Stability Enhancement of Inverter Dominated Systems using Virtual Inertia Control

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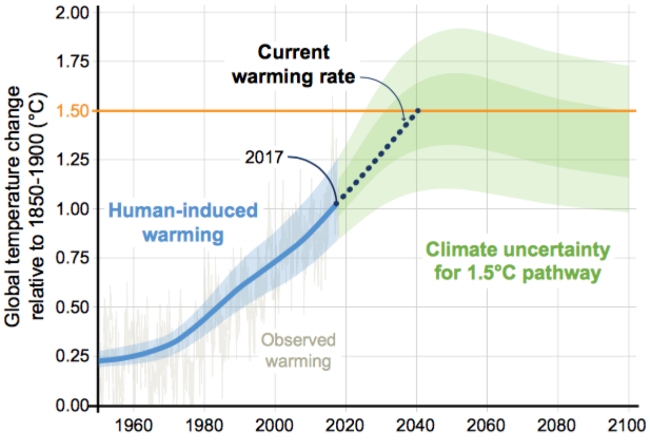
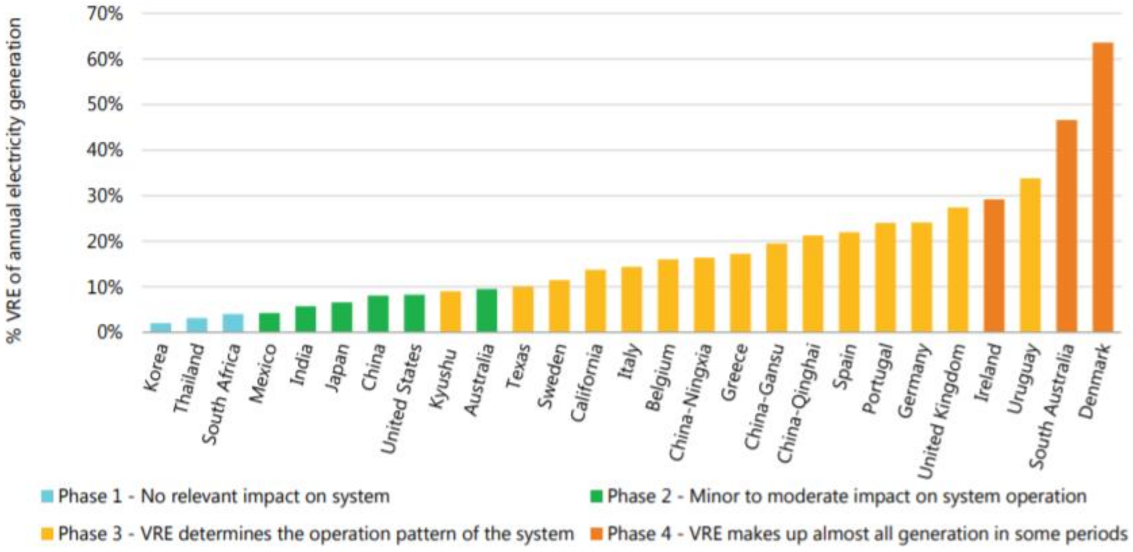
Motivation



Human Induced Climate Change

Source: NASA's Global Climate Change Website: A Degree of Concern: Why Global Temperatures Matter (2019)

- Extreme weather events challenging the resiliency of Power System
- High variability from the Generation-side

