SESSION 2: International Practices for Planning the Operability of Power Systems with High Shares of Variable Renewable Energy Resources—International Experience

Presenter: Eduard Muljadi
National Renewable Energy Laboratory
15013 Denver West Parkway, Golden CO 80401

Workshop on Integrating Renewables into Power Systems in Central America

Part B: October 28, 2016: Planning the Secure and Reliable Operation of the Grid in Central America with High Shares of Variable Renewable Energy Resources

Panama City, Panama

NREL/PR-5D00-67355

Renewable Energy

Image from Sun Power Corp., 23816

PV Plant (5~50 MW)

Rooftop PV (1~30 kW)

Image by Dennis Schroeder, NREL 22192

Image from DOE FEMP, 27638

Mobile 9-kW PV system
Bechler Meadows Ranger Station
Yellowstone National Park

Solar—PV

Renewable Energy

Concentrating Solar Power Plant

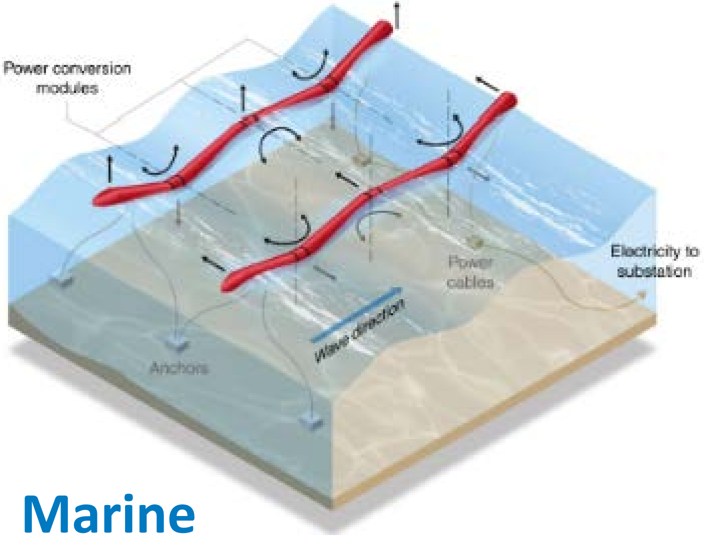
Image from David Hicks, NREL 18557

Image from Bill Timmerman, 08989

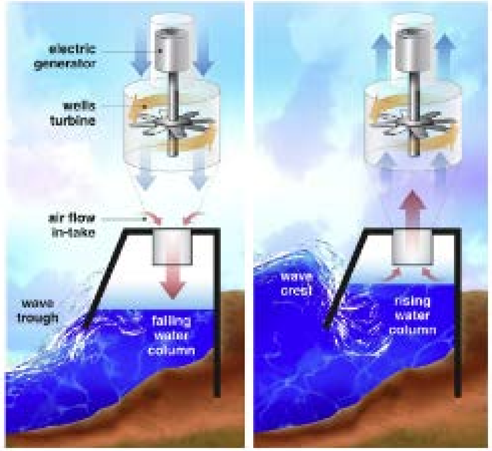
Image from Greg Glatzmaier, NREL 19807

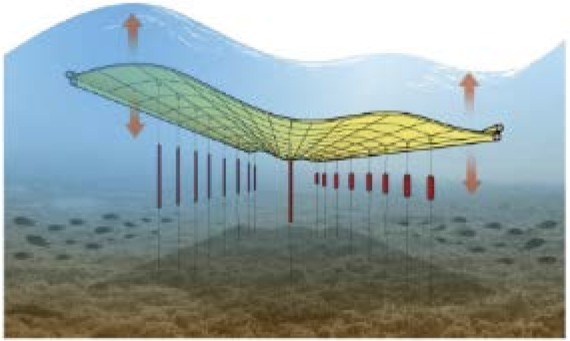
Image from David Hicks, NREL 19881

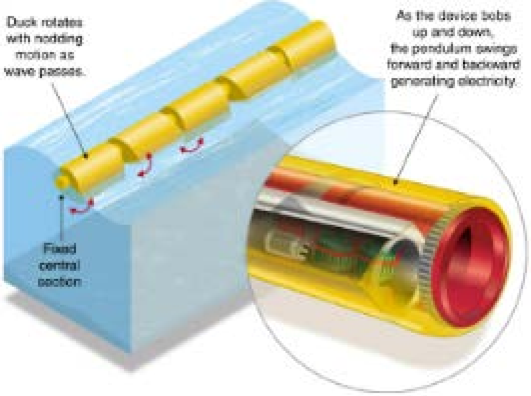
Renewable Energy

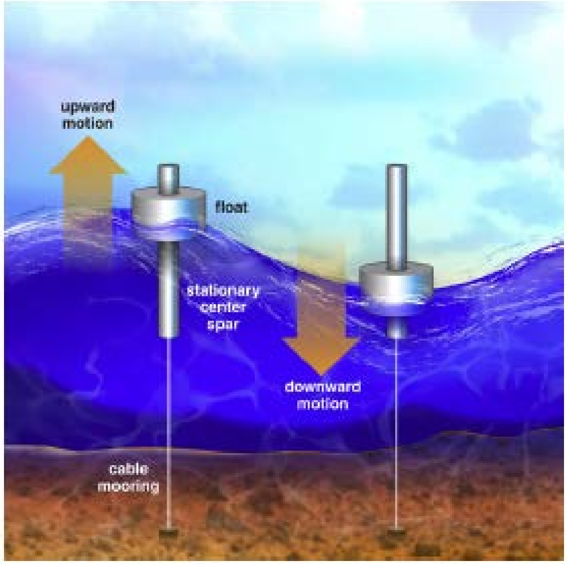


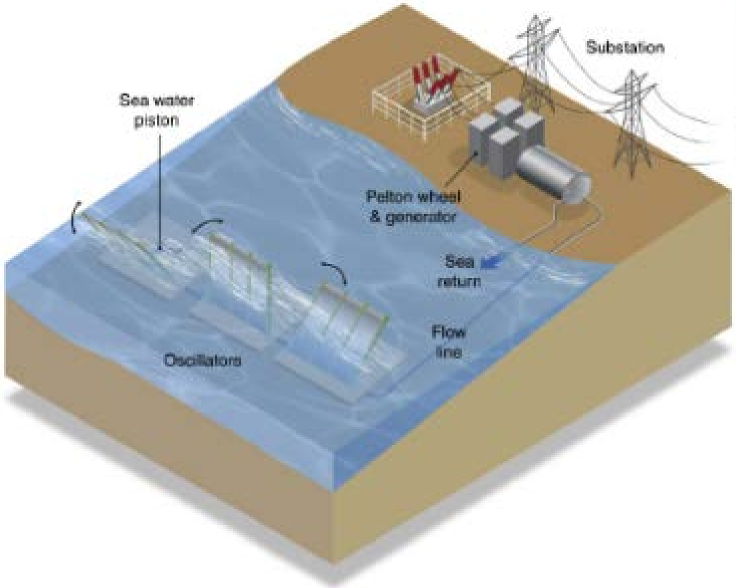
Marine Hydrokinetic

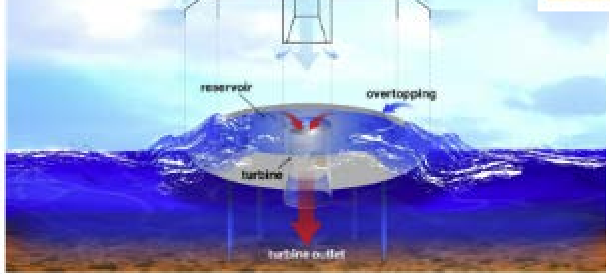








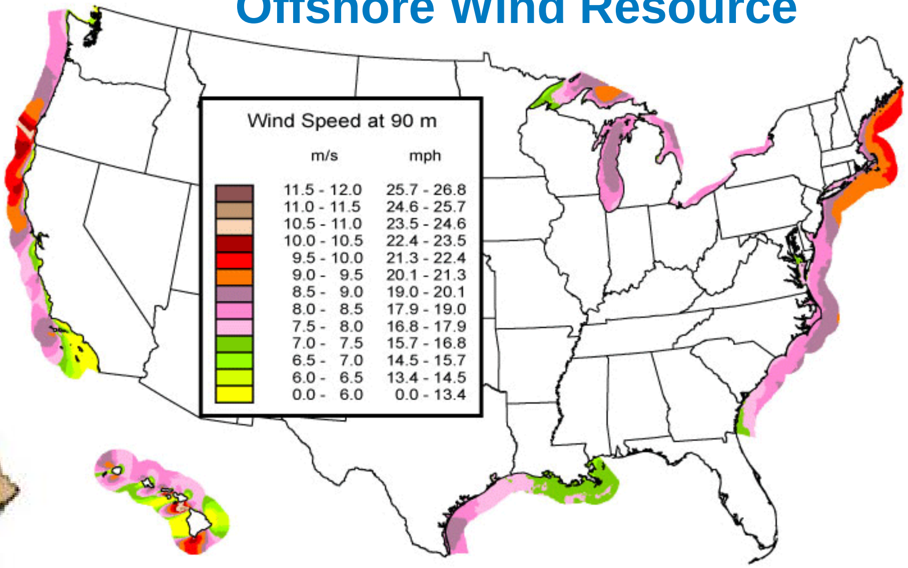




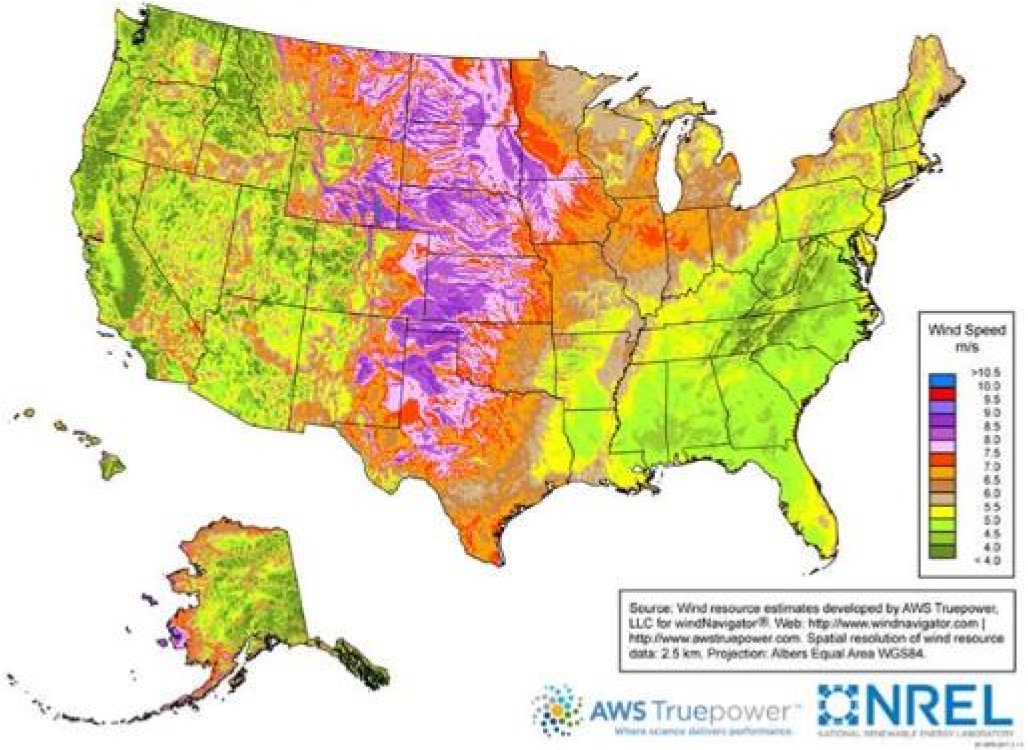
Reference: Y. Li and Y.H. Yu. 2012. “Synthesis of Numerical Methods for Modeling Wave Energy Converter-Point Absorbers.” Preprint. NREL/JA-5000-52115.

Renewable Energy Resources

Offshore Wind Resource

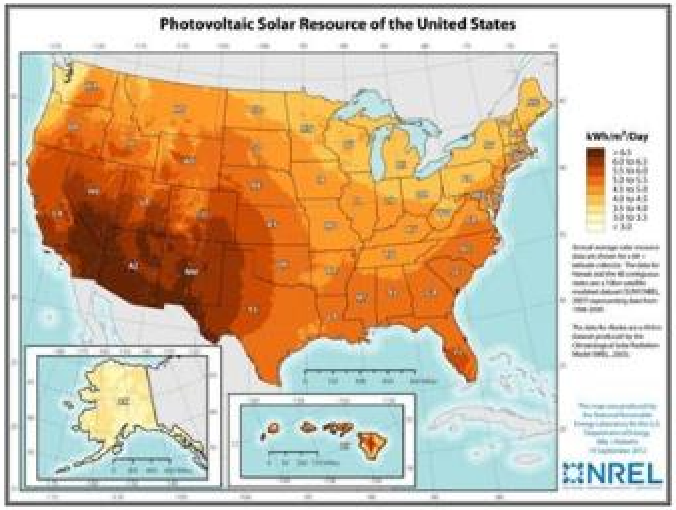


U.S. Wind Resource



Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: Albers Equal Area WGS84.

