GE Energy Consulting

CAISO Workshop on Reactive Power Requirements and Financial Compensation

Jason MacDowell

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Wind Turbines and Reactive Power Control

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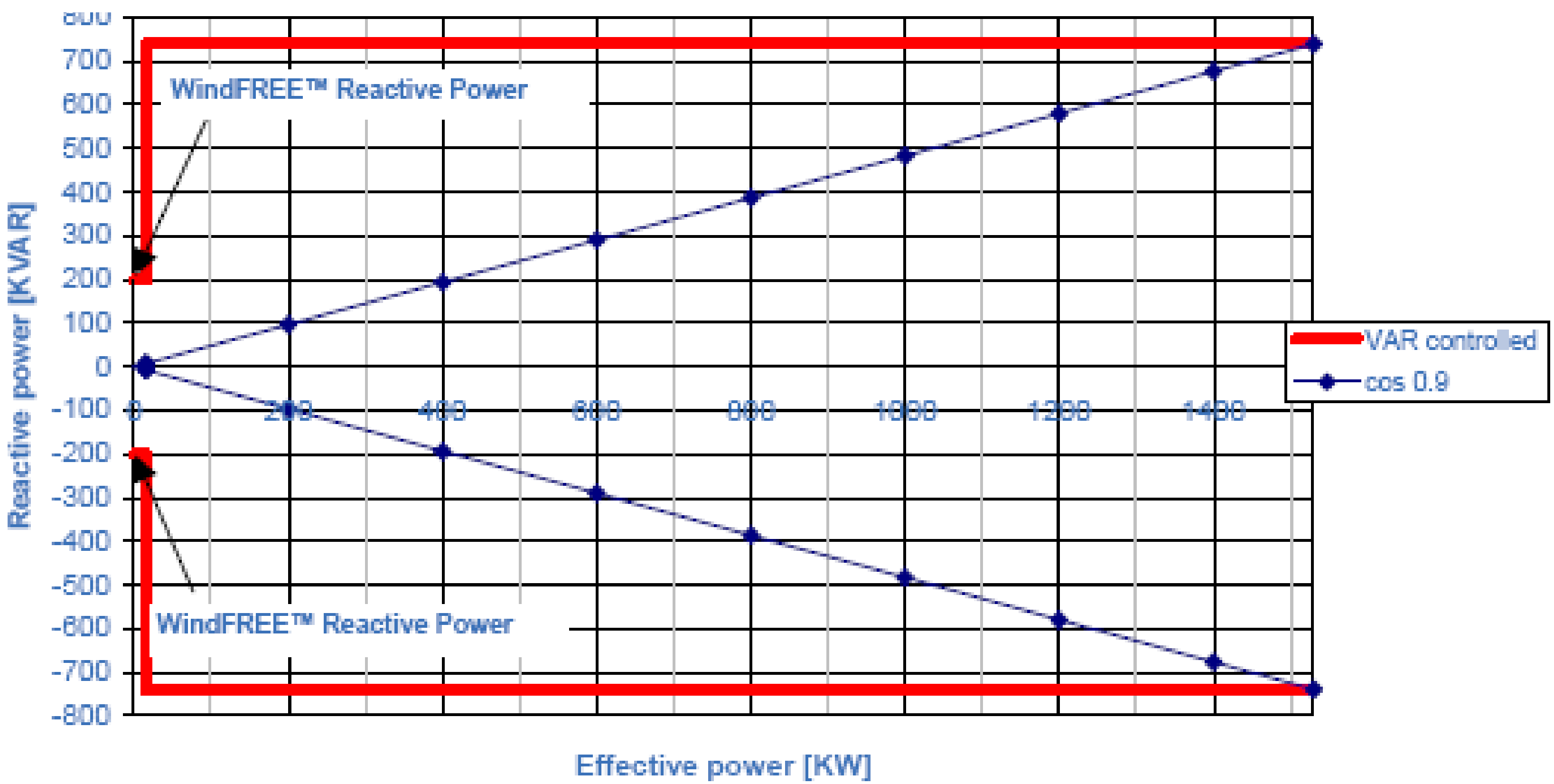
GE 1.5 MW Reactive Capability



