Inertia-based Fast Frequency Response from Wind Turbines

Power system balancing and operation with large shares of wind power workshop

EU Marie Curie WinGrid project,

June 18, 2021

Nick Miller

Acknowledgements

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Thanks.

Why? System Needs

In large grids with significant penetration of wind (and solar PV) power:

- Modern variable speed wind turbine-generators do not contribute to system inertia
- System inertia declines as wind generation displaces synchronous generators (which are de-committed)
- Result is deeper, faster frequency excursions for system disturbances
- Increased risk of under-frequency load shedding (UFLS) and cascading outages

Source: GE Energy Consulting

Why this Language (and not synthetic inertia)?

A little history….

- The preceding slide was used in 2009, for initial marketing of this concept.
- Many of us thought "*We'll use the turbine's inertia to help counteract the decline in synchronous inertia*"
- We "can use control to '*synthesize*' inertia, through the power electronics".
- "*Synthetic Inertia*" seems like a good name.
- BUT, as you will see the name is a bit misleading, and has caused some problems in understanding.

More …..

Source: GE Energy Consulting

Wind Plant Frequency Responsive Controls

Inertial control responds to frequency drops only in 0.5-10 second time frame:

- Uses inertial energy from rotating wind turbine to supply power to system
- Requires energy recovery from system to return wind turbines to nominal speed
- Is more responsive at higher wind speeds

In the language of NERC Essential Reliability Services:*

This is Fast Frequency Response, NOT System Inertial Response.

Governor control responds:

- To both frequency drops and increases
- In 5-60 second time frame
- Requires curtailment to be able to increase power

In the language of NERC Essential Reliability Services:

This is either Fast Frequency Response, or Primary Frequency Response (depending on aggressiveness of the control)

So, for this lecture we adopt the name
“Inertia-based Fast Frequency Control (IBFFR)

* NERC Frequency Response Initiative Report Oct 2012

Control Concept

- Use controls to extract stored inertial energy
- Provide incremental arresting energy 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*

Have the best impact on frequency nadir for the available power and energy

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** Been saying this for years… more relevant than ever! More to follow*

Source: GE Energy Consulting

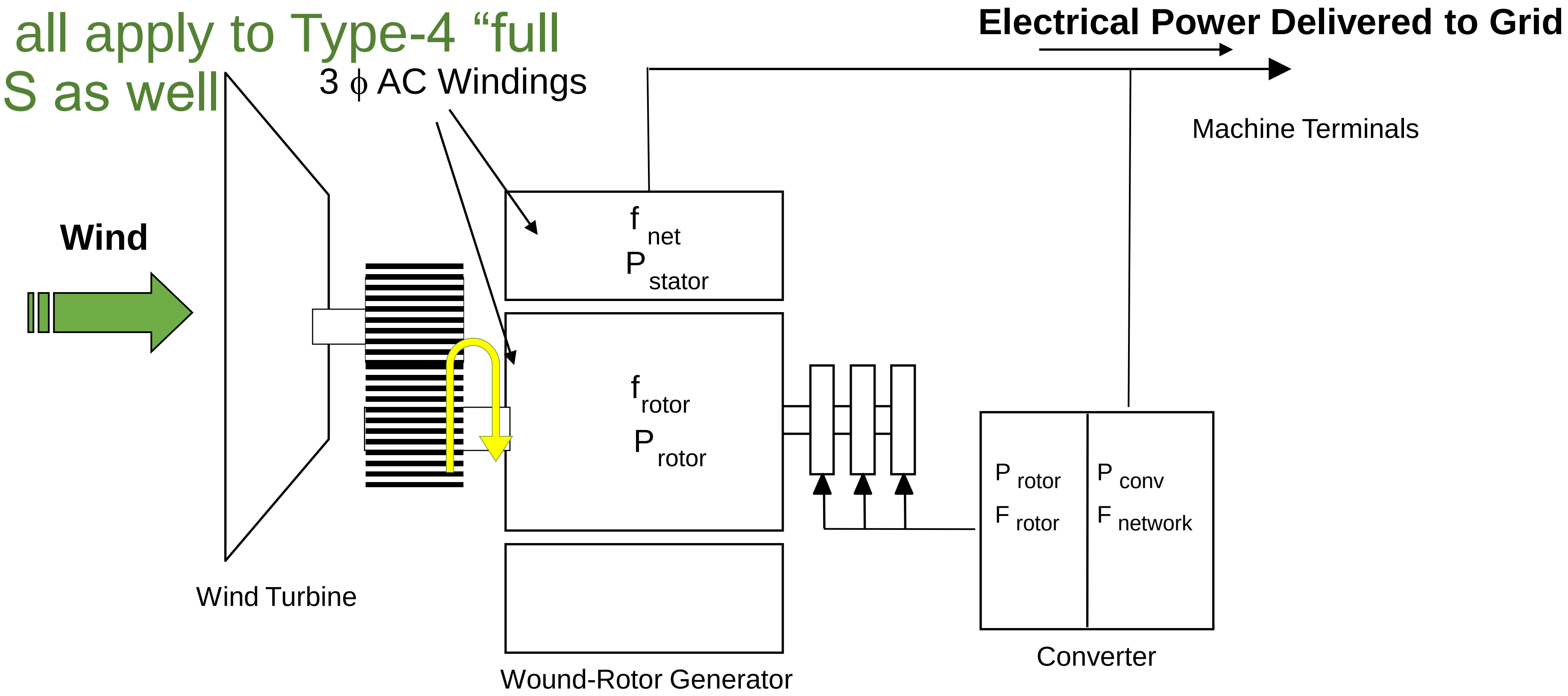
Constraints

- Not possible to increase wind speed
  - Slowing wind turbine reduces aerodynamic lift:
  - Must avoid stall
- Must respect WTG component ratings:
  - Mechanical loading
  - Converter and generator electrical ratings
- Must respect other controls:
  - Turbulence management
  - Drive-train and tower loads management

Source: GE Energy Consulting

How does it work?

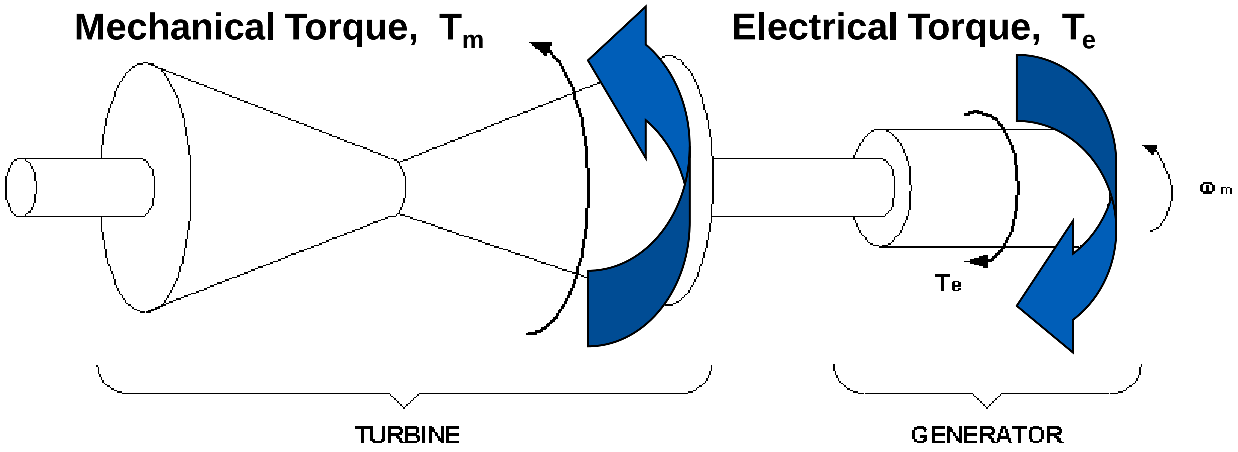
- Basic components of a Double-fed Wind Turbine Generator:
- These concepts all apply to Type-4 “full converter” WTGS as well



Source: GE Energy Consulting

How does it work? (part 2)

- Basic machine equations for all rotating machines



$$J\frac{d\omega}{dt} = T_a = T_m - T_e$$

$$H \equiv \frac{1}{2}\frac{J\,\omega_{mo}^{2}}{VA_{base}}$$

$$H = \frac{Kinetic\ Energy\ Stored\ in\ the\ Rotor\ (\mathrm{Watt\text{-}sec})}{VA_{base}}$$

Basic Notation:

J is the inertia of the entire drive-train in physical units

H is the inertia constant – it is scaled to the size of the machine.

