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Use and Testing of a Wind Turbine for the Supply of Balancing Reserves and Wide-Area Grid Stability

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Abstract

This report documents the use of wind turbine inertial energy for the supply of two specific electric power grid services; system balancing and real power modulation to improve grid stability. Each service is developed to require zero net energy consumption. Grid stability was accomplished by modulating the real power output of the wind turbine at a frequency and phase associated with wide-area modes. System balancing was conducted using a grid frequency signal that was high-pass filtered to ensure zero net energy. Both services used Phasor Measurement Units (PMUs) as their primary source of system data in a feedforward control (for system balancing) and feedback control (for system stability).

ACKNOWLEDGMENTS

The authors would like to thank Josh Paquette, Dave Minster, Brian Naughton, Brian Pierre, Will Atkins, and the DOE Small Business Voucher program for their invaluable aid in conducting this demonstation.

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NOMENCLATURE

BPA	Bonneville Power Administration
CONET	Control and Optimization of Networked Energy Technologies laboratory (Sandia/Albquerque, building 6585)
dB	decibel
DOE	Department of Energy
PDCI	Pacific Direct Current Intertie
SNL	Sandia National Laboratories
SWiFT	Scalable Wind Farm Technologies site (Lubbock Texas)
XNET	eXperimental NETwork at Sandia/Albuquerque
IP	Internet Protocol
UDP	User Datagram Protocol

INTRODUCTION

The addition of wind turbines into the US grid offers tremendous benefits in terms of positive environmental impact and the ability for our country to economically move toward 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 controls systems, the storing and release of rotational kinetic energy in wind turbines can provide many grid services. The means of accessing wind turbine stored energy for these services can be accomplished through the modulation of the turbine torque control signal.

This paper records the design and use of control systems to provide grid services typically provided by synchronous machines. The services utilize stored rotational energy in the wind turbine without the need to spill wind -- that is, without the need to reduce output below what is able to be produced by the wind turbine in order 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. The application of these ideas can translate to demand response, solar, and other resources capable of controlling the real power output. Although some resources, such as solar, must spill sun in order to accomplish the task, and others such as energy storage requires investment in the storage infrastructure itself, wind is somewhat unique in that the asset already exists, it provides no consumer disruption (as is the case with demand response), and the cost of exploiting the resource is the cost to appropriately control it.

Surprisingly, the amount of accessible stored energy in a late model wind turbine (per installed MW) is significantly higher than can be found in a synchronous generator and found to range up to 75 times greater than that in a synchronous generator [1]. The flexibility of this energy is also much greater than a synchronous machine. Some of the problems caused by loss of synchronous inertia are true, including a reduced system frequency nadir, loss of high frequency balancing, transient stability margins, and others. But most of these problems need not exist. The stored inertial energy in a wind turbine is available for use, but only by accessing it using updated control systems. This report focuses on two particular services, demonstrating how stored energy in a wind turbine was accessed and how the grid industry can gain additional value while enhancing the reputation for wind as a team player on the grid.

One significant point is that the strict comparison of inertial constants (H-values) between synchronous machines and wind turbines is not relevant, since the grid services being provided are dependent upon the accessibility of kinetic energy rather than total stored kinetic energy. Due to system frequency restrictions of the grid and the constraints linking system frequency to rotational speed, the accessibility of kinetic energy is far more restrictive for synchronous machines than it is for wind turbines, which have no such constraints.

Accessing stored rotational kinetic energy can be most easily accomplished through the modulation of the turbine torque control signal but can impose wear and tear on the turbine. This causes abrupt changes in torque that deserve deeper attention. Initial review of potential fatigue has prompted the need for a deeper analysis although loss of life occurs is anticipated to be minor. Evaluating blade stress, torsional stress, and lifetime fatigue are also expected to exhibit little if any harm while providing these 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.

Wide-Area Stability

Wide area stability, often called small-signal stability is important in some systems such as the WECC. In 1996, The WECC experienced an instability due to wide-area instability and 30,000MW of load was lost in the ensuing blackout [2]. The phenomenon is a naturally occurring resonance between groups of generators separated by long distances [3]. Although a dispatch and associated generator output setpoints may be constant, low frequency power oscillations (between 0.1Hz and 1Hz) will exist between groups of generators in the system. Several of these modes exist- oscillations are excited by system noise, but are normally well damped so they remain observable but harmless. Under various grid conditions, these resonances will become less damped, and approach an unstable conditions, threatening cascading outages. An active modulation control system was developed and tested at BPA over five years, receiving an R&D 100 award in 2017 [4]. This control system increased the damping of the power oscillation and improved stability margin. Since several modes exist, it's necessary to inject and withdraw modulated power at specific locations in the grid, associated with each mode. Since the remaining HVDC lines do not correlate with the controllability of the remaining modes, the power injections must occur at other geographic locations. The pervasive use of wind turbines provides a means to cost effectively provide grid services.

Balancing

The use of stored wind turbine kinetic energy can also be used for system balance. When the wind turbine electrical output power is increased above what the mechanical wind power input provides, the energy is taken from the stored rotorational kinetic energy of the rotor system, lowering the rotor speed. The opposite effect occurs as well. The amount of energy available is a fraction of the total stored rotating kinetic energy of the rotor. By intentionally increasing and decreasing the rotor speed (via torque control), energy is stored, then subsequently released, modulating the electrical output power. The amount of energy allocated from the wind turbine will create bounds for frequency and amplitude for the power delivered power. For example, accessing a specified amount of kinetic energy from the rotor may provide high amplitude, high frequency modulation of electrical output power. The same amount of energy can provide low amplitude, lower freuquency modulation. As the modulation gain is increased, the control signal is amplified, acting as a volume control to establish how much response is provided by the wind turbine, at the frequency band selected. A large response benefits the grid more, however, increasing gain too far could drive the turbine RPM out of its specified band as it attempts to store or deliver larger amounts of energy.

WIND CONTROL SYSTEM LAYOUT

The wind turbine site for this project is located at the Scalable Wind Farm Technologies (SWiFT) site operated by Sandia Labs on the grounds of the Reece Technology Center in Lubbock Texas, see figure A. Reece is owned/operated by Texas Tech University.

The Vestas V27 wind turbine has been modified extensively to support the research efforts of the Department of Energy's Wind Program Office. The current configuration most resembles a modified Type 4 wind turbine generator, having full AC to DC rectification and three-phase DC to AC inversion. In addition to a pitch controller, the turbine also includes a separate torque controller as shown in **Error! Reference source not found.**. The revised capabilities of this turbine are specified in [4],which can be found by searching the Sandia online library. The generator is rated at 225kW, 1200 RPM, and a gearbox ratio of 27.9 resulting in a maximum rotor speed of 43 RPM. Design λ (tip speed ratio) and Cp (aerodynamic efficiency) values are 7.5 and 0.46 consecutively with a rated wind velocity of 12 m/s. There are three blades with a rotor diameter of 27 meters and a hub height of 31 meters.

The turbine nacelle controller commands the generator to induce a torque on the rotor that regulates the rotor speed approprciately. This typically puts the systems at maximum power generation for a given wind-speed, but may also limit rotor speed within safe bounds in the case of high winds. This project's purpose was to add a modulation signal to the commanded torque (also termed the "torque demand").

Figure 1 Photo of The Swift Site And its Three Turbines.

SWiFT nacelle controllers were custom designed by Sandia personnel using the National Instruments VeriStand embedded real-time platform. The real-time system (an embedded computer in the nacelle) transmits measurements data to computers in the nearby SWiFT control house; these computers also display real-time charts and plots relevant to system operation.

The torque demand modulation signal originated in the Control and Optimization of Networked Energy Technologies (CONET) laboratory at Sandia/Albquerque, building 6585. The CONET controller is built on a National Instruments real-time LabView platform. It accepts synchrophasor (PMU) data from two or more PMUs in geographically separated locations, and produces a desired torque modulation command signal.

During project development, a hardware-in-the-loop turbine simulator was used to verify proper system operation. The simulator replaces the rotor with an electric motor but is otherwise essentially identical (including control hardware and software) to the actual turbine nacelle equipment. The system interconnection is illustrated in Figure 5, along with a simplified block diagram in Figure **6**. The control shown was successfully tested on a Vestas V27 wind turbine at the SWIFT wind facility in Lubbock, TX

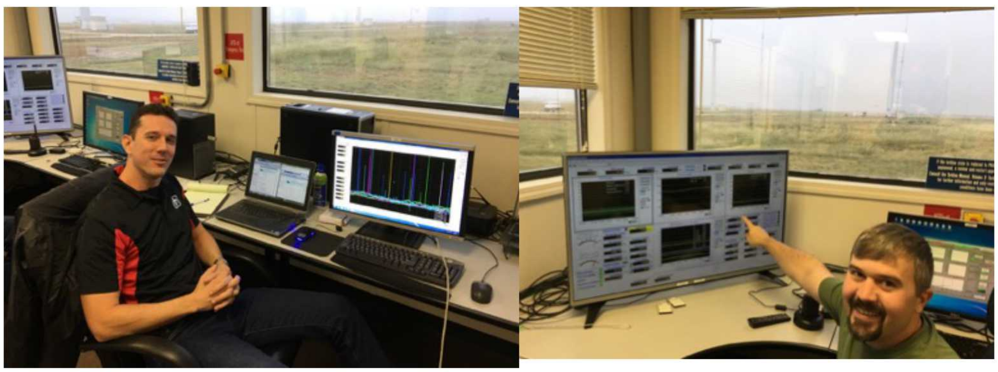

Figure 2 Wind Turbine Testing from the SWIFT Control Center in Lubbock, Texas**.**

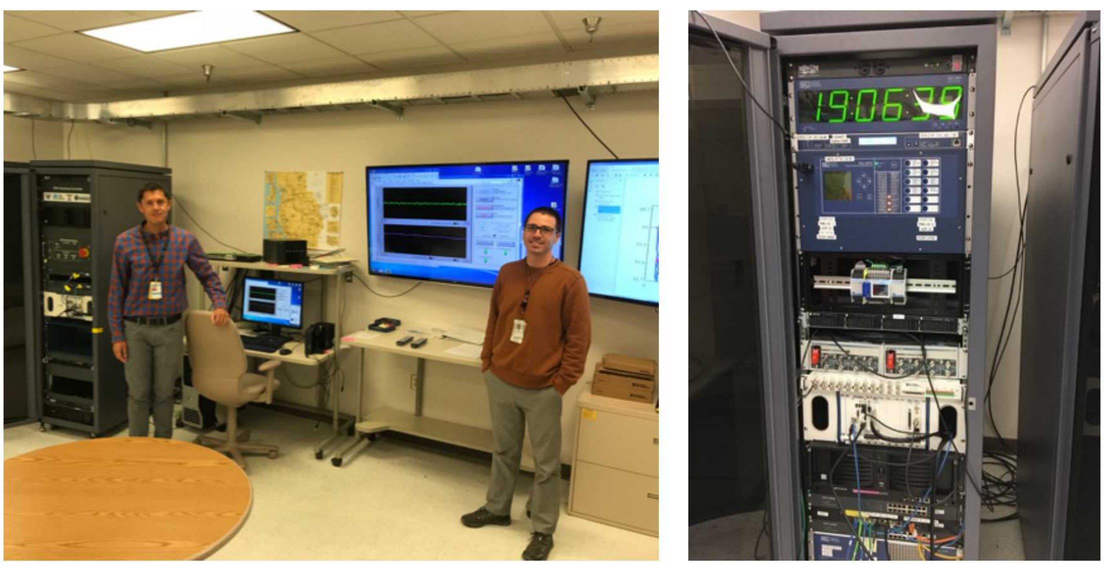

Figure 3 Sandia Staff Participating in the Wind Demonstration and Test.