- Full leading and lagging range over full power range
- Faster reactive response than synch. generator
- Capability of reactive compensation with no wind
- No need for FACTS devices

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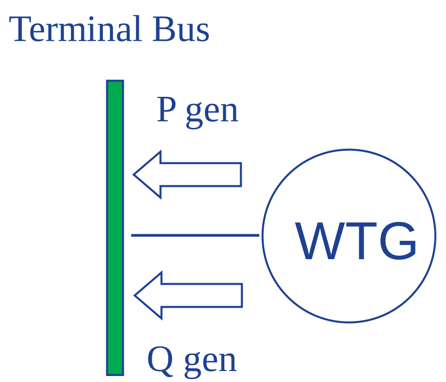
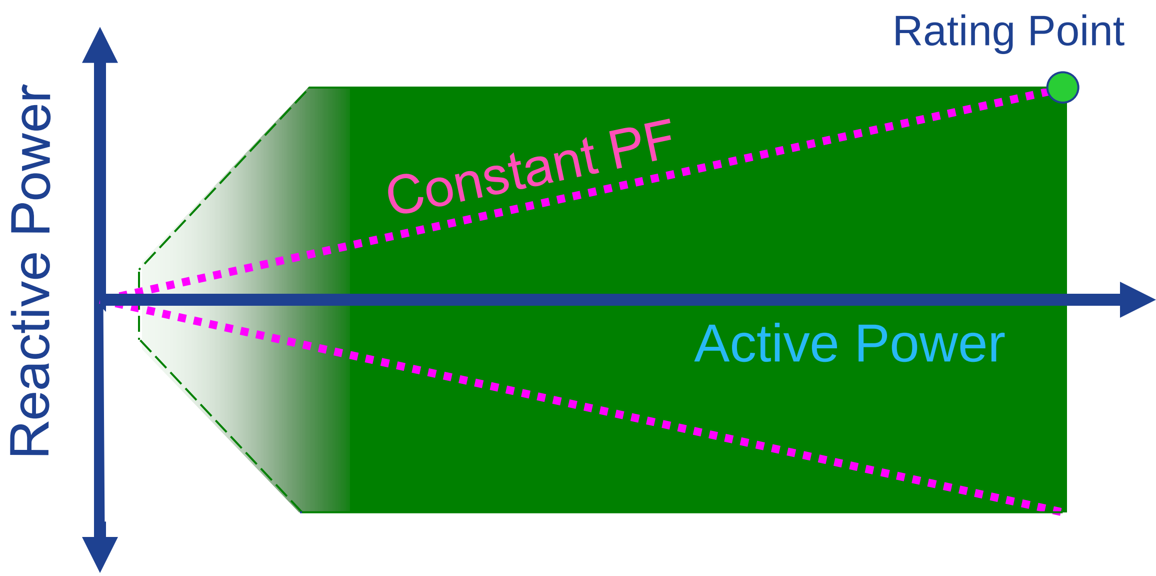
WTG Reactive Power Capability

Reactive Power for Voltage Support

- Steady-state PF range - 0.90 under-excited/0.90 over-excited
- Dynamic range meets or exceeds steady-state range
- WTG reactive capability often sufficient to satisfy PF requirements at POI
- VAR capability reduced at low power due to units cycling off-line

