Beneficial performance from IBRs for provision of bulk power system services

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ESIG Webinar
28th June 2023

Acknowledgement and Disclaimer

- The material covered in this presentation is based on work supported in-part by:
  - EPRI Member funded research, and
  - U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Numbers DE-EE0008776, DE-EE0009019, DE-EE0009025, DE-EE0002437. The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government

- Collaborators from EPRI:
  - Lakshmi Sundaresh, Vikas Singhvi, Parag Mitra, Stavros Konstantinopoulos, and Wenzong Wang

Evolving system needs expected from Inverter Based Resources (IBRs)

Power System

Past:

SG dominated system

Present:

Increased penetration of IBRs

Future:

IBR dominated system

System needs from IBR

Unity power factor, minimal fault ride-through …

Automatic voltage control, frequency response, V/F ride-through …

Without relying on SGs, provide the above services and more (fast frequency response, maintain system stability…)

Moving toward an inverter dominated power system, IBRs will gradually substitute SGs in providing grid services and ensuring grid reliability

Technology terminology in this presentation

Legacy IBR

- Injects active power at unity power factor
- Provides no grid support services

Conventional IBR

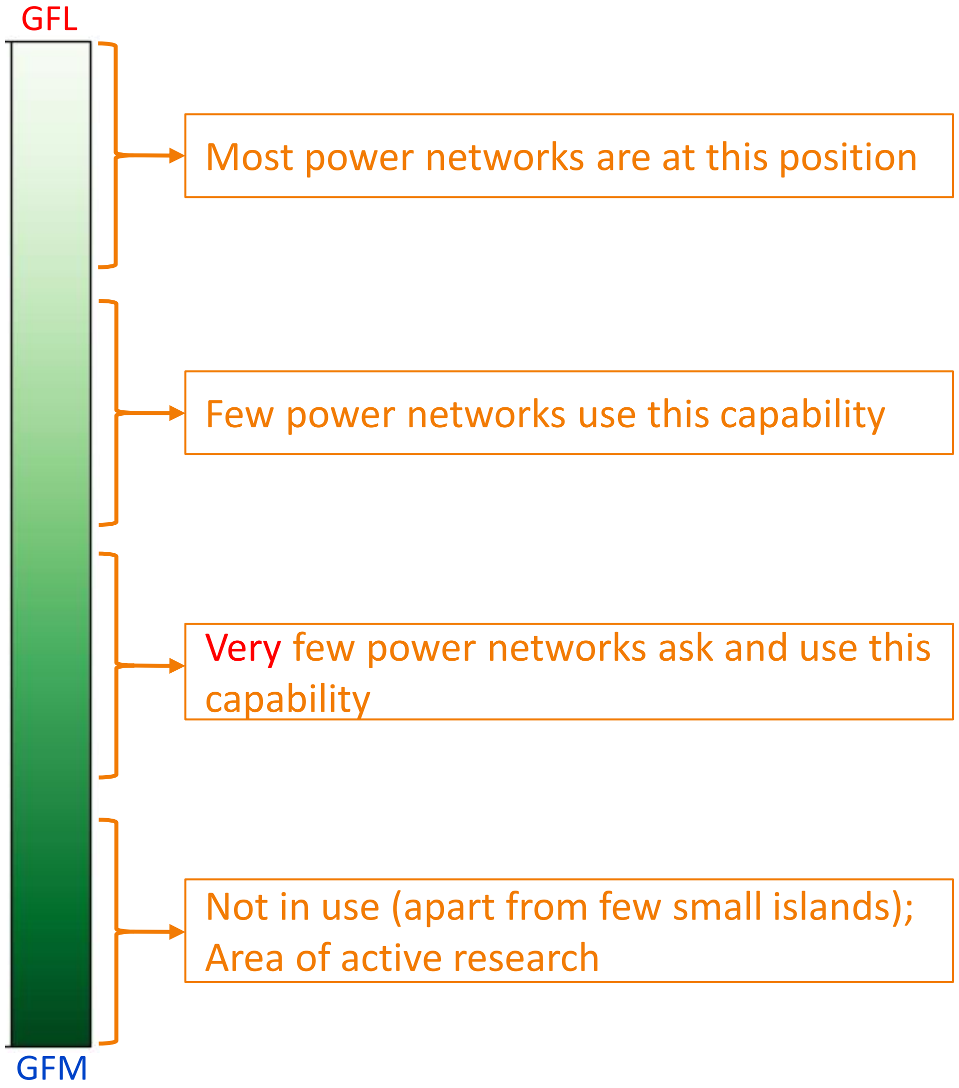
- Has capability to provide both frequency and voltage response
- Typically at a plant level and full delivery over multiple seconds

Enhanced IBR

- Delivers full frequency and voltage response within 1s of event
- Could survive loss of last synchronous machine

Future IBR

- Is capable of blackstart
- Could potentially single handedly survive extreme events



GFL and GFM – refer to a single inverter
IBR – refers to entire plant containing numerous inverters

Services from IBRs

- Gigawatts (GWs) of IBRs in the present power network, whose capability is underutilized

- Hundreds of GWs of IBRs presently in the interconnection queue for whom, utilization/delivery of full capability is either not required, or is optional (market product).

- Underutilization of capability today can lead to increased burden and timeline of capability provision on future IBR.

- Power system operation is a team sport
  - Improved reliability when each player contributes a little, in a beneficial manner
  - Entire burden cannot (and should not) fall on the MVP*

Subsequent sections of presentation discusses concepts of how each IBR could contribute in a beneficial manner

*Most Valuable Player

Categories of services from IBRs

Fast & stable response to events

Help maintain voltage

Help maintain frequency

Robust fault ride through

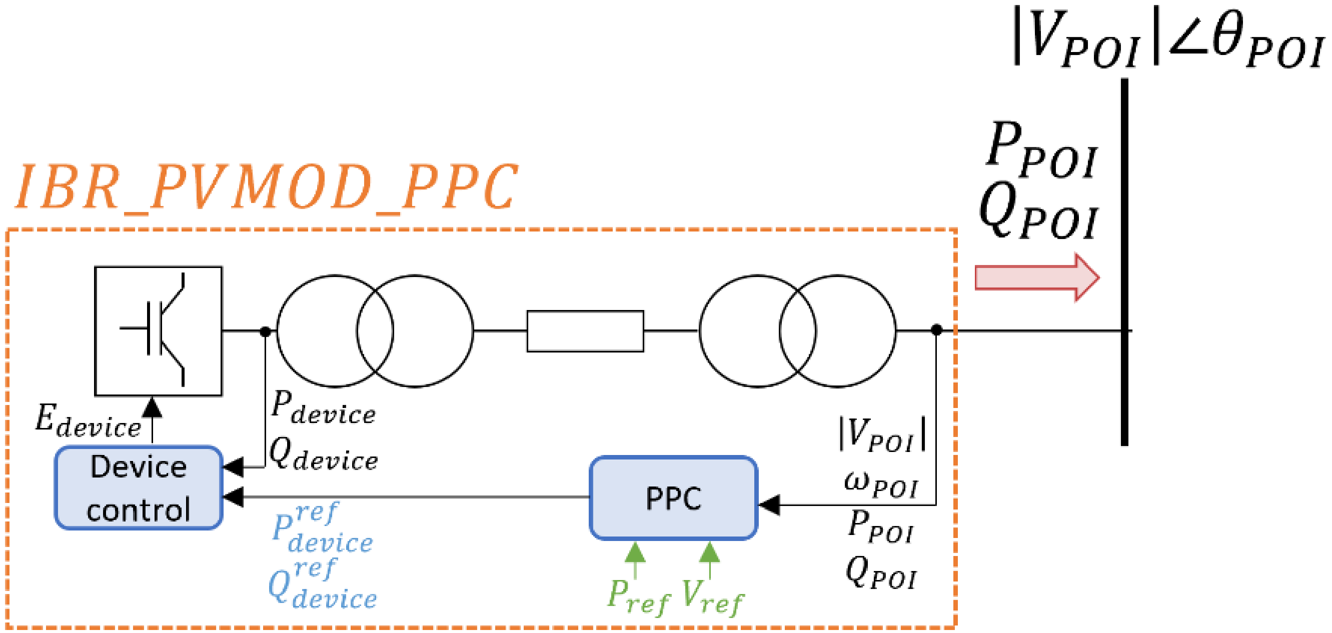
Network benefits when devices work as a team

Blackstart capability

Network requires MVP

Hierarchy of delivery of services in conventional IBR

- Conventional IBR plant has two hierarchy of control
  - plant controller responsible for power, voltage, and frequency control of the plant
  - inverter/turbine controller responsible for active and reactive power control

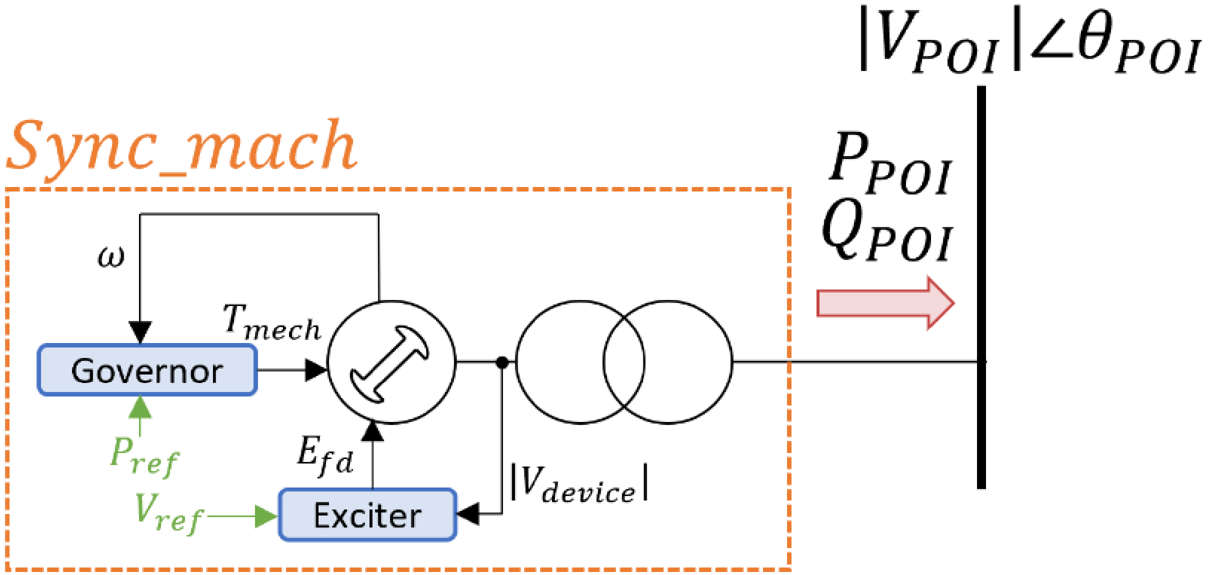


- Plant level controller incorporates principles of droop for voltage and frequency control
  - Typically slow control
- Inverter level controller may have open or closed loop power control
  - Generally fast control

https://www.epri.com/pvmod

Hierarchy of delivery of services in synchronous machine

- Conventional synchronous machine has one hierarchy of control
  - Machine level controllers responsible for frequency and voltage control
- No plant level control

