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Use of Wind Turbine Kinetic Energy to Supply Transmission Level Services

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Abstract

This paper discusses the broad use of rotational kinetic energy stored in wind turbine rotors to supply services to the electrical power grid. The grid services are discussed in terms of zero-net-energy, which do not require a reduction in power output via pitch control (spill), but neither do they preclude doing so. The services discussed include zero-net-energy regulation, transient and small signal stability, and other frequency management services. The delivery of this energy requires a trade-off between the frequency and amplitude of power modulation and is limited, in some cases, by equipment ratings and the unresearched long-term mechanical effects on the turbine. As wind displaces synchronous generation, the grid's inertial storage is being reduced, but the amount of accessible kinetic energy in a wind turbine at rated speed is approximately 6 times greater than that of a generator with only a 0.12% loss in efficiency and 75 times greater at 10% loss. The potential flexibility of the wind's kinetic storage is also high. However, the true cost of providing grid services using wind turbines, which includes a potential increase in operations and maintenance costs, have not been compared to the value of the services themselves.

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FIGURES

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NOMENCLATURE

AGC	automatic generation control
Cp	wind turbine blade coefficient
dB	decibel
DOE	Department of Energy
H	inertial constant
IP	Internet protocol
ISO	Independent System Operator
MVA	mega volt-amperes
MW	megawatts
OEM	original equipment manufacturer
PJM	Pennsylvania, New Jersey, Maryland ISO
PMU	Phasor Measurement Unit
PPA	power purchase agreement
PSS	power system stabilizer
QoS	quality of service for IP based networks
RegD	regulation 'D' market signal from PJM
RPM	revolutions per minute
SNL	Sandia National Laboratories
SWIFT	Sandia scaled wind farm technology

INTRODUCTION

The addition of wind turbines into the US grid offers tremendous benefits to our environment and energy independence. Wind integration implies the displacement of synchronous generation and has resulted in a decline of several services that are inherent to synchronous generation, such as the ability to store and release energy from rotational kinetic energy. However, using control systems, the storing and release of rotational kinetic energy in wind turbines can provide many grid services, increasing grid flexibility and resilience.

This paper consolidates some well-established principles from both literature [1] as well as practice [2], but also offers some new perspectives and ideas. The primary focus of this paper is the use of stored rotational energy in the wind turbine without the need to spill wind– that is, the need to reduce output below its maximum output to gain the ability to increase its power output on demand. This, per-se, is not a new idea but it has not been exploited to near its potential.

Wind turbines can be thought of as two distinctly different resources; a wind turbine and a flywheel storage device. The ability to access energy from a flywheel requires it to be sped up and slowed down. Doing this, however, reduces the efficiency of the wind power conversion process. But if the value of the flywheel storage exceeds the value of the lost efficiency, it will make sense to use the flywheel resource, where possible. Another limitation is the power rating of the wind turbine. For example, the delivery of stored energy requires a modulation of power output—a temporary increase above that which is already being produced—which in some cases may exceed the rating of the power electronics or mechanical limits. These issues need further research.

Surprisingly, the amount of accessible stored energy in a late model wind turbine (per installed MW) is significantly higher than in a synchronous generator, but requires operation away from maximum power point tracking set point. When operating ± 5% from the maximum power tracking point, wind has about 6 times the accessible inertial storage than a synchronous generator with a reduction in efficiency of 0.12%. However, if efficiency is allowed to decrease to a value equivalent to battery energy storage (efficiency drop of about 10%) the wind turbine can offer 75 times the amount of storage offered by a synchronous generator (see
Figure 6 and
Figure **7**).

Accessing stored rotational kinetic energy can be accomplished through the modulation of the turbine torque control signal but can impose wear and tear on the turbine. Blade stress, torsional stress, and lifetime fatigue are expected to exhibit little long-term effect from providing grid services, however more detailed research is needed. Wind turbines experience frequent changes in torque due to normal operation such as changing wind conditions, however the long-term effects of additional stress from modulating the power output is unknown. Researching this question will allow the wind turbine to safely provide grid services within its capabilities.

The safe provision of these services implies the proper selection of an amplitude and frequency band with which to modulate the turbine, which in turn restricts the amount of a particular service that can be provided. The development of cost functions for the provision of various grid services would allow the efficient and competitive use of the wind turbine when appropriate.

Terminology

This paper requires explanation of it terminology for rotational speed. The reader will see two separate symbols in frequent use—ω and Ω. General equations, such as (1) use the common notation of ω with units of radians per second. The common use of Ω to denote wind turbine mechanical rotor speed has been preserved. It is shown in figures and graphs, as is typical in literature, in units of revolutions per minute, (RPM), however its use in calculations is conducted in radians per second. Therefore, descriptions of wind turbine speed will always use the symbol Ω, always calculated in radians per second, but typically presented in RPM.

With regard to stored energy, the term E_w is used to represent the available rotational kinetic energy in a wind turbine within a rotor speed range $[\Omega_1\ \Omega_2]$. This terminology assumes the maximum difference in the operating speed range and is described by (11). Equation (15) omits the 'w' subscript because does not refer to a specific band of energy but rather derives the relationship between instantaneous power, changes in stored energy and changes in rotor RPM.

Turbine Efficiency Loss

The reader will find frequent discussion on the *efficiency loss* of the wind turbine. This terminology is intended to avoid the need to calculate overall wind turbine efficiency, which would require significant analysis, including power electronics, bearings and gears, and other electrical losses. Instead, the term relates to only the change in power due to aerodynamic efficiency as determined by (7-9). Therefore, efficiency loss is calculated as the power output while operating at a point off the maximum power tracking point divided by the power output while operating at the maximum power tracking point.

The description above still leaves room for further explanation, since the discussion on efficiency loss is being applied to a power range. A sinusoidal modulation of the wind turbine electric power output requires a continuous movement of the wind turbine RPM (between specified RMP limits). The assumption made in this paper is that the rotor RPM will spend equal time at each of these RPMs, thus providing a weighted average power output which can be compared to a maximum power tracking point for an efficiency calculation. This assumption is false for three reasons. First, since rotational kinetic energy is a function of Ω^2, the energy delivered at lower RPMs requires a faster movement of turbine RPM than it does at higher RPMs. Secondly, the delivery of energy is not typically sinusoidal, so any discussion of efficiency is actually specific to a particular service being provided (i.e. a specific energy delivered by a unique modulation of power amplitude and frequency). Finally, as Ω moves back and forth, away from the maximum power tracking point, the wind turbine output $P_w(\Omega)$ decreases then increases (see Figure 3), shaping the modulated power output with it. Avoiding this requires additional controls, introducing nonlinearities that will also affect efficiency.

One final note on efficiency is that all calculations are based on the assumption of steady-state conditions. Because of this, efficiencies presented for lower frequency modulations are more accurate than for higher frequency modulations of power. The development of control systems to implement any of these concepts would reason for the calculation of efficiencies using dynamic representations.

Bases of Comparison

The presentation of stored rotational kinetic energy in a wind turbine is difficult in that it lacks an apples-to-apples comparison to other resources. Comparisons can offer imperfect information. Finding favor in one aspect often accompanies a detriment in another. The comparisons offered are not intended to identify winners or losers, but to provide context to the potential benefits of wind. There are too many unknowns to determine winners or losers among those compared.

When comparing the stored energy to synchronous generator inertia, one finds that the storage potential from wind energy is superior. However, that is only a partial comparison, since wind turbines cannot provide dispatchable outputs. One may also argue that the changes in efficiency of a synchronous generator due to its providing frequency services is negligible, unlike a wind turbine. When compared to battery storage, wind provides significant benefit in terms of efficiency, but can't compete with the quantity of storage provided by batteries. If compared to a flywheel, the wind turbine would likely fall short on all aspects, except that it already exists, and has no additional capital cost.

ACCESSIBLE KINETIC ENERGY OF A SYNCHRONOUS GENERATOR

Rotating machines have the property of inertia, which allows them to store and release rotational kinetic energy. Synchronous machines store and release this energy automatically, without a control system because the rotor is synchronously locked with the frequency of the grid. As grid frequency falls, the rotor slows and the stored energy is released in the form of electrical power [3, 4].

IEC 34-1 specifies frequency design limits for synchronous generators, although normal variations of frequency are narrower. In order to make a fair comparison of the accessible stored energy between synchronous generation and wind turbines, one needs to understand how much stored energy is accessible, not how much is stored.