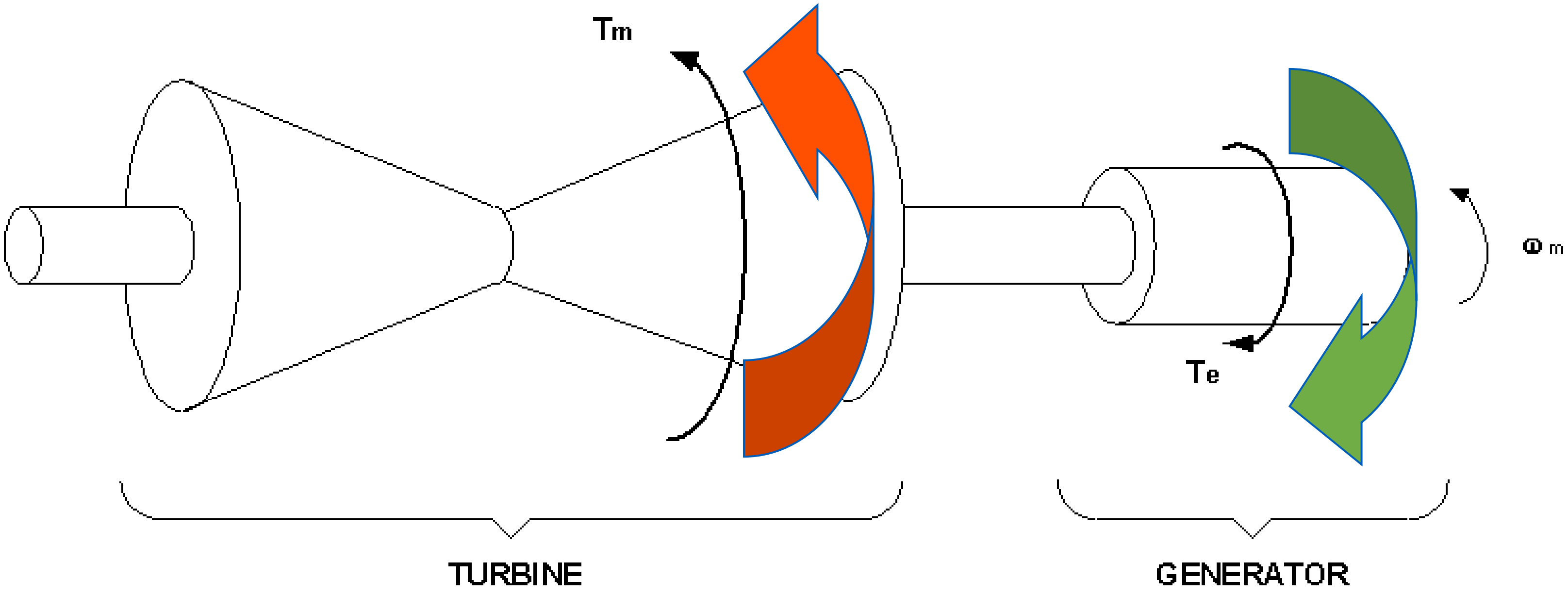
- A typical synchronous turbine-generator has an H of about 3.5 MW-sec/MW.

How does it work? (part 3)

Mechanical Torque, T_m

Electrical Torque, T_e

- In steady-state, torques must be balanced
- When electrical torqu
  greater than mechanic
  torque,
  the rotation slows,
  extracting stored inerti
  energy from the rotati
  mass



Source: GE Energy Consulting

With wind, what's different from synchronous machines?

	Synchronous Generator	Wind Turbine*
Mechanical Power	Governor Response / Fuel Flow Control	Pitch Control / Uncontrolled Wind Speed
Electrical Power	Machine Angle (d-q Axis) / Passive	Converter Control / Active
Inertial Response	Inherent / Uncontrolled	By Control Action

For a wind turbine:

Mechanical Torque is a function of:

(1) Wind Speed
(2) Blade Pitch
(3) Blade Speed (ά Rotor Speed)

Electrical Torque is a function of:

(1) Converter Control
(2) Commands from Turbine Control

* Variable speed, pitch controlled WTGs

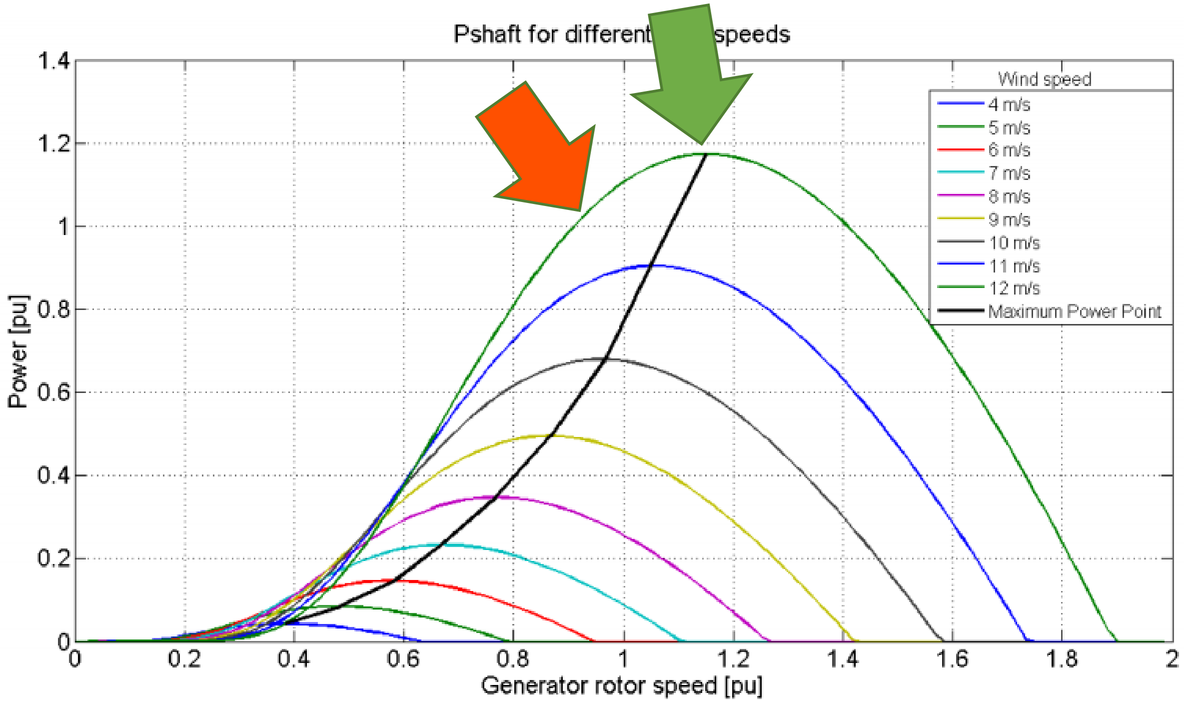
Source: GE Energy Consulting

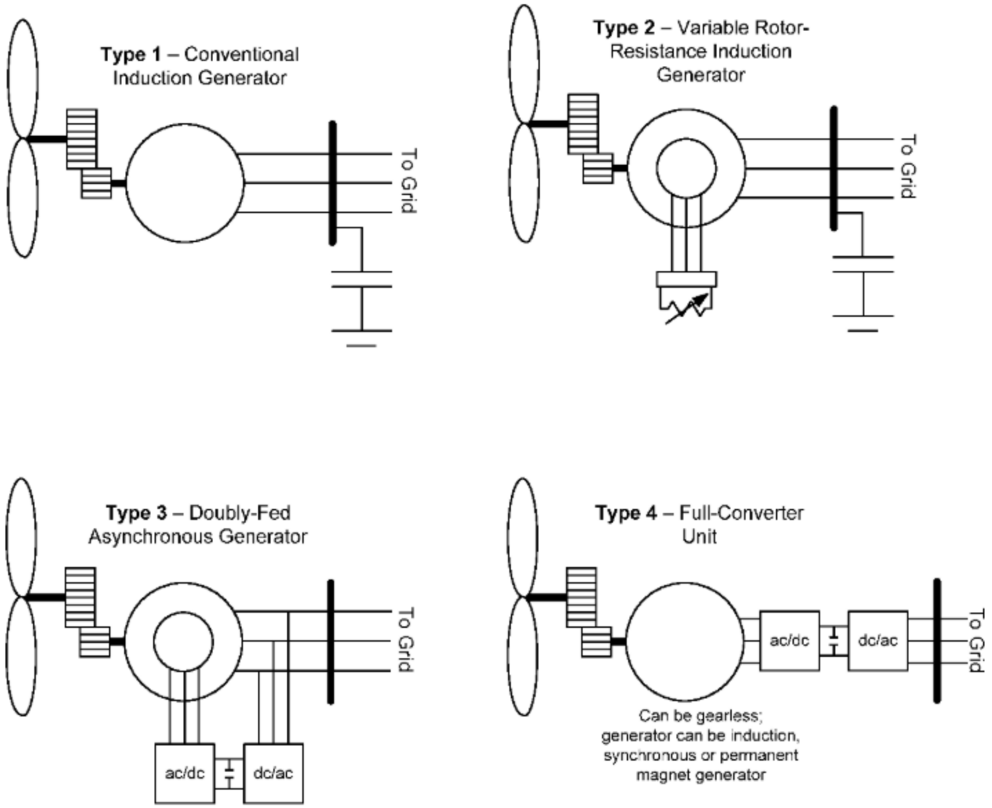
What happens during a grid event?

