



Role of Wind Power in Primary Frequency Response of an Interconnection

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Role of Wind Power in the Primary Frequency Response of an Interconnection

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Abstract—The practice in North America is to maintain the electrical frequency of the three major interconnections very close to its nominal level at all times. Large frequency deviations can lead to unintended consequences such as load shedding, instability, and machine damage, among others. The action of turbine governors of conventional generating units provides primary frequency response (PFR) to ensure that frequency deviations are not significant during large transient events. Increasing penetrations of variable renewable generation, such as wind and solar power, and planned retirements of conventional thermal plants—and thus a reduction in the amount of suppliers with PFR capabilities—causes concerns about a decline of PFR and system inertia in North America. The majority of wind generation is connected to the grid via power inverters. If appropriately equipped with the necessary control features, inverter-coupled wind generation technologies are capable of contributing to PFR and inertia. This capability can help alleviate those concerns. However, these responses differ from those supplied by conventional generation, and it is not entirely understood how they will affect the system response at different penetration levels. The focus of the simulation work presented in this paper is to evaluate the impact of wind generation providing PFR and synthetic inertial response on a large interconnection. All simulations were conducted on the Western Interconnection system with different assumptions of wind power penetration levels. It should be noted that the results presented here are hypothetical, so they do not claim to demonstrate the actual present of the North American Western Interconnection. Although we found little risk of events causing the need for under frequency load shedding without controls from wind power, the ability of wind power plants to provide PFR, and the combination of inertial response and PFR, gave a significant improvement in the frequency response performance of the system; providing inertia alone did not improve performance. The simulation results also showed how other individual responsive units are affected by different levels of wind power and various control strategies. Last, we provided a case study with the realistic assumption that not all conventional units would be providing PFR; whereas the provision of wind power providing PFR in high wind power penetrations actually avoided triggering under frequency load shedding. The simulation results provide insight in designing and operating wind generation active power controls to facilitate adequate PFR of an interconnection.

Index Terms—wind generation, primary frequency response, active power control, inertial control, primary frequency control

I. INTRODUCTION

The ability of a power system to maintain its electrical frequency within a specified range is a crucial element in maintaining a reliable and secure power system. An interconnected power system must have adequate resources to respond to a variety of contingency events to ensure rapid restoration of the balance between generation and load. Primary frequency response (PFR)—also called primary control reserve [1] and frequency responsive reserve [2]—is the capacity available for automatic local response to correct frequency excursions through turbine speed governors and frequency responsive demand that adjust counter-frequency deviations and stabilize frequency. System inertia is the cumulative synchronous generation and load inertia that slows the initial rate of change of frequency deviation. The combined response of PFR and inertia is essential to arrest electrical frequency changes before triggering under frequency load-shedding (UFLS) relays. In extreme cases, large deviations in frequency may result in generation protection relays operating or machine damage, or unstable frequencies that could potentially lead to a blackout.

The frequency response of the system is the aggregated result of PFR from all resources on the power system, including the natural load response. It is typically measured in MW/0.1 Hz, which measures the megawatt response provided for a 0.1-Hz steady-state frequency deviation. Other metrics have also been proposed recently that focus more on the frequency nadir [3]. The frequency response of the power system with high levels of variable generation to sudden, large imbalances between generation and load has been a focal point of many studies both nationally and internationally [3]–[5]. Currently, many variable energy resources typically do not provide PFR. Many renewable generation technologies are controlled by and interface with the grid using power electronics. As such, not only are they asynchronous, but the megawatt output of the unit is tightly controlled and maintained at a fixed value for given operating conditions. Thus, they do not inherently provide inertial response. Lower system inertia as a result of increased renewable penetration will cause increased rates of change of frequency immediately following a disturbance. Lower amounts of PFR caused by the displacement of conventional generators with active governors by variable

generation will cause greater steady-state frequency deviations.

In the United States, recent studies have suggested that the frequency response has been declining during the last several years [6], [7]. Some potential reasons for this include generators that operate in modes that do not offer PFR (e.g., sliding pressure mode) and blocked governors [8], [9]. Other reasons may include institutional reasons [10] and electricity market designs [11]. Such a decline may translate to a decrease in bulk power system reliability. In particular, the Eastern Interconnection of the United States and Canada has been seeing steady decline of approximately 60 MW/0.1 Hz to 70 MW/0.1 Hz per year during the past two decades [7]. An IEEE task force report studied the issue with great detail and developed a number of conclusions and recommendations [12]. These concerns prompted further industry-wide efforts by the North American Electric Reliability Corporation (NERC) and the regional reliability entities to broaden the understanding and increase transparency by highlighting mitigation efforts to ensure adequate frequency response. The Federal Energy Regulatory Commission (FERC)'s Frequency Response Initiative sets a number of objectives to comprehensively address the issues related to frequency response [13]. Such objectives include a) clearer identification of frequency-related reliability factors, b) improvements of frequency response metrics, and c) assessing impacts of emerging technologies, including inverter-coupled renewable energy generation. The proposed BAL-003-1 standard would set a minimum frequency response obligation for balancing authorities (BAs) within an interconnection and means for measuring their performance [14]. It requires sufficient frequency response from the BA to maintain interconnection frequency within predefined bounds. A systematic approach to identifying frequency response that is useful for operating a reliable system with increased amounts of variable renewable generation is presented in [3]. It also confirmed the validity of using frequency response as predictive metrics to assess the reliable operation of interconnected systems.