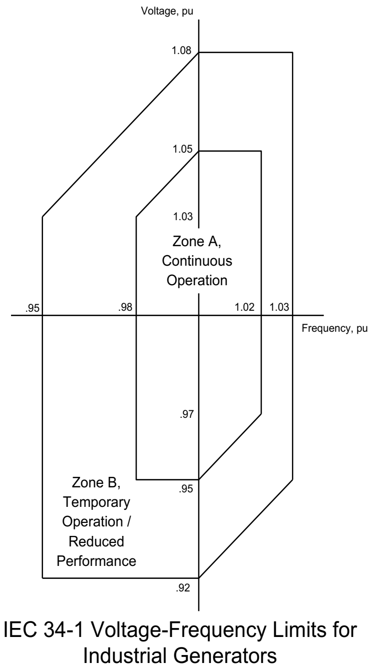


Figure 1 IEC 34-1 Voltage-Frequency Limits for Industrial Generators [5, 6]

The mass of the combined turbine-generator rotors store kinetic energy by the following relationship.

$$Rotational\ Kinetic\ Energy = \frac{1}{2}J\omega^2 \tag{1}$$

The constant, H is the value of energy stored in a rotor when its spinning at rated speed, ω, with units pu-sec or second [4]. (3) relates the H value to the inertial constant J.

$$H = \frac{Stored\ energy\ at\ rated\ speed\ in\ MW{-}sec}{MVA\ rating\ of\ the\ generator} \tag{2}$$

$$H = \frac{J\omega^2}{2 \cdot MVA\ Rating} \tag{3}$$

A 100 MVA rated synchronous generator may have H = 4 sec, corresponding to 400 MWs stored energy at rated speed. But the frequency of the grid must be maintained between tight tolerances. Therefore, only a portion of the stored energy is accessible; that which corresponds to deviations in frequency. Given the generator frequency design criteria of +3% to -5% specified by IEC 34-1, one can calculate the amount of useable stored energy in a turbine generator using (4, 5).

$$\frac{H}{E_{stored}} = \frac{\frac{1}{2}J\omega_{rated}^2}{\frac{1}{2}J\omega_{stored}^2} \tag{4}$$

$$E_{stored} = H\frac{\omega_{stored}^2}{\omega_{rated}^2} \tag{5}$$

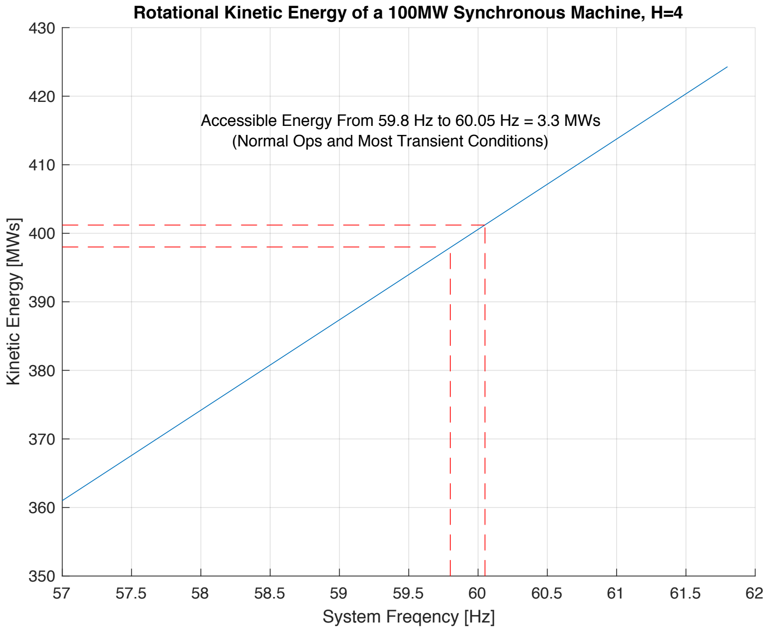


Figure 2 Description of Accessible Rotational Kinetic Energy of A Synchronous Turbine Generator (H=4)

The diagonal line in Figure 2 shows that the amount of available stored energy in 100 MW of synchronous generation is 63.3 MWs when operating within IEC 34-1 limits, but these limits are far broader than system frequency variations. A realistic frequency range is 59.8 Hz to 60.05 Hz, which covers nearly all normal and transient conditions [4]. Within this more realistic range, the accessible stored energy is 3.3 MWs.

ACCESSIBLE STORED ENERGY IN A WIND TURBINE

Wind turbines also have inertia resulting in stored rotational kinetic energy, but the ability of a wind turbine to store and release energy to the grid is decoupled from system frequency. Therefore, the strict comparison of inertial constants (H-values) between synchronous machines and wind turbines is not relevant. This fact, however, offers more opportunities than problems. Controllers can be designed to store and release energy at the most optimal times, for any purpose. This affords wind turbines a high degree of flexibility.

Although wind turbines have a similar H-value [7] as typical synchronous machines, their accessible stored energy is disproportionately higher. The stored rotational kinetic energy available in a wind turbine is a function of its rotor speed, not grid frequency. Although H remains the same at all power levels, the stored energy of the wind turbine increases as the rotor RPM increases.

Amount of Accessible Wind Turbine Stored Energy

Just as the construction of Figure 2 required assumptions regarding the system frequency, the calculation of accessible stored energy capacity in a wind turbine requires similar assumptions. The assumed ± 5% of optimal rotor speed was based on a reasonable attempt at minimizing the losses due to off optimal operation using visual inspection of Figure 4. (7-9) describe the power output of a GE wind turbine as a function of its rotor speed [8]. Figure 3 shows this power output with a shaded region showing ± 5% of optimal power (denoted by *).

$$C_p = \frac{1}{2}\left(\frac{RC_f}{\lambda} - 0.022\beta - 2\right) e^{-0.255\frac{RC_f}{\lambda}} \tag{7}$$

$$T_w = \frac{.5\rho\pi R^2 C_p V_w^3}{\Omega_{Rot}} \tag{8}$$

$$P_w = T_w\Omega_{Rot} = .5\rho\pi R^2 C_p V_w^3 \tag{9}$$

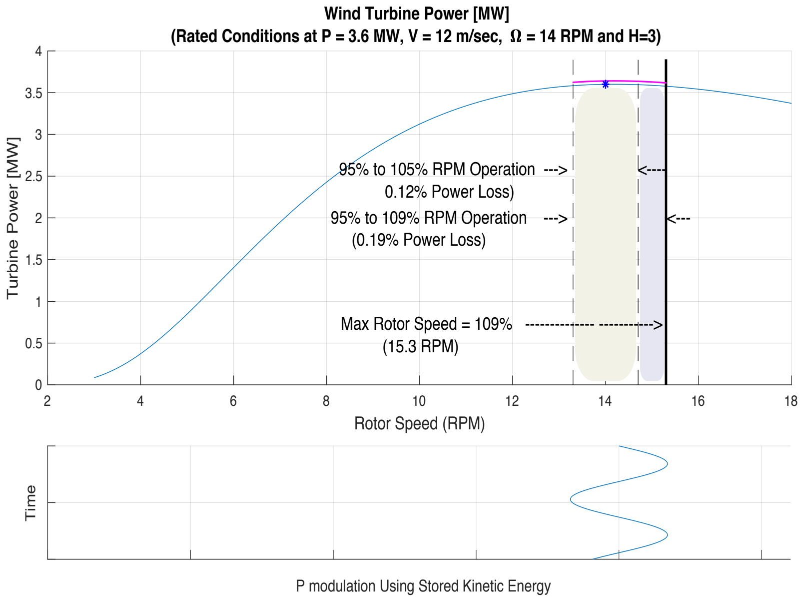


Figure 3. Operation of a Wind Turbine to Provide Balancing Services. Efficiency Loss is 0.12% with Rotor Speed at 14 RPM ±5%

For a given wind speed, operating at higher or lower rotor RPMs results in movement along the blue power curve. Moving this operating point with time modulates the real power output in accordance with control system parameters. Controlling this operating point (*) between an upper and lower limit should be thought of as controlling the state-of-charge.

Figure 4 shows the same GE wind turbine at two different operating conditions. The larger graph depicts operation at rated conditions. The smaller graph depicts operation with reduced wind velocity. One can see that a lower power output offers higher energy storage at decent efficiency (similar to a battery storage device) when utilizing its upper range of available rotor speed. Although most any point under a power curve be selected for operation, values that are underneath the curve are less efficient, and represent spilling wind to provide continuous power reserve.