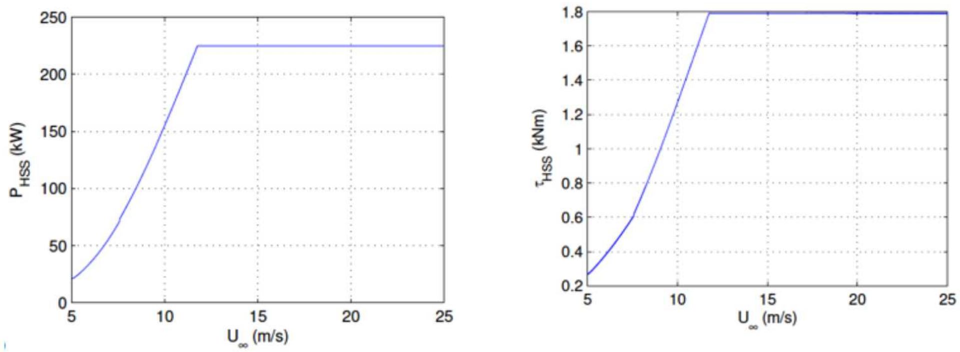

Figure 4 Vestas Wind Turbine Power and Torque Curves

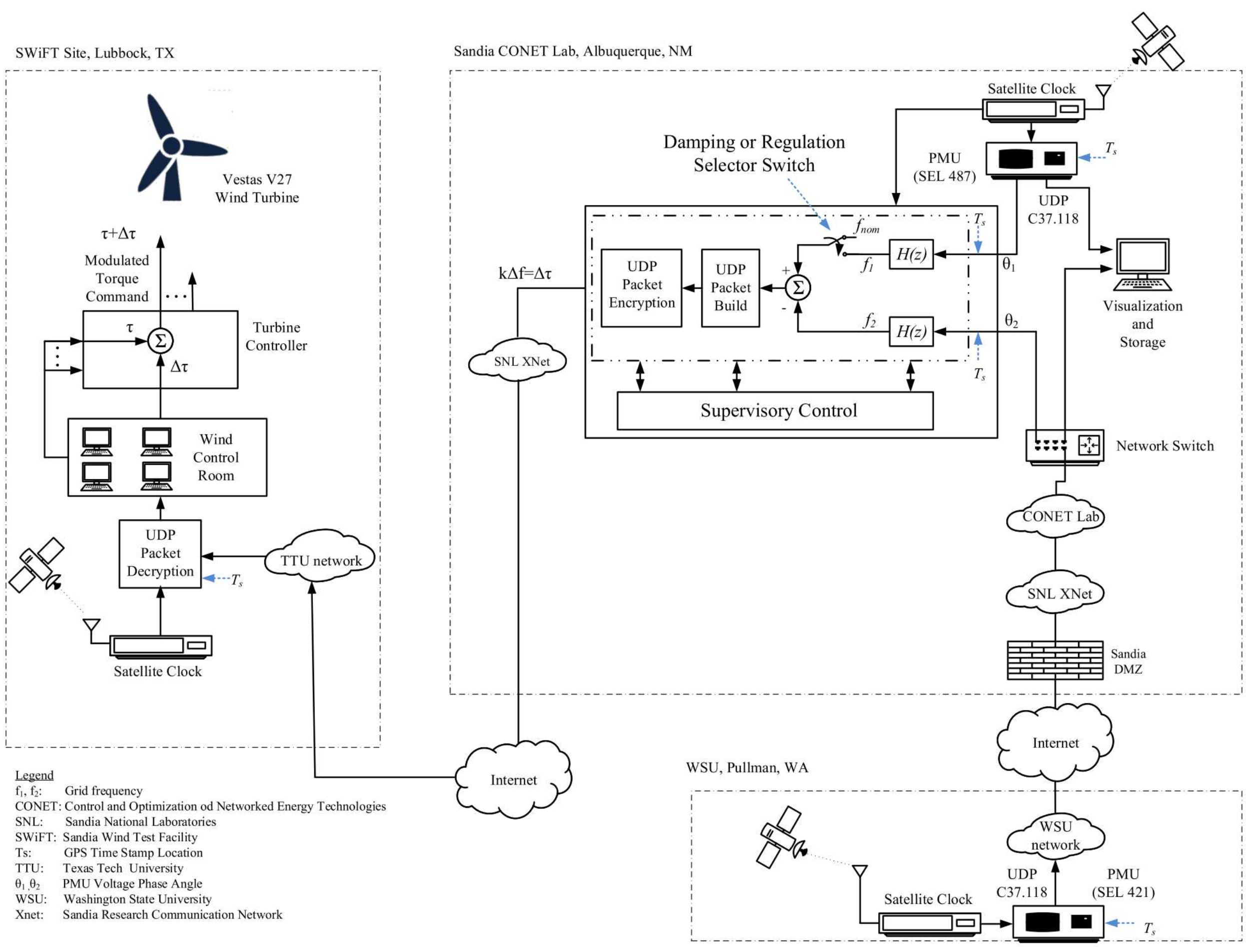

Figure 5 Block Diagram of Wind Modulation for Grid Stability Control and Regulating Reserves.

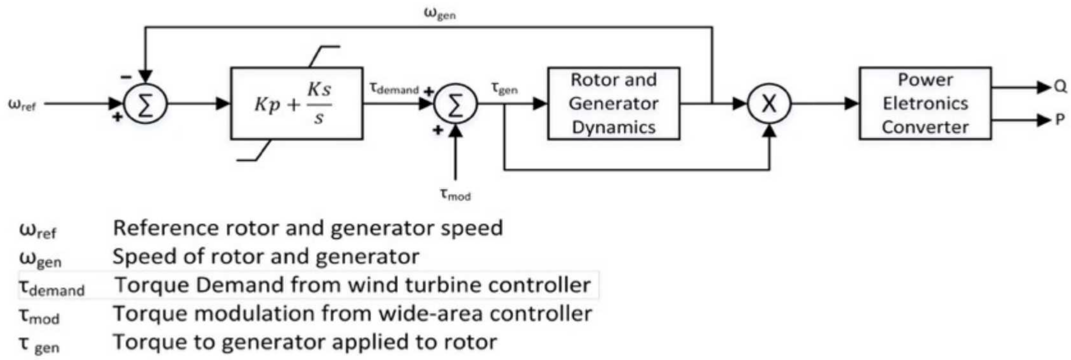

Figure 6 Illustration of the Turbine Torque Modulation Controller Scheme.

COMMUNICATIONS

The project's network communications requirements posed several challenges. Sandia's "XNET" network was installed in the 6585/CONET laboratory. XNET is an experimental network consisting of physically separated fiber between buildings, and logically partitioned network topology at the level of Sandia's main firewalls and routers. As a consequence, XNET operates safely without the degree of network traffic inspection and throttling inherent to Sandia's secure networks.

An XNET subnet was created for this project work, with a public-facing IP address configured to accept UDP packets from certain external IP addresses and forward the packets to lab computers. UDP outbound transmission was also permitted. UDP transmission exhibits the lowest possible network packet latency compared to most other IP-based network protocols (including TCP).

The project required three principal communications pathways:

1.) Synchrophasor (PMU) data streamed via UDP from a PMU located in Washington State to the controller in the CONET Lab.
2.) PMU data streamed via UDP from a PMU located in 6585 to the controller in the CONET Lab.
3.) Control signals streamed via UDP from CONET lab to the SWiFT control house in Lubbock. On the SWiFT end, Texas Tech University opened a public-facing IP address to accept incoming UDP packets from Sandia's XNET IP address.

Communications Protocols

PMU data was streamed to the CONET laboratory via XNET using the IEEE C37.118-2005 standard for synchrophasor data transmission. Measurements were streamed at 60 messages per second. PMU-1 (located in 6585) was a model SEL-487E, PMU-2 (located at Washington State University) was a model SEL-421. Notably, both PMUs were situated within the western grid. Both PMUs utilized GPS-synchronized clocks to achieve sub-millisecond timestamp accuracy.

For monitoring and testing purposes, it was necessary for more than one computer to receive the PMU data – the wide-area controller, as well as a logging PC. To accomplish this, PMU UPD packets were directed to the PC, and a stream-splitter utility was configured to relay packets to the controller and any other machines requiring them. Communication latency was always a concern, but lab tests showed no significant (1-3 ms) delay associated with the stream splitter.

The LabVIEW-based controller processed PMU data and produced a control signal either (a) proportional to the difference between grid frequencies at the two PMU locations, or (b) proportional the difference in grid frequency of one PMU relative to 60Hz. The control signal was transmitted via UDP to the SWiFT turbine nacelle controller. For this purpose, a UDP framing standard was written (Appendix A) and tested using the wind generator HIL simulator. (The standard also includes framing specifications for data transmitted from the nacelle, but this is only for logging and monitoring purposes and was not necessary for real-time operation.)

Cybersecurity

Cybersecurity for networked grid control designs remains a valid concern, especially as remote assets such as PMUs and controllers work together to influence grid operation through closed-loop control schemes.

Enterprise network security meausres (e.g. at Sandia and Texas Tech) included IP address and port filtering, described earlier. Additionally, messages from CONET to SWiFT were encrypted using message authentication codes based on the industry-standard SHA-256 hash algorithm with pre-shared private keys. This step was taken to minimize the risk of replay or "man-in-the-middle" attacks on UDP packets during transmission. The system is described in more detail in Appendix A.

We particularly note that, because of the presence of an incrementing clock in the message control signal payload, no two UDP packets will ever be identical, increasing the security of the encryption.

PMU C37-118 tranmissions were not secured, however. This is an ongoing subject of research.

CONTROL SYSTEM DESIGN

This project builds on the work, and the technology, of the Bonneville Power Administration (BPA) wide-area Pacific DC Intertie (PDCI) controller. In essence, the PDCI controller modulates the real power flowing across the PDCI in proportion (and opposite to) the frequency difference between two points on the western grid. The project has demonstrated that this method can improve overall small-signal damping of the north-south inter-area mode [5, 6].

This project's objective was to show that a real power output of a wind turbine can be modulated in a manner likely to mitigate wide-area oscillations or to assist with frequency regulation. However, as a demonstration project using only one small wind turbine, it was clearly not possible to measurably influence the grid and therefore the usual metrics for control system performance (stability margins, damping charcteristics, etc.) were relatively less important than concerns related to data transmission latency/security and safety at the SWiFT site.

A critical safety issue at SWiFT is to avoid exciting the dominant resonant mode of a turbine tower, around 1Hz.
Figure **7** illustrates various resonant modes for the V27s at SWiFT. Notably, the 1Hz tower mode is independent of rotor velocity.

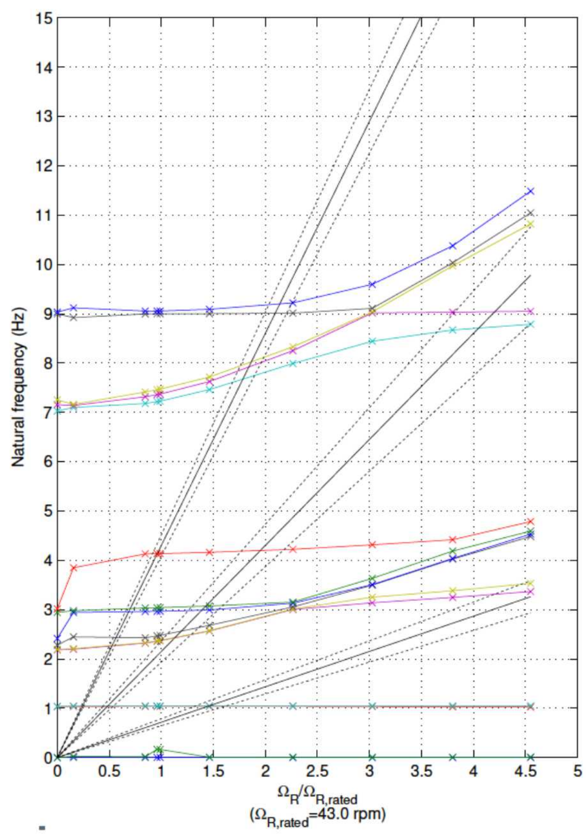

Figure 7 Aeroelastic Frequencies (Modes) For a Swift V27 Turbine

Real power modulation at the turbine was accomplished by intercepting the generator torque command and adding the zero-based modulation signal to it, as illustrated in

Figure **7**. This had the effect of altneratively "robbing" and "giving" small amounts potential energy to the turbine rotor. The rotor cannot, of course cannot "give" energy above that which is removes from the wind stream forever, but as long as the give-and-take occurs within an appropriate frequency band there is no net power loss and no need to spill wind.