Frequency response study for the US Eastern Interconnection (EI) is described in [22], and was intended to create a meaningful baseline model for the EI for examining its frequency response to investigate the possible impacts of large amounts of wind generation. Among other useful results, this EI study demonstrated benefits of wind power providing PFR.

A typical wind power plant appears to the grid as a substantially different generation source than a conventional hydro or thermal power plant. Without special controls, a wind power plant does not participate in PFR. Further, inverter-based wind turbine generators (WTGs) (i.e., Type 3 and Type 4 units) do not, without special controls, provide any inherent inertial response. In this paper, we will present a detailed account of these two control features, PFR and inertial response, and illustrate some of the issues related to applying both these control strategies and how they might work best together. In contrast to previous studies, the focus

of this work is more on the different effects that each of these controls has on the large, interconnected system response and how the two controls can complement each other.

Many researchers and wind turbine manufacturers have proposed different designs that allow wind power plants to provide capabilities similar to PFR and inertial control [15]. The work reported here is a continuation of previous work. The initial findings of this work were described in [16], in which impacts of wind power providing separately inertial and PFR were investigated. It was demonstrated in [16] that synthetic inertial control from WTGs, if tuned properly, can significantly improve the frequency nadir during disturbances. PFR from WTGs can be tuned to provide droop-like response and can significantly improve frequency nadir as well as settling (steady-state) frequency. This paper provides further in-depth analysis of the system-level frequency response at higher levels of wind power penetration and various levels of enabled governors in the conventional fleet. This work uses many methods and assumptions used in a similar simulation study [4]. In Section II, we give an overview of the frequency response metrics used in this study. Section III provides an overview of the system and assumptions used in the study. Section IV provides results for different active power control strategies from wind power, different penetration levels, and different levels of contribution from thermal plants. Section V concludes.

II. OVERVIEW OF FREQUENCY RESPONSE METRICS

In this work, we adopted a similar approach to frequency response metrics as that described in [3]. Consider a real frequency event that took place in the Western Interconnection (WI) on August 6, 2011. This event started after a large generation loss at $t=0$ sec, as shown in Fig.1. The Point A value of frequency is the pre-disturbance frequency and is calculated as an average of frequency values from $t=0$ to $t=-16$ seconds [14]. The grid frequency started declining immediately because of an imbalance between generation and load. The initial rate of change of frequency was about -63 mHz/sec, and is determined by the amount of rotating mass (mechanical inertia) in the interconnection. The PFR of conventional generation with active governors starts to respond immediately after the frequency decline passes beyond their governor deadband thresholds. The characteristics of system inertia and PFR determine the lowest frequency (nadir), which is shown as Point C in Fig 1. The important characteristics are the system inertia, amount of PFR available, and the response speed of PFR. Point C has to be higher than the highest set point for UFLS within an interconnection. Measuring the level of Point C based on what large, credible disturbances the interconnection plans for helps determine the amount and characteristics of PFR that are needed to arrest frequency decline above the first stage of UFLS.

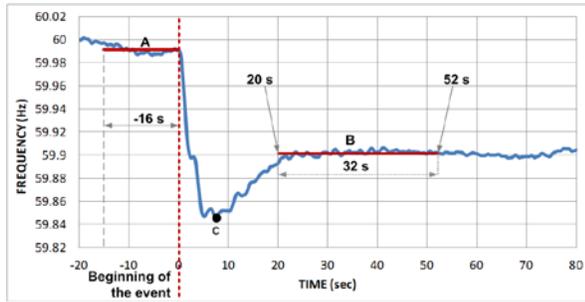


Fig. 1. Description of frequency response metrics

After the frequency decline has been arrested, continued delivery of PFR will stabilize frequency at a steady-state settling level (Point B). This point at which frequency is stabilized is often referred to as the settling frequency. The B-value is determined by averaging the frequency values from a period of 32 s starting at $t=20$ s after the disturbance [14].

The work presented in this paper is focused on assessing the impact of wind generation on the frequency response of the WI. We study this case while considering wind power as usual without any frequency response capabilities, as well as allowing wind power to have combinations of inertial and PFR response capabilities. The following frequency metrics are used in the study:

1. Initial rate of decline of frequency, or rate of change of frequency
2. Value of frequency nadir (Point C)
3. Transition time between beginning of disturbance and frequency nadir (transition time from Point A to Point C)
4. Value of settling frequency (Point B)
5. Transition time between frequency nadir and settling frequency (transition time from Point C to Point B)

According to [3], the Interconnection Frequency Response Obligation is calculated from statistical observations of many events similar to the one shown in Fig. 1. Various parameters, such as the ratio of Point C to value B (CB_R), are used in Interconnection Frequency Response Obligation calculations. For the WI, BAL-003-1 requires $IFRO = -840$ MW/0.1 Hz [14].