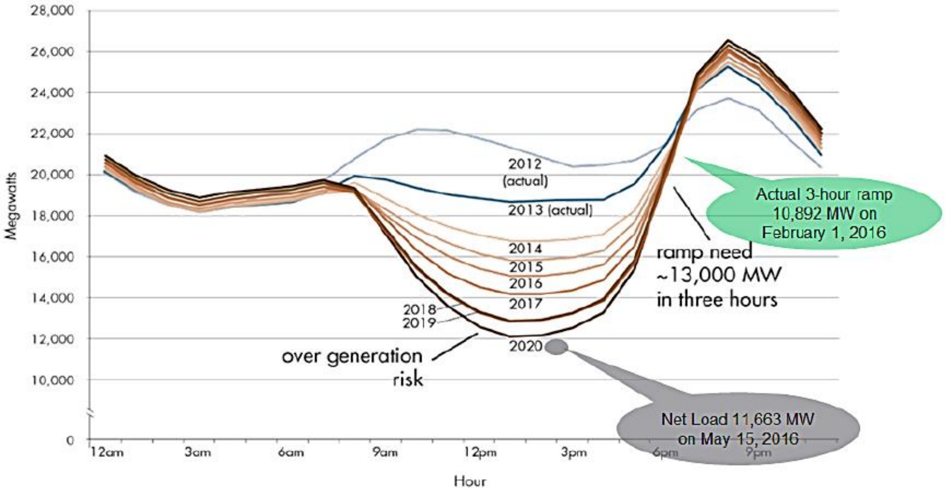


Annual Variable Renewable Energy (VRE) Share and Integration Phase as of 2018

Source: IEA Renewables 2019 report: Analysis and Forecasts to 2024

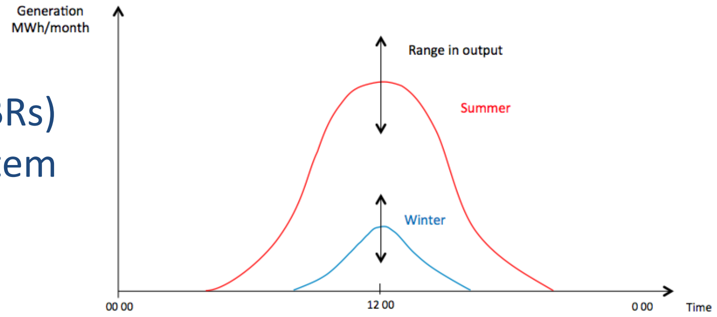
Research Interest

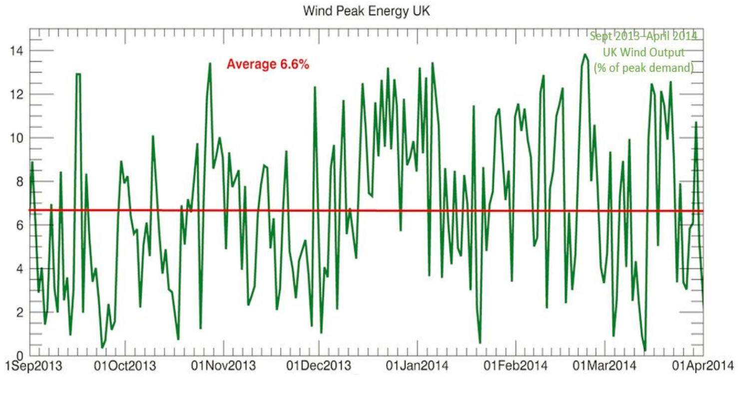
- ➢ **Intermittencies** of VRE challenging the balancing control
- ➢ The VREs are '**non-synchronous**' inverter-based resources (IBRs)
- ➢ Reducing the **inherent inertial response** capability of the system



Increased Ramp Requirements

Source: California Independent System Operator, www.caiso.com



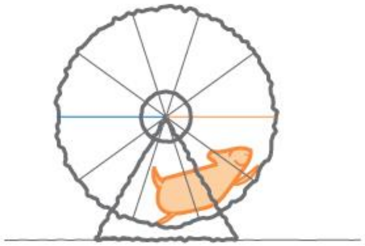


Intermittency of VREs – PV and Wind

Source: https://eelpower.co.uk/challenges-for-the-grid

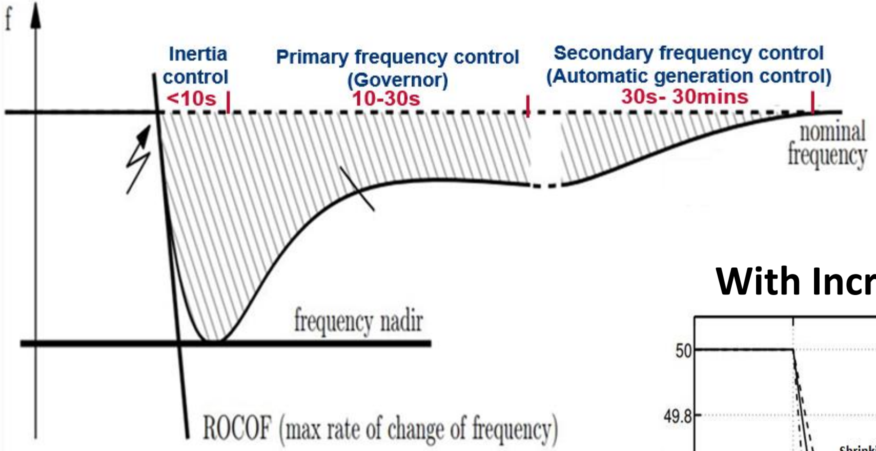
Research Interest

➢ **Non-synchronous VREs -** inverter-based resources (IBRs) and **Power System Inertia**



$$J\omega_m \frac{d^2\delta_m}{dt^2} = P_a = P_m - P_e$$

$$2H\frac{S_{\text{rated}}}{\omega_s^2}\omega_m \frac{d^2\delta_m}{dt^2} = P_m - P_e = P_a$$



