Essential Reliability Services from Wind, Solar, Battery Storage (IBR) and Conventional Power Plants

ESIG Fall Technical Workshop

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Essential Reliability Services from Wind, Solar, Storage and Conventional Power Plants

CAUTION CONCERNING FORWARD-LOOKING STATEMENTS:

This document contains "forward-looking statements" – that is, statements related to future events that by their nature address matters that are, to different degrees, uncertain. For details on the uncertainties that may cause our actual future results to be materially different than those expressed in our forward-looking statements, see http://www.ge.com/investor-relations/disclaimer-caution-concerning-forwardlooking-statements as well as our annual reports on Form 10-K and quarterly reports on Form 10-Q. We do not undertake to update our forward-looking statements. This document also includes certain forward-looking projected financial information that is based on current estimates and forecasts. Actual results could differ materially. to total risk-weighted assets.]

NON-GAAP FINANCIAL MEASURES:

In this document, we sometimes use information derived from consolidated financial data but not presented in our financial statements prepared in accordance with U.S. generally accepted accounting principles (GAAP). Certain of these data are considered "non-GAAP financial measures" under the U.S. Securities and Exchange Commission rules. These non-GAAP financial measures supplement our GAAP disclosures and should not be considered an alternative to the GAAP measure. The reasons we use these non-GAAP financial measures and the reconciliations to their most directly comparable GAAP financial measures are posted to the investor relations section of our website at www.ge.com. [We use non-GAAP financial measures including the following:

- Operating earnings and EPS, which is earnings from continuing operations excluding non-service-related pension costs of our principal pension plans.
- GE Industrial operating & Verticals earnings and EPS, which is operating earnings of our industrial businesses and the GE Capital businesses that we expect to retain.
- GE Industrial & Verticals revenues, which is revenue of our industrial businesses and the GE Capital businesses that we expect to retain.
- Industrial segment organic revenue, which is the sum of revenue from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial segment organic operating profit, which is the sum of segment profit from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial cash flows from operating activities (Industrial CFOA), which is GE's cash flow from operating activities excluding dividends received from GE Capital.
- Capital ending net investment (ENI), excluding liquidity, which is a measure we use to measure the size of our Capital segment.
- GE Capital Tier 1 Common ratio estimate is a ratio of equity

Topics

Essential Reliability Services that power plants may provide:

Voltage Regulation
- Reactive Capability
- Dynamic voltage response

Performance during disturbances
- Voltage and Frequency Ride-Through

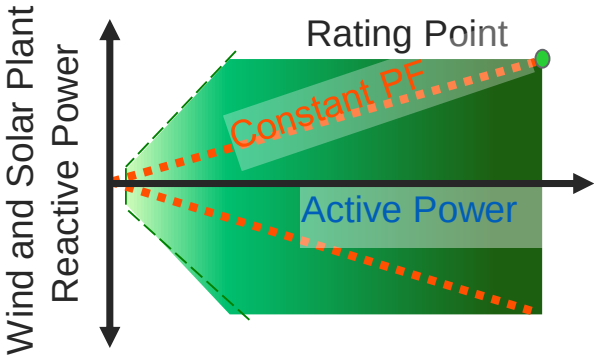
Stability
- Maintaining Synchronism

Active Power Control
- Frequency Regulation
- Primary Frequency Response
- Fast Frequency Response

Black Start

Voltage Regulation and Reactive Power Control

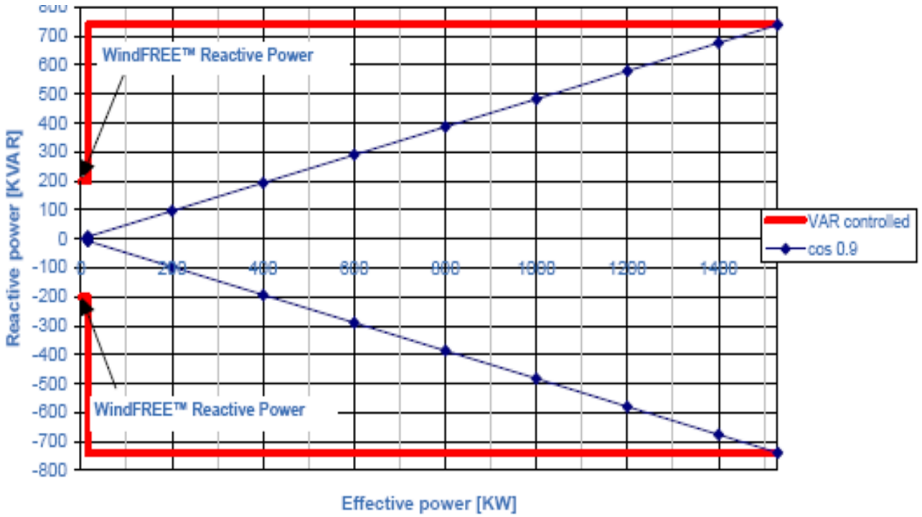
Reactive Power Capability



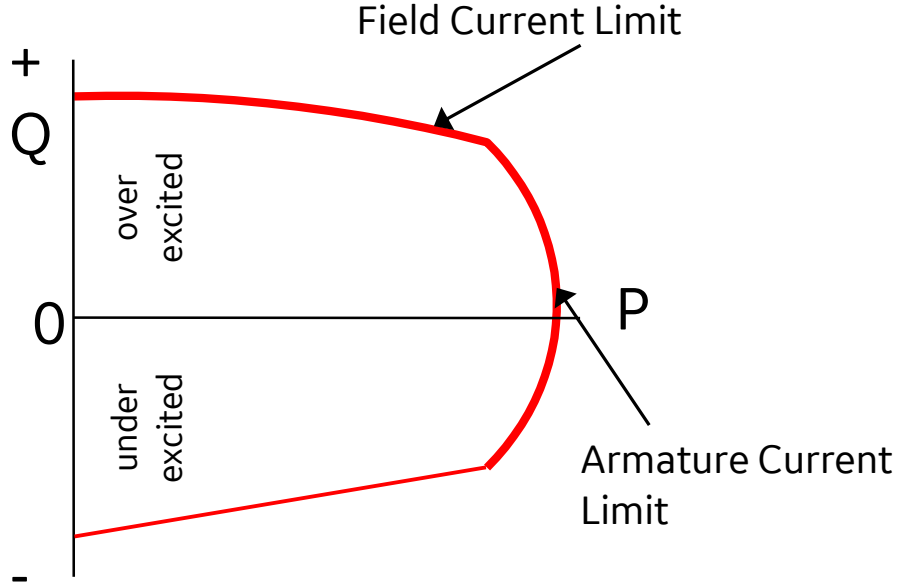
Reactive Power for Voltage Support

- Wind, Solar & BESS Steady-state PF range -
  +/-0.90 at converter/inverter, typically +/-0.95 at POI
  Can provide reactive power and Vreg during no wind/sun periods
- Conventional up to 0.80pf at machine terminals (typically 0.85pf)
- Both constrained by voltage (terminal, collector, auxiliary)

