SESSION 3: Grid Integration Studies for Planning Secure and Reliable System Operations with Expected Shares of Variable Renewables

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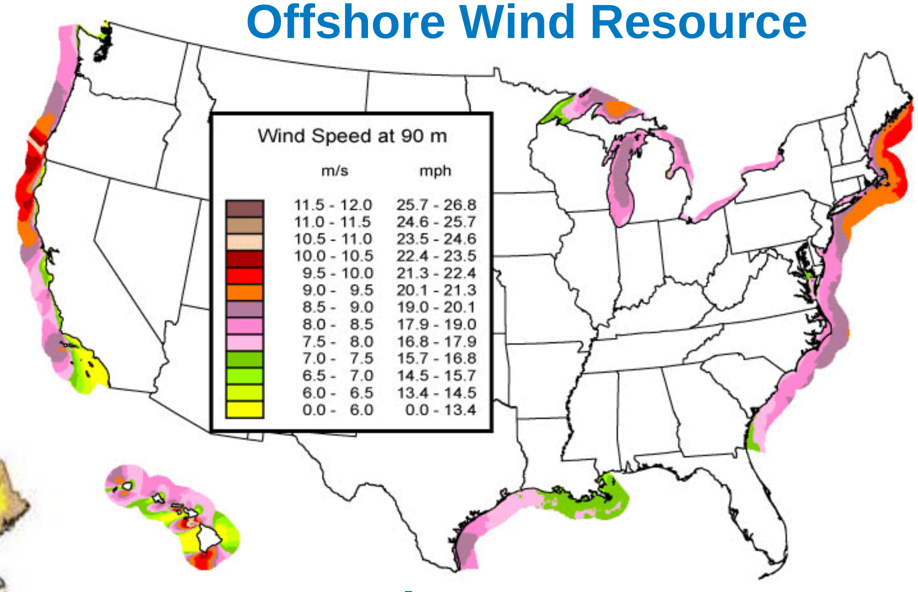
Workshop on Integrating Renewables into Power Systems in Central America

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

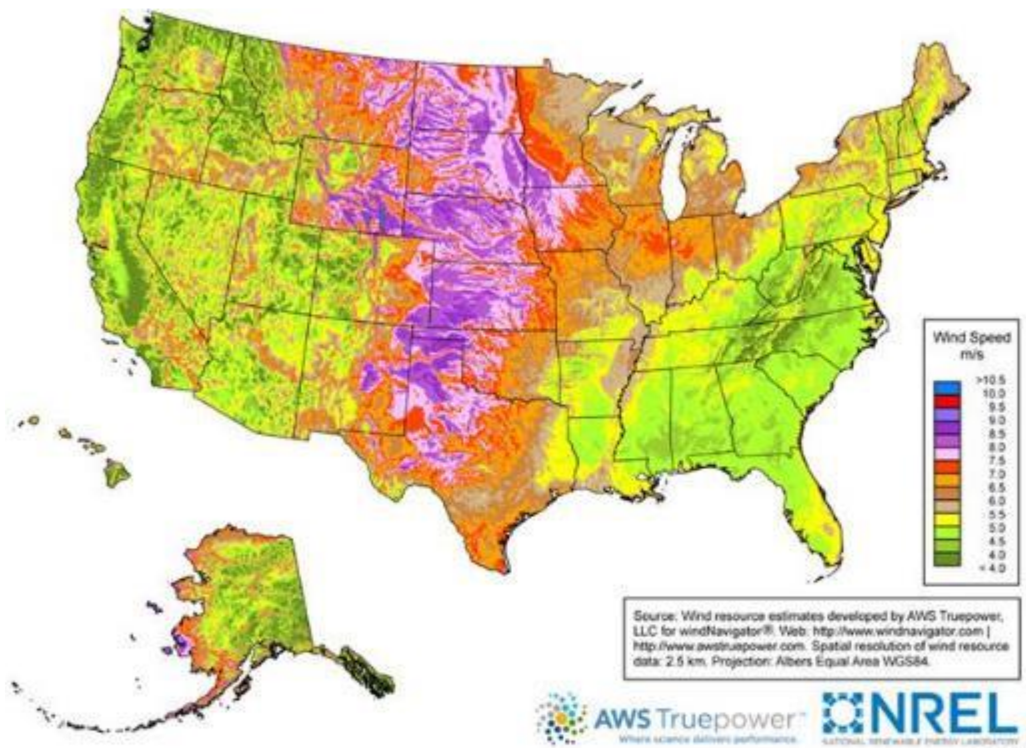
Panama City, Panama

Renewable Energy Resources

Offshore Wind Resource



U.S. Wind Resource

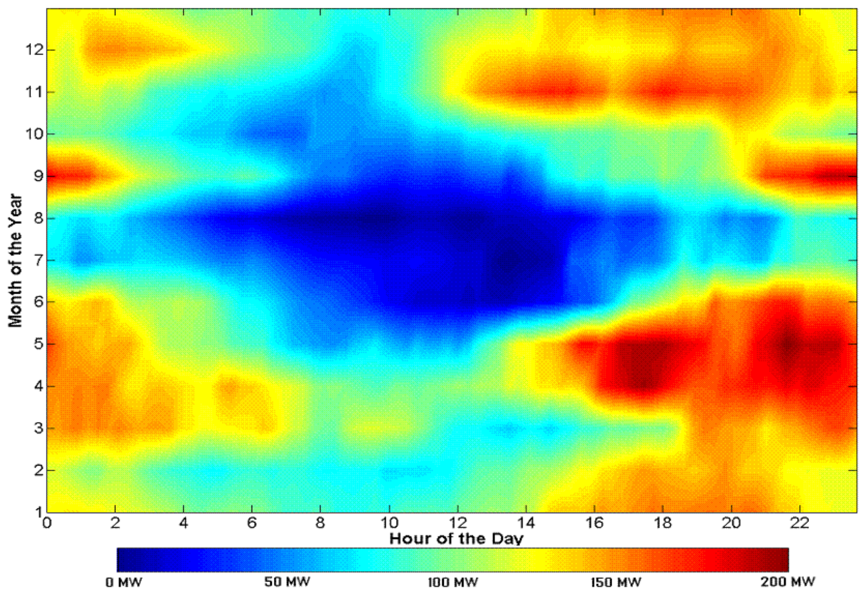


Solar Resource

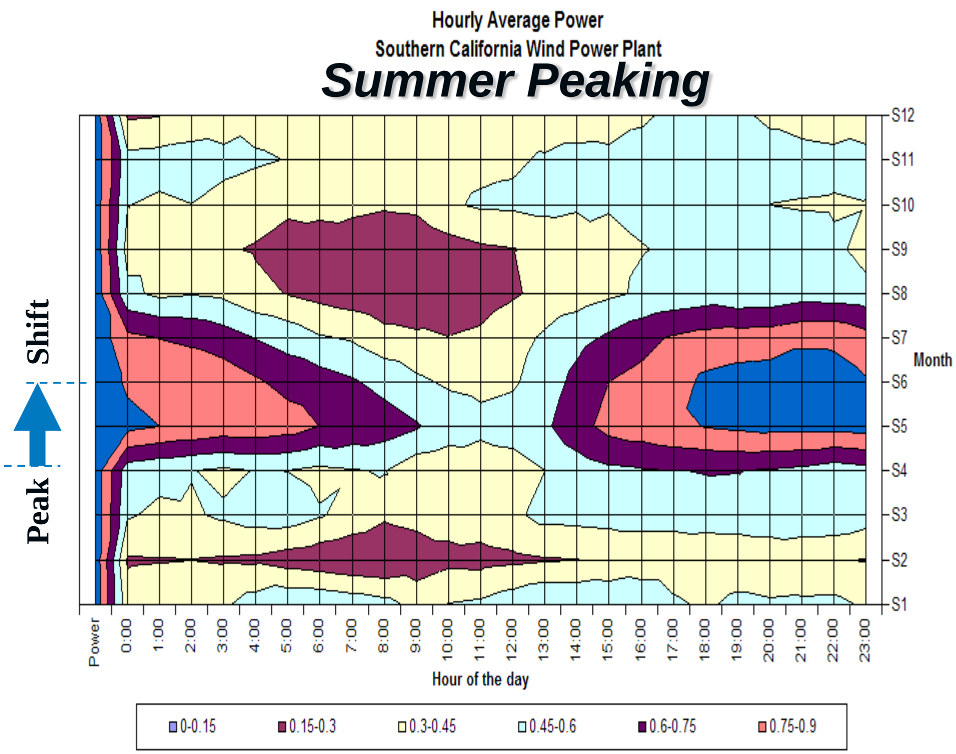
Wind Power Resource

Annual Hourly Average

Spring Peaking



Summer Peaking



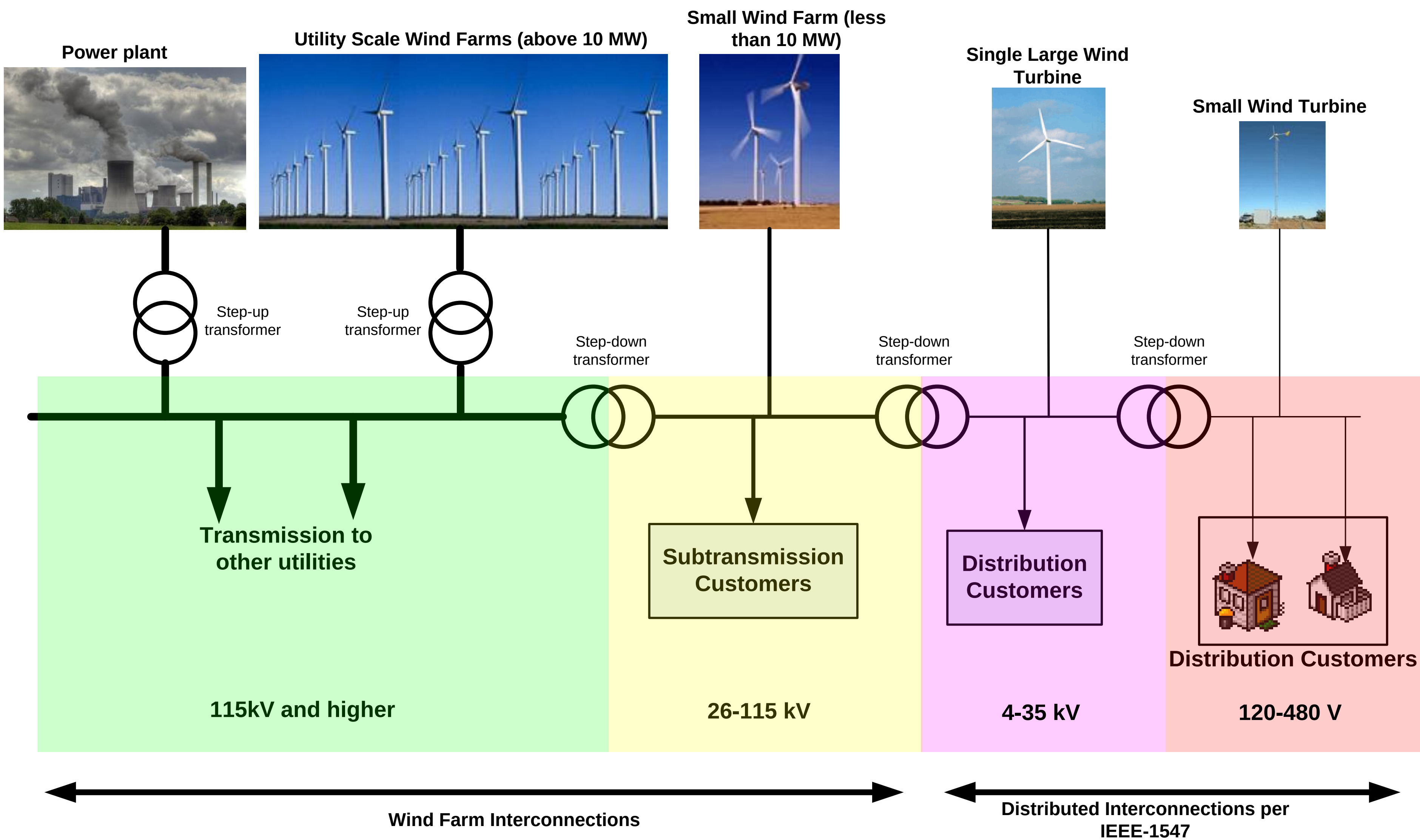
Midwest Region

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



Planning and Operational Issues

Power System Operations

- Operational strategy modeling
- Operating reserve requirements
- Operations of emerging resources (e.g. DR, storage)
- Integration Studies

Electricity Market Design

- Flexibility market designs
- Revenue sufficiency
- Ancillary service market designs, primary frequency response market

Power System Planning

- ELCC, LOLP, with renewables
- Generation and transmission expansion
- Policy issues
- Flexibility needs of the future

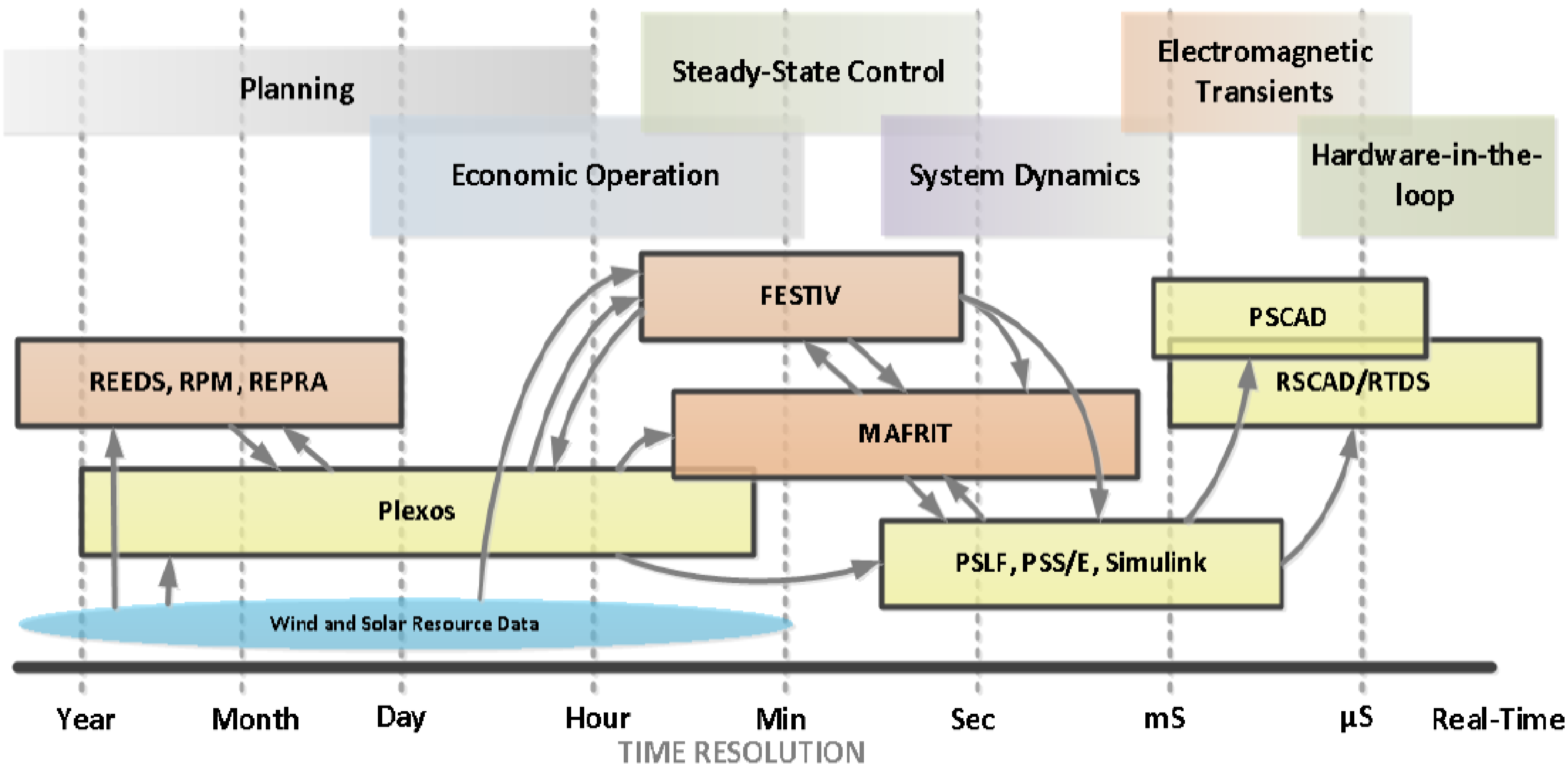
Generator Modeling

- Generic wind and solar models
- Three phase and positive sequence
- Validation using PMUs
- New frequency, voltage, damping controls