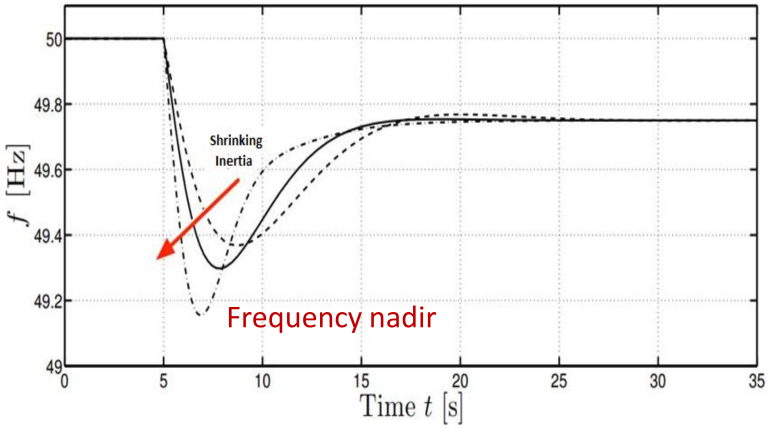
Frequency Response Characteristics

Source: Tielens, P., Van Hertem, "The relevance of inertia in power systems", Renewable and Sustainable Energy Reviews, Vol. 55, March 2016, pp. 999-1009.

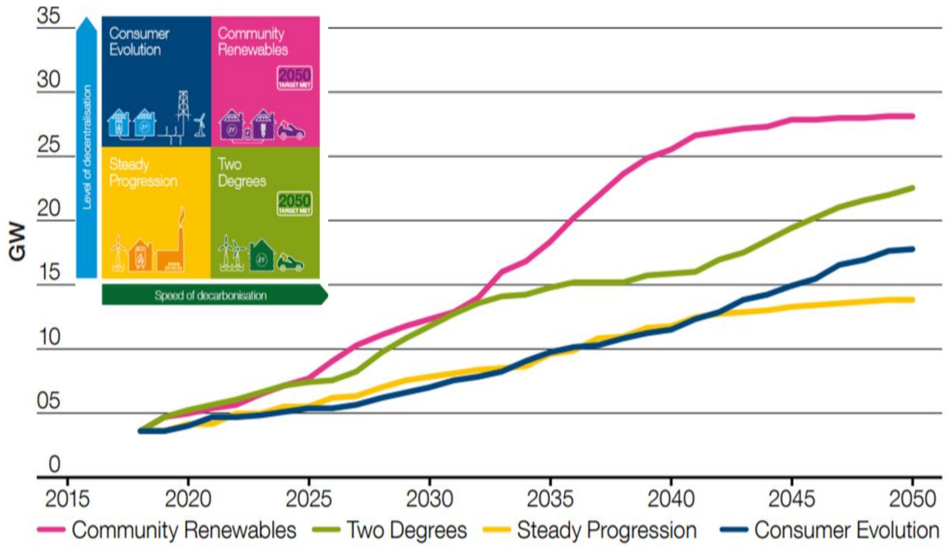
➢ ROCOF -> inertia

➢ fnadir -> inertia and response delay of primary frequency control

With Increasing Penetration of VREs

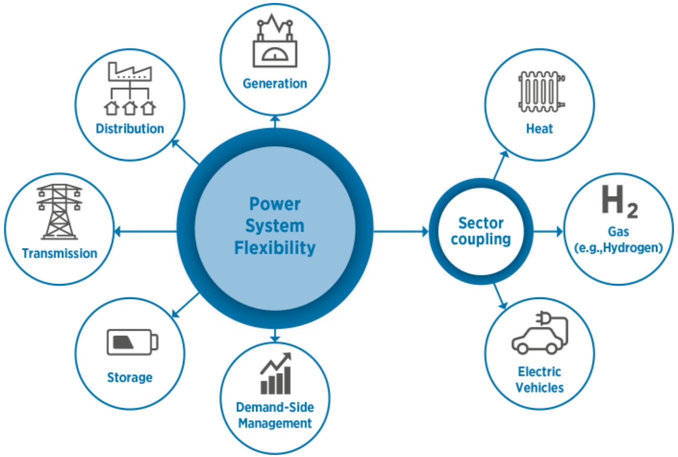


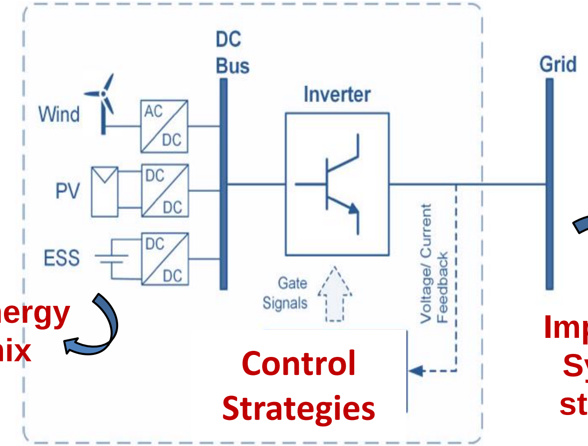
Flexibility Solutions - Objectives



Projected Storage requirements
(Expected increase ~ 3 GW over 5 years)