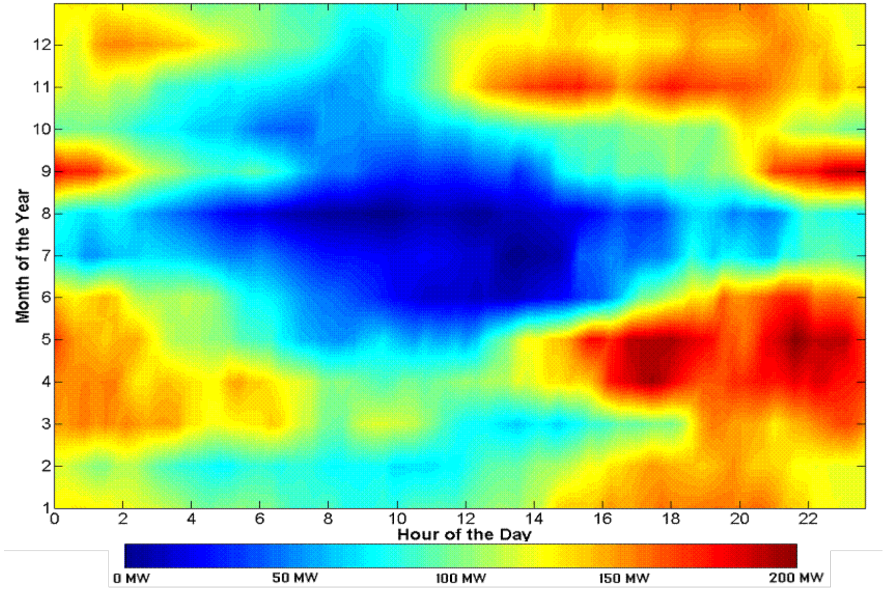
Solar Resource



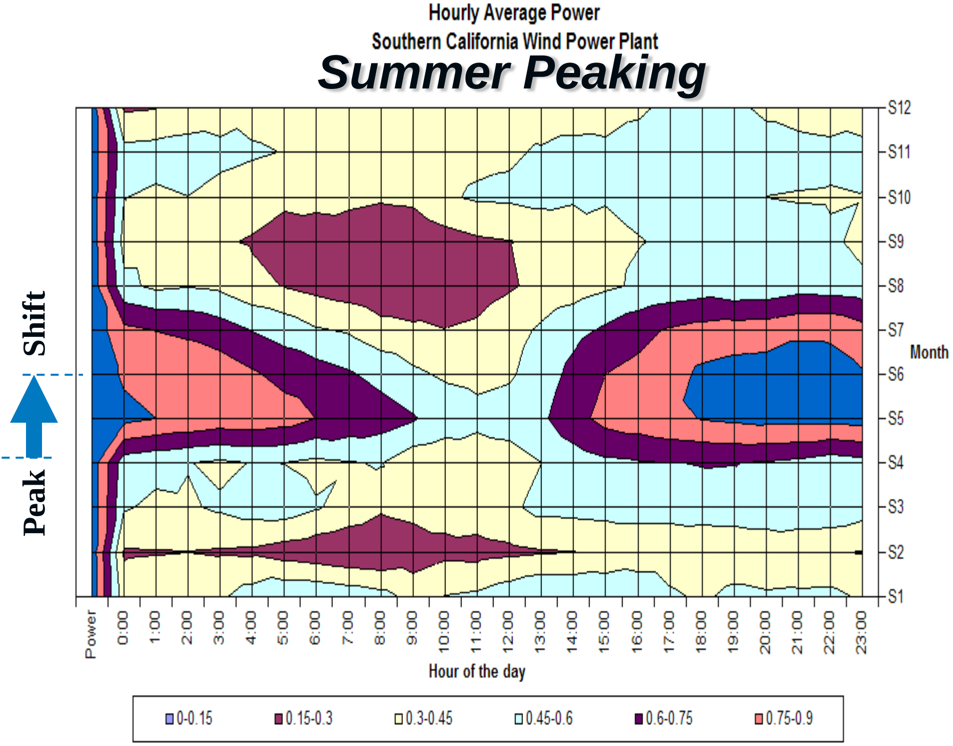
Wind Power Resource

Annual Hourly Average

Spring Peaking



Midwest Region



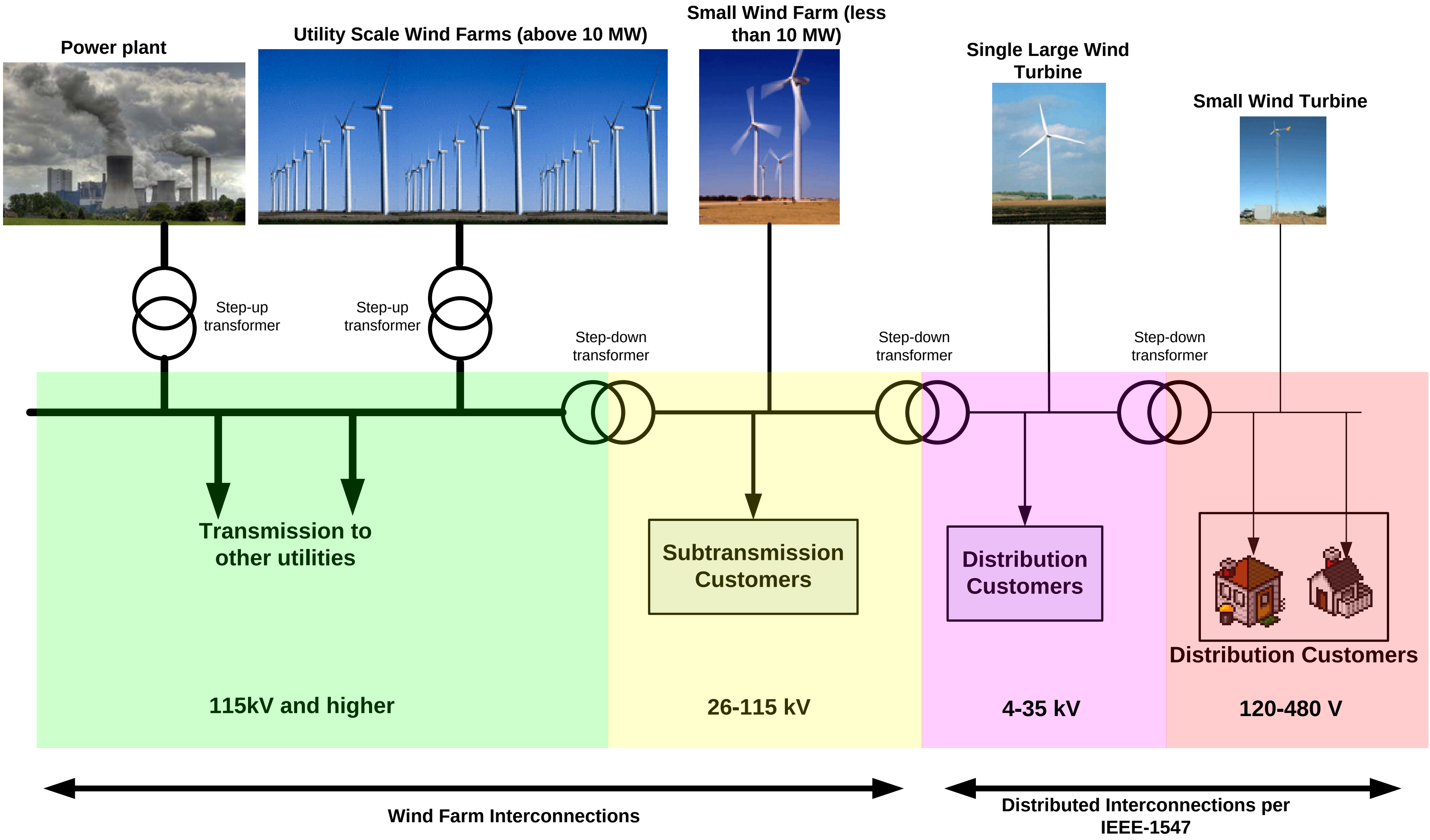
Summer Peaking

California Region

Future consideration:

- **Smart deployment of energy storage (e.g. pumped storage hydro - PSH) in coordinated controlled fashion**
- **Match the characteristics the load (demand-side management -DSM) to the local source.**
- **Understand the regional behavior of the wind pattern and other renewable energy resources.**
- **Multiple types of renewable energy resources in coordinated operation.**

Renewable Power Integration



Power plant

Utility Scale Wind Farms (above 10 MW)

Small Wind Farm (less than 10 MW)

Single Large Wind Turbine

Small Wind Turbine

Step-up transformer

Step-up transformer

Step-down transformer

Step-down transformer

Step-down transformer

Transmission to other utilities

Subtransmission Customers

Distribution Customers

Distribution Customers

115kV and higher

26-115 kV

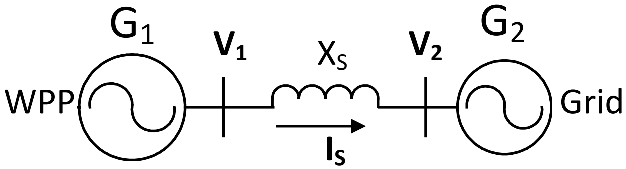
4-35 kV

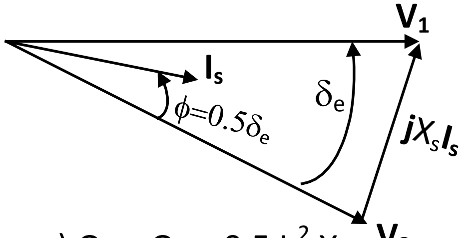
120-480 V

Wind Farm Interconnections

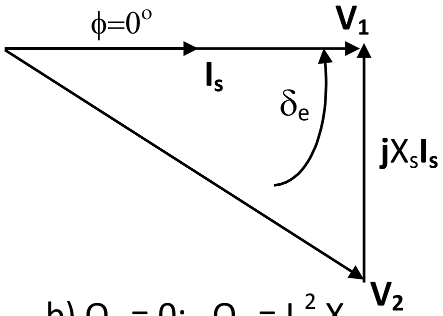
Distributed Interconnections per IEEE-1547

Grid Stiffness

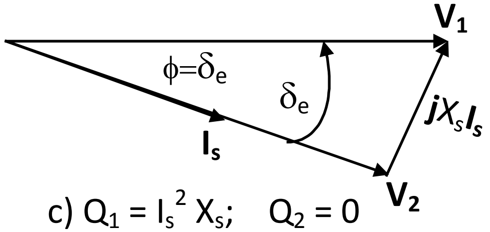




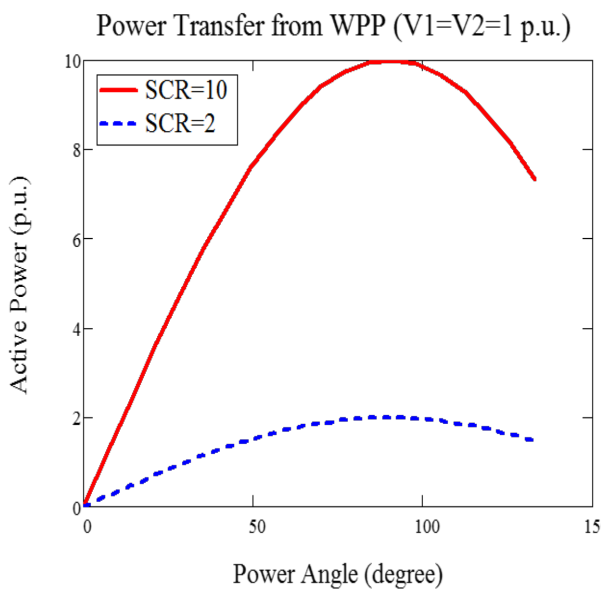
a) $Q_1 = Q_2 = 0.5\ I_s^2\ X_s$

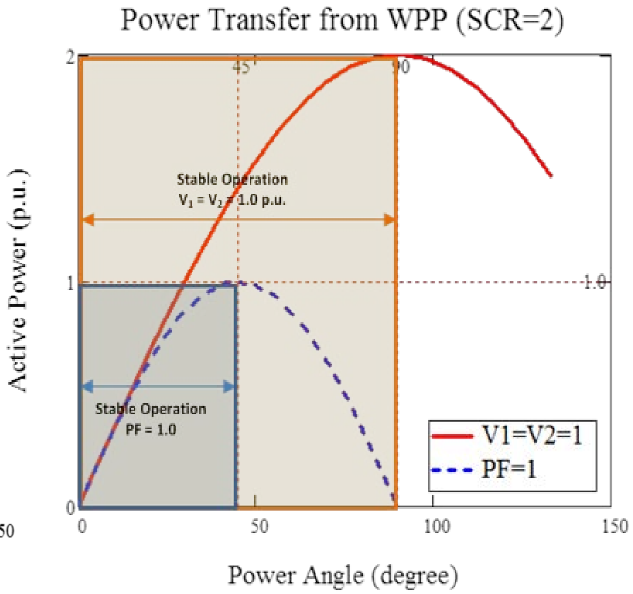


b) $Q_1 = 0; \quad Q_2 = I_s^2\ X_s$



c) $Q_1 = I_s^2\ X_s; \quad Q_2 = 0$

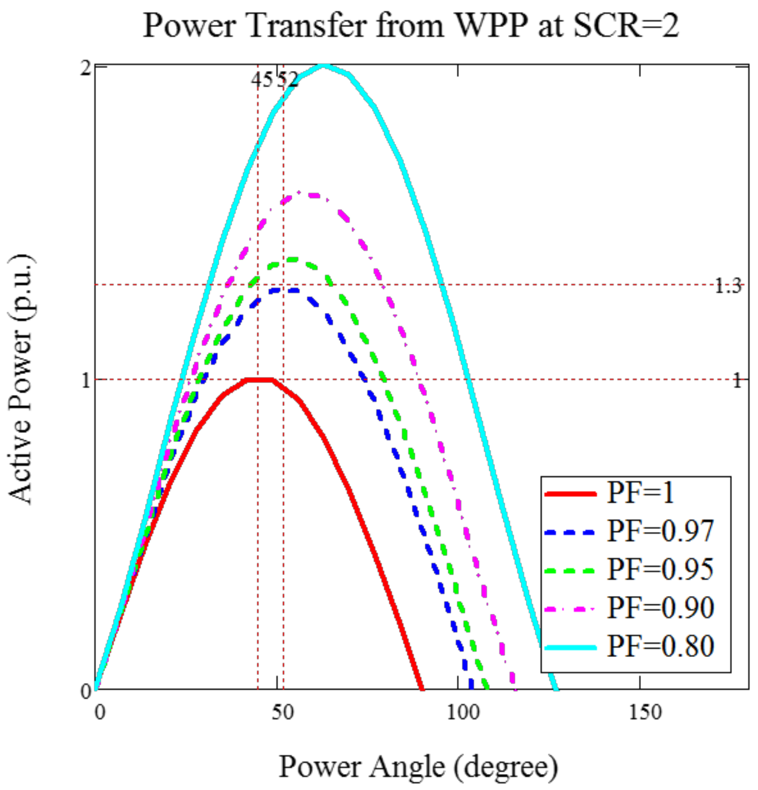




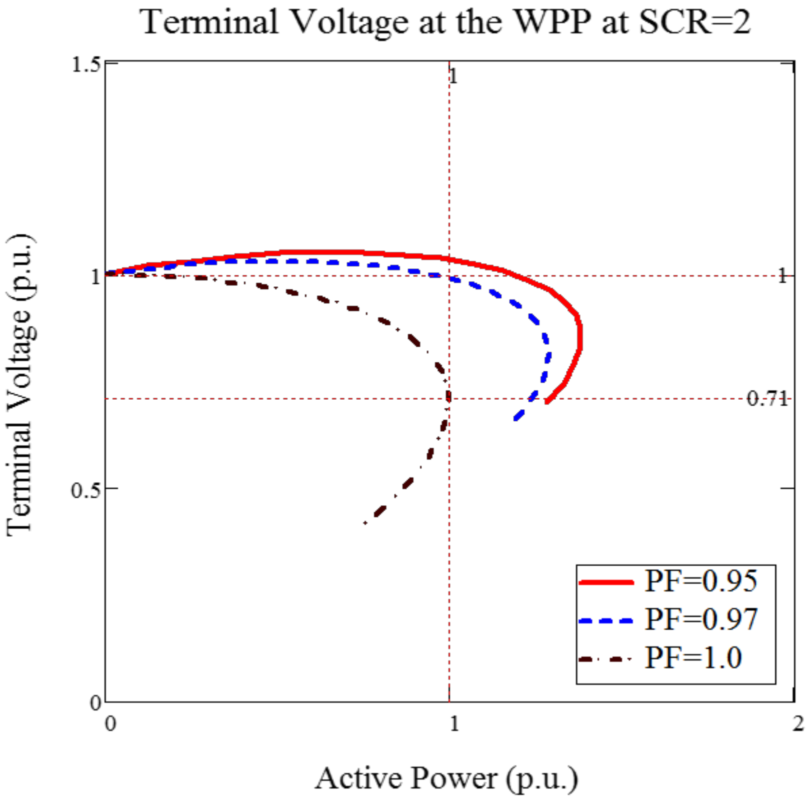
Weak grid vs. stiff grid:

- If the reactive power consumed by the reactive loss $I_s^2X_s$ is compensated by both Bus 1 and Bus 2, the voltage $V_1 = V_2 = 1.0$ p.u. can be maintained.
- Operating a wind power plant (WPP) at a unity power factor (PF=1) can lead to an undervoltage at the WPP, especially for a weak grid condition (e.g., short-circuit MVA < 2.0 p.u.)
- A weak grid has a lower power transfer capability compared to a stiff grid; thus, changing the output power in a weak grid pushes the operating point closer to the stability limit.
- The ability to generate reactive power from a wind turbine generator (WTG) will expand the power transfer from a wind power plant (WPP) significantly compared to PF=1.

