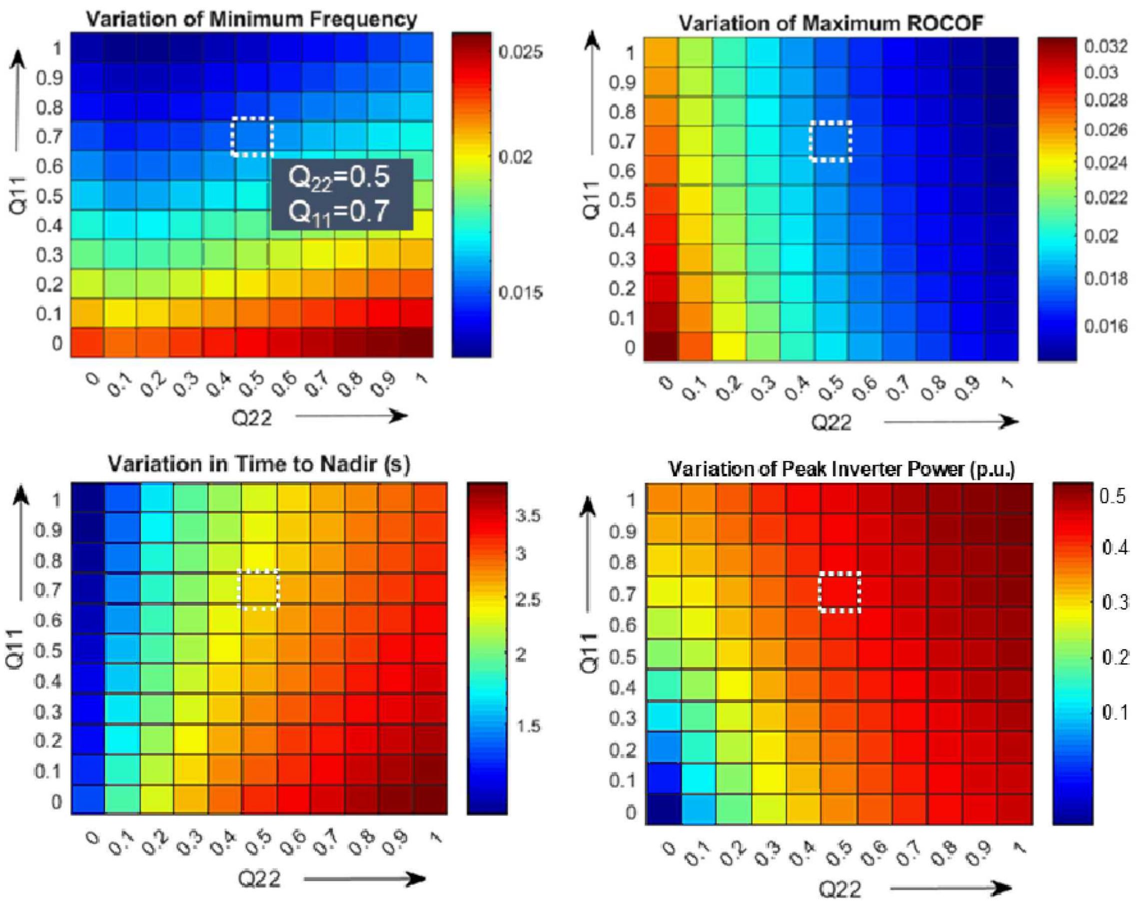
Parameter	Values
Inertia constant (M)	4 s
Damping coefficient (D)	1.5%
Speed regulation droop (R_p)	5%
Turbine-Governor time constant (T_g)	0.2 s
Sample time (τ)	0.02 s
Prediction and Control Horizon (T)	1 s

__U. Tamrakar__, T. M. Hansen, R. Tonkoski and D. A. Copp, "Model Predictive Frequency Control of Low Inertia Microgrids," in IEEE 28th International Symposium on Industrial Electronics (ISIE), Vancouver, BC, Canada, 2019, pp. 2111-2116, doi: 10.1109/ISIE.2019.8781263