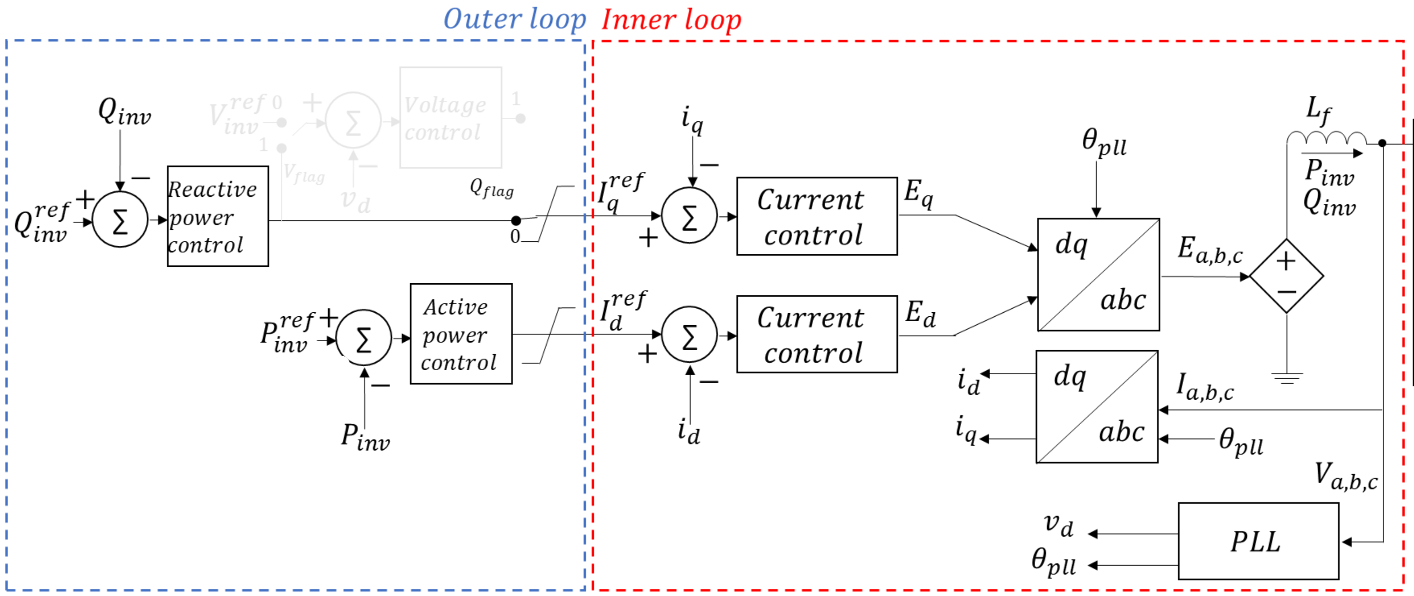


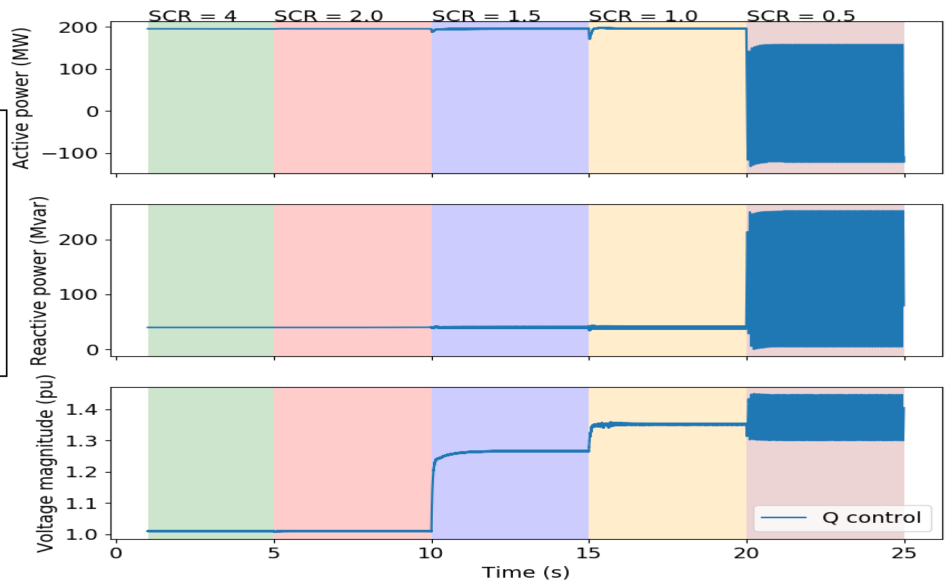
- Device (machine) level control is fast in modern synchronous machine plants

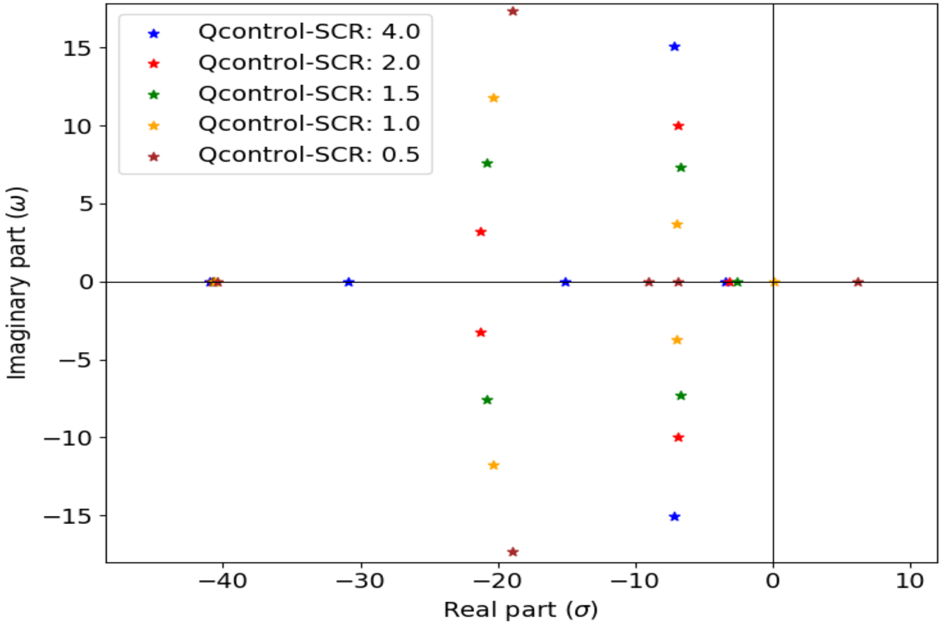
Difference in hierarchy of delivery of services plays a crucial role in determining improvement of system reliability