Wind Turbine Reactive Capability



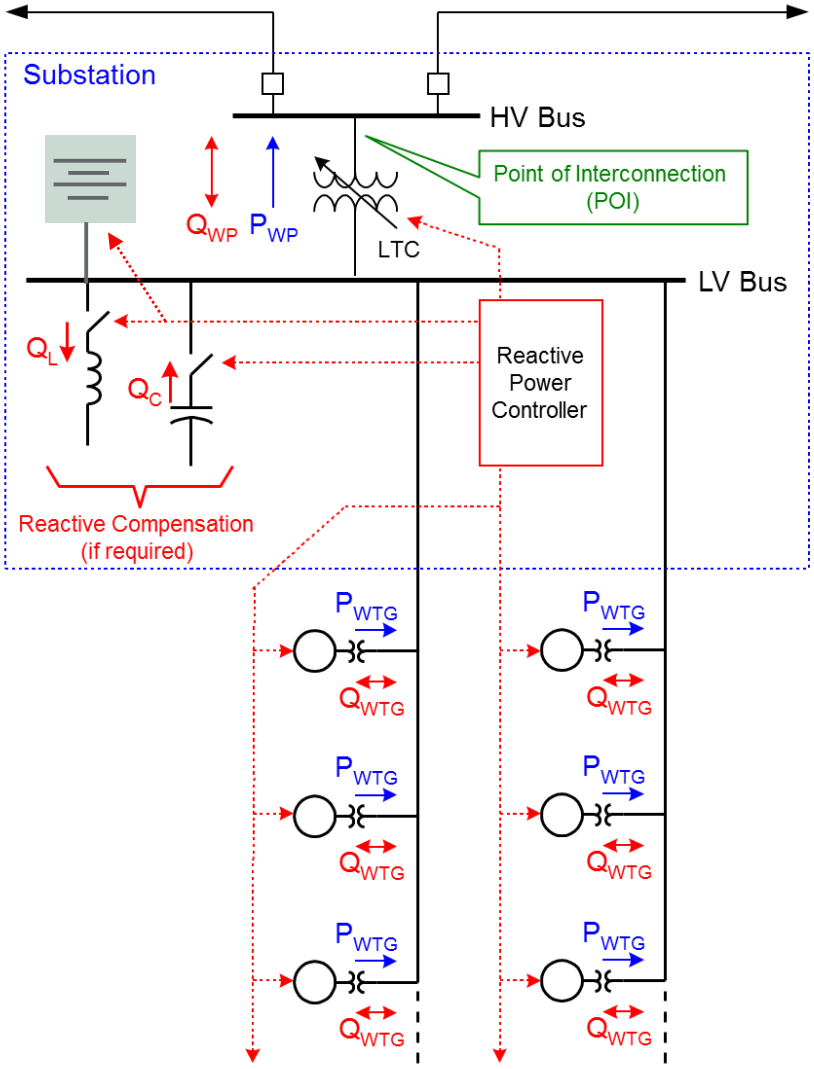
Synchronous Machine Reactive Capability

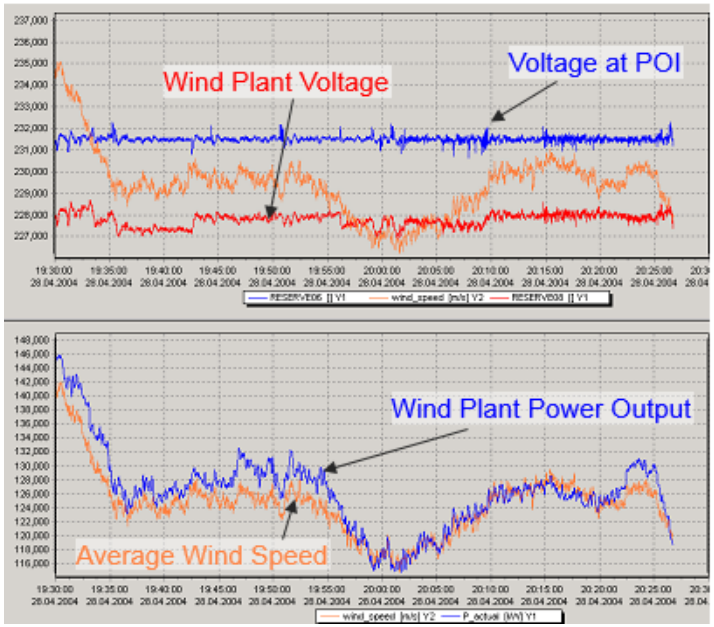


Wind and Solar Plant Voltage Control

Example: GE WindCONTROL, SunIQ

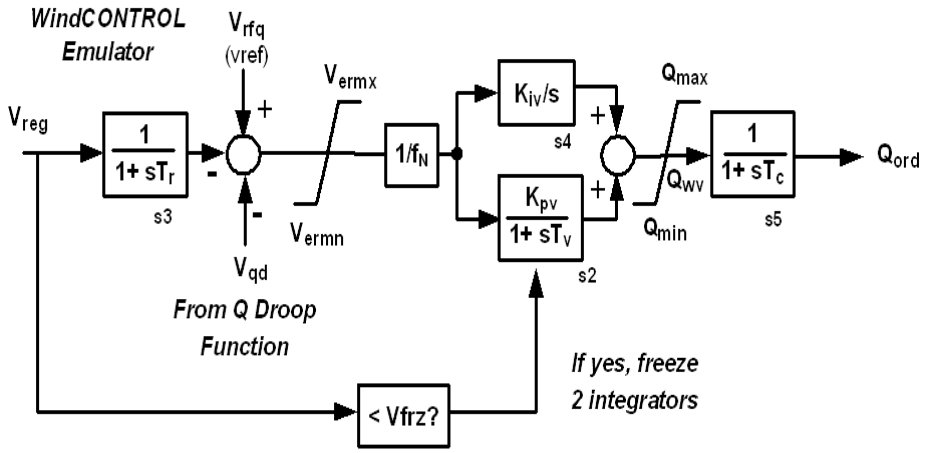
- Coordinated turbine and plant supervisory control tightly regulates Plant POI voltage & beyond
- WTG/Inverter control responds fast for grid faults
- Plant Voltage, VAR, & PF control
- PF requirements primarily met by WTG reactive capability, but augmented by mechanically switched shunt devices if necessary



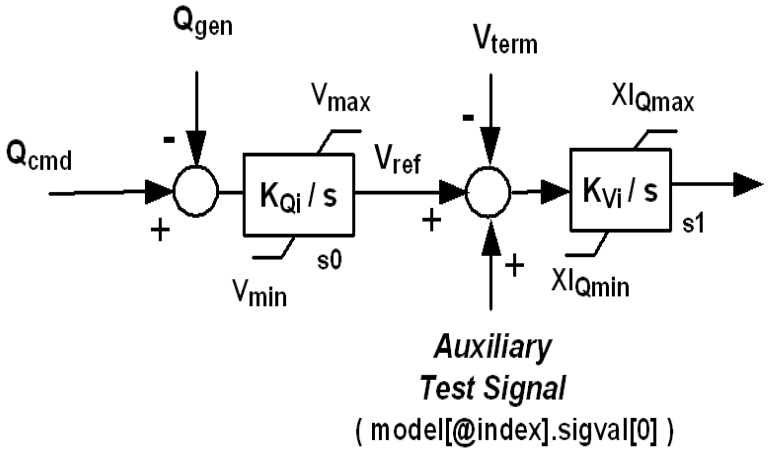


Volt/VAr Control: Hierarchical plant vs. unit AVR

Grid Friendly Wind/Solar Plant-Level Control

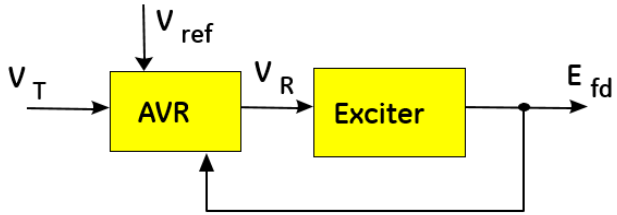


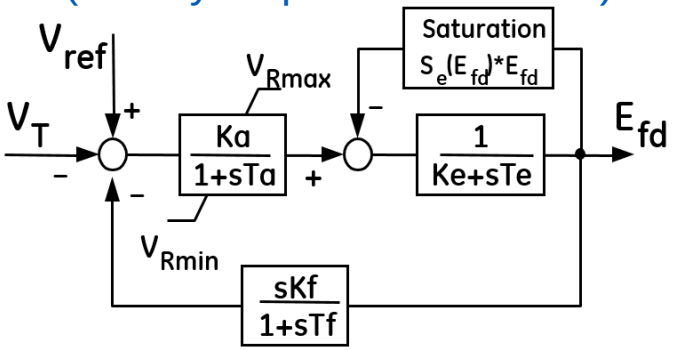
Unit Q Control



Unit Voltage Control

Unit Excitation Control (AVR) of Synchronous Machine (usually no plant POI control)