Effect of Weighting Parameters on Fast Frequency Support

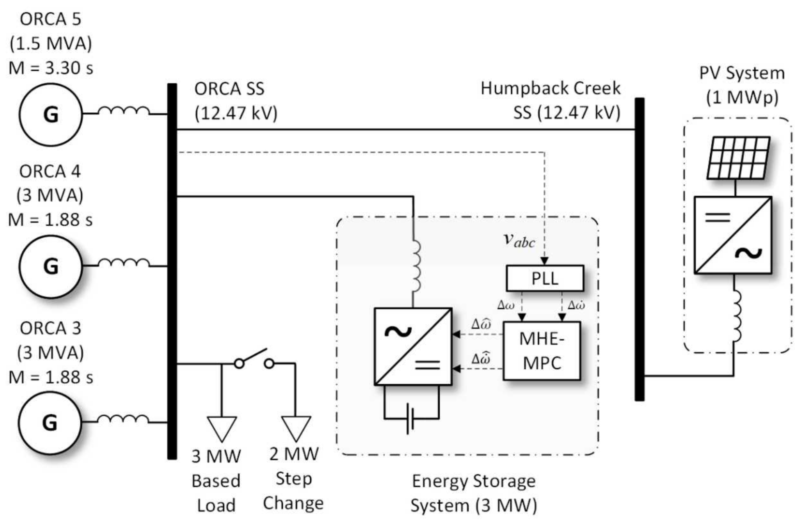
- Selection of ‘Q’ and ‘R’ effects performance
- Number of simulations by varying Q11 and Q22 performed



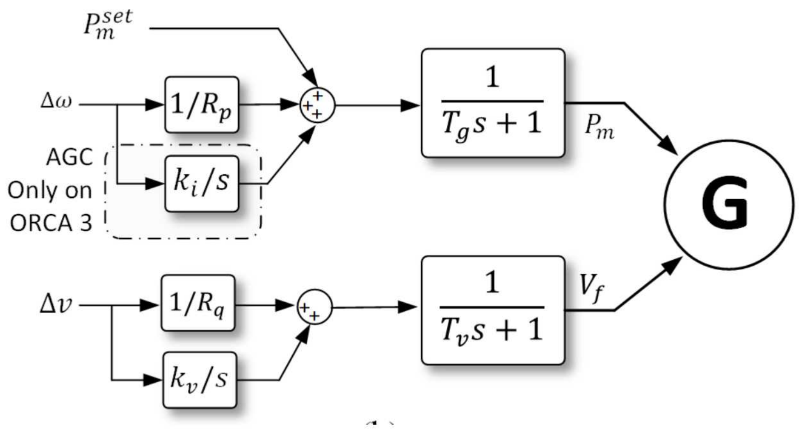


- Q11 = 0.7 and Q22=0.5
- Good trade-off between frequency and ROCOF reduction and power requirement
- Provides intuitive approach to control performance

Test System : Cordova, Alaska



Modified Test System from Cordova, Alaska



Governor and Excitation System

- Thee diesel-gensets, 1 MW PV → Reduces system inertia
  - 3 MW ESS
- Detailed models implemented MATLAB\Simulink
  - To verify simplified predictive model is sufficient
- Combined MHE-MPC framework implemented in the 3 MW ESS

__U. Tamrakar__, D. A. Copp, T. Nguyen, T. M. Hansen and R. Tonkoski, "Optimization-Based Fast-Frequency Estimation and Control of Low-Inertia Microgrids," IEEE Transactions on Energy Conversion: Model Predictive Control in Energy Conversion (submitted, under review).

Operational Flexibility of the Model Predictive Controller

N = 50; Sampling Time = 0.02 s

$$\boldsymbol{Q} = \begin{bmatrix} Q_{11} & 0 \\ 0 & Q_{22} \end{bmatrix} \rightarrow$$

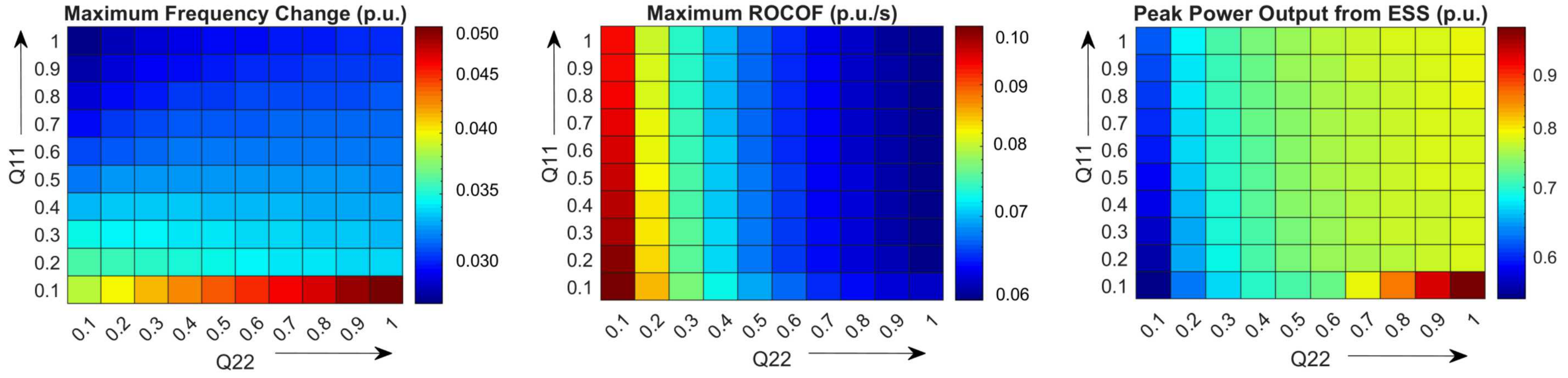
Penalize states:

- Frequency change (Q_{11}= 0.1→1)
- ROCOF (Q_{22}= 0.1→1)

$$\boldsymbol{R} = [R] \rightarrow$$

Penalize inverter output power

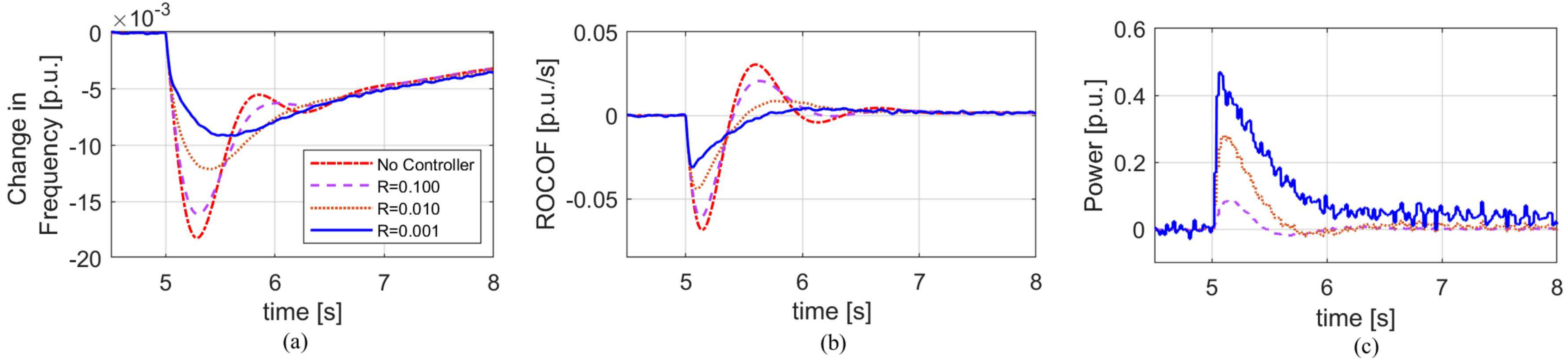
R = 0.0001



- ESS operator can change dynamic performance
  - Based on available resources
  - Desired QoS (Desired frequency or ROCOF reduction)