III. BASE CASE DEVELOPMENT AND MODELING ASSUMPTIONS

The purpose of this study is to investigate the overall frequency response of the WI with different levels of variable wind generation with enabled inertial and PFR controls using the GE Positive Sequence Load Flow (PSLFTM) dynamic simulation software. For this purpose, it was decided to use one of the PSLF base cases developed under guidance by the Transmission Expansion Planning Policy Committee (TEPPC). In particular, the TEPPC 2022

light spring load base case (model 221sp1s) with approximately 15% wind power penetration was selected as a basis for simulating future penetration scenarios. This particular base case under light spring load conditions throughout the WI and renewable penetrations is consistent with state renewable portfolio standard requirements for 2022. Generation, load, and transmission topology are based on conditions modeled in the TEPPC 2022 common case [17]. It should be noted that the results presented here are hypothetical, so they do not claim to represent the actual present or future response of the North American WI. This is a research study with the goal of identifying what realistic behavior might be expected.

It is important to note that this modeling study does not address any changes to the limits of transmission lines that will take place at higher penetration levels. Instead, we adopted an approach of replacing the existing conventional power plants with wind power plants to achieve the desired penetration levels without transmission upgrades. At the snapshots of time represented in these cases for different penetration levels, the portion of generation coming from wind power was in accordance with the results of the Western Wind and Solar Integration Study Phase 1 (WWSIS-1) [18]. WWSIS-1 examined three different wind and PV power scenarios to obtain 30% penetration across the WI footprint. For this study, it was decided to base wind power location assumptions on the “In-Area Scenario,” in which each state meets its target using best in-state resources so no additional interstate transmission is needed. The other two WWSIS-1 scenarios (“Local Priority” and “Mega Project”) required different levels of interstate transmission. In addition, the “Mega Project” scenario located most of the wind power in few best wind-resource areas, causing localized frequency response from wind power.

Five different wind penetration scenarios were studied in WWSIS-1. The level of installed wind capacity for these scenarios is different for different regions in WI. The total installed wind capacities used in WWSIS-1 are 33.24, 42.9 and 75.39 GW for 10, 20 and 30% penetration cases respectively. These numbers have been used as a guideline for developing penetration scenarios for this study. The selection of conventional thermal units that are displaced by wind power plants is based on the approach to put new wind power plants at existing large, fossil-fueled (steam) unit plants. During this high-wind spring period, these wind power plants operate within the range of 50% to 60% of rated capacity. Such approach gives an approximate but reasonable distribution of loadings on the wind power plants in the Western Electricity Coordinating Council.

The scenarios for this study were developed for four penetration cases using Equation (1) for replacing conventional plants with wind power plants:

$$\text{Total Wind Capacity} = \text{Penetration \%} \times \text{Western Electricity Coordinating Council Total Load (MW)} / 0.56 \quad (1)$$

This rule is based on an average 56% capacity factor for the wind power plants. The 56% capacity factor is based on the average capacity factor for all wind power in WI during the lowest demand hour, as described in [4]. This approach is

different from the re-dispatch methodology used in [4] that implemented the 2/3 to 1/3 rule (which means that for every 3 MW of additional wind power production, there is a 2-MW reduction in thermal unit commitment and a 1-MW reduction in thermal unit dispatch). This rule was based on the Multi-Area Production Simulation (MAPS) modeling used in [18]. In this study, we simply replaced conventional thermal units with wind power plants. This approach is a simplistic way of emulating the shutdown of steam units because of Environmental Protection Agency regulations. Clearly, detailed transmission planning and dispatch consideration are an absolutely essential part of actually planning a system; however, the focus here is on basic research.

The total light spring load in the TEPPC 2022 base case is approximately 113 GW, so the total wind power nameplate capacities for each penetration case used in this study can be calculated using Equation (1). Table I shows the nameplate capacities and generation level by wind power for each penetration case.

TABLE I. Wind Power Nameplate Capacities and Current Generation Levels

Wind Penetration Case	Total Wind Nameplate Capacity, GW	Generation Level, GW
15% base case	23	17.92
20%	41.65	22.5
30%	60.34	33.76
40%	80.45	45.19
50%	101.67	56.89

The breakdown of wind generation by turbine type for TEPPC 2022 base case (15% penetration) is shown in Table II.

For the purpose of this work, all Type 3 and Type 4 generic models were replaced with GE dynamic models for doubly-fed induction generator and full-size power-converter-based wind turbines as implemented in the PSLF dynamic simulation program [19]. These models were developed and validated specifically for the latest GE WTGs, and include an inertial control scheme and active power control emulator for PFR. The Type 1 and Type 2 wind power plants were not replaced by the GE dynamic model, so there was still a small amount of Type 1 and Type 2 WTGs present in all simulated cases.