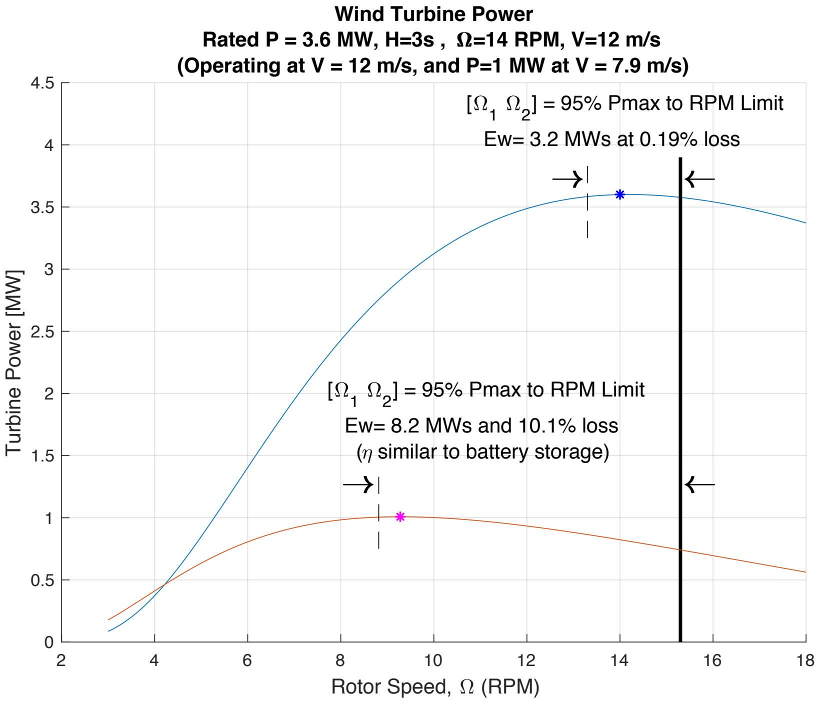


Figure 4 Efficient Access to Energy Storage Increases for Lower Operating Outputs

Losses in Wind Turbine Stored Energy

The range for rotor speed above $[\Omega_1\ \Omega_2]$ was selected somewhat arbitrarily, but it could have been selected optimally. The selection of an operating range $[\Omega_1\ \Omega_2]$, will always identify a unique energy E_w that can be accessed, described by (11). However, $P_w(\Omega \in [\Omega_1\ \Omega_2])$ will not necessarily be maximized for this selection since neither power nor energy is symmetric around P_{max}. Thus, we desire to choose the range $[\Omega_1\ \Omega_2]$ to concurrently meets our required storage needs, E_w and maximize P_w across $[\Omega_1\ \Omega_2]$. This can be accomplished by minimizing Area A shown in Figure 5. (10-12) define a nonlinear optimization to determine this optimal range [Ω_1 Ω_2] for any given energy capacity, E_w.

$$\min A = min \int_{\Omega_1}^{\Omega_2} P_w^{max} - P_w(\Omega)\, d\Omega \tag{10}$$

subject to the constraints

$$E_w = \frac{H}{\Omega_{rated}^2}(\Omega_2^2 - \Omega_1^2) \tag{11}$$

$$\Omega_2 \leq \Omega_{\max rotor} \tag{12}$$

The area shown in Figure 5 represents the loss in power efficiency due to operating away from the maximum power tracking point (ignoring inefficiencies from mechanical and bearing losses, which are first order losses as a function of Ω).

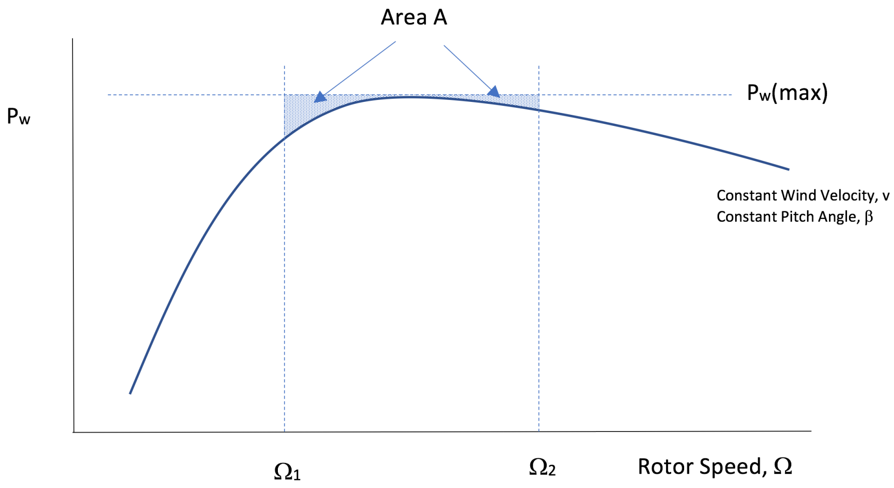


Figure 5 Losses as a Function of Accessible Energy Stored

The solution of (10-12), shown in
Figure 6, results in an optimal range [Ω_1 Ω_2] for each energy storage value E_w. At most wind speeds, any value of E_w is possible to select, given that it is below its stored inertial energy for its rotor RPM limit. For this turbine, there is 10.8 MWs of stored energy at rated speed, and slightly more at its rated rotor speed limit. For selections of E_w greater than about 2MWs, Ω_2 becomes constrained at the maximum allowable RPM, resulting in increasing loss.

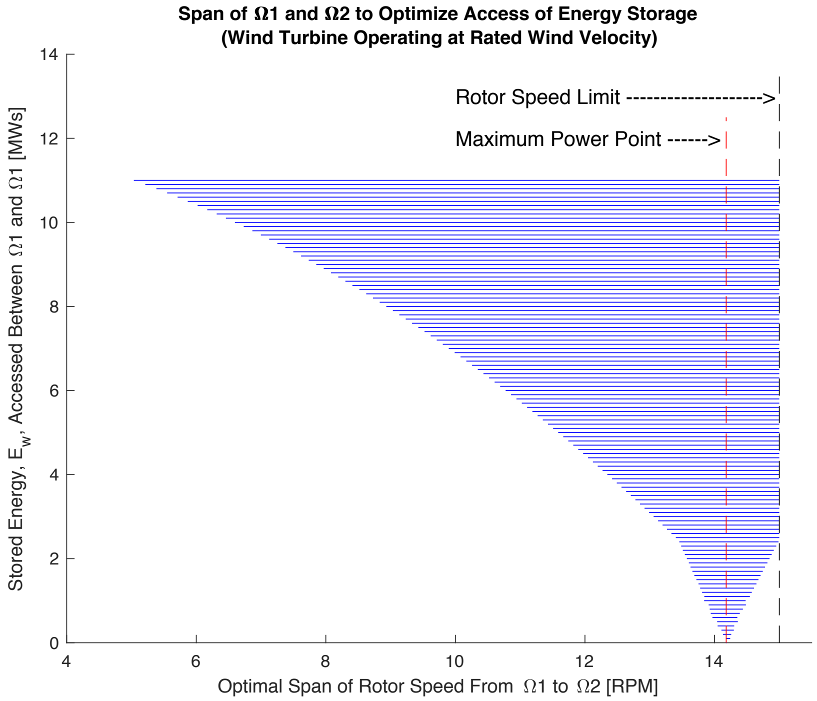


Figure 6 Optimal Selection of [Ω1 Ω2] to Minimize Wind Turbine Loss for a Given Stored Inertial Energy

Figure 6 was calculated for the turbine's rated condition of 12 m/s wind velocity. At lower wind velocities, the optimal power tracking point will shift to the left resulting in fewer values that are constrained by the maximum rotor limit. Thus, a different curve exists for wind velocity and blade pitch angle.

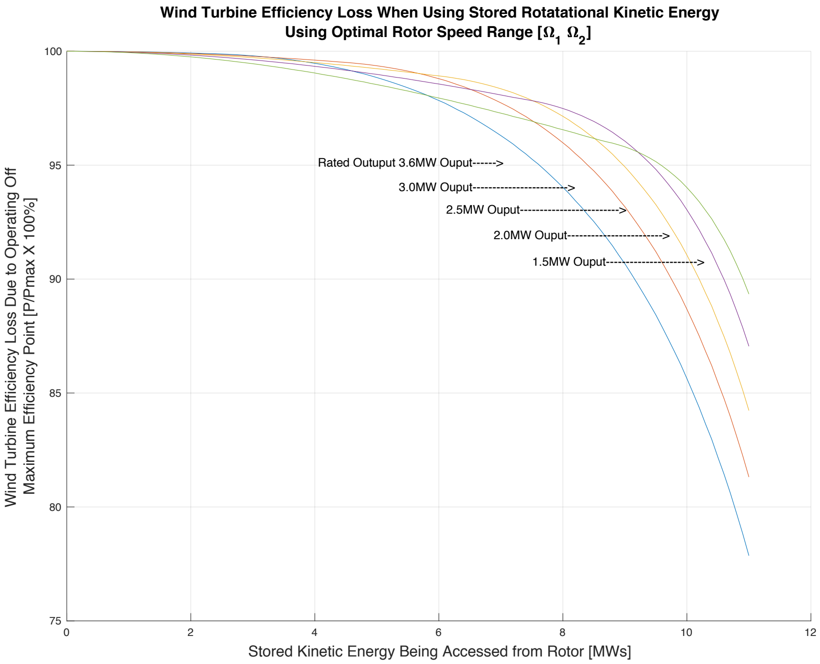


Figure 7 Efficiency Loss Versus Accessible Stored Inertial Energy from a Single GE Wind Turbine at Various Power Outputs

As the spread of [Ω_1 Ω_2] increases, the drop in the P_w curve reduces operating efficiency further. Figure **7** identifies the decrease in efficiency when higher values of stored energy, E_w are accessed. The figure identifies efficiencies for five different wind turbine power outputs. There is significant asymmetry associated with these curves due to the changes in shape of the power curves for different power outputs, changes in shape of the integral curves, and the location of the maximum power output as referenced from the maximum rotor speed limit.