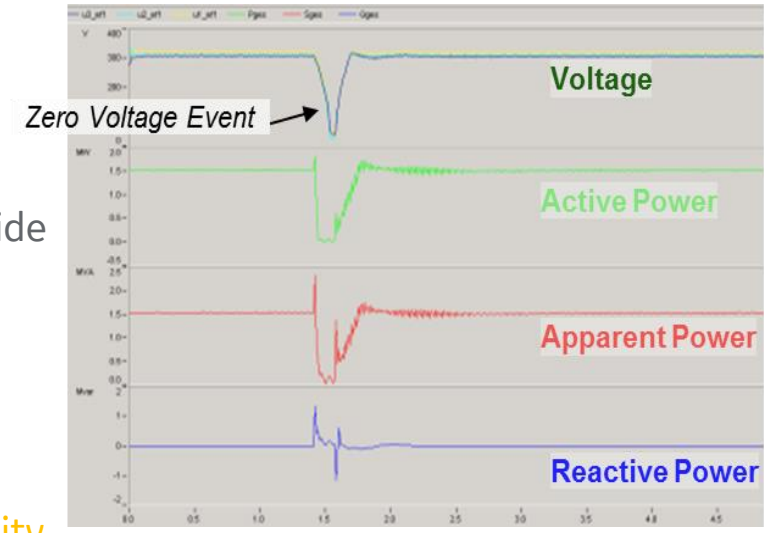


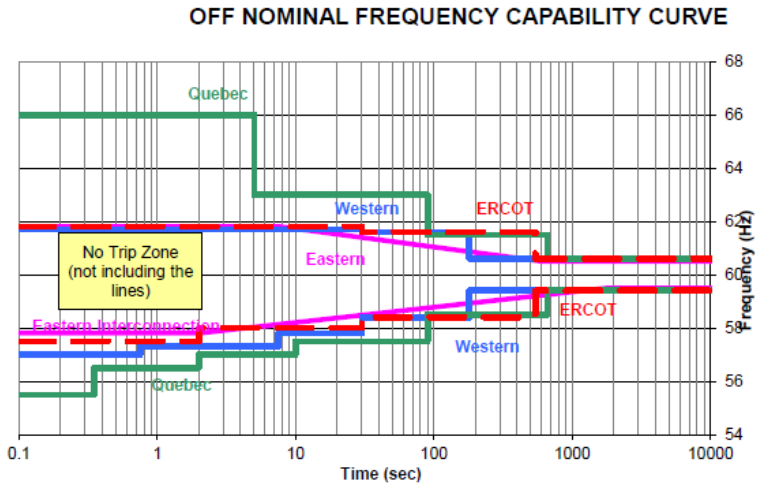


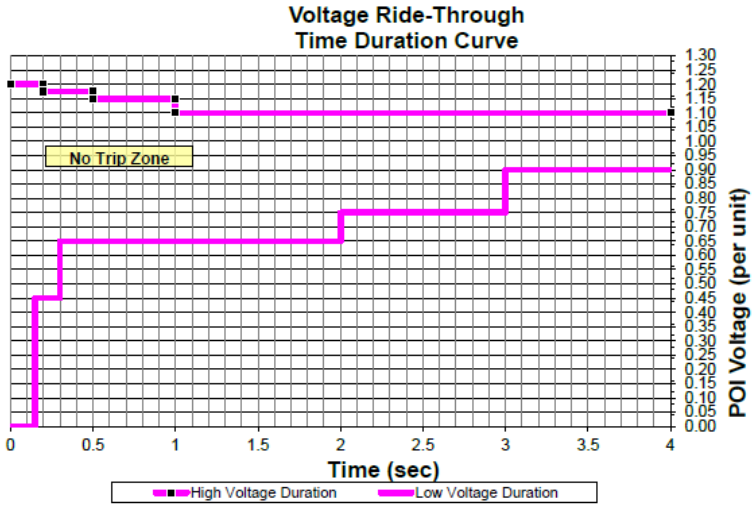
Fault Tolerance and Ride Through

Ride-Through Capabilities

- Remains on-line and feeds reactive power through system disturbances
- All technologies are able to meet present grid requirements with Low/Zero Voltage and Frequency Ride Through (LVRT/ZVRT)
- NA requirement applies to protection settings only
- Transient Stability limits in synchronous machines – Critical Clearing Time
- Auxiliary system and fuel combustion/ delivery capability



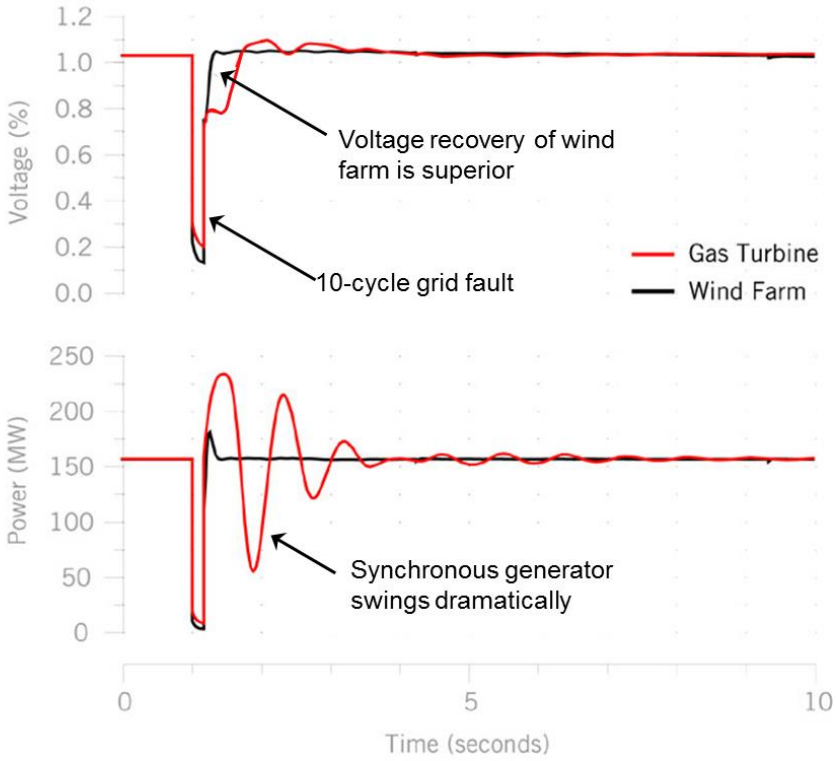




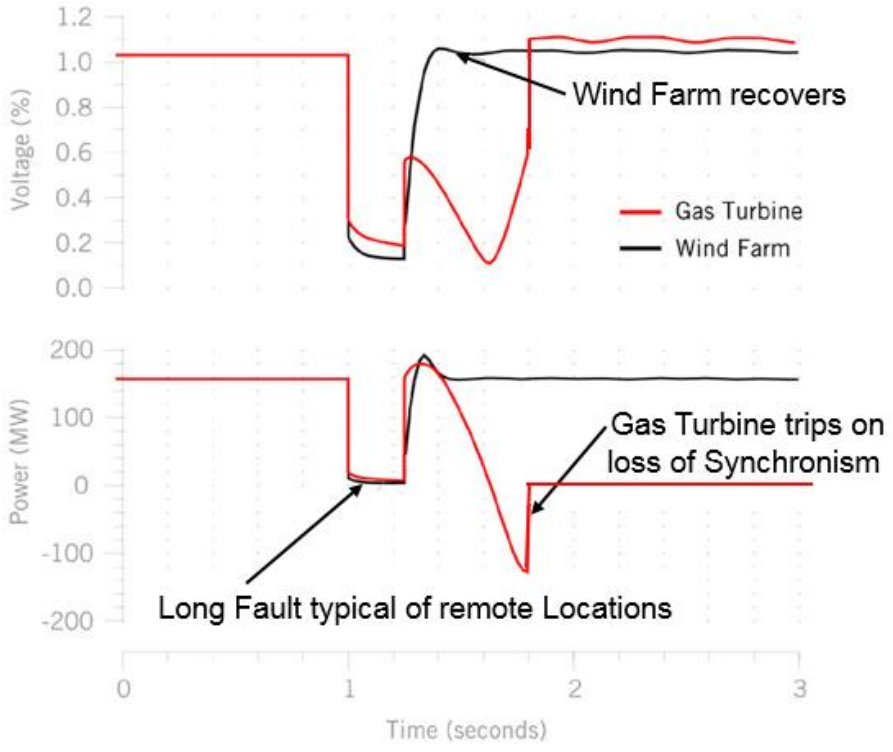
Transient Stability

Transient stability and voltage recovery

Wind/solar/BESS can be more stable than conventional synchronous generators



In fact, Wind/Solar/BESS will survive some disturbances that trip conventional synchronous generators