TABLE II. TEPPC Base Case Wind Generation by Type

Wind Turbine Model	Total Nameplate Rating (GW)	Current Output (MW)	% of current output out of total current generation
Type 1 (wt1g)	0.5	425.8	0.3%
Type 2 (wt2g)	1.5	1479.6	1.3%
Type 3 Generic (wt3g)	5.4	4145.7	3.5%
Type 4 Generic (wt4g)	15.6	8631.7	7.4%
Type 3 and Type 4 GE Model (gewtg)	4.9	3238.5	2.8%

All simulations were conducted using the PSLF simulation tool. Each interconnection has a target Resource Contingency Protection Criteria based on the largest N-2 loss-of-resource event [10]. For the WI, that would be the loss of the two largest generating units in the Palo Verde nuclear facility totaling 2,625 MW [20].

Additional details on a development of a base case for this study are described in [16]. The simulations performed in [16] were to investigate sensitivity of various active power control parameters of wind generation on the performance metrics discussed above. In particular, the sensitivities to wind power providing only PFR or only inertial controls were investigated at 20%, 30%, and 40% penetration levels. In this work, we present cases with combined inertial and PFR response by wind power for various wind power penetration levels up to 50%.

A wind turbine must operate in curtailed mode to provide enough reserve for PFR response during under frequency conditions. Under normal operating conditions with near-nominal system frequency, the control is set to provide a specified margin by generating less power than is available from the unit. The reserve margin (or headroom) determines what is specified as the operational point of a wind turbine, as shown in the Fig. 2.

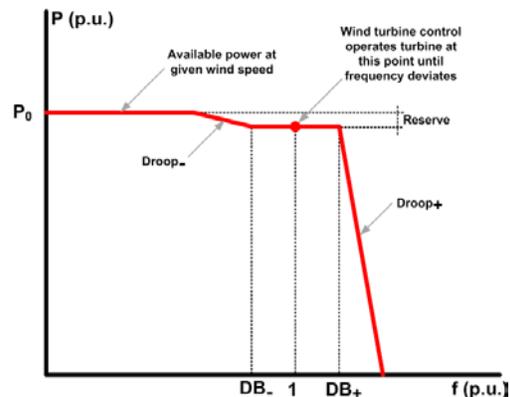


Fig. 2. Wind power droop

The inertial control provides an inertial response capability for wind turbines, emulating inertial response similar to conventional synchronous generators, for large under frequency events. The response is provided by temporarily increasing the power output of the wind turbines in the range of 5% to 10% of the rated turbine power by extracting the inertial energy stored in the rotating masses. This quick power injection can benefit the grid by essentially limiting the rate of decline of frequency at the inception of the load/generation imbalance event.

Another characteristic that influences system frequency behavior is the fraction of generators participating in governor control. This fraction (K_t) is a primary metric for expected performance first introduced by Undrill in [5]. The exact definition of K_t is not standardized. For this report, we conducted simulations to show the impact of K_t in the WI simulations using the following definition:

$$K_t = \frac{\text{MW Generation Capability of Units with Governor Response}}{\text{Total MW Capability of Conventional Generation}}$$

The lower K_t corresponds to the smaller fraction of generation providing PFR. Note that all synchronous machines will still provide inertia regardless of the K_t value. The 15% base case has a number of enabled governors that corresponds to $K_t=54.9\%$.

Table III provides a summary of the simulations performed to investigate the sensitivity of various active power control parameters of wind generation on the performance metrics discussed above. For each simulated case, the grid frequency was calculated at 10 key 500-kV buses in the WI. For visual clarity, only the average of 10 frequencies is shown in the plots.

TABLE III. SIMULATIONS PERFORMED

Case	Simulation Scenarios			
15% 20% 30% 40% 50%	No inertia, no PFC ^a	Inertia only	PFC only (5% headroom; 4% droop)	Inertia + PFC (5% headroom; 4% droop)
50%	No inertia, no PFC, $K_t=68\%$, 60%, 50%,40%	Inertia only, $K_t=40\%$	PFC only (5% headroom; 4 droop), $K_t=40\%$	Inertia + PFC (5% headroom; 4% droop), $K_t=40\%$

IV. SIMULATION RESULTS

A. Impact of Wind Power Penetration Levels and Active Power Control Strategies on Frequency Response

Figs. 3–7 show simulated frequency response for five different wind power penetration levels (15%, 20%, 30%, 40%, and 50%), and different active power control strategies from the wind power fleet. As shown, the increase of wind power penetration has a visible impact on the performance metrics: the frequency nadir and settling frequency decline with penetration levels for the base case (blue plots) as a result of non-frequency responsive wind power replacing the responsive conventional generation.