For purposes of comparing a wind turbine inertial storage to that of a synchronous generator, the value of wind turbine efficiency must be selected, which was selected as the efficiency of the most cost-effective alternative. Battery systems operate near 90% round trip efficiency, so the amount of wind turbine storage at that efficiency equates to 9 MWs per wind turbine or 250 MWs per 100 MW of capacity (operating at rated output). Notice, however, that lowering the output of the wind turbine actually increases the efficiency of its stored energy. This is due to the flattening of the power curve and can be visualized in Figure 4. As shown in (13), the ratio of stored energy of wind turbine to a synchronous generator, given a 10% reduction in wind turbine efficiency, results in a factor of 75.

$$\frac{E_w^{\eta_{drop}=10\%}}{E_{Synch\,Gen}^{f_{sys}\in[59.8\,Hz\ \ 60.05\,Hz]}} = \frac{250\,MWs}{3.34\,MWs} = \text{Factor of 75} \tag{13}$$

For an alternative comparison, we select a wind turbine efficiency bound of 97.5%. This corresponds to the approximate efficiency of an electric generator, albeit, the comparison holds little value beyond a point of reference since the generator itself does not lose efficiency through its provision of inertial storage. At 97.5% efficiency, we can utilize 6 MWs of energy per 3.6 MW wind turbine. At 100 MW capacity, this value equates to 167 MWs, and a factor of 50.

$$\frac{E_w^{\eta_{drop}=2.5\%}}{E_{Synch\,Gen}^{f_{sys}\in[59.8\,Hz\ \ 60.05\,Hz]}} = \frac{167\,MWs}{3.34\,MWs} = \text{Factor of 50} \tag{14}$$

Power Modulation

The use of stored kinetic energy to modulate real power occurs by changing the rotor speed within the bounds of (Ω_1, Ω_2). This can be done through the development and use of a controller to follow a power signal such as a RegD zero-net-energy regulation signal [9]. The energy used to modulate the power is shown in (15) and the power can be obtained from (17).

$$E(t) = \frac{H}{\Omega_{rated}^2}\Omega^2(t) \tag{15}$$

$$P_{mod}(t) = \frac{\partial E}{\partial \mathrm{t}} = \frac{\partial E(\Omega)}{\partial \Omega(\mathrm{t})}\frac{\partial \Omega(\mathrm{t})}{\partial t} \tag{16}$$

$$P_{mod}(t) = \frac{2H}{\Omega_{rated}^2}\Omega(\mathrm{t})\dot{\Omega}(t) \quad (17)$$

Notice in (17) that power is accessed from the stored energy only when rotor speed is changing, as denoted by $\dot{\Omega}$. This makes sense since the stored rotor energy must change in order to access it. Alternatively, the wind turbine has stored energy at an arbitrary operating point Ω, but unless it changes, it cannot be harnessed.

As the wind turbine follows a control signal, it will adjust Ω and $\dot{\Omega}$ to ensure it operates across the entire range of $[\Omega_1\ \Omega_2]$. If it is desired to access more or less energy, the range of $[\Omega_1\ \Omega_2]$ can be modified per
Figure **6**.

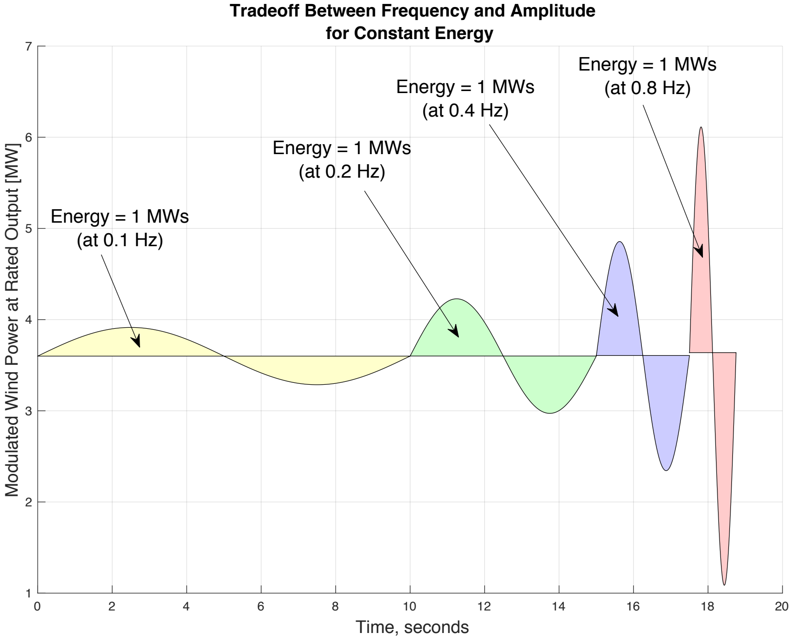


Figure 8 Comparison of Power Modulation Frequency and Amplitude for Constant Energy Delivered

The modulation of power is limited by its power electronics ratings and other mechanical wind turbine limits such as torque limits. If the wind turbine is already putting out its rated steady state capacity (in this case, 3.6 MW), its modulation of 1 MWs at 0.8 Hz implies ±2.5 MW for a total power output between 6.1 MW and 1.1 MW. At lower steady state wind output levels, for example 1 MW, the modulation signal will peak at 3.5 MW, below its rating, but its minimum modulation peak will be constrained to zero, as a -1.5 MW modulation power would imply motoring the wind turbine.

Lower frequencies require less power as can be seen in Figure 8. The necessary power to deliver an amount of energy is also dependent upon its wave shape. For example, if the wave shape of the power modulation were square, it would deliver more energy than if it were sinusoidal. For applications such as stability modulation, this type of bang-bang control could yield greater effectiveness if power limits were constraining. Additionally, the power ratings of electrical equipment, including power electronics are normally based on heating effects. Given that heating cycles with power output, the power modulation ratings could be increased beyond the steady state ratings, to achieve equivalent thermal ratings. Each grid services being provided will require its own unique frequency content, which will constrain the wind turbine power output based on its capabilities.

Expanding Resilience and Flexibility

The shaded region shown in Figure 9 represents a combination of using blade pitch control (β control) and rotor energy storage. A change in blade pitch will optimize the aerodynamic efficiency of the wind turbine for a given wind speed, or prevent an over-speed condition when the wind exceeds the turbine's rated velocity. Blade pitch can also be used to artificially lower power below it capability, known as spilling wind. This is done to gain the option of increasing its power, which would otherwise not be possible. Spilling wind via pitch control gives the wind turbine an unlimited energy reserve but constrained to a power output. For low frequency modulation, pitch control can provide continuous energy, but at a high cost. For higher frequency modulation, accessing stored kinetic energy via torque control is very efficient. Combining these two methods can provide very flexible and resilience operation. Just as ISOs dispatch additional reserves during storms, which provide flexibility and resilience at an added cost, the use of these two methods of control can provide similar flexibility at added temporary cost.

A controller must dynamically position the operating point within the shaded region to most economical point to provide a particular service. The expansion of the shaded region (beyond what is shown) implies an increase in operational flexibility at higher operating cost. So far, the explanations provided have not discussed wind dynamics, which will complicate the approach to identifying optimal solutions as wind velocities change, but will not change the underlying principles. For any grid service application such as frequency regulation, a unique bounding of $\beta \in [\beta_1 \ \beta_2]$ and $\Omega \in [\Omega_1 \ \Omega_2]$ need to be selected to maximize the ratio of service provided per the cost to provide it. The rotor speed range $[\Omega_1 \ \Omega_2]$ will offer maximum efficiency and should be utilized before β limits, however they offer finite energy and thus limited power duration. Blade pitch (β) limits, however, offer long term power duration, but lower efficiencies. Combining the two types of modulation can offer even more flexibility, but the boundaries of pitch and rotor speed must be optimally selected for an objective related to a grid service of interest. After the boundaries are efficiently selected, an optimal control system must be defined to operate efficiently within them, a topic for further study.