Fast Voltage Response

Conventional IBR and system strength reduction



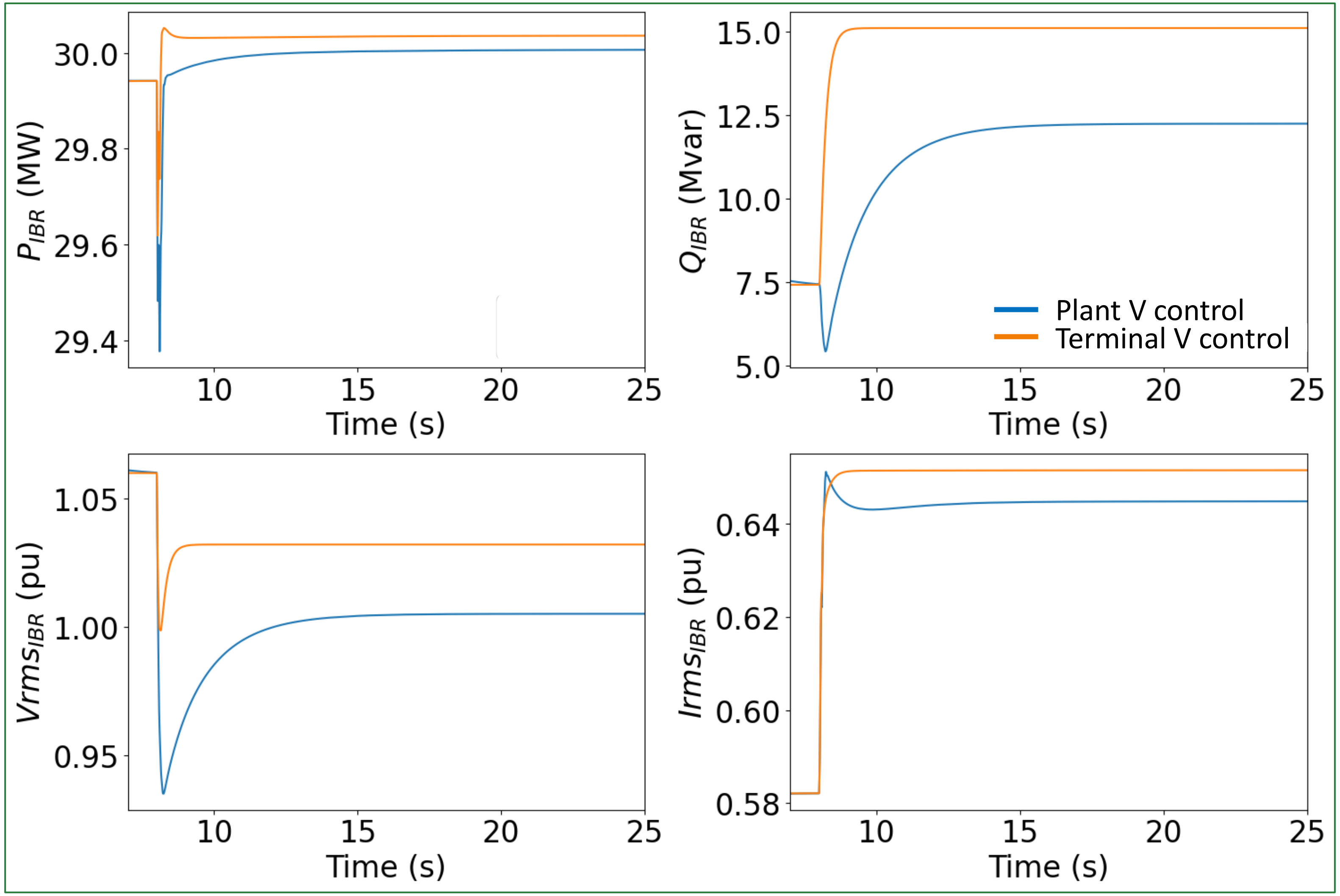




- Reduction in short circuit ratio (SCR) below 2.0 results in instability
- However, phase locked loop (PLL) and inner current control loop are not the sole elements responsible.

Bringing about fast voltage response at device level

Terminal V control



- Plant level voltage control can be augmented with inverter level voltage control
- Could provide improved benefit with high IBR systems

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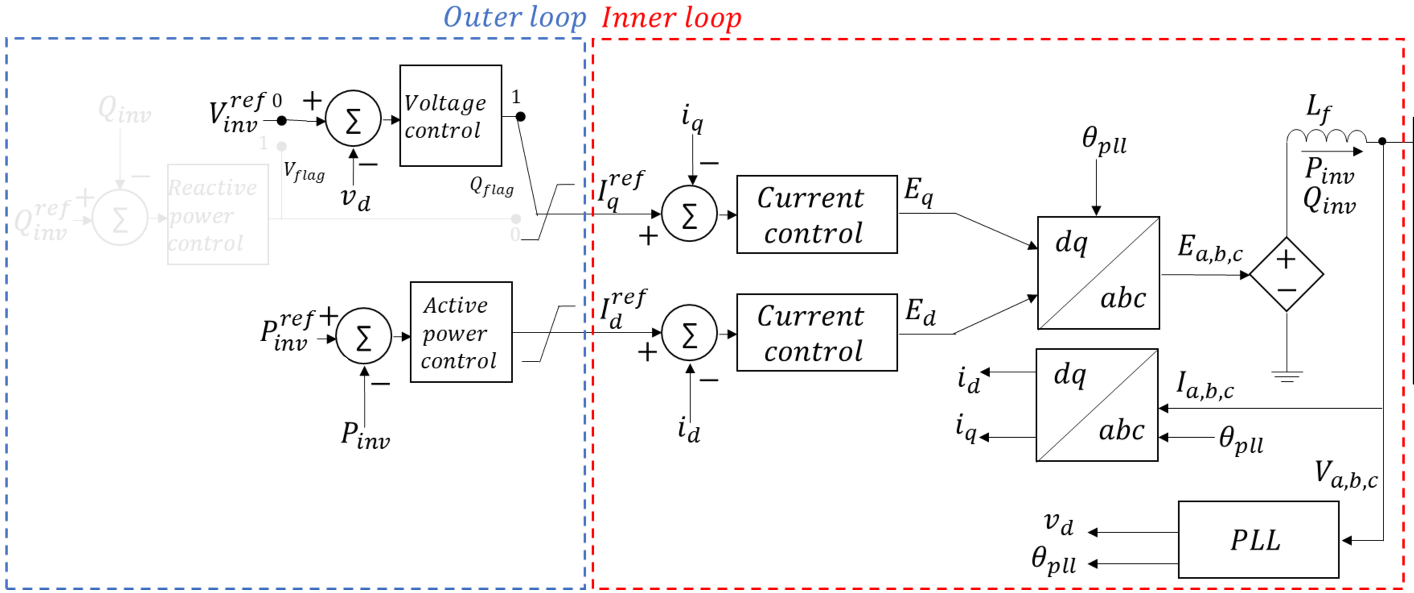
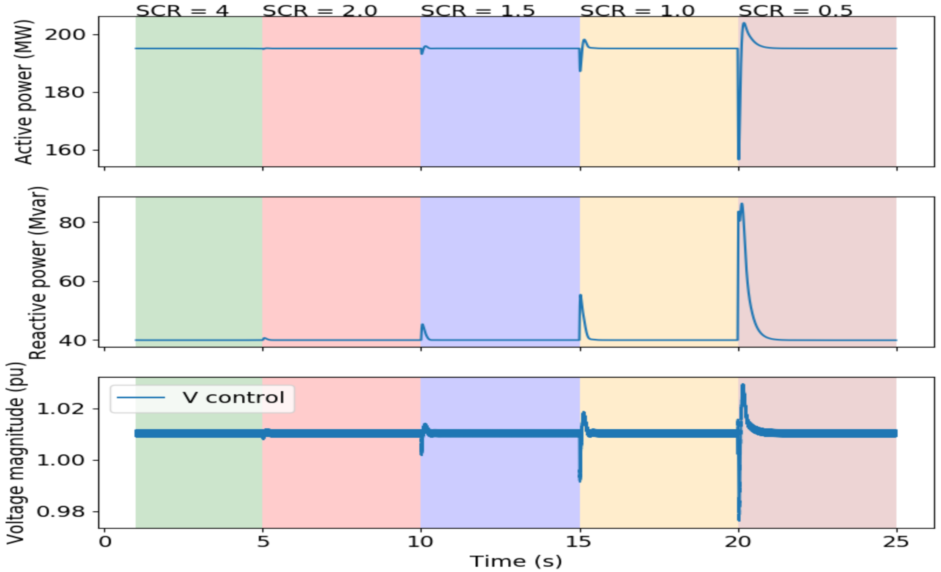
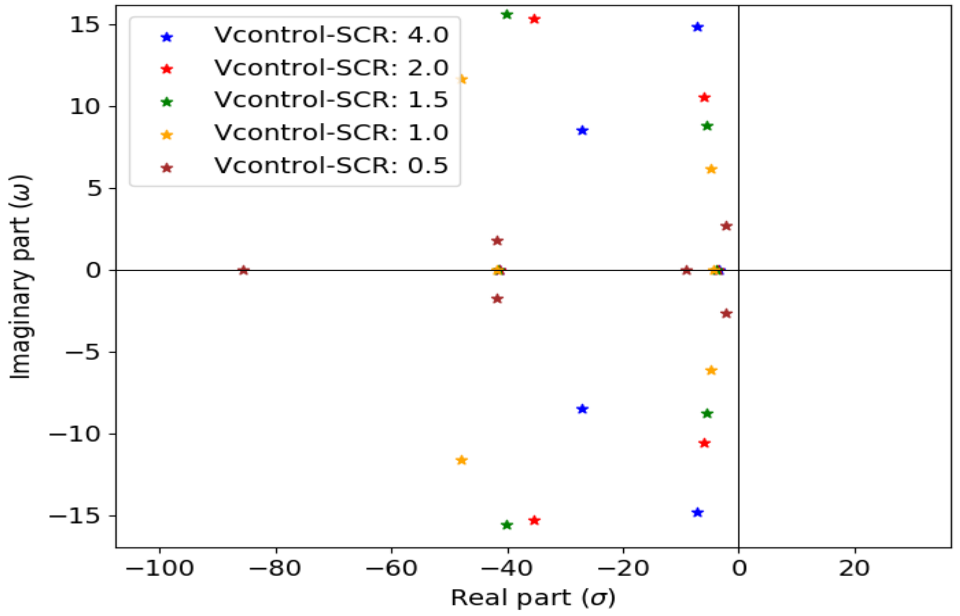
Switching to fast inverter level voltage control