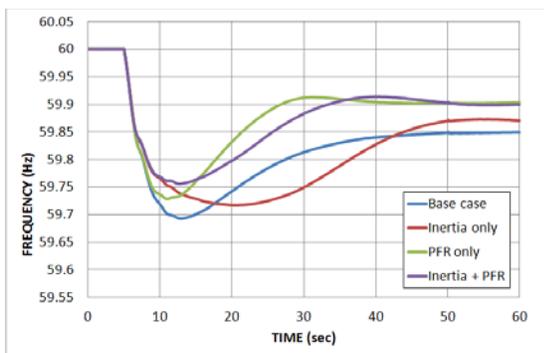


Fig. 3. WI frequency response for 15% wind power penetration

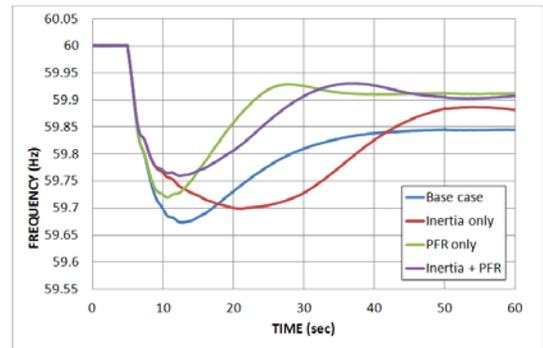


Fig. 4. WI frequency response for 20% wind power penetration

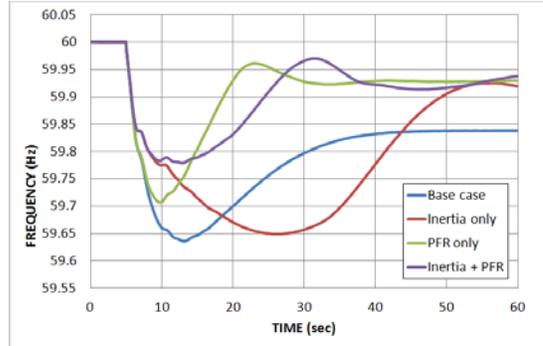


Fig. 5. WI frequency response for 30% wind power penetration

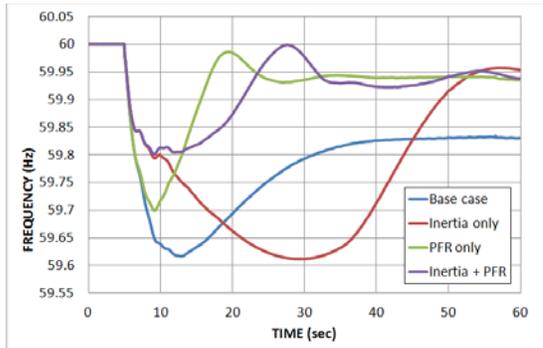


Fig. 6. WI frequency response for 40% wind power penetration

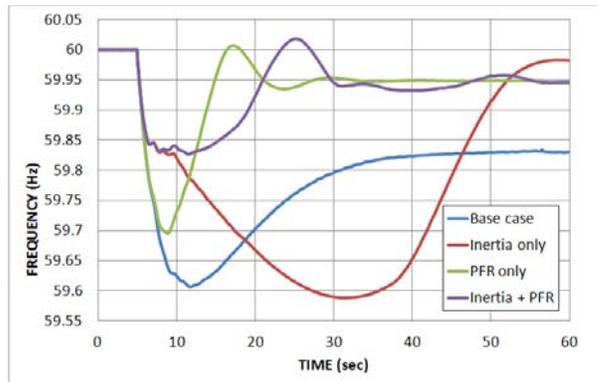


Fig. 7. WI frequency response for 50% wind power penetration

Further analysis of Figs. 3–7 reveals the impact of different active power control strategies. The inertial control by wind power (red trace) shows marginal improvement in

frequency nadir compared to the base case for lower penetration levels (Figs. 3–5). At higher penetration levels, the frequency nadir is essentially the same as the base case at 40% penetration (Fig. 6), and is lower than the base case at 50% penetration (Fig. 7). Also, the nadir transition time shifts farther and farther right with penetration levels. This is because inertial control alone only helps reduce the initial rate of decline of the frequency, which comes at the expense of slowing down wind turbine rotors. Because of this slowdown, the wind turbines depart from their maximum power point, thus creating a deficiency of active power (period of underproduction relative to the initial pre-fault operating point), and resulting in slower frequency recovery time. In addition, as shown in Figs. 3–7, the recovery is of oscillatory nature with overshoots and takes longer to settle at a steady-state frequency (i.e., there is a longer transition to Point B).

On the other hand, enabling the PFR feature creates visible improvement in frequency response, resulting in better nadir and higher steady-state frequency, as shown in Figs. 3–7 (green trace). The frequency nadir of the PFR-only case does not change significantly with penetration levels because of the same 5% headroom in all simulation scenarios. However, it is consistently higher than the base case nadir for all penetration cases. The recovery of frequency is almost as fast as in the base case, with some oscillatory behavior depending on penetration level. The biggest improvement is in settling frequency level, which in the 50% case increases from 59.84 to 59.95.