Reactive Power Control

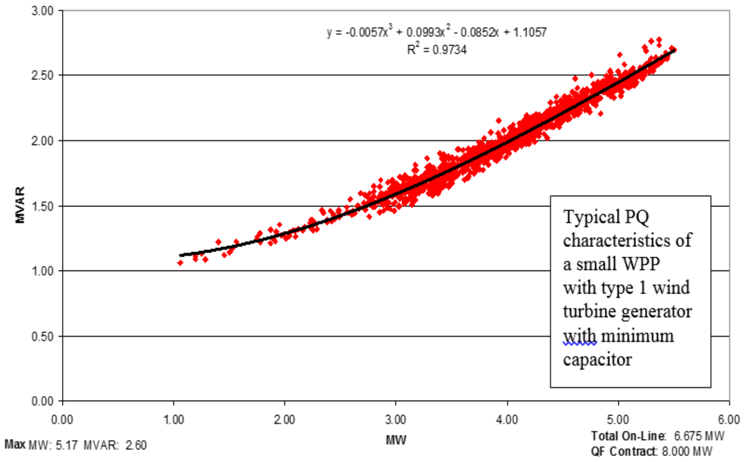


Power-angle characteristics of the WPP operated at different power factor settings

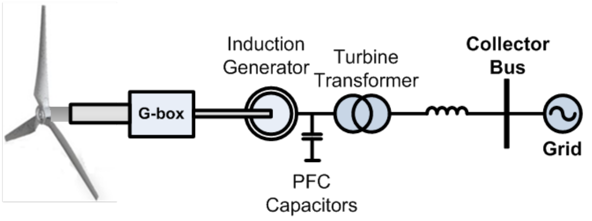


Power-voltage characteristics of the WPP operated at different power factor settings

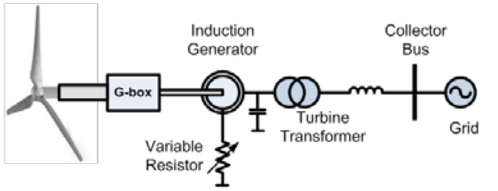
Reactive Power Compensation



PQ characteristics of Tehachapi, California, Type 1 WTG



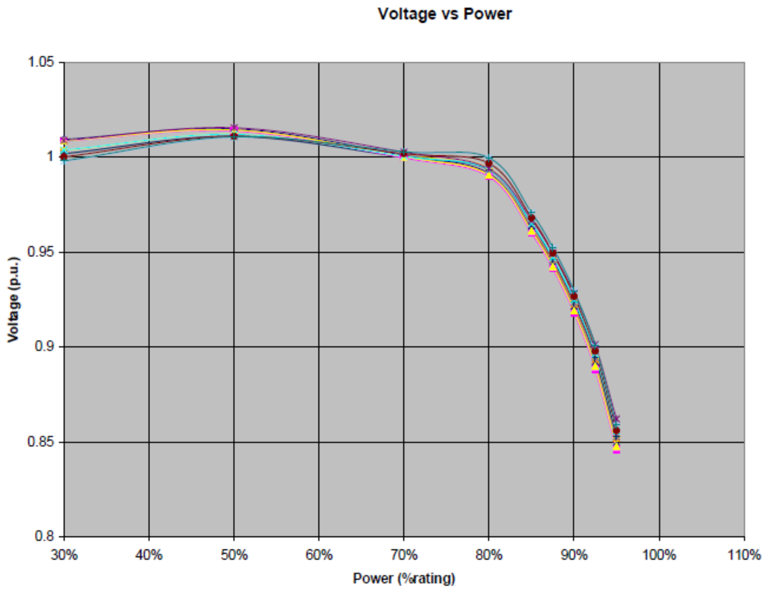
Type 1 Fixed Speed Induction Generator



Type 2 Variable Slip Induction Generator

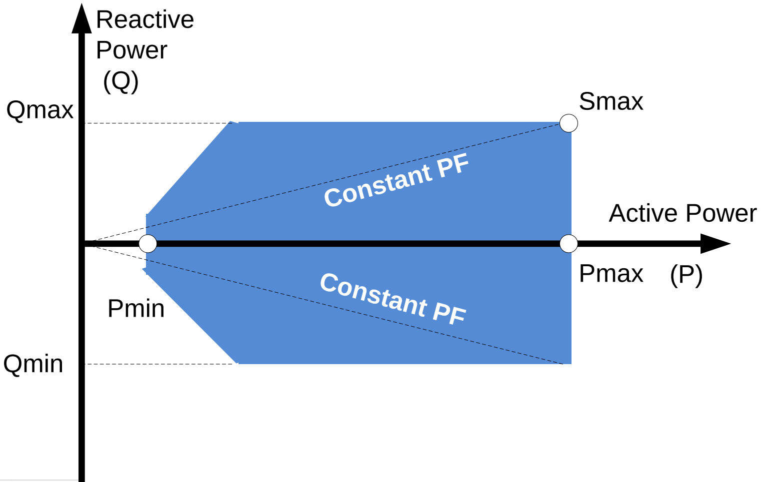
Reactive power compensation for WTG-1 and WTG-2:

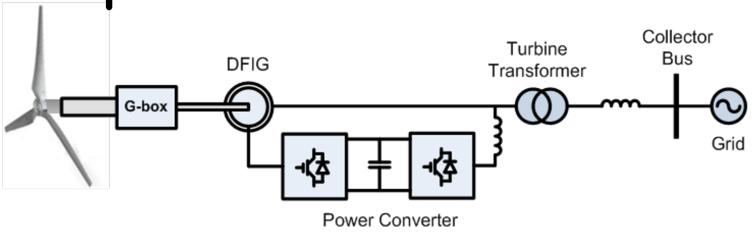
- Type 1 and Type 2 WTGs are based on an induction generator.
- Reactive power compensation is needed as a function of the output power generation.
- Without proper reactive compensation, the grid voltage will drop significantly and a voltage collapse occurs.
- An undervoltage relay at the WTG will disconnect the WTG, and the power system is self-corrected
- There is a loss of valuable generation if not compensated.
- Switched bank capacitors are needed to compensate the reactive power at the individual WTGs and in some cases at the plant level.



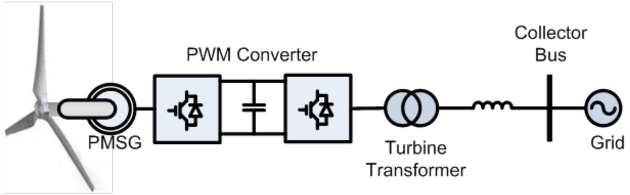
Voltage collapse observed at several WPPs

Reactive Power Compensation





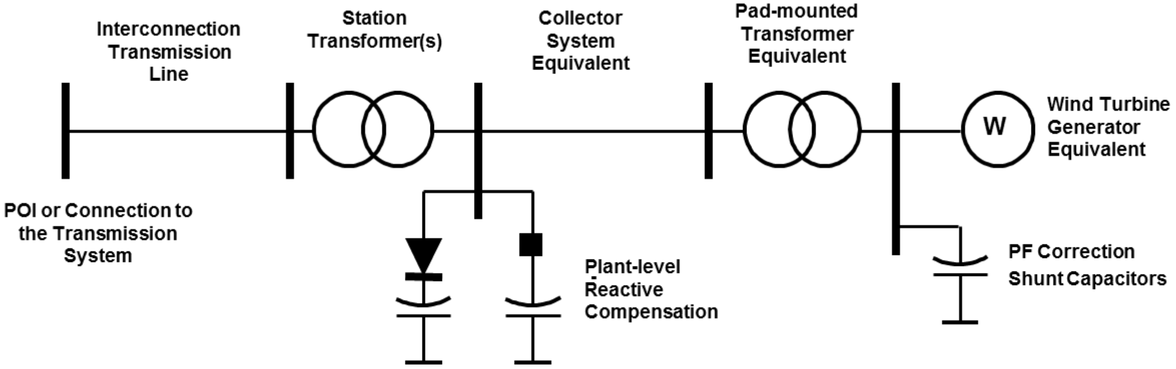
Type 3 Doubly Fed Induction Generator (DFIG)
(Variable Speed WTG)



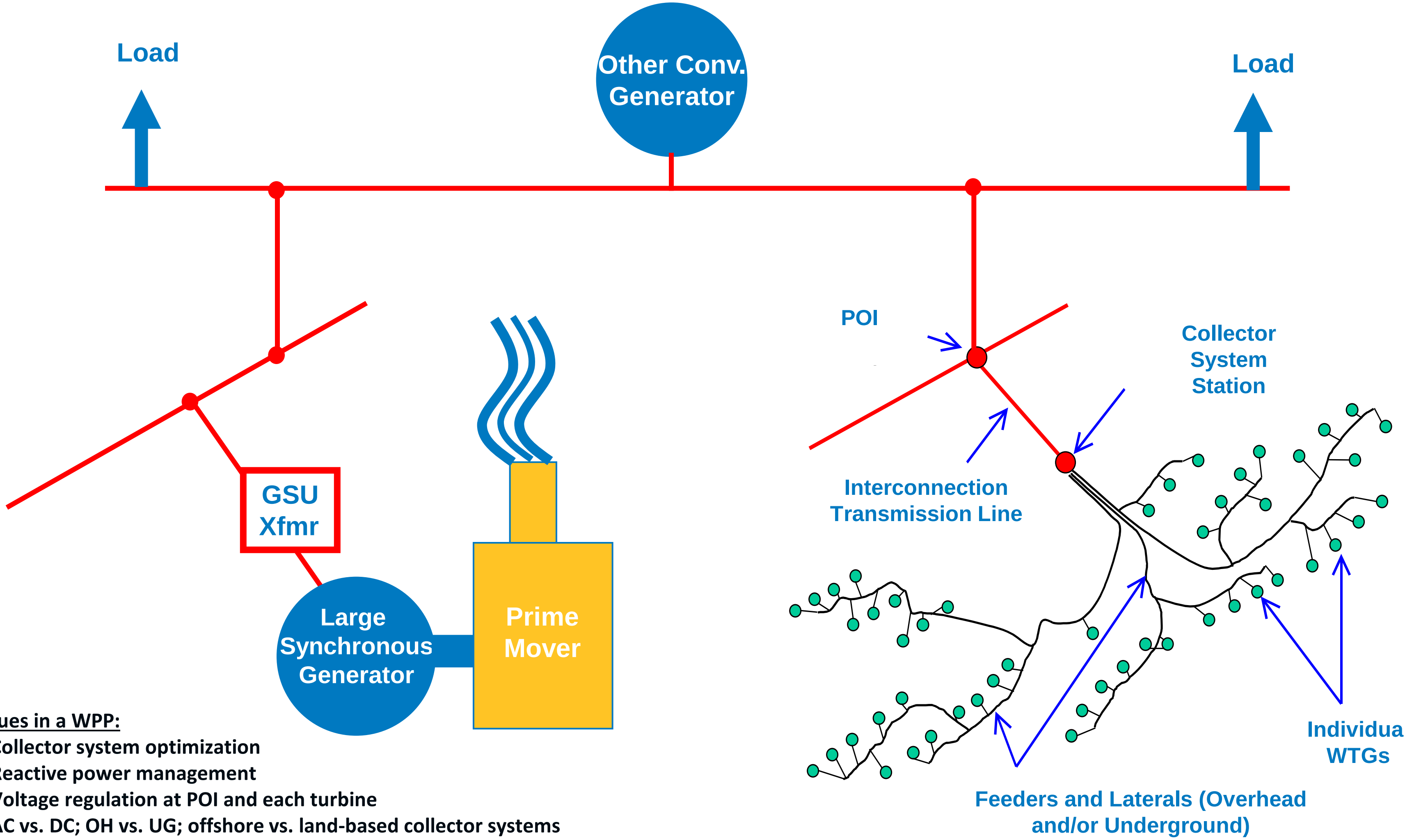
Type 4 Full Power Conversion
(Variable Speed WTG)

Reactive power for voltage support:

- The power factor range may vary depending on the local requirement— typically - 0.90 underexcited/0.90 overexcited range.
- Variable-speed WTGs with power converters usually satisfy power factor requirements at the point of interconnection (POI).
- Variable-speed WTGs can generate reactive power even when not generating.
- In some cases, plant-level reactive power may be necessary, especially for a weak grid condition.



