GE Energy

Impact of Frequency Responsive Wind Plant Controls on Grid Performance

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GE imagination at work

Frequency Response: Basics

- Grid must maintain balance between load and generation
- Large disturbances, particularly trips of large generating plants, cause unbalance that must be corrected by "Frequency Response"
- Frequency response covers multiple time frames
  - inertial response (up to a few seconds)
  - governor response (aka "Primary Response" – 1s to 10s of seconds)
  - AGC response (re-dispatch) (aka "Secondary Response" - tens of seconds to tens of minutes)
- ***Committed*** synchronous generation ***naturally*** contributes to system inertia.
  - inertial response for these resources is ***not controllable***, and is not a function of loading level
- ***Some*** synchronous generation provides governor response, ***if***
  - (a) governors are enabled ***and***
  - (b) it has "headroom" to increase output

Frequency Response: Today's Reality

- System governor response (primary response) has been declining steadily in some parts of the US for many years: Subject of Sept 23, 2010 FERC Technical Conference and NERC Comments of October 14, 2010 [**The work presented here was executed and documented before the TC**]
- This ***predates*** the rapid recent growth of ***wind*** generation in North America
- Declining response results in deeper frequency (nadir) excursions for system disturbances, increasing the risk of under-frequency load shedding (UFLS) and cascading outages
- Concern is most acute at lighter load conditions
    - economics favor fewer generators committed with less governor response
    - worst disturbances are not dependent on system load level
- The issue is getting considerable attention in many circles

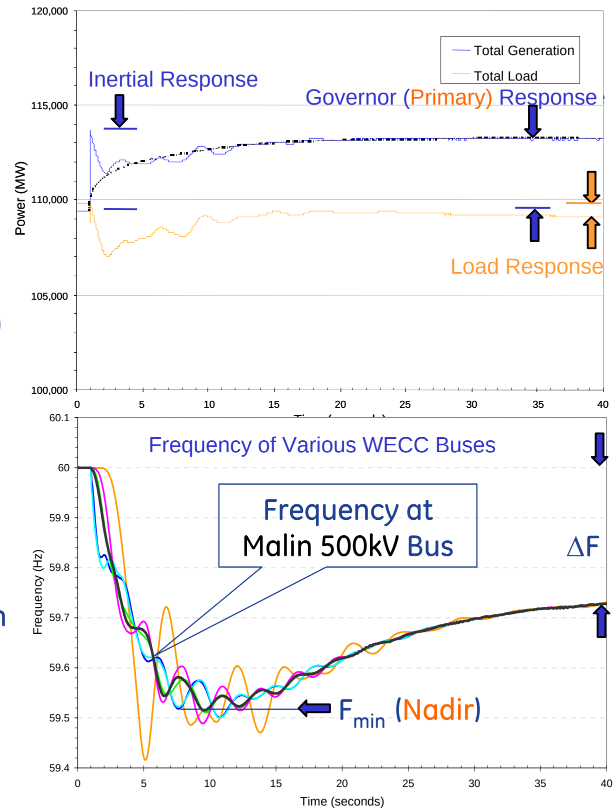
A Example from WECC

- 2010 WECC database
- Light summer load (110GW: 65-75% peak)
- Full dynamic modeling
    - data used today to make planning decisions
- Disturbance: 3 x Palo Verde NPS (loss of 4132 MW)
    - really big event
    - not design basis, but has happened

The authors gratefully acknowledge the support of the Western Electricity Coordinating Council (WECC) Renewable Energy Modeling Task Force (REMTF), and its chairman, Abraham Ellis, in supplying access to planning data for this work

Inertia vs. Governor Response

- Inertial response dominates initial frequency decline
- Combination of inertia & governor response dictates minimum frequency (F_{min}) (Nadir)
- Governor response dominates later (ΔF), until AGC takes over (not modeled here)
- At 40 seconds:
  - ~3800 MW Governor Response
  - ~270 mHz Frequency Deviation
  - ~1400 MW/0.1 Hz
    (~ 0.9 % of peak load)
    Nominal Frequency Response
    (NERC requirement is >1%)



Frequency Response with Wind: What's Different?

Commitment and dispatch

- Wind generation causes *some* synchronous generators to be *de-committed*, and *some* to be *dispatched down* to lower power levels

Inertia

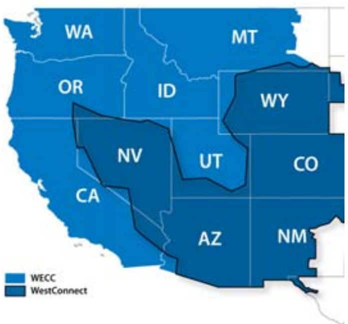
- Modern variable speed wind turbine-generators do not *naturally* contribute to system inertia
- De-commitment of *some* generators reduces system inertia

Governor Response

- Wind generation, like many generation resources, including nuclear, boiler follow steam, etc., does not contribute to governor response without incurring significant operational cost penalties
- Other resources that have governor response may be
  - De-committed, removing their contribution
  - Dispatched down, giving more "headroom"

Adding Wind to WECC

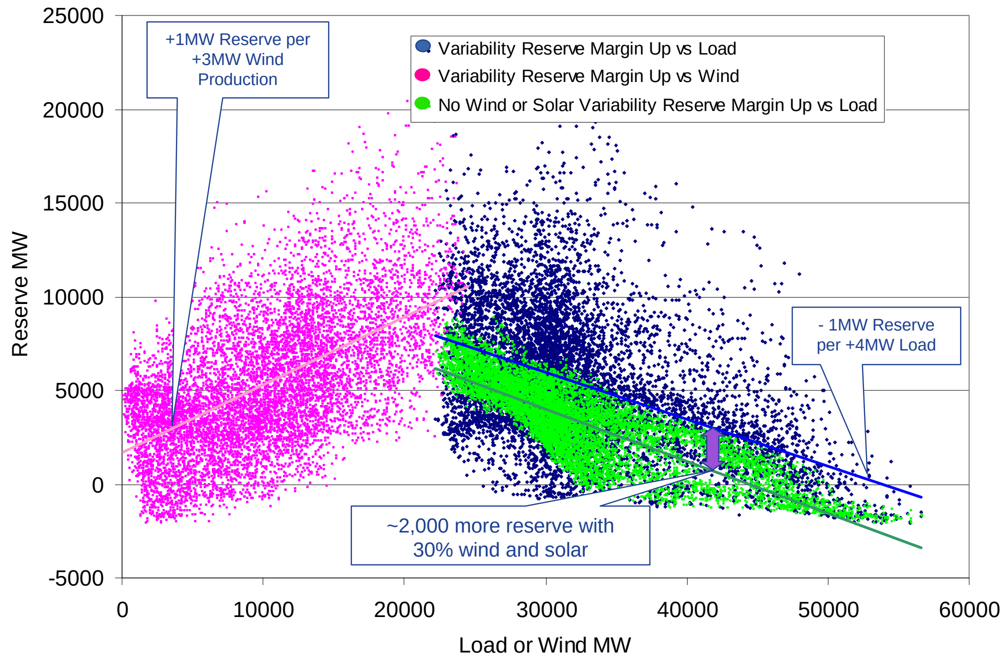
- New wind added to reach 10 and 20% *by Energy*
- MW build-out by area based on Western Wind & Solar Integration Study* (WWSIS)
- Physical location: at existing thermal plants
- Commitment & Dispatch: guided by WWSIS economic analysis.
  - Gas CC usually on margin: mostly CC displaced by wind power
  - on average +3 MW Wind power causes:
    - 1 MW of other generation to be dispatched down
    - 2 MW of other generation to be decommitted