Source: UK National Grid Future Energy Scenarios 2019





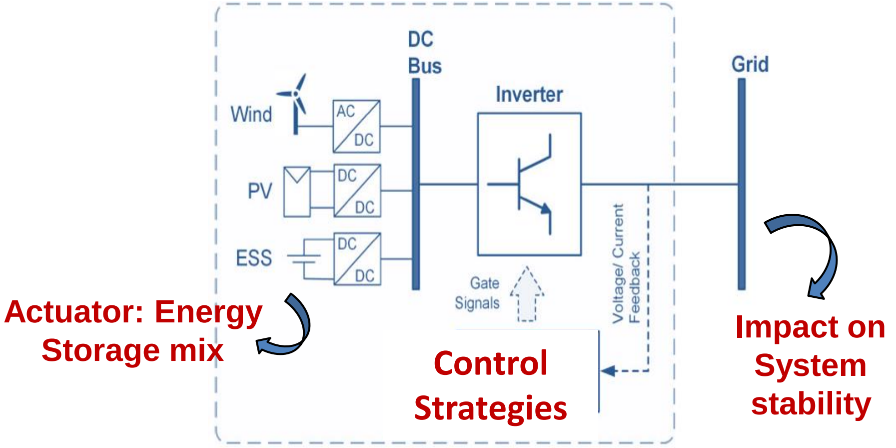
Actuator: Energy Storage mix

Control Strategies

Impact on System stability

Objectives

- To Study and characterize the different flexible resources that can deliver balancing services.
- To explore predictive control strategies for grid-following and grid-forming converter controls.
- To test and validate the proposed control strategies on a power hardware-in the-loop platform.
- To study the impact of the frequency response control parameters on the oscillatory stability of the system



Why Hybrid Energy Storage?

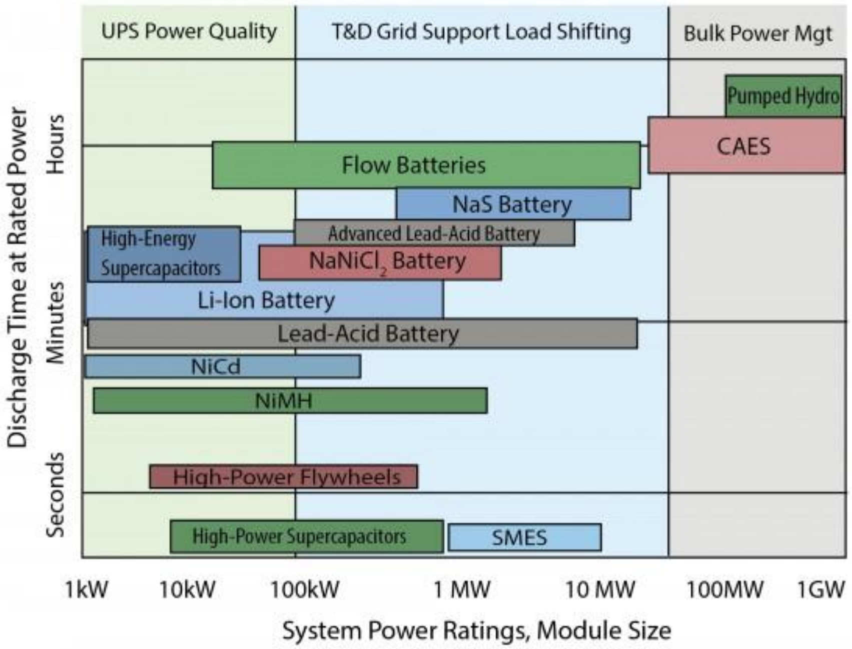
Desired Frequency Response Characteristics

- Grid code requirements

Region	Instantaneous Δf limits (Hz)	Δf_{ss} limits (Hz)	ROCOF limits (Hz/s)
Singapore	49.7 UFLS	± 0.2	± 1 for 500s window

- Combine different operating characteristics based on application
- Power and Energy densities
- **Battery – slow varying power**
- **Supercapacitor – high frequency demand**
- Other flexible resources can be represented by an equivalent virtual battery model

$$\begin{cases} \dot{C}(t) = -d_s C(t) - P(t) \\ C_{min} \le C(t) \le C_{max} \\ P^- \le P(t) \le P^+ \end{cases}$$

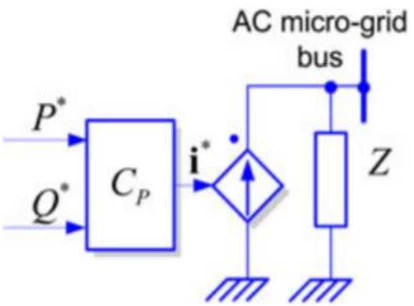


Energy Storage Characteristics

Source: https://css.umich.edu/factsheets/us-grid-energy-storage-factsheet

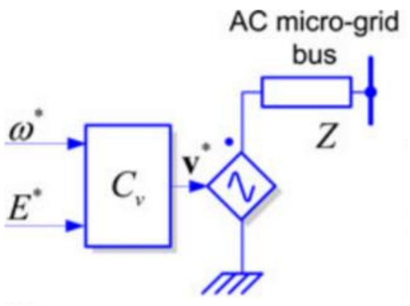
Types of Inverter-based Resources (IBRs)