Operational Flexibility of the Model Predictive Controller

N = 50; Sampling Time = 0.02 s , $Q = diag(0.1,0.9)$

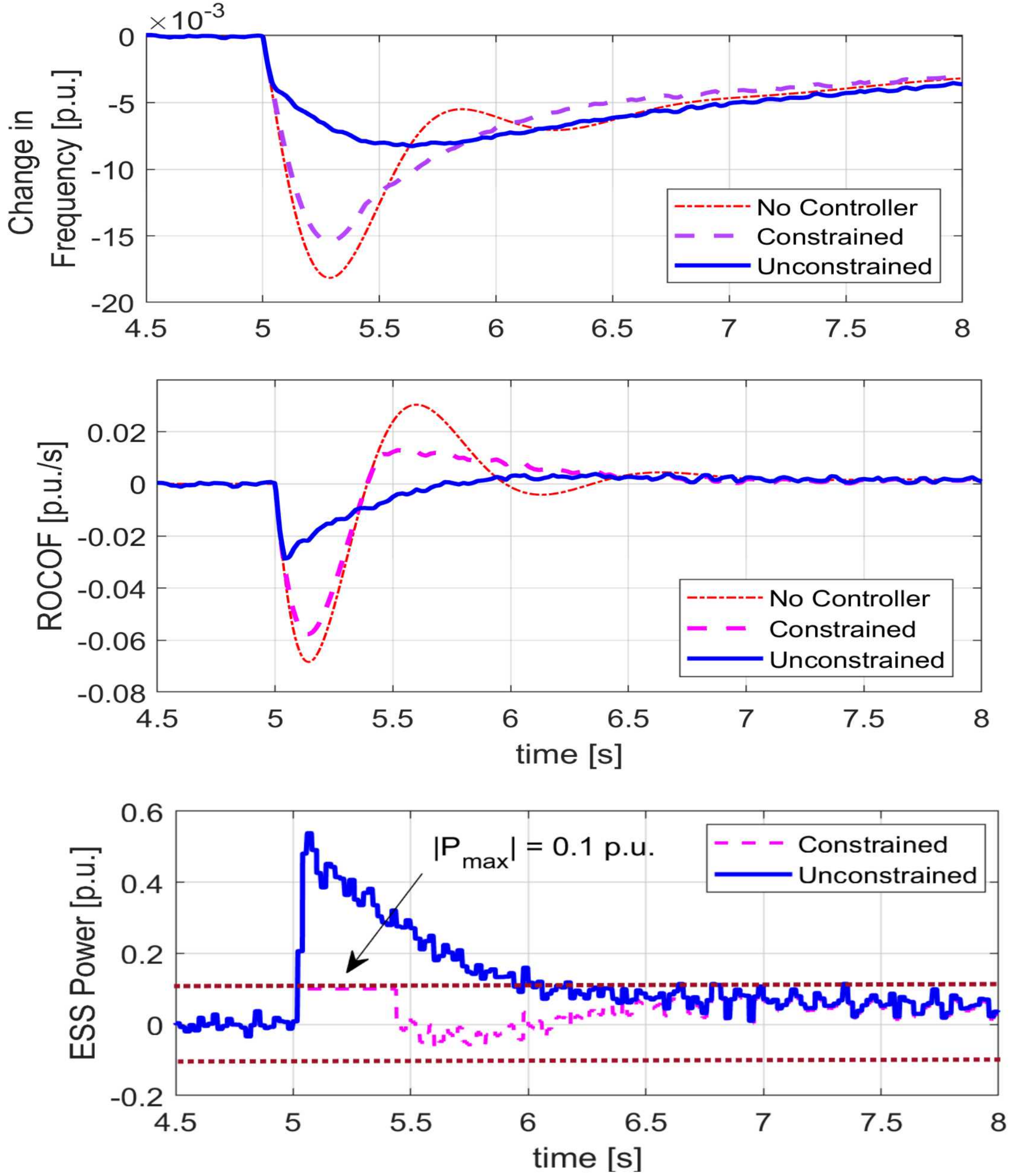


- ESS operator can change R value to put a "***cost***" on the ESS power output
- Example:
  - Higher QoS is desired
  - ESS operator uses R = 0.001
  - Higher reduction in frequency and ROCOF (improved QoS)
  - Higher peak-power/ energy usage per event
  - Fast ESS lifetime degradation! → OK, if incentives are in place

Constraint Handling Capabilities

N = 50; Sampling Time = 0.02 s ,
$Q = diag(0.1,0.9)$
$R = 0.001$

- **Assumption**:
  - Peak power-limit = 0.10 p.u. (0.3 MW)
  - Physical limit of ESS
  - Limited for other ESS services like arbitrage
- Lower QoS
- Low power/energy usage



Conclusions

- High renewable penetration = Reduction in Inertia
- Compromises frequency stability and system reliability
- Numerous inertia emulation technologies developed in literature
  - Advancements focused on improving dynamic response while reducing power/energy needs
- Future research on optimizing and coordinating inertia resources needed