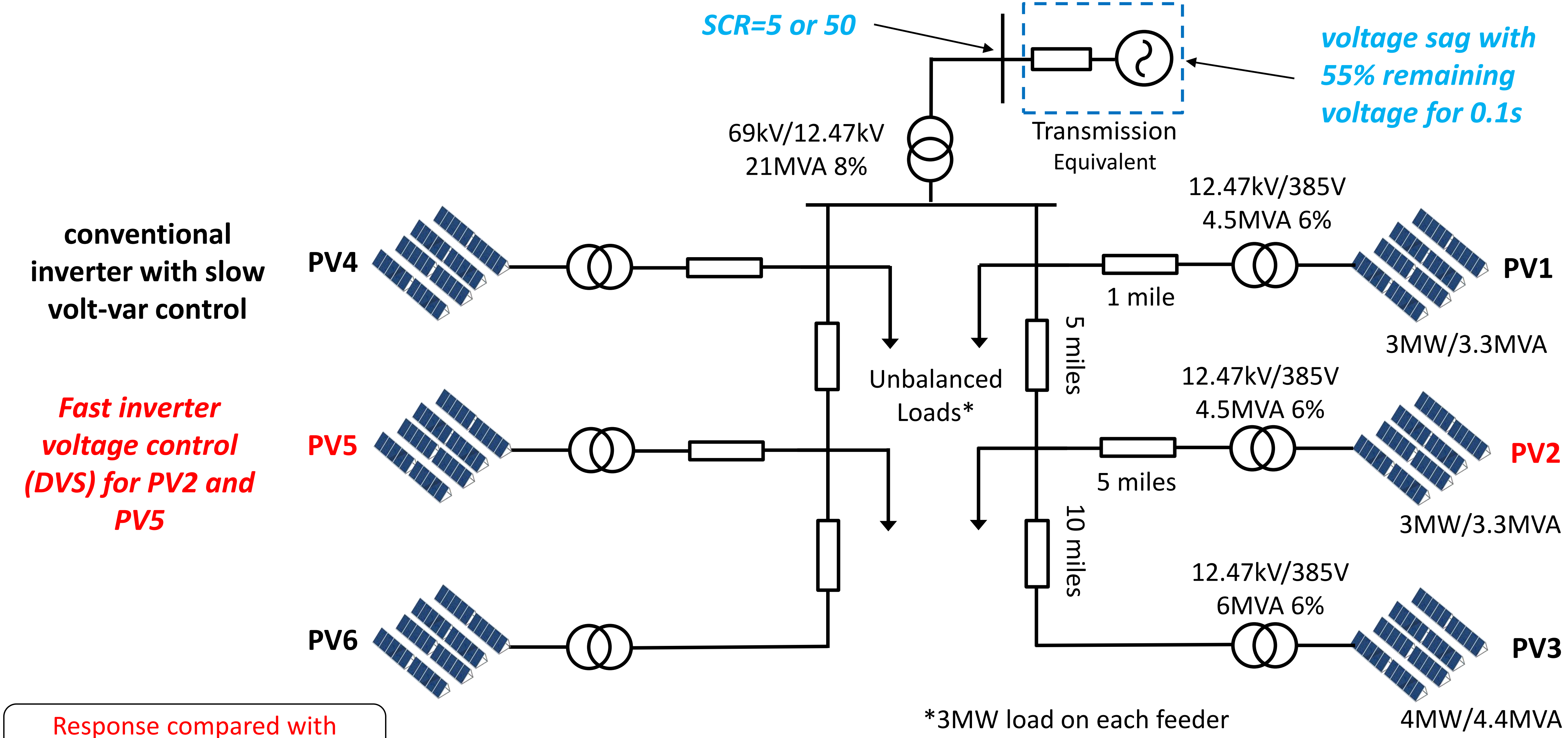






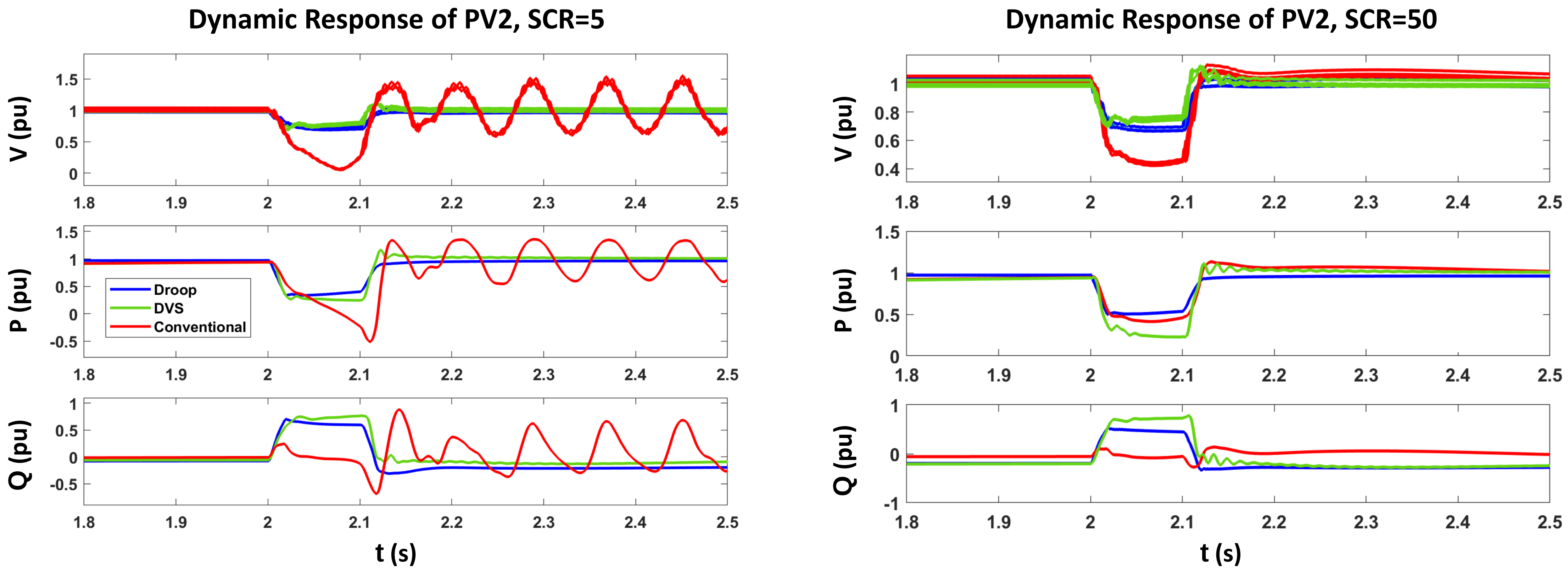
- Keeping the PLL and current controller gains the same, switch to inverter level voltage control.
- From a small signal sense, the control is now stable even for SCR of 0.5!

System level application example



Response compared with Future IBR with droop control

Performance comparison



- Use of fast inverter level voltage control, could help improve the reliability of the network

Note this is not to imply that future IBR technology may not be required

Interim takeaway

- Traditional hierarchy of inverter level reactive power control is a contributing factor to instability in low short circuit conditions

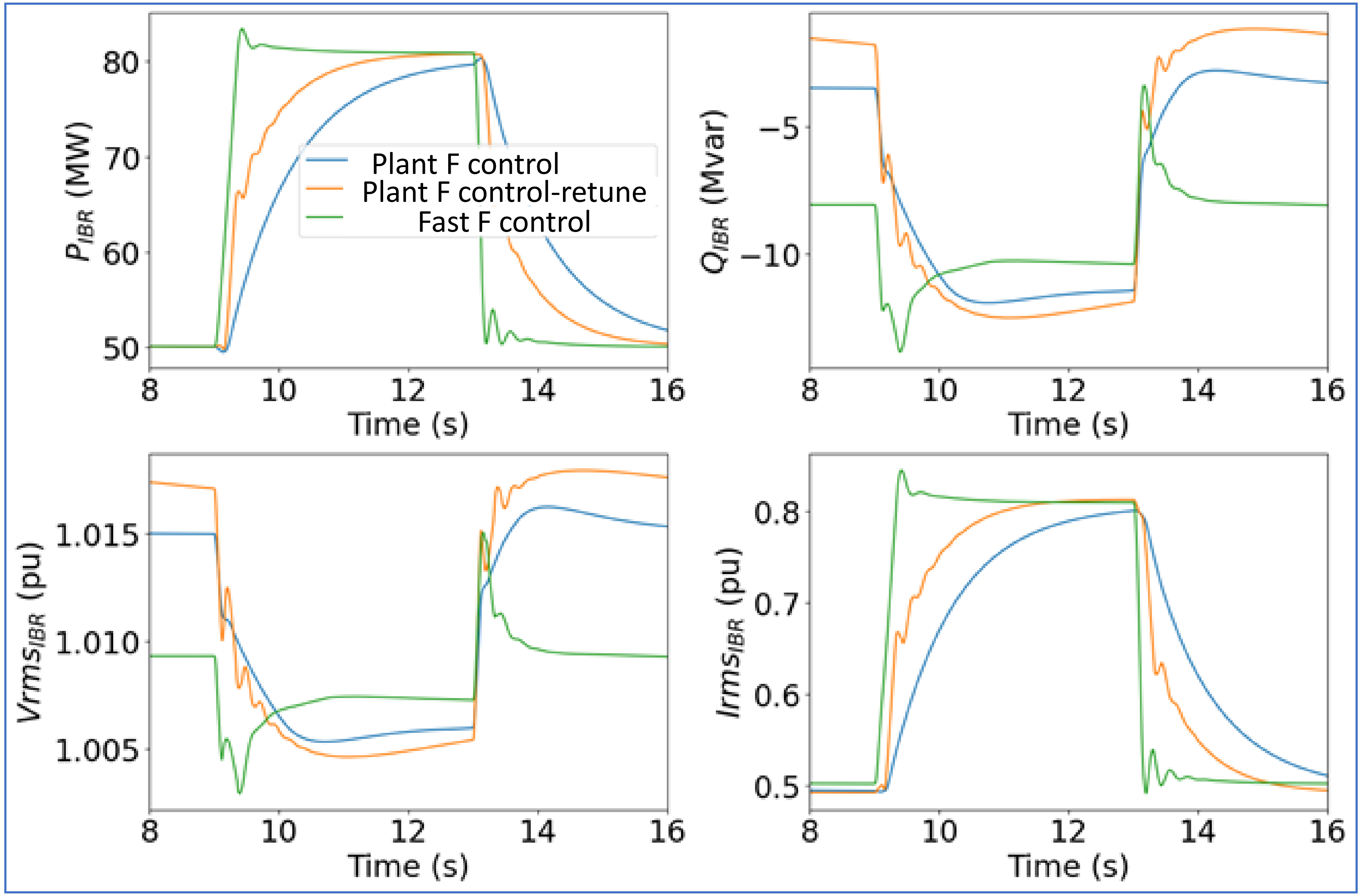
- Going to fast inverter level voltage control provides improved stability and reliability benefits

- To understand this from a power flow perspective:
  - Traditional inverter level reactive power control can be related to a PQ bus in power flow
  - Switching to inverter level voltage control can be related to a PV bus in power flow
  - Increased number of PV buses is beneficial from a power flow solution
    - A similar benefit is obtained in dynamic stability

Fast Frequency Response

Bringing about fast frequency response at device level

Fast frequency control



- Plant level frequency control can be augmented with inverter level fast frequency control
- Could provide improved benefit with high IBR systems