Operational Forecasting

- Error characteristics of wind, solar, load forecasts
- Economic and reliability metrics of forecasts
- Probabilistic forecasts

Broad Spectrum of Time Resolution



Resource Adequacy **Economic Dispatch** **Stability—Reliability**

Load Flow Modeling

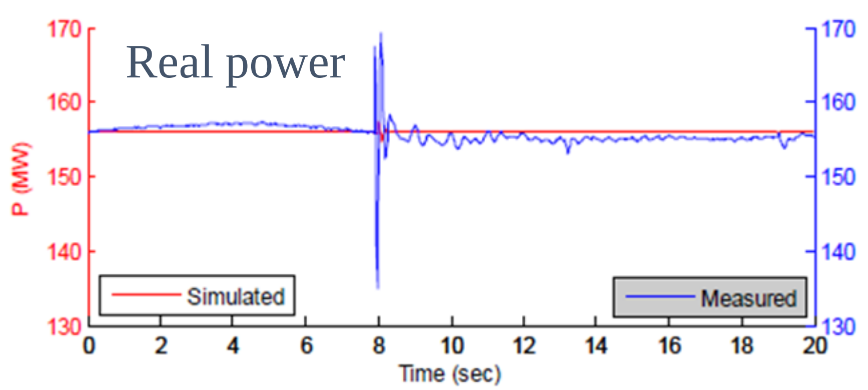
- Engineering, not economic model
- Common power system simulators: PSLF, PSSE, and PowerWorld
- Bus-level detail
- Analyze multiple post-contingency events
- Steady-state contingency for n-1 event (thermal and voltage analysis, static voltage stability, transfer limits)
- Example uses include PV curve analysis, reactive power adequacy

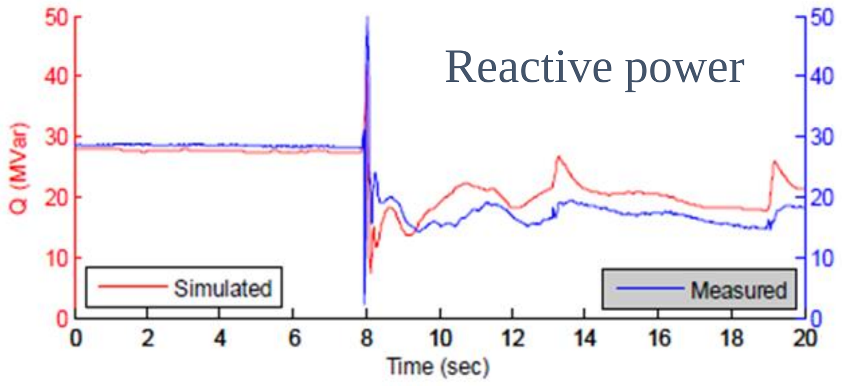
Dynamic Modeling

- It is important to determine the power system survival after a disturbance. The post-transient dynamic condition must be a stable operation.
- Power system disturbances may include faults, unbalance, voltage/frequency dips, oscillations, and they may be short-term or persistent.
- Resource disturbances may include a sudden change of output power (forecast error, ramping rates of wind power plants, temporary cloud shading on photovoltaic [PV] plant).
- A correct/up-to-date representation of the model of the generator, system network, control/protection, or sequence of events is required.
- The collective behavior of the plant (hundreds of wind turbines or PV inverters) is more important than that of a single generator.

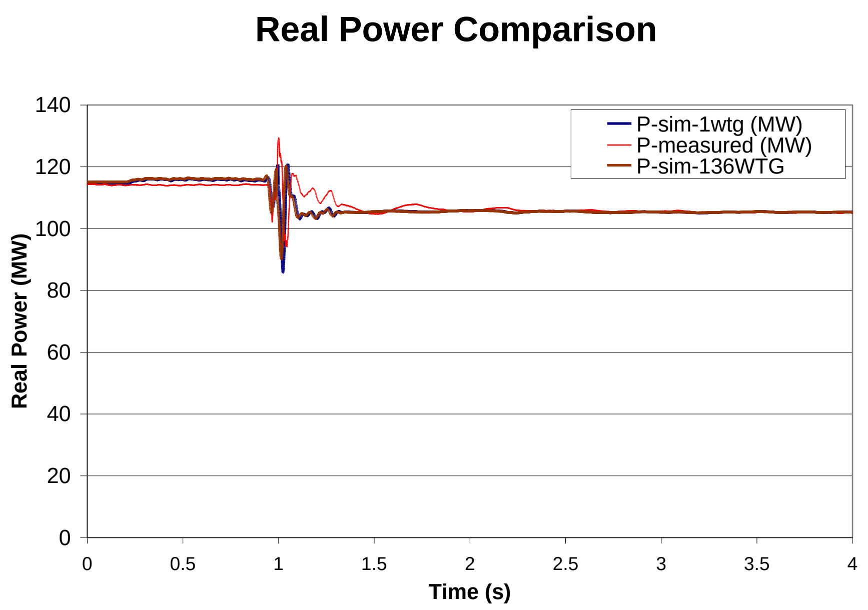
Dynamic Model Validation—Wind Power Plant

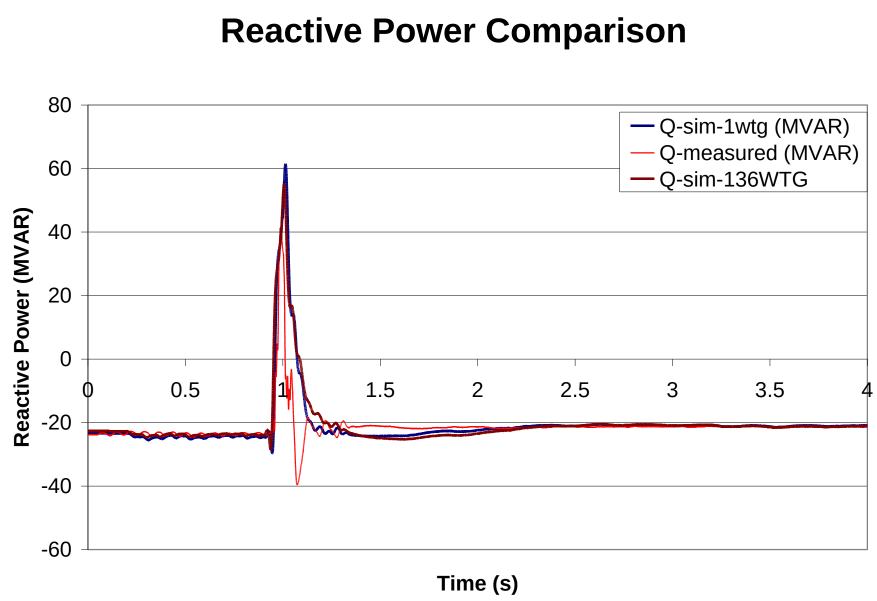
A Wind Power Plant in the Northwest United States





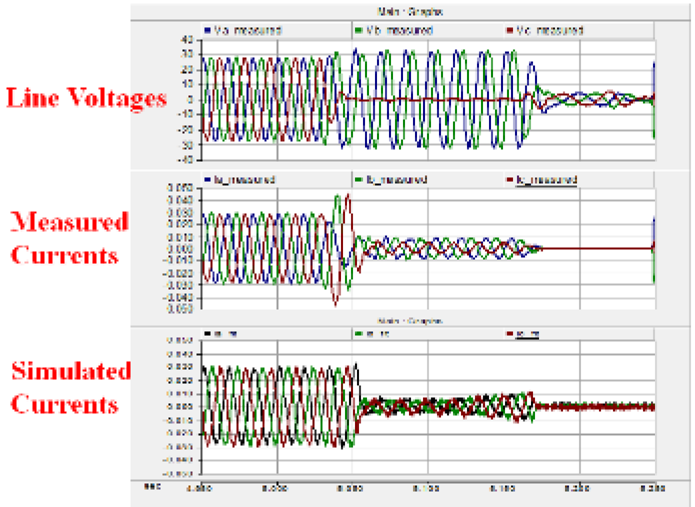
A Wind Power Plant in the Midwest United States



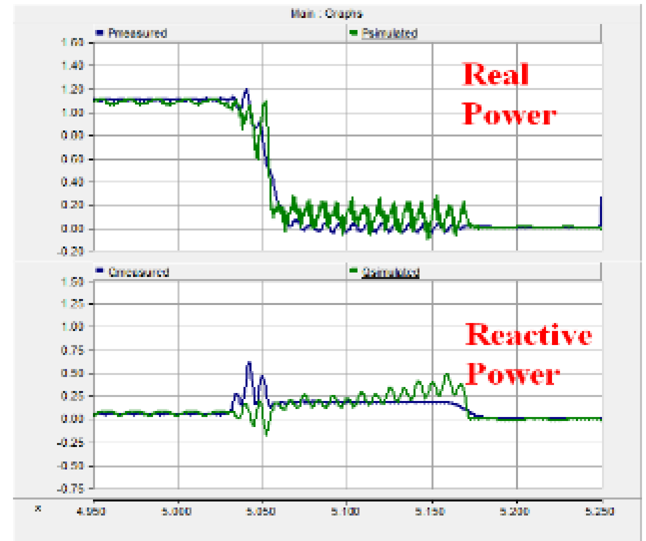


Dynamic Model Validation—Photovoltaic Power Plant

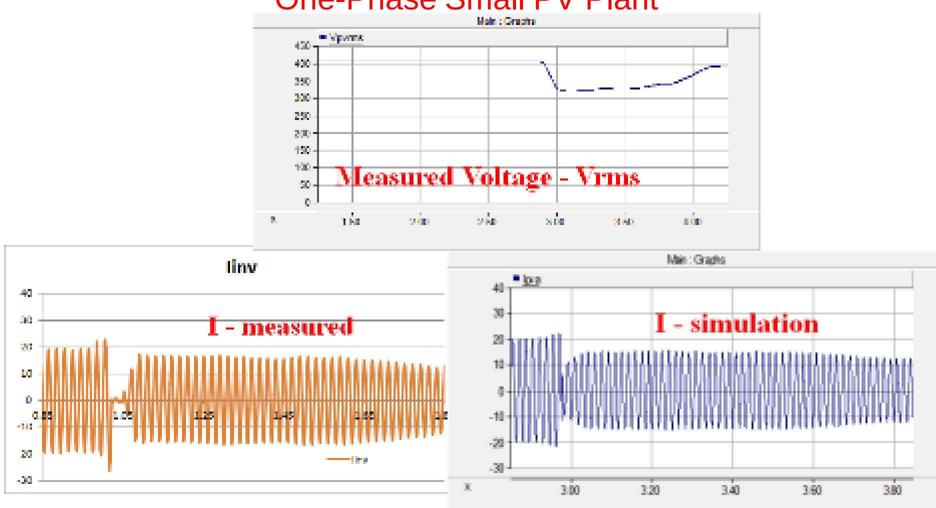
Transient Solar Model Development
Three-Phase Large PV Plant



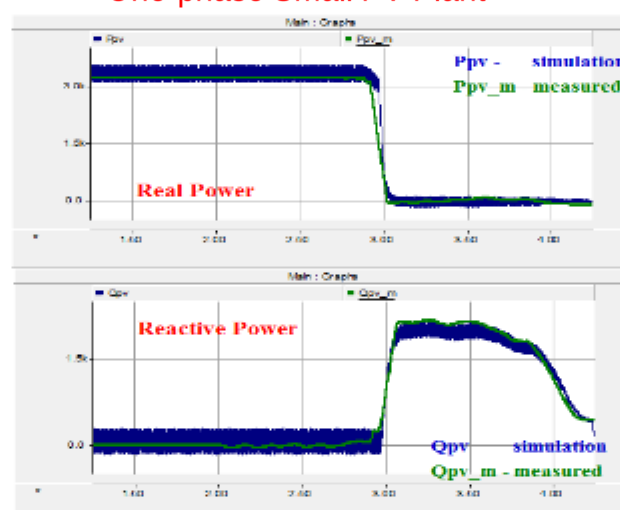
Transient Solar Model Development
Three-Phase Large PV Plant



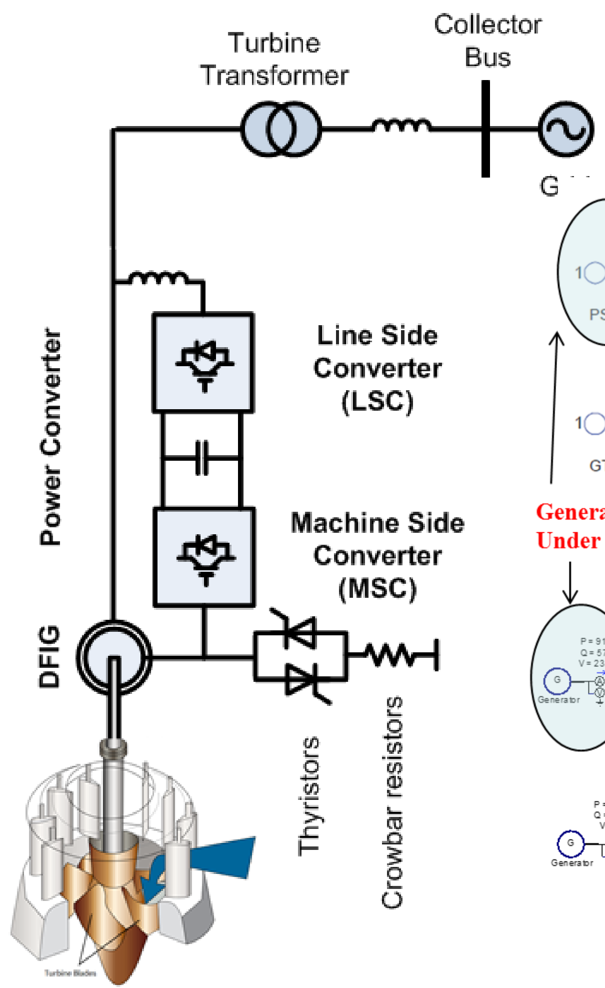
Transient Solar Model Development
One-Phase Small PV Plant