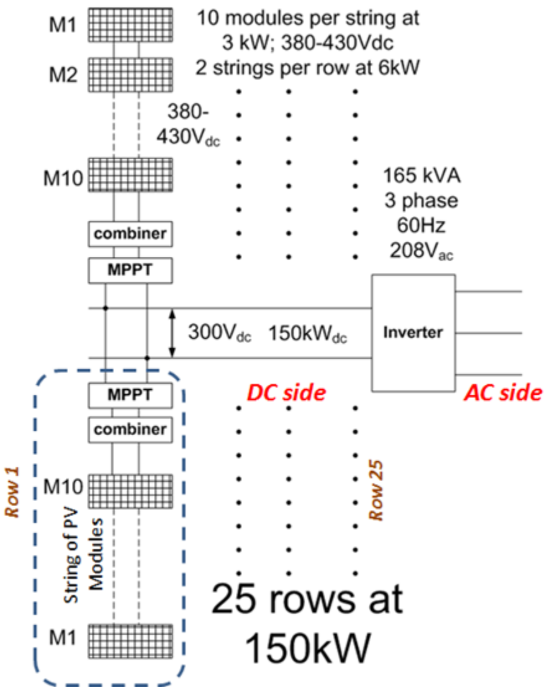
Conventional vs. Wind Power Plant

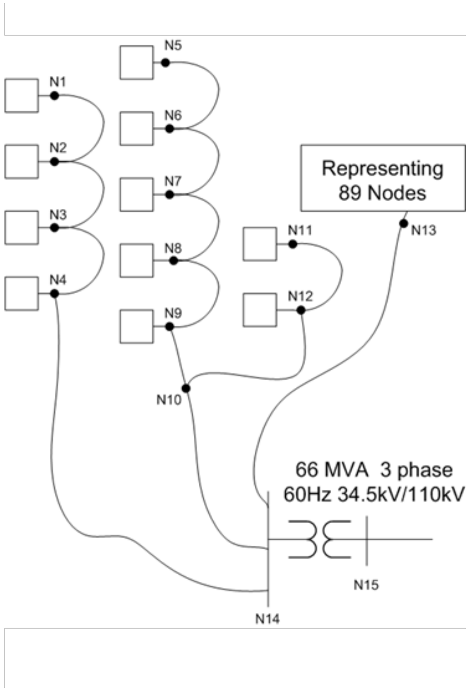


Issues in a WPP:

- **Collector system optimization**
- **Reactive power management**
- **Voltage regulation at POI and each turbine**
- **AC vs. DC; OH vs. UG; offshore vs. land-based collector systems**
- **Predictive maintenance**
- **WPP model vs. WTG model.**

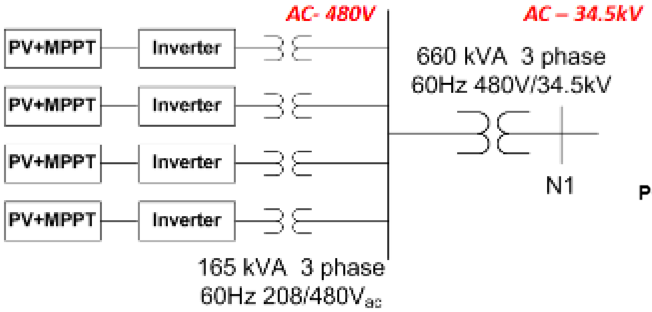
Photovoltaic Power Plant

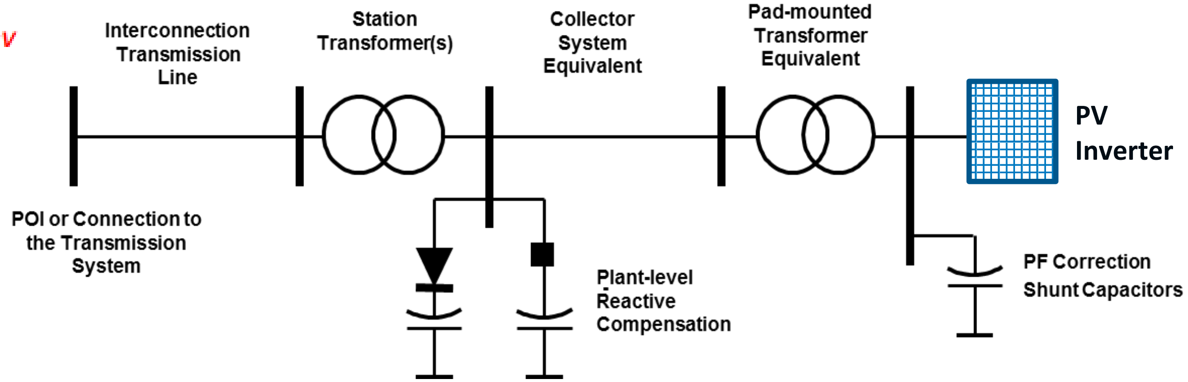




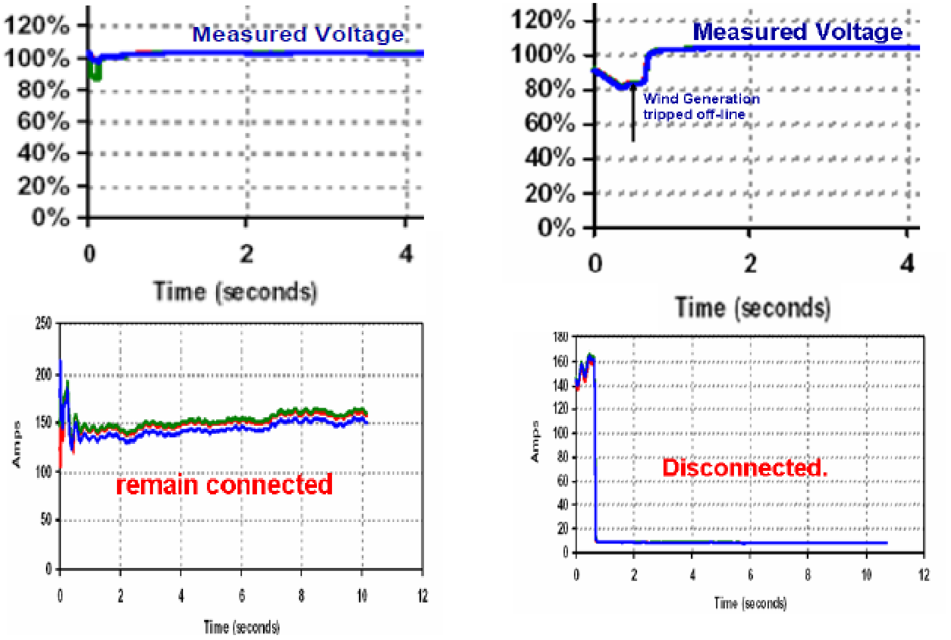
Photovoltaic (PV) plant interconnection:

- From the perspective of the plant, a PV plant is very similar to a WPP.
- A PV generator is similar to a Type 4 (full power conversion) WTG.
- A PV generator does not have rotating inertia like a WTG.
- It can generate reactive power when generating or even when not generating.
- In some cases, plant level reactive power may be necessary, especially for a weak grid condition.





Wind Power Plant—One Year of Observation in Texas



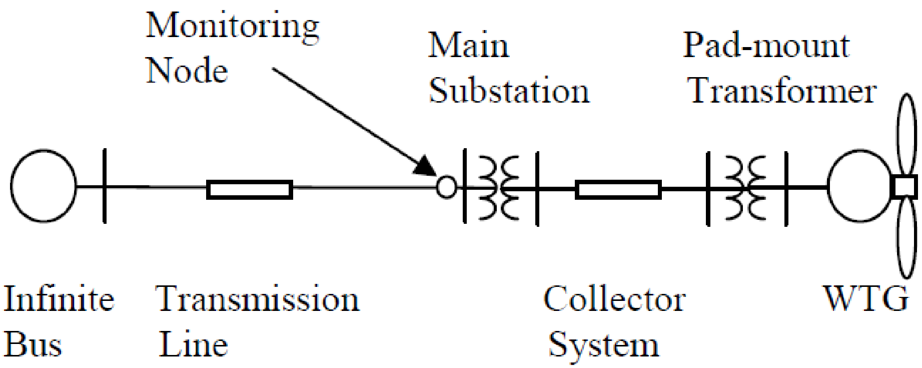


Figure 1. A typical network topology of a large wind power plant.

A WPP is very large with hundreds of WTGs.

- There is diversity within a WPP:
  - Wind resource at each WTG
  - Collector system impedance and electrical distance from the substation transformer
  - Terminal voltage, V_t, at each WTG.
- The diversity develops a higher immunity for the WPP against a disturbance.
- A fault at the transmission line may disconnect some of the WTGs but rarely all of the WTGs.
- A fault rarely occurs when the plant is at full power operation.
- Most faults are single-line-to-ground, self-clearing, and of short duration and isolated from the network by circuit breakers.

Wind Power Plant—One Year of Observation in Texas

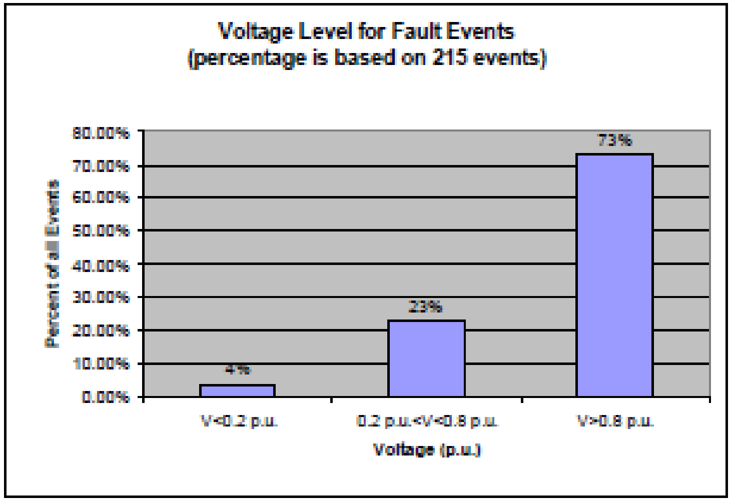


Figure 6. Voltage at the POI during the fault.

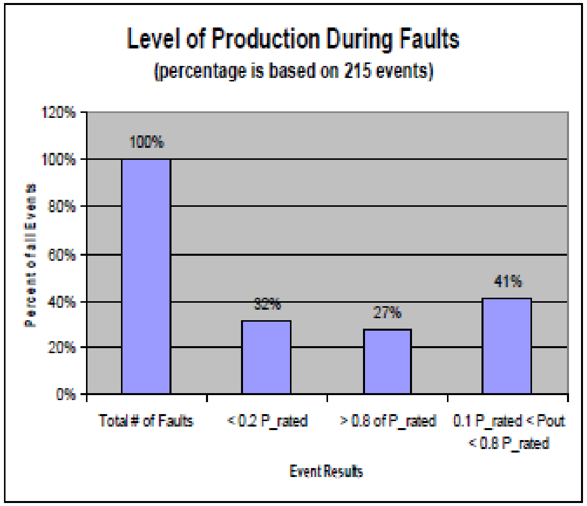


Figure 8. Wind power plant output at the pre-fault condition.

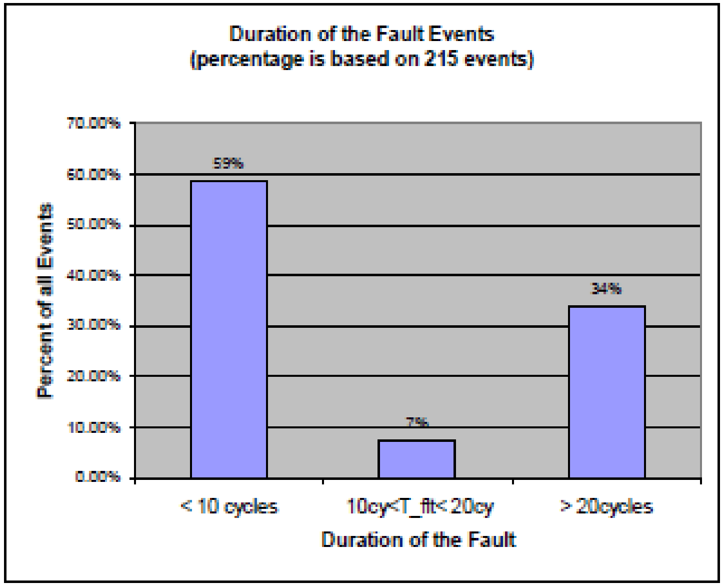


Figure 7. Duration of the fault.