Related Publications and Accomplishments

- **Journals**:
  - **U. Tamrakar**, D. A. Copp, T. Nguyen, T. M. Hansen, and R. Tonkoski, "Optimization-Based Fast-Frequency Estimation and Control of Low-Inertia Microgrids," IEEE Transactions on Energy Conversion (under review).
  - **U. Tamrakar**, D. Shrestha, N. Malla, Z. Ni, T.M. Hansen, I. Tamrakar, R. Tonkoski, "Comparative Analysis of Current Control Techniques to Support Virtual Inertia Applications," *Applied Sciences.,* vol. *8*, no. 7, pp. 2695, December 2018, doi: 10.3390/app8122695.
  - **U. Tamrakar**, D. Shrestha, M. Maharjan, B.P. Bhattarai, T.M. Hansen, R. Tonkoski, "Virtual Inertia: Current Trends and Future Directions," Applied Sciences, vol. 7, no. 8, pp. 654, June 2017, doi: 10.3390/app7070654.
  - M. Farrokhabadi, **U. Tamrakar**, et al., "Microgrid Stability Definitions, Analysis, and Examples," in IEEE Transactions on Power Systems, vol. 35, no. 1, pp. 13-29, Jan. 2020, doi: 10.1109/TPWRS.2019.2925703.
- **Conferences:**
  - **U. Tamrakar**, D. Galipeau, R. Tonkoski and I. Tamrakar, "Improving transient stability of photovoltaic-hydro microgrids using virtual synchronous machines," in IEEE Eindhoven PowerTech, Eindhoven, 2015, pp. 1-6, doi: 10.1109/PTC.2015.7232663
  - **U. Tamrakar**, T. M. Hansen, R. Tonkoski and D. A. Copp, "Model Predictive Frequency Control of Low Inertia Microgrids," in IEEE 28th International Symposium on Industrial Electronics (ISIE), Vancouver, BC, Canada, 2019, pp. 2111-2116, doi: 10.1109/ISIE.2019.8781263.
  - **U. Tamrakar**, F. B. dos Reis, A. Luna, D. Shrestha, R. Fourney and R. Tonkoski, "Virtual Inertia Emulation using Commercial Off-The-Shelf Inverters," in IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 1111-1116, doi: 10.1109/ECCE.2018.8557592.
  - A. Ingalalli**, U. Tamrakar**, T. M. Hansen and R. Tonkoski, "Modeling Hydro Power System Frequency Dynamics for Virtual Inertia Emulation," in IEEE 28th International Symposium on Industrial Electronics (ISIE), Vancouver, BC, Canada, 2019, pp. 2565-2570. (Best Presentation Award)
  - A. Luna**, U. Tamrakar**, R. Tonkoski and S. Hietpas, "Linear Quadratic Regulator Controller to Improve Transient Frequency Stability Through Virtual Inertia," in 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2020, pp. 1-5, doi: 10.1109/ISGT45199.2020.9087755.
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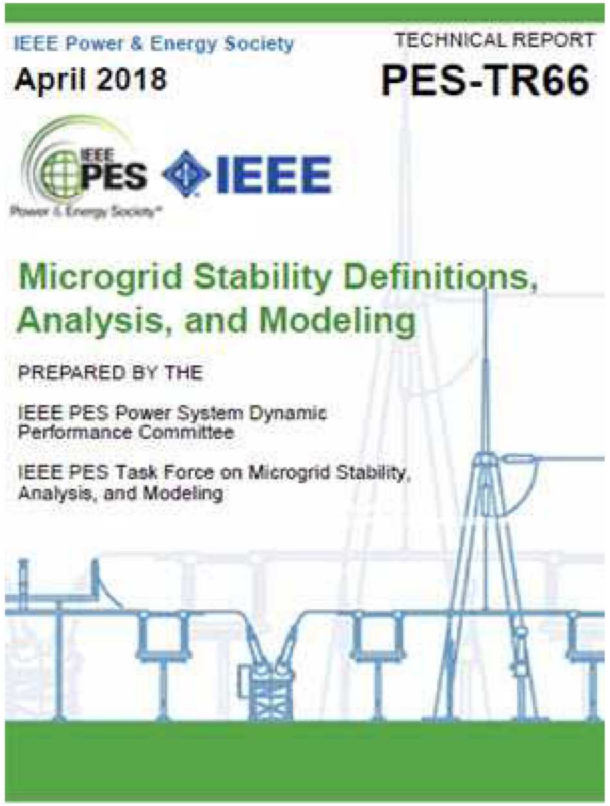
  - M. Rauniyar, **U. Tamrakar**, S. E. Berg, S. Subedi, T. M. Hansen, R. Fourney, and R. Tonkoski, "Evaluation of probing signals for implementing moving horizon inertia estimation in microgrids," in IEEE North American Power Symposium (NAPS), Tempe, Arizona, Jun 2020, April 2021, accepted.

Related Publications and Accomplishments

- Reports:
  - Assisted in preparing the report "Microgrid Stability Definitions, Analysis, and Modeling" as a part of the IEEE Task Force on Microgrid Stability Analysis and Modeling.
  - Received the 2020 IEEE Power and Energy Society Working Group Award



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