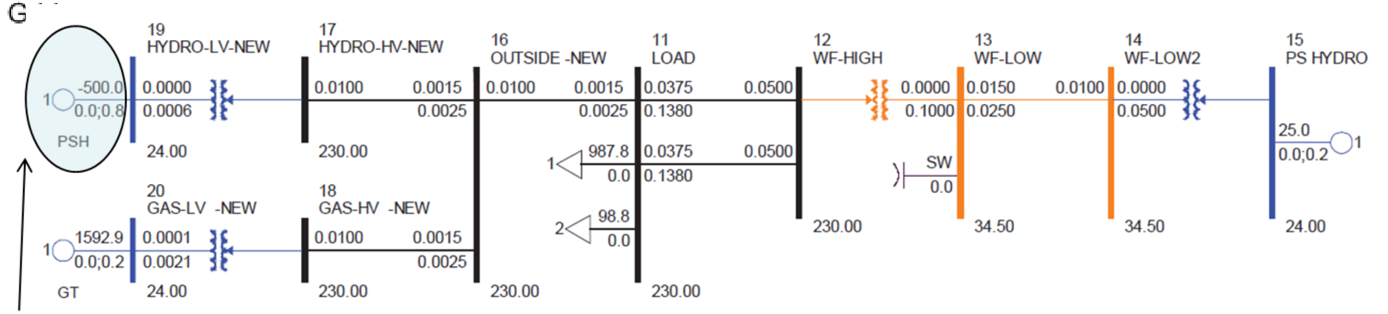
Transient Solar Model Development
One-phase Small PV Plant



Dynamic Model Validation—Pumped Storage Hydro

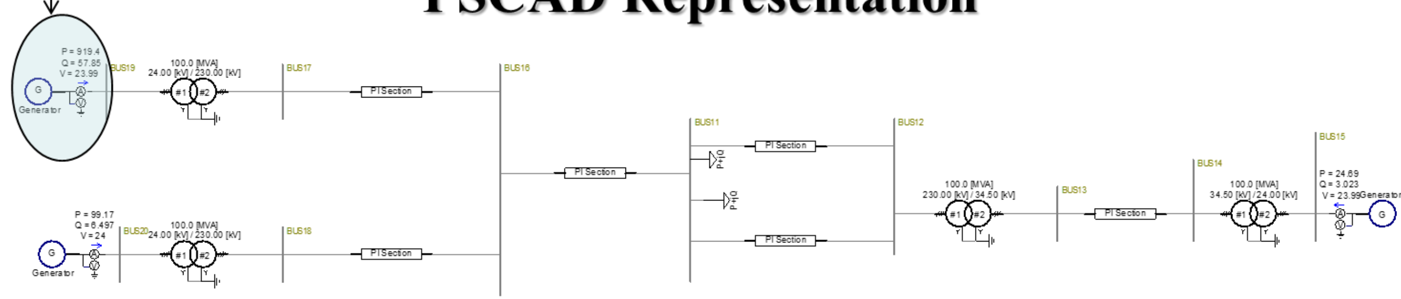


PSSE Representation

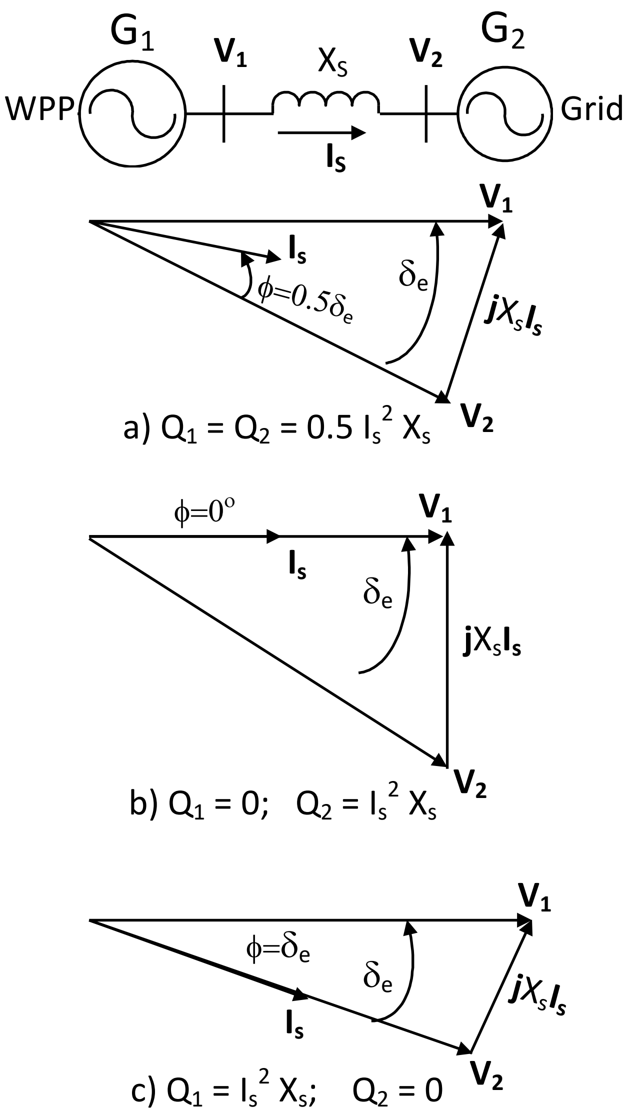


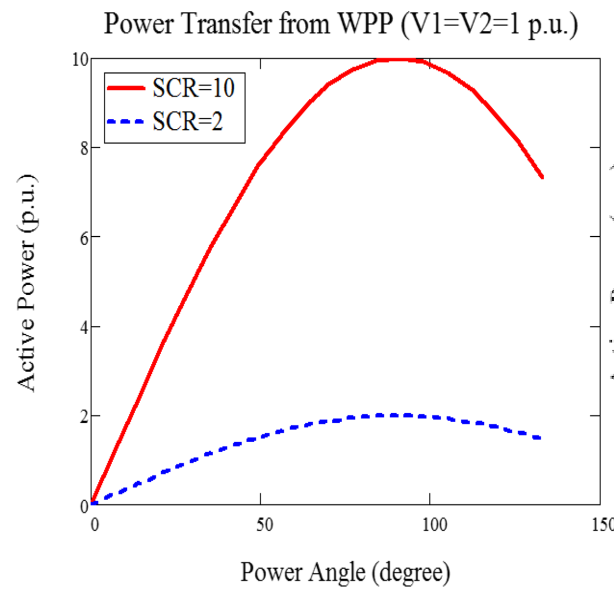
Generator Under Test

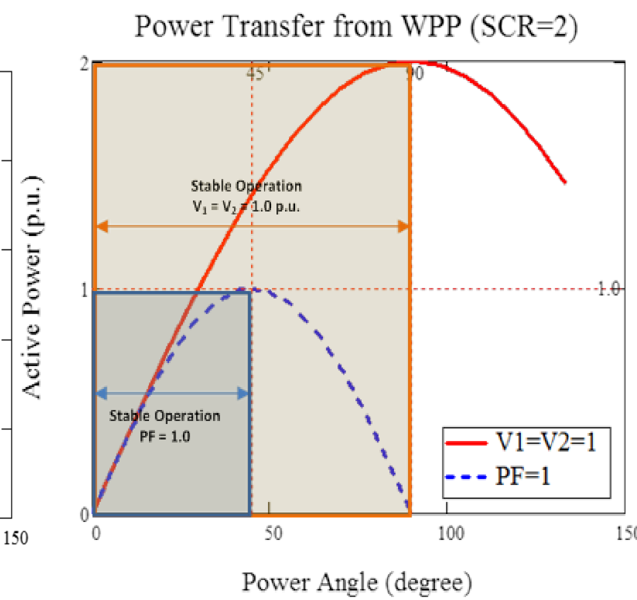
PSCAD Representation



Grid Stiffness



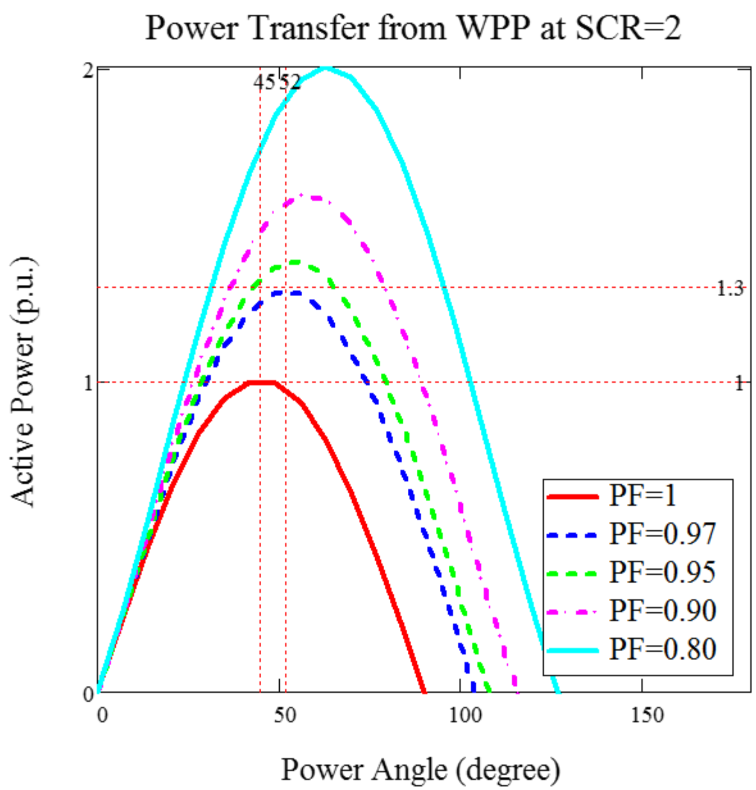




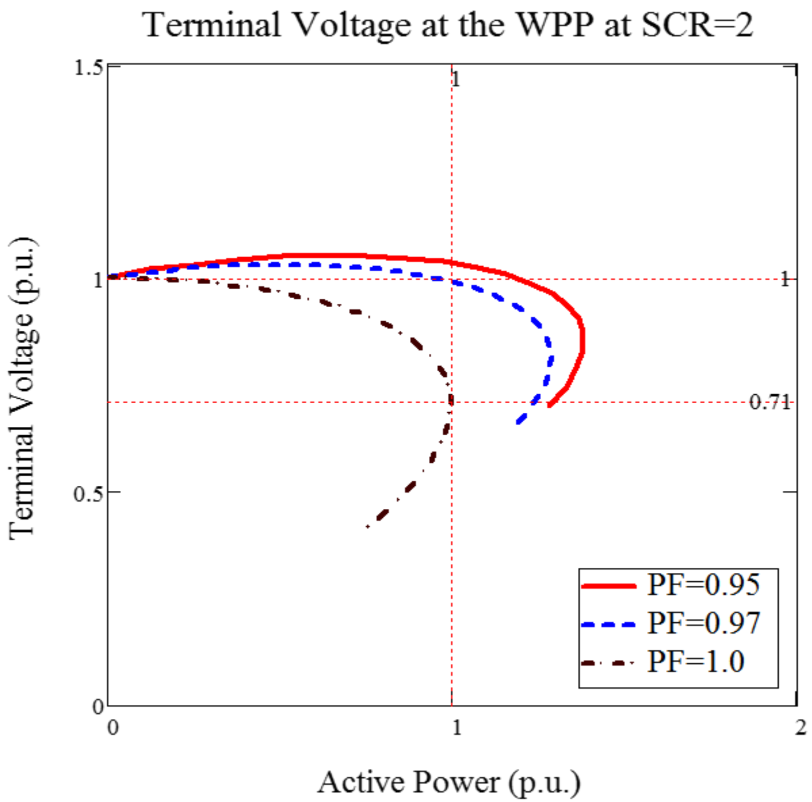
Weak grid vs. stiff grid:

- 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

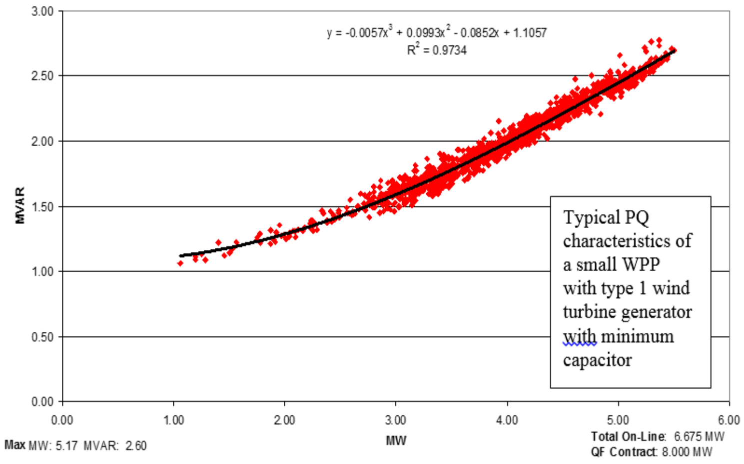


Power-angle characteristics of the WPP operated at different power factor settings

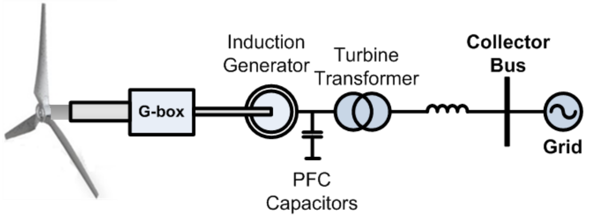


Power-voltage characteristics of the WPP operated at different power factor settings