1. Disturbance (e.g., generator trip) initiates grid frequency decline
2. IBFFR control detects significant frequency drop
3. Instructs WTG controls to increase electrical power
4. Additional electric power delivered to the grid
5. Rate and depth of grid frequency excursion improves
6. WTG slows as energy extracted from inertia; lift drops
7. Other grid controls, especially governors, engage to restore grid frequency towards nominal
8. IBFFR control releases increased power instruction
9. WTG electric power drops, to allow recovery of rotational inertial energy and energy lost to temporarily reduced lift
10. Transient event ends with grid restored

Source: GE Energy Consulting

Wind Turbines are variable speed: slowing down causes a loss of mechanical torque





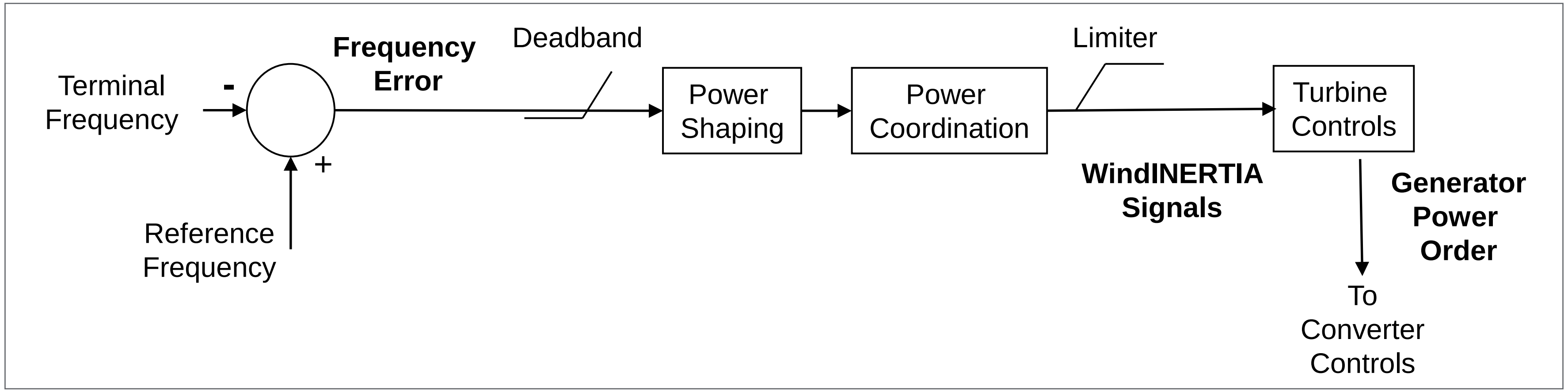
- So what? If you slow down by increasing electrical power, you also lose mechanical power, and need to make it up later. Backlash

Source: Aalborg University, Institute of Energy Technology

Source: WECC

Back to IBFFR:

Control Overview . . one (GE's) approach



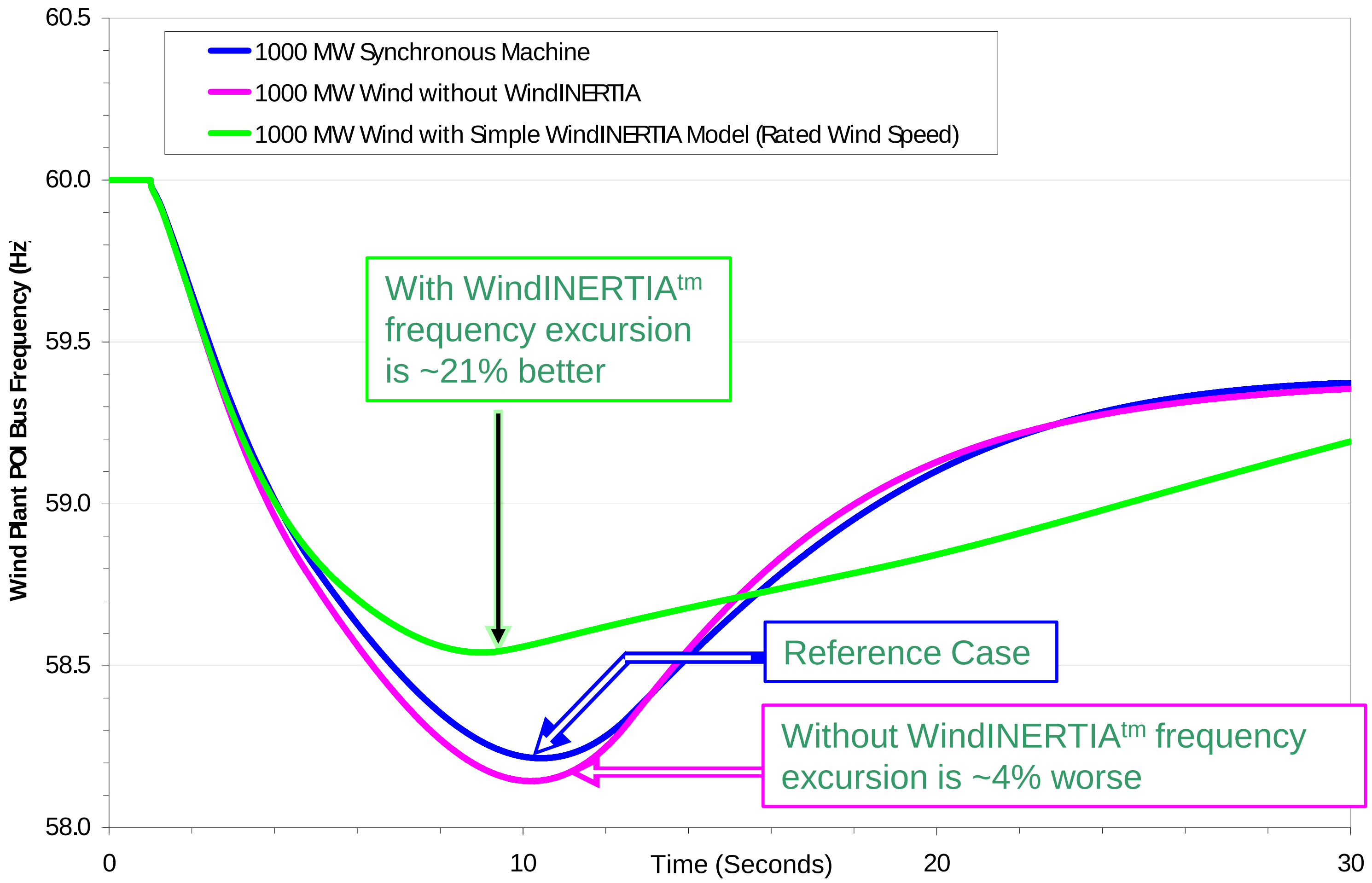
- Advantage of this approach (tradename: WindINERTIA^{tm}): it is highly flexible, allows customization to benefit of the host grid.
- But other control approaches are possible, and are being developed.
- We will look at them in a minute.