- Grid-following IBRs



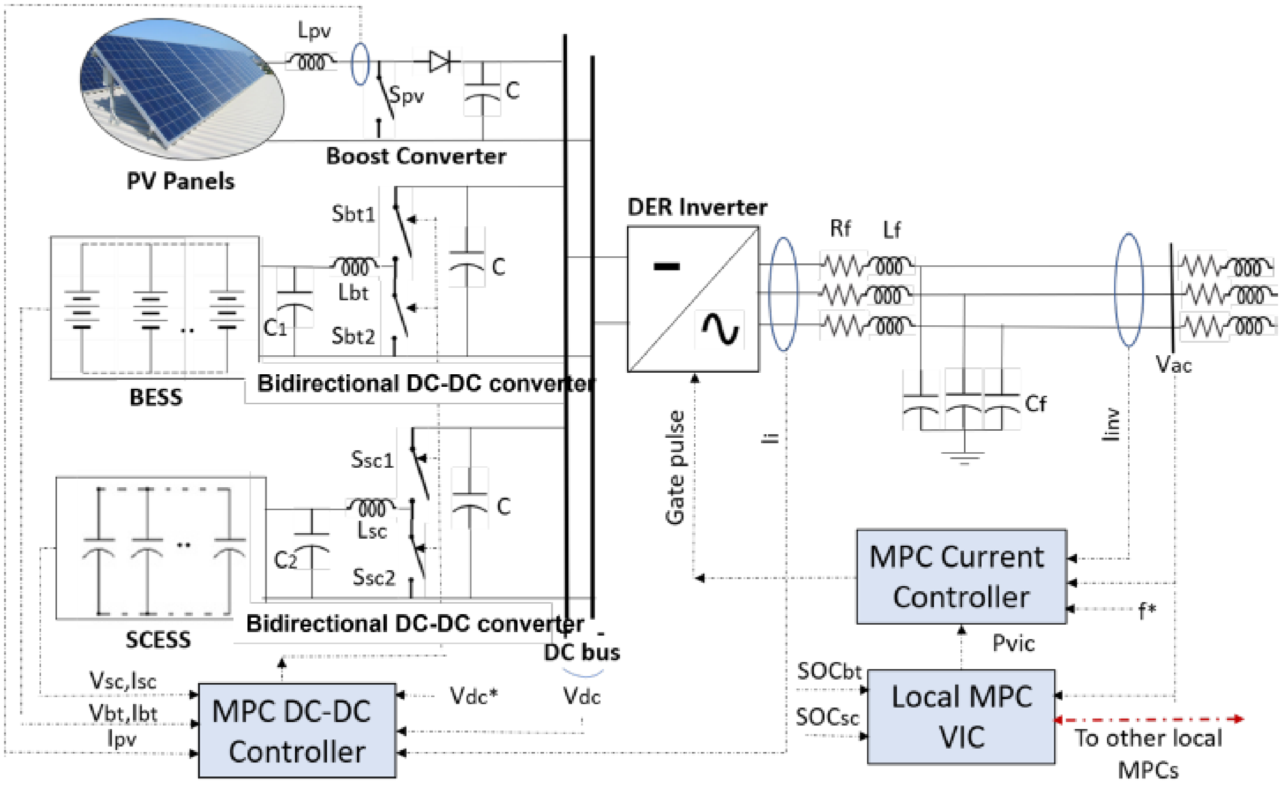
- **Frequency-responsive grid-following IBR control**
- **Frequency-responsive grid-following IBR implemented using model predictive control (MPC)**
- **Rate-based MPC controller**
- **Coordinating Frequency-responsive DERs**
- **Validation**

- Grid-forming IBRs



- **Isochronous grid-forming control**
- **Grid-forming control implemented with MPC**
- **Validation**