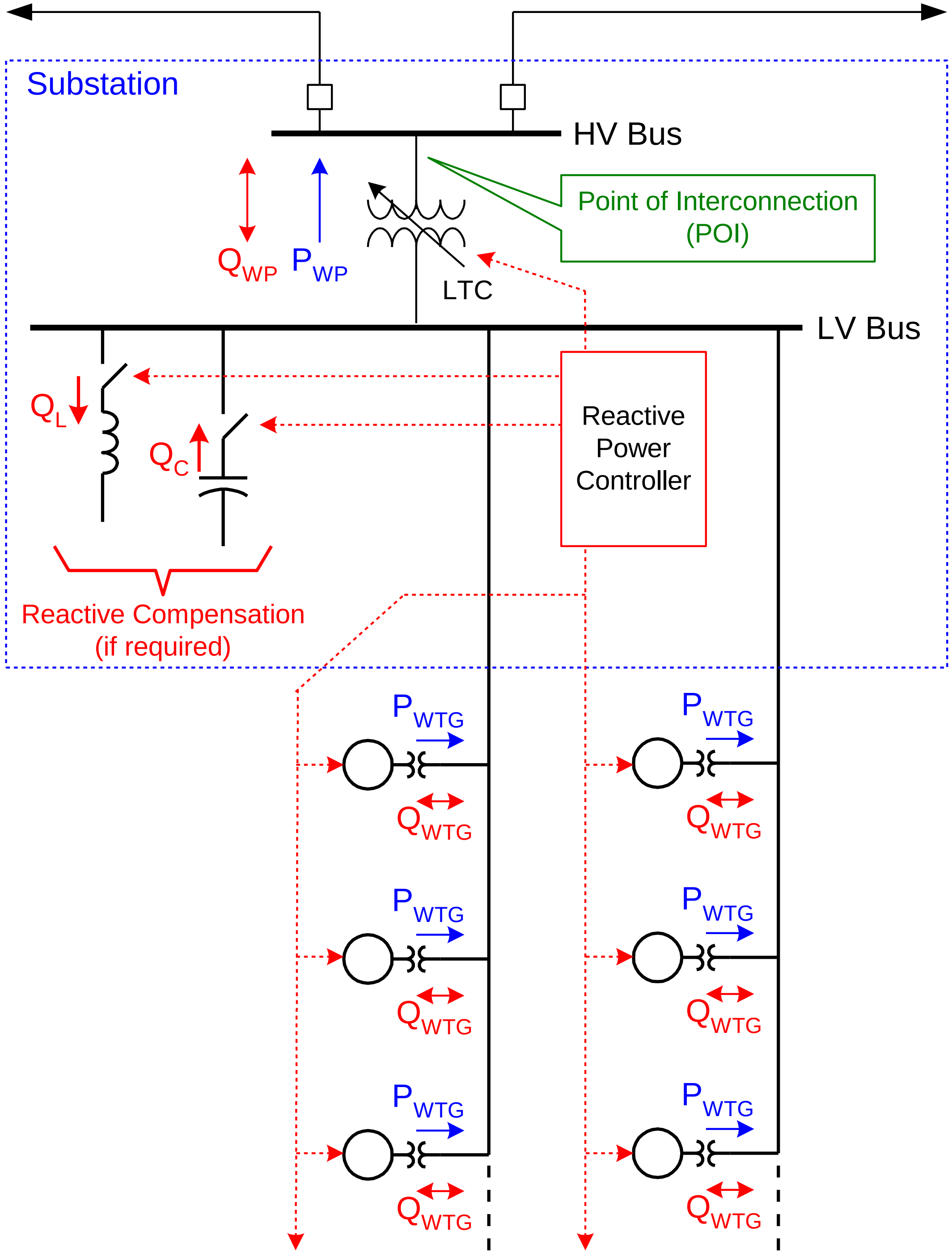




WindCONTROL

Plant Level Control System

- Coordinated turbine and plant supervisory control structure
- Voltage, VAR, & PF control
- PF requirements primarily met by WTG reactive capability, but augmented by mechanically switched shunt devices if necessary
- Combined plant response eliminates need for SVC, STATCOM, or other expensive equipment
- Integrated with substation SCADA



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Wind Plant vs. Wind Turbine Reactive Capabilities

Wind Plant pf capability ≠ wind turbine pf spec

Reactive Losses

- I^2X of unit transformer
- I^2X of collector lines and cables
- I^2X of substation transformer

- V^2B_L of shunt reactors
- Q_L of dynamic compensator

Reactive Gains

- V^2B_C of collector cables
- V^2B_C of harmonic filters

- V^2B_C of shunt cap banks
- Q_C of dynamic compensator

Extra compensation provided to make up the difference

- Switched caps and reactors all step-wise compensation
- Dynamic compensation needed for smooth control unless WTG has variable reactive capability