To ensure data integrity of the torque modulation signal, UDP control packets from CONET were decrypted, decoded, and then processed to remove any packet time-reversals that might occur (packets arriving in a non-chronological order), Figure 8. The resulting torque modulation demand signal was then amplitude-limited if necessary, and processed through a band-pass filter to ensure a zero-based signal in the chosen frequency band. Code to accomplish these tasks was written in Simulink, compiled for real-time execution, and uploaded into the SWiFT nacelle embedded controller's National Instruments VeriStand system.

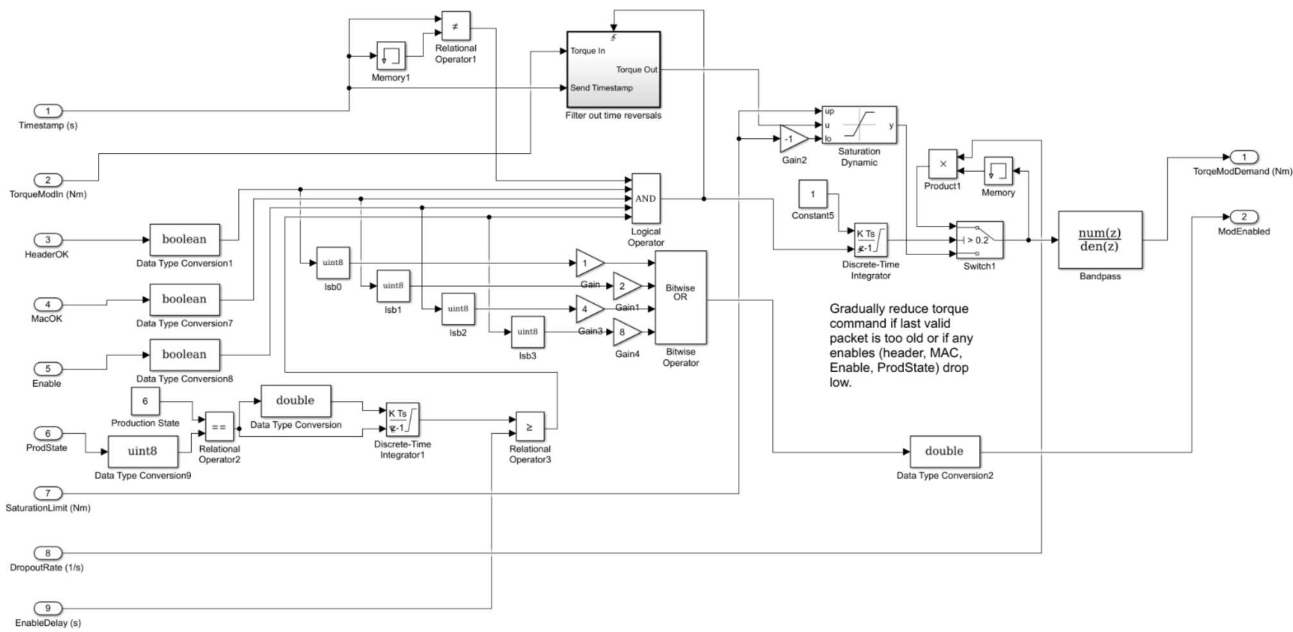

Figure 8 Signal processing and reconstruction of the torque modulation demand signal.

Machines in CONET and at SWiFT recorded GPS-timestamped logs of all relavant signals. Additionally, during testing logs were recorded of the transmission latency between CONET and SWiFT. Transmission latency is a stochastic process. The issue is further complicated by the fact that inter-area oscillations are measured by geographically separate PMUs that report data over different communication pathways with different (i.e. asymmetric) latencies and delays. Latency-related problems and their ramifications for grid services controllers have been studied recently [5, 7, 8].

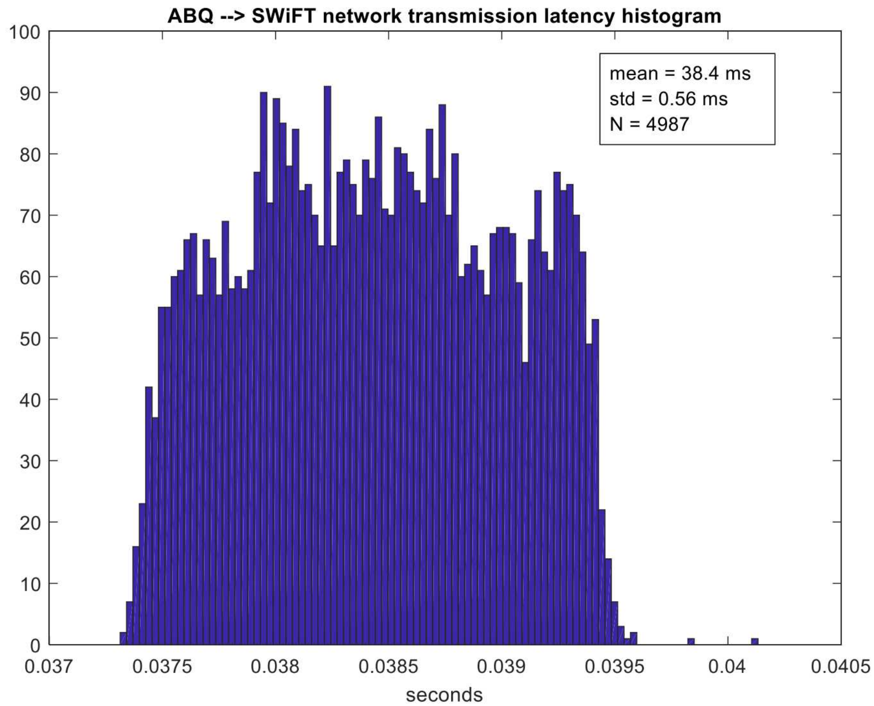

Figure 9 Network Packet Transmission Latencies, ABQ to SWiFT.

Note the relatively small variance in the distribution above; this was considered a fast and reliable connection.

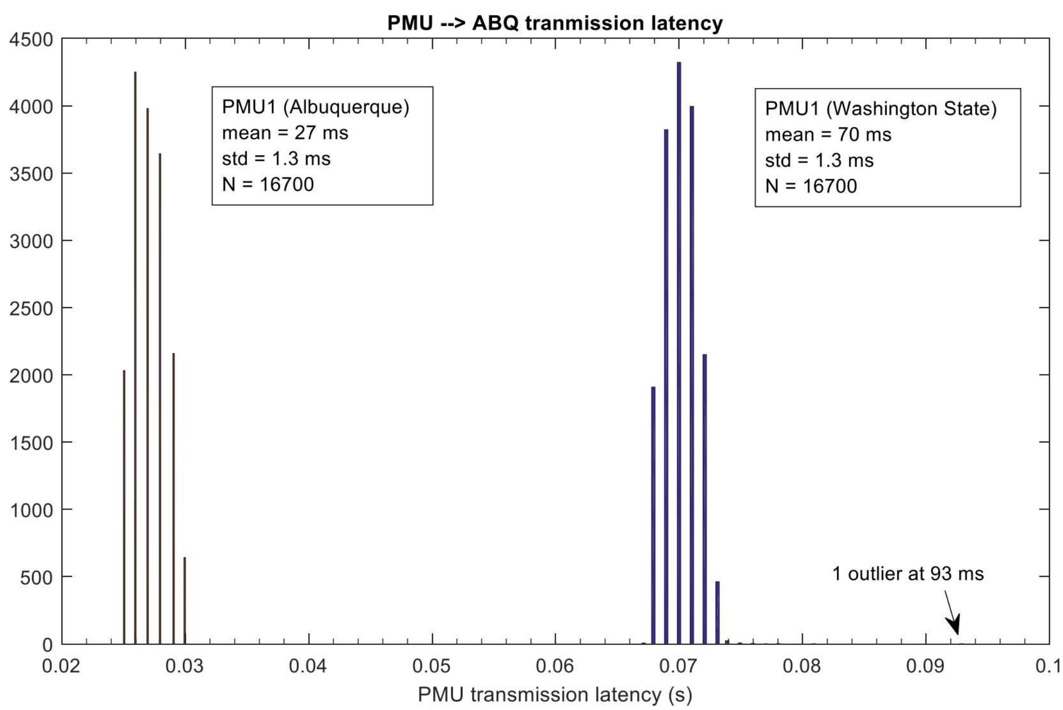

Figure 10 Network packet transmission latencies, PMUs to ABQ.

Latencies were timestamped to the nearest 1ms, so there are gaps in the histogram due to lack of sub-millisecond differences.

Real-time tests were executed on 28 Sept, 2017. The test procedure (Appendix B) allowed for a number of test signals to be sent to the turbine controller from a computer in the SWiFT control house, for testing and debugging purposes. These test signals were, in chronological order:

Table 1 Real-time tests performed on 28 Sept, 2017. *See below.

Test Type	Notes
Sine	Frequency 0.1, 0.2, 0.4, 0.8, 0.8, 1.2, 1.6, 2.0 Hz. Amplitude 10 Nm at T = 0.125*
Chirp	Frequency 0.1 to 2 Hz. Amplitude 12.5 and 20.0 Nm at T = 0.125. Amplitudes 10 Nm and 20 Nm at T = 0.025.
Wide-area stability	One test with peak amplitude limited to approximately 5 Nm One test with peak amplitude limited to approximately 15 Nm
Regulation (balancing)	Three tests, identical parameters (see text)

To promote stability of the rotor speed control, all torque command signals are low-pass filtered as $H(z) = \frac{1-a}{1-az^{-1}}$ where $a = \frac{T}{T+0.002}$. For some of the initial tests, $T = 0.125$; however this filter exhibited a frequency roll-off (and corresponding phase shift) too low for the desired bandwidth of 0.1 to 2 Hz. Therefore, for all subsequent testing, an adjustment was made to $T = 0.025$. The revised filter ($T = 0.025$) exhibits less phase lag at the higher end of the design frequency band. See Figure 11.