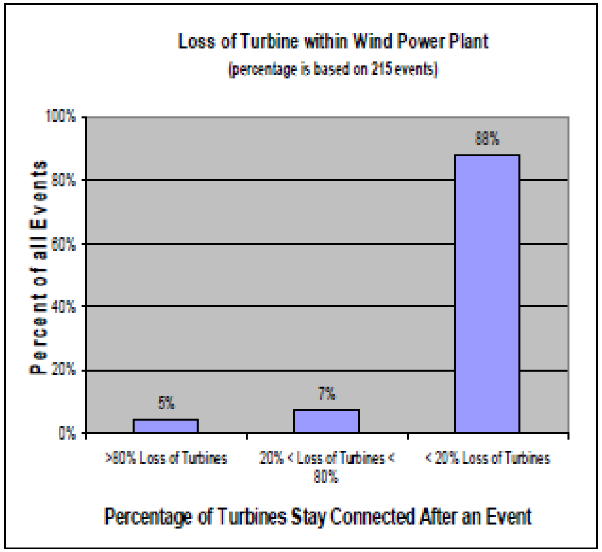
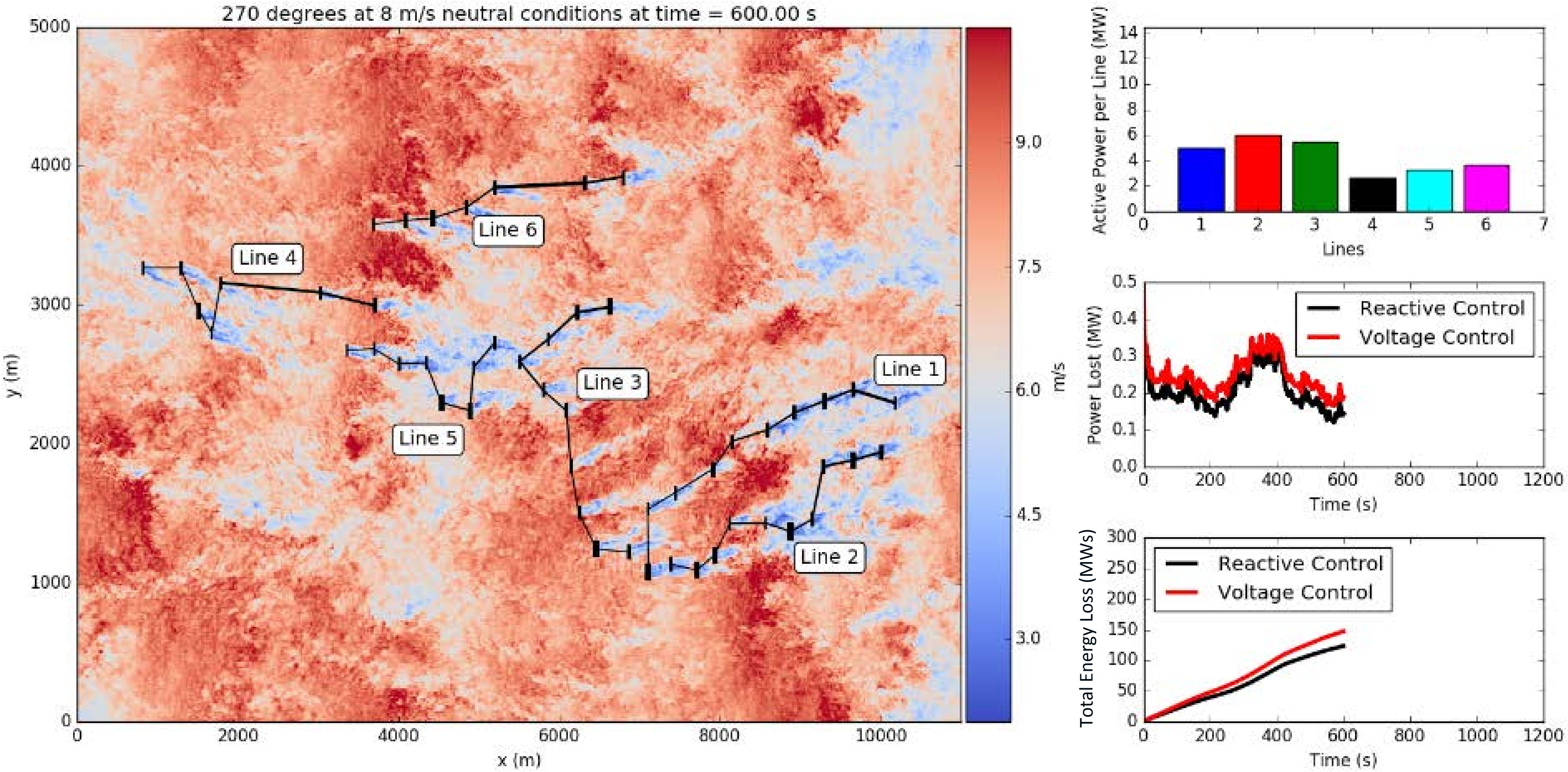


Figure 9. Percentage of turbines that stay on line.

Wind Power Plant—Overall Design Optimization

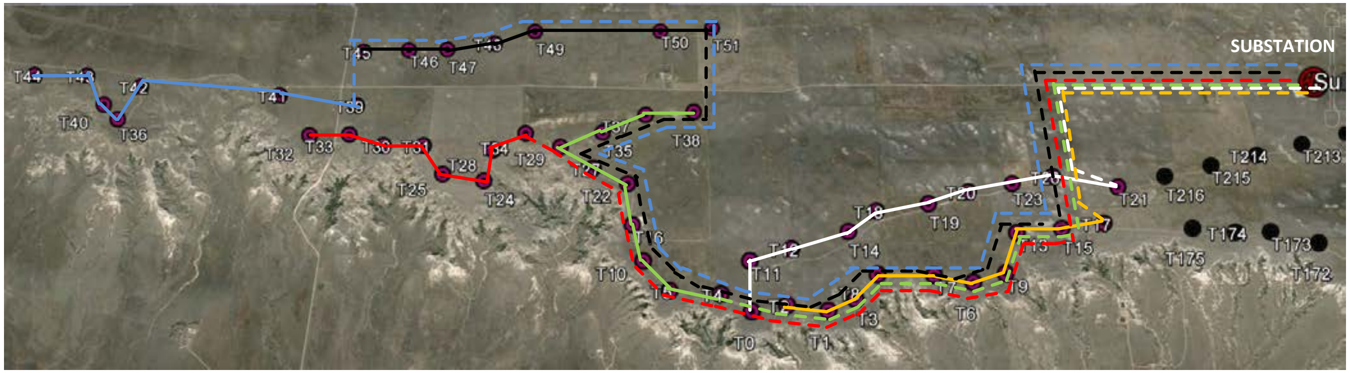
Aerodynamic and Electrical Co-Simulations



Credit: Jennifer Annoni

Wind Power Plant—Overall Design Optimization in Colorado

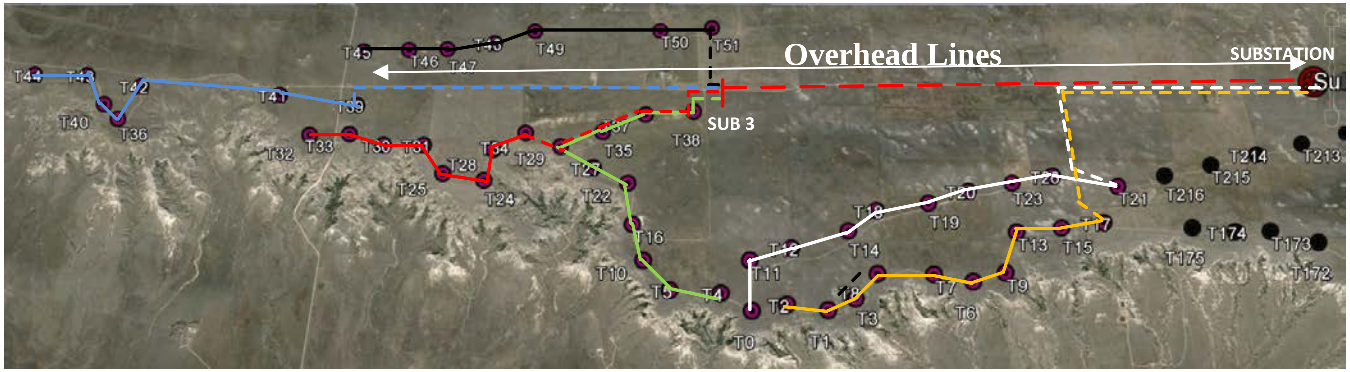
Collector System Design



Wind turbine layout for Option 1 (Limited Right of Way)

Collector System Loss Comparison

	Line	Losses (%)
Group	Option 1	Option 2
1	1.62%	1.62%
2	1.73%	1.73%
3	1.59%	0.95%
4	3.09%	1.21%
5	2.49%	1.21%
6	2.53%	1.36%
OH	N/A	1.34%



Wind Turbine Layout for Option 2 (With Overhead Lines)

Simulation/output data available (for analysis and plotting):

- Voltage at each generator bus
- Currents at line segments
- Ploss at line segments
- Output power at each generator
- Ptot at each group
- WPP efficiency.

Variable Renewable Energy Power Plant—Stability of Power System in New Mexico

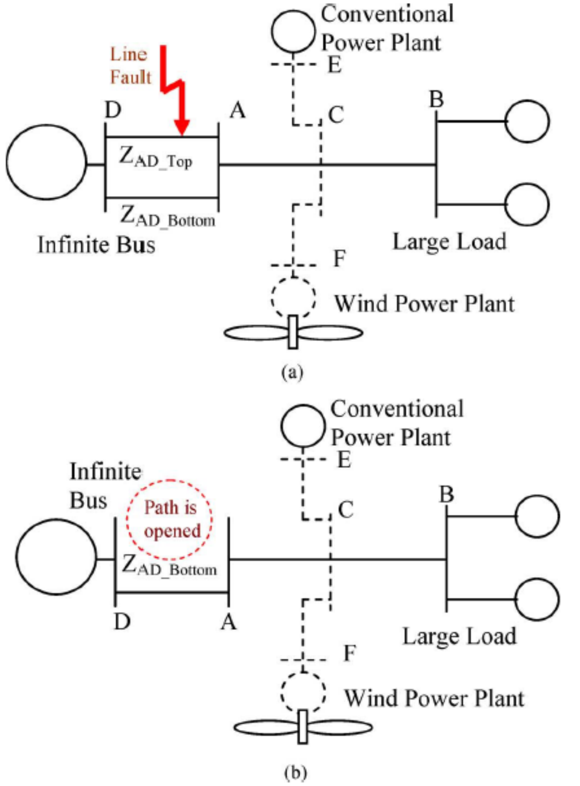


Fig. 3. Major path before and after the line fault is cleared. (a) Before the line fault is cleared. (b) After the line fault is cleared.

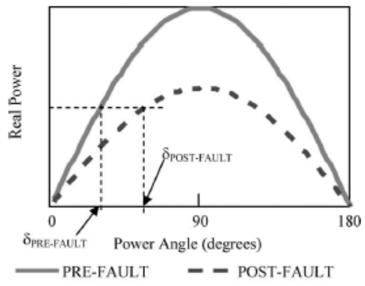
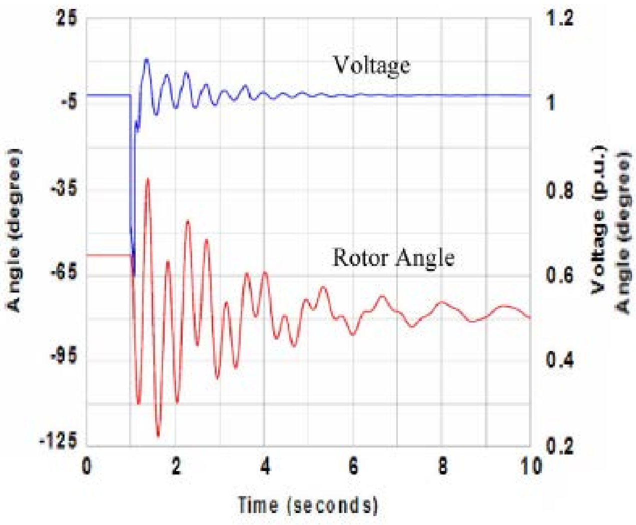
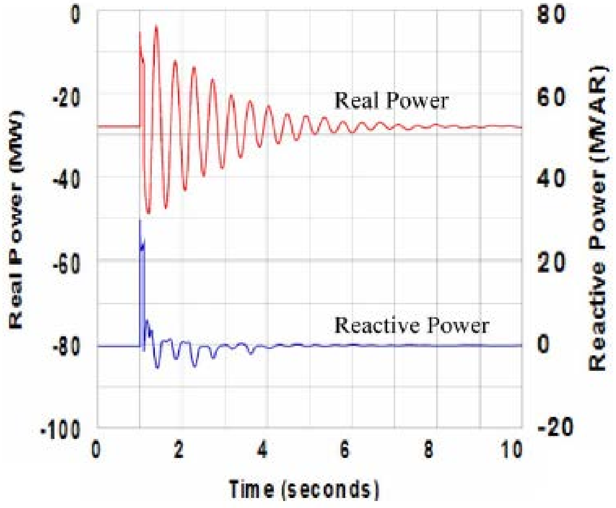


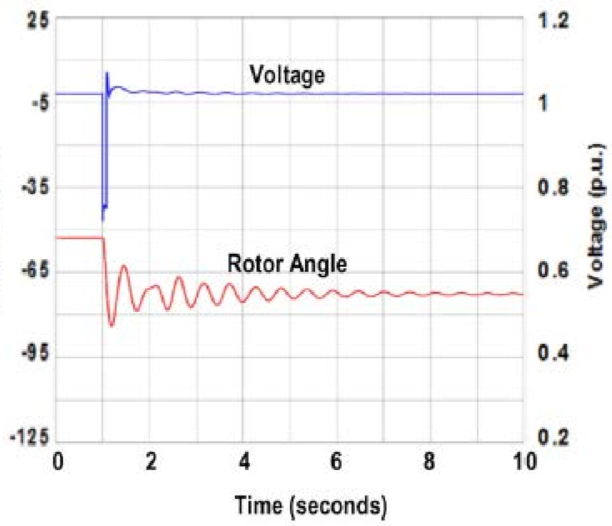
Fig. 5. Power transfer between two buses.