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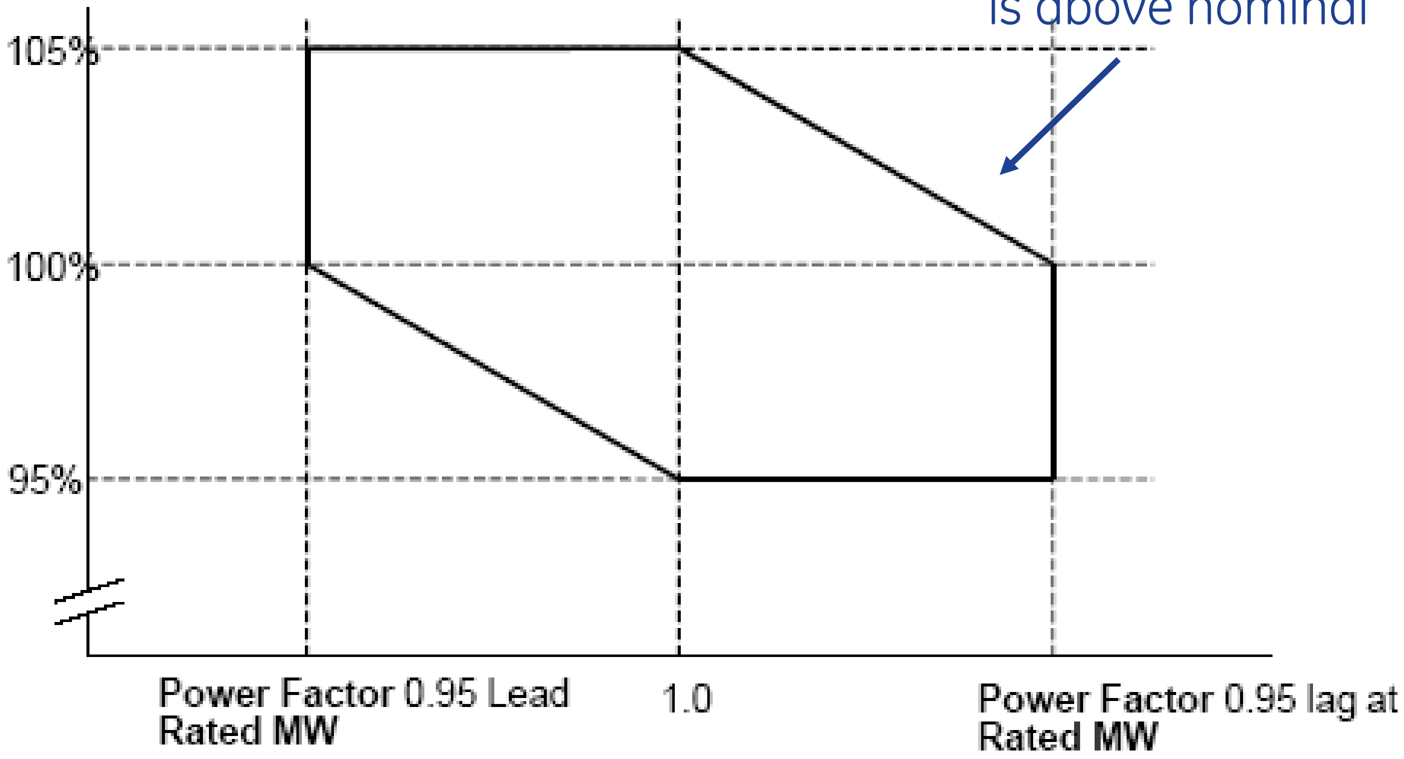
Voltage-Dependent Power Factor Spec

From UK grid code

Assumes less reactive power injection when grid voltage is above nominal



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System Strength

What is it?

- Usually measured in short circuit MVA
- $MVA_{sc} = kV_b^2/X_{sc} = 3^{½}kV_b kI_{sc}$

Why is it the single most important factor?