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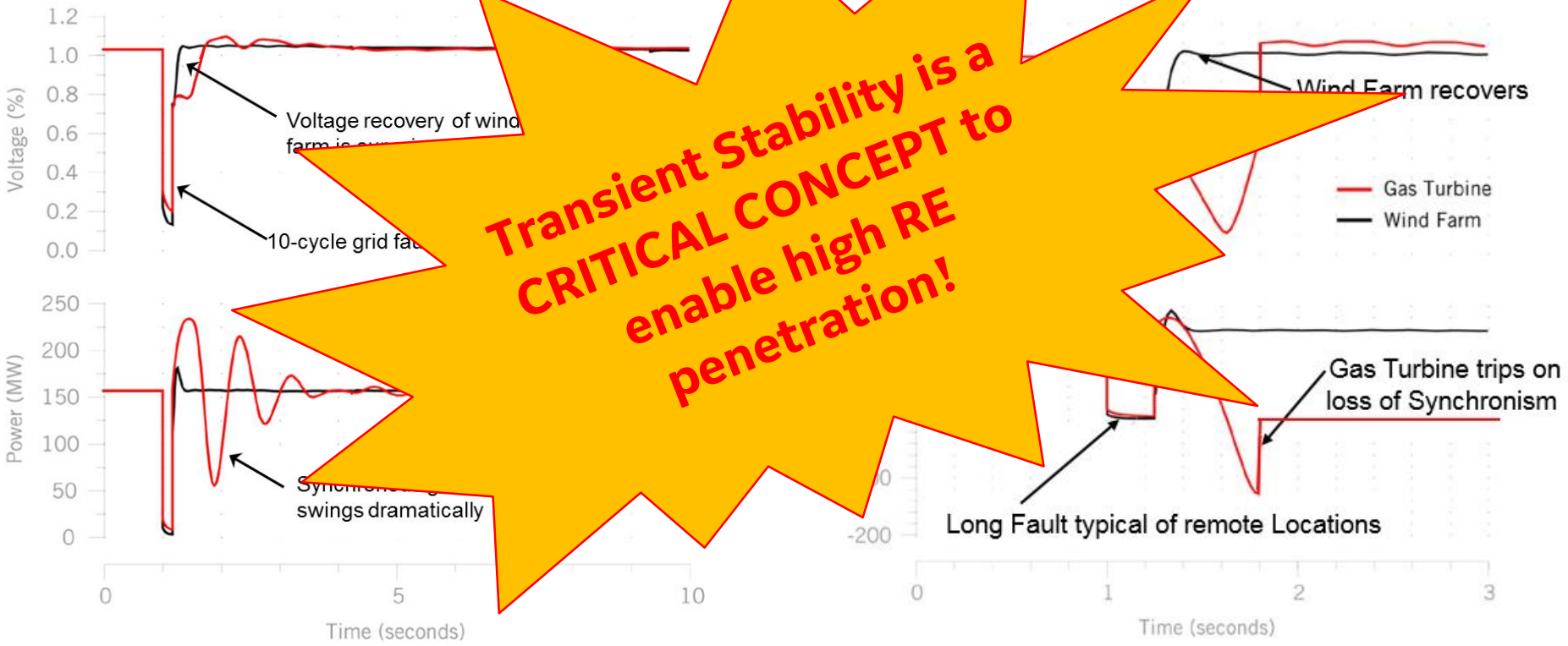
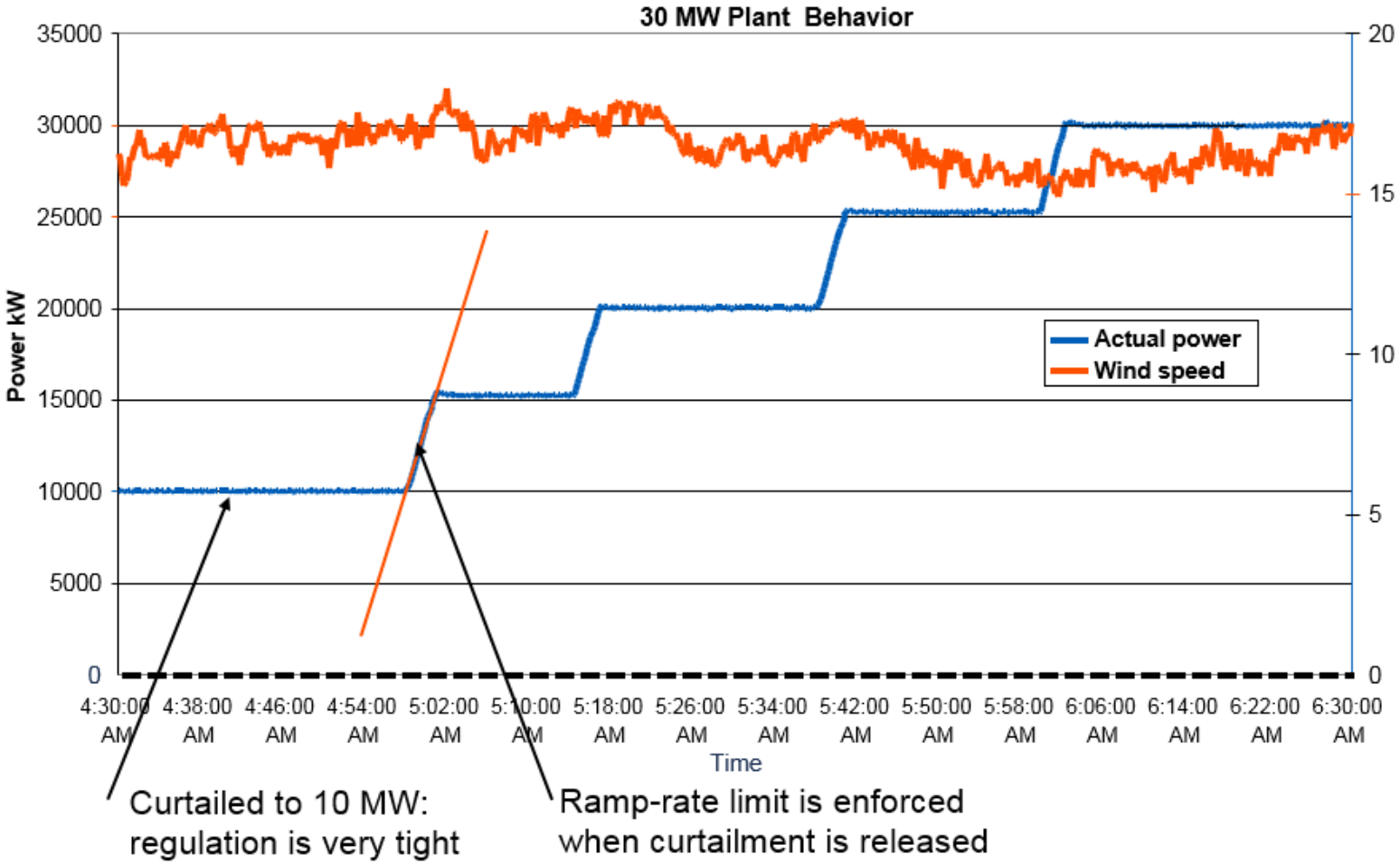


Active Power Control

Curtailment and Ramping (30 MW Wind Plant)



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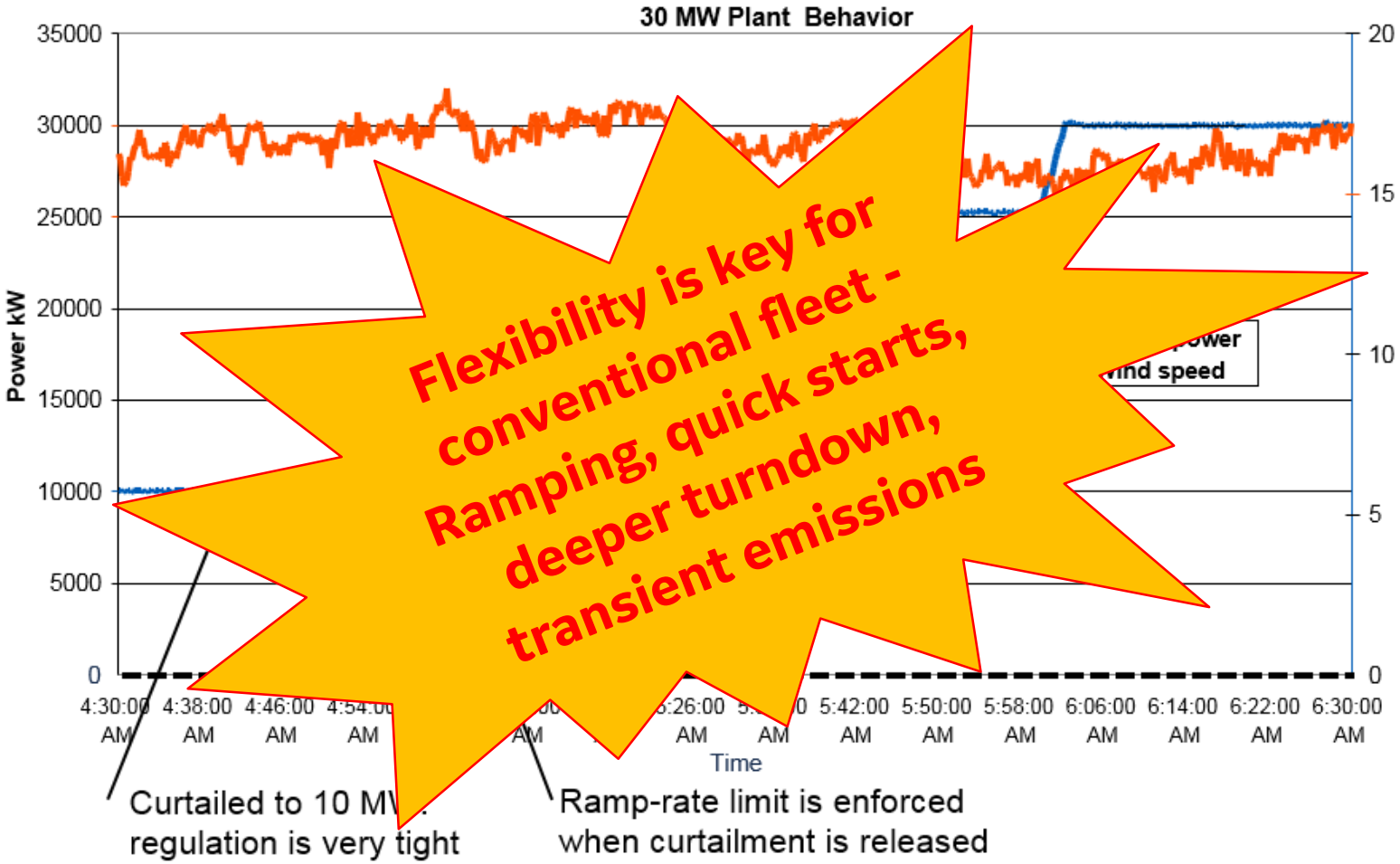
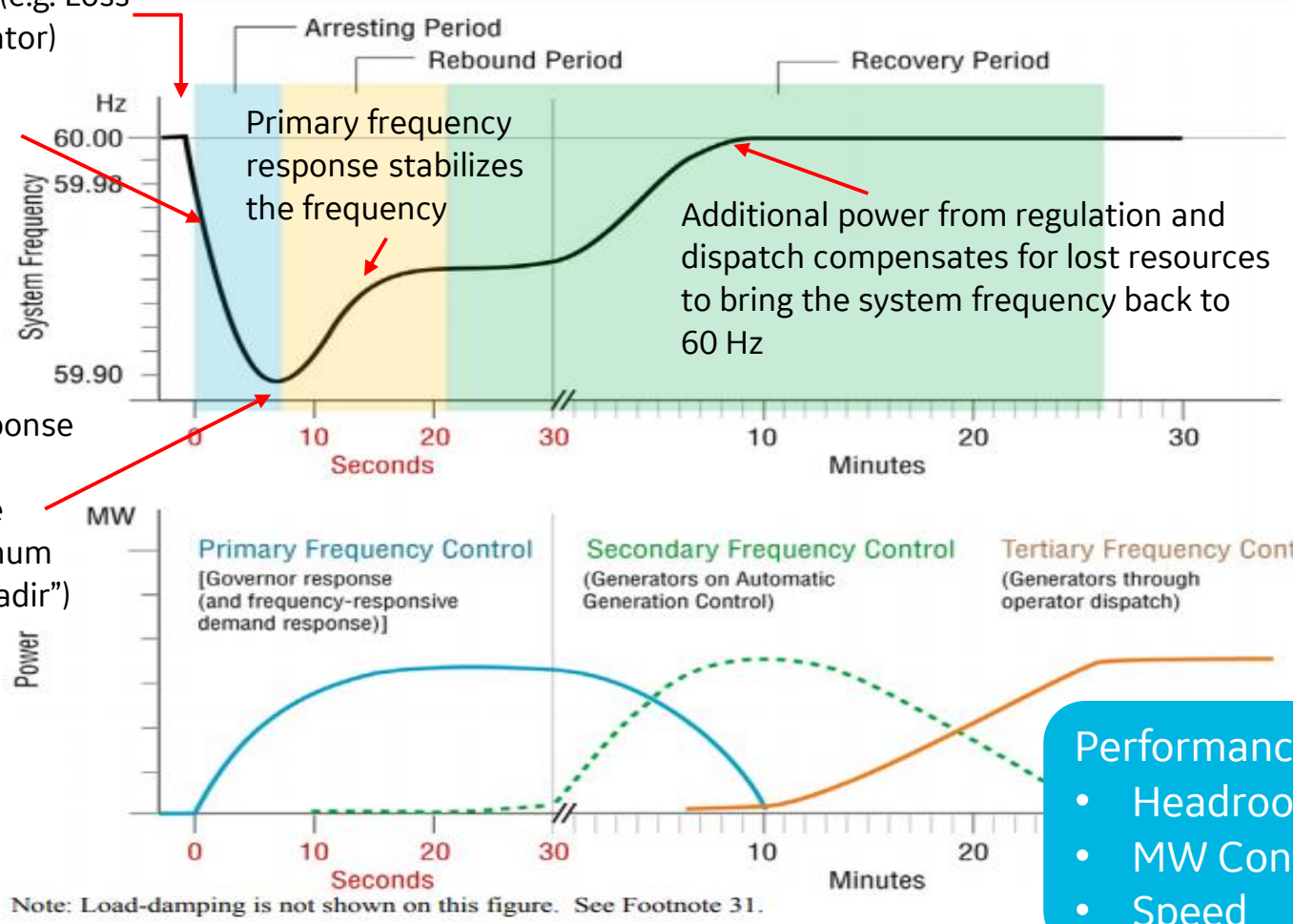