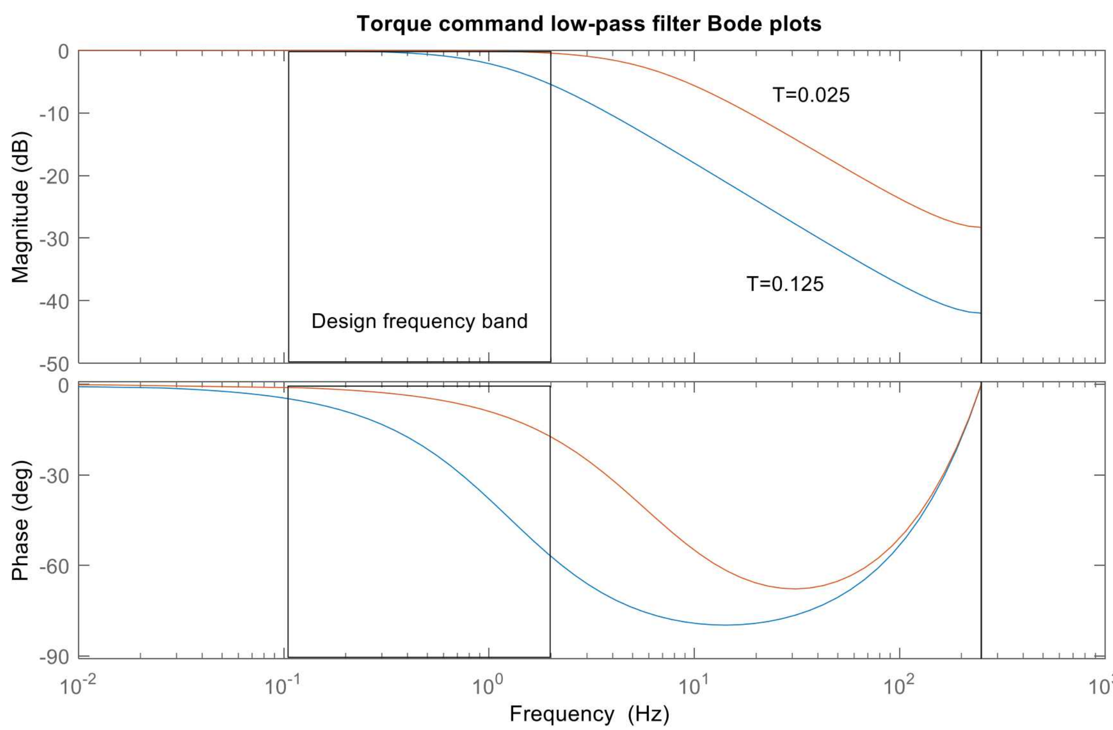

Figure 11 Torque Demand Signal Filter Bode Plots.

Example plots of chirp test signal results follow below. Note that generator power output is measured by the generator at a relatively slow sample rate (20 samples per second), and quantized to apprixmately 1/3 kW per step.

Wind conditions on test day were low and variable, ranging from approximately 1 to 6 m/s with an average around 3.5 m/s. Occasionally, the turbine controller would transition to a low-wind state in which the generator was temporarily disconnected. Power output modulation is clearly visible, with an approximately peak amplitude of 2.2 KW. Note that generator RPM oscillations are barely detectable under the larger trend caused by varying wind conditions. Quantization of the power measurement is clearly seen, as well as wome phase lag attributable to a combination of signal processing and measurement time/amplitude quantization.

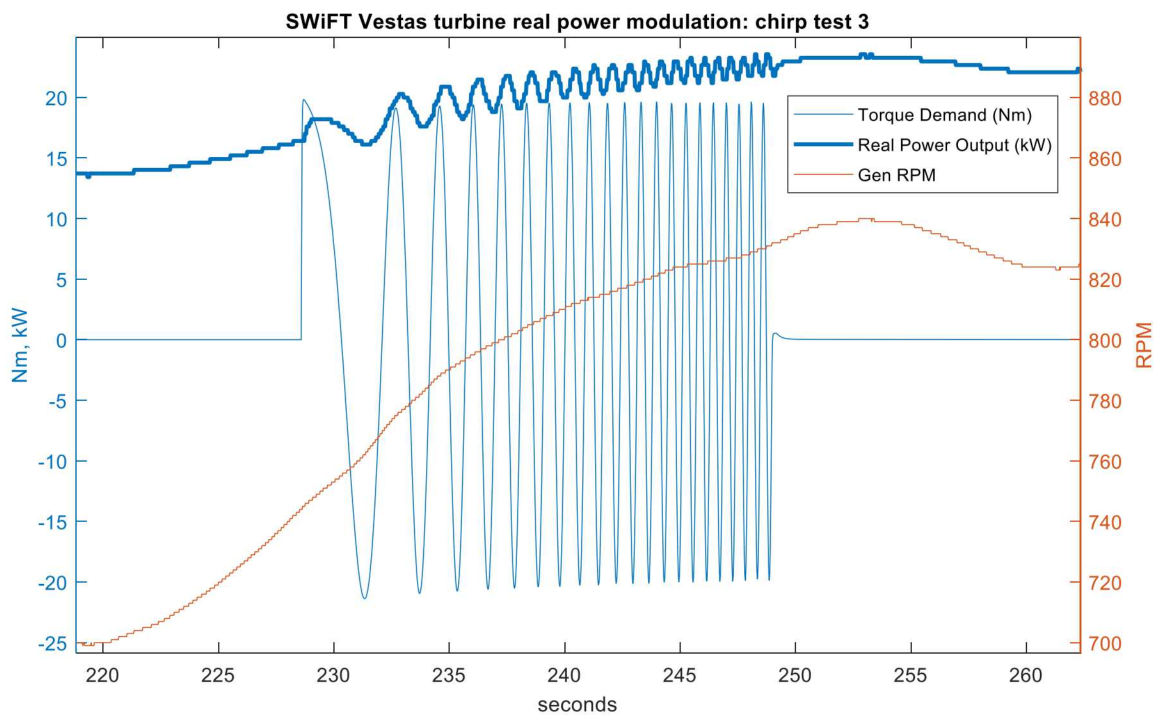

Figure 12 Chirp Test (0.1 To 2Hz) With T = 0.125 And 20Nm Peak Modulation.

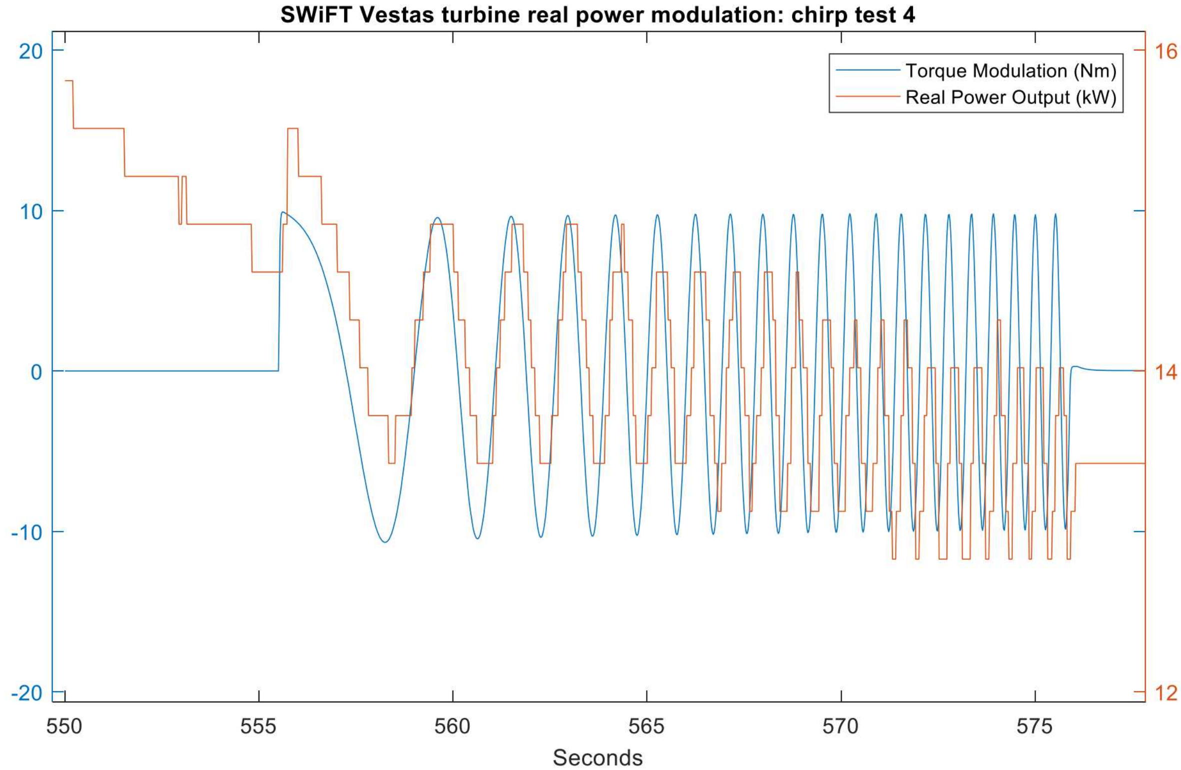

Figure 13 A Chirp Test Close-Up, Peak Amplitude 10 Nm, T=0.025.

Wide-area Stability Control

Subsequent to the basic signal tests, the CONET lab stability controller was enable and transmission were streamed to SWiFT. Three tests were executed to illustrate wide-area stability operation. Modulation commands were produced in the CONET lab Labview system and reflect the difference in grid frequency between PMUs in Washington state and the Sandia CONET lab. An example appears below in Figure 14.

No discernable tower resonance events were detected during testing. They were not expected because the signal power around the resonance point of 1Hz was low relative to the power of dominant wide-area modes, especially near 0.25 Hz; see Figure 145. In this trial, only 2% of the signal energy is contained within the 0.9 To 1.1 Hz region around the tower resonance frequency of 1Hz. The torque modulator is designed to accept inputs in the frequency range of 0.1 to 2Hz, with roll-off on either side.

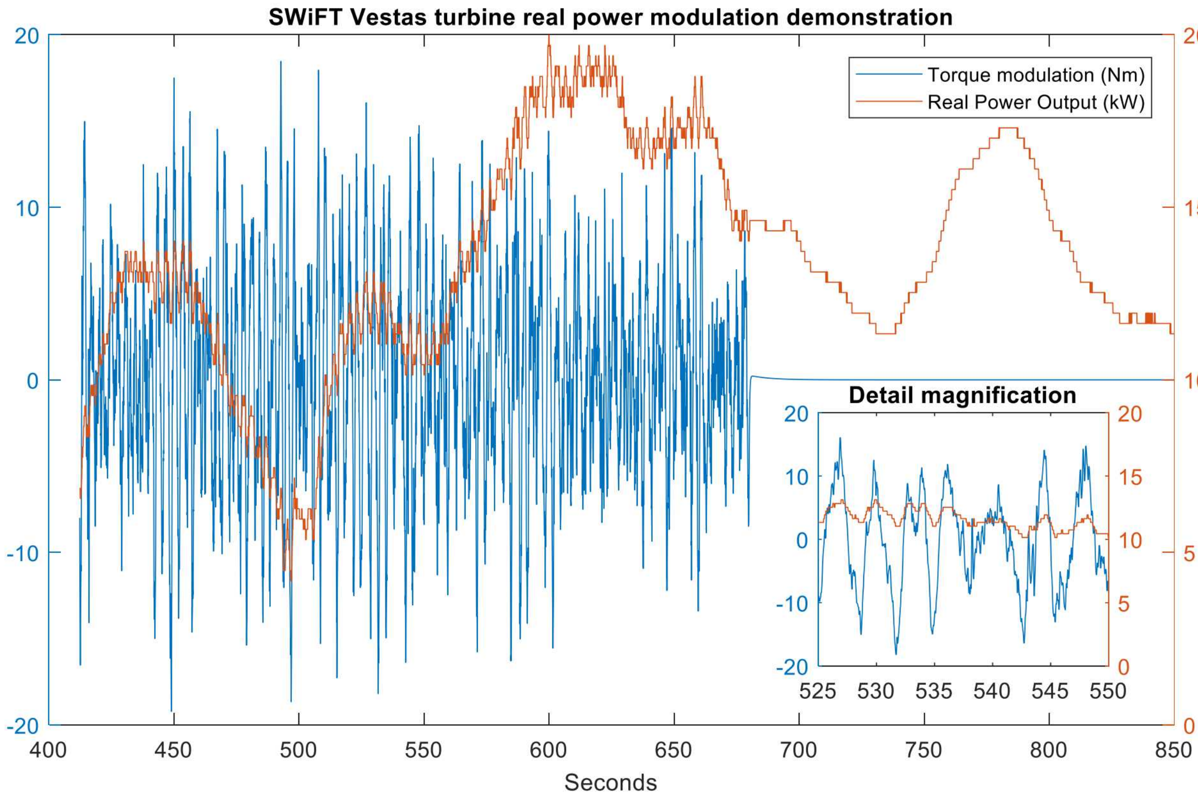

Figure 14 Torque Modulation (Received at the Turbine Nacelle) and Power Output.