Example requirements from around the world

National Grid UK

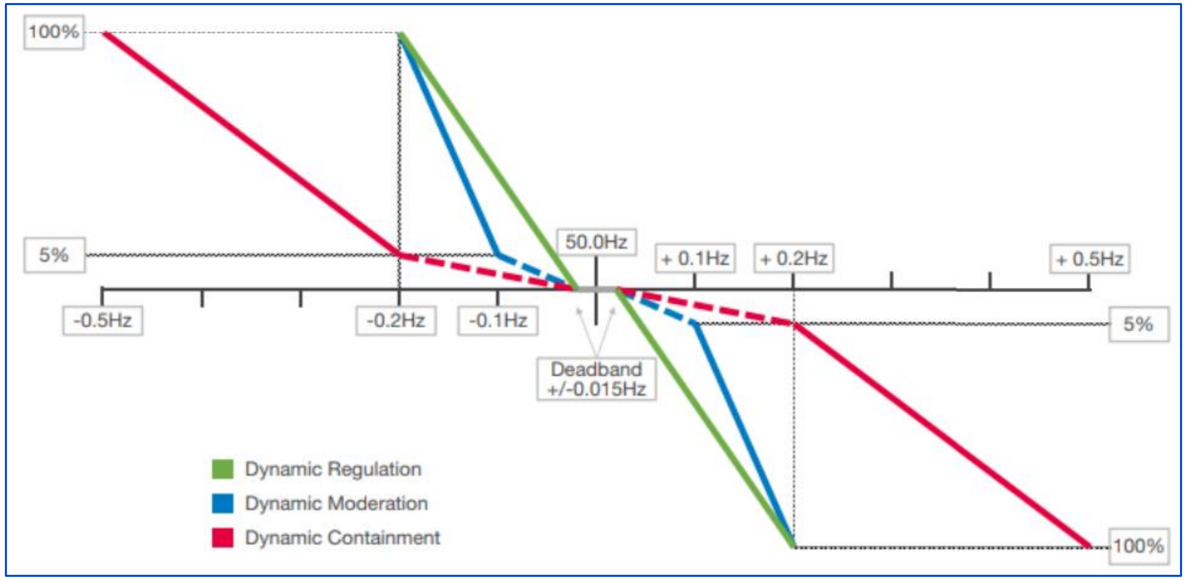


Figure source: https://www.nationalgrideso.com/document/276606/download

- Dynamic containment and dynamic moderation services to be delivered within 1s
- Piecewise droop with minimum value of 0.21%!!
- Expectation is to deliver a linear (and not switched) response

AEMO

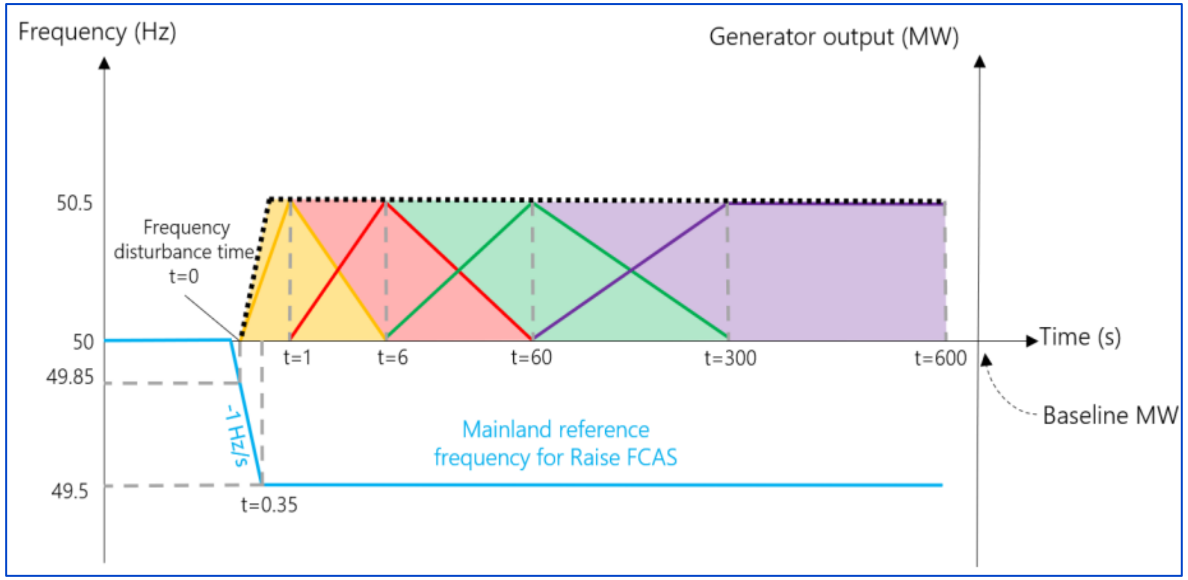


Figure source: https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2022/amendment-of-the-mass/final-determination/market-ancillary-services-specification---v80-effective-9-oct-2023.pdf?la=en

- Very fast frequency control ancillary service to be delivered within 1s
- Minimum droop of 1.7%
- Expectation is to deliver a linear (and not switched) response

IEEE 2800 – 2022 has similar requirements for capability related to fast frequency response

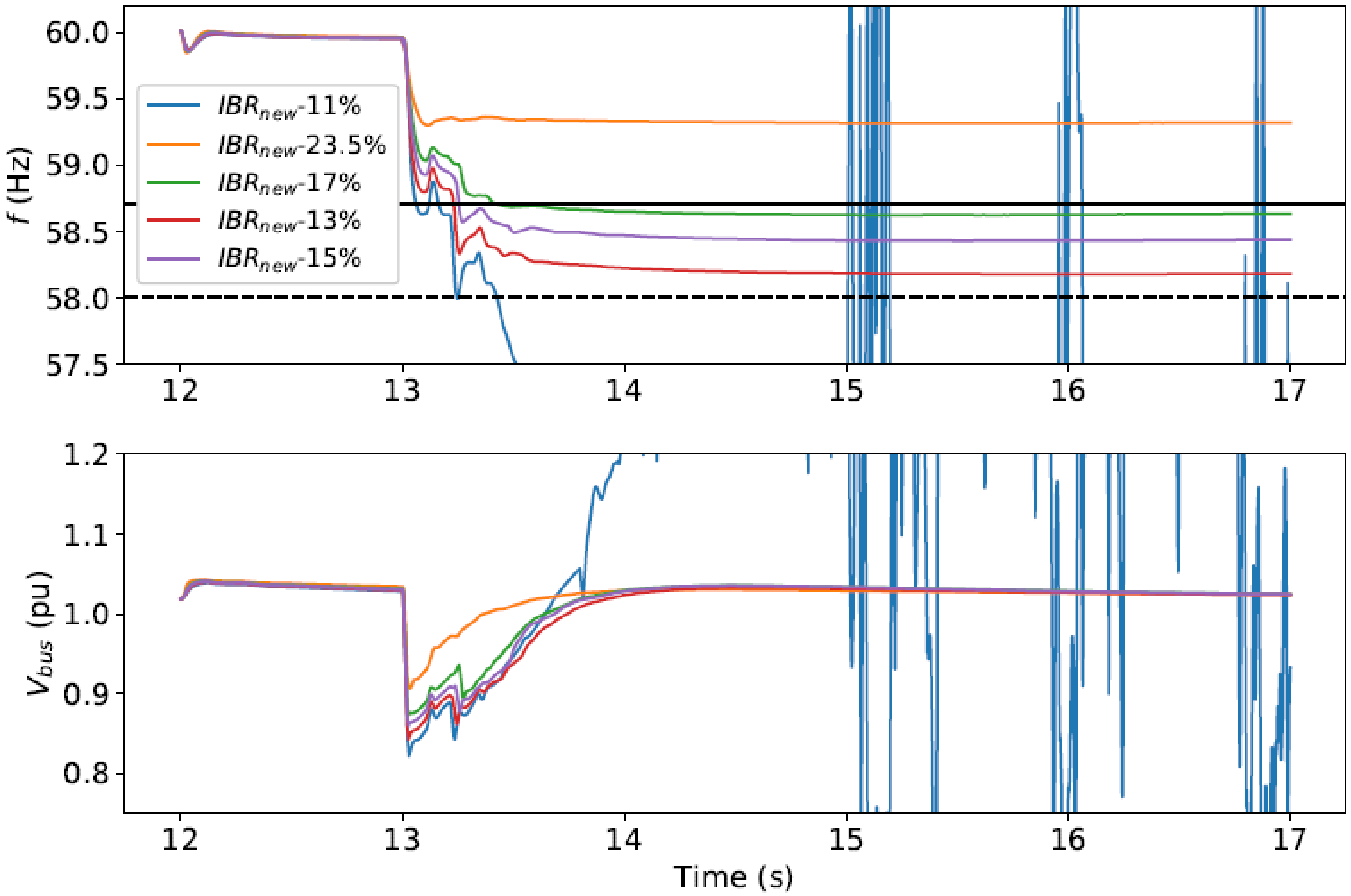
Example system level application

- Real island network with:
  - PV – 8.25 MVA
  - BESS – 8 MVA
  - DER – 3.25 MVA
  - Load – 2.9 MW
  - Sync condenser – 2.75 MVA
- System contains ac coupled PV-BESS hybrid plants, and standalone PV and BESS plants.
- Total base case IBR MVA is 19.50 MVA
- Variety of scenarios based on ability of PV and BESS to provide fast frequency response at inverter level
- In addition, the size of a Future IBR is to be determined to maintain stability