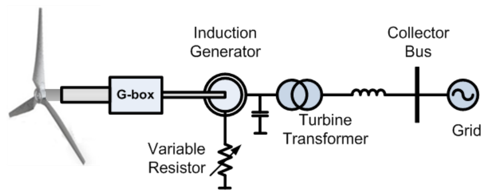
Reactive Power Compensation



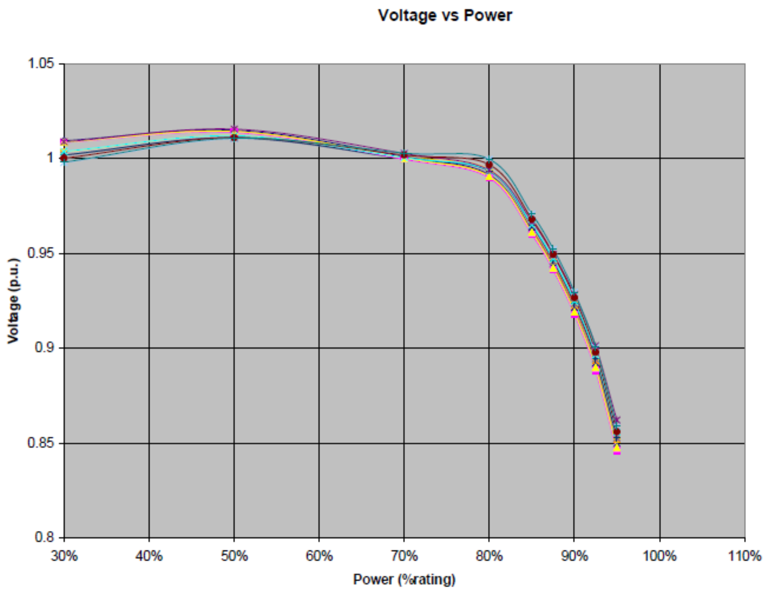
PQ characteristics of Tehachapi, California, Type 1 WTG



Type 1 Fixed Speed Induction Generator



Type 2 Variable Slip Induction Generator

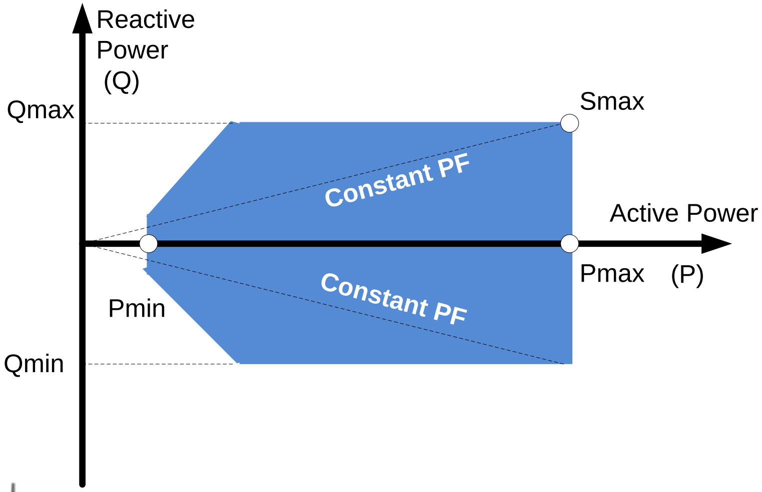


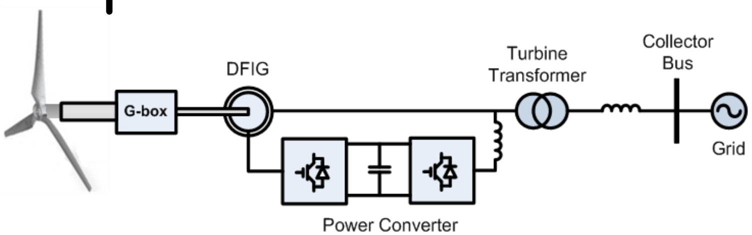
Voltage collapse observed at several WPPs

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

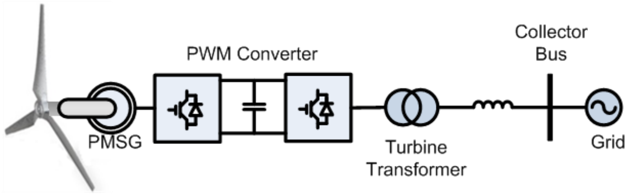
- Type 1 and Type 2 WTGs are based on an induction generator.
- Reactive power compensation is needed as a function of the output power generation.
- Without proper reactive compensation, the grid voltage will drop significantly and a voltage collapse occurs.
- An undervoltage relay at the WTG will disconnect 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.

Reactive Power Compensation





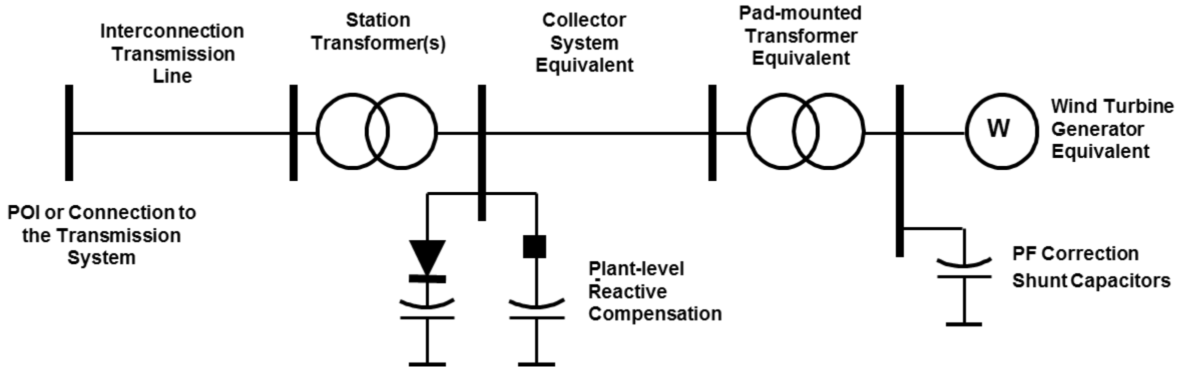
Type 3 Doubly Fed Induction Generator (DFIG)
(Variable Speed WTG)



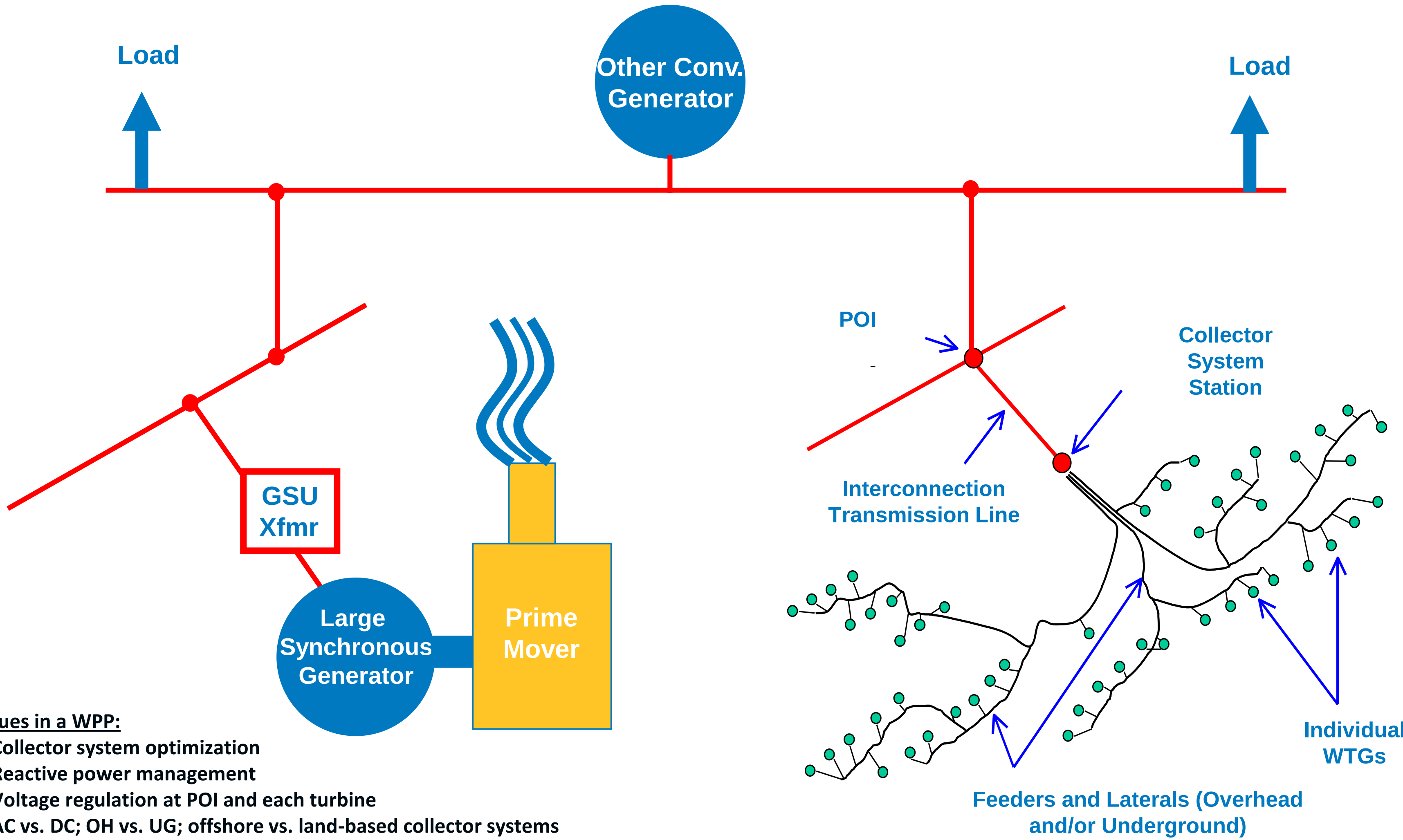
Type 4 Full Power Conversion
(Variable Speed WTG)

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.



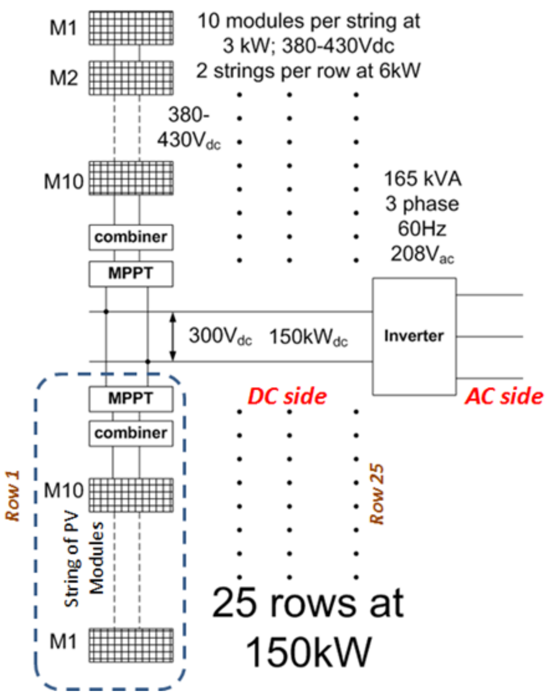
Conventional vs. Wind Power Plant

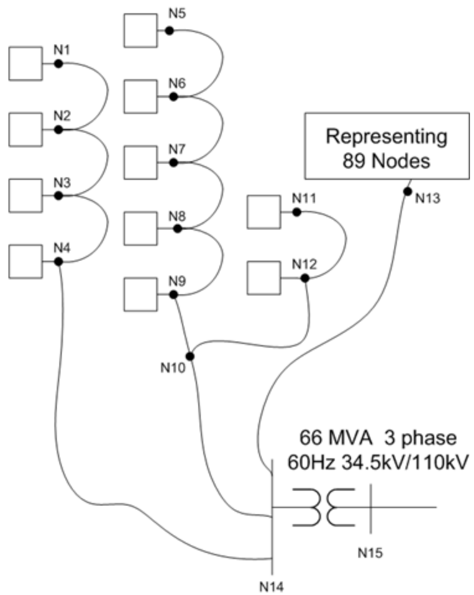


<u>Issues in a WPP:</u>

- **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.**

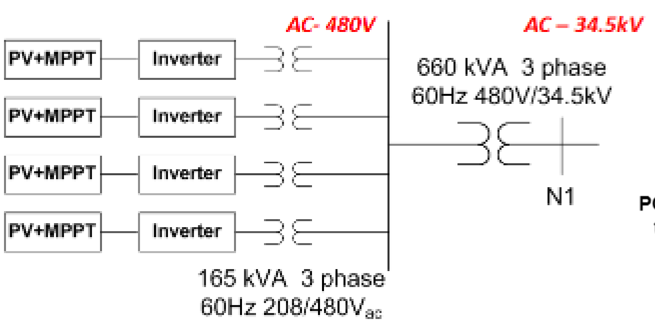
Photovoltaic Power Plant

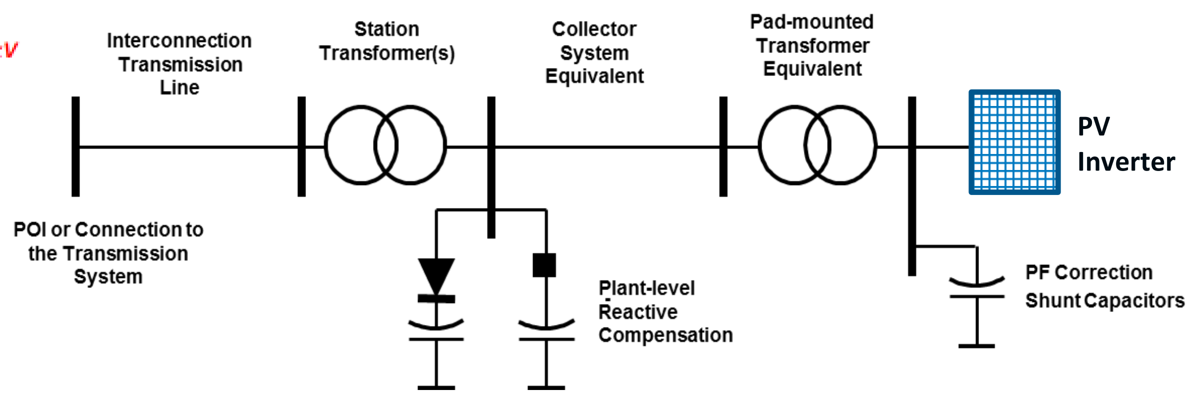




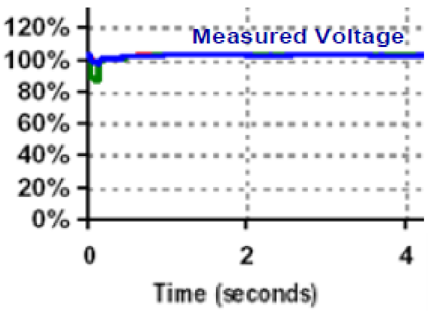
Photovoltaic (PV) plant interconnection:

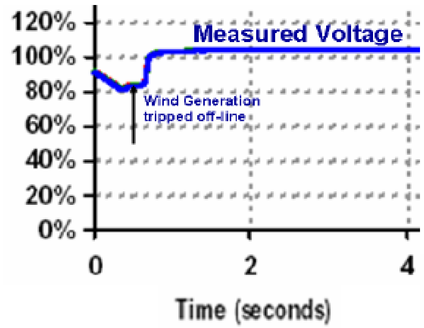
- From the perspective of the plant, a PV plant is very similar to a WPP.
- A PV generator is similar to a Type 4 (full power conversion) WTG.
- A PV generator does not have rotating inertia like a WTG.
- It can generate reactive power when generating or even when not generating.
- In some cases, plant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

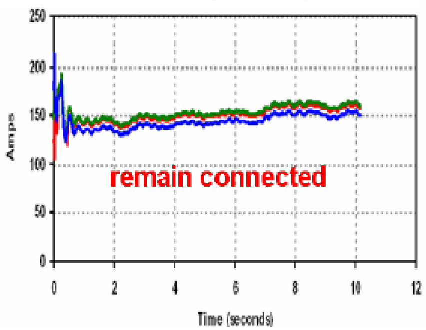


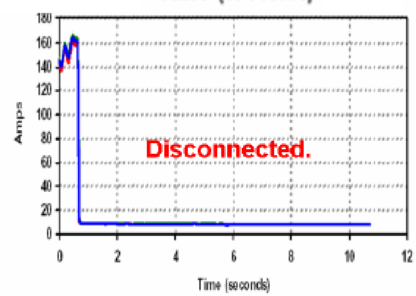


Wind Power Plant—One Year of Observation in Texas









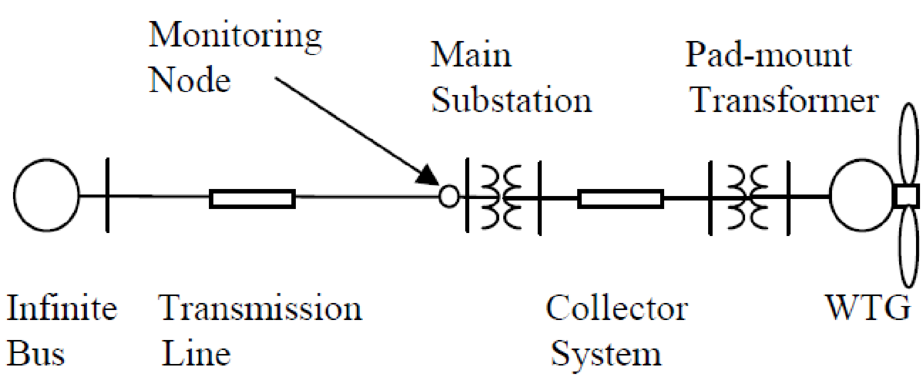


Figure 1. A typical network topology of a large wind power plant.