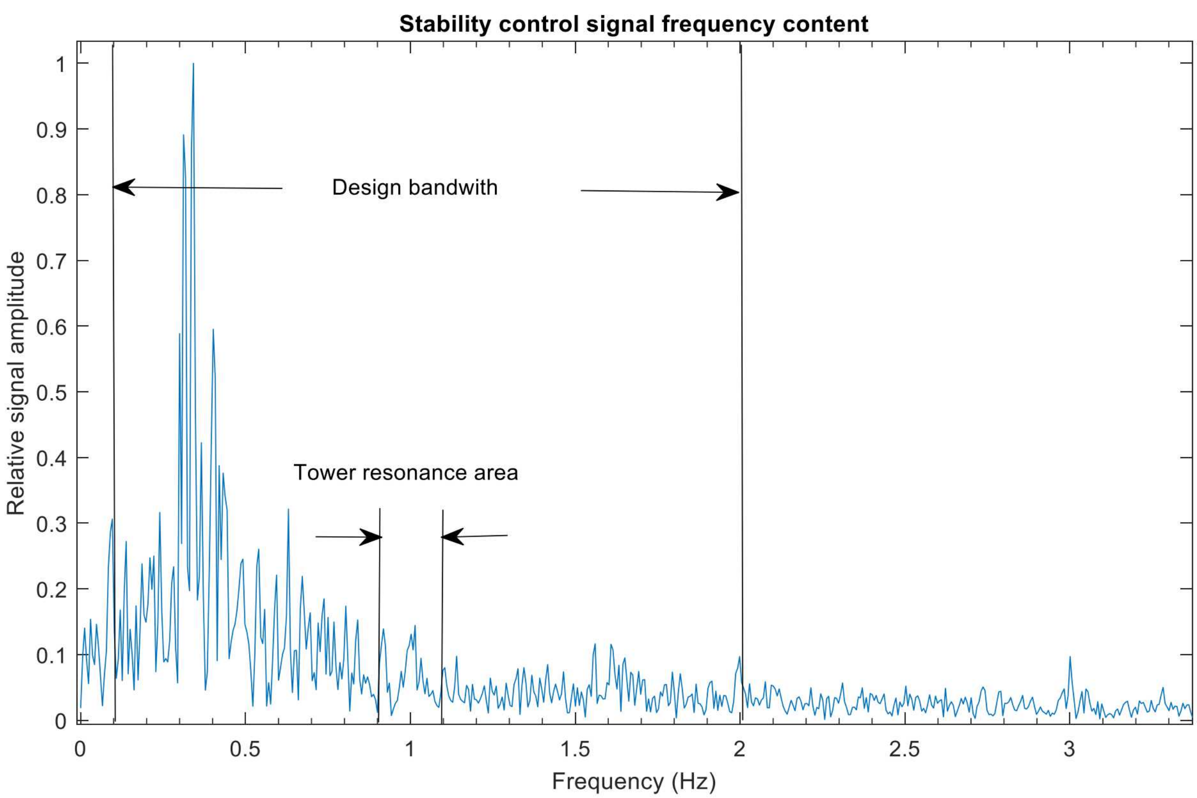

Figure 15 The Frequency Content of a Typical Control Signal, Two-Area Mode.

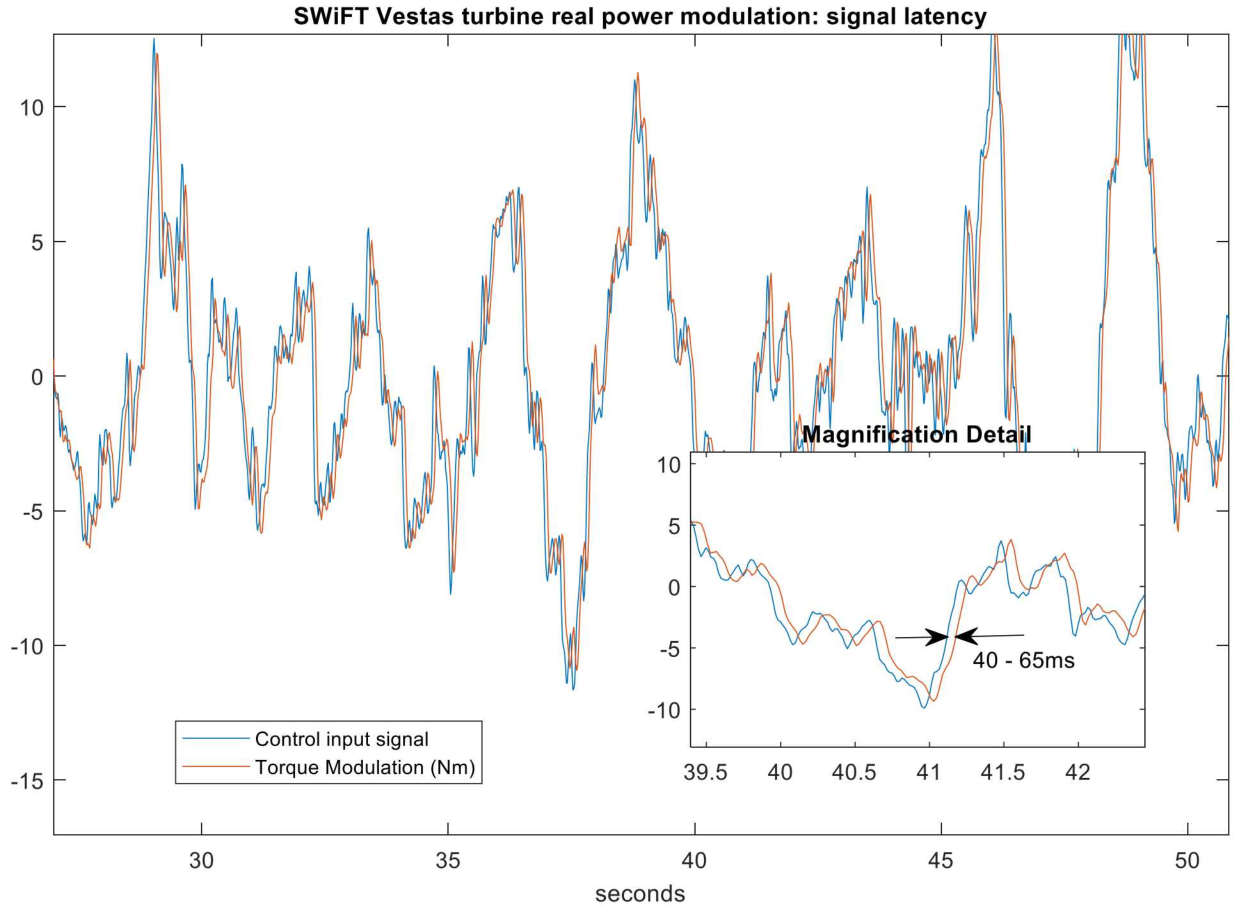

Figure 16 Total Signal Latency From CONET to Modulation Injection.

Total latency is a combination of network transmission latency and frequency-dependent signal processing phase lags, and is also impacted by the differing sample rates of the two systems. The conet wide-area control system issues commands at 60 messages per second; all swift nacelle controllers update generator torque demand at 50 messages per second.

System Balancing (Regulation)

The demonstration system was originally designed primarily to modulate torque proportional to the frequency difference between two geographically separated points on the western grid. However, system balancing can be achieved in essentially the same manner and using the same control methodology if one of the grid locations is thought to be "ideal" (in other words, produces zero frequency deviation relative to 60Hz). In this case, the torque modulation signal is proportional to the frequency deviation measured by one PMU relative to 60 Hz (rather the frequency difference between two PMUs).

The downside of this approach is that, where relative frequency between two grid locations is generally of limited amplitude and confined to a predictable bandwith, absolute frequency deviation at any single point on the grid may vary widely and exhibit systained low-frequency or "DC" components (e.g. drift and offset).

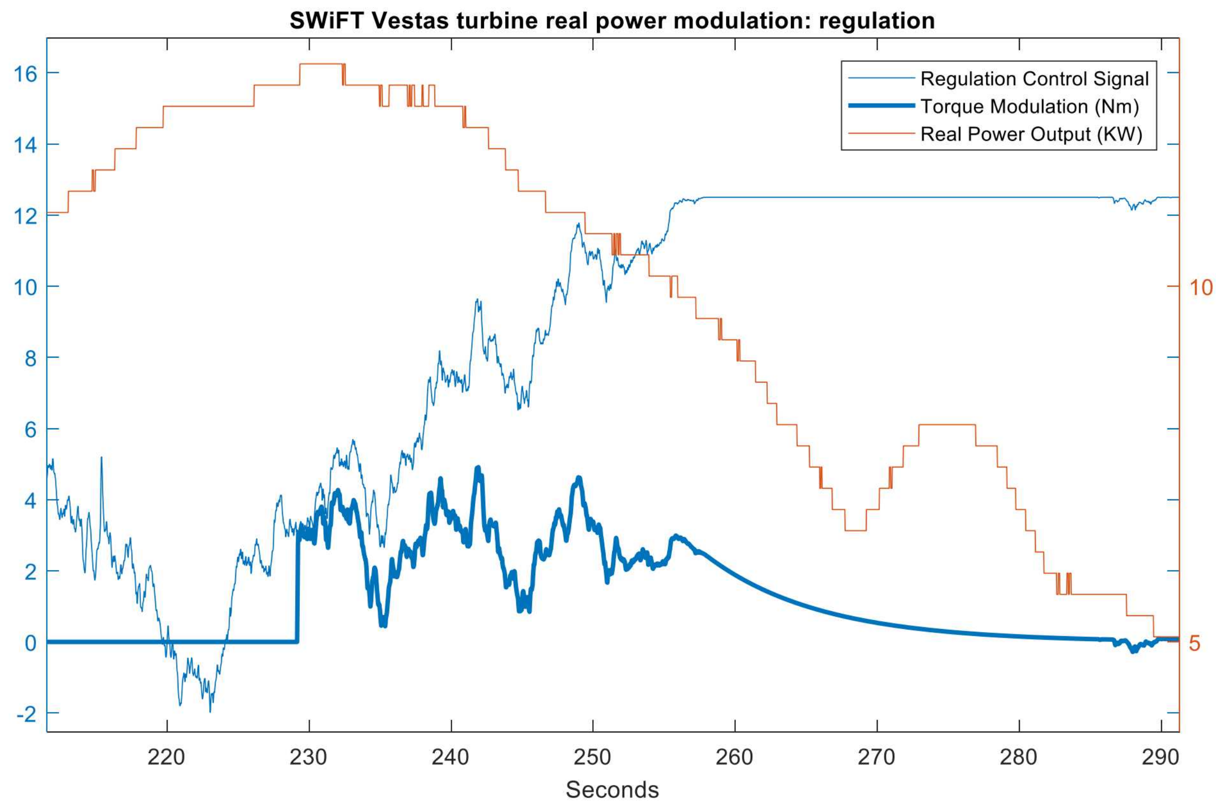

Figure 17 Grid Frequency Deviation at the ABQ PMU Location.