Frequency Response – Physical and Controls

Disturbance – (e.g. Loss of large generator)

Synchronous Inertial Response sets initial slope

Fast frequency response and initial primary frequency response establish the minimum frequency point (“nadir”)



Performance:
- Headroom
- MW Contribution
- Speed

Courtesy J. Eto, J. Undrill, M. O’Malley et al, “Use of Frequency Response Metrics to Assess the Planning and Operating Requirements for Reliable Integration of Variable Renewable Generation”, 2010

Annotations by M. Ahlstrom, Nextera

https://www.ferc.gov/industries/electric/indus-act/reliability/frequencyresponsemetrics-report.pdf

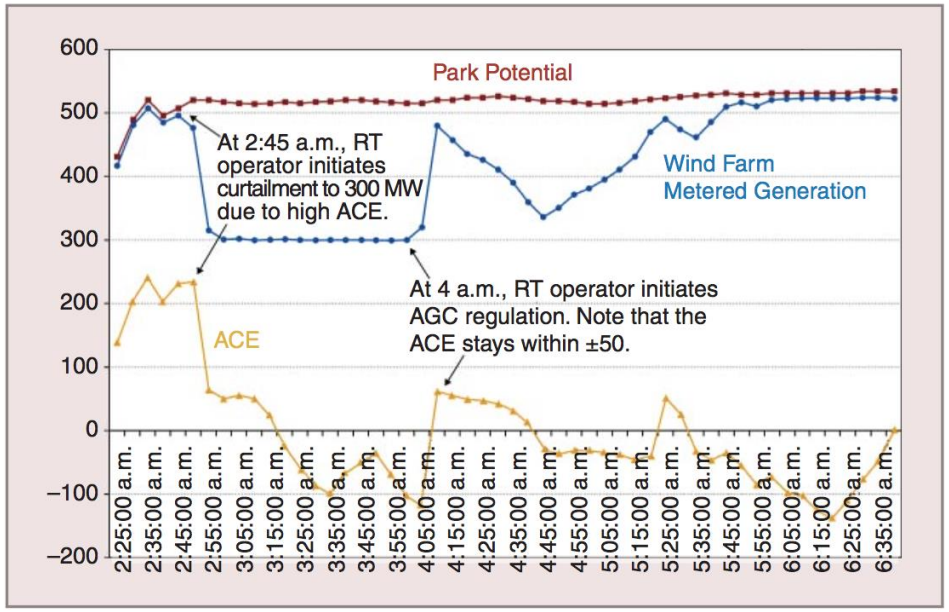
IBRs can provide regulating (secondary) reserves like Thermal plants

Demonstrated, commercially available functionality that is in use today around the world

ISO's in the US typically dispatch wind to set points at 5 minute intervals, using short-term forecasts.

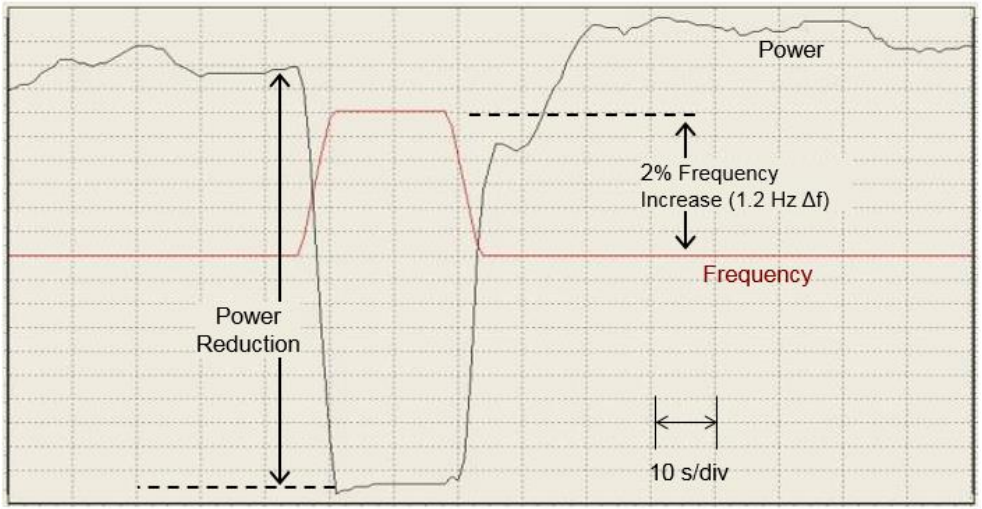
About 6 years ago, Xcel/PSCO went one step further and had wind provide regulating (also called secondary, or AGC) reserve. Wind responds to a 4 second AGC signal that helps maintain frequency.

PSCO now has 1678 MW providing regulating reserve. In 2016, 23% of electricity in PSCO was served by wind.