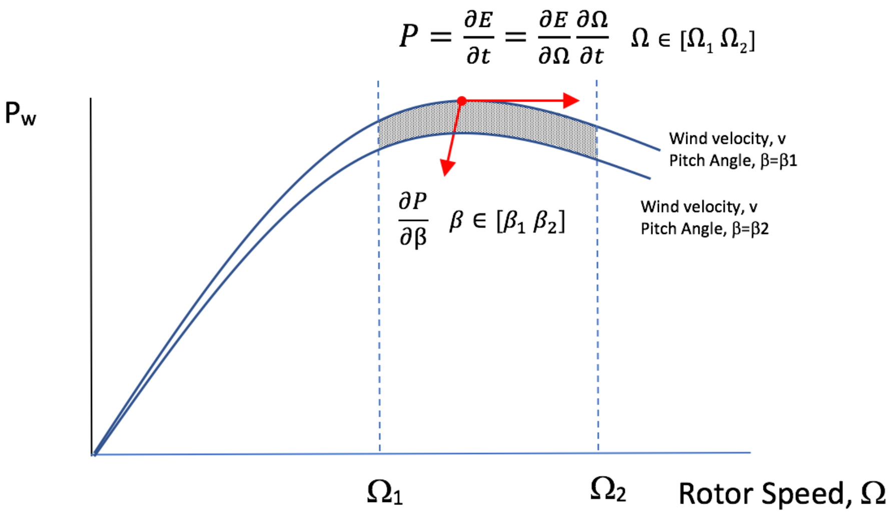


Figure 9 Expanded Grid Flexibility from Wind Turbine Operation Can Use Both Storage and Spill (Blade Pitch/β Control)

Wind Turbine Mechanical Topics

Blade stress, torsional stress, and lifetime fatigue are expected to exhibit little harm while providing grid services, however more detailed research is needed on these topics, which will be unique to each turbine design. This same analysis should be used to understand whether low to mid frequency mechanical modes might be excited during modulation. Wind turbines experience frequent changes in torque due to normal operation such as changing wind conditions, however the long-term effects of additional stress from modulating the power output has not been studied. Researching this question will not provide a yes-no answer regarding possible harmful effects, but will allow the wind turbine to safely provide grid services within its capabilities. The safe provision of these services implies the proper selection of amplitude and frequency band with which to modulate the turbine, which in turn restricts the amount of a particular service that can be provided. It is likely possible to determine the change in O&M costs as a function of providing different levels of grid services. In this case, a cost function can be developed which represents the cost of providing a particular grid service, allowing the selective and competitive use of the wind turbine only when appropriate. This approach can also help to identify resilience and grid flexibility options when needed.

Modulation of a Vestas V27 wind turbine was conducted at low amplitudes for the demonstration of system balancing and system stability [10]. This wind turbine, like all, has several resonant mechanical modes. The details of the turbine are provided in [11], but this relatively small turbine has a tower height of 30 m and a maximum tower diameter of 2.4 m, providing it with somewhat higher resonant modes. The mechanical modes for this turbine were identified using both ANSYS finite element model as well as BModes beam model, which agreed well.

Figure 10 is commonly called a Campbell Diagram, and denotes various resonant modes that exist within the Vestas V27 wind turbine. Through inspection, one can see that the primary operating region is between 0pu and 1pu rated rotor speed, although the diagram extends to 5pu rotor speed. The diagonal lines, each of which are bound by dotted lines, represent harmonic excitations caused by the three-bladed rotor. Therefore, at each rotor speed, three different frequencies will be excited due to blade harmonics.

When modulating turbine torque command to accomplish a grid service, an excitation frequency (or band) is considered. Each mode represents a different type of resonance, which responds to different orientations of mechanical excitation. For the use cases of concern, there are two resonant modes of significance, and one mode of greater importance. A tower mode at 1 Hz was to be avoided. Most importantly, there is a 2.5 Hz drivetrain mode that should not excited during operation. Other modes, less important to the type of excitation imposed, include 2-2.5 Hz and 7 Hz blade flapwise modes, a 3 Hz blade edgewise mode, and a second tower mode at 9 Hz.

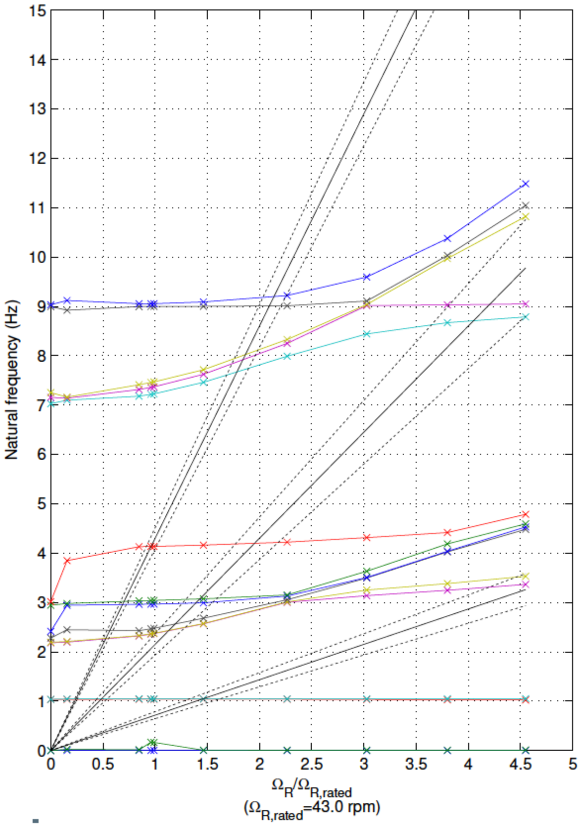


Figure 10 Aeroelastic Frequencies (modes) for the Vestas V27 Wind Turbine at the Sandia SWIFT Facility in Lubbock, TX

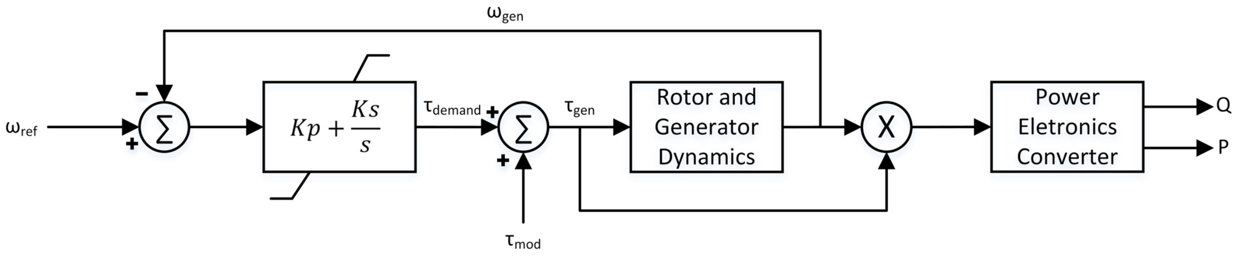
USE CASES

Using Wind to Aid System Balance

There has been significant literature on the use of wind turbines for managing frequency nadir during a system transient, but little related to zero-net-energy up or down regulation, using stored rotational kinetic energy, as was accomplished by Sandia on a Vestas V27 Wind turbine generator in Lubbock, TX [10].

For most machinery, frequent changes in output can increase fatigue and wear. The use of wind turbines to manage zero-net-energy frequency imbalance will cause near instantaneous change in power output, and torque (but not rotor speed). However, the long-term effects are unknown for the provision of various grid services.

Figure 11 provides a basic depiction of the wind turbine control system modification used to modulate the turbine, although a more detailed model, specific to the Vestas V27 turbine was used in calculations. A larger block diagram, shown in Figure 13, shows a switch that selects between using grid frequency for balance or for system stability.



ω_{ref}	Reference rotor and generator speed
ω_{gen}	Speed of rotor and generator
τ_{demand}	Torque Demand from wind turbine controller
τ_{mod}	Torque modulation from wide-area controller
τ_{gen}	Torque to generator applied to rotor

Figure 11. Simplified Wind Turbine Control for System Modulation

There are two practical ways of controlling the wind turbine to accomplish the task of mechanical energy storage and release. These are blade pitch control and torque control. The second is the most responsive, efficient, and easiest to implement. Blade pitch control is slower, and would not allow for real power control of frequency bands greater than about 0.5 Hz, which corresponds to about a 2 second time constant. Additionally, the use of pitch control is typically less efficient that using inertial storage. By managing the power output more directly, these controls were layered, and were able to very quickly store and retrieve energy from the turbine blades and rotor system. If the electrical energy leaving the inverter does not equal the wind energy entering the turbine blades, then excess energy is ‘trapped’ in the turbine blades as rotational kinetic energy.