As discussed in Figure 17, the low-frequency trends in the regulation command signal were not followed by the torque modulation system. Additionally, to allow for a wider amplitude range of command inputs, the modulation gain was reduced. Consequently, modulation had little if any effect on generator output power.

Note that the regulation signal (thin blue) exhibits both "high" frequency elements as well as drift and offset. At the start of the experiment (230s), the torque modulation demand (bold blue) signal is able to track the higher-frequency moves, but cannot track the lower-frequency upwards drift. At around 255s the control signal saturates at the safety limit of +/- 12.5 nm and the modulation signal returns to zero.

CONCLUSIONS AND NEXT STEPS

This project successfully demonstrates the feasibility of modulating the real power output of a wind turbine over a specified modulation bandwith without the need to “spill” wind, or operate off the maximum power point. In essence, rotational kinetic energy is alternately added and subtracted to the rotor. The purpose of power modulation is to provide grid services such as small-signal stability, regulation, or short-time storage, at a cost substantially lower than would be incurred for these services to be constructed and operated separately.

The project also uncovered several areas for further work. At the basic technical level, this demonstration was unable to track a regulation input signal, primarily because the equipement had been designed to accept and respond to signals with a different frequency profile (such as interarea grid oscillation). However, this shortcoming should be easily fixed by a redesign of the various signal processing algorithms and filters, along with some additional hardware-in-the-loop testing. Also, the modulation limits for these tests were chosen very conservatively – so much so, that rotor/generator RPM is almost neglible. This suggests that the modulation limits can probably be increased quite substantially, with a dynamic limiter that adjusts for wind speed.

As the changes above are implemented, it will become more important to fully quantify the physical effects on the turbines and towers. These effects may be more pronounced with larger modulation limits, but they also may be subtly different depending on the particular service that is being provided. Understanding of phsycial effects can be largely attained by simulation methods, provided that accurate sample modulation command data is available.

Lastly, there is the open question of cost functions to help value the services wind operators could provide (assuming this type of modulation is amplified across one or more large wind farms); wind services are, in this context, essentially a specialized form of energy storage [1, 9-12]. A particularly thorny issue stems from the fact that wind-based grid services will be necessarily limited to certain bandwidths. In other words, wind-based grid services can only address deviations of grid frequency or voltage within a limited bandwidth. Long-time events spanning more than, say, 20-30 seconds are probably outside capability of a wind service; similarly, very short-time transients may occur too fast for either the communications system or the generator power electronics to respond. How should a wind-based service be valued given the magnitude and frequency band of its availability?

Overall, this project met or exceeded its original aims and clearly illustrates that power modulation, and the subsequent provision of services that modulation enables, are within technical reach.

REFERENCES

[1] R. Guttromson, I. Gravagne, J. White, J. Berg, F. Wilches-Bernal, and C. Hansen, "SAND2018-772151: Use of Wind Turbine Kinetic Energy to Supply Transmission Level Services," Sandia National Laborotories, Albuquerque, NMMarch, 2018 2018.

[2] D. N. Kosterev, C. W. Taylor, and W. A. Mittelstadt, "Model validation for the August 10, 1996 WSCC system outage," *IEEE Transactions on Power Systems,* vol. 14, no. 3, pp. 967-979, 1999.

[3] P. Kundur, *Power system stability and control*. McGraw-hill New York, 1994.

[4] B. J. Pierre *et al.*, "Open-loop testing results for the pacific DC intertie wide area damping controller," in *2017 IEEE Manchester PowerTech*, 2017, pp. 1-6.

[5] R. H. Byrne, D. J. Trudnowski, J. C. Neely, D. A. Schoenwald, D. G. Wilson, and L. J. Rashkin, "Small signal stability analysis and distributed control with communications uncertainty," in *2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 2016, pp. 1284-1291.

[6] B. Pierre *et al.*, "Supervisory system for a wide area damping controller using PDCI modulation and real-time PMU feedback," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, 2016, pp. 1-5.

[7] F. Wilches-Bernal, R. Concepcion, and R. H. Byrne, "Impact of communication latencies and availability on droop-implemented primary frequency regulation," in *2017 North American Power Symposium (NAPS)*, 2017, pp. 1-6.

[8] D. Ameme and R. Guttromson, "Stochastic Characterization of Communication Network Latency for Wide Area Grid Control Applications," Sandia National Laboratory Report, Report October, 2017 2017, vol. SAND2017-714481.

[9] R. H. Byrne, R. J. Concepcion, and C. A. Silva-Monroy, "Estimating potential revenue from electrical energy storage in PJM," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, 2016, pp. 1-5.

[10] R. H. Byrne and C. A. Silva-Monroy, "Estimating the maximum potential revenue for grid connected electricity storage: Arbitrage and regulation," *Sandia National Laboratories,* 2012.

[11] R. H. Byrne and C. A. Silva-Monroy, "Potential revenue from electrical energy storage in the Electricity Reliability Council of Texas (ERCOT)," in *2014 IEEE PES General Meeting | Conference & Exposition*, 2014, pp. 1-5.

[12] R. Guttromson, I. Gravagne, and e. al., "Use and Testing of a Vestas V27 Wind Turbine for the Supply of Balancing Reserves and Wide Area Grid Stability," Sandia National Laboratories, Albuquerue, NM2018.

APPENDIX A: APPROVED TEST PLAN FOR WIND TURBINE POWER MODULATION

ABSTRACT

This document outlines a plan for testing the ability of a turbine at Sandia's SWiFT (Scaled Wind arm Technology) site to modulate its real power output in proportion to a signal transmitted to it from a controller in Albuquerque (hereafter the "damping controller"). The damping controller receives signals from one or more phasor measurement units (PMUs) and processes the PMU data to produce input signals for the turbine's nacelle controller.

The overall objectives of the test are:

1.) To illustrate that it is technically feasible to build and operate a closed-loop grid damping control system using a wind turbine;

2.) To understand the technical limits of wind-based damping control on a real system in order to inform future work

APPROVALS

The following test plan may not be implemented until the following individuals approve by signing and dating below.

Approved by: David R. Mitchell   Date: 9/28/2017
Dave Mitchell, SWiFT Site Supervisor

Approved by: Jonathan Berg   Date: 9/28/2017
Jon Berg, SWiFT Site Lead and Test Controller

Approved by: ____________________   Date: ____________________
Ian Gravagne, Project PI

Approved by: ____________________   Date: ____________________

EMERGENCY CONTACTS

Title	Name	Phone	Email
Test Controller	Jon Berg	(505) 573-7689	jcberg@sandia.gov
SWiFT Site Supervisor	Dave Mitchell	(806) 241-1654	dmitche@sandia.gov
Wind Department Manager	Dave Minster	(505) 933-3481	dgminst@sandia.gov

Include other important stakeholders	Ian Gravagne Ross Guttromson		Ian_Gravagne@baylor.edu rguttro@sandia.gov

INTRODUCTION

Growing load demand and growing renewable energy penetration have at time stressed the power transmission grid to its stability limits – the point at which it is no longer possible to maintain a near-60 Hz power frequency because there is not enough inertial generation or transmission capacity. Building new capacity is a lengthy and expensive process, so researchers are focusing on methods to counteract frequency deviations. (Frequency may be measured at one location and compared to true 60Hz, or measured at two locations and compared relative to each other.)

One method under investigation at Sandia is to modulate the power flow of the Pacific DC Intertie (PDCI) in inverse proportion to the frequency difference between the northern and southern ends. Similarly, this test plan proposes to modulate the output of a wind turbine in inverse proportion to the frequency difference between Washington (state) and New Mexico (both on the western grid). Although one single turbine cannot by itself influence the dynamics of the grid, a successful test could in principle be scaled up to include farms of hundreds or thousands or turbines acting in concert.

The damping controller, which accepts PMU measurements and processes them to extract relative frequency difference, is essentially the same as the one used for the PDCI work with a few modifications. Software has been written and tested that will allow the turbine nacelle controller to receive the damping controller's signal and modulate the torque command of the turbine generator, in turn modulating the real output power. All software components were designed with safety and security in view.

TEST OBJECTIVES AND SUCCESS CRITERIA

The following table summarizes the primary and secondary test objectives for the test plan along with the criteria used to evaluate the success of the test in achieving the objectives. Primary objectives are required to be completed while secondary objectives are only to be pursued after successful completion of the primary objectives.

Table 1. Test objectives and success criteria

Primary Test Objective(s) – Must be completed for a successful test
PTO1: Install modified production control code into turbine controller.
Success Criteria: Turbine control operates normally with no modulation signal applied. (In other words, turbine control should operate as before in the absence of a modulation input, proving that the core turbine production control code remains unaffected.)
PTO2: Apply test modulation signals from a computer in the control house and observe measurements, including RPM, power output and torque demand. This should be done under "low wind speed" conditions. Modulation signals will include sine-wave frequencies starting at 0.1Hz and progressing to 2Hz, but with no input modulation from 0.9 to 1.1 Hz (to avoid tower resonance). Modulation amplitudes will range from 1 to 20 Nm, unless the operator determines

that higher values present risk to the system. Success Criteria: Turbine measurements align reasonably well with expected values. No measurements fall outside established acceptable limits.
PTO3: Apply the modulation signal being transmitted from the damping controller in Albuquerque, using PMU feedback from Washington State University and Albuquerque. Various amplitude scaling factors may be tested, with modulation remaining at or under 20 Nm.
Success Criteria: Measurements of torque demand and instantaneous real power output "track" the modulation input. No measurements fall outside established acceptable limits.
Secondary Test Objective(s) – May be completed after primary test objective is complete
STO1: Apply a modulation signal being transmitted from the damping controller in Albuquerque, using the relative difference between true 60Hz and a PMU located in Lubbock. Similar to PTO3.
Success Criteria: Same as PTO3.
STO2:
Success Criteria:
STO3:
Success Criteria:

ROLES AND RESPONSIBILITIES

Describe all the roles and responsibilities of the personnel that will be involved in all stages of the test plan.

Table 2. Roles and Responsibilities

Title	Name(s)	Responsibilities
	Ian Gravagne	• Observe and coordinate test from SWiFT control room. • Apply test signals from computer software in SWiFT control room during PTO2.
	Jon Berg	• Install modified production control code at SWiFT turbine. • Operate and monitor turbine. • Final "go" or "no-go" authority.
	Adam Summers Felipe Wilches-Bernal	• Operate damping controller in Albuquerque, communicate with SWiFT personnel via phone link

UNIQUE HAZARDS

The following table provides a high-level summary of major hazards that are unique to this test. Further information on hazards and controls for this test are provided in the safety documents.

Table 3. Unique Hazards

Hazard	Description
Structural Resonance	A driving input such as generator torque has the potential to excite structural resonance frequencies if the driving signal dwells at particular frequencies. Simulation of modulated torque demand has indicated that tower resonance in the vicinity of 1.0 Hz can be excited but the magnitude of response is expected to be within normal operating limits. Dwelling at this frequency will still be avoided. Simulation has also indicated a potential drivetrain resonance in the vicinity of 4.6 Hz. The magnitude of the high-speed shaft torque response is more pronounced with up to 3-times the amplitude of the driving input oscillation but is still within the system's torque limits. The amplitudes of rotor/generator speed oscillations and blade edgewise bending in the vicinity of 4.6 Hz were only slightly affected (less than 1%). This frequency will be avoided, limiting the frequency of sinusoidal test signals to 2 Hz or less.

SCHEDULE

Describe the major phases of the test. This could be in the format of a calendar or other format that best conveys the information.

Table 4. Test Schedule

Dates	Description
2017 Sep 27-28	Test communications to/from Albuquerque and SWiFT. Install modulation-enabled production control software. Perform PTO1 to ensure normal turbine behavior in absence of modulation.
2017 Sep 28-29	Perform PTO2 and PTO3.