Case	PV1,PV2, PV3	BESS1,BESS2, BESS3	New IBR capacity	New IBR % of total IBR
A	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ V_1, V_2, V_3	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ $\cancel{V_1}, \cancel{V_2}, \cancel{V_3}$	2.5	11%
B	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ V_1, V_2, V_3	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ $\cancel{V_1}, \cancel{V_2}, \cancel{V_3}$	6.0	23.5%
C	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ V_1, V_2, V_3	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ $\cancel{V_1}, \cancel{V_2}, \cancel{V_3}$	4.0	17%
D	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ V_1, V_2, V_3	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ $\cancel{V_1}, \cancel{V_2}, \cancel{V_3}$	3.0	13%
E	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ V_1, V_2, V_3	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ $\cancel{V_1}, \cancel{V_2}, \cancel{V_3}$	3.5	15%
F	$\omega_1, \omega_2, \omega_3$ V_1, V_2, V_3	$\omega_1, \omega_2, \omega_3$ $\cancel{V_1}, \cancel{V_2}, \cancel{V_3}$	2.5	11%
G	$\omega_1, \omega_2, \omega_3$ V_1, V_2, V_3	$\omega_1, \omega_2, \omega_3$ $\cancel{V_1}, \cancel{V_2}, \cancel{V_3}$	1.5	7%
H	$\omega_1, \omega_2, \omega_3$ V_1, V_2, V_3	$\omega_1, \omega_2, \omega_3$ $\cancel{V_1}, \cancel{V_2}, \cancel{V_3}$	1.0	5%
J	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ V_1, V_2, V_3	$\omega_1, \omega_2, \omega_3$ $\cancel{V_1}, \cancel{V_2}, \cancel{V_3}$	1.5	7%
K	$\cancel{\omega_1}, \cancel{\omega_2}, \cancel{\omega_3}$ V_1, V_2, V_3	$\omega_1, \omega_2, \omega_3$ $\cancel{V_1}, \cancel{V_2}, \cancel{V_3}$	2.5	11%

Note: here fast terminal voltage control is not considered

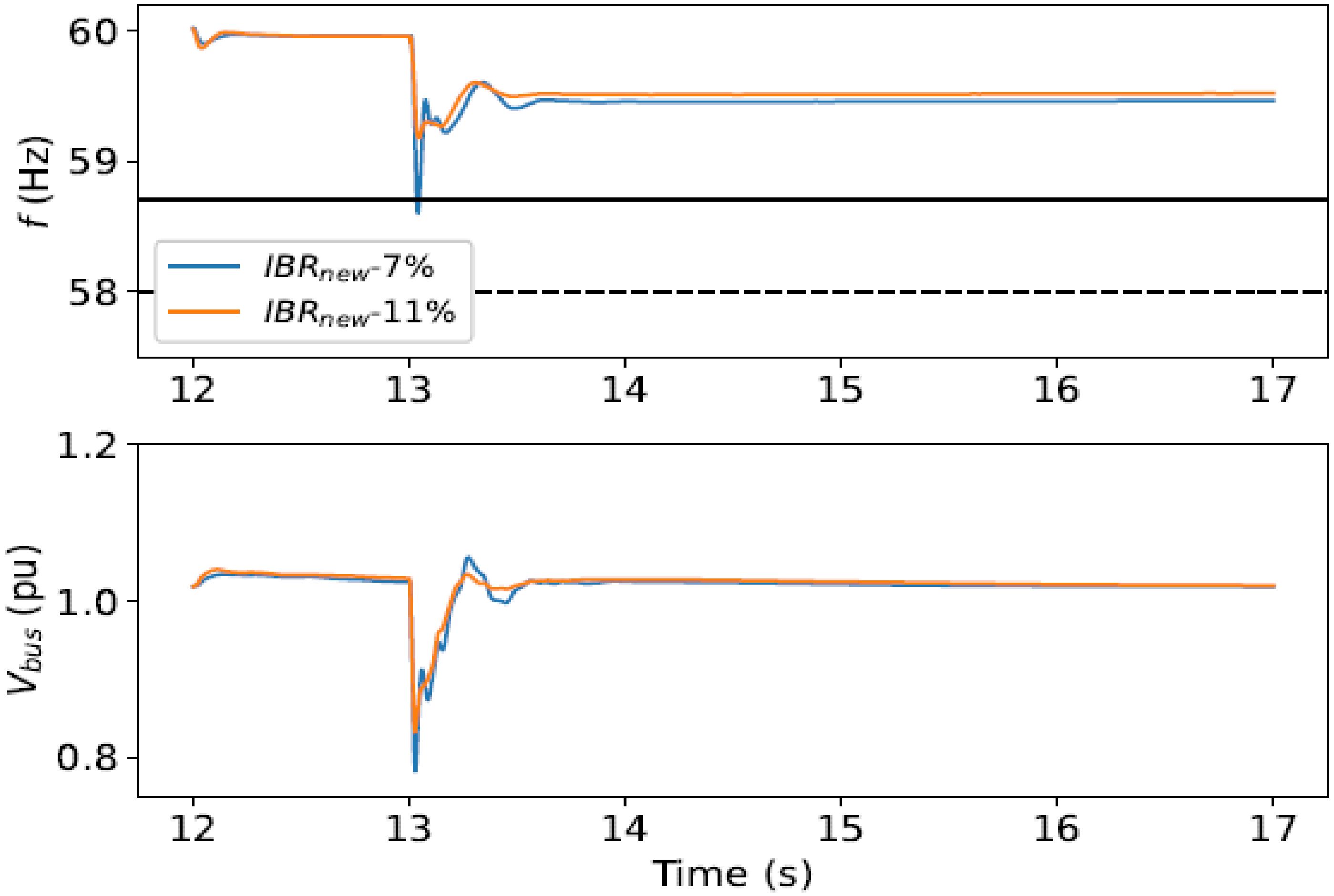
Scenario results



Case	PV1,PV2, PV3	BESS1,BESS2, BESS3	New IBR capacity	New IBR % of total IBR
A	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ V_1, V_2, V_3	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ ~~V_1~~, ~~V_2~~, ~~V_3~~	2.5	11%
B	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ V_1, V_2, V_3	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ ~~V_1~~, ~~V_2~~, ~~V_3~~	6.0	23.5%
C	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ V_1, V_2, V_3	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ ~~V_1~~, ~~V_2~~, ~~V_3~~	4.0	17%
D	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ V_1, V_2, V_3	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ ~~V_1~~, ~~V_2~~, ~~V_3~~	3.0	13%
E	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ V_1, V_2, V_3	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ ~~V_1~~, ~~V_2~~, ~~V_3~~	3.5	15%

- When fast frequency response is not utilized, new Future IBR of around 25% is needed for system to be reliable

Scenario results



Case	PV1,PV2, PV3	BESS1,BESS2, BESS3	New IBR capacity	New IBR % of total IBR
J	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ V_1, V_2, V_3	ω_1, ω_2, ω_3 ~~V_1~~, ~~V_2~~, ~~V_3~~	1.5	7%
K	~~ω_1~~, ~~ω_2~~, ~~ω_3~~ V_1, V_2, V_3	ω_1, ω_2, ω_3 ~~V_1~~, ~~V_2~~, ~~V_3~~	2.5	11%

- When fast frequency response of only BESS is used, new Future IBR of around 11% is needed for system to be reliable