Area	10% Wind Generation (MW)	10% Wind Rating (MW)	20% Wind Generation (MW)	20% Wind Rating (MW)
Arizona	2,254	2,906	4,419	5,247
Colorado	802	2,186	1,745	4,284
Nevada	120	1,504	210	2,428
New Mexico	811	1,271	1,712	2,087
Wyoming	467	1,638	1,018	4,348
Rest of WECC	10,927	21,854	21,711	43,422
Total =	**15,381**	**31,359**	**30,815**	**61,816**

*http://www.nrel.gov/wind/systemsintegration/wwsis.html

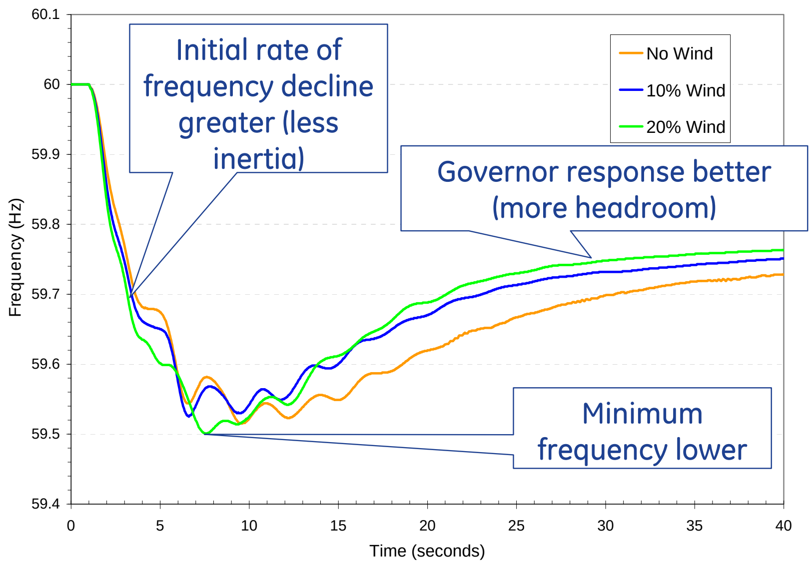
Variability Reserve Margins (headroom)



Slide from WWSIS Study

Frequency Response to Loss of Generation with Increasing Levels of Wind

- Wind generation without any frequency responsive controls
- Nominal response at 40 seconds: ~1.0%/0.1Hz Meets NERC Criteria



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Inertial Response: GE WindINERTIA™

Control Concept:

- 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

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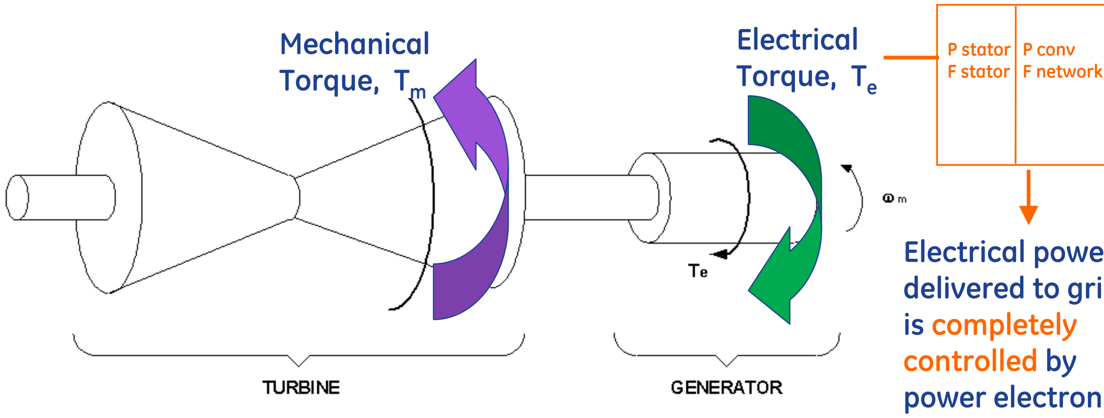
How does it work?



Electrical power delivered to grid is completely controlled by power electronics

- In steady-state, torques must be balanced
- When electrical torque is greater than mechanical torque, the rotation slows extracting stored inertial energy from the rotating mass

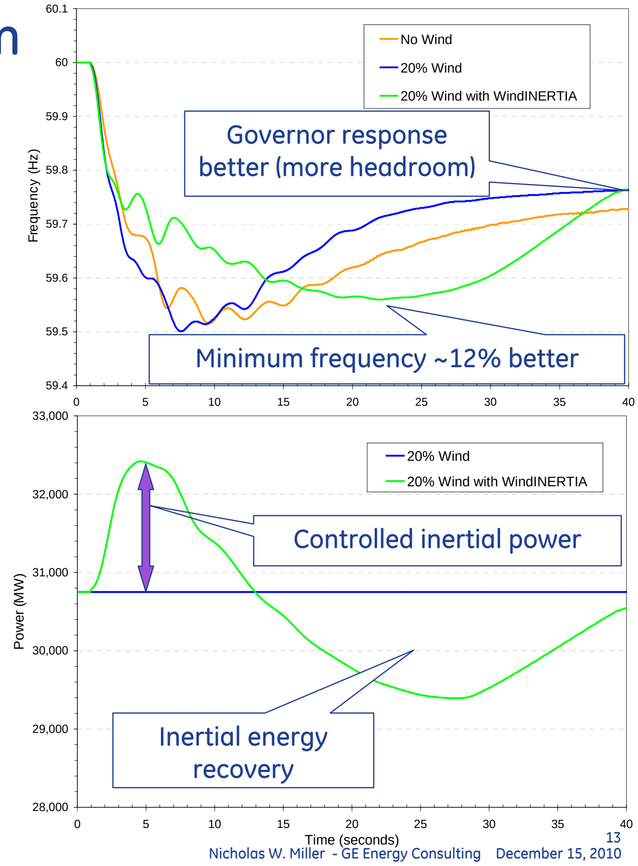
WindINERTIA uses controls to increase electric power during the initial stages of a significant downward frequency event

Objectives and Constraints

- 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
- 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

Inertial Response from Wind Generation

- Inertial response reduces and delays minimum frequency
- Margin above UFLS increases by about 40mHz
- Response in this case is overly aggressive: Inertia is now another control variable that can be tuned.



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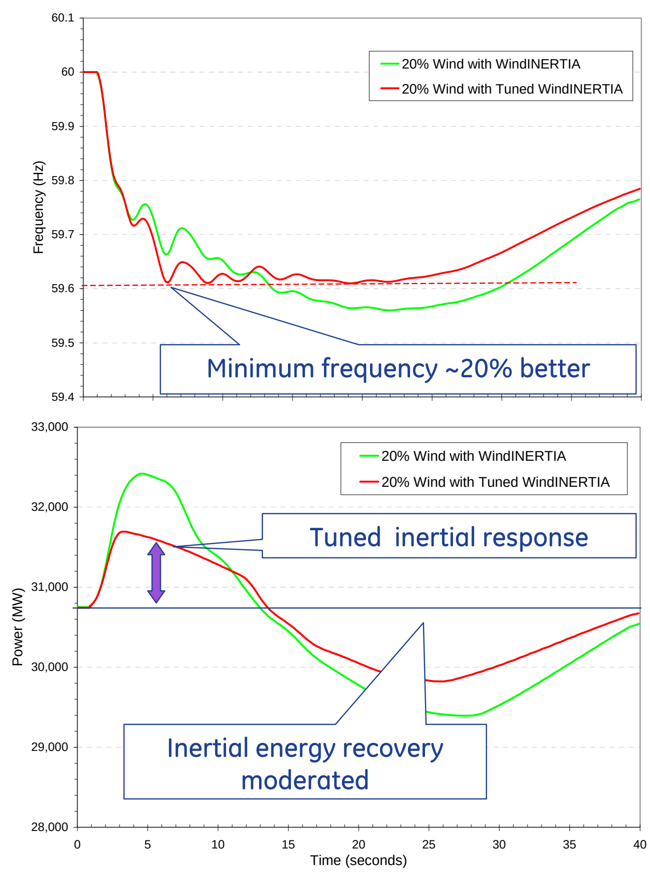
Tuning Inertial Response from Wind

- Tuning inertial response further improves frequency nadir and reduces impact of recovery energy
- Margin above UFLS increases by about 80mHz
- (i.e. case without wind is about 20% worse than with wind)



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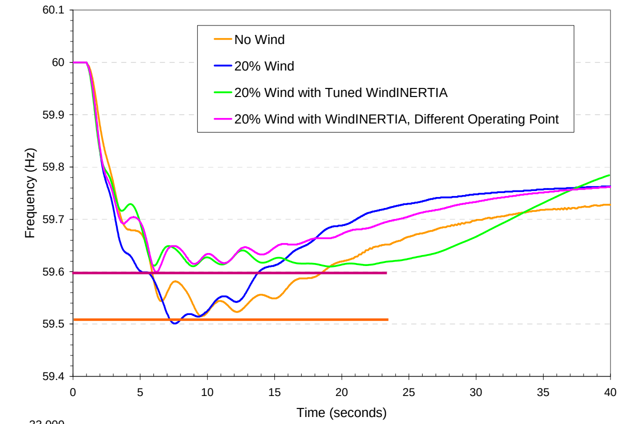
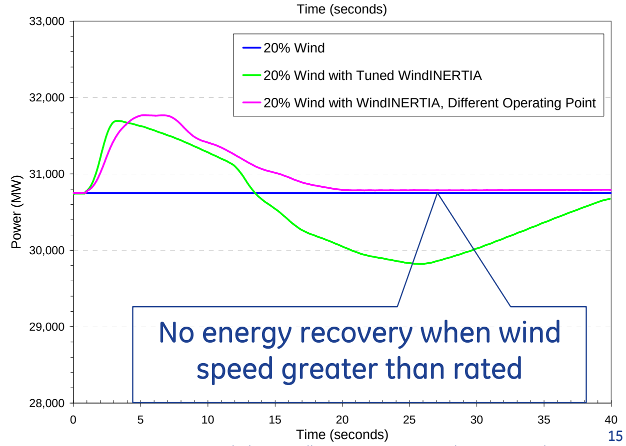
Impact of Operating Point on Inertial Response

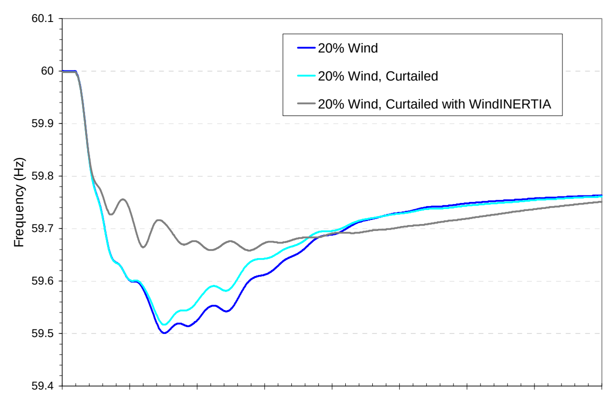
- Same initial loadflow condition: fewer WTGs producing the same MW at higher wind speed
- When wind speed is high, system response is superior throughout
- Margin to UFLS improved by ~80mHz

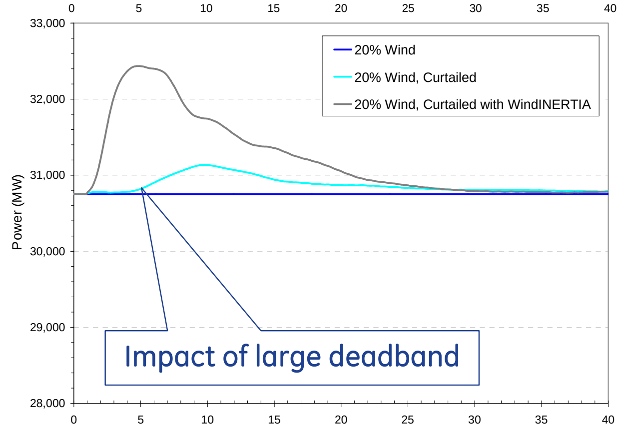




Governor Response

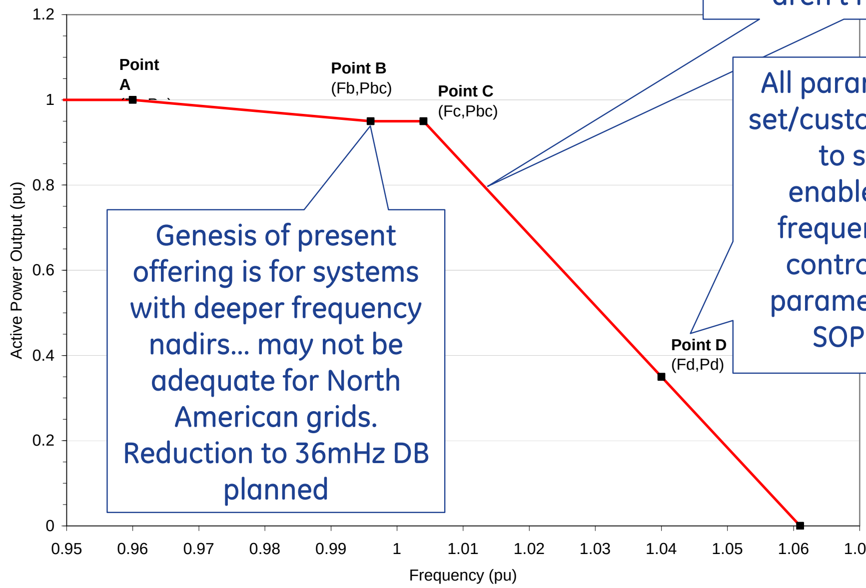
- Same initial loadflow condition: same WTGs producing the same MW. WTGs curtailed to 90% of the available wind power
- Modest benefit from governor response (large deadband used here: a NERC debate today)
- Curtailment enables WindINERTIA to greatly benefit system
- Margin to UFLS increased about 140mHz





Frequency Response Curve

WTGs reduce power very effectively. Symmetric Droops aren't required.



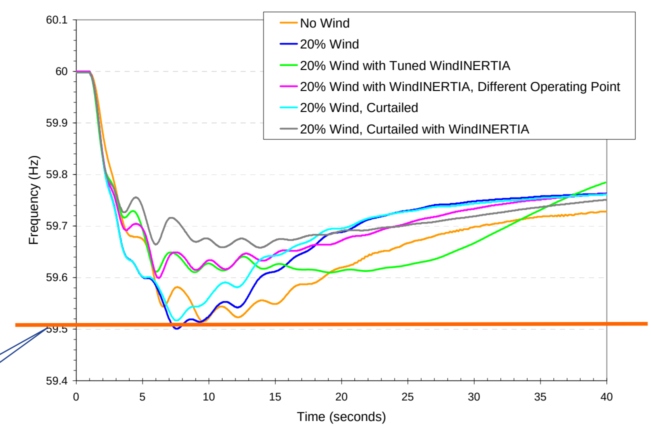
All parameters can be set/customized. Is easy to selectively enable/disable all frequency sensitive controls. 2 sets of parameters allowed: SOP in Ireland

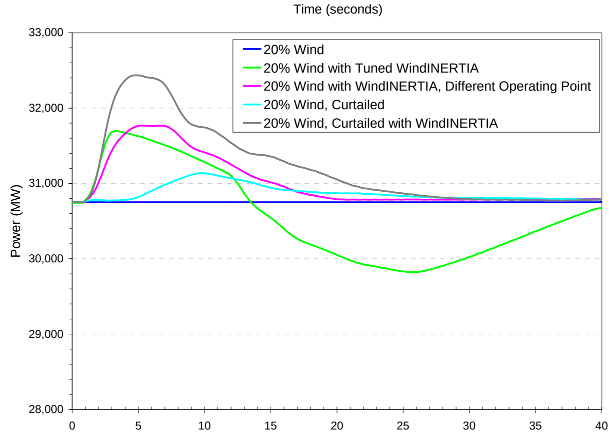
Genesis of present offering is for systems with deeper frequency nadirs… may not be adequate for North American grids. Reduction to 36mHz DB planned

From PSLF manual

Summary of Frequency Performance

Every condition with wind has better frequency recovery: Meets NERC 1%/0.1Hz requirement





Every condition with frequency responsive wind controls has minimum frequency better than base case

Conclusions

- Systems with high wind penetration ***can*** exhibit superior frequency performance
- Presently available wind plants controls can contribute positively to system frequency performance and can be tuned
- It is ***possible*** for systems with wind generation to experience degraded frequency performance
- Statements that wind generation ***necessarily*** results in degraded frequency performance are ***incorrect***
- System frequency performance is, as always, dependent on
  - power plant performance
  - overall unit dispatch and commitment
- The addition of wind generation does not change the fundamental truth that system operation must respect frequency response requirements

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Thank you!

Based on Paper Presented:

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Impact of Frequency Responsive Wind Plant Controls on Grid Performance

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***Abstract*-- Grid integration of wind power plants is complicated by a number of issues, primarily related to wind variability and the electrical characteristics of wind generators. A typical wind plant appears to the grid as a substantially different generation source than a conventional power plant.**

The most significant difference is that the wind energy source is inherently uncontrollable. Such uncontrolled real power output variations can have an impact on the grid, including frequency variations. In addition, the electrical characteristics of wind generators result in a disturbance response that is naturally different from that of conventional synchronous generators. Without special controls, a wind plant does not inherently participate in the regulation of grid frequency. By contrast, synchronous machines do participate in frequency regulation through their inherent inertia, and their governor controls. When wind generation displaces conventional synchronous generation, the burden of frequency regulation placed upon the remaining synchronous generators is increased.

Frequency control is a particularly significant issue with high levels of wind and solar penetration, in weak systems, and in control areas where tie-line interchange is constrained or non-existent. This paper summarizes results from a recent investigation of system frequency response in the Western US as it may be affected by large amounts of wind generation. Impacts and benefits of wind plant controls that provide frequency and inertial response are illustrated with quantitative examples.

***Index Terms*—Frequency response, Inertial response, Power generation, Power systems, Wind energy, Wind power generation.**

I. Introduction

THIS paper summarizes results from a recent investigation of system frequency response in the Western US as it may be affected by large amounts of wind generation. The benefits of wind plant controls that provide frequency and inertial response are illustrated with quantitative examples.

In the first few seconds following the loss of a large generating plant, the frequency dynamics of the system are dominated by the inertial response of the on-line generation. Synchronous machines inherently contribute some of their stored inertial energy to the grid, reducing the initial rate of frequency decline, and allowing slower governor actions to stabilize grid frequency. Similar performance can also be achieved with a wind plant via a controlled inertial response.

With higher levels of wind and solar penetration, system operation changes. Thermal units may be de-committed as their output is displaced by lower marginal cost wind generation, or they may be dispatched to lower power levels. It may be that the units most economical to displace, also have the most desirable governor response. This would leave other resources that do not provide the same governor characteristics. The remaining thermal units are also more frequently operated at a lower power output. During these conditions the system would benefit from the frequency sensitive response of wind plants to (1) over-frequency events caused by load rejections, whereby thermal plants are less likely to have substantial down regulation capability, and to (2) under-frequency events caused by generation trips.

The work presented in this paper will focus on the latter issue, as there is widespread and growing concern in North America about system response to under-frequency events. These quantitative results will help provide context to these ongoing industry discussions.

II. Wind Plant Response Today

A fundamental aspect of operating an electric power grid reliably is that the amount of power produced at any given instant, must match almost exactly the amount of power being consumed [1,2]. If extra power is produced, the frequency will tend to increase. If less power is produced, the frequency will tend to decrease.

There is a fundamental difference between a wind turbine and the turbines supplying motive power to the majority of the world's traditional power plants, be they gas turbines, steam turbines, or hydro turbines. With traditional turbines the rotational speed is nearly constant and locked to system frequency. However, the speed of a wind turbine is not synchronous with the grid and is controlled to maximize active power production. Therefore, wind plant power production is not inherently coupled to the system frequency, and historically, wind plants have not been required to participate in frequency regulation.

III. Wind Plant Active Power controls

Modern wind plants with GE turbines and plant controls, have the ability to control active power output in response to grid frequency in ways that are important to overall grid performance. This section provides a brief overview of the relevant controls. More detailed discussions are available in references [3,4].

A. Inertial Response

As described above, the initial frequency response of the system is dominated by the inertial response of the operating generation. However, most modern MW-class wind generation does not exhibit this inertial response. It is possible to program the wind plant controls to provide a form of inertial response. The GE WindINERTIA™ control feature is described below.

For large under-frequency events, the GE WindINERTIA™ inertial control feature temporarily increases the power output of the wind turbine in the range of 5% to 10% of the rated turbine power. The duration of the power increase is on the order of several seconds. This inertial response is essentially energy neutral, meaning that the period of increased power is followed by a period of decreased power. Below rated wind, stored kinetic energy from the turbine-generator rotor is temporarily donated to the grid, but is recovered later. At higher wind speeds, it is possible to increase the captured wind power, using pitch control, to temporarily exceed the steady-state rating of the turbine. Under these conditions, the decline in rotor speed is less and the energy recovery is minimal.

Unlike the inherent response of synchronous machines, inertial wind turbine generator (WTG) response is dependent on active controls. The design has sufficient margin over the turbine operating range to meet the equivalent energy (kW-sec) contribution of a synchronous machine with 3.5 sec pu inertia for the initial 10 seconds.

Overall, the inertial control feature is designed to provide similar functional response to that of a synchronous machine. However, there are important differences. Unlike the inherent response of a synchronous machine, the response is not exactly the same under all operating conditions. The control is also asymmetric. It only responds to low frequencies. A different controller, as discussed below, handles high frequency response separately. And, the control only responds to large events – those for which inertial response is important to maintain grid stability, and for which seriously disruptive consequences, like under-frequency load shedding (UFLS), may result. The continuous small perturbations in frequency that characterize normal grid operation are not passed through to the controller. The inertial control feature uses the energy stored in the rotor to provide an increase in power only when needed. Hence, this feature does not adversely impact annual energy production.

B. Governor Frequency Response

It is also possible to implement active power management functions in wind plants to provide a response similar to a governor response. One type of active power control offered as part of the GE WindCONTROL™ wind plant control system is closely akin to governor controls for thermal and hydro generation. It responds to significant deviations in grid frequency, increasing or decreasing power output in response to low or high grid frequency events, respectively. To accomplish this, the control alters the active power control reference targeted by the turbine controls. The command for this response emanates from the wind plant level, and is delivered to each individual WTG through the plant SCADA system. In order to allow for an increase of wind plant active power output in response to an under-frequency condition, some active power production must be kept in reserve [5]. Therefore, the maximum power production of the wind plant is constrained to a value less than that available from the wind. During the period where this function is enabled, there is a loss of energy production due to an intentional under-utilization of the wind plant.

Grid over-frequency events are stressful to power components. Further, temporary high frequency swings can present a reliability concern. For example, in one recent well-publicized grid event [6], the high frequency backswing from a major grid disturbance caused power plant trips and aggravated an already severe event. When enabled, the response of the wind plant control system will rapidly reduce power output for the duration of the over-frequency event. This behavior is similar to that of governor control on thermal generation, except that it is faster and allows deeper runback of power than is typical of conventional thermal generation.

The wind plant inertial control discussed in the previous section, if enabled, will also respond to significant under-frequency events. The total response of the WTG to these two signals is coordinated to respect the physical capabilities of the WTG.

IV. Operations with High Wind Penetration

In response to the rapid growth of wind and solar generation in North America, a number of jurisdictions commissioned studies to determine potential operational impacts [7-11]. Overall, the studies have repeatedly found that large modern power grids can accommodate substantial amounts of wind and solar generation reliably and economically, with appropriate changes in practice, rules and infrastructure

These studies showed that the addition of wind and solar generation displaces thermal generation in an economically dispatched system. Whether that thermal generation is gas-fired or coal-fired depends upon the relative cost of those two fuels. Regardless of the fuel, the displacement of thermal generation has two components. Some of it is de-committed, and some of it is dispatched at a lower level.

Many factors and constraints, both economic and physical, affect unit commitment and dispatch decisions. In a system with high wind and solar penetration, the operational flexibility of the remaining generation portfolio is key to accommodating the variable renewable generation. Operational flexibility includes such attributes as quick start capability, fast ramp rates, and minimum unit turndown.

Specific quantitative results from one such study, the Western Wind and Solar Integration Study (WWSIS) [11], formed the basis for the analysis described in the next section. First, a WWSIS study scenario was used to define the overall study conditions – i.e., load level, generation commitment and dispatch. Specifically, the In-Area scenario, which uses local wind resources to serve local load, at 10% wind penetration was selected. Second, the WWSIS showed that for every 3 MW of additional wind production, there is on average a 2 MW reduction in thermal unit commitment and a 1 MW reduction in thermal unit dispatch. This 2/3 de-commitment, 1/3 re-dispatch approach is a basic assumption incorporated into the analysis. Considerable variation in dispatch and commitment will occur, as it does today in low renewable systems. However, this average commitment and dispatch approach is one that is supported by the extensive operational analysis performed in the WWSIS.

V. Western US Example System

As part of its support for the Western Electricity Coordinating Council's (WECC) Renewable Energy Modeling Task Force (REMTF), GE Energy investigated the impact of significant wind penetration on frequency response of the WECC system.

A. Base Case

A standard WECC power flow and dynamic dataset for 2010 light summer conditions was used. This database represented relatively light load conditions (65-75% of summer peak) in the early morning hours (2 am to 5 am). Therefore, it represented a credible system condition for high levels of wind penetration.

To streamline this analysis and provide a clearer comparison between various cases, all relay models were removed from the dynamic data. It may be desirable for future analysis to consider load shedding as an additional performance metric.

Since the focus of the simulations is short-term dynamic performance, no long-term models (e.g., AGC or Automatic Generation Control) were included.

Many of the load models included a frequency dependent component.

In WECC, many generators are base-loaded, and the effect of this operating condition is captured in the corresponding governor models by appropriate parameter settings (i.e., base load flag).

B. Wind Scenarios

The standard WECC database described above became the reference case. Some wind generation is, of course, included. For this analysis, however, the reference case is also called the no-wind case – short hand for a case with no *additional* wind. Selected areas and zones in the WECC database were aggregated to approximate the study areas used in the WWSIS. These study areas, in turn, approximated the states of Arizona, Colorado, Nevada, New Mexico, and Wyoming.

As noted above, the WWSIS In-Area scenario at 10% wind penetration was selected as a starting point. Production simulation results for an entire study year were screened to identify a time period with the best match to the power flow in terms of load level, season, time of day, and generation dispatch in the Arizona, Colorado, Nevada, New Mexico, and Wyoming study areas. A midnight in July was identified. The aggregate wind production and wind nameplate rating in each study area during that time period defined the objective in the development of the 10% wind case, as shown in Table 1. Wind output as a % of rating is also shown. This relative output varies widely across the areas, from 8% in Nevada to 78% in Arizona.

The objective in the development of the 20% wind case was to simply double the wind production and rating of the 10% case.

Table 1. WWSIS Objectives for 10% Wind Case.

Area	Wind Generation		Wind Rating
	(MW)	(% of Rating)	(MW)
Arizona	2,211	78	2,850
Colorado	880	37	2,400
Nevada	108	8	1,350
New Mexico	862	64	1,350
Wyoming	471	29	1,650
Rest of WECC	10,838	50	21,676

C. Wind Cases

From a power flow perspective, there is no difference between a wind generator and a thermal generator. Both are modeled as a conventional source with a specified real power output, a reactive power range, and a bus voltage to regulate. For simplicity, it was assumed that wind generation was located at the same bus where displaced conventional generation was located. Therefore, the same WECC 2010 light summer power flow provided the initial conditions for all of the dynamic simulations. The addition of wind, and the associated de-commitment and re-dispatch of thermal generation, was implemented by modifying the dynamic data alone. The load and interface flows remained unchanged. This approach ensures that the performance differences are associated with a change in generation technology and not due to a change in generation location.

Based on the WWSIS results, the addition of every 3 MW of wind generation was accomplished with a 2 MW de-commitment and a 1 MW reduction in other generation. As an example, assume that 500 MW of wind production with a rating of 750 MW needs to be accommodated and there are two thermal generators that could be displaced. One thermal unit is a 600 MVA plant with 500 MW output and the other is a 1,200 MVA plant with 1,000 MW output. The total output of the thermal units is 1,500 MW and the total rating is 1,800 MVA. For 500 MW of additional wind production, the 2/3 de-commitment objective is 333 MVA, and the 1/3 re-dispatch objective is 167 MW.

First, the dynamic model of the 600 MVA thermal plant is replaced by a 750 MW rated wind plant model with 500 MW of output. This constitutes a thermal de-commitment of 600 MVA. Second, the MVA in the dynamic model of the second thermal unit (1,000 MW, 1,200 MVA) is increased to 1,467 MVA. This represents a transfer of 267 MVA of thermal commitment to this unit. As a result, the net thermal commitment is reduced by 333 MVA: -600 MVA at the first plant and +267 MVA at the second plant. In other words, the original total thermal MVA has been reduced by 333 MVA, from 1,800 MVA to 1,467 MVA.

Consider the above changes from the perspective of the thermal plant dispatch, rather than commitment. The total thermal plant output was originally 1,500 MW. The de-commitment of 333 MVA results in an equivalent reduction in actual output, or an interim thermal output of 1,167 MW. Then, the 167 MW re-dispatch is implemented, giving a final total thermal output of 1,000 MW on the second unit.

The final dynamic model includes the 750 MW rated wind plant model with 500 MW of output, and a single thermal plant with an output of 1,000 MW and a rating of 1,467 MVA. Thus, there is no need to modify the power flow. In general, the thermal plants have the correct loading, the correct MVA and inertia, and the correct range between dispatch and maximum power (i.e., "headroom") available for governor action.

The final 10% wind case is summarized in Table 2. The 20% wind case was developed using the same de-commitment/re-dispatch approach for exactly twice the wind in the 10% case.

Table 2. Actual Wind in 10% Wind Case.

Area	Wind Generation		Wind Rating
	(MW)	(% of Rating)	(MW)
Arizona	2,254	78	2,906
Colorado	802	37	2,186
Nevada	120	8	1,504
New Mexico	811	64	1,271
Wyoming	467	29	1,638
Rest of WECC	10,927	50	21,854

D. Disturbance

Tripping all three generating units at the Palo Verde nuclear power station imposes a substantial frequency excursion on the WECC system. While this multi-unit event of 4,100 MW is outside of normal design basis events (e.g., NERC type B and C), it has happened. Thus, an actual event with substantial frequency and stability consequences is a good starting point for the examination of frequency response issues. Since Palo Verde is base loaded, this is an event that could occur under almost any credible operating condition.

Two key aspects of the overall system's power response to the large generation trip are shown in Figure 1. The sum of all the generation, other than Palo Verde, is shown in blue. The 4,100 MW trip occurs at 1 second. The system load is shown in orange. The voltage and frequency sensitivity of the load transiently reduces the load to a relative minimum about 2 seconds after the event. As the system voltage and frequency are partially restored by generator control actions, the load recovers to within about 700 MW by the end of the 40-second simulation.

The response of the generators shows two important and distinct elements. Initially, the falling frequency results in all synchronous machines decelerating. The active power output of all the synchronous generators jumps about 4,000 MW. This *inertial response* is a characteristic of synchronous generators and is neither controllable nor tunable. Immediately following the disturbance, the electric power of the generators exceeds the mechanical power being delivered by their respective turbines. After a few seconds, this balance is roughly restored, and the dynamic response becomes dominated by the governor response. A subset of the synchronous generators has both active governors and room to move. At any given time, some conventional generators will be operating without active governors (e.g. nuclear power stations) or at maximum power (e.g. valves wide open). These units do not contribute to governor response. A dotted curve is sketched in the figure to show the approximate aggregate response of all the generators with active governors and headroom. By the end of the simulation, this *governor response* has contributed about 3,700 MW.

The frequency response of the system is shown in Figure 2. Several buses across WECC are plotted. The frequency behavior, which is typical of large events, has two major components: a common frequency as well as more oscillatory components that are evidence of inter-area or other power swings. In this figure, the black trace is for the Malin 500 kV substation. While this frequency trace still includes some of the oscillatory behavior, the common mode, which reaches a relative minimum of about 59.52 Hz at about 10 seconds, is dominant. The 9-second interval from the beginning of the event to minimum frequency is representative of many large power systems.

While swing modes are important for system stability, it is this common mode that is of most concern in discussions about system frequency response. In the subsequent results, the frequency at Malin will be shown for comparison purposes.

Minimum frequency is used as the key performance metric in this analysis, since it can be correlated to tripping thresholds in UFLS schemes.

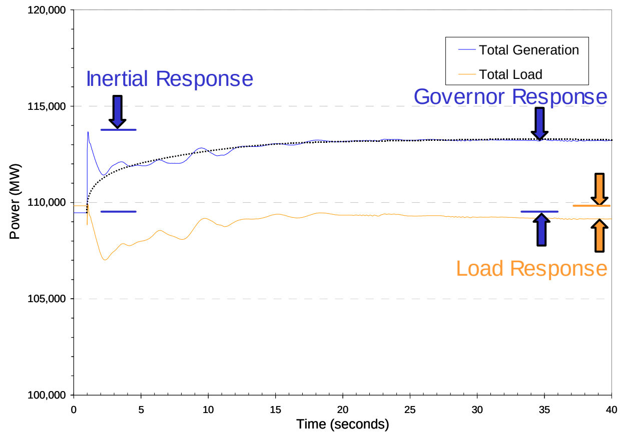

Figure 1. Inertial and Governor Response to Loss of Generation, No-Wind Case.

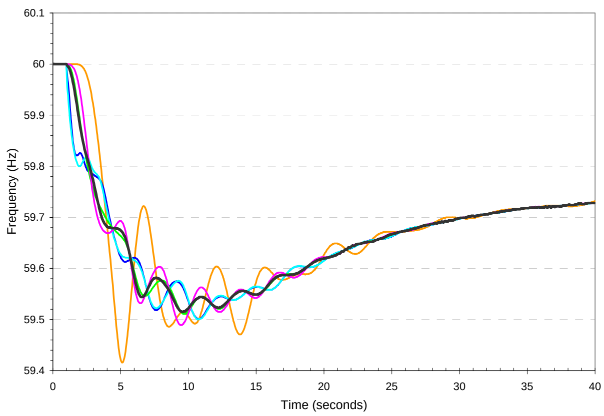

Figure 2. Frequency Response to Loss of Generation, No-Wind Case.

VI. Performance

A. Performance without Frequency Responsive Controls

As wind generation displaces synchronous generation, overall system inertia will decrease due to de-committed synchronous machines. The synchronous machines that remain committed, but which are dispatched to lower power levels, continue to contribute to the inertial response of the system. In general, those units will also have more range to increase power in response to governor control. The impact of these two effects can be observed in Figure 3, which shows frequency for the base (orange trace), 10% (blue trace) and 20% (green trace) wind scenarios. Initially, the reduction in net system inertia causes the system frequency to decline more rapidly. This can be seen in the first few seconds of the 10% and 20% wind traces. The decline of frequency is countered by governor action. Qualitatively, there are fewer governors with more room to move as the wind penetration increases. The net result is that the minimum frequency of the swing decreases with increasing wind power, and the longer-term response is somewhat better.

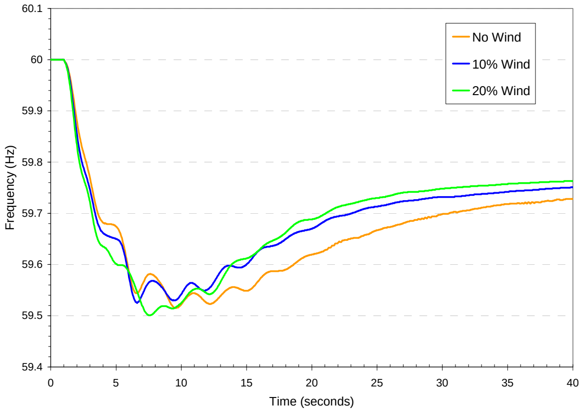

Figure 3. Frequency Response to Loss of Generation with Increasing Levels of Wind.

B. Performance with WindINERTIA™

Using the inertial controls has a substantial impact on system performance. In Figure 4, the frequencies for the no-wind case and 20% wind case are shown, along with the frequency when the WindINERTIA control is enabled. The delivery of extra power from the control substantially reduces the rate of frequency decline, allowing time for the active governors to respond. The minimum frequency with the inertial control is about 0.06 Hz, or about 12%, better than in the no-wind case.

The frequency recovery is longer with the control, reaching a minimum about 22 seconds after the disturbance, and recovering above the no-wind case at about 37 seconds.

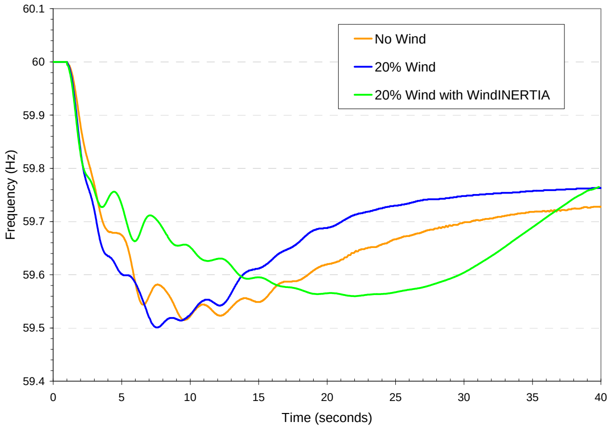

Figure 4. Impact of WindINERTIA on Frequency Response to Loss of Generation.

The impact on system frequency can be better understood by examining the active power response of the wind turbines, as shown in Figure 5. The wind power for the 20% wind case without WindINERTIA control (blue trace) is flat, as expected. The inertial control (green trace) increases the output of the wind plants substantially. It reaches a maximum about 5 seconds into the event, just as the system frequency is experiencing a high rate of decline. Extra power is delivered for about 13 seconds, after which the power drops below the initial level. As discussed above, the energy extracted from the rotating energy of the wind turbines must be recovered from the grid to reaccelerate the WTGs to normal speed. The active synchronous machine governors have had time to respond at this point. Therefore, the system frequency minimum, which is the critical performance metric, is better.

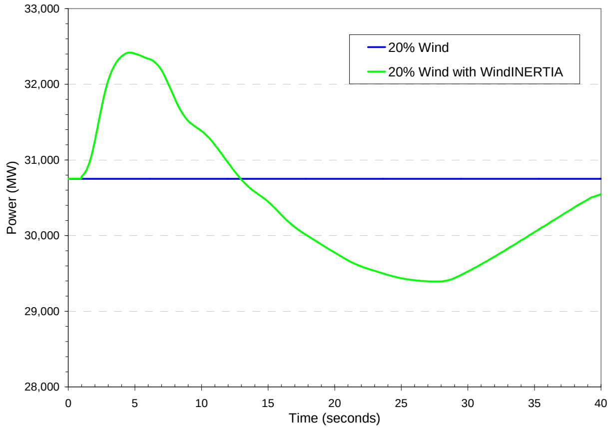

Figure 5. Incremental Power from WindINERTIA after Loss of Generation.

C. Sensitivity to Initial Conditions

Unlike conventional synchronous generation, the controlled inertial response is dependent on the wind turbine initial conditions. In general, when the wind is stronger, the controlled inertial response is better.

Figure 6 shows the impact of changing the wind conditions. In this case, the total wind power is held constant, but the wind speed is assumed to be uniformly high across the system. This means that fewer wind turbines are necessary to provide the same total power. In this extreme case, every operating wind turbine is assumed to have a wind speed above rated. The minimum frequency is about 0.08 Hz better than the no-wind case, and the recovery is faster than the no-wind case.

The reason for this different behavior can be seen in Figure 7. The WindINERTIA control still must respect the individual turbine maximum short-term power rating. With fewer turbines running at this operating point, the maximum power is lower (pink trace vs. green trace). However, since the wind speed is above rated, there is power available from the wind to supply the incremental electric power. At about 20 seconds, the inertial control returns the total wind power to pre-disturbance levels. It does not need to recover the incremental energy delivered to the grid. The wind has supplied that energy via turbine pitch control.

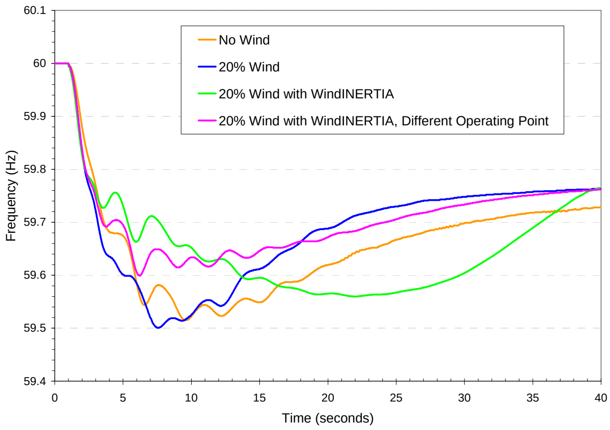

Figure 6. Impact of Operating Point on Frequency Response to Loss of Generation.

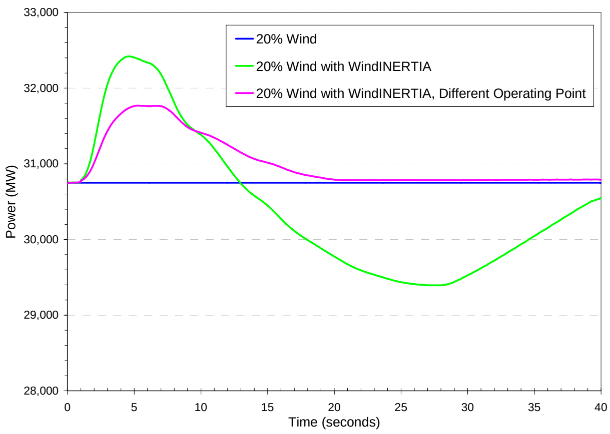

Figure 7. Impact of Operating Point on Incremental Power from WindINERTIA after Loss of Generation.

D. Performance with Governor Controls

For the above inertial control examples, the wind plants were initially operating at the maximum power possible for a given wind condition, i.e., at the available power level.

In order for a wind plant to provide *governor* response to low frequency events of the type examined here, the plant must be operating below the available power. That is, the plant must be curtailed. Curtailment has serious economic consequences, in terms of lost energy production.

When wind plants are curtailed, governor-like controls will allow the plant to provide a frequency response functionally similar to that of a conventional plant. In Figure 8, the operating plants are curtailed by 10% of the available wind power. As with the other sensitivity cases, the total wind power production level stays the same. It is only the wind speed that changes. In this case, the wind speed at each plant is assumed to be such that the plant is producing 90% of what is possible.

With the WindCONTROL governor control function enabled, the plant is responsive to substantial frequency drops. This function was initially developed to meet the Irish grid code [12]. However, the frequency dead-band settings for this case are tighter than those of the Irish grid code. In these cases, when the frequency drops below 59.76 Hz, the proportional governor control increases the plant power. The first case (light blue trace) has only this control enabled. The minimum frequency is improved somewhat, bringing the minimum frequency up to about the level of the no-wind case. However, when the WindINERTIA control is *also* enabled, the system minimum frequency is dramatically better, reaching a minimum of about 59.66 Hz, a roughly 37% improvement over the no-wind case. The effect of the governor control on total wind generation, and the combined response of the two controls, is shown in Figure 9.

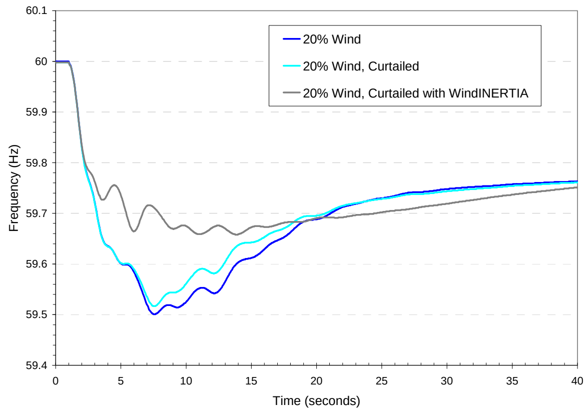

Figure 8. Impact of Curtailment on Frequency Response to Loss of Generation.

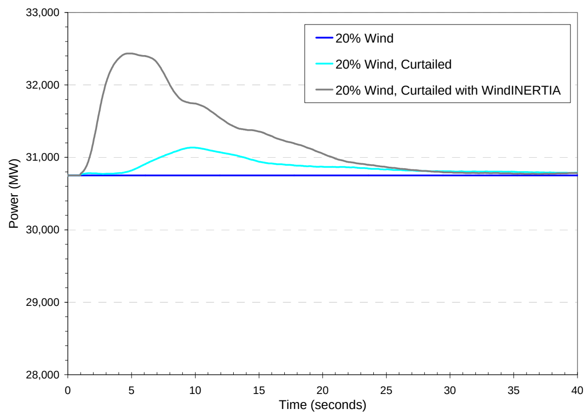

Figure 9. Impact of Curtailment on Incremental Power from WindINERTIA after Loss of Generation.

VII. Summary

The potential range of wind plant response to a major frequency excursion is substantial. The available GE plant controls examined here have a significant impact on performance. The wind plant operating point also plays a significant role. As with all system dynamics, the initial conditions and assumptions about the state and performance of other system resources are critical.

Figure 10 shows the frequency response of all of the 20% wind cases discussed above, as well as the no-wind case. In every case with an available wind plant control enabled, the minimum system frequency is above that observed in the no-wind reference case. Figure 11 shows the active power response of the plants.

It is of considerable interest to note that with 20% wind, the system performance can be dramatically better than the system without wind. Significant effort was expended to ensure that the conditions studied reflect realistic boundary conditions. In particular, the commitment and dispatch of *other system resources* reflects how the system would likely be operated. This is not to say that *all* other credible operating conditions will necessarily result in improved system frequency response. Rather, these cases show that it is technically and economically possible, with controls commercially available today, to have better system frequency response with high levels of wind generation.

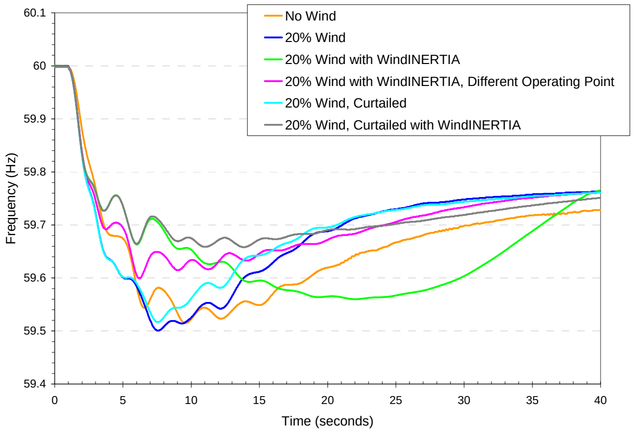

Figure 10. Summary of Frequency Performance.

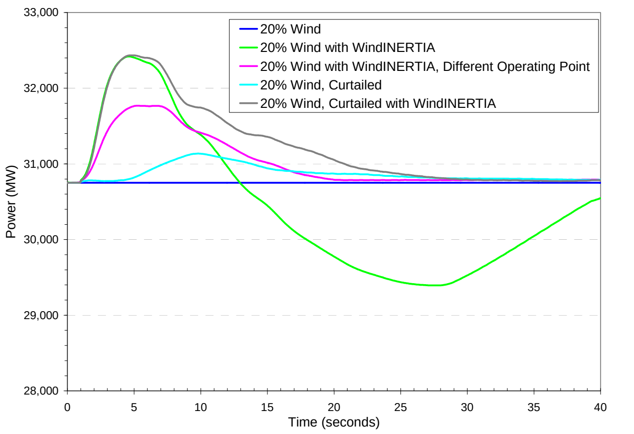

Figure 11. Summary of Wind Plant Active Power Response.

VIII. Conclusions and Recommendations

The above exploration of system frequency response with high levels of wind penetration is by no means exhaustive. It is, however, a significant first step - intended to further industry discussion and analysis of the topic. The reality of system operations, including the dispatch and commitment, are critical to understanding the impact.

With higher levels of wind and solar penetration, system operation changes. Thermal units may be de-committed as their output is displaced by lower marginal cost wind generation, or they may be dispatched to lower power levels. Many factors and constraints, both economic and physical, affect unit commitment and dispatch decisions. In a system with high wind and solar penetration, the operational flexibility of the remaining generation portfolio is key.

In the first few seconds following a loss of a large generating plant, the depth of the frequency excursion is affected by the inertial response of the on-line generation. Synchronous machines inherently contribute some of their stored inertial energy to the grid. GE wind plants with WindINERTIA control provide a functionally similar response.

The longer-term frequency response and recovery is driven by the governor action of the committed and dispatched synchronous machines. Wind does not contribute to these primary reserves unless market structures encourage it to do so. At relatively low penetration levels, the benefits of requiring or using active power management capabilities, such as governor response, may not outweigh the cost. This is nothing new, and no different from other types of generating resources that run “flat out” under the present structure. There is a system cost associated with providing this capability from *any* generating resource. The role of the system operator is to make sure that the response is there, and that the least expensive resource that can do so, is doing so. Under some conditions, wind may be the economic choice. GE wind plants with governor control provide just this type of response.

This analysis has shown that WindINERTIA has a substantial impact. The minimum frequency is improved, not degraded, with significant levels of wind generation. It is technically and economically possible, with controls commercially available today, to have better system frequency response with high levels of wind generation.

Ultimately, grid codes may be modified to include some type of inertial response requirement. The development of the inertial control feature shows that such functionality is, indeed, possible and available. However, it also shows that inertial response identical to that of synchronous generation is neither possible nor necessary. Inertial response of wind generation is limited to large under-frequency events that represent reliability and continuity-of-service risks to the grid. The crafting of new grid codes should therefore proceed cautiously and focus on functional, systemic needs.

IX. Acknowledgements

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XI. Biographies

Nicholas W. Miller is a Director for GE Energy in Schenectady, NY. He has 30 years of experience in analysis of power systems dynamics. He is currently leading analytical developments for large-scale integration of wind generation into power systems. Nick is a Fellow of IEEE, and a member of CIGRE. He is chairman of the IEEE Task Force on Dynamic Performance of Wind Generation. He was a principal contributor to the landmark New York State Wind study, and is a principal on the current California Intermittency Analysis Project. He received the 2005 Utility Wind Interest Group Achievement Award 'for Outstanding Contributions to the Advancement of Utility Compatible Wind Turbine Technology'. He is a licensed professional engineer in the State of New York. He was part of the GE team that received the 2007 American Wind Energy Association (AWEA) Technical Achievement Award "For significant contributions to understanding the technical and economic aspects of utility wind integration issues."

Kara Clark is a Principal in GE's Energy Applications and System Engineering group, which provides engineering expertise in the analysis of large-scale power systems. Ms. Clark's current focus is on the control of wind-turbine generators and wind plants, modeling for both cycle-by-cycle and fundamental frequency analysis, and analyzing the impact of significant levels of wind and solar generation on power system performance. She was a principal contributor to the New York, California, and Western Wind and Solar integration studies, and a member of the GE team receiving the 2007 American Wind Energy Association (AWEA) Technical Achievement Award and the 2010 Utility Wind Industry Group (UWIG) Achievement Award. She is a senior member of IEEE, author of many technical papers, and a registered Professional Engineer in New York.

Miaolei Shao received his Ph.D. in Electrical Engineering at Wichita State University in 2008 and his Bachelors' degree and M.S. in Electrical Engineering from Harbin Engineering University, Harbin, China, in 1999 and 2002 respectively. Since 2008, he has been with GE Energy, as a member of the Transmission Systems Consulting group. Currently, he is working on steady state, dynamic and transient stability studies.