Grid-following IBR – Model Predictive Control

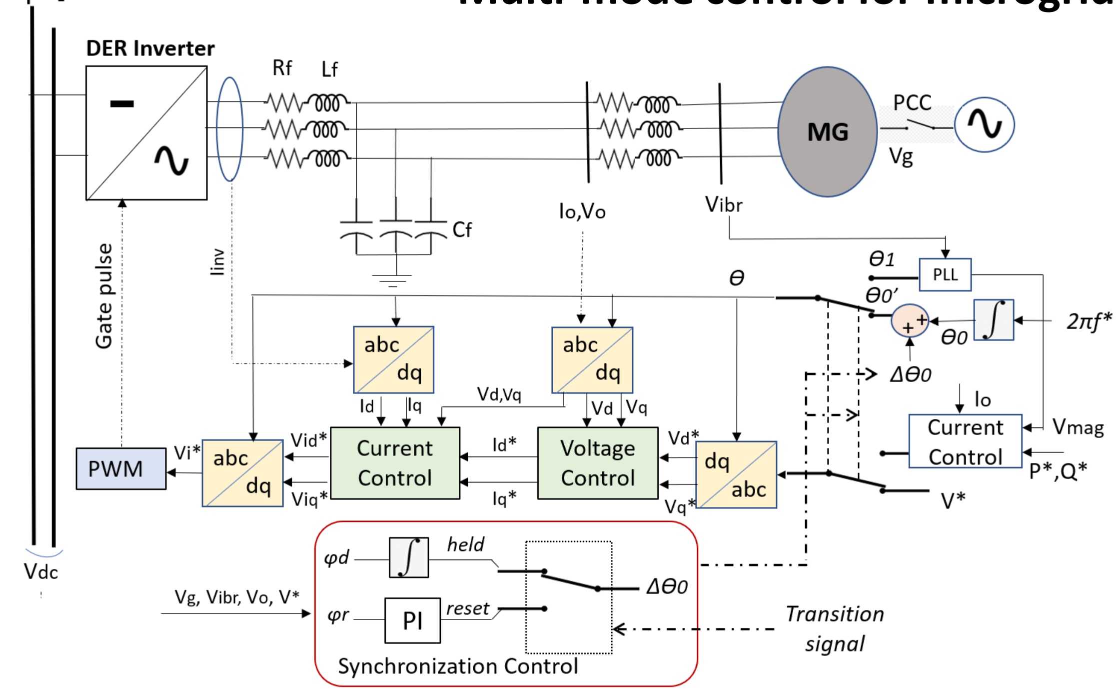


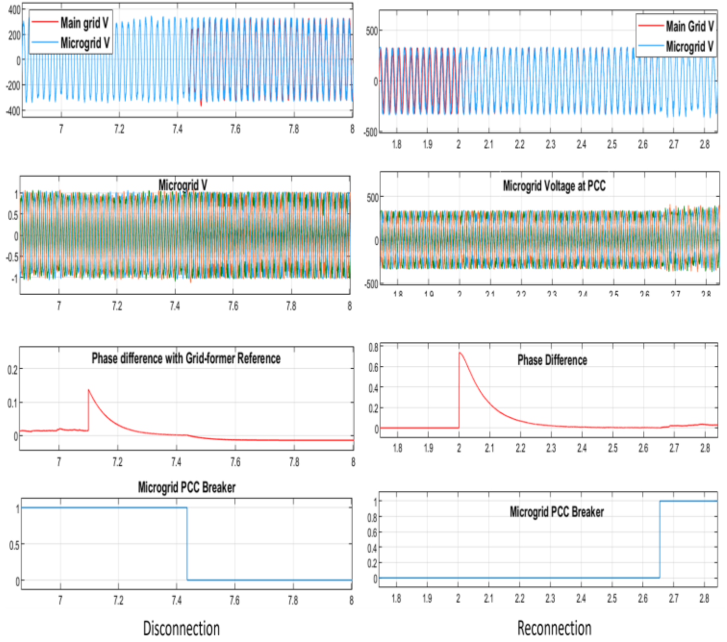
*Virtual Inertia Controller

Consensus-based coordination

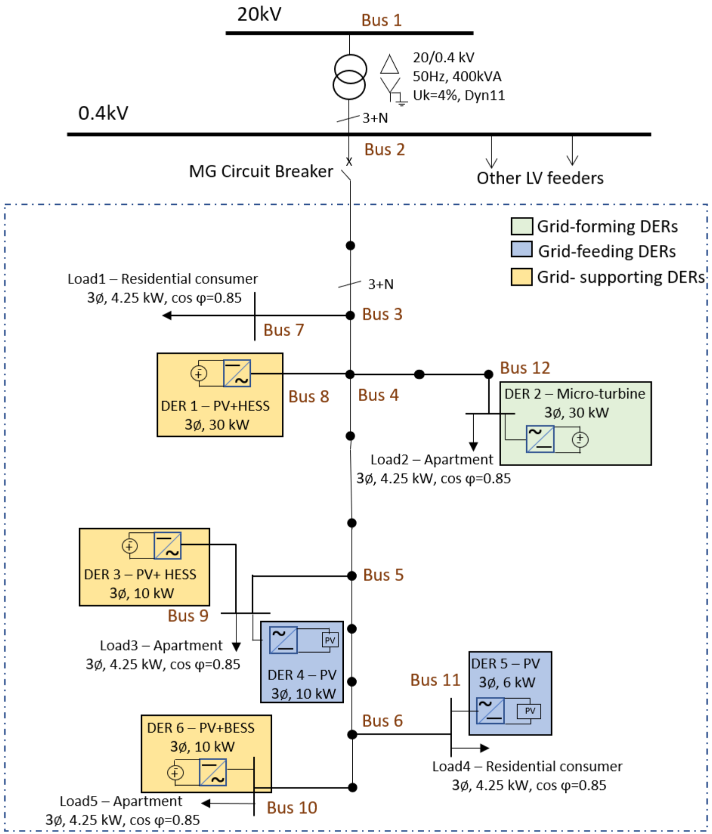
Grid-forming IBR – MPC implementation and Validation