CONFIGURATION

Definition of test area and conditions

Test area and configuration
The test area consists of the SWiFT site in its standard configuration. Turbine A1 or turbine A2, only one at a time, may be utilized during the tests.

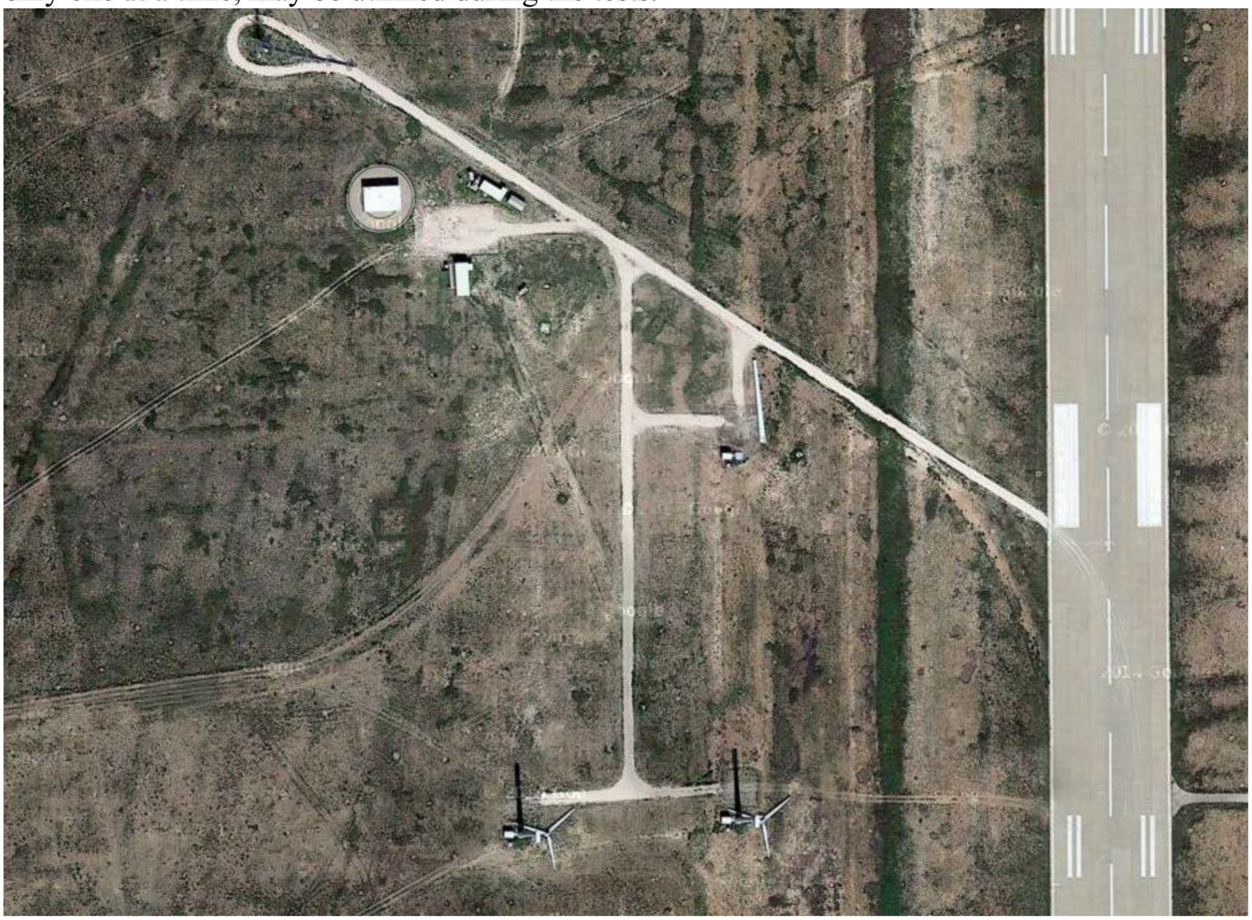

Figure 1. Schematic of test site at the SWiFT Facility

Site conditions
All activities will take place under safe environmental conditions per current SWiFT facility guidelines (Ref. 1) and within equipment operational windows. Generally this includes wind speeds below 20 m/s, no lightning, or extreme weather.

Wind speeds between 3 m/s and 8 m/s are desired so that the turbine operates within the variable speed portion of the turbine's torque control.

EQUIPMENT, FACILITIES, AND MATERIALS

The following is a list of major equipment, facilities, and materials required for the test activities along with the supplier as indicated in the parentheses.

Equipment

- Phasor measurement unit (provided by Org 8813 Electric Power Systems Research)
  Description: Self-contained PMU and GPS antenna placed in SWiFT Control Building
- Satellite clock (provided by Org 8813 Electric Power Systems Research)
  Description: Timing source to be used with the PMU in SWiFT Control Building

Power

- Standard 115vac wall outlet (provided by SWiFT Control Building)

Data

- Standard turbine data logs (provided by SWiFT)

PROCEDURES

This section will present the major test procedures that will be used to achieve the test objectives. Details regarding specific steps related to safety should reference relevant safety documents (OP, JSA, TWD, etc.). Daily briefings will be conducted by the Test Controller prior to the commencement of test activities using pre-test checklists in the appendix.

Pre-test approvals

The standard software validation and management-of-change (MOC) procedures apply for any turbine controller modifications. The software validation and MOC have been completed, see references.

Setup

No additional physical equipment is required to carry out this test plan. Dr. Gravagne will have a laptop with signal generation capability and a variety of IP network analyzers. This laptop will be connected to the private network hosting the computers and controllers at SWiFT. Jon Berg will install the modulation-enabled production control software per PTO1.

Alignment

N/A.

Testing And Data Collection

During testing for PTO1, confirmation of success will be determined on the basis of real-time measurements observed in the SWiFT control room.

During testing for PTO2, PTO3 and STO1, input signals will be applied. Personnel will record details about the type of signal (amplitude/gain, frequency, etc) and the time of signal application on the satellite clock. It is not necessary to be extremely precise – these details will be used to locate the rough start/stop times of a particular test in the turbine measurement data logs.

Data logs will be parsed to extract torque demand, rotor RPM, instantaneous real power output, and GPS-satellite time stamps for all measurements.

Personnel will have access to real-time data indicating the operation of the software, such as whether message authentication codes match (as expected) and whether network latency is within acceptable limits.

TEARDOWN

Upon the completion of testing, all equipment and materials will be removed from the site and returned to their respective owners. The site will be returned to the pre-test state as much as possible.

Reporting

There are no additional reporting requirements. All site operating procedures will be followed in the event of safety incidents or other atypical events.

REFERENCES

1. Jonathan White, *Sandia SWiFT Site Operations Manual*, SAND2016-0651, Sandia National Laboratories, Albuquerque, NM, January 2016
2. SWiFT_SoftwareValidation_v1.1.5-TMC summary, dated 26-Sep-2017
3. SWiFT_MOC_2017-007 (Grid Modulated Torque), Revision A
4. Jonathan Berg, Torque-Mod-Controller-Analysis.pdf, Memo of Record "Regarding SWiFT MOC 2017-007 (Grid Modulated Torque)" dated 25-Sep-2017

PRE-TEST CHECKLISTS

Daily Checklist

The following items will be reviewed daily by the Test Controller or delegae, with all personnel on site prior to any activities :

Task	Comments
PRE-TESTING	
1. Review weather forecast with SWiFT Site Supervisor to confirm conditions will be within safe operating limits for equipment and personnel.	

2. Review roles and responsibilities with personnel and confirm adequate qualifications are met.	
3. Review current test objective(s) and list of activities for the day and confirm completion of specific checklists for those activities. (see additional checklists)	
4. Review and address any safety concerns and highlight significant hazards for day's work activities.	
5. Verify that all required and optional PPE has been issued and is functioning correctly.	
POST-TESTING	
6. At end of daily operations, review activities with personnel and note any areas of improvement	
7. Confirm all equipment is put into a safe storage mode.	
8. Notify SWiFT Site Manager that operations have ceased for the day.	

System 1 Checklist

The follow items will be reviewed by the System 1 Operator daily prior to use:

Task	Comments
PRE-TESTING	
1. Operator confirms weather conditions are within the safe operating envelope of the equipment	
2. Operator confirms safe working order of equipment	
POST-TESTING	

3. At end of testing, operator secures system for overnight storage	

APPENDIX B FRAMING AND ENCRYPTION SPECIFICATIONS

Data Transmission Framing Specifications
Wide Area Damping Wind SBV Project
Ian Gravagne, Org 6113

Overview

The purpose of this project is to demonstrate the feasibility of operating a closed-loop wide area damping system for a power transmission grid by modulating the output power of a small wind turbine. Specifically, the turbine will be one of Sandia's Vestas V27 units at the Sandia's Scaled Wind Farm Technology (SWiFT) site in Lubbock, TX.

The principal components of the system are:

1.) A pair of phasor measurement units (PMUs) streaming grid frequency and angle measurements to the Controls, Optimization and Network Technology Lab (CONET) at Sandia, Albuquerque.
2.) A control unit at CONET (referred to as the "damping controller") to receive measurements, process them, and transmit modulation commands to the SWiFT site in real time.
3.) A control and data acquisition unit in the nacelle of the turbine at SWiFT (referred to as the "nacelle controller") to receive modulation commands, process them, and transmit relevant measurements back to CONET in real time.

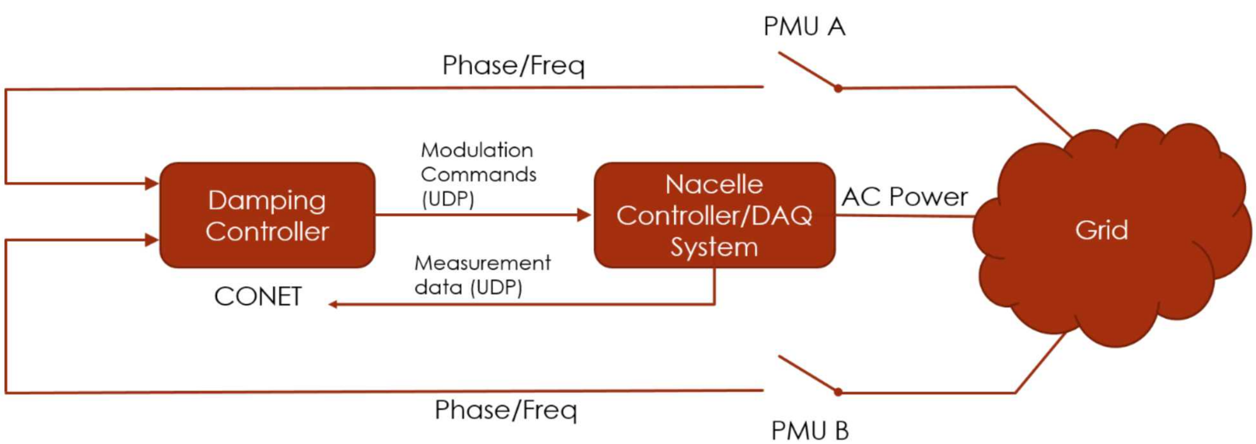

Figure 18 Data Aquistion Diagram for Wind Turbine Control

Modulations commands transmitted from the damping controller to the nacelle controller, and data measurements returned from the nacelle controller to CONET, will use UDP/IP as the transmission protocol. What follows are the UDP payload framing specifications, message rate, IP addresses and ports, and related detail necessary for instantiation of the design in LabView.

Modulation Command Framing

The wind damping controller architecture is essentially identical to the BPA damping controller, with the following principal exception. In the BPA controller, power modulation is achieved by writing command values to a Digital-to-Analog (D/A) converter, typically at an update rate of 60 updates per second. Analog values are then interpreted by BPA's equipment as desired power modulation levels on the Pacific DC Intertie.