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

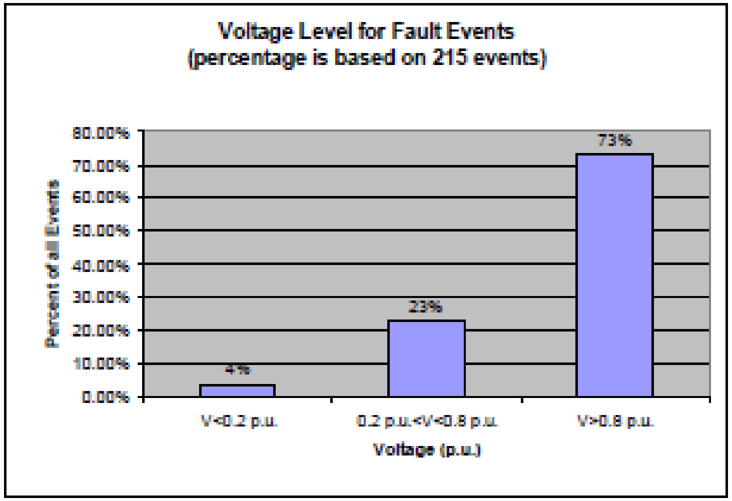


Figure 6. Voltage at the POI during the fault.

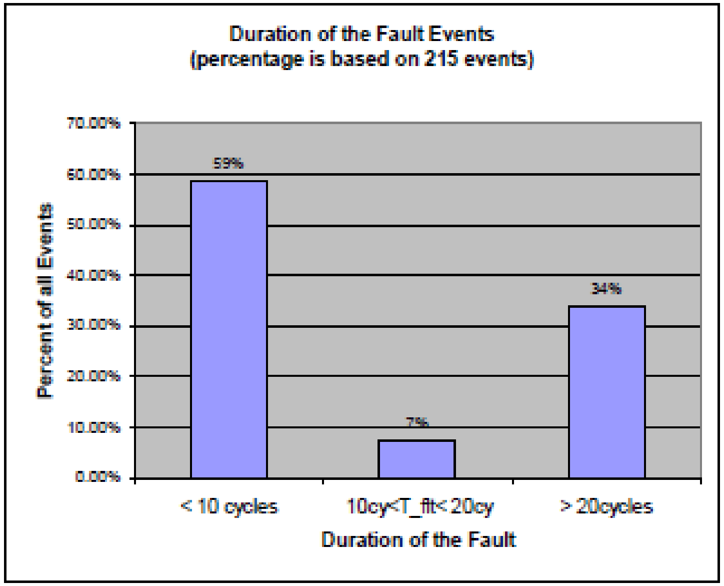


Figure 7. Duration of the fault.

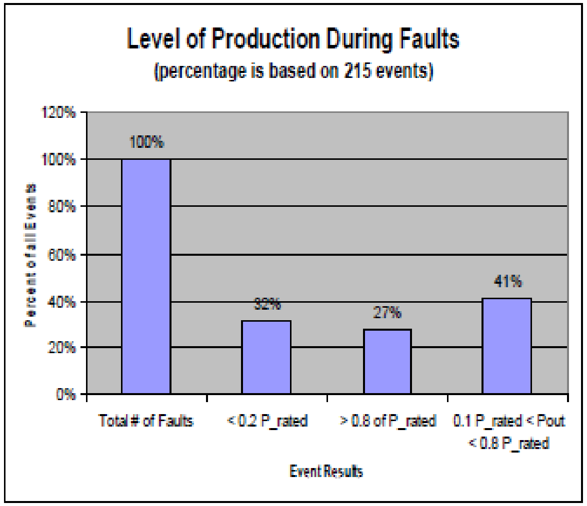


Figure 8. Wind power plant output at the pre-fault condition.

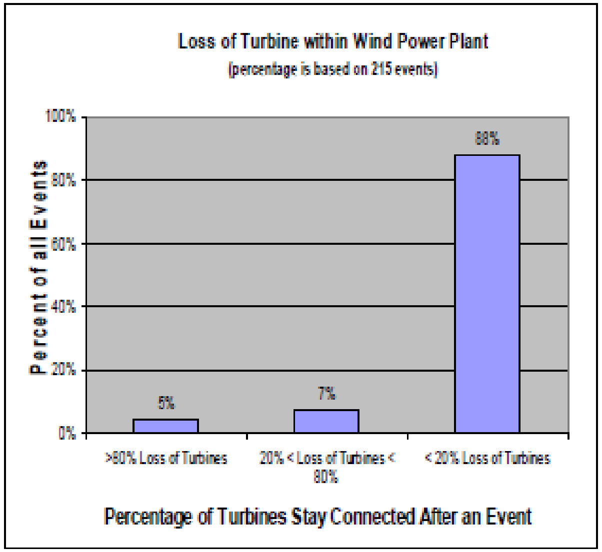
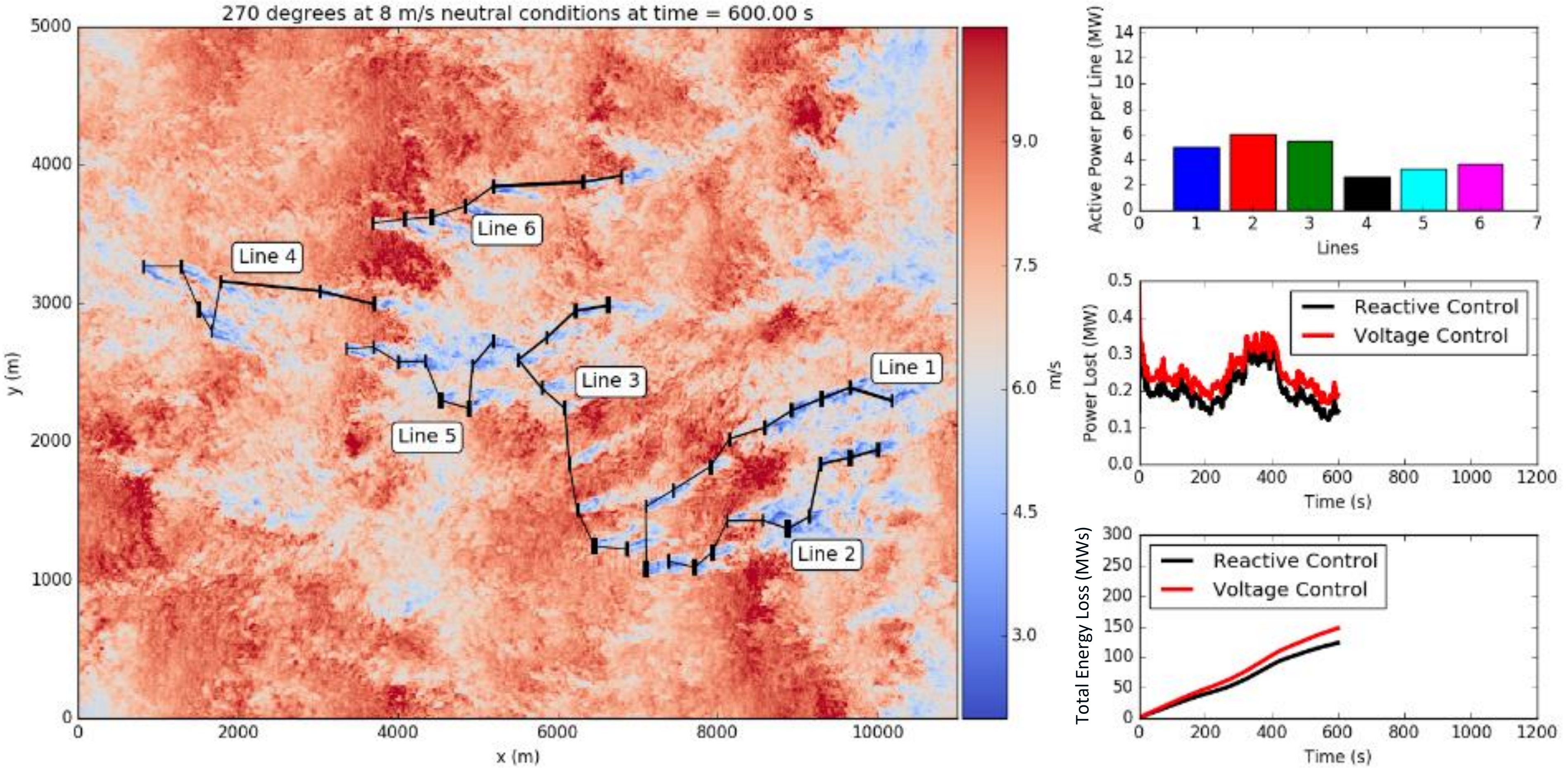


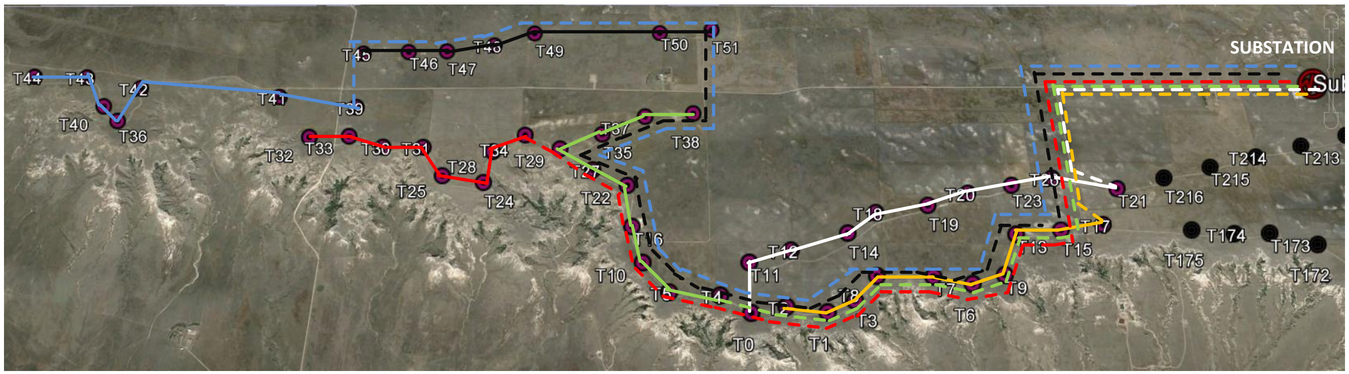
Figure 9. Percentage of turbines that stay on line.

Aerodynamic and Electrical Co-Simulations



Credit: Jennifer Annoni

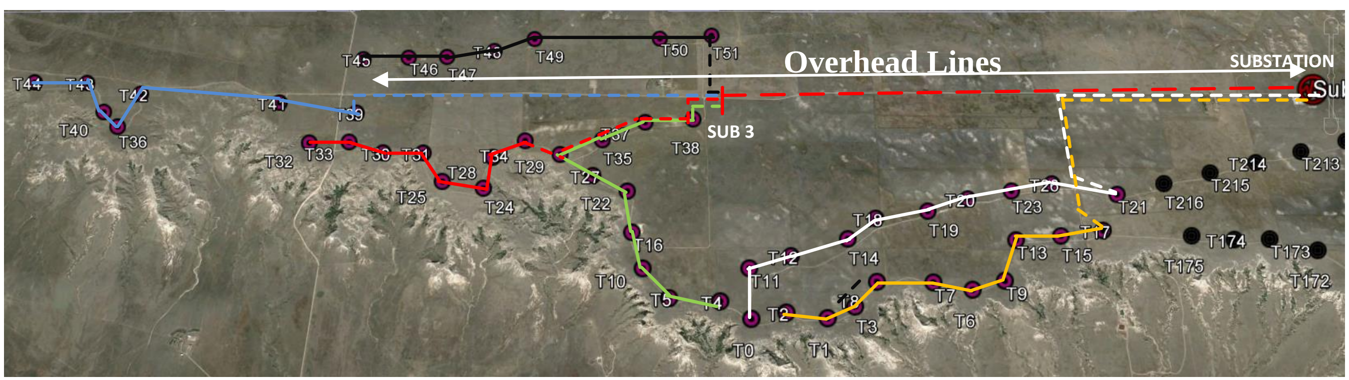
Collector System Design



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

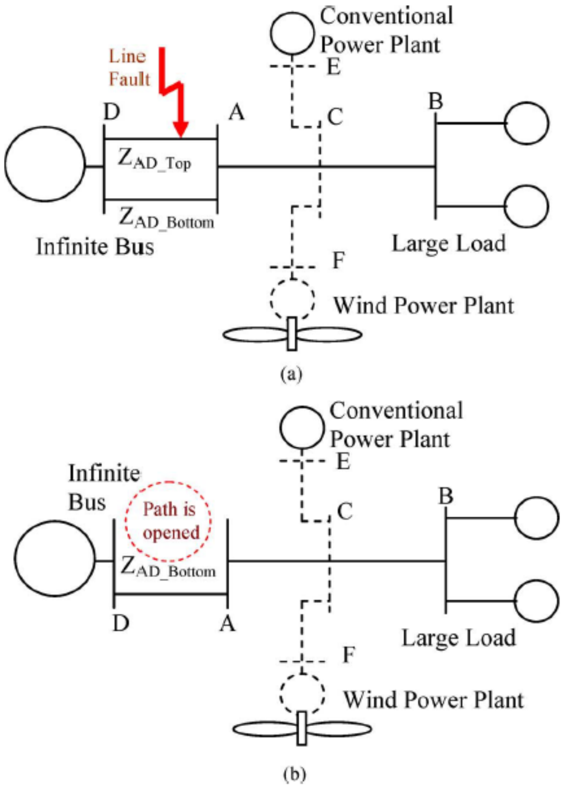


Fig. 3. Major path before and after the line fault is cleared. (a) Before the line fault is cleared. (b) After the line fault is cleared.