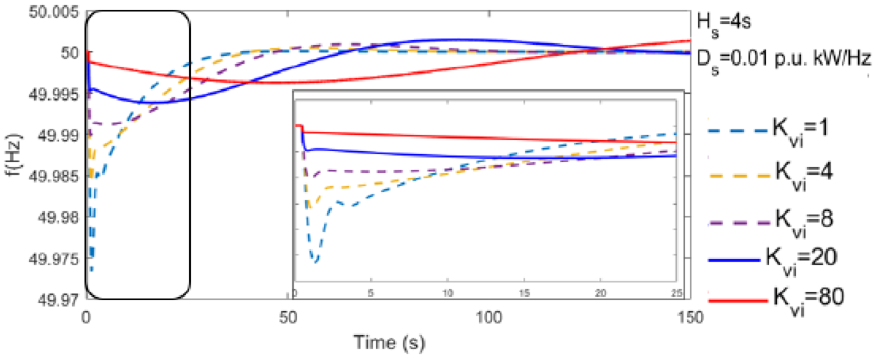
Multi-mode control for microgrid transition



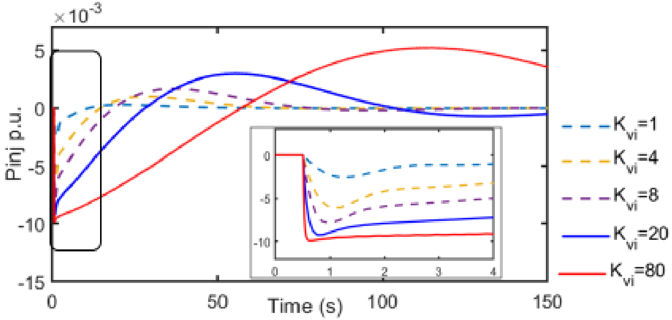


Test System and Simulation Results



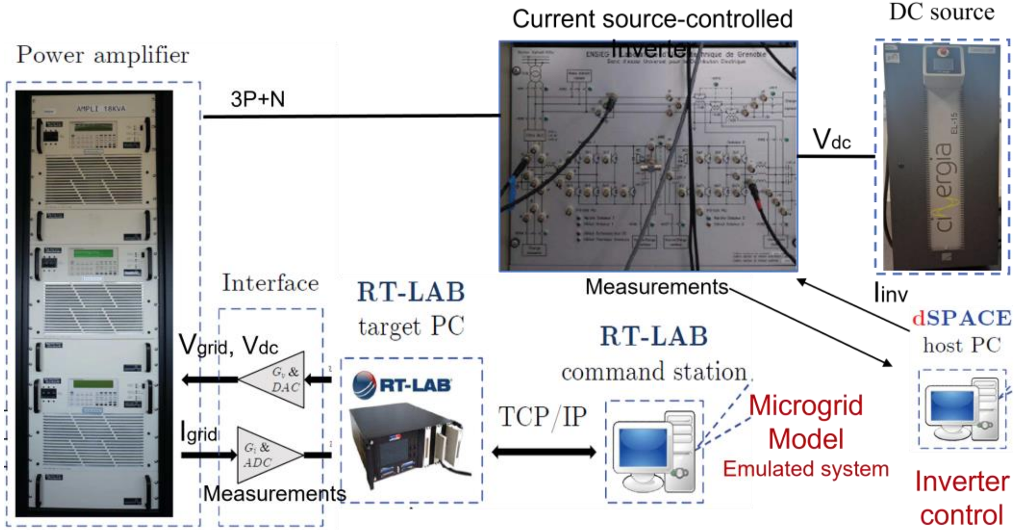


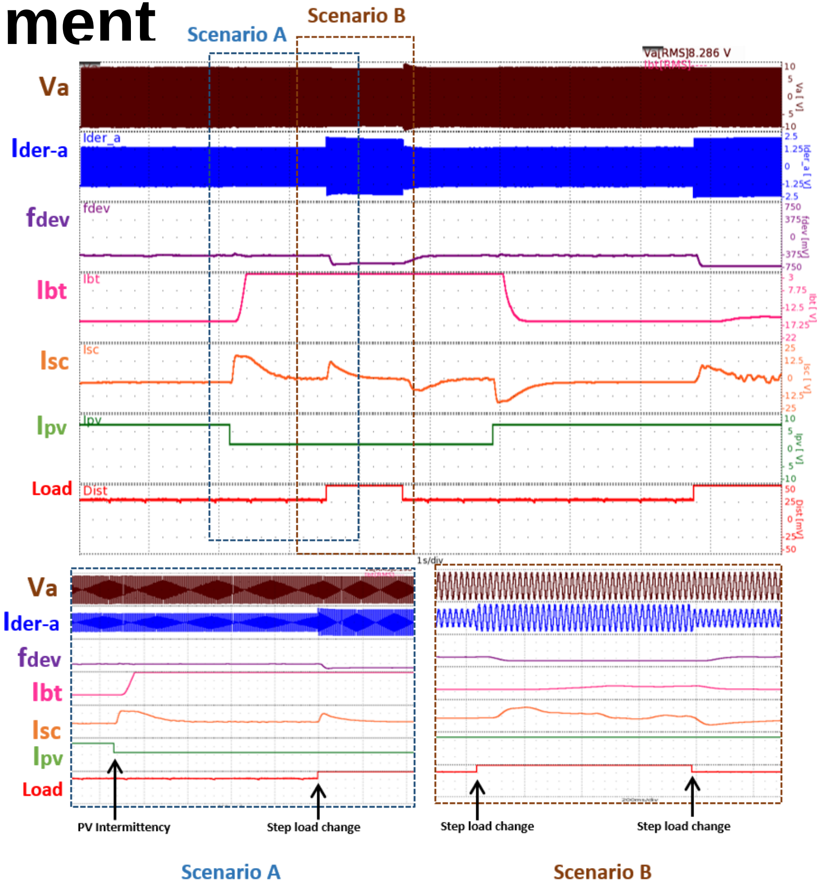
(a) Frequency Response with Different Synthetic Inertia Control Coefficients.



(b) Power Injected by VICs for Fast-Frequency Support.

Power Hardware-in-the-loop Experiment





- ➢ The remaining system, apart from the inverter is simulated on OPAL RT in real-time
- ➢ Challenges with OPAL RT run-time
- ➢ Switched to in-built ARTEMiS model reduction

Summary of Contributions

- A storage sizing methodology for primary frequency and inertia reserve requirements
- A model predictive control strategy with rate-based linearization for elimination of offset errors in grid-friendly DERs.
- A distributed model predictive control framework for grid-friendly DERs in grid-forming and grid-following operation modes.
- Validation of proposed control strategies using power hardware-in-the-loop experiment.
- A stochastic backward-forward sweep power flow algorithm of islanded microgrids with microgrid frequency as a state-variable.
- Small signal modelling of grid-following and grid-forming DERs. Analysis of the impact of frequency response parameter variation on the small signal stability of the system.

Interesting Areas for Future Work

- Requirements for fault-ride through capabilities (FRC) for non-synchronous reserve providers.
- Placement of inertia reserves in large power systems.
- Demand-side elasticity requirement and market mechanisms for new types of ancillary services.
- Urban energy planning for collective self-consumption and decentralization