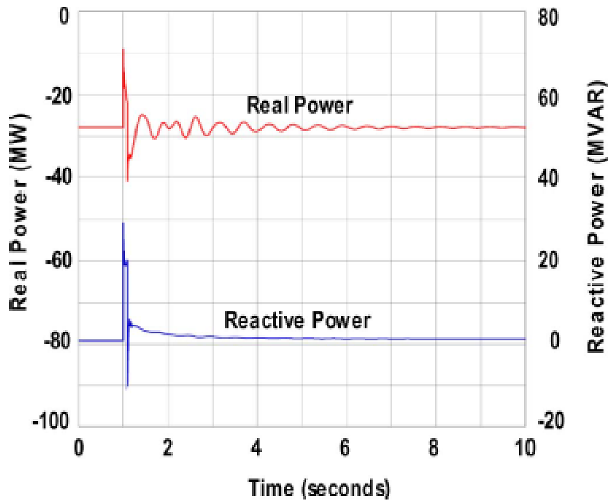
Conventional Plant



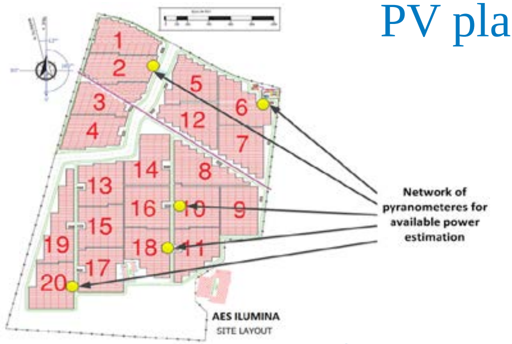


Wind Power Plant

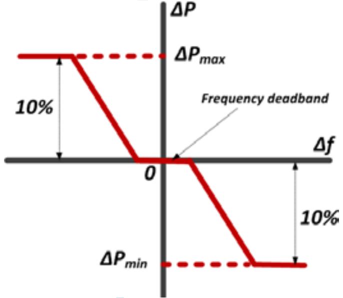




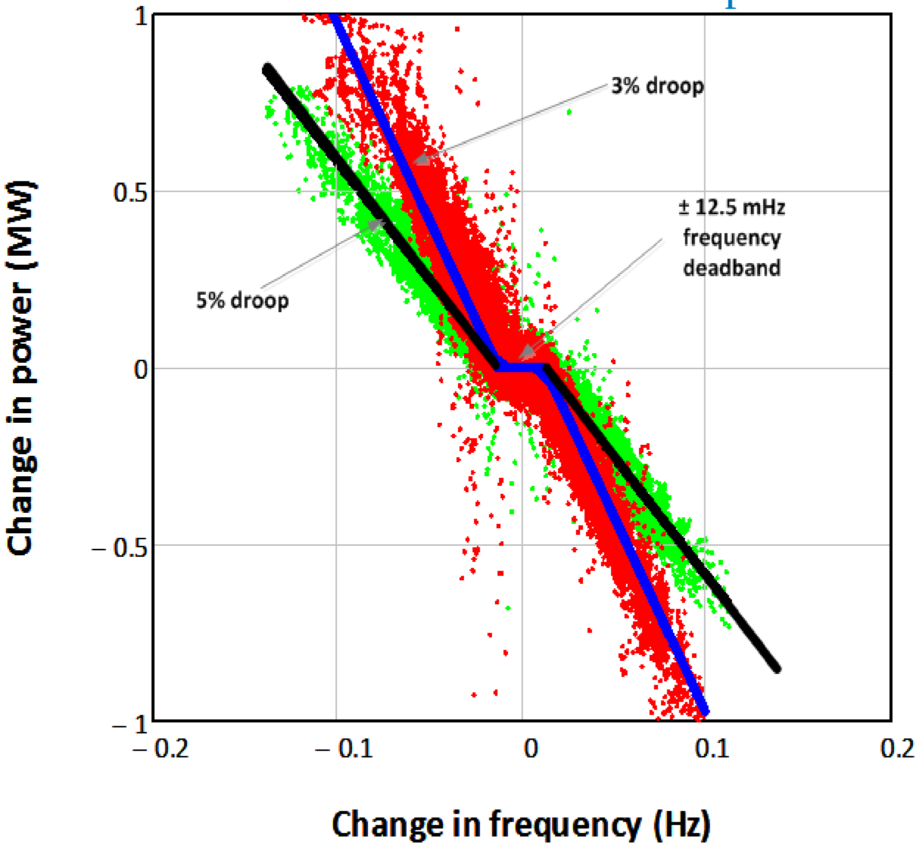
Photovoltaic Power Plant— Frequency Regulation Demonstration in Puerto Rico



PV plant’s droop characteristic

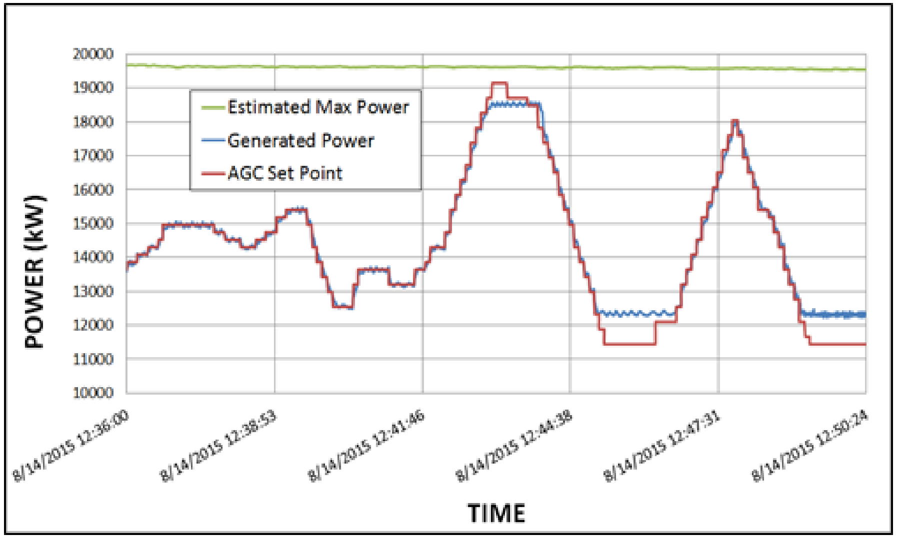


Results for 3% and 5 % droop tests

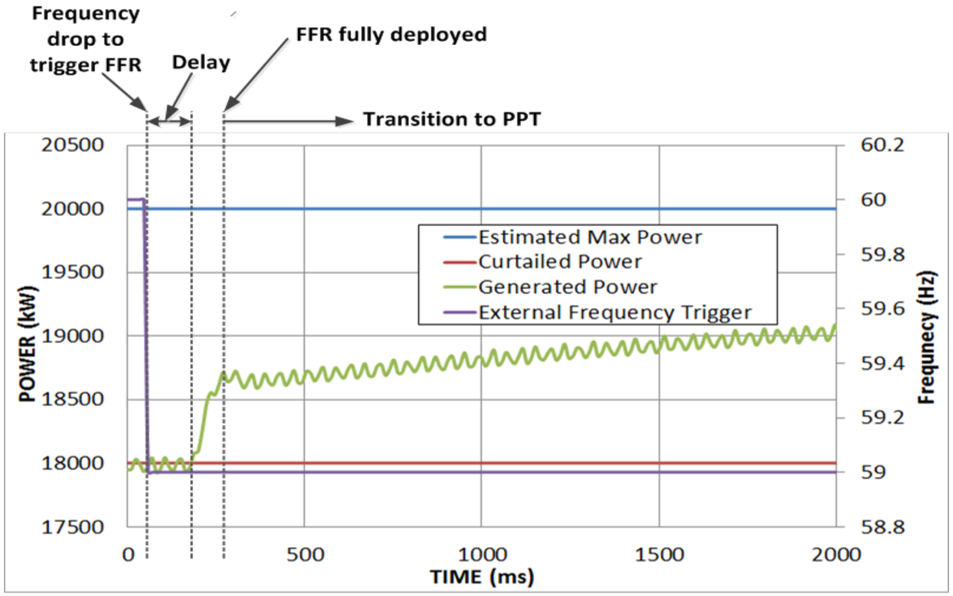


- Title: “Demonstration of Active Power Controls by Utility-Scale PV Power Plant in an Island Grid (Puerto Rico),” by Vahan Gevorgian and Barbara O’Neill, Wind and Solar Integration Workshop, Nov. 2016
- Total installed generation capacity: 6 GW with 173 MW of wind and solar PV generation; the rest is based on petroleum and natural gas.
- Puerto Rico’s transmission system consists of 230-kV and 115-kV lines, 38-kV subtransmission lines and 334 substations.
- PREPA’s typical summer daytime peak load is approximately 2.8 GW.
- AES’s 20-MW Ilumina PV power plant is located in Guayama, Puerto Rico (40 inverters rated at 500 kWac each).

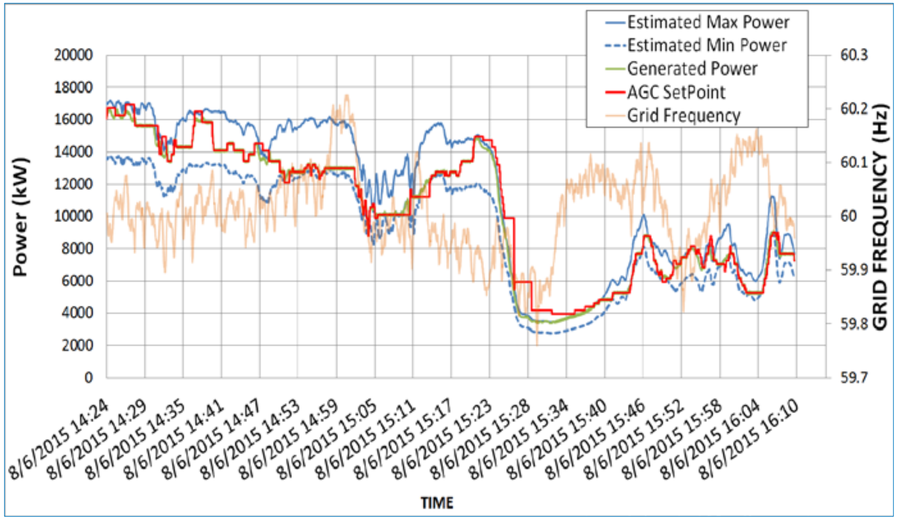
Photovoltaic Power Plant— Frequency Regulation Demonstration



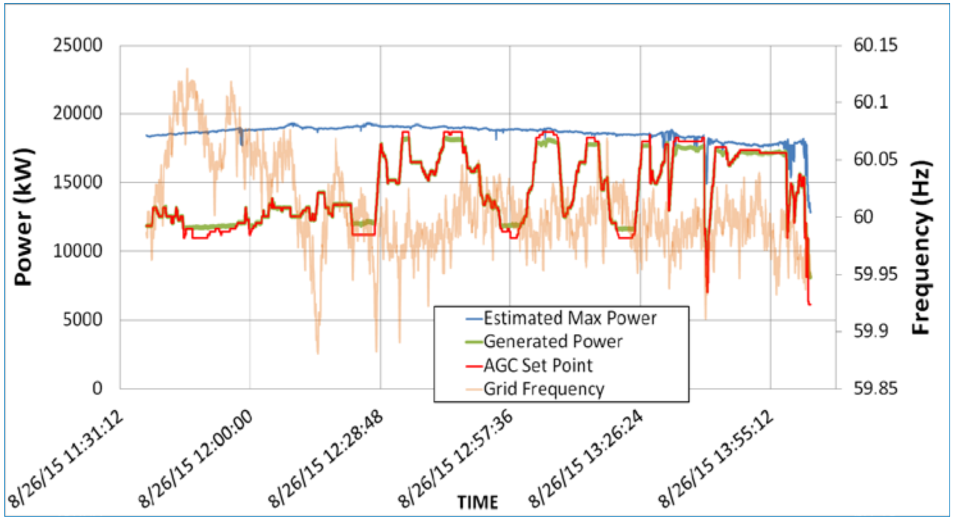
AGC performance



Example results of one FFR test

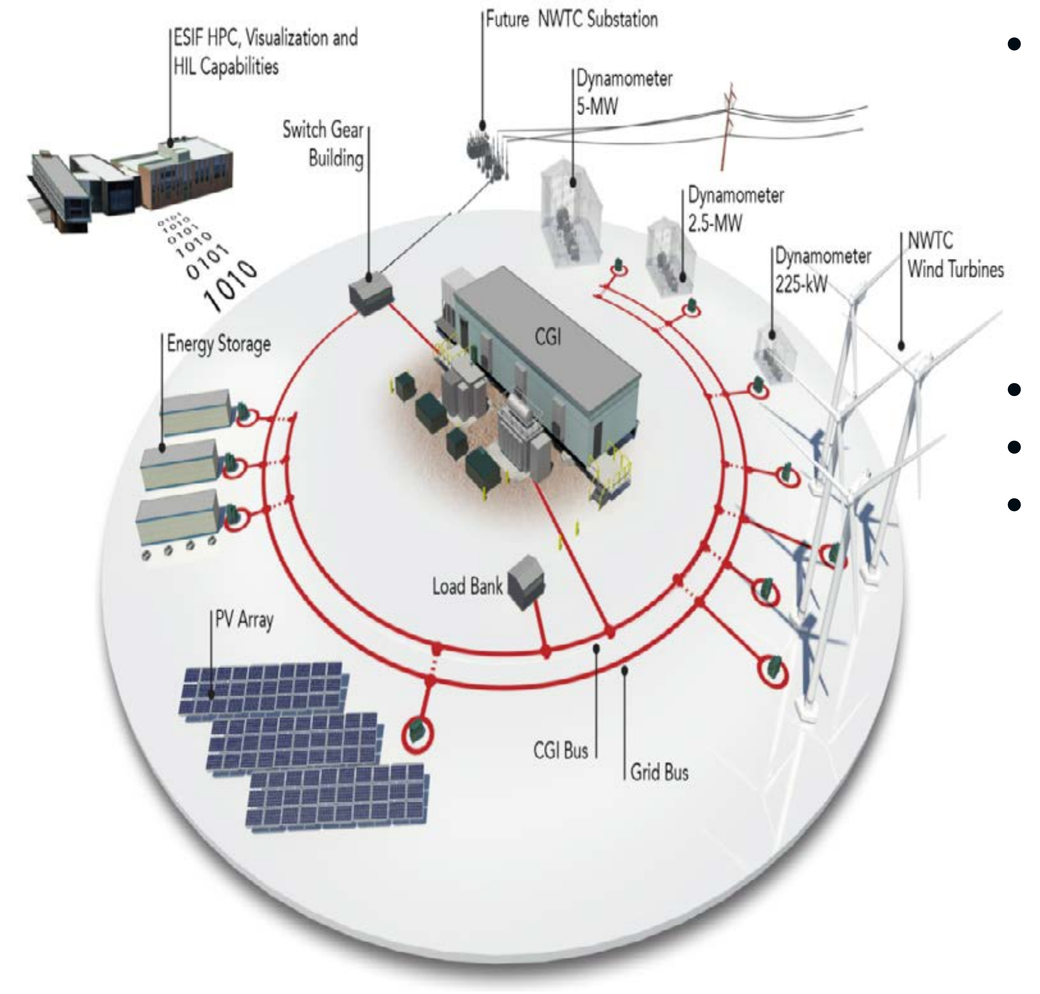


AGC test using 20% range



AGC test using 40% range

Wind Turbine—Ancillary Services Testing

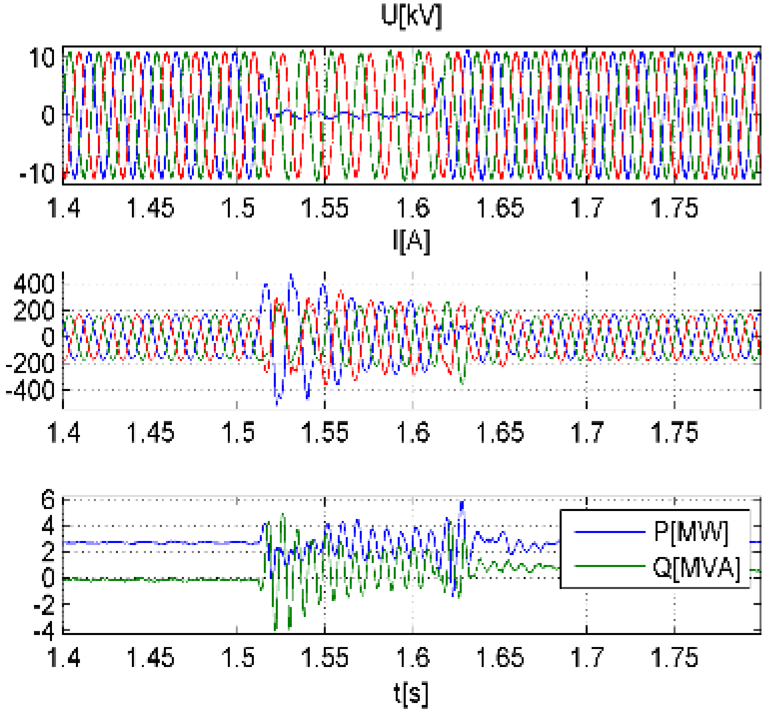


NREL/NWTC infrastructure for renewable energy systems grid integration testing. *Illustration by Josh Bauer, NREL*