- Maximum short circuit (I.e. max kI_{sc} or min X_{sc}) dictates breaker duties, many equipment ratings (later lecture)
- Minimum short circuit (I.e. min kI_{sc} or max X_{sc}) dictates worst sensitivities, e.g. dV/dC, dV/dP, etc. (we'll look at this some more below)

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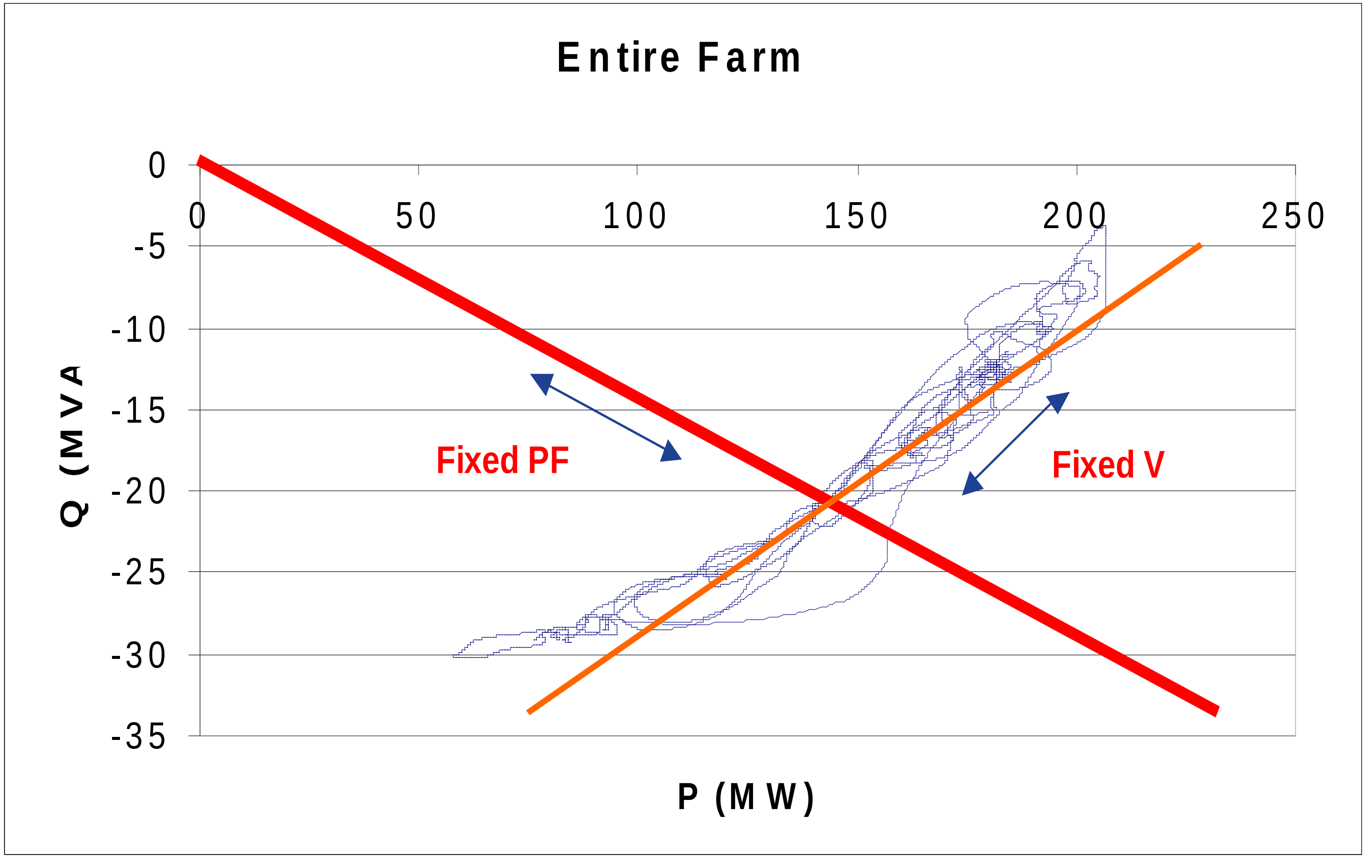
Wind Farm P, Q, V Relationship