- Singaporean context – possible interconnections for importing green energy (huge impact on system reliability) – GW scale energy storage systems and subsea HVDC
- Economic challenges impacting power producers with increasing penetration of VREs, scope for potential capacity markets.
- Pay for energy consumption -> Pay for reliability

Publications

1. L. Subramanian, V. Debusschere, H. B. Gooi and N. Hadjsaid, "**A Distributed Model Predictive Control Framework for Grid-friendly Distributed Energy Resources**,“ in IEEE Transactions on Sustainable Energy, doi: 10.1109/TSTE.2020.3018913.

2. L. Subramanian, V. Debusschere, H. B. Gooi, and N. Hadjsaid, "**A Cooperative Rate-based Model Predictive Framework for Flexibility Management of DERs**,“ in IEEE Transactions on Energy Conversion, doi:10.1109/TEC.2021.3105612.

3. L. Subramanian, V. Debusschere and H. B. Gooi, "**Design and Control of Storage Systems for Voltage Source Controlled Autonomous Microgrids**," 2019 IEEE Power & Energy Society General Meeting (PESGM), Atlanta, GA, USA, 2019, pp. 1-5, doi: 10.1109/PESGM40551.2019.8973887.

4. L. Subramanian and H. B Gooi, "**Stabilizing Droop Variation of Converter-Connected Generation in Autonomous Microgrids with Virtual Inertia Control**," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 3746-3753, doi: 10.1109/ECCE.2018.8557936.

5. L. Subramanian and H. B. Gooi, "**Stochastic Backward/Forward Sweep Power Flow Analysis for Islanded Microgrids**," 2018 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), Singapore, 2018, pp. 48-53, doi: 10.1109/ISGTAsia. 2018.8467763.

6. L. Subramanian, M. Goundiam, V. Debusschere, H. B. Gooi, R. Caire, and N. Hadjsaid, "**Impact of the Interaction of Synchronous Machines and Virtual Provisions on the Small Signal Stability of Microgrids**," CIRED 2021, Geneva, 2021. (Accepted)

Thanks for the attention