For the wind controller, power modulation is achieved by sending command values as packet payloads via UDP/IP to the nacelle controller. Arriving packets are then interpreted by the nacelle controller as desired torque modulation levels at the turbine generator input, which in turn cause real power modulation at the generator output.

Internet Addressing
Only two fields are necessary for addressing packets to the nacelle controller:

IP_NACELLE	The IPv4 address of the nacelle controller for receiving modulation commands
PORT_NACELLE	The port number of the nacelle controller's receiving UDP socket.

Network addressing parameters

See section 2.3 (Default Values) for further discussion of these fields.

Payload frame composition
Each modulation command and associated data form a "frame" (the byte sequence that forms a UDP packet payload). Each frame shall be constructed in the following sequence:

0x4947	2 byte frame identifier (hexadecimal "49" and "47")
TIME_DIV	4 byte unsigned integer time divisor
TIME_SEC	4 byte unsigned integer seconds elapsed since 00:00:1970, derived from GPS clock
TIME_FRAC	4 byte unsigned integer fraction-of-second since 00:00:1970, derived from GPS clock
DATA_DIV	4 byte unsigned integer data divisor
TORQ_MOD	4 byte signed integer torque modulation value, Nm
RESERVED	8 byte field, reserved for future use
MAC	32 byte SHA-256 message authentication code using pre-shared key. Hash input includes all preceding fields, including 0x4947.

Modulation controller output fields

Frames are constructed MSB to LSB (left-to-right). Each frame is described in more detail below.

TIME_DIV, TIME_SEC and TIME_FRAC: Each frame is time-stamped with the current satellite time expressed at the number of seconds elapsed with midnight, 1970, at the time of transmission of the frame. The nacelle controller will receive these fields and interpret the timestamp by computing:

$$T = TIME\_SEC + (TIME\_FRAC / TIME\_DIV).$$

For example, on date April 27, 2017 at 21:02:07.038642 the three time fields would be

TIME_DIV = 1,000,000 (0x000F4240)
TIME_SEC = 1,492,722,127 (0x58F921CF)
TIME_FRAC = 38,642 (0x000096C8)

The question of whether to include leap-seconds is left open, assuming both the Nacelle Controller and Damping Controller use the same standard.

DATA_DIV: Similarly, DATA_DIV is the divisor for all data fields to help make modulation command packets more easily human-readable. For example, if TORQ_MOD = 0x009AE070 and DAVA_DIV = 0x000F4240, then the true decimal value of the torque modulation is 10,150,000/1,000,000 = 10.15 Nm.

TORQ_MOD: The value of the desired torque modulation, in units of Nm, scaled up by a factor of DATA_DIV. For example, a desired modulation of 10.15 Nm with a DATA_DIV of 1,000,000 would be a value of 10,150,000 or 0x009AE070.

RESERVED: Bytes reserved for future data fields, currently unused.

MAC: A 32-byte (256 bit) message authentication code (MAC). A MAC functions essentially like a signature. Generating the MAC requires a "key" (a password), known only to the transmitter and the receiver, and a 'message", in this case the framing bytes preceding the MAC field and including 0x4947.

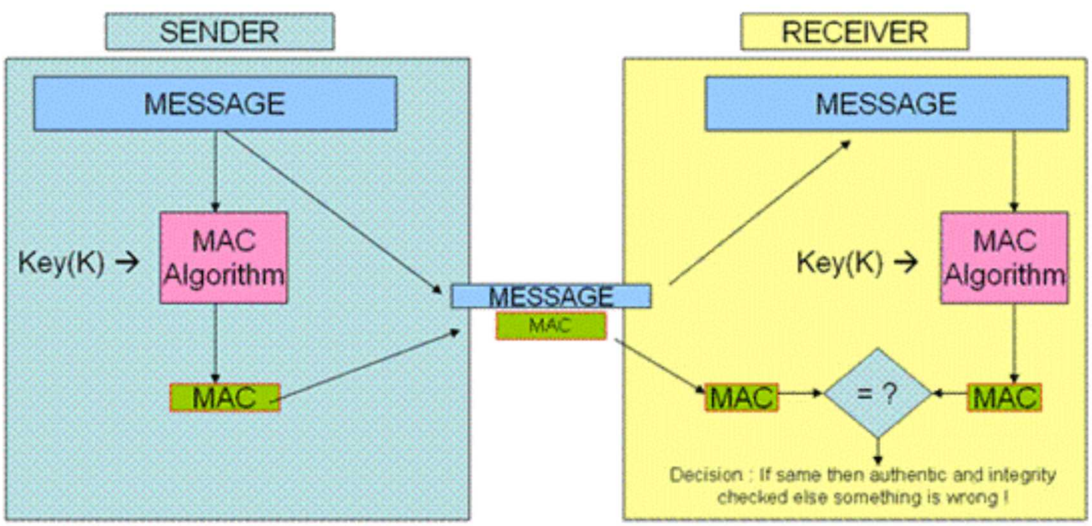

Illustration of Message Authentication Code (taken from www.sqa.org.uk)

The MAC should use the publicly available "HMAC-SHA256" algorithm. For example, if the data fields in the frame are as follows

0x49 47 00 0F 42 40 58 F9 21 CF 00 00 96 C8 00 0F 42 40 00 9A E0 70 00 00 00 00 00 00 00 00 and the pre-shared key (which may be of any length) is

0x01 02 03 04 05 06 07 08

then the resulting SHA256 MAC will be

0x68 32 5E 9B DF 87 8F 9A C0 43 F7 30 4B D3 93 70 13 F8 42 ED DE FE FA 50 47 E6 8F E8 AB 25 83 9B

Default parameter values
From sections 2.1 and 2.2, parameters (values that are fixed from frame to frame) may either be hard-coded or obtained from front-panel GUI dialogs. Suggested default values are:

IP_NACELLE	192.58.125.241
PORT_NACELLE	4716
TIME_DIV	1,000,000 (0x000F4240)
DATA_DIV	1,000,000 (0x000F4240)
DATA_RES	0x00 00 00 00 00 00 00 00

Default parameter values

Frame transmission rate
UDP packet transmission trigger and rate criteria will be specified by the wind control design team. Trigger refers to the event that causes a message to be transmitted. Rate refers to how many messages per second are transmitted.

Measurement data framing
The nacelle controller and data acquisition system will transmit UDP packets with data that includes time stamps and measurements from nacelle instrumentation. Measurement packets will be transmitted to an IP address at CONET, for the purposes of data logging, debugging, and verifying overall operation of the system in real time.

Internet addressing
Two fields are necessary for addressing measurement packets to the CONET laboratory:

IP_CONET	The IPv4 address of the CONET lab's data acquisition and storage system
PORT_CONET	The port number CONET lab's receiving IP socket

Network addressing parameters

Payload frame composition
Each measurement data frame to be transmitted from the nacelle shall have the following byte contents and sequence:

0x4153	2 byte frame identifier (hexadecimal "41" and "53")
TIME_DIV	4 byte unsigned integer time divisor
TIME_SEC	4 byte unsigned integer seconds elapsed since 00:00:1970, derived from GPS clock

TIME_FRAC	4 byte unsigned integer fraction-of-second since 00:00:1970, derived from GPS clock
COM1_SEC	4 byte unsigned integer seconds from the TIME_SEC field from the most recently received torque modulation command frame
COM1_FRAC	4 byte unsigned integer TIME_FRAC field from the most recently received torque modulation command frame
COM1_SEC_TS	4 byte unsigned integer seconds of the time when the most recently received modulation command frame arrived at the nacelle controller. (Arrival time-stamp.)
COM1_FRAC_TS	4 byte unsigned integer fraction-of-second time arrival time of the most recently received modulation command frame.
PROD_STATE	2-byte unsigned integer from the "ProdCtrlState" variable of the nacelle production controller
MOD_EN	2 byte unsigned integer indicating state of the torque modulation system
DATA_DIV	4 byte unsigned integer divisor for all subsequent data frames
WIND_SPEED	4 byte signed integer = wind speed (m/s) x DATA_DIV
GEN_TORQUE	4 byte signed integer = demanded generator torque (Nm) x DATA_DIV
GEN_SPEED	4 byte signed integer = actual generator speed (rpm) x DATA_DIV
GEN_POWER	4 byte signed integer = generator real power output (W) x DATA_DIV
RESERVED	16 byte reserved space for future measurement variables
MAC	32 byte SHA256 message authentication code

Measurement data fields

Most fields above are either explained in section 2.2, or self-explanatory. Several require clarification, however.

TIME_DIV is taken from the most recently received command frame (sent from the damping controller to the nacelle controller). Note that this implies the nacelle controller is not transmitting measurement packets until it receives at least one valid command packet.

COM1_SEC and COM1_FRAC are simply exact copies of time fields from the most recent preceding command frame (sent from the damping controller to the nacelle controller). Returning these values, along with **COM1_SEC_TS and COM1_FRAC_TS**, in the measurement frame allows operators to characterize network latency in real time and take corrective action if necessary.

PROD_STATE is an integer indicating the state of the nacelle production control subsystem. Taken from the "FS Production Controller: V27 Variable Speed" specifications:

State	Production State	Rotor Speed
1	Prepare	Low
2	FreeWheel	Low
3	RunningUp	Low
4	Connecting	Low
5	PowerUp	High
6	Production	High

7	LowWIndDisconnect	Low
8	PowerDown	Low
9	Disconnect	Low
10	RunningDown	Low
11	Idle	Low

MOD_EN is an integer indicating the state of the torque modulation subsystem. MOD_EN currently utilizes only the four least significant bits, and can therefore range between values of 0 to 15 according to the following definitions:

…	LSB3	LSB2	LSB1	LSB0

MOD_EN 16-bit (2-byte) uint16

LSB0 = 1 if the incoming command frame's header == 0x4947
LSB1 = 1 if the incoming command frame's MAC is correct, based on the pre-shared key
LSB2 = 1 if modulation has been enabled by the operator (by front-panel switch)
LSB3 = 1 if the production state == 6 and a prescribed modulation start delay has elapsed. The delay is prescribed by operator front-panel dialog.

All four bits must be set ("1") in order for torque modulation to be enabled at the nacelle.

MAC is computed in the manner described in section 2.2. The "message" is all fields preceding the MAC including 0x4153. The "key" must be the same as the key used in the command frame MAC.

Default Parameter Values
Values for parameters may be hard-coded, or taken from dialogs in the system GUI.

IP_CONET	132.175.11.61
PORT_CONET	4725
TIME_DIV	1,000,000 (0x000F4240)
MOD_EN	1 (0x01, enabled)
DATA_DIV	1,000,000 (0x000F4240)
RESERVED	zeros

Default parameter values for measurement frames

Measurement Packet Message Rate
UDP packets containing measurement frames will be continuously transmitted to the IP_CONET address at a rate of 50 messages per second, each 0.02 seconds apart. Each transmission will be triggered at a time such that one out of every 50 messages occurs as near as possible to the top of the minute as determined by satellite time. So, for example, if TIME_DIV is 1,000,000 then the following sequence of frame timestamps will occur for transmissions just before and after April 20, 2017, 21:02:07 at 60 messages per second:

…
April 20, 2017, 21:02:06.9667 [TIME_SEC = 1,492,722,126, TIME_FRAC = 966667]
April 20, 2017, 21:02:06.9883 [TIME_SEC = 1,492,722,126, TIME_FRAC = 983333]
April 20, 2017, 21:02:07.0000 [TIME_SEC = 1,492,722,127, TIME_FRAC = 0]
April 20, 2017, 21:02:07.0167 [TIME_SEC = 1,492,722,127, TIME_FRAC = 16667]
April 20, 2017, 21:02:07.0333 [TIME_SEC = 1,492,722,127, TIME_FRAC = 33333]
…

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