HickoryLedge

Source: GE Energy Consulting

Example:

14GW, mostly hydro system, for trip of a large generator



With WindINERTIA^{tm} frequency excursion is ~21% better

Reference Case

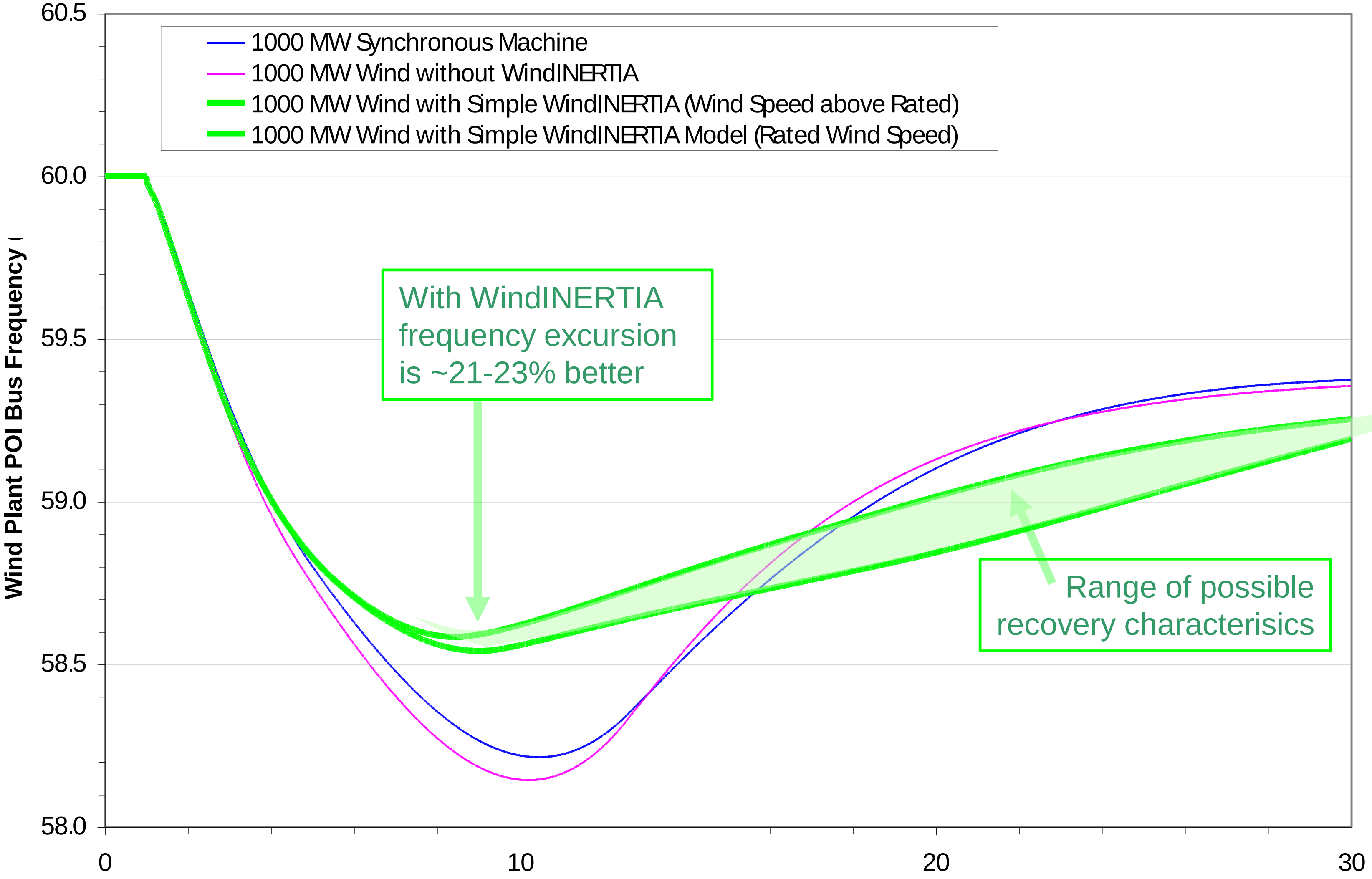
Without WindINERTIA^{tm} frequency excursion is ~4% worse

Minimum frequency is the critical performance concern for reliability

Source: GE Energy Consulting

Example: (cont.)

Performance is a function of wind and other conditions: not perfectly deterministic like synchronous machine inertial response



With WindINERTIA frequency excursion is ~21-23% better

Range of possible recovery characterisics

Nicholas Miller

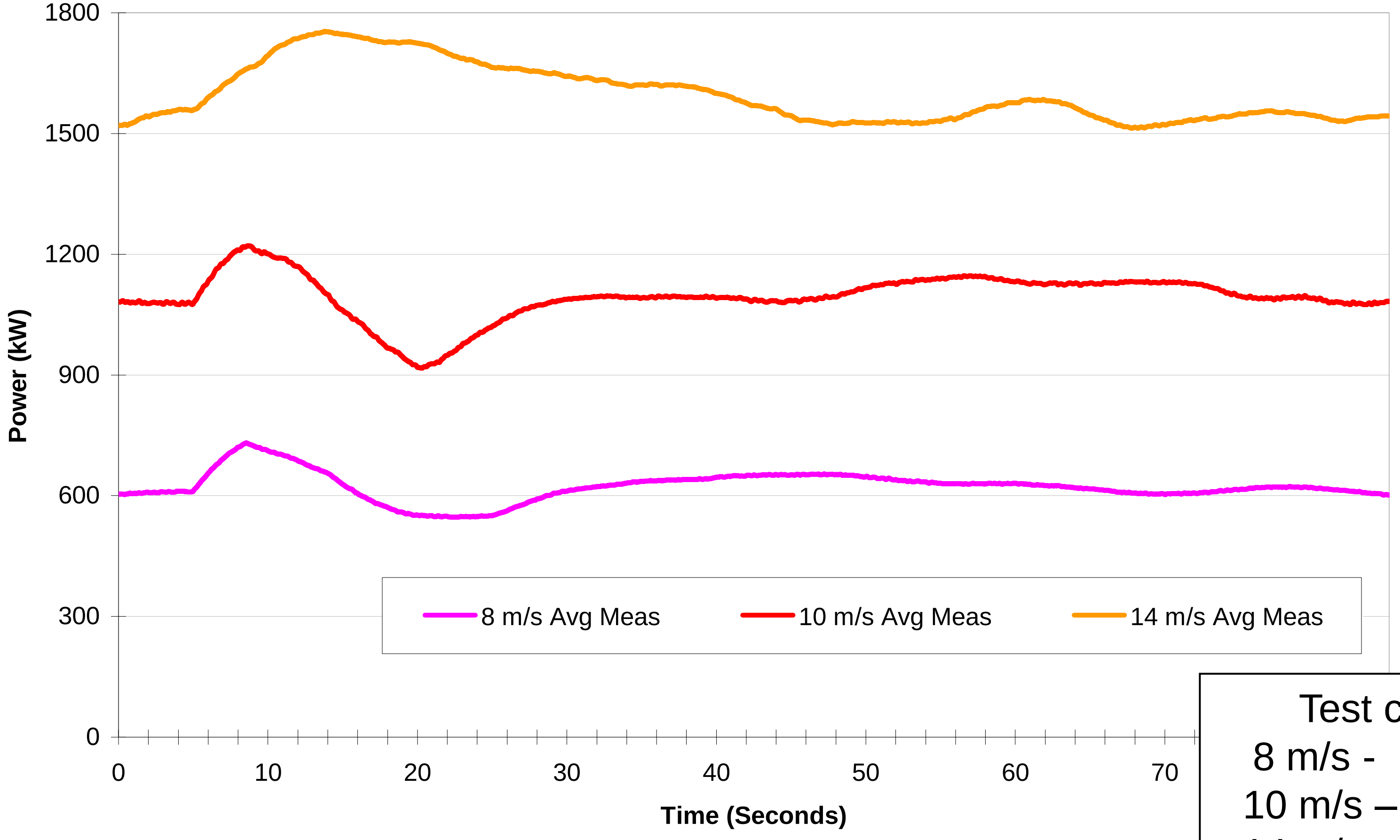
Source: GE Energy Consulting

Field Tests: Approach and Constraints

- Not possible to drive grid frequency
  - Controls driven with an external frequency signal
  - (very similar to frequency of previous example)
- Performance a function of wind speed
  - (also, not possible to hold wind speed constant during tests)
- Since WTG must respect other controls
  - Turbulence & drivetrain and tower loads management affect performance of individual WTGs at any particular instant
- Exact performance of single WTG for a single test is not too meaningful
- Aggregate behavior of interest to grid