Combining inertial and PFR controls gives the most superior performance (magenta trace on Figs. 3–7). This control strategy results in a significantly higher frequency nadir with somewhat slower recovery time compared to the PFR-only case.

Fig. 8 shows the consolidated results of the simulations and the impact on frequency nadir for all penetration cases and wind power control strategies. Combining inertial and PFR controls for wind power results in a frequency nadir that is constantly increasing with penetration level (magenta trace in Fig. 8), and has the best nadir performance at any wind power penetration level compared to other control strategies.

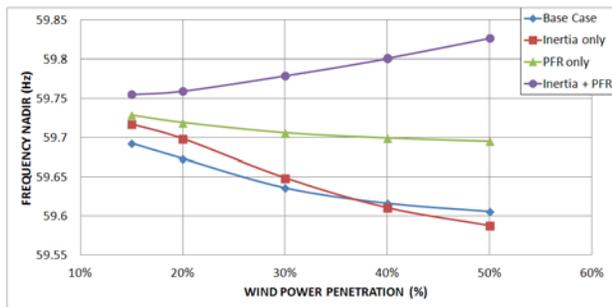


Fig. 8. Impact of wind power controls on frequency nadir

Another conclusion (mentioned earlier), also shown in Fig. 8, is that by providing inertial control only does not give significant improvements compared to the base case. In fact, starting at approximately 36% to 37% wind power penetration, inertial control leads to lower frequency nadir compared to the base case. One important conclusion from Fig. 8 is that the wind power inertial control by itself is not a

significant contributor to frequency nadir improvements on the interconnection level; however, the impact of inertial control on nadir performance is beneficial when it is combined with PFR control.

It is important to note that, despite the significant decline in frequency nadir for the base case, as wind power penetration increases (blue trace in Fig. 8) it still stays above the highest UFLS setting of 59.5 Hz in WI after the loss of the two Palo Verde units. The highest wind power penetration level, 50%, is still approximately 0.11Hz above the UFLS setting. However, it is conceivable that some extreme conditions were not envisioned in the study that may result in unsatisfactory performance. In this regard, the advanced controls by wind power can help provide improved frequency response and reliability of the power system. Advantages of inertial control by wind power can be more obvious in smaller island systems experiencing inertia response deficiencies caused by high levels of inverter-based variable generation. In such an island system, the wind power inertia may play an important role in arresting the initial rate of change of frequency. The role of wind power inertia in islands systems is a subject of separate studies and will be investigated in future work.

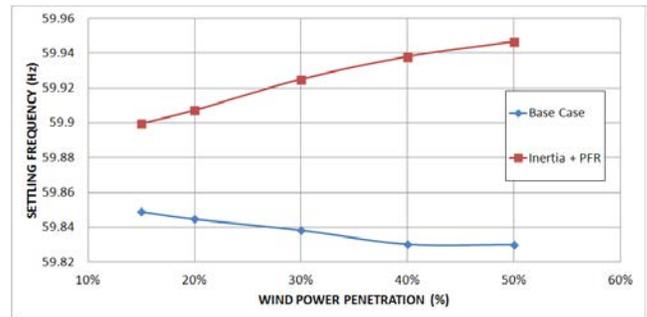


Fig. 9. Impact of wind power controls on settling frequency

The impact of wind power control on settling frequency is shown in Fig. 9. The combination of inertial and PFR controls results in significant improvements of settling frequency at all penetration levels. Similar to frequency nadir, the settling frequency also increases with penetration level when wind power provides control. The frequency response of WI was calculated from these settling frequencies and is shown in Table IV. Both MW/0.1 Hz and CB_R metrics show sufficient improvements in overall frequency response of the WI. It is worth noting again that both metrics improve with penetration level when wind power provides a combination of inertial and PFR response during the contingency event.

TABLE IV. Impact of WI Frequency Response

Case	Base Case		Inertia + PFR	
	MW/0.1 Hz	CB_R	MW/0.1 Hz	CB_R
15%	1737	2.035	2616	2.439
20%	1690	2.105	2830	2.592
30%	1623	2.250	3500	2.944
40%	1546	2.259	4232	3.208
50%	1544	2.317	4908	3.247

B. Impact of Wind Power Penetration Levels and Active Power Control Strategies on Generation Response

The active power controls by wind power will have a profound impact on frequency response of conventional generation. Such impact will become more obvious at higher penetration levels. The performance impact for selected WI conventional units during the same event is shown in Figs. 9–13. These figures allow for estimating the evolution of frequency response by combined-cycle, combustion, hydro, and nuclear units, respectively, depending on wind power penetration level and active power control strategy by wind power.

A closer look at Figs. 9–11 reveals significant reduction in the active power output of single thermal and hydro units for the cases in which wind power was providing only PFR or a combination of PFR and inertial controls. These units were selected to represent a typical response of conventional generation units for each fuel type. The power contribution from each unit type was calculated as a percentage of its installed capacity, and increases with wind power penetration level for a base case (blue trace) when all frequency response is provided by the conventional fleet. The magnitude of power contribution by conventional units is higher when wind power is providing only inertial control (red trace). This is because conventional units have to provide additional energy to compensate for periods of underproduction by wind power caused by the deceleration of wind turbine rotors. However, PFR and combined controls by wind power reduce the burden of frequency response by conventional units significantly, as shown in Figs. 9–11 (green and magenta traces).