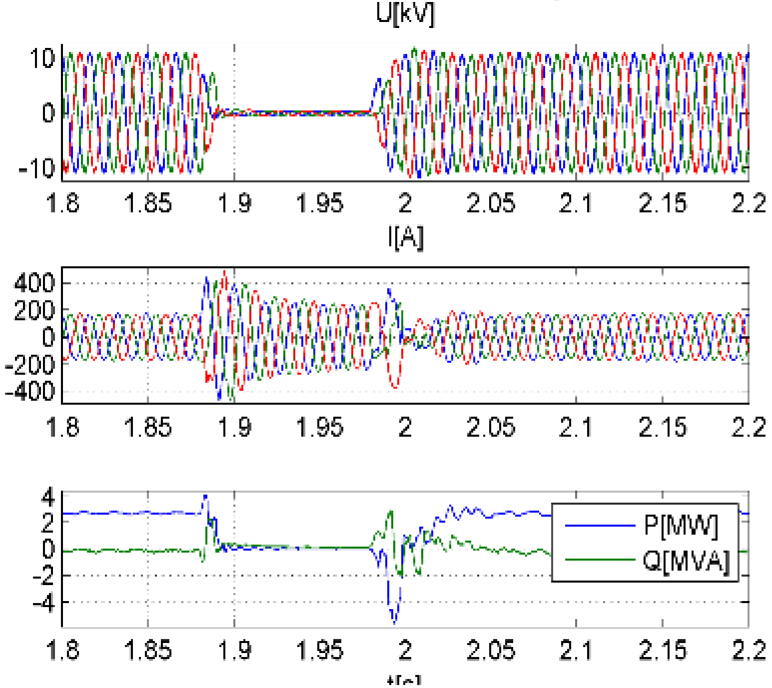
- Title: “Controllable Grid Interface (CGI) for Testing Ancillary Service Controls and Fault Performance of Utility-Scale Wind Power Generation,” by V. Gevorgian et al., Wind and Solar Integration Workshop, Nov. 2016
- 7.5-MVA power system simulator (CGI)
- 2.75-MW GE wind turbine drivetrain
- Testing includes fault ride-through, frequency response (governor and inertial response), short circuit, power oscillation damping, power hardware-in-the-loop (PHIL), impedance compensation.