Source: GE Renewables

GE WindINERTIA^{tm} Field Tests Results



Test count:
8 m/s - 19 tests
10 m/s – 19 tests
14 m/s – 52 tests

Source: GE Renewables c2008

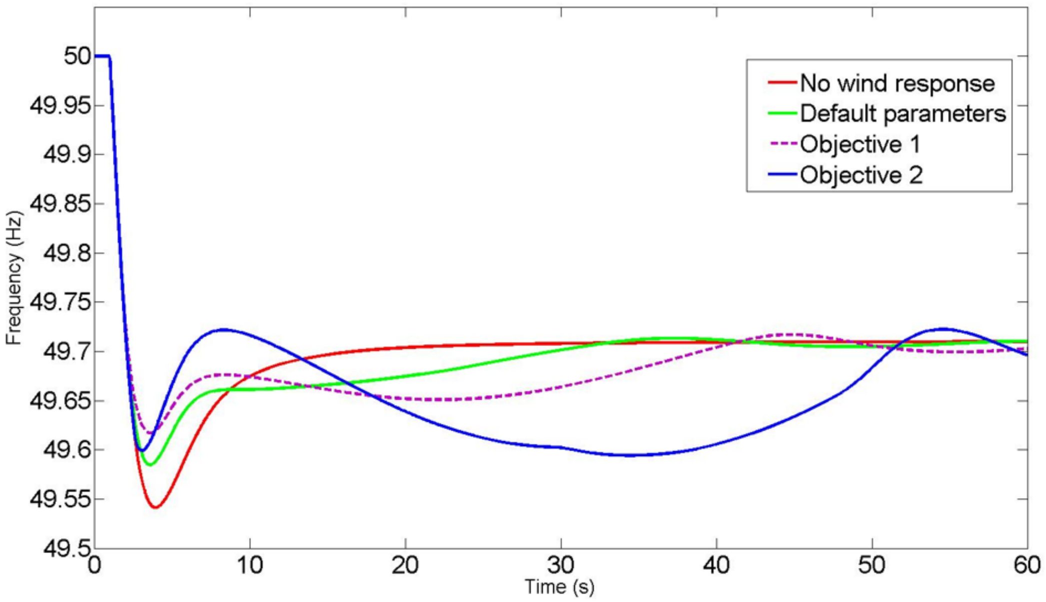
Recovery, Backswing and Double Dips

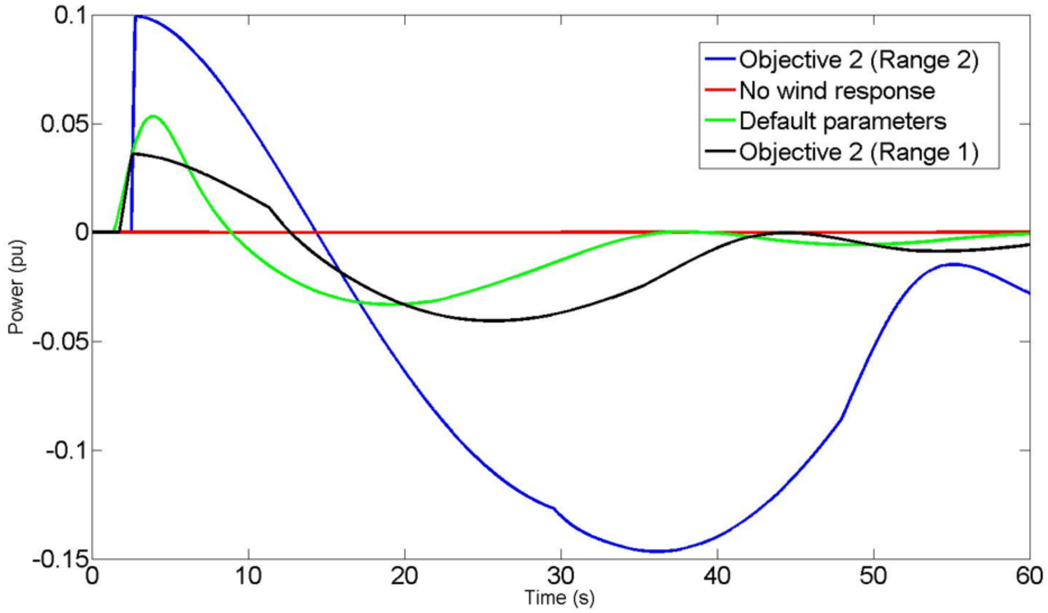
IBFFR controls are tune-able

Synchronous Inertia is NOT

- There are trade-offs in performance
- Not all settings are good for each application
- Faster isn't necessarily better
- Beware of recovery backswing

Don't ask me:
"How does 'IT' behave?"



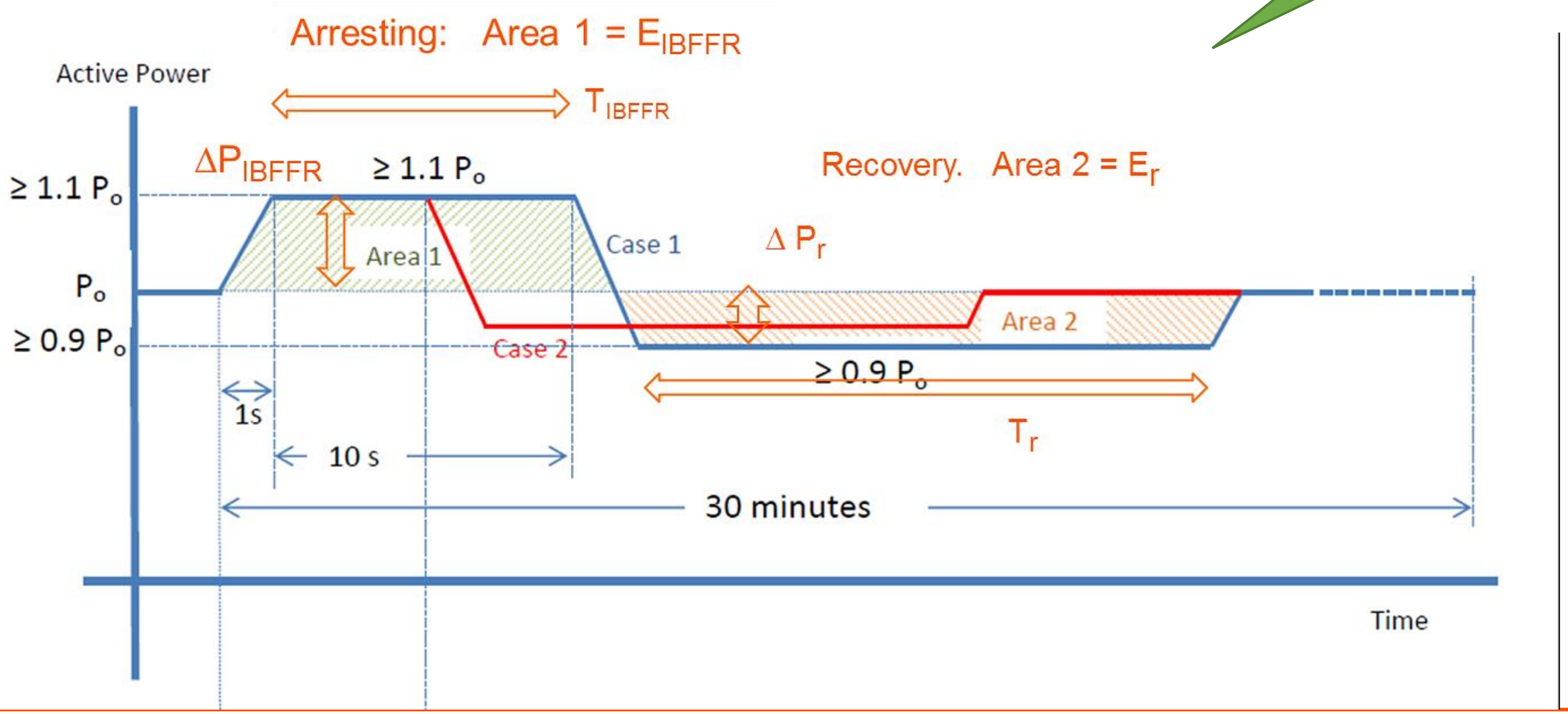


Source: Damian Flynn, Lisa Ruttledge UCD

An emerging Grid Code - example

This is an IESO (Ontario) figure, with some additional parameters added.