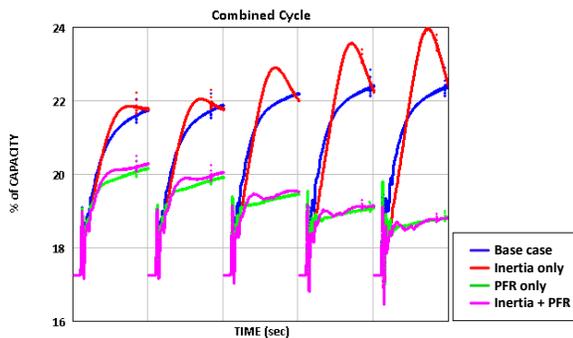


Fig. 9. Impact on combined-cycle units

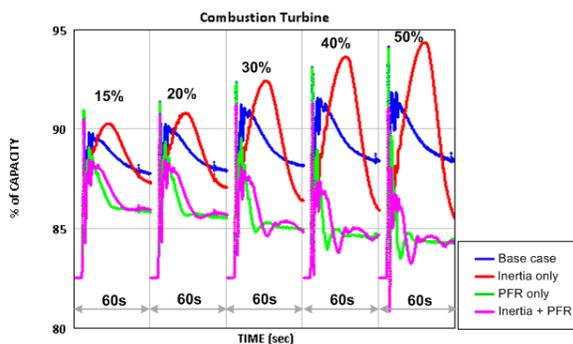


Fig. 10. Impact on combustion units

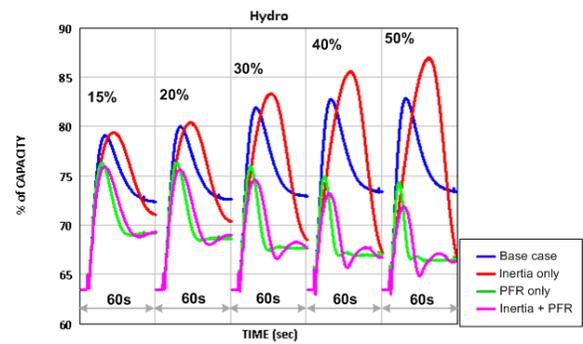


Fig. 11. Impact on hydro units

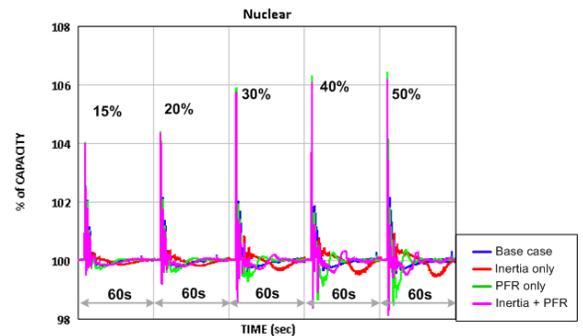


Fig. 12. Impact on nuclear units

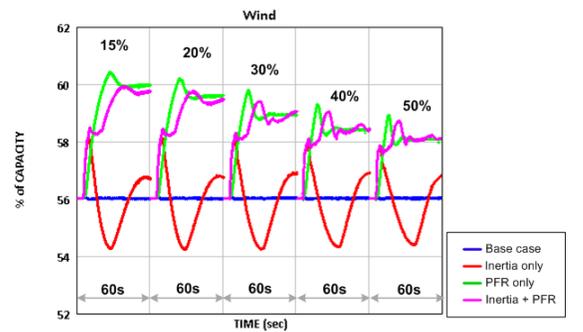


Fig. 13. Impact on wind power plants

The impact on nuclear units is less obvious (Fig. 13), because in this modeled case the nuclear power was not providing any PFR. The response of nuclear plants is only inertial and is not associated with governor response. The magnitude of such inertial response by synchronous generators is determined by the initial rate of change of the frequency immediately following generation loss.

The impact of wind power control strategies on the power output of the selected wind power plant is shown in Fig. 13. The active power magnitudes do not change significantly with penetration when wind power is providing only inertial response (red trace in Fig. 13). It does change, however, in the cases in which wind power is providing PFR or combined inertial and PFR response (green and magenta traces). In fact, the burden of frequency response on individual wind power plants decreases with penetration level because such response is spread among a larger number of wind power plants that are online.

It is important to note that the results presented here do not consider the economic impact of curtailing wind power to have 5% reserve margin to provide PFR. Based on above results, such controls tend to improve the PFR of the system. Further analysis on providing rules during unit commitment or economic dispatch procedures can help ensure sufficient response at minimal cost [21].