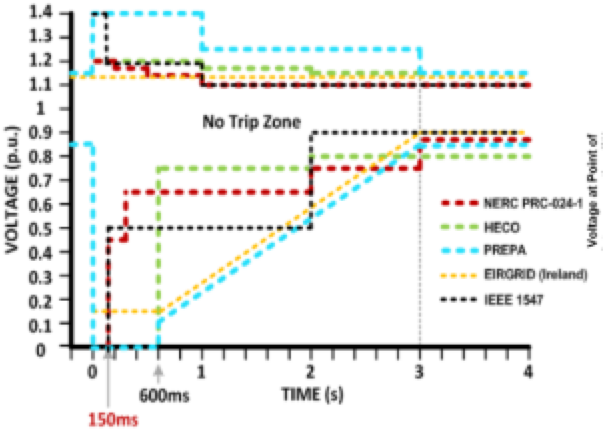
Wind Turbine—Ancillary Services Testing

Single-phase zero voltage test

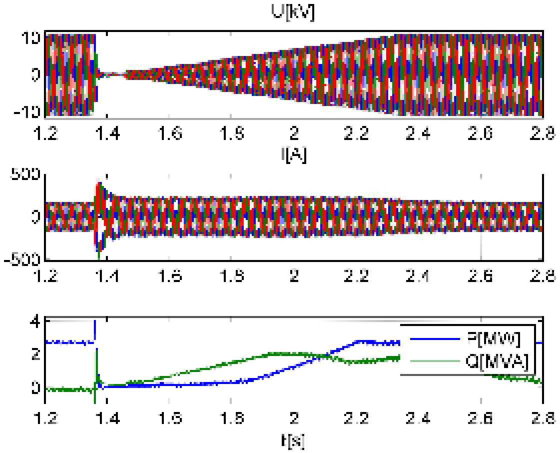


Three-phase zero voltage test

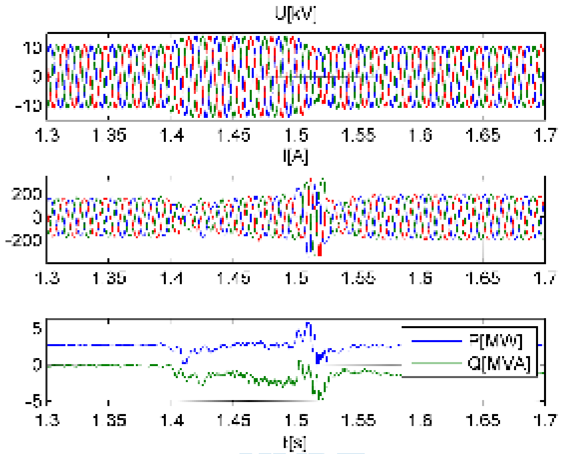




Grid Code

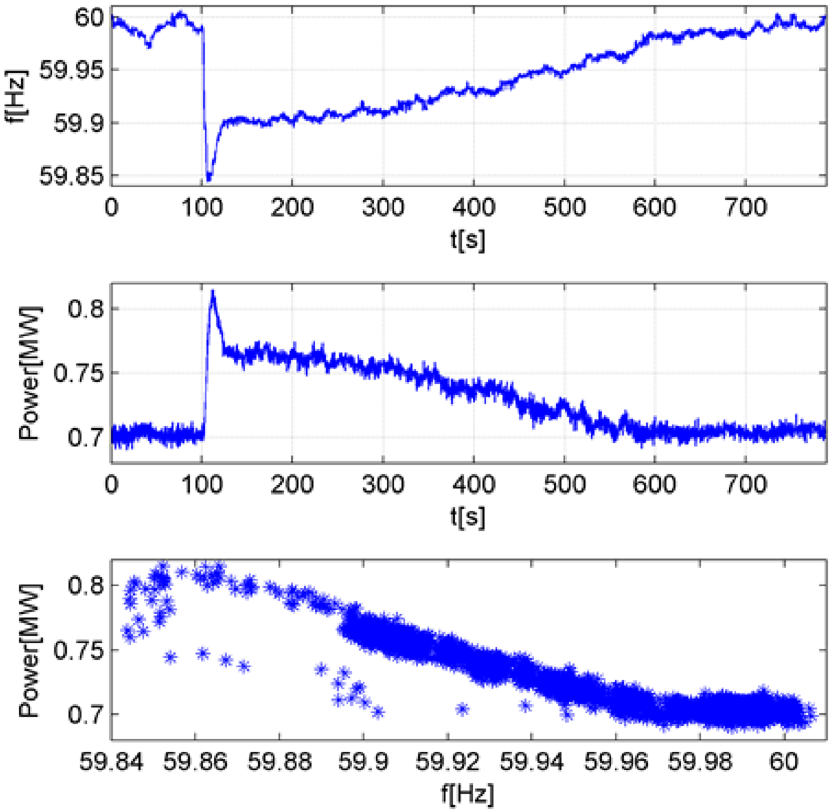


LVRT

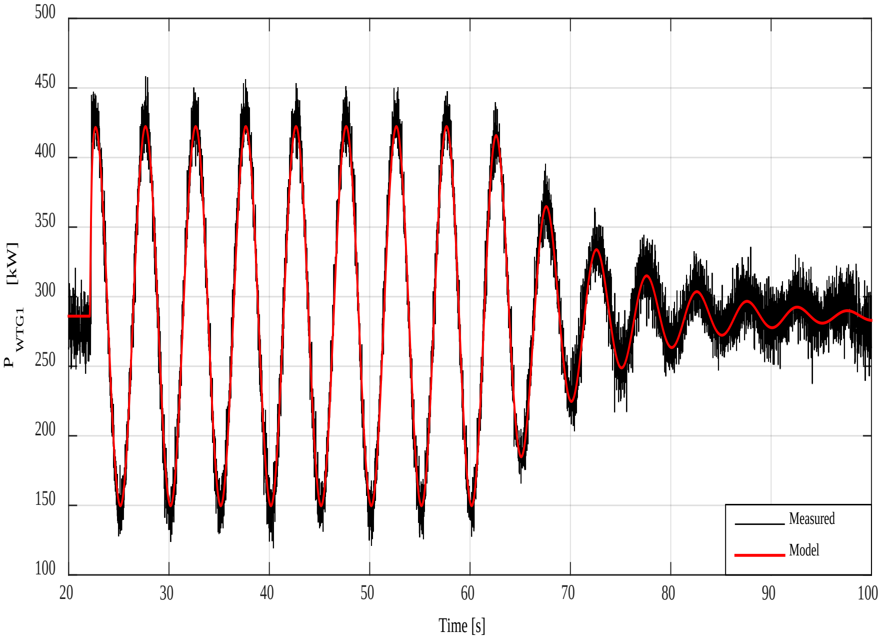


HVRT

Wind Turbine—Ancillary Services Testing

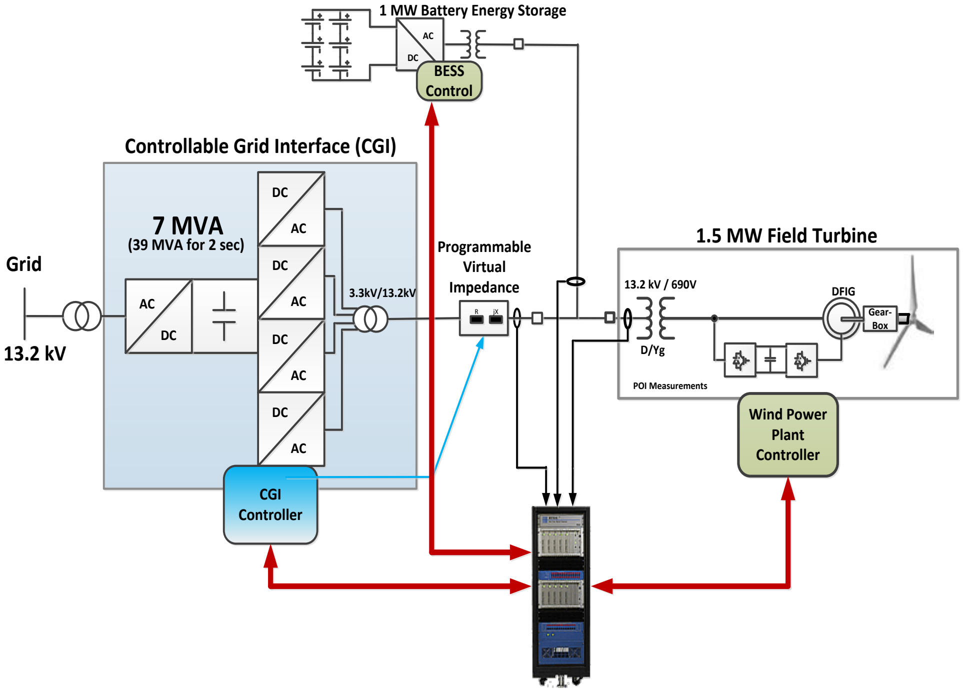


Frequency droop test

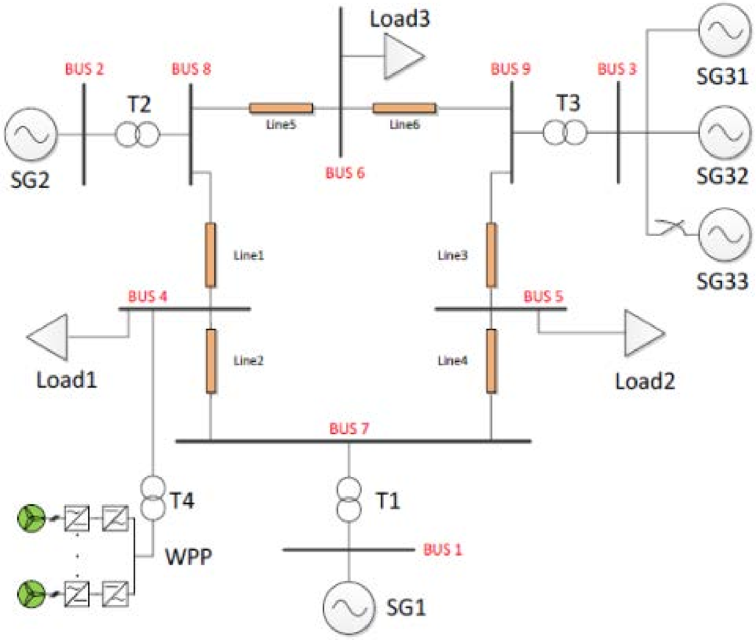


Power oscillation damping test results

Wind Turbine—Ancillary Services Testing

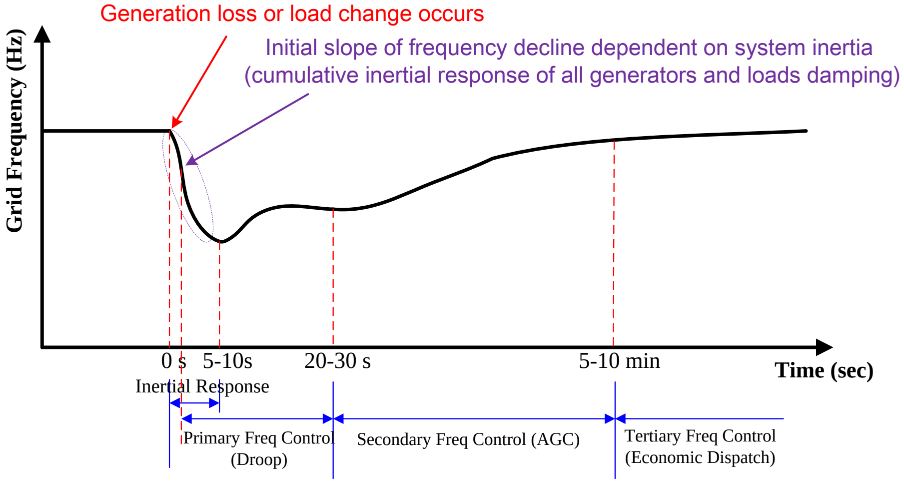


PHIL test setup with CGI and RTDS

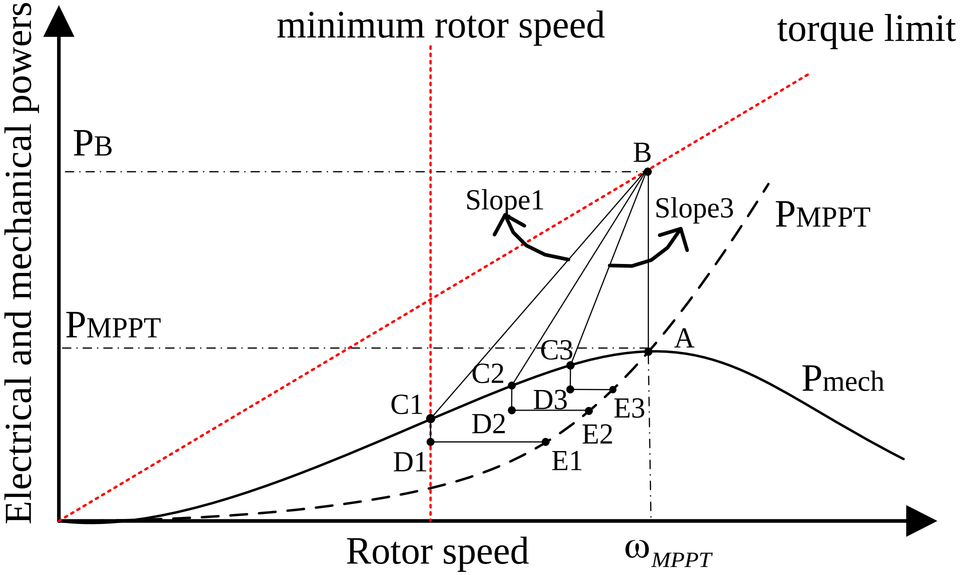


RTDS model of 9-bus power system

Inertial Response of a Wind Power Plant



Torque-Limited Inertial Control

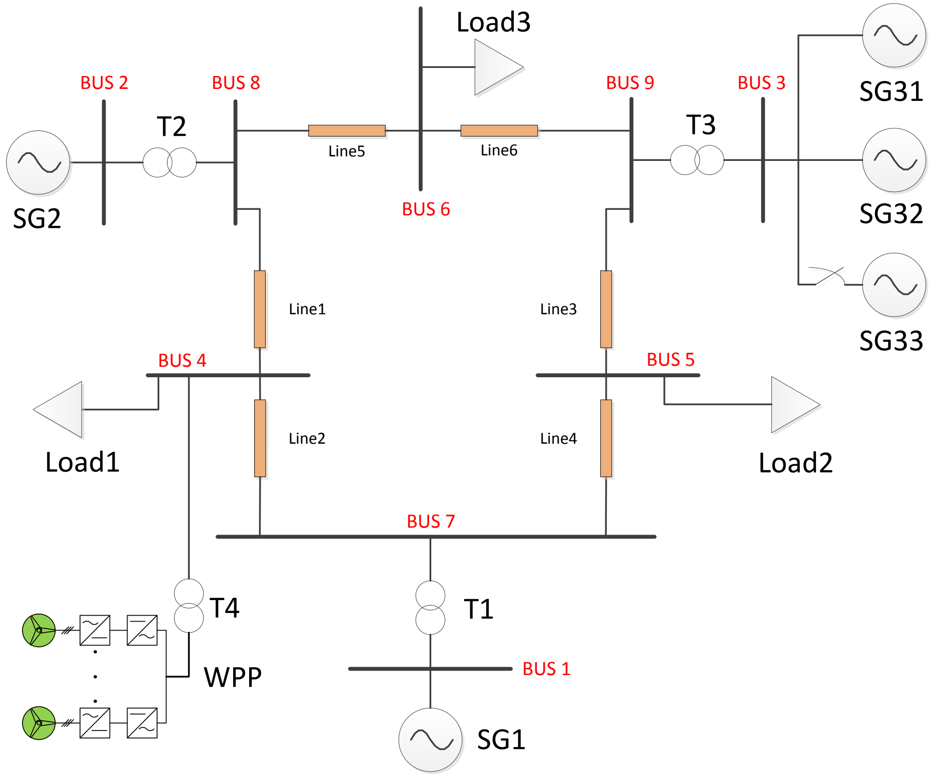


1. **Inertial response** releases kinetic energy and restricts the rate of change of frequency.
2. **Primary frequency response** is deployed by the speed governors of synchronous generators. It improves the frequency nadir and stabilizes the frequency.
3. **Secondary frequency response** recovers the frequency back to the nominal value.

The **inertial response** suppresses and slows the frequency drops before the action of underfrequency load-shedding relays, when a loss of generators or transmission lines occurs. It is crucial to the power system reliability before the relatively slow response of speed governors.

Inertial Response of a Wind Power Plant

Modified Nine-Bus Power System

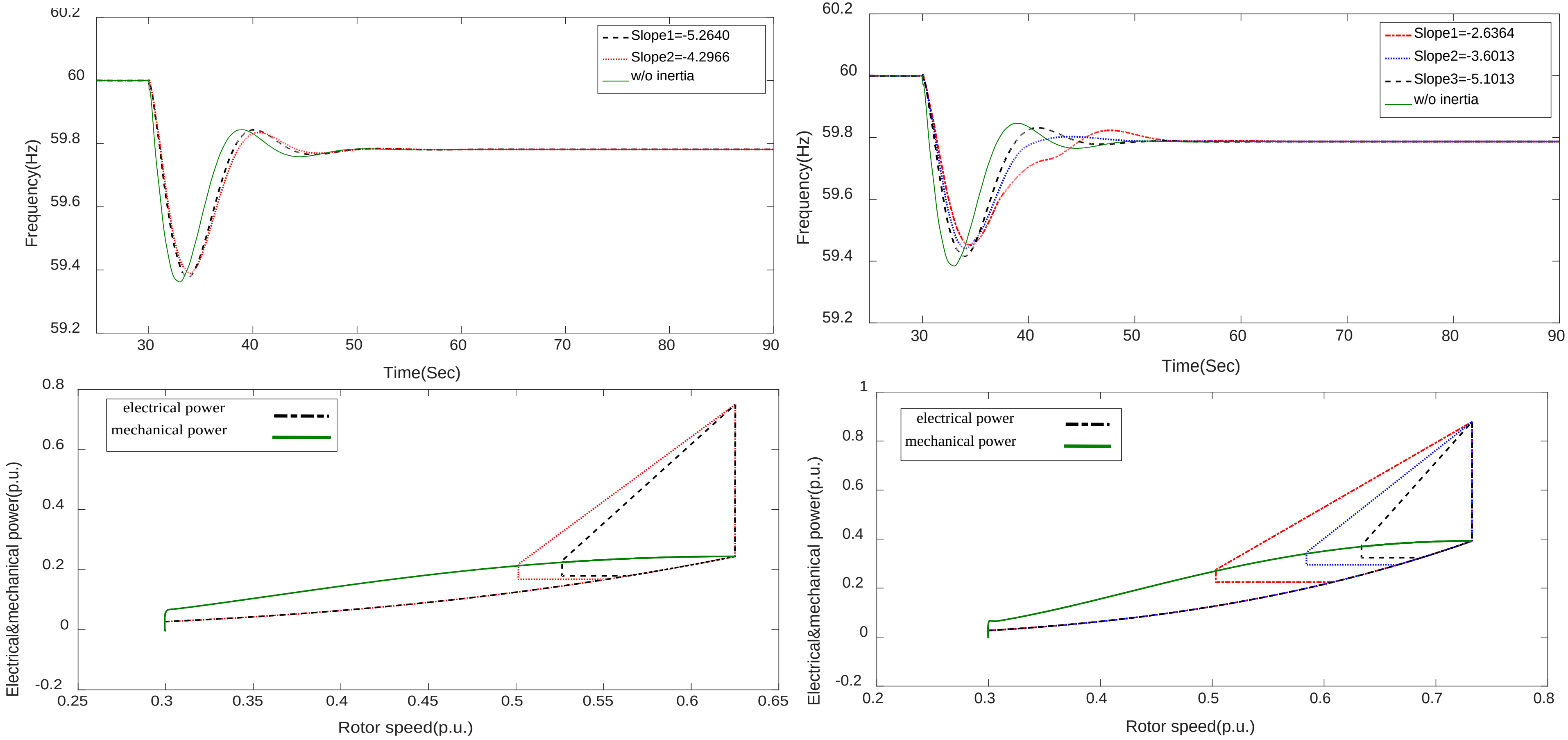


	Rated Capacity (MVA)	Rated voltage (kV)	Inertial Constant (s)	Tdo'(s)	Tdo''(s)	Tqo'(s)	Tqo''(s)
SG1	200	16.5	6.64	8.96	0.12	-	0.95
SG2	80	18	5.31	8.0	0.03	1.0	0.07
SG31	30	13.8	4.01	8.0	0.03	1.0	0.07
SG32	30	13.8	4.01	8.0	0.03	1.0	0.07
SG33	40	13.8	4.01	8.0	0.03	1.0	0.07

Rated Voltage	**690 V**
Rated Power	2 MW
Rated Rotor Speed (GEN)	22.5 rpm
Np	26
Rated Torque	848.826 kN.m
Diameter of Blades	78.52 m
Rated Wind Speed	11.2 m/s
Rated Rotor Speed (WT)	2.32 rad/s
Air Density	1.225 kg/m3
Cp,max	0.48
λ_{opt}	8.1

Inertial Response of a Wind Power Plant

Case studies: The performance of torque-limited inertial control under different wind speed conditions.



Low-wind-speed cases: 7 m/s and 8.2 m/s

Summary

- Variable and renewable energy resources have similar characteristics:
  - May take different forms (wind, PV, concentrating solar power [CSP], marine hydrokinetic, etc.)
  - The electrical output power varies with the resource.
  - Distributed generation or centralized as a power plant
  - Voltage variations can be minimized by adjustable VAR compensation.
  - Frequency variations can be minimized by fast-acting spinning reserves and storage availability and capability.
  - Load-wind matching can be improved by including other renewable energy resources (CSP, PV, geo, hydro, bio), cleaner and cheaper conventional power plants, DSM, and storage (long-term: PSH, CAES, plug-in hybrid electric vehicles, fuel cell—H_2, battery, flywheel).

- The forecast error can be minimized by shorter scheduling periods, incentivizing PSH, coordinated nationwide wind measurements, and better forecasting methods.

- Transmission constraints and curtailment can be minimized by improvements on the transmission lines (FACTS devices, series/parallel capacitors, additional lines, dynamic ratings, storage).

- Grid codes may vary depending on the local/regional regulation and the power system network to which it is connected.

Summary

- Phasor measurement unit deployment allows the WWP to be monitored more precisely during normal and transient operation. The stability margin can be measured more accurately, and remedial action schemes can be deployed at the correct time confidently; thus, blackouts and outages can be prevented.

- Wide area monitoring, protection, and control can help monitor and coordinate protection of the surrounding power system relative to the stability limit and anticipate the next coordinated control action to protect the WPP ahead of potential/impending disturbances in the vicinity.

- Use of a smart grid, modern control, high-speed data communications, and power system intelligence allows the system to operate in autopilot and reduces the burden on operators to manage normal operations but allows for special intervention in critical events.

- High-penetration renewable energy sources may force us to follow a new paradigm (AC vs. DC, centralized vs. distributed, constant f vs. 60 Hz, synchronized vs. floating/island networks, instant delivery vs. stored energy).

References

- E. Muljadi, C.P. Butterfield, B. Parsons, and A. Ellis. 2007. “Effect of Variable-Speed Wind Turbine Generator on Stability of a Weak Grid.” *IEEE Transactions on Energy Conversion* 22(1) (March).

- N.W. Miller, M. Shao, R. D’Aquila, and S. Pajic. 2015. “Frequency Response of the U.S. Eastern Interconnection under Conditions of High Wind and Solar Generation.” Paper presented at the 2015 Seventh Annual IEEE Green Technologies Conference, New Orleans, Louisiana, April 15–17.

- E. Muljadi, Z. Mills, R. Foster, J. Conto, and A. Ellis. 2008. “Fault Analysis at a Wind Power Plant for One Year of Observation.” Paper presented at the 2008 IEEE Power and Energy Society General Meeting, Pittsburgh, Pennsylvania, July 20–24.

- T. Ackermann, A. Ellis, et al. 2013. “Code Shift, Grid Specifications, and Dynamic Wind Turbine Models.” *IEEE Power & Energy Magazine* (November/December).

- N.W. Miller, B. Leonardi, R. D’Aquila, and K. Clark. 2015. *Western Wind and Solar Integration Study Phase 3A: Low Levels of Synchronous Generation* (Technical Report NREL/TP-5D00-64822). Golden, CO: National Renewable Energy Laboratory.

- X. Wang et al. 2016. “Assessment of System Frequency Support Effect of a PMSG-WTG Using Torque-Limit-Based Inertial Control.” Paper presented at the IEEE Energy Conversion Congress and Exposition, Milwaukee, Wisconsin, September 18–22.

- E. Muljadi et al. 2016. “Understanding Dynamic Model Validation of a Wind Turbine Generator and a Wind Power Plant.” Paper presented at the IEEE Energy Conversion Congress and Exposition, Milwaukee, Wisconsin, September 18–22.

- V. Gevorgian et al. Forthcoming. “Controllable Grid Interface for Testing Ancillary Service Controls and Fault Performance of Utility-Scale Wind Power Generation.” Paper to be presented at the 15th Wind and Solar Integration Workshop, Vienna, Austria, November 15–17, 2016.

- V. Gevorgian et al. Forthcoming. “Demonstration of Active Power Controls by Utility-Scale PV Power Plant in an Island Grid.” Paper to be presented at the 15th Wind and Solar Integration Workshop, Vienna, Austria, November 15–17, 2016.

- Additional publications can be found at www.nrel.gov/publications.

Thank you!

www.nrel.gov

NATIONAL RENEWABLE ENERGY LABORATORY

Note: Except as otherwise indicated, all images are NREL owned.