Let's make some rules that the are enforceable… "help the grid isn't good enough"

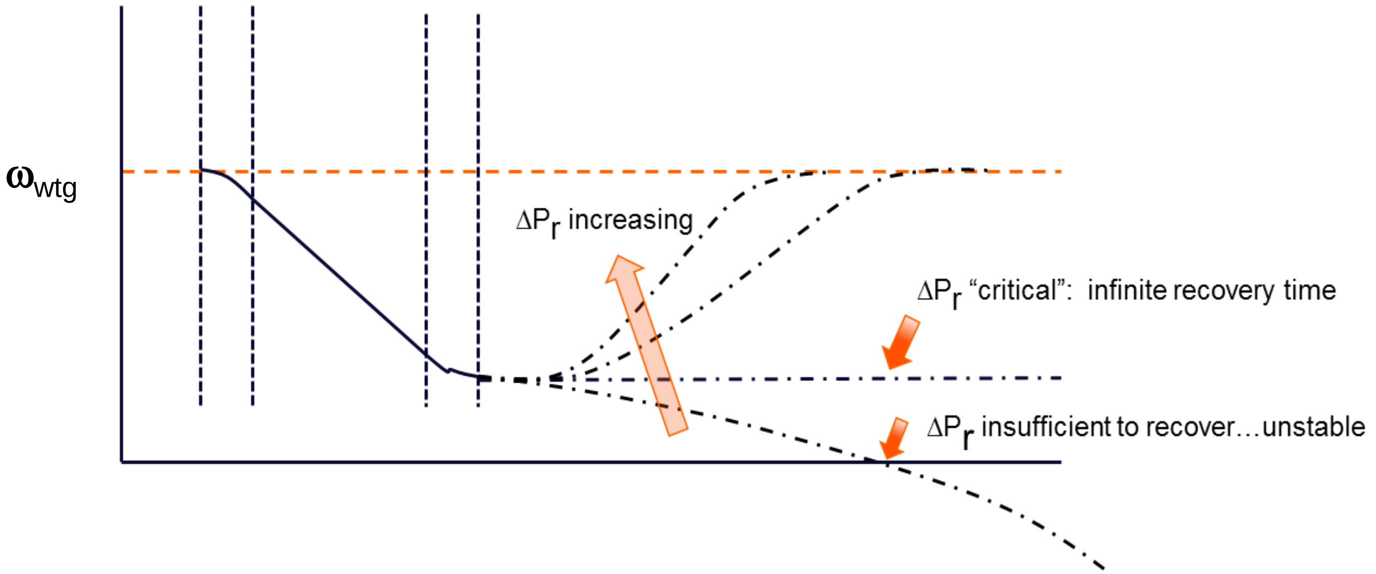


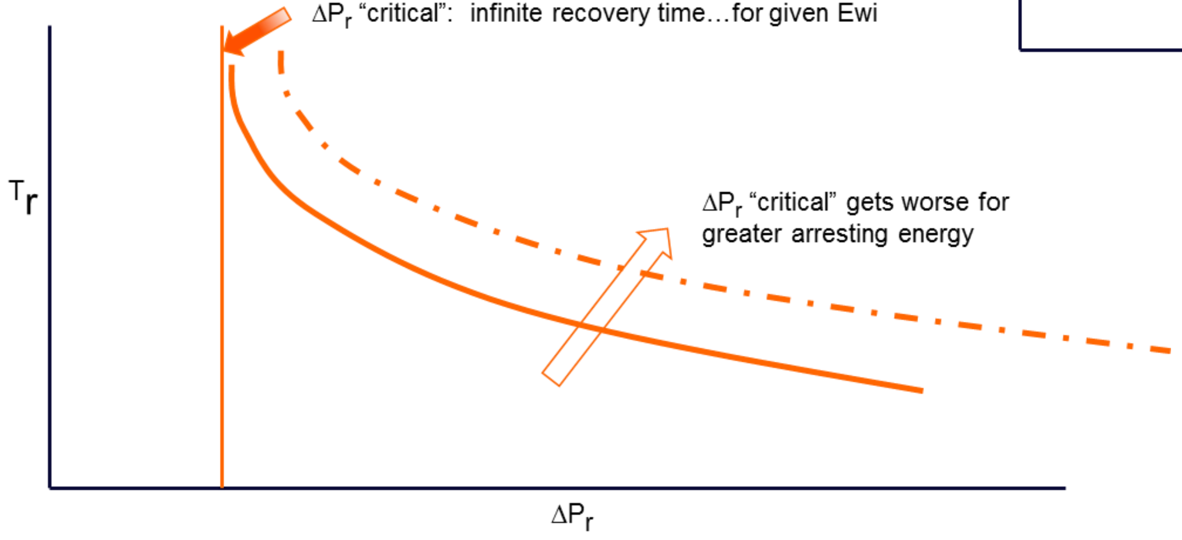
T_r = time necessary for turbine speed to recover to pre-disturbance, allowing P to recover to P_o

Source: IESO Ontario

Recovery Power and Time Required

- This is for a given $P_o < P_{rated}$
- Each P_o will have its own critical power for each arresting energy

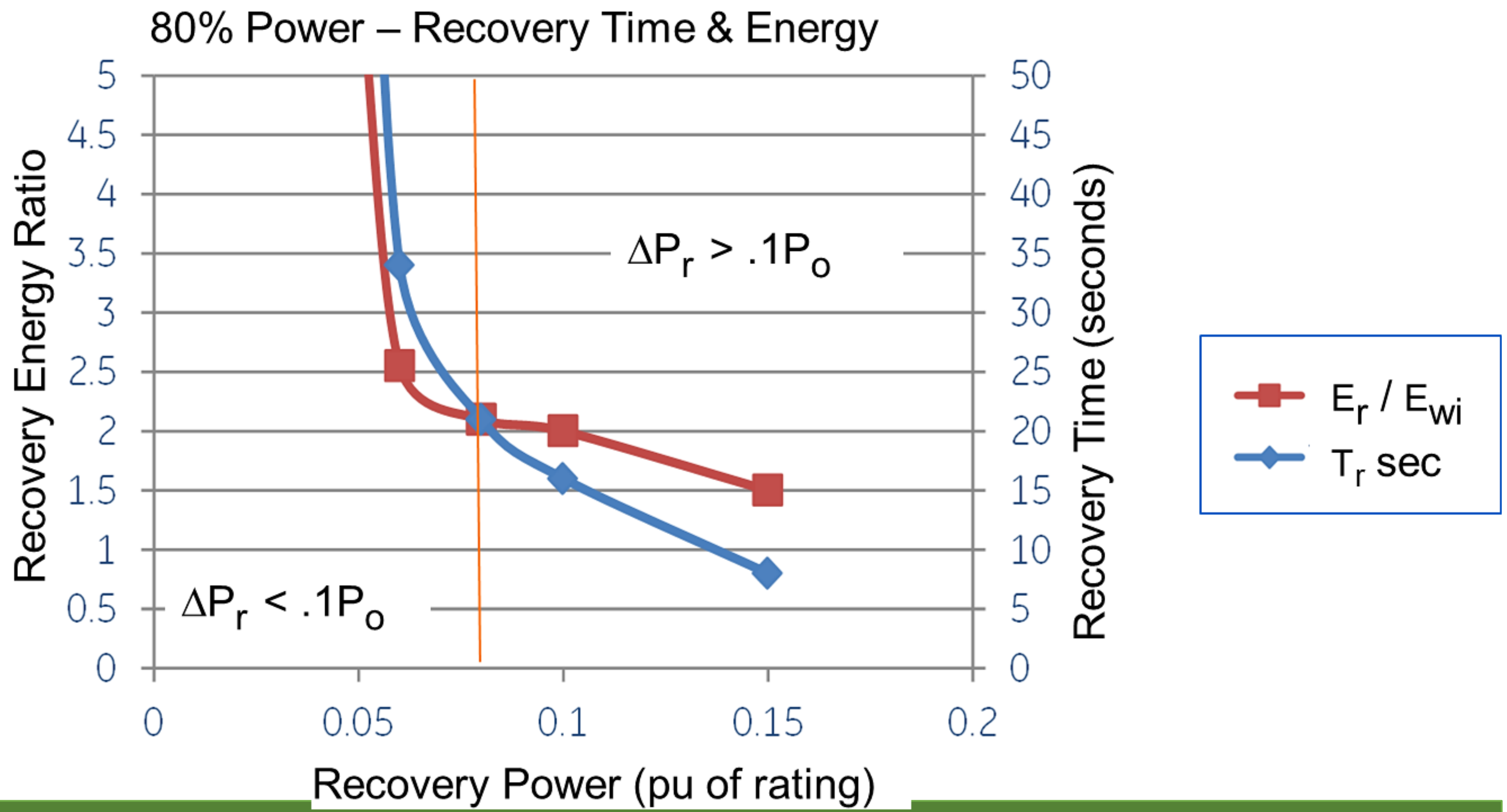




Limiting recovery power increases the time and energy needed to recover.