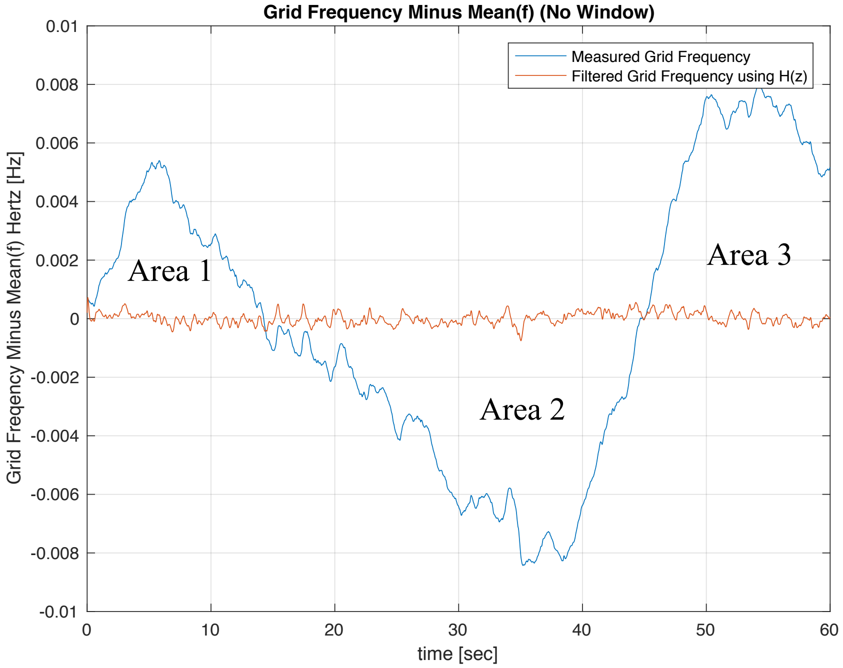


Figure 12 De-trended WECC Grid Frequency, and its High Pass Filtered Output

Figure 12 presents a de-trended frequency signal, randomly selected from the WECC system. The filtered signal results from passing the measurement through a filter identified by (18). Conditioning the signal establishes the frequency spectrum and amplitude at which the modulation occurs. The proper selection of parameters in (18) ensures that the wind turbine will not exceed its shaft RPM band limits [Ω_1 Ω_2], nor create excessive changes in torque.

$$H_f(z) = \frac{0.29-0.29z^{-2}}{1-1.56z^{-1}+0.62z^{-2}} \tag{18}$$

Even small to moderate amounts of wind capacity can have significant value for the grid. The WECC frequency signal shown in Figure 12 identifies three areas, each with energy supplied (or taken) from synchronous generators in the WECC. The areas do not reflect the overall system balancing needs, but do provide context in terms of wind generation's capability to manage system balance. Table 1 identifies the amount of wind required to balance the remaining frequency deviation. As shown by Figure 6, much more storage is accessible by expanding wind shaft RPM limits [Ω_1 Ω_2]. As a point of comparison, the Pacific Northwest, located in the WECC, contains about 7 GW of deployed wind capacity.

Table 1 Wind Capacity’s Ability to Provide System Balancing. System inertial response is approximately 5.5 GW/Hz

Area Number from Figure 12	Representative Energy as Measured using WECC Inertial Response	Capacity of Wind Needed to Supply the Energy Using Wind Turbine Inertia (staying within ±5% of optimal rotor speed)
Area 1	214 MWs	1.1 GW
Area 2	-695 MWs	3.5 GW
Area 3	481 MWs	2.4 GW

Wide-Area Stability

Several papers have been written on the use of real power modulation for damping small signal stability modes [12, 13]. Recently, this work has been shown to be effective in the WECC by modulating the Pacific DC Intertie between Celilo, OR and Sylmar, CA [14]. Sandia National Laboratories, Baylor University, and Group Nire implemented a modification of that control algorithm and modulated the real power of a Vestas V27 wind turbine located at the SWIFT wind test site in Lubbock, TX [15] . Since control had already been validated, the demonstration was not intended to effect small signal stability of the grid, rather to prove feasibility, which included turbine controllability and latencies associated with PMU communications feedback as shown in Figure 13.

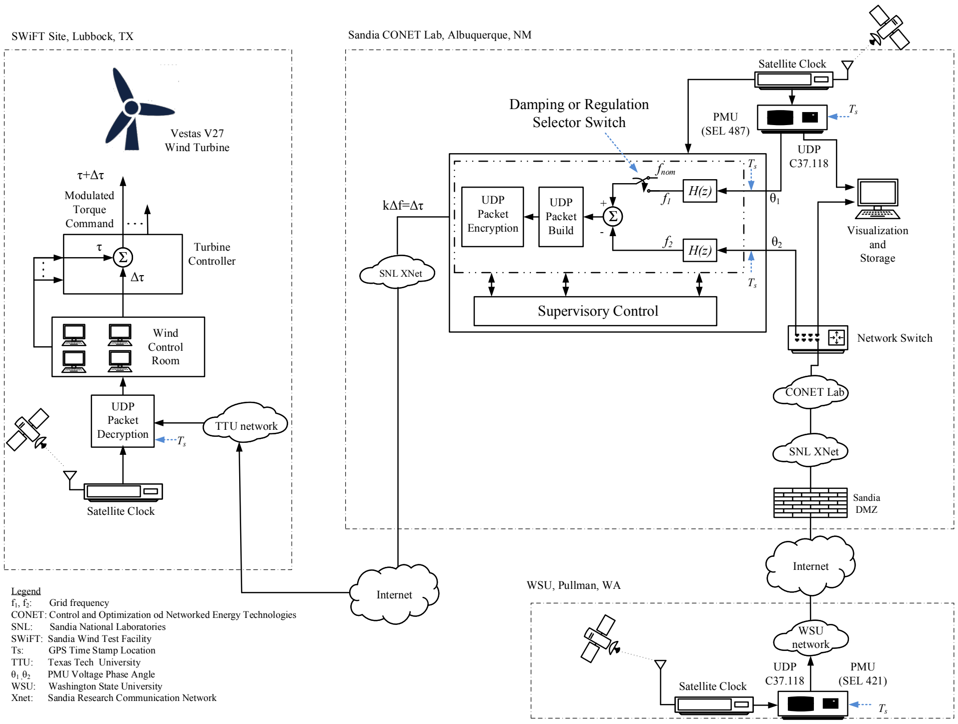


Figure 13. Block Diagram of Wind Modulation for Grid Stability Control and Regulating Reserves. This Control was Successfully Tested on a Vestas V27 Wind Turbine at the SWIFT Wind Facility in Lubbock, TX [16]

Arresting Frequency Nadir

The frequency nadir of a synchronous system is defined as the lowest level that system frequency dips during a loss of a large generation event [17]. There have been a number of papers written on this subject, some of which utilize the spill and/or discharge of rotor inertia to provide the means of injecting power during a frequency event [18-20]. GE's WindCONTROL™ system is an example of an implemented system control that accomplishes this function [2].

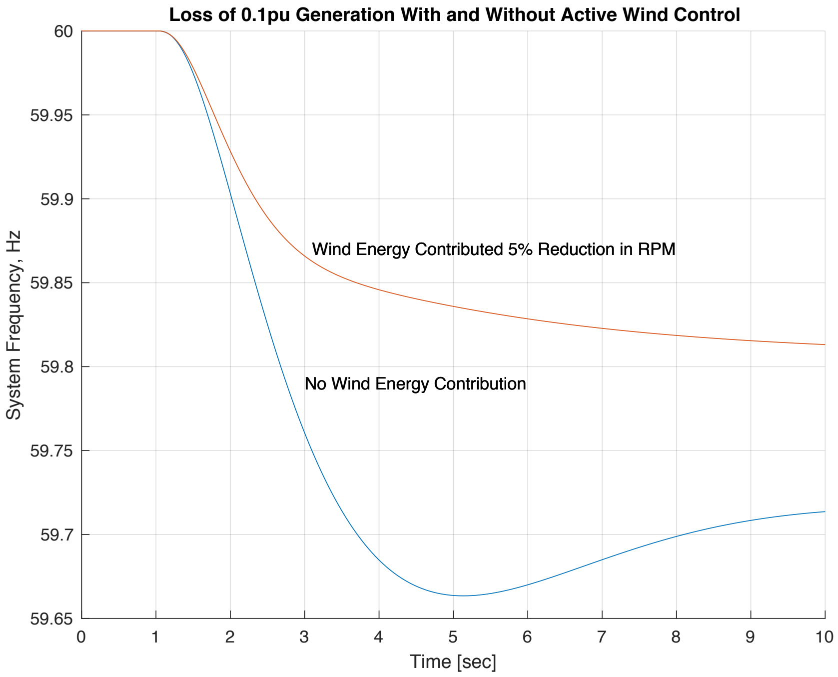


Figure 14. System Frequency Resulting From 10% of System Synchronous Generation Tripping Off Line. Equal Amounts of Wind Energy (H=4) and Synchronous Generation (H=4) Assumed for this Example.