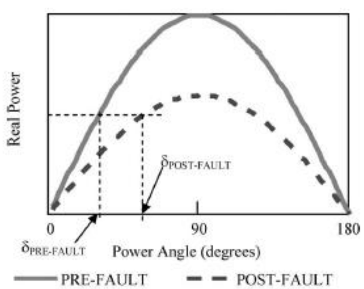
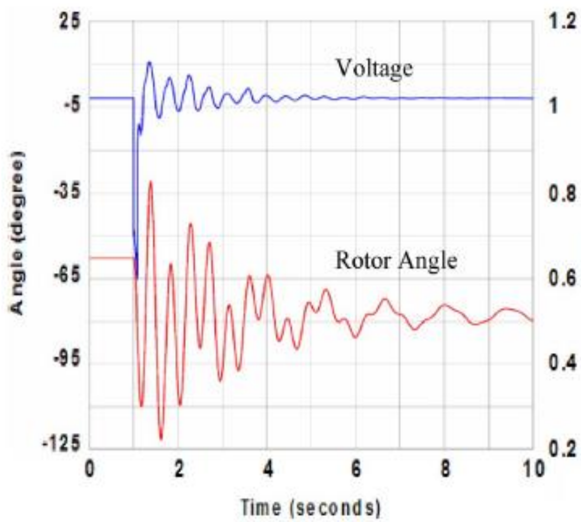
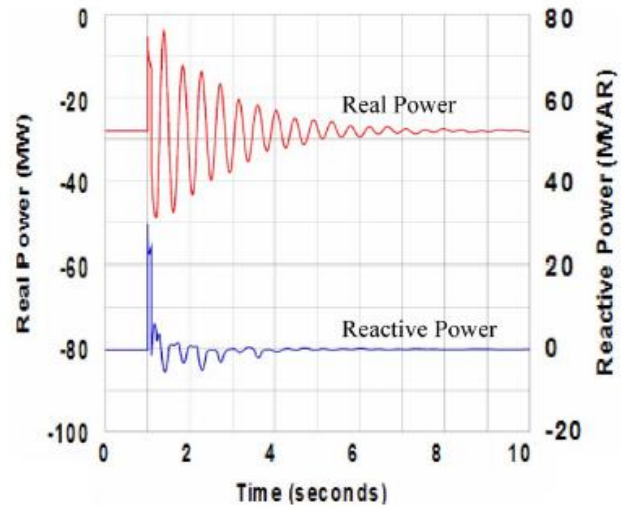


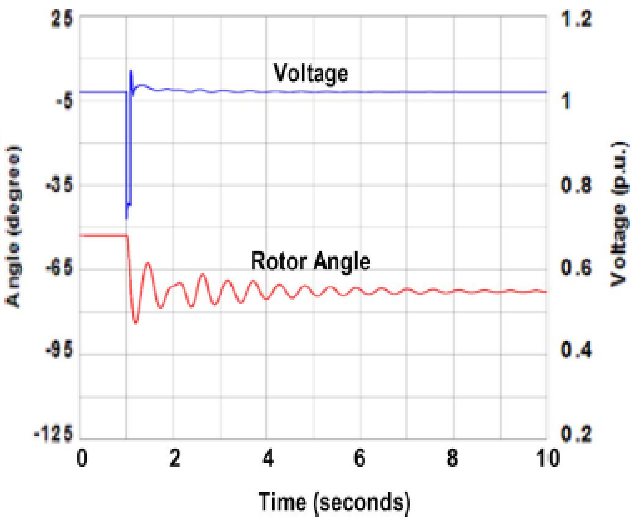
Fig. 5. Power transfer between two buses.

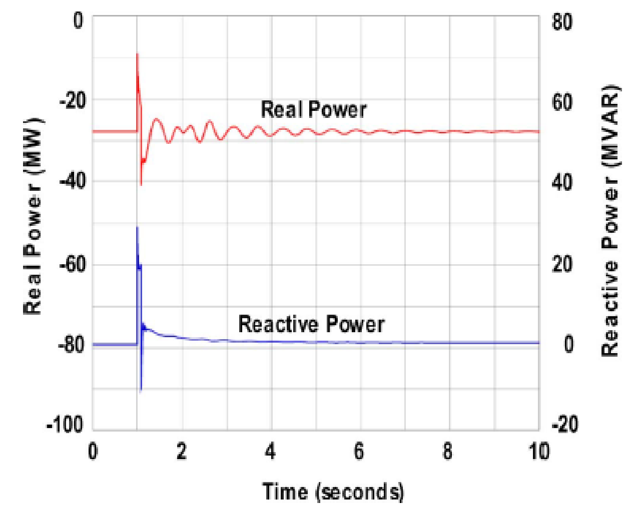
Conventional Plant



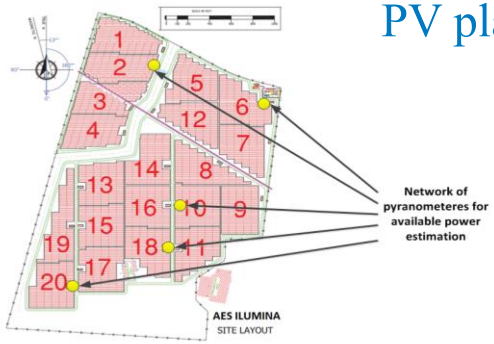


Wind Power Plant

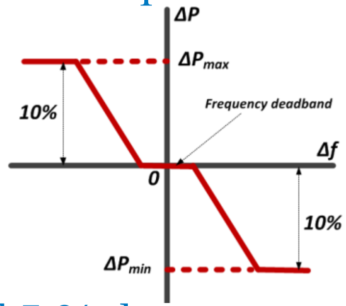




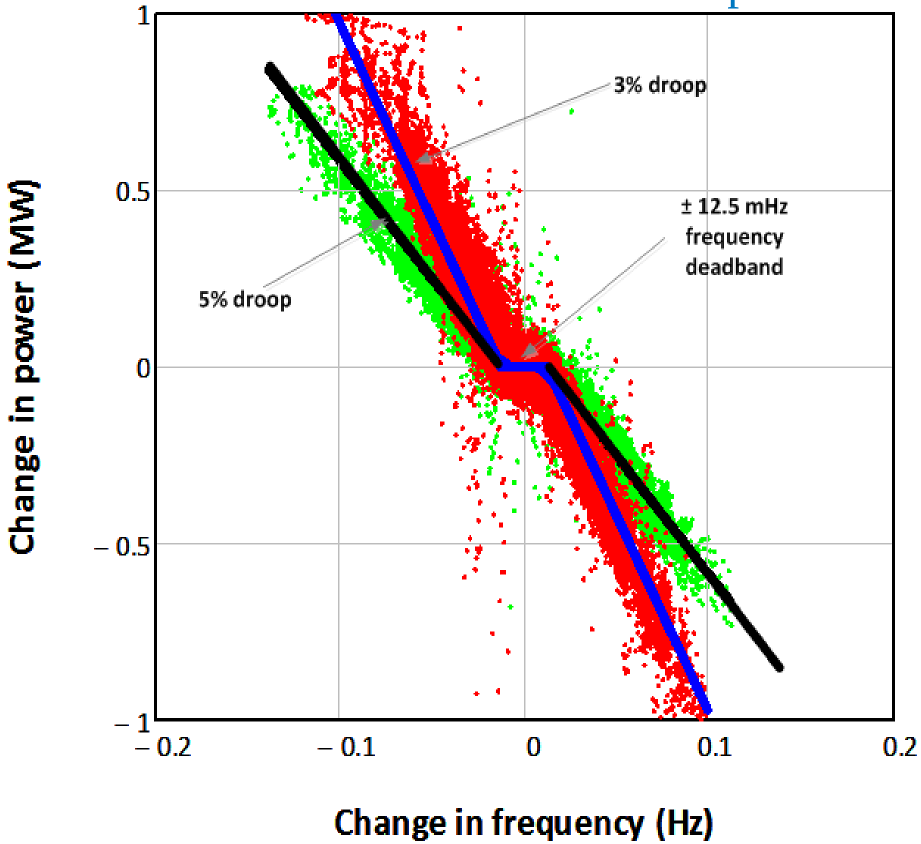
Photovoltaic Power Plant—
Frequency Regulation Demonstration in Puerto Rico



PV plant's droop characteristic

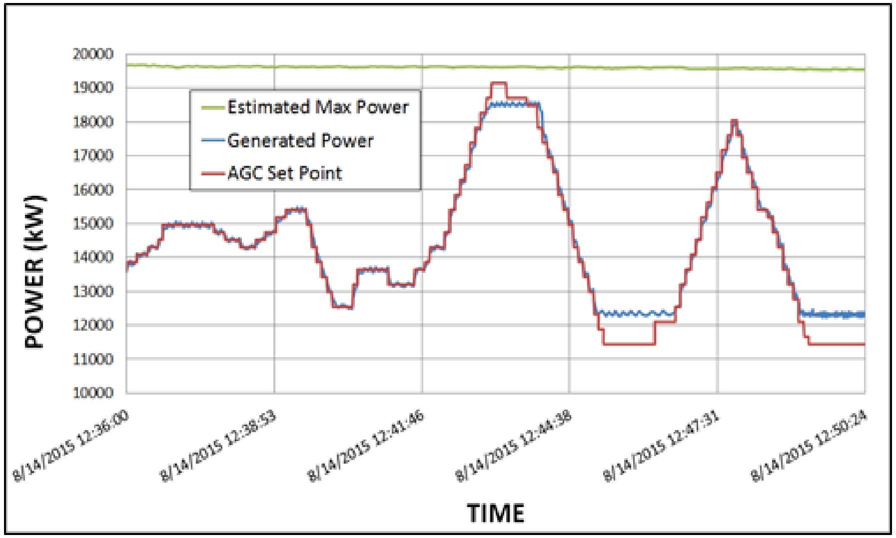


Results for 3% and 5 % droop tests

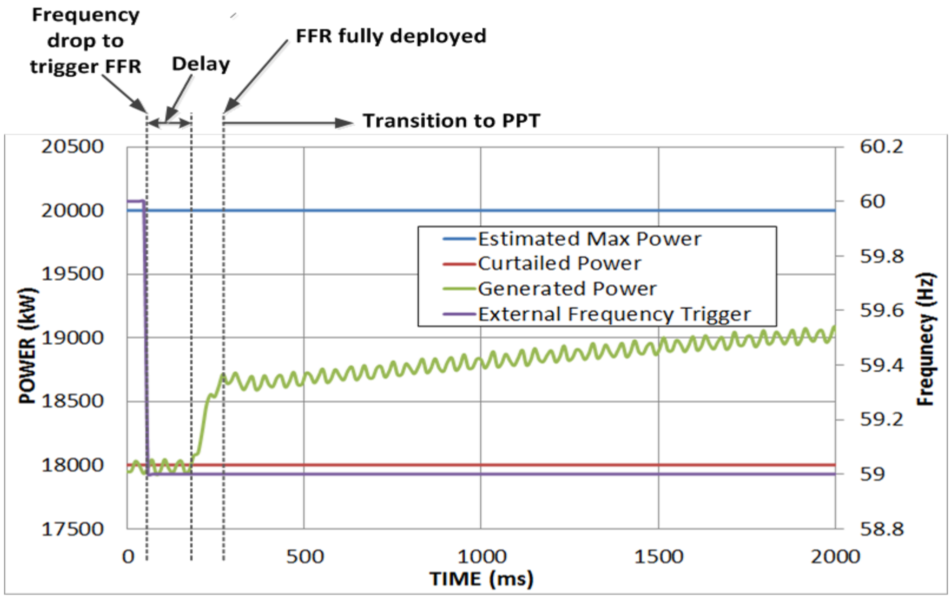


- Title: "Demonstration of Active Power Controls by Utility-Scale PV Power Plant in an Island Grid (Puerto Rico)," by Vahan Gevorgian and Barbara O'Neill, Wind and Solar Integration Workshop, Nov. 2016
- Total installed generation capacity: 6 GW with 173 MW of wind and solar PV generation; the rest is 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).