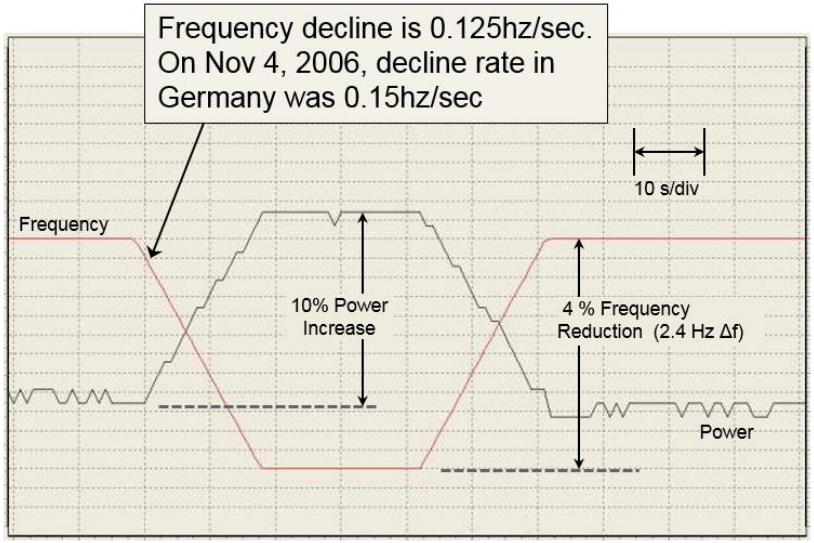


Source: Xcel/PSCO, Feb. 2012

Primary Frequency Response (Droop)



Field Test: Over-Frequency Response



Field Test: Under-Frequency Response

PFR is faster than regulating reserves and directly responds to frequency (like governor response with droop on thermal plants)

IBRs have provided PFR in Texas, Ireland, Canada for >7-8 years

In the US, FERC requires this capability for new (BES connected) generators

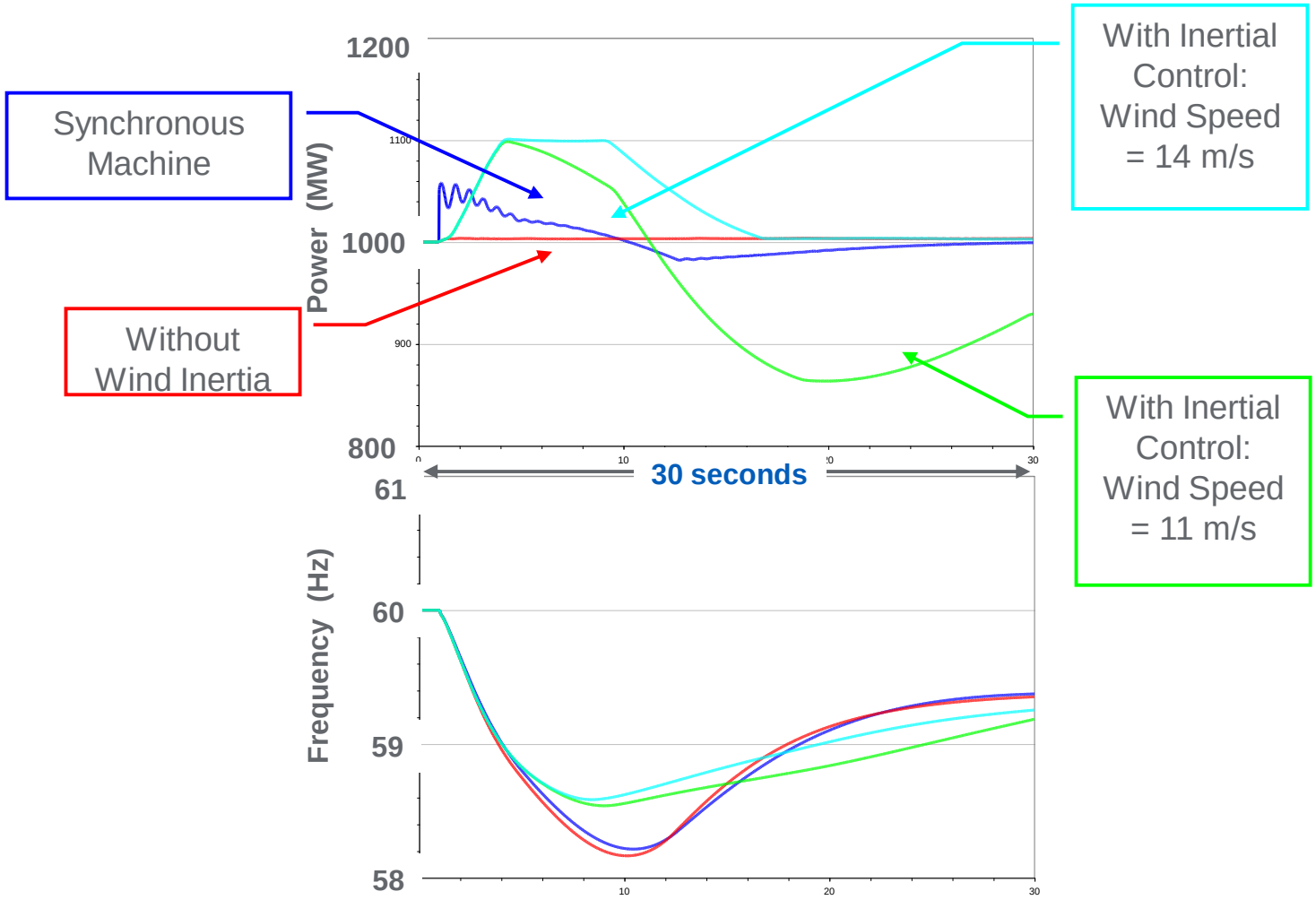
IBRs have the capability to provide PFR in both directions. Under-frequency response requires headroom (pre-curtailment has opportunity cost).

Wind Turbine Fast Frequency Control and Inertia from Synchronous Machines

Fast Frequency Response from Wind

- Use controls to extract stored inertial energy
- Provide incremental energy contribution during the 1st 10 seconds of grid events;
  Allow time for governors and other controls to act
- Target incremental energy similar to that provided by a synchronous turbine-generator with inertia (H constant) of 3.5 pu-sec.
- Focus on functional behavior and grid response:
  do not try to exactly replicate synchronous machine behavior

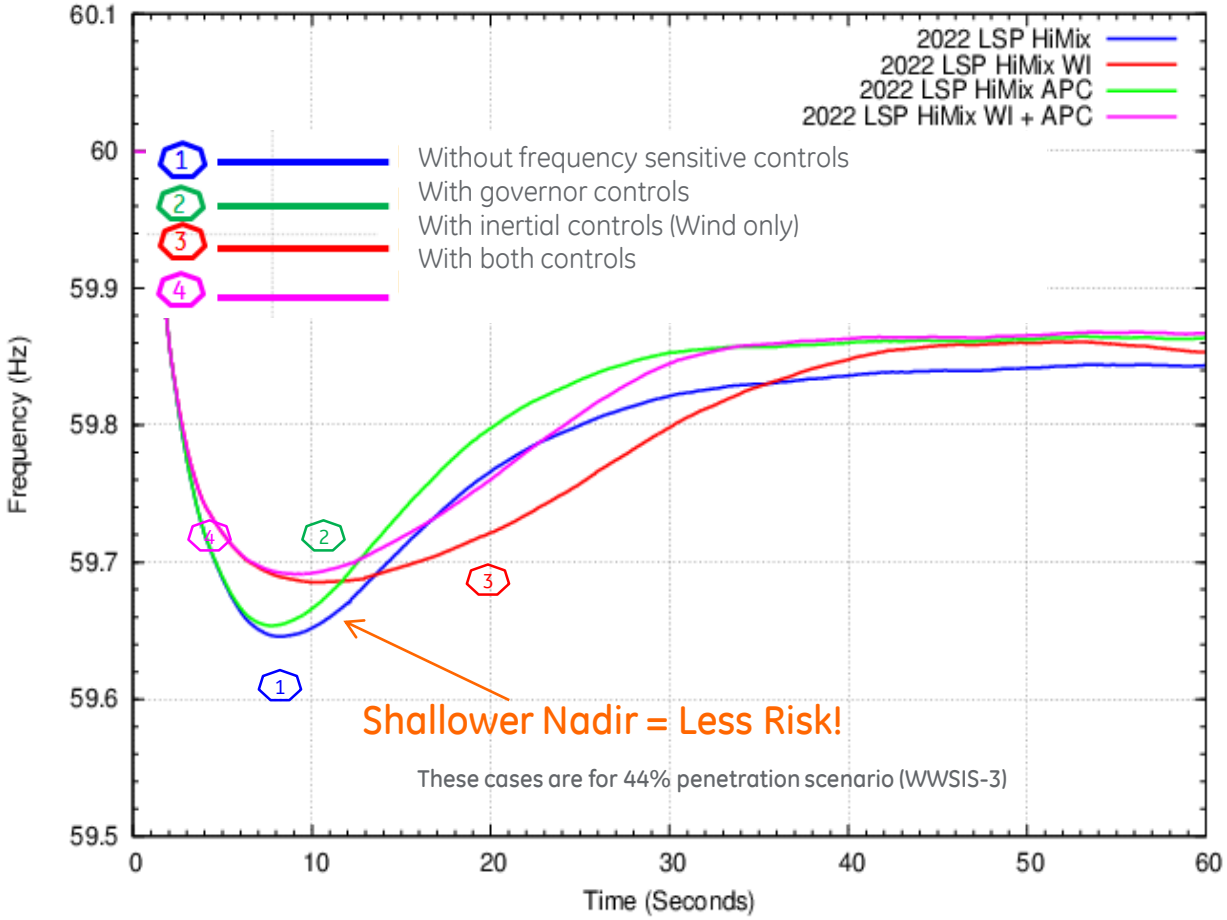
Wind Fast Frequency Response vs. Conventional