Figure 14 shows the effects of a sudden imbalance on a simple grid model from [4] (fig. 11-20). The model was modified to allow an additional frequency feedback, which injected stored kinetic energy from wind turbines into the grid, totaling a 5% decrease in wind turbines' RPM. The assumption within the model compares the effects of generation capacity in a system, split evenly between synchronous generation (H=4) and wind generation (H=4). For fairness, the wind output was assumed with a lower kinetic energy associated with 85% output. This fact decreased the amount of stored energy in the wind turbines available for frequency restoration. Although the sustained output of excess wind power is not possible, the time bought through this control action can improve reliability, provide time for AGC systems to operate, and save money.

Managing Transient Stability

There are several ways of managing transient stability, including the restriction of transmission line flows, adding of high speed relaying, synchronous condensers, FACTS units and braking resistors. The ability to increase transient stability margin using stored energy from wind turbines is also possible. The transient stability margin of a synchronous machine decreases as its steady state output nears a power angle of π/2 radians [4, 21]. This happens due to a loss of available deceleration power due to the physics of the rotating machine. Referencing Figure 15, when a line fault (with impedance) occurs at $\delta = \delta_o$, the electrical output power curve jumps from curve P_{e1} to curve P_{e2}, caused by a decrease in system reactance. But the mechanical power, P_m, does not decrease instantly, therefore the rotor accelerates, storing excess mechanical power in inertia. As the generator rotor accelerates, its power angle increases from δ_o toward its equilibrium, δ_d, where $P_m = P_e(\delta_d)$. But the rotor overshoots equilibrium, decelerating since the electrical power is greater than the mechanical power input. If the rotor has not fully decelerated by the time it reaches angle δ_{a2}, then the rotor angle will again be accelerated into instability. If this occurs, the generator will disconnect from the system via protective relay to prevent physical damage to itself.

$$P_e = \frac{V_1 V_2 Sin(\delta_2 - \delta_1)}{X_{eq}} \tag{19}$$

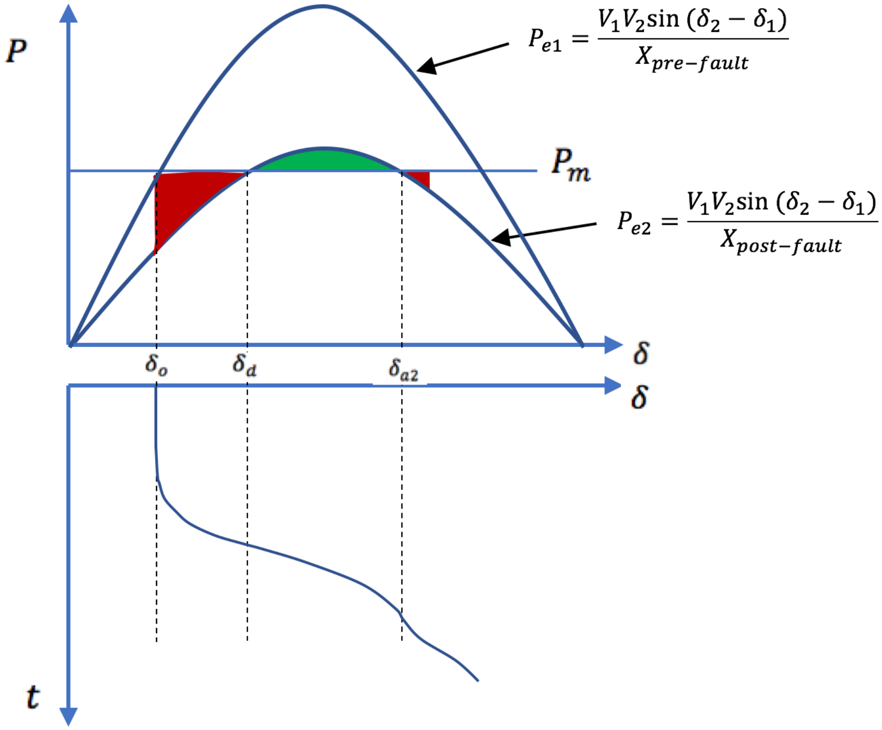


Figure 15 Explanation of Transient Instability Using Equal Area Criterion

If the mechanical power, P_m, were to quickly decrease during this transient, this would result in increased transient stability margin. Unfortunately, electrical transients occur much faster than the mechanical linkage of the prime mover can accommodate. However, if the electrical output P_{e2} were able to quickly increase, the same effect would occur as if P_m were quickly decreasing. This condition can be artificially made to occur if wind generation is located nearby the synchronous generation as shown in Figure 16. In that case, fast acting wind controls can consume electrical power much faster than a synchronous generator can reduce its power. The consumption of power by wind turbines only needs to occur for a couple seconds, enough time for the prime mover to reduce its power output, after which the wind turbines can slowly release their excess stored energy back to the grid.

In some recent situations, the displacement of synchronous generation with wind has resulted in a loss of local inertia and subsequent decrease in transfer capacity due to low transient stability margins. The use of wind described in the following manner can preserve transfer capacity without additional infrastructure such as synchronous condensers.

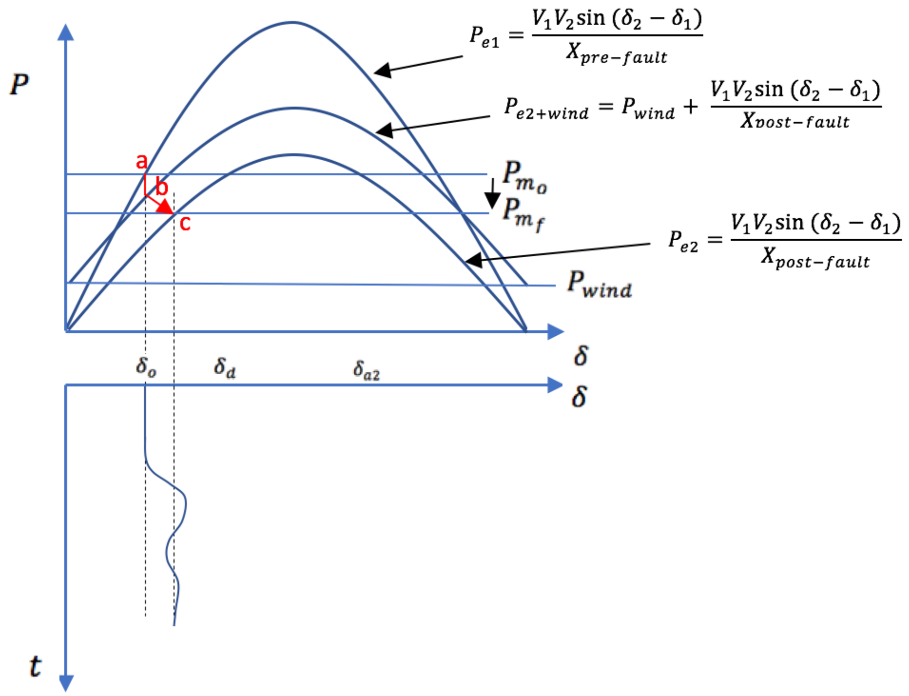


Figure 16 Use of Wind PQ Injection to Increase Transient Stability Margin

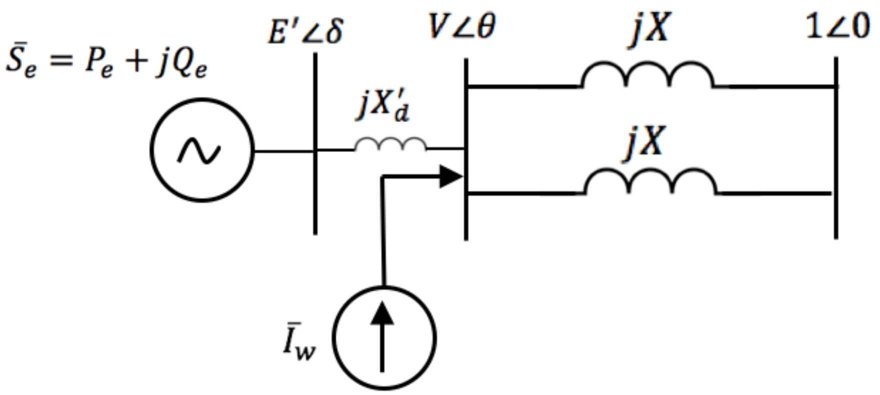


Figure 17. Test System for Demonstrating an Increase in Transient Stability Margin Due to Current Injection (Consumption) by Wind Turbines