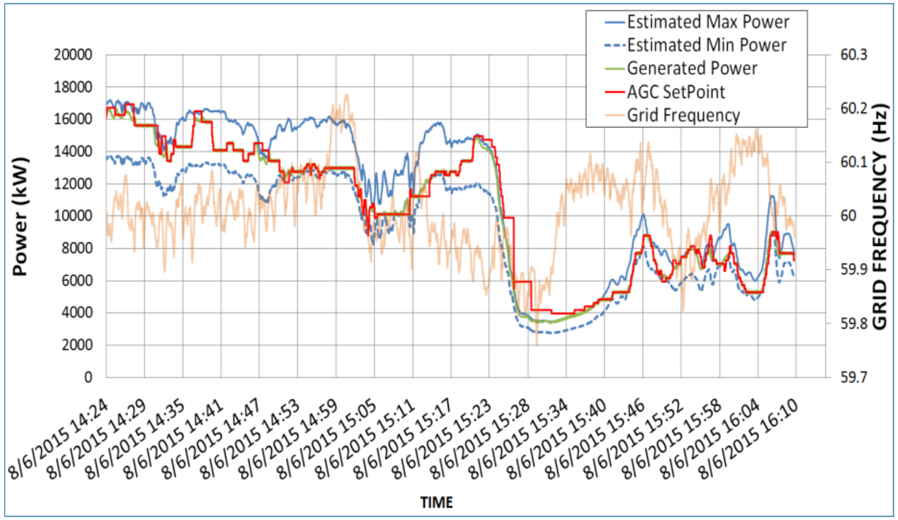
Photovoltaic Power Plant— Frequency Regulation Demonstration



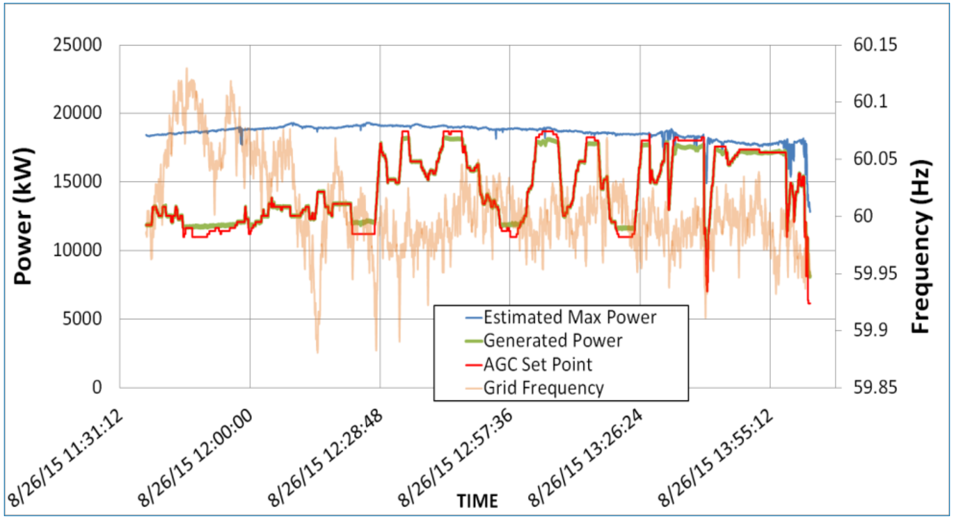
AGC performance



Example results of one FFR test

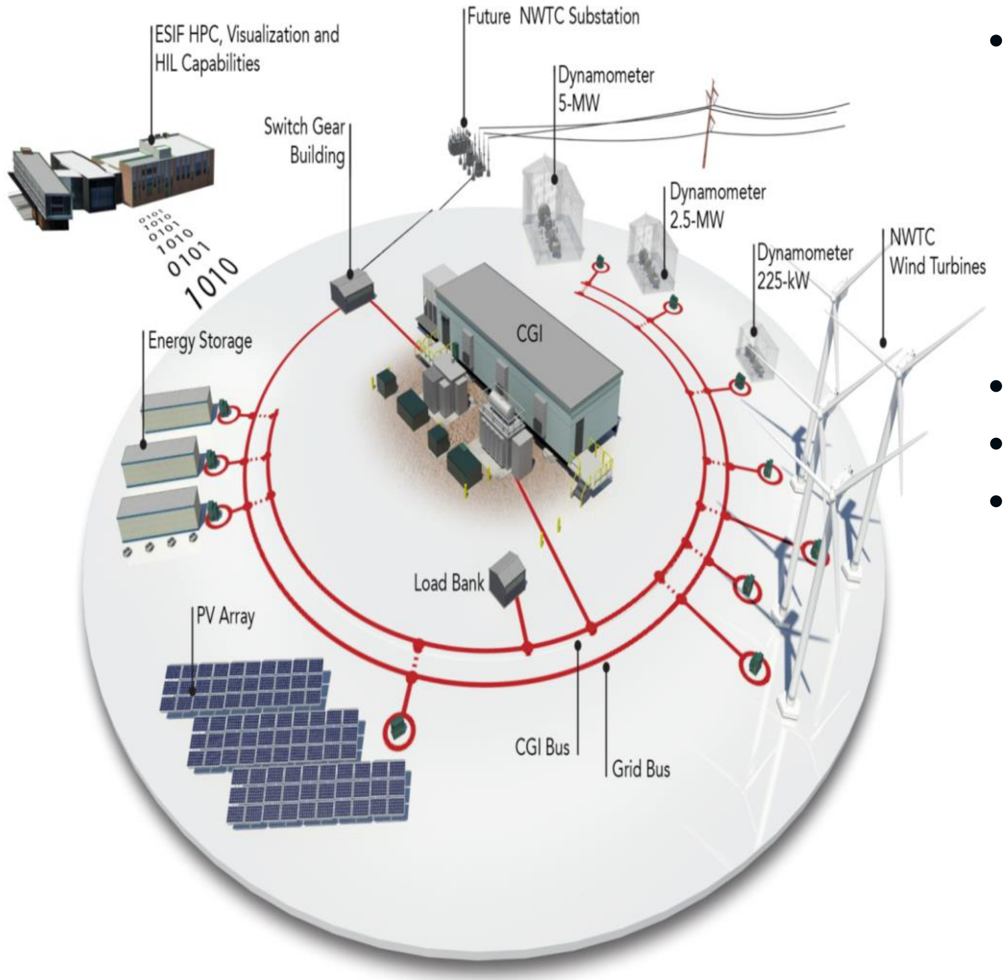


AGC test using 20% range



AGC test using 40% range

Wind Turbine—Ancillary Services Testing

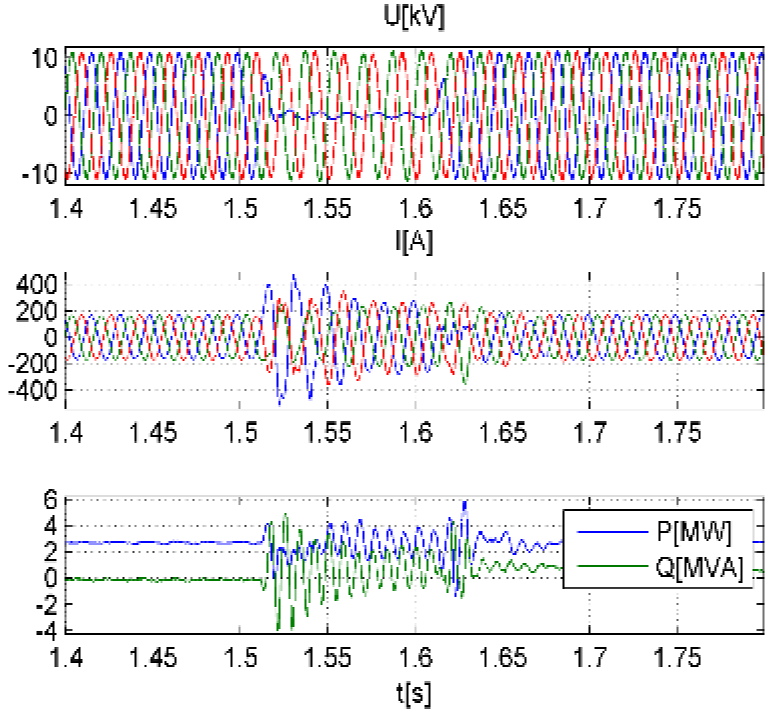


NREL/NWTC infrastructure for renewable energy systems grid integration testing. *Illustration by Josh Bauer, NREL*

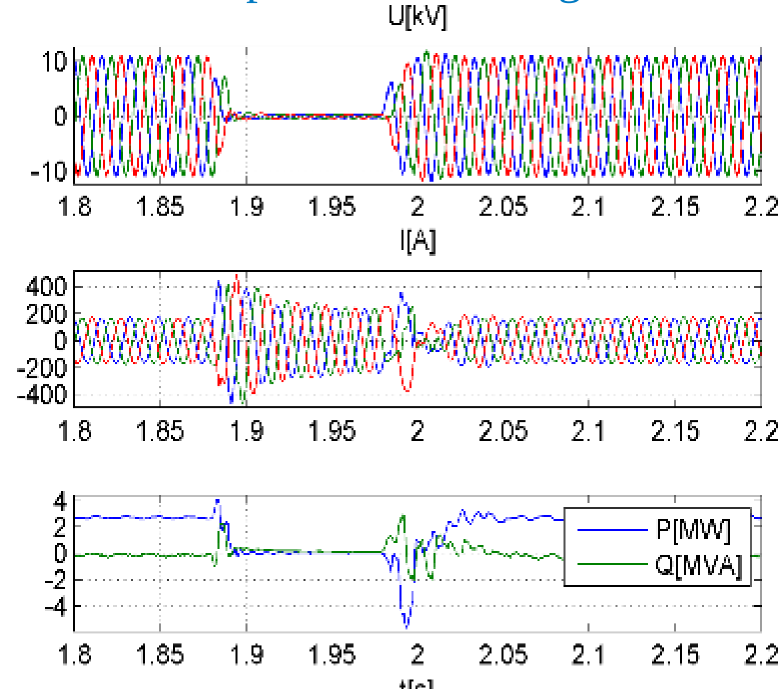
- Title: "Controllable Grid Interface (CGI) for Testing Ancillary Service Controls and Fault Performance of Utility-Scale Wind Power Generation," by V. Gevorgian et al., Wind and Solar Integration Workshop, Nov. 2016
- 7.5-MVA power system simulator (CGI)
- 2.75-MW GE wind turbine drivetrain
- Testing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