System Impact of Frequency Control

The total response of the IBR to the Fast Frequency Response (inertial – wind only) and Primary Frequency Response (governor – wind and solar) control signals is coordinated to respect the physical capabilities of the equipment

- 40% of wind plants (i.e., new ones) had these controls
- 300 MW initial curtailment (out of 27GW production)

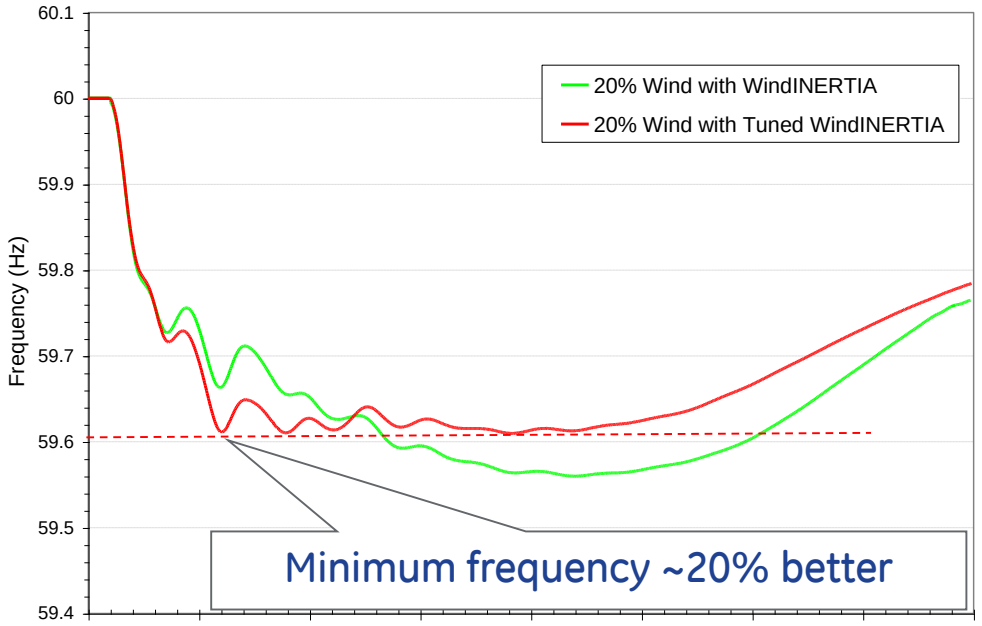


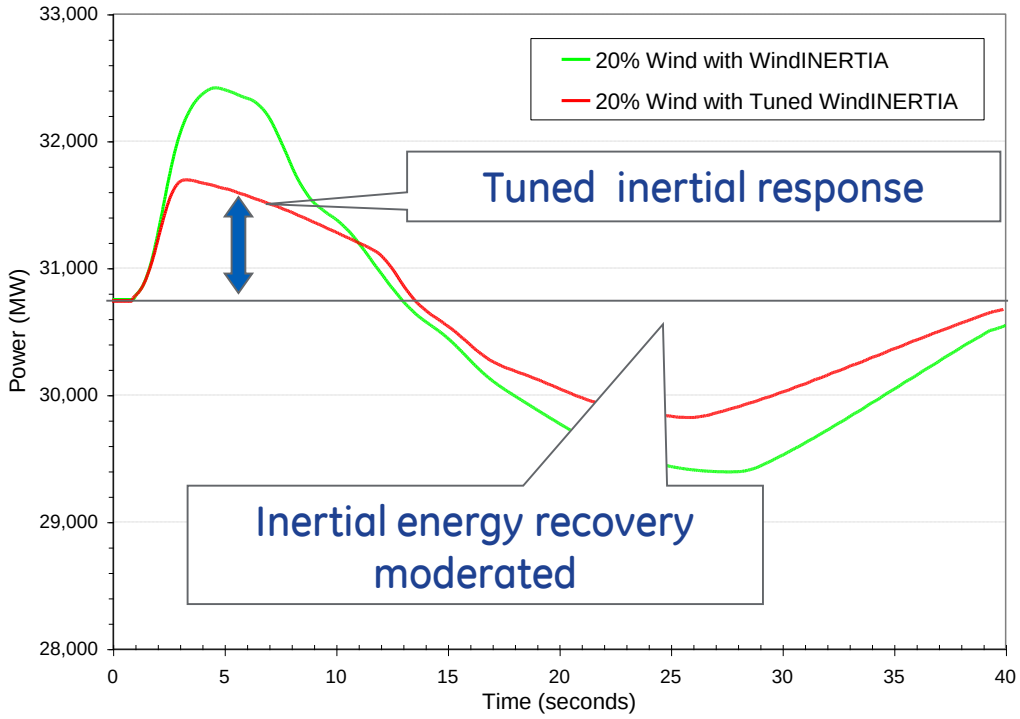
Performance is superior to synchronous machines

Tuning Inertial Response from Wind

From previous WWSIS analysis: tuning inertial response further improves frequency nadir and reduces impact of recovery energy

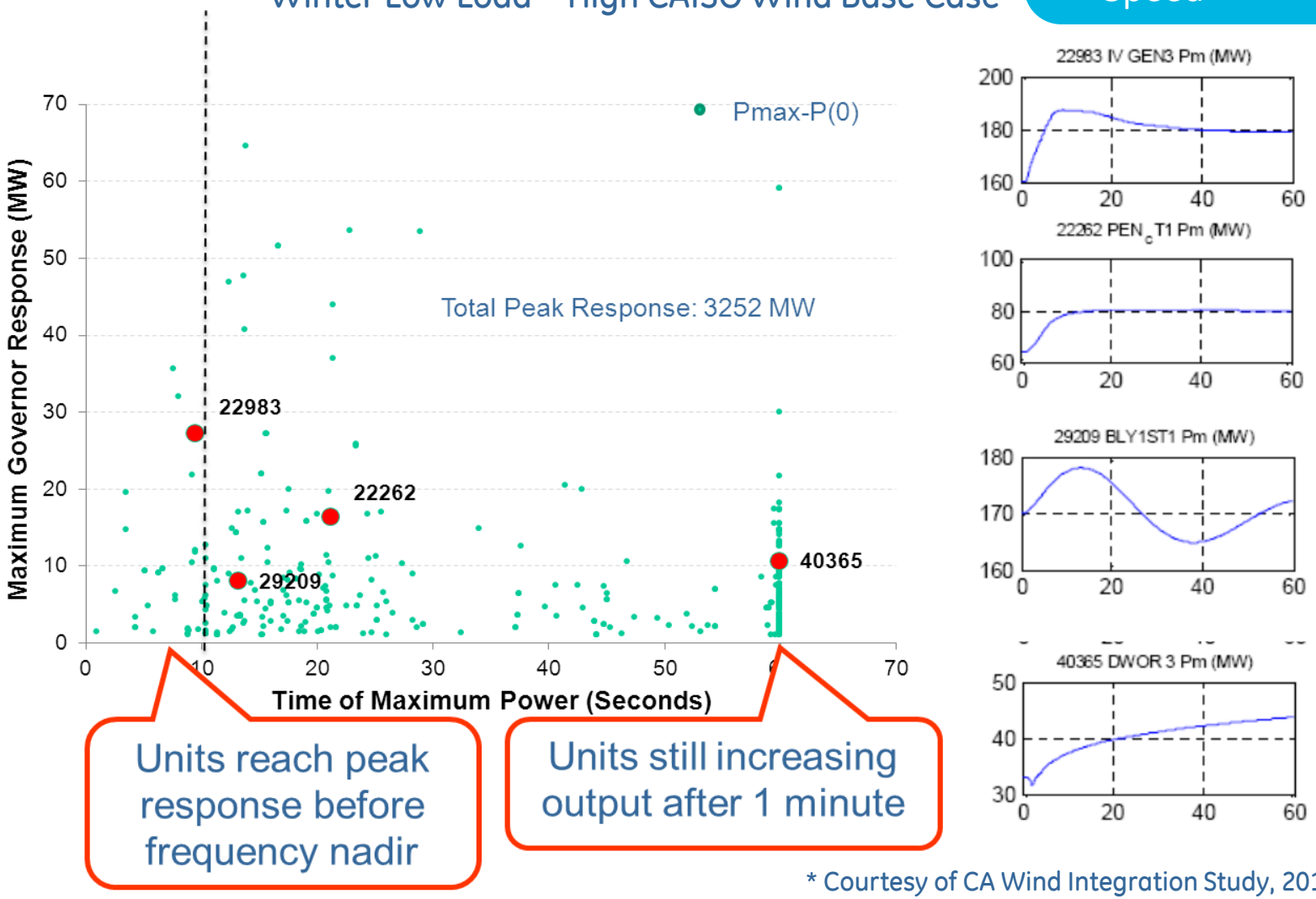
Inertia from synchronous machines is a fixed physical property