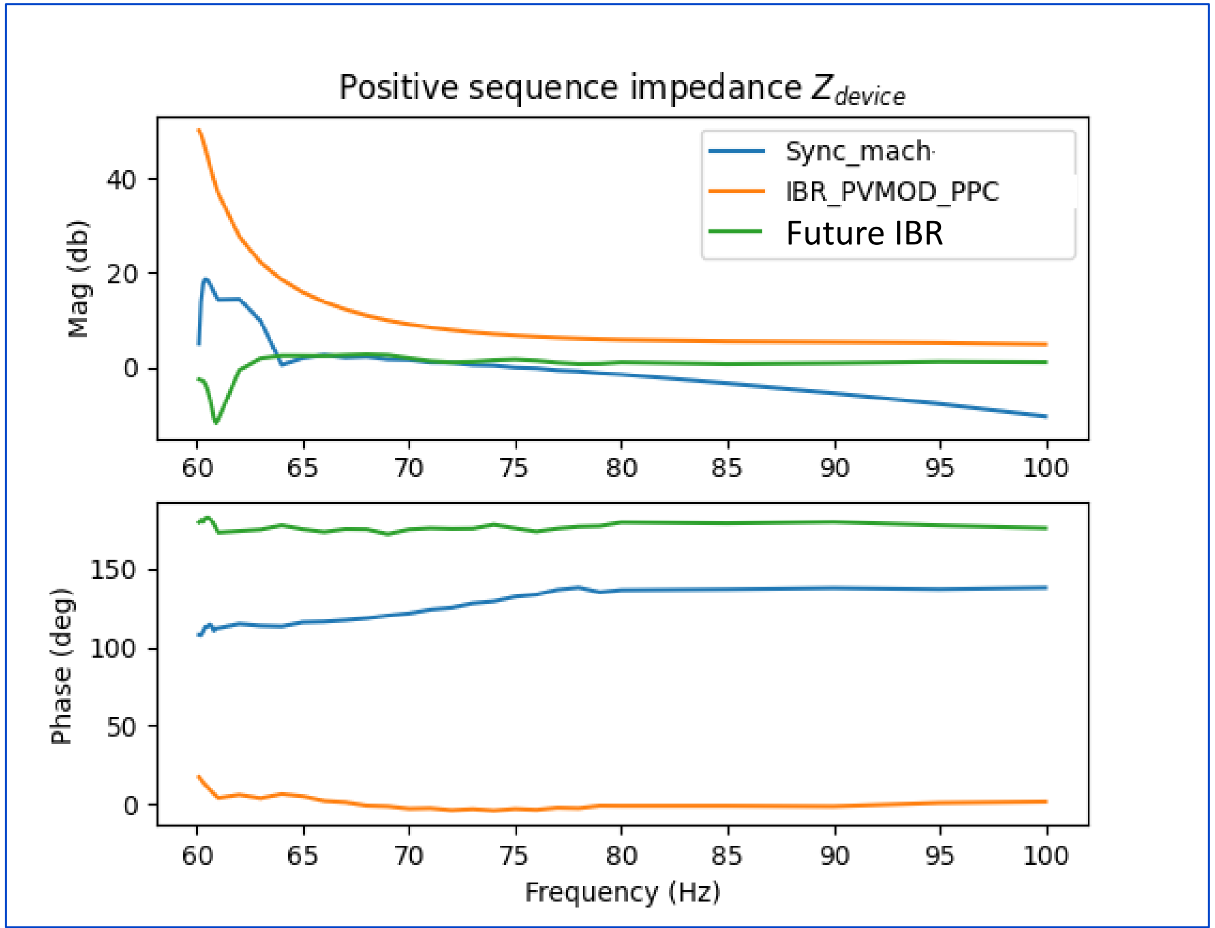
Interim takeaway

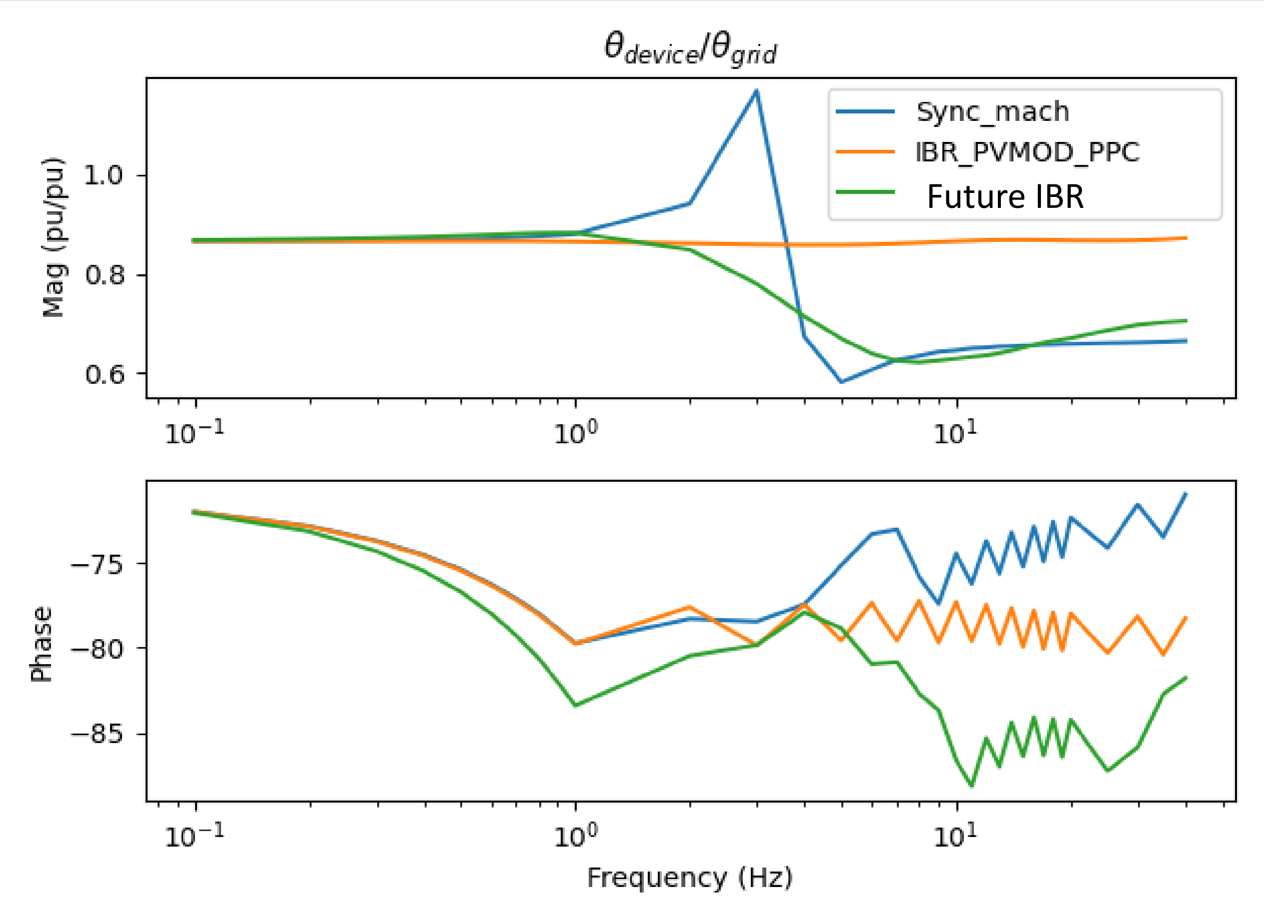
- Going to fast inverter level frequency control could provide improved stability and reliability benefits

- Needs to be carefully evaluated and verified as it could cause control interactions if not designed appropriately.
  - The more resources that provide this response, the lesser incremental amount will each resource need to provide
  - This reduced burden on each resource can help improve stability

Stability and damping

Criteria for stability and damping





- Threshold for damping ratio are useful, but may have limitations regarding guarantees in a large network
- Frequency domain criteria is gaining more traction but still an open research topic to verify if criteria can be generalized

Different flavors of such criteria across various stakeholders. To be harmonized

Blackstart and system restoration

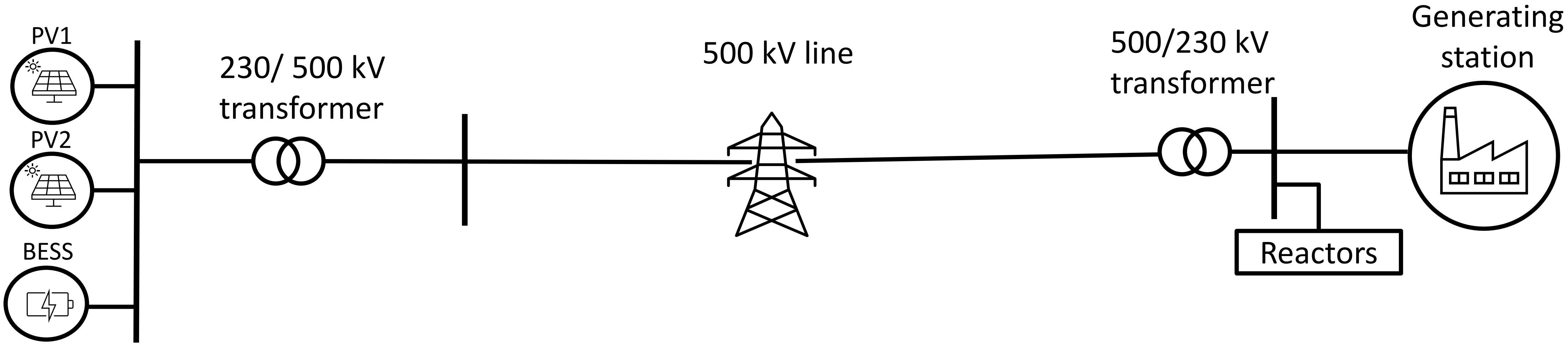
Objective

Determine the capability of IBR to meet future needs and provide services related to blackstart and system restoration

- Study carried out on real-world network.
- The cranking path of the network modeled using actual parameters to closely replicate practical conditions
- Evaluate ability of inverter-based resources (IBRs) to successfully energize transformers, transmission lines, and pick up load/generation sources
- Study impact of limited availability of IBR resources on system restoration
- Sensitivity studies to understand the impact of transformer saturation and hysteresis

EPRI – SCE – NREL collaborative effort

Cranking path of the network for restoration



IBR
Rating:
PV1 300 MVA
PV2 250 MVA
BESS 400 MVA

- ✓ Inverters with capability for restoration (PV/BESS)

Transformers
Rating: 400- 1100 MVA

- ✓ Saturation/Hysteresis model included (Typical saturation data was assumed)

Transmission lines
(20- 60 miles)

- ✓ Frequency dependent line model used
- ✓ Parameters obtained from real data

Generator station
auxilary load

- ✓ Load composition details obtained from real data
- ✓ Three phase induction motor models (NEMA type B)

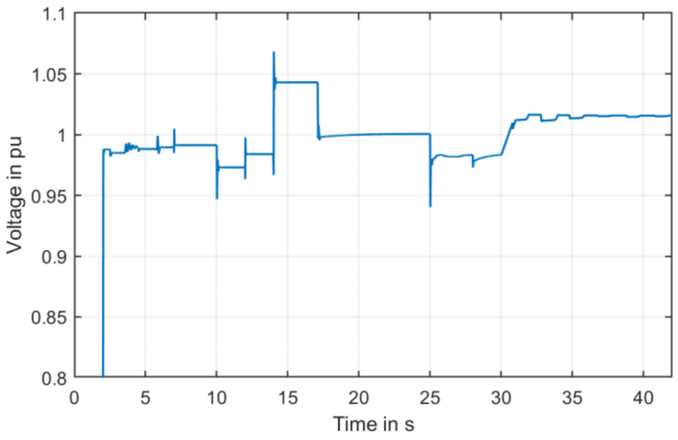
Methodology and objectives that were achieved

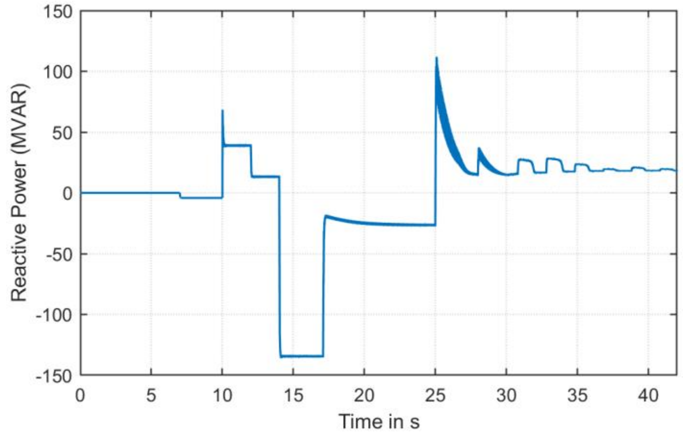
Methodology	Objective achieved
Data Gathering	Detailed data collection of the different components in the crank path
BESS/PV EMT Model Development	BESS/PV model created with blackstart capabilities
Development of Frequency Dependent line model	Development of frequency dependent line model and validated the model using real data
Detailed load modeling of the generating station	Development of detailed model of a generating station with three phase motors
EMT transformer energization studies	Study the impact of remnant flux/ saturation parameters of transformers
EMT simulation of the energization of restoration path	Established IBRs are able to controls voltage/frequency within limits
EMT simulation of load pickup	Established the IBRs are able to support inrush currents without exceeding voltage/frequency limits
Impact of using soft energization to restore the cranking path	Demonstrated the advantages of soft starting a portion of the network at lower voltage level
Impact of limited IBR resource on the restoration process	Highlighted the impact of limited IBR resource on the voltage/frequency