Voltage Control Takes Advantage of Reactive Power Capability

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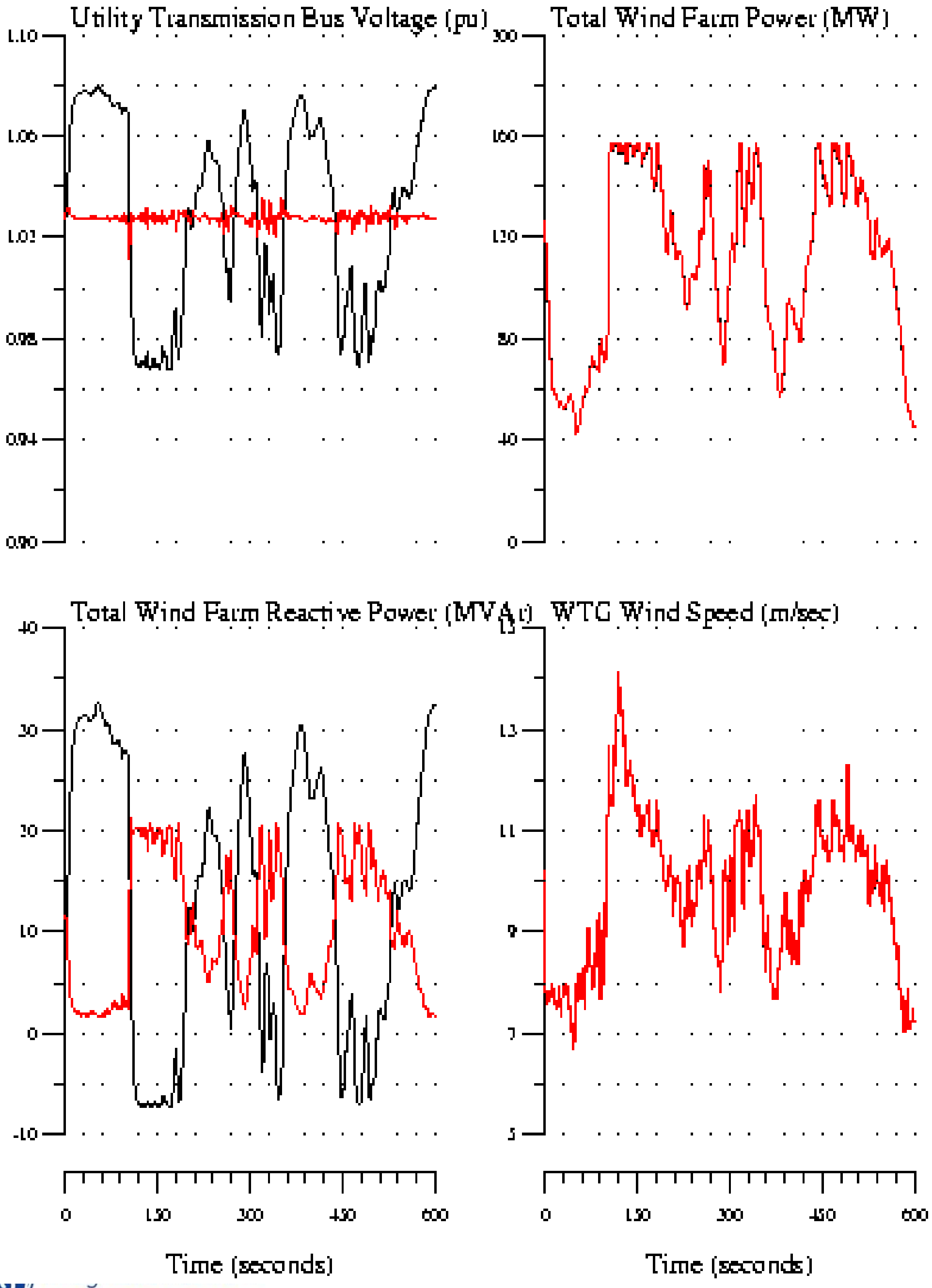