Gas/Steam PFR widely varies…

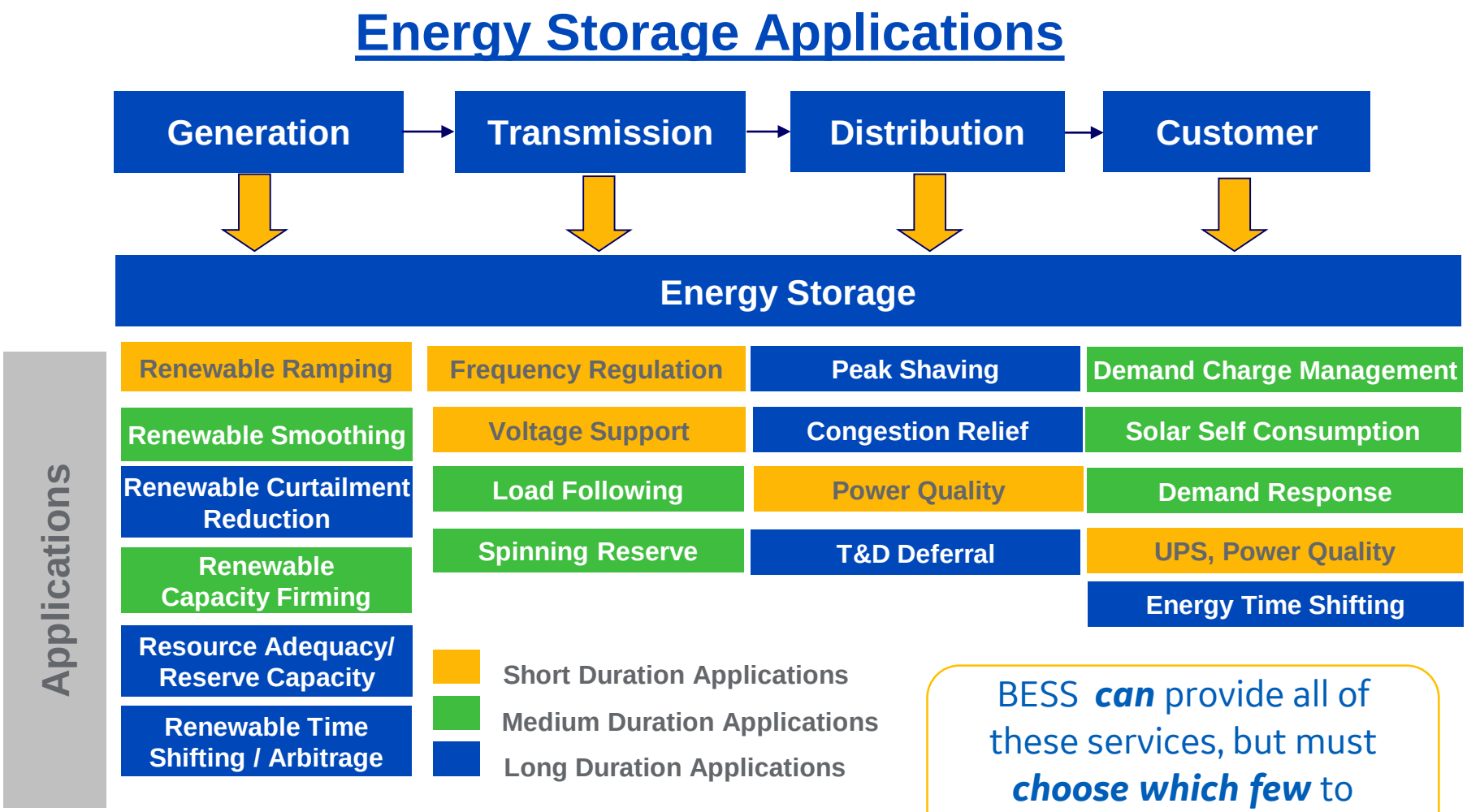
Performance:
- Headroom
- MW Contribution
- Speed



* Courtesy of CA Wind Integration Study, 2012

Battery Storage

ERS of BESS spans multiple disciplines…



BESS ***can*** provide all of these services, but must ***choose which few*** to provide in each application…

* Courtesy Jeff Plew, Nextera Energy Resources

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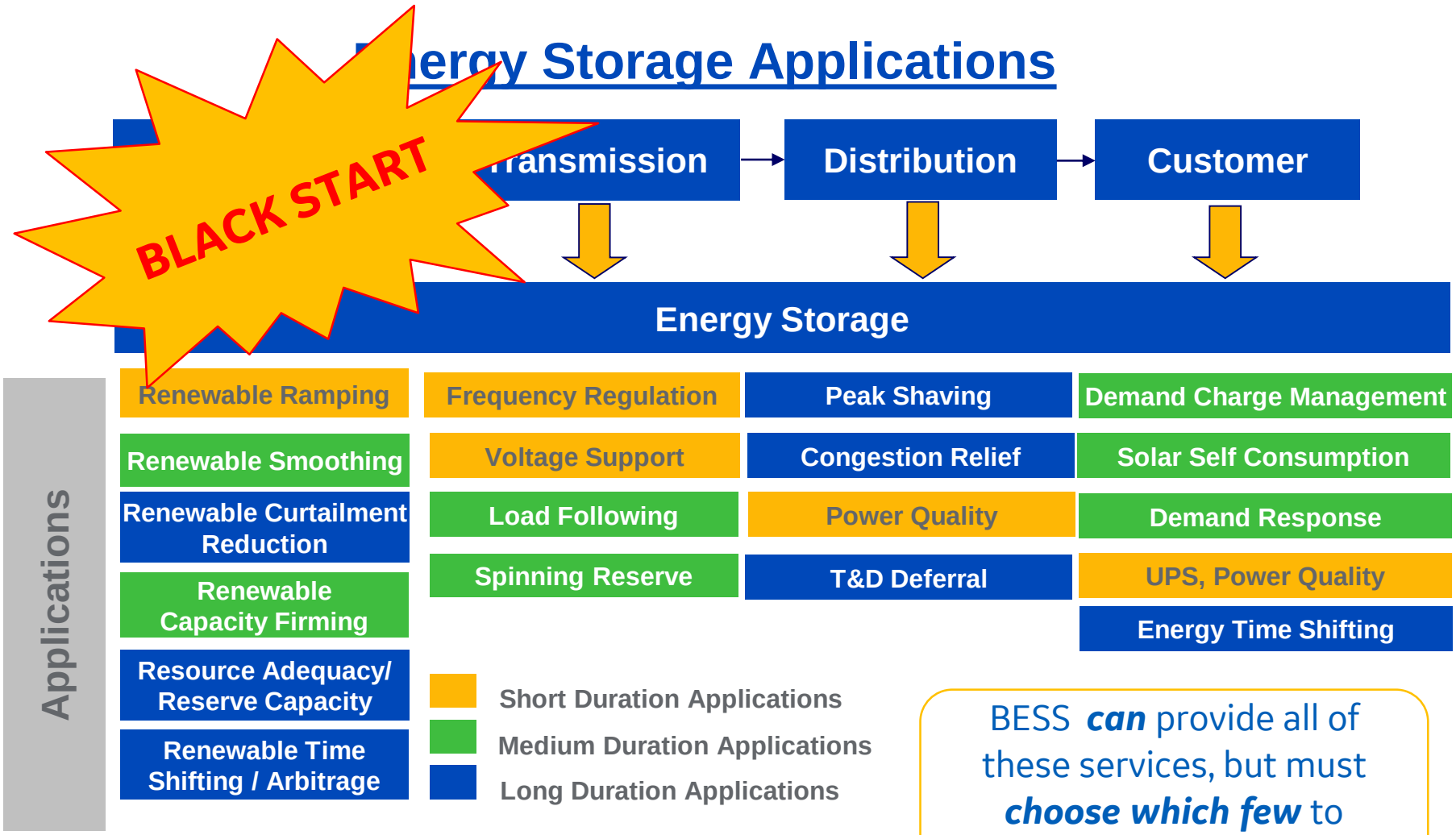

BESS ***can*** provide all of these services, but must ***choose which few*** to provide in each application…

* Courtesy Jeff Plew, Nextera Energy Resources

Summary

- IBRs can stabilize the grid voltage by rapid, smooth bidirectional control of reactive power as well as or better than synchronous machines
- IBRs are capable of contributing to regulation and primary frequency response
- Wind (and in some cases Solar) can provide fast frequency response to support frequency and allow higher penetration of IBR
- Plant-level supervisory controls enable IBR performance that is comparable, and in many respects superior, to that of conventional power plants

Advanced IBR grid-friendly technology is available and widely used today! Incentives (markets) and sound requirements are key to unlocking this capability and achieving higher penetration.


Thank You!
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