Source: GE Energy Consulting

Recovery Power and Time Required



Limiting recovery power increases the time and energy needed to recover

Source: GE Energy Consulting

Discussion Continued:

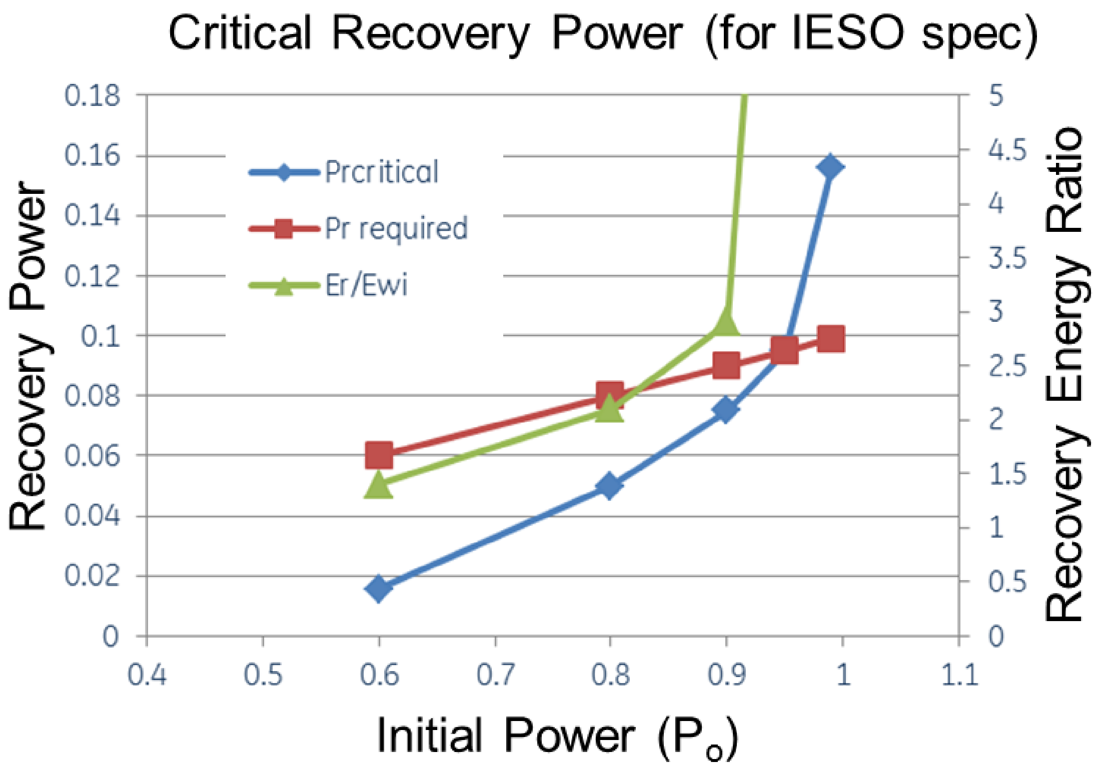
- As P_o increases, the critical recovery power increases
- As E_{IBFFR} increases, the critical recovery power increases
- As recovery power increases, the recovery period shortens
- As recovery power increases, the backlash increases
- As recovery power decreases, the ratio of recovery energy to arresting energy increases

This figure is for the IESO proposal, with

- $\Delta P_{IBFFR} = 0.1P_o$
- $\Delta P_r = 0.1P_o$ (the red line: Pr required)

A generic aeromechanical and drive-train model

Square approximation to IESO open-loop trapezoids



Some observations:

- This aero-mechanical model says requirement of P_r > 0.9Po is impossible above ~90% nameplate
- Recovery energy 2 to 3x arresting energy

Nick's opinion: Be careful what your grid-code asks for . . .

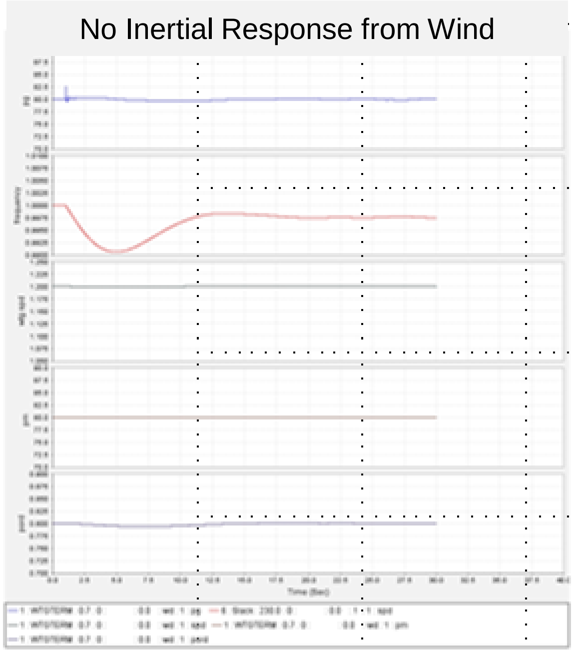
HickoryLedge

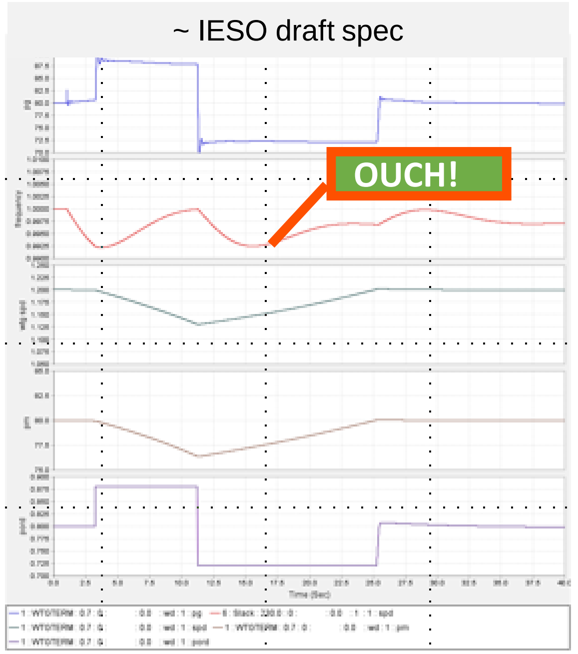
Nicholas Miller

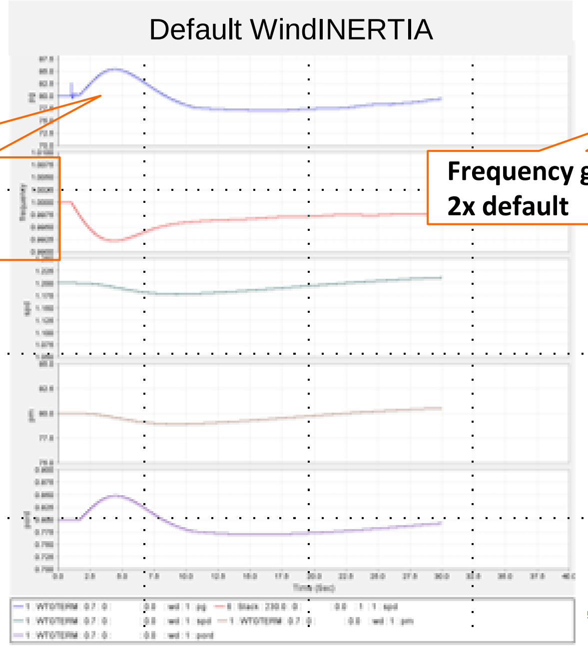
Source: GE Energy Consulting,

Example:

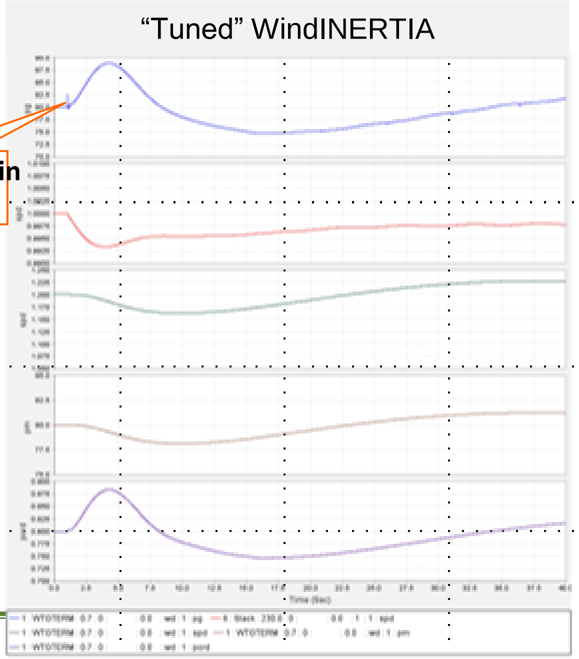
- Simple, high penetration system:
- ~50% instantaneous wind penetration
- ~ 2:1 synchronous/wind MVA
- Simple generation trip event