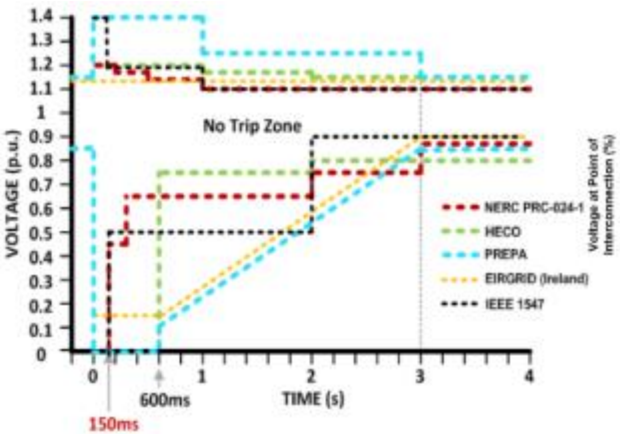
Wind Turbine—Ancillary Services Testing

Single-phase zero voltage test

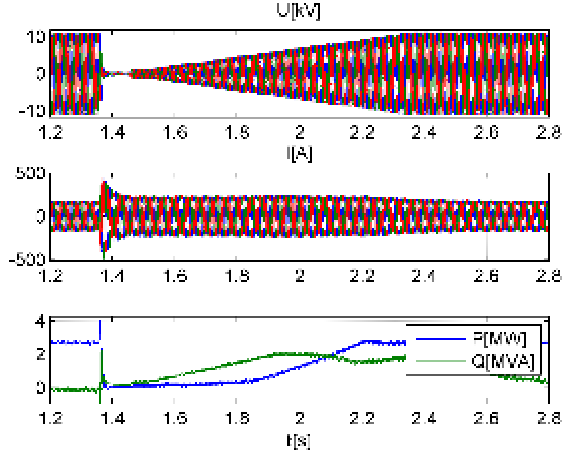


Three-phase zero voltage test

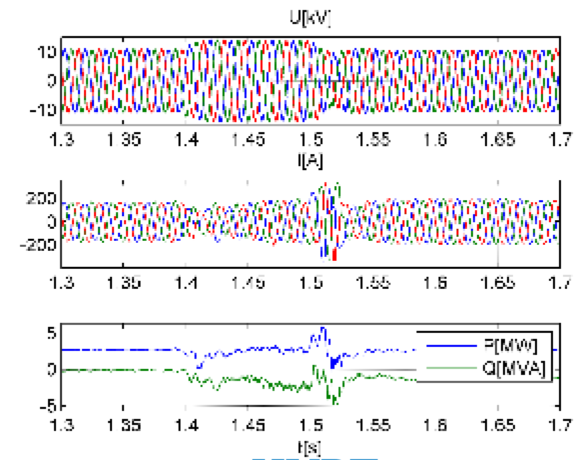




Grid Code

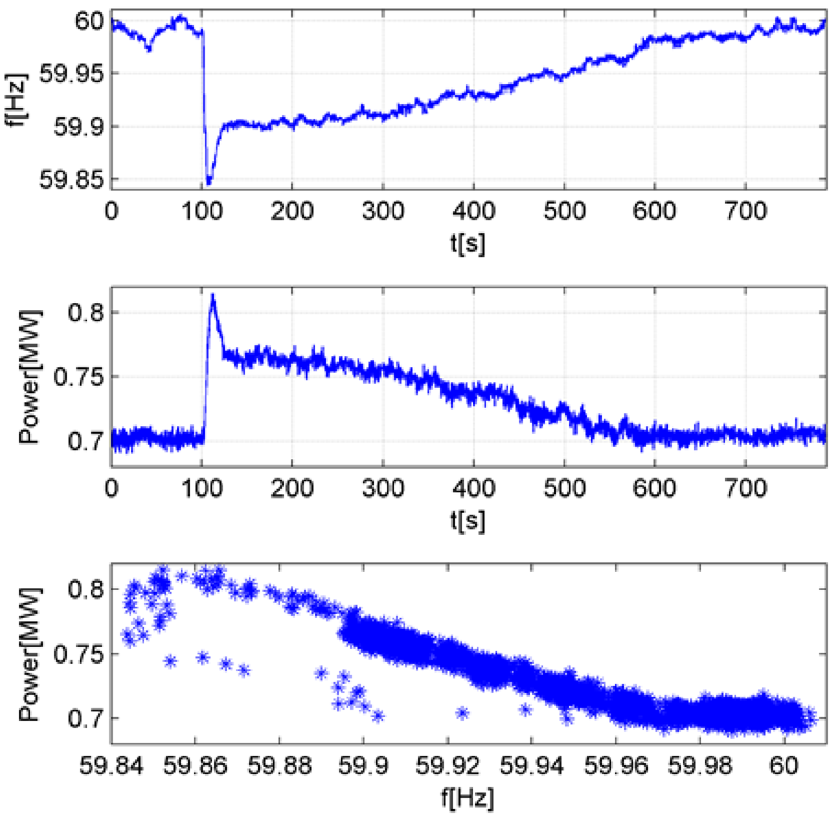


LVRT

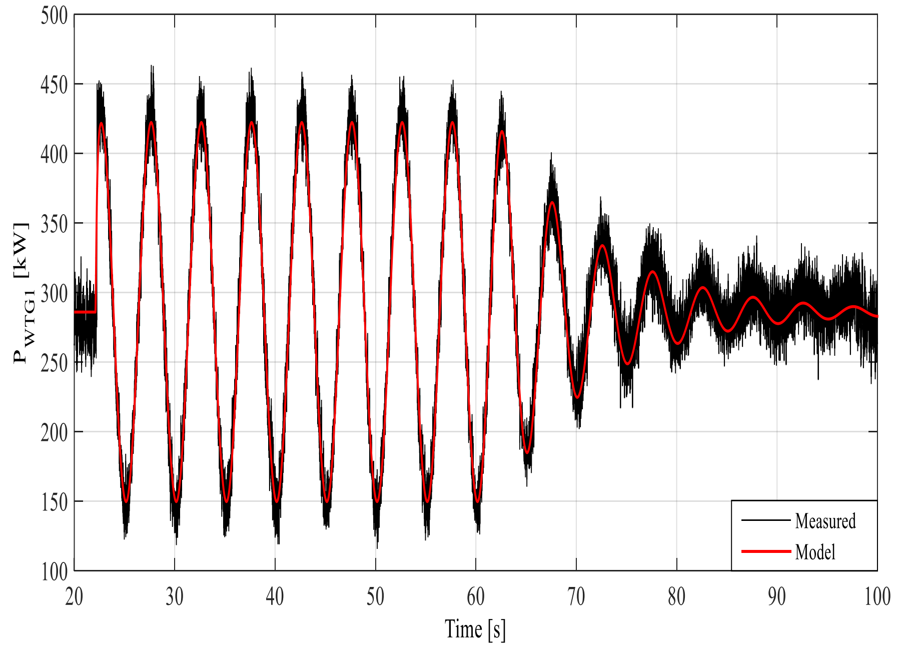


HVRT

Wind Turbine—Ancillary Services Testing

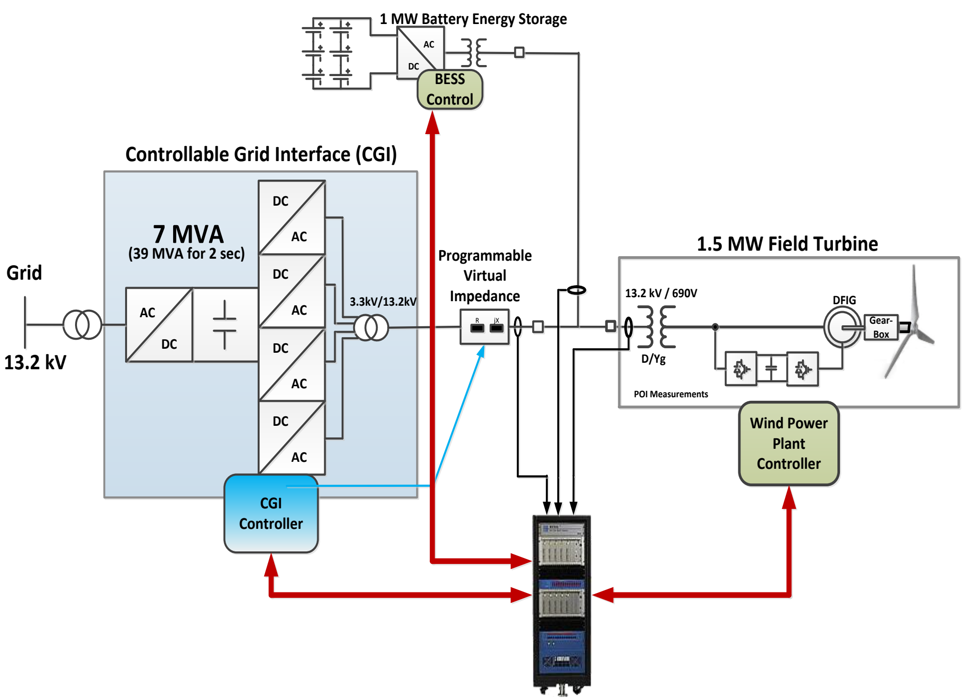


Frequency droop test

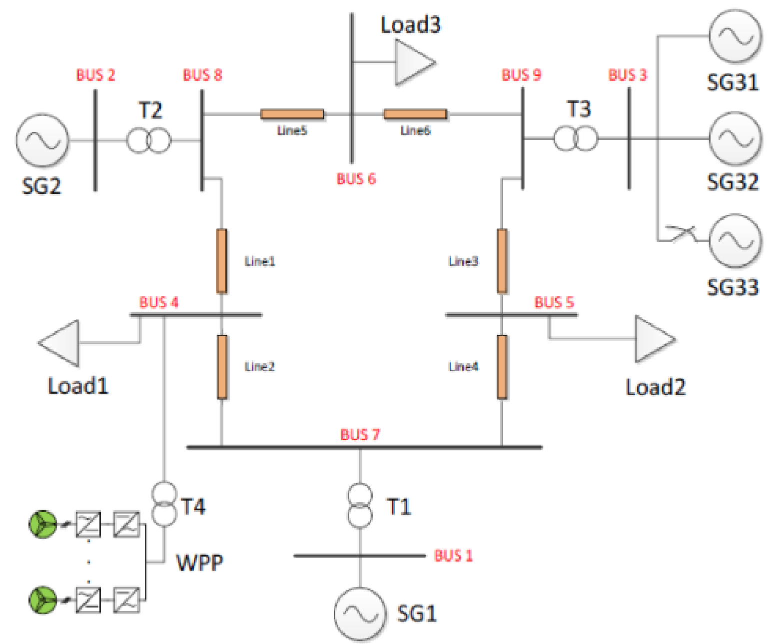


Power oscillation damping test results

Wind Turbine—Ancillary Services Testing

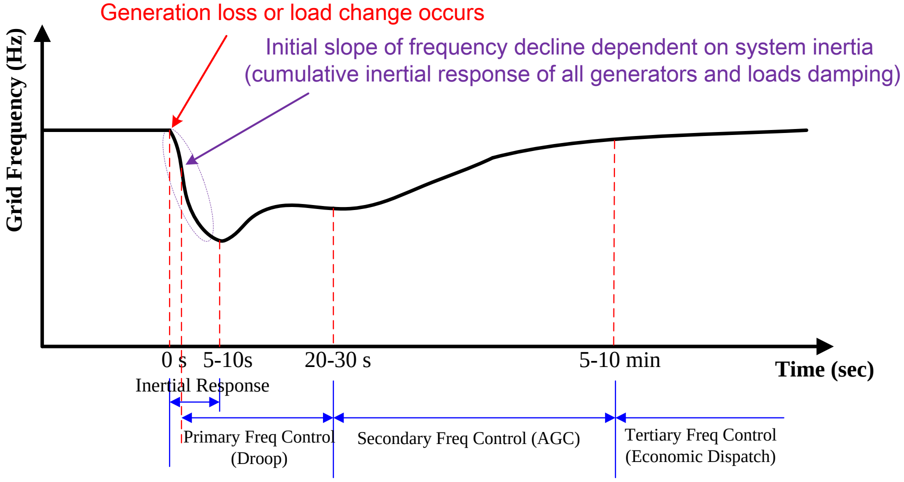


PHIL test setup with CGI and RTDS

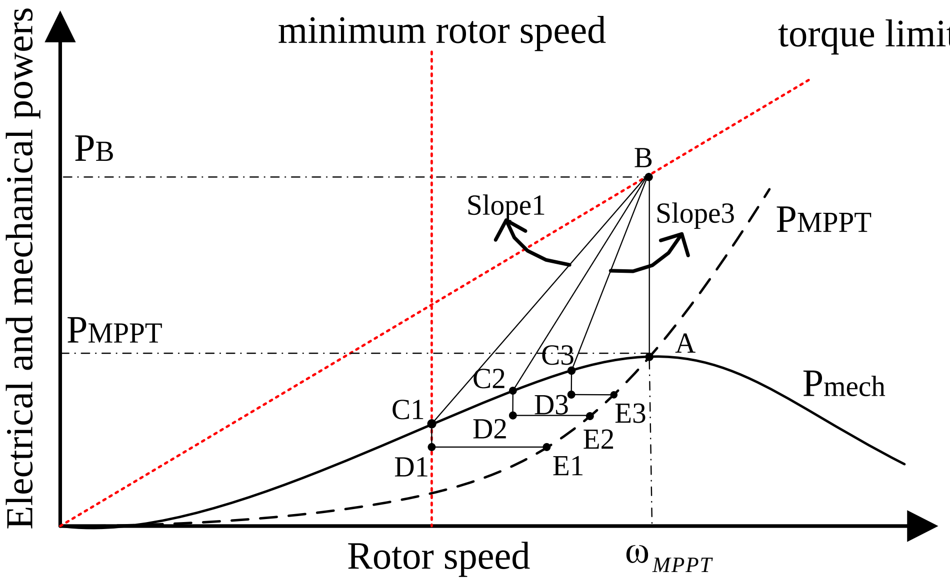


RTDS model of 9-bus power system

Inertial Response of a Wind Power Plant



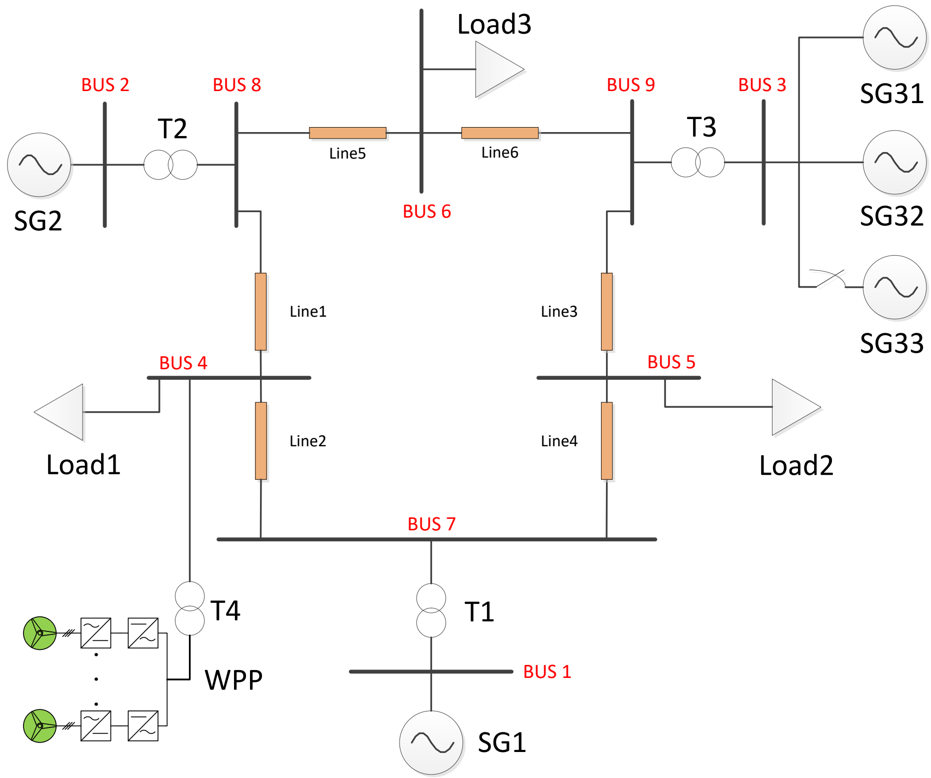
Torque-Limited Inertial Control



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.

Modified Nine-Bus Power System

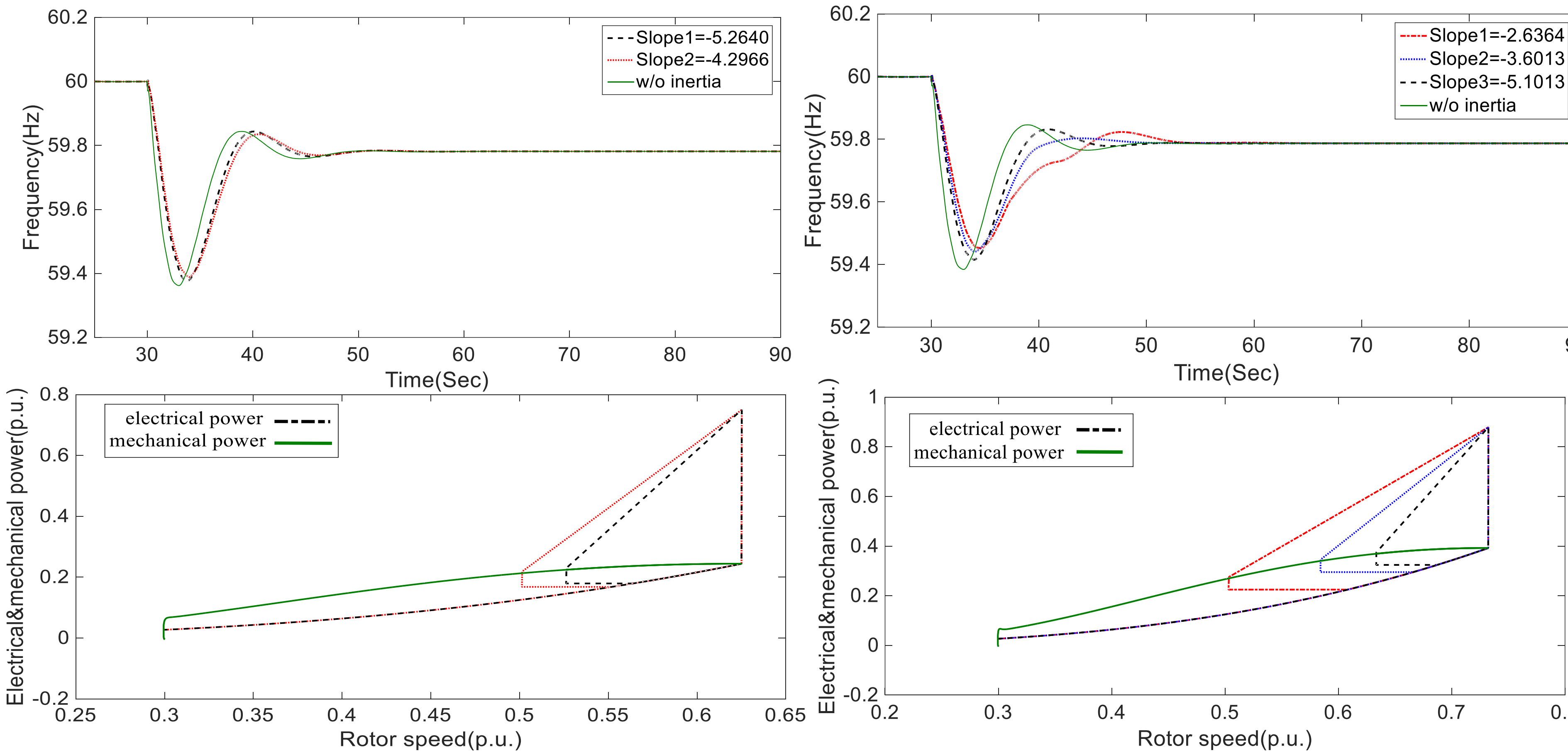


	Rated Capacity (MVA)	Rated voltage (kV)	Inertial Constant (s)	Tdo'(s)	Tdo''(s)	Tqo'(s)	Tqo''(s)
SG1	200	16.5	6.64	8.96	0.12	-	0.95
SG2	80	18	5.31	8.0	0.03	1.0	0.07
SG31	30	13.8	4.01	8.0	0.03	1.0	0.07
SG32	30	13.8	4.01	8.0	0.03	1.0	0.07
SG33	40	13.8	4.01	8.0	0.03	1.0	0.07

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

- Energy systems integration consists of renewable and efficiency aspects. It includes energy carriers, spatial scales, and functional layers.
- The integration of variable and renewable energy resources into the grid should be considered from many different angles and across different time resolutions.
- The grid of the future has different characteristics from those of the conventional grid in several way (e.g., bidirectional power flow; many inverter-based generators; less susceptible to frequency/voltage deviations; high penetrations of variable and renewable energy resources; the presence of long-/short-term energy storage and FACTS devices; market and technically driven; coexistence of AC and DC systems; wide-area-based coordination in monitoring, control, and protection).
- Power systems of the future will be more dynamic and require a shorter cycle of system planning, operation, and market design as technology moves at a rapid pace.
- Grid codes are expected to be revised at the national, regional, and local levels to reflect the continuing changes in the system network and existing technologies.

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- 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!

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