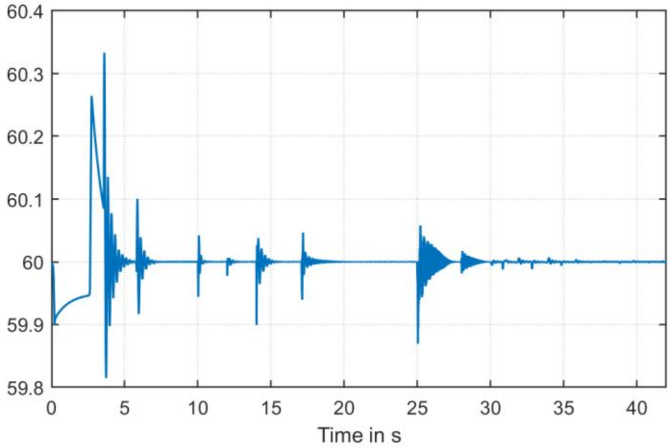
Objective achieved
Methodology

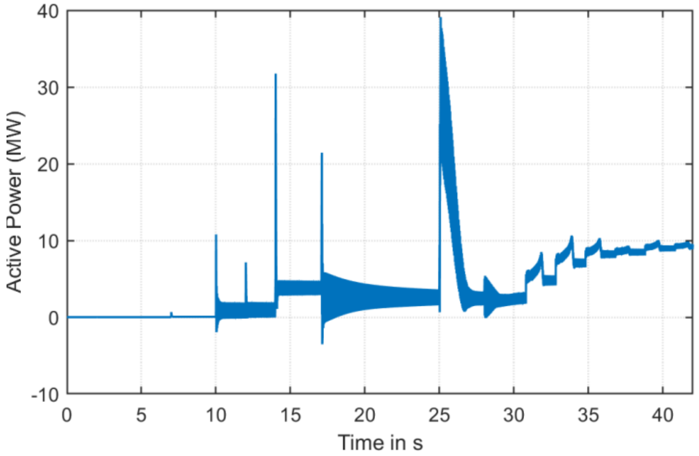
Overview of restoration from IBR to motor pickup

Sequence	Time
Synchronize the IBR plants	2-5 seconds
Energize the 230/500kV transformer	10-11 seconds
Energize 500kV Line	12-15 seconds
Energize the reactors	17-20 seconds
Energize the 500/230kV transformer	25-28 seconds
Energize motors sequentially	31-45 seconds









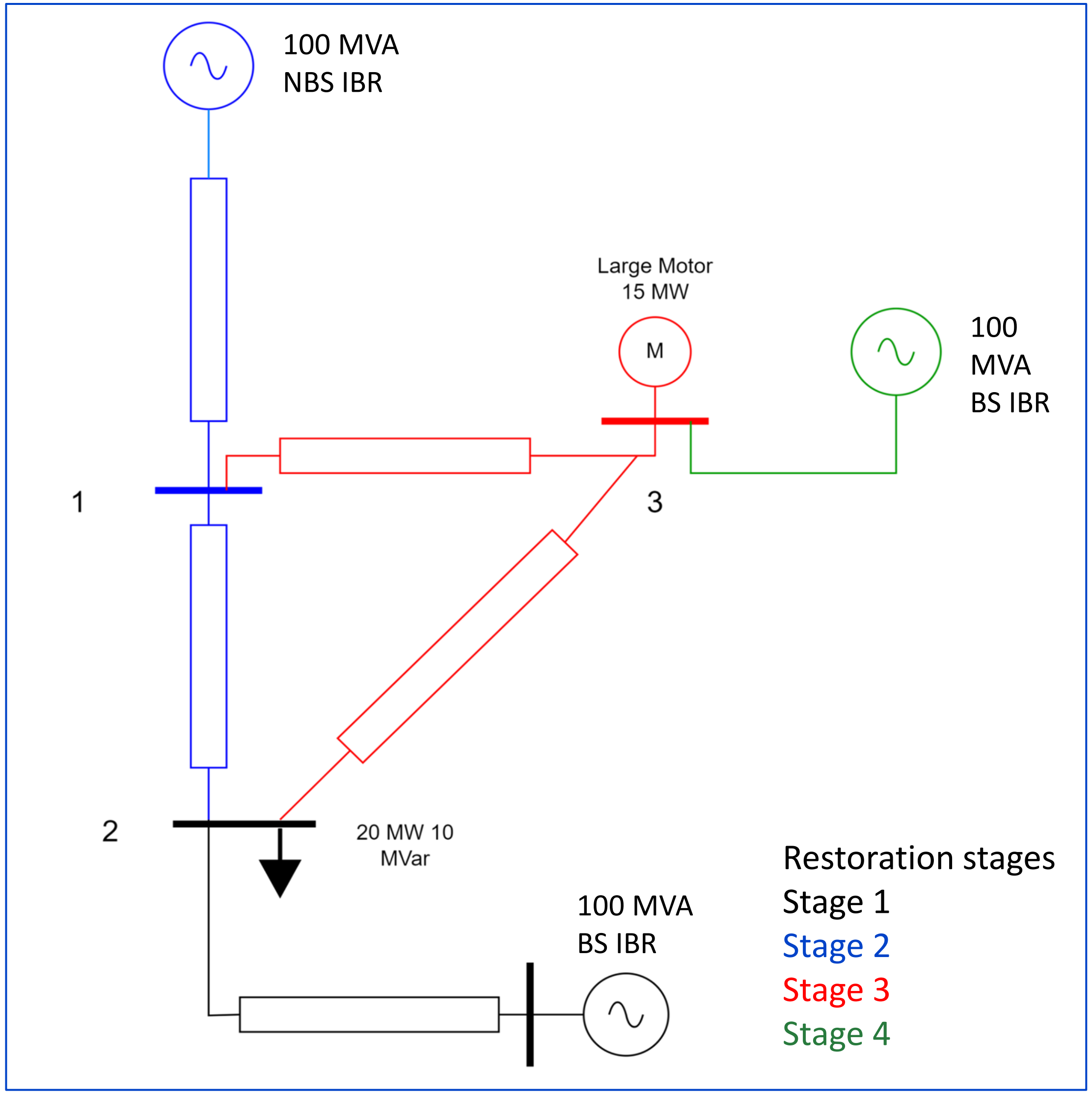
Key Takeaways

- ❖ No instability in voltage/frequency is observed under these conditions
- ❖ Generator auxilary load was successfully energized
- ❖ Transmission line generates high levels of charging current to be absorbed by IBR (~3Mvar/Mile)

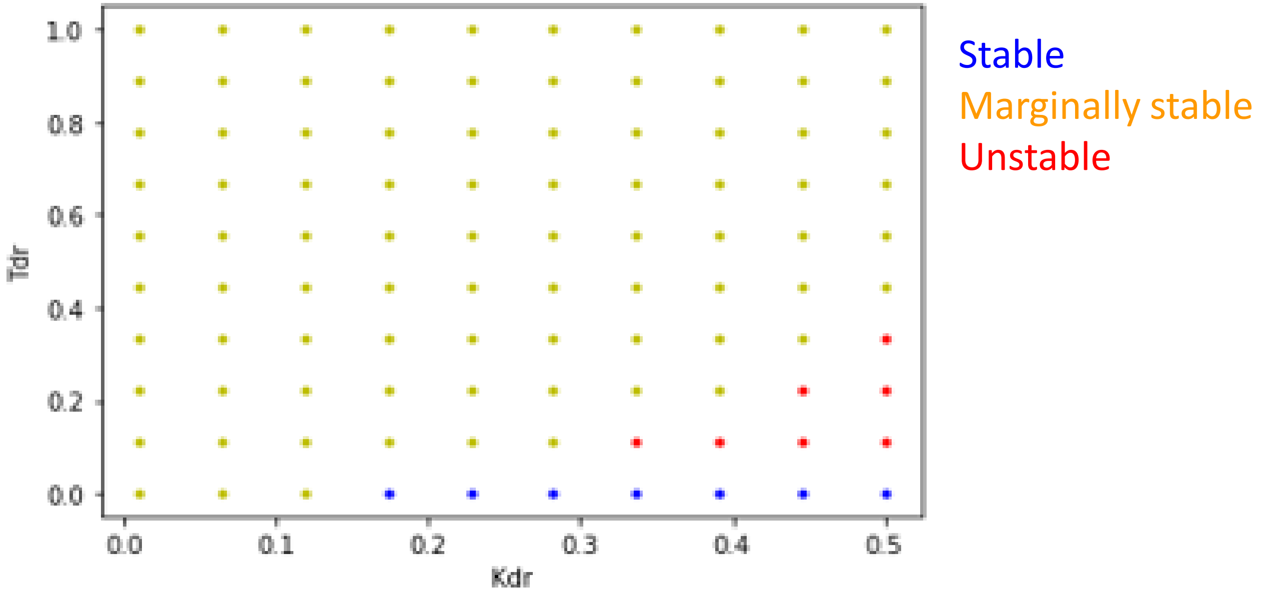
Plots show output from IBR

Oscillatory behavior observed in active power measurements is a result of non-linear magnetization characteristics of the network and should be considered carefully when evaluating IBR capability for restoration

Importance of control stability during restoration



NBS – Non blackstart
BS – Blackstart



- Early restoration stages typically have lightly loaded network
- Control interactions between different types of inverter control and load dynamics an occur
- These interactions may not be visible when setting up control of an IBR in a SMIB setup

Summary

Takeaways

- Maintaining reliability in the power network is a team sport
  - If each device (player) contributes a bit, the benefits can be tremendous
- Increased utilization of fast inverter level voltage and frequency control can improve reliability
  - A lot of capability from IBRs is being left under utilized
- Simultaneously, adoption of newer forms of robust IBR control is important, after verifying their performance

ESIG Services Task Force

- Objective of the Task Force
  - Identify various services that can be delivered by Enhanced IBR and Future IBR
  - Quantify magnitude of service required by the power network
  - Evaluate if type and magnitude of service is generalizable across networks

- Send a note to Ryan Willis (ryan@esig.energy) and Julia Matevosyan (julia@esig.energy) if interested in participating

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