No Inertial Response from Wind


~ IESO draft spec


Default WindINERTIA

These settings
for relatively small system,
subject to big (~1.5Hz) events


“Tuned” WindINERTIA

Frequency gain
2x default

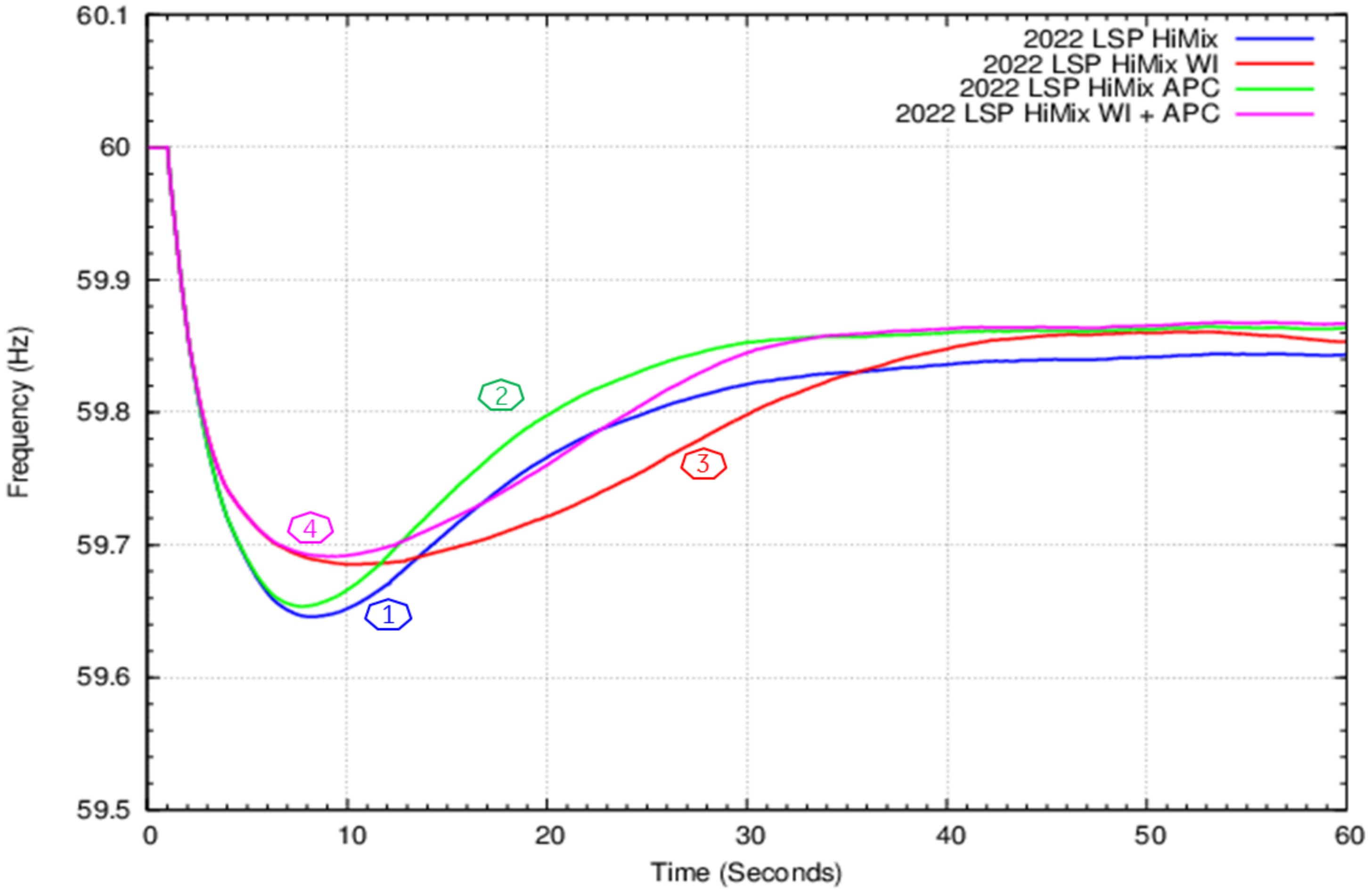
Source: GE Energy Consulting

Big System Example:

Frequency Control on Wind Plants

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

Disturbance: Trip 2 Palo Verde units (~2,750MW)



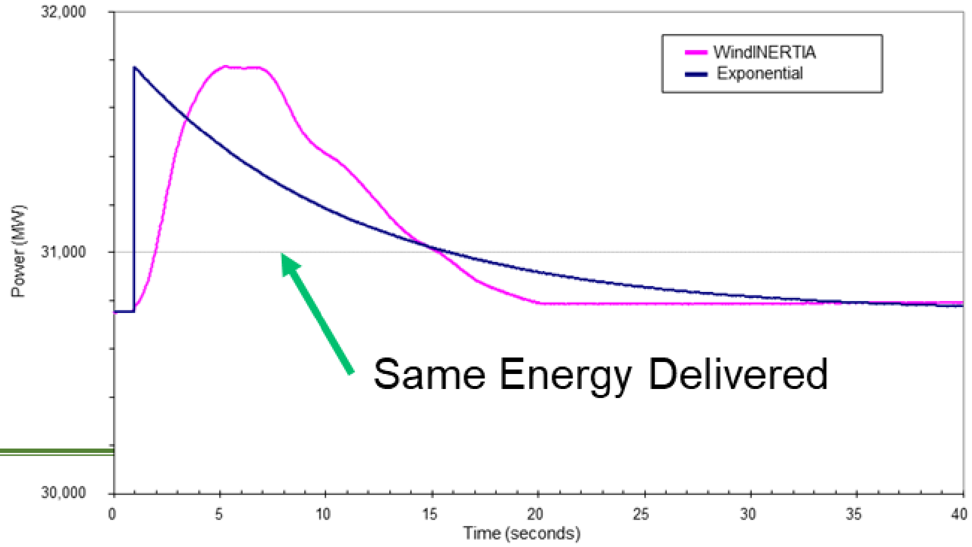
Source: NREL WWSIS 3

A last thought on inertial Controls

- Inertial response of Type 3 & 4 WTGs are constrained by
  - Ability to measure angle and frequency with adequate accuracy.
  - Maximum electric power/ratings
  - Mechanical loadings/ratings/loss of life considerations
  - Control stability considerations
  - Aeromechanical limitations, including stall
- BUT NOT by standard synchronous machine equations, which
  - Do not naturally respect WTG constraints
  - Do not take full advantage of WTG capability

>Grid frequency performance can be better with new inertial controls

>WTG inertial controls should not mimic synchronous machines



Same Energy Delivered

Virtual Synchronous Machines or FFR?

A new debate . . .

- We’ve made a strong statement that the controls described here, and those offered today are NOT equivalent to synchronous machine inertia
- A debate rages today over whether inverter-based generation should be “grid forming”.
- Not necessarily identical to synchronous machines (my opinion), but more like them, including:
- Effectively a phasor voltage (state variable) behind reactance. The concept is broadly termed “virtual synchronous machines”.
- We’ve got a long ways to go...

Source: GE Energy Consulting

Grid-following vs Grid-forming:
In a nutshell

- Grid following: Look to the grid for voltage phasor, try to inject the right Watts & VARs relative to that voltage
- Grid forming: Create an internal voltage, try to move that voltage to cause the desired Watts & VARs to flow into the system

Yes, it's a bit oversimplified, but close enough for the moment…
the point is this behavior is fundamentally different, and fails differently.

A topic for another day….

Summary and Conclusion

- Need and demand for inertial response from WTGs has been growing.
- GE (for example) has offered this feature to meet this need since 2009.
- Other OEMs are offering other inertia-based controls.
- Diverse approaches are being offered (and developed) today.
- Fundamental physical differences in WTGs mean that inertial behavior is not identical to synchronous machines.
- It is better considered a Fast-Frequency Response rather than surrogate-synchronous inertia.
- Emerging grid codes are starting to require inertial response; the codes must recognize physical reality & constraints
- “virtual synchronous machine” type controls are coming, but the industry has some very serious thinking about what is needed before they create requirements!

Source: GE Energy Consulting

Thanks

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