Consider the system shown in Figure 17 where wind is integrated into the same bus as a synchronous generator. We wish to find the value of wind current, $\bar{I}_w$ which will maximize the generator electrical real power output, P_e. Recognizing that the value of $\bar{I}_w$ which maximizes P_e may be a complex number, we calculate in terms of $\bar{\mathrm{S}}_{\mathrm{gen}}$. Solving for apparent power out of the generator, we find $\bar{\mathrm{S}}_{\mathrm{gen}}$ using (20-22).

$$\bar{I}_g = \frac{E\angle\delta - V\angle\theta}{jX_d^{'}} \tag{20}$$

$$\bar{S} = \bar{V}\bar{I}^* \tag{21}$$

$$\bar{S}_{gen} = \frac{VE}{X_d'}\angle(\theta - \delta + 90) - \frac{V^2}{X_d^{'}}\angle 90 \tag{22}$$

Applying Kirchhoff's Current Law at the bus $V\angle\theta$:

$$\bar{I}_T = \bar{I}_g + \bar{\mathrm{I}}_{\mathrm{w}} \tag{23}$$

$$\frac{V\angle\theta}{jX_d'} + \frac{V\angle\theta}{jX_T} = \bar{I}_w + \frac{E\angle\delta}{jX_d'} + \frac{1}{jX_T} \tag{24}$$

iff $X_d' = X_T = 1, and\ |E| = |V| = 1$ then (22) → (25) and (24) → (26).

$$\bar{S}_{gen} = 1\angle(\theta - \delta + 90) - 1\angle 90 \tag{25}$$

$$1\angle\theta = \frac{1}{2} + \frac{1}{2}\angle\delta + \frac{1}{2}\bar{I}_w\angle 90 \tag{26}$$

By plotting the phasor diagram of (25), shown in Figure 18, we can find the maximum possible real power output. By inspection, the term defined by $1\angle(\theta - \delta + 90)$ must be equal to a phasor defined by $1\angle 0$ in order to maximize Re($\bar{\mathrm{S}}_{\mathrm{gen}}$), resulting in (27). Consequently, for an arbitrary generator real power output defined by angle $\theta - \delta$, a wind power current injection that satisfies (27) will maximize the generator electrical power output, thus increasing transient stability margin.

$$1\angle(\theta - \delta + 90) = 1\angle 0 \tag{27}$$

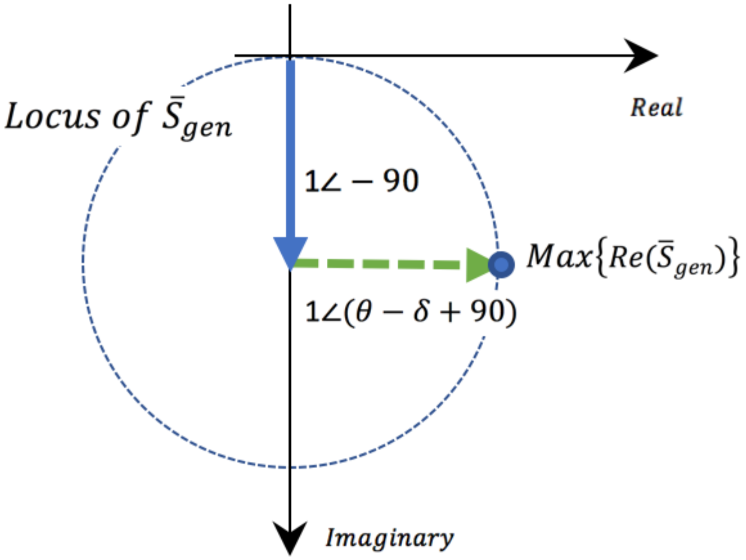


Figure 18 Phasor Diagram of (25). Locus of $\bar{S}_{gen}$ for Finding Max (Pe).

Solving (27) for $1\angle\theta$, one finds:

$$1\angle\theta = 1\angle(\delta - 90) \tag{28}$$

By substitution of (28) → (26), one derives (29), which defines the apparent power injection from the wind turbine which will maximize the generator real power output for three load conditions. (29) is plot in Figure 19. Under the assumptions of maximizing real power output of the synchronous machine, the wind farm must absorb real power in each case, but will inject or absorb reactive power depending upon the synchronous machine initial rotor angle.

$$\bar{I}_w = -2\angle\delta + 1\angle 90 + 1\angle(\delta + 90) \tag{29}$$

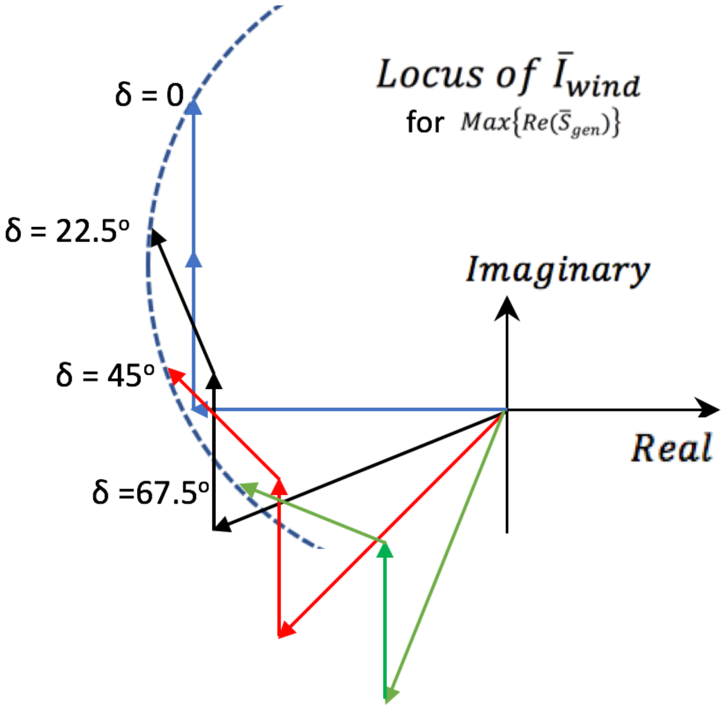


Figure 19. Phasor Diagram of (29). Current Injection, $\bar{I}_w$, Required by Wind Turbines to Increase Transient Stability Margin.

For synchronous generators in near proximity to a wind farm, the process can be established using high speed control systems. If wind power can be changed quickly, a substantial amount of transient stability margin can be added. The necessity for speed implies that torque control should be used in lieu of blade-pitch control. In situations where wind is replacing synchronous generation, this method can provide an inexpensive means of preserving transient stability margins (hence transmission line transfer capacity) as local inertia decreases.

FINANCIAL RECOVERY

Valuing Services and Recovering Costs

The use of markets adds efficiency and lowers cost of delivered electricity. As resources are called upon to perform non-traditional services, the structure of markets [22] can be inherently biased toward certain resource types.

For many transmission services there is no market, rather it is a required reliability function of the resources being integrated. Non-cost-recovered services such as inertia, droop regulation, VAR/PF support, 5% VWO capability, short circuit current capability and power system stabilization have been either inherent to the type of resources (such as synchronous generators which provide rotating inertia) or have been expressly required (such as power system stabilization systems) as a prerequisite to system integration. Since the resource base is changing from dispatchable synchronous generation to include more semi-dispatchable power electronic based generation, transmission operators must find new ways to meet the system needs. In all cases, doing so costs money. The use of wind inertial energy in tandem with new control methods has largely been unrecognized as having the ability to provide these services. In many cases, wind OEMs have not provided the necessary controls to enable these because industry has failed to demand them. In cases where the OEM has offered the capabilities [2], industry has not been compelled to purchase them. Perhaps a regulatory action which compels these services in a cost-effective manner should be considered.

Value through PPA

Another avenue of compensating these services provided by wind is to include them into a PPA with the integrating utility. The value of the services themselves would be a negotiation between the ISO (or host utility) and the wind owner/operators, providing cost recovery.

CONCLUSIONS

Although there has been significant deployment of wind generation, it is not contributing to grid services at its full potential. The wind industry is leaving money on the table, and the US is overlooking a significant source of flexibility and resilience. Wind turbines are capable of critical and valuable services that they could be providing at very competitive costs. Ultimately, these poorly tapped resources revolve around the use of wind turbine's accessible rotational kinetic energy as is displaces synchronous generation. This decline in synchronous generator inertia is actually an opportunity. Modern wind turbines can access a significant amount of stored energy without the need to spill wind. Adding the practice of spilling wind offers a greater flexibility at decreasing efficiency.

Some important grid services which wind generation can be provide without spilling wind include:

- Enhancement to transient and small signal stability margins
- Raising the system frequency nadir
- Provision of balancing reserves

Research is needed to better understand the long-term effects of mechanical stress caused by providing these services. Analogously, it will help to find the true cost of providing these services so wind can efficiently and competitively increase the grid's flexibility and resilience.

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