C. Impact of Conventional Generation Frequency Response Participation on Frequency Response

It was mentioned earlier that the simulated frequency nadir of the WI stays above the highest UFLS setting even at 50% wind power penetration with wind power providing no frequency response. Further simulations were conducted to determine the impact of K_t (as specified in Section III) on frequency nadir. Simulations demonstrated that even for the 50% wind power penetration case, it takes $K_t=40\%$ for frequency nadir to go below the UFLS setting of 59.5 Hz. This finding is illustrated in Fig. 14, in which the frequency response of the WI at 50% wind power penetration was simulated for different values of K_t . (UFLS features were disabled in these simulations.)

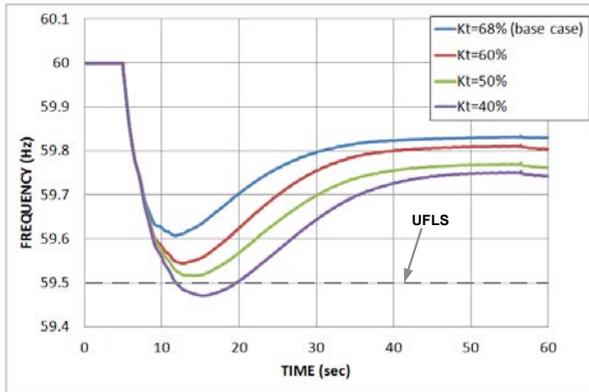


Fig. 14. Impact of K_t for the 50% penetration base case

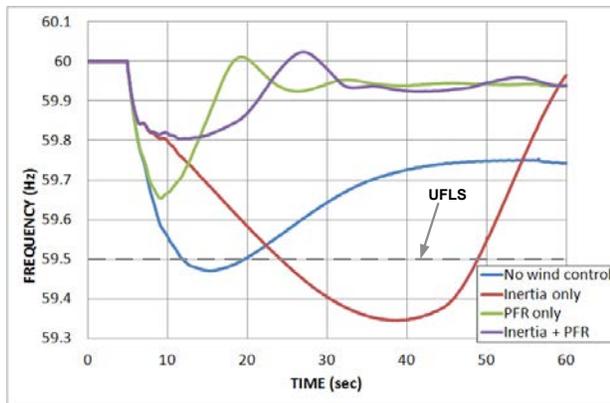


Fig. 15. Impact of wind power controls (50% penetration and $K_t=40\%$)

As a next step, we conducted simulations for the case with 50% penetration and $K_t=40\%$ to evaluate the impact of wind power active power control strategies on frequency response of the WI with reduced governor response by conventional units. The results of these simulations are illustrated in Fig.15. As expected, the inertia-only control (red plot)

demonstrates significantly lower performance compared to the base case when wind power was not providing any frequency response (blue trace). Such a high level of wind power penetration combined with fewer governor-enabled conventional generators causes a much deeper frequency nadir, slower nadir transition and recovery time, and potentially a large overshoot during frequency recovery. This simulation used the default model parameters for wind power inertial control. The inertial response from wind can be somewhat modified by further tuning these control parameters. Such parameter tuning is beyond the scope of this study, and is subject of future work.

On the other hand, both PFR and combined controls (green and magenta traces) show significant improvements compared to the base case. In particular, the combined control shows the most superior performance, resulting in shallow nadir and fast recovery time. This hypothetical simulated case demonstrates the capability of wind power controls to provide frequency response under conditions with reduced PFR capabilities by conventional generation ($K_t=40\%$) at extremely high levels of wind power penetration, when wind power can assist in ensuring UFLS relays are not triggered.

V. CONCLUSIONS

The above insights of frequency response of the WI under various penetration levels of wind power are by no means comprehensive. They are, however, an attempt to provide additional contributions to ongoing industry wide discussions on the topic of frequency response of power systems with larger penetrations of variable generation. This simulation effort was conducted specifically to investigate the frequency response of the WI after a large loss of generation and was not intended to address any stability-related impacts on transmission. Many factors and constraints (both technical and economic) affect the operation of the power system with high levels of wind generation. The depth of frequency excursions followed by generation loss can be improved by inertial and/or governor-like controls of variable-speed WTGs. The industry is concerned about having inadequate frequency response in light of this changing generation mix because of the increasing penetration of variable generation and planned retirements of fossil-fueled generation. Currently, the PFRs from generation sources are not technology neutral. To consider all options toward improving the frequency performance, the industry needs to research, develop, and demonstrate newer and less familiar sources to provide frequency support.

The focus of the research work presented in this paper was to assess the impact of different active power control strategies on the frequency response of an interconnection with a high level of wind power penetration. Inertial and PFR control from WTGs can be tuned to improve frequency response of the system and can become an additional source of flexibility for power system operators.

Finally, although not addressed in this paper, we simply note that both inertial response and PFR as provided by wind generation is inherently stochastic. This is because the wind resource is highly variable. As such, future work will need to assess the impact of the stochastic nature of this resource as

provided by wind power as opposed to inertial response and PFR provided by conventional generation, which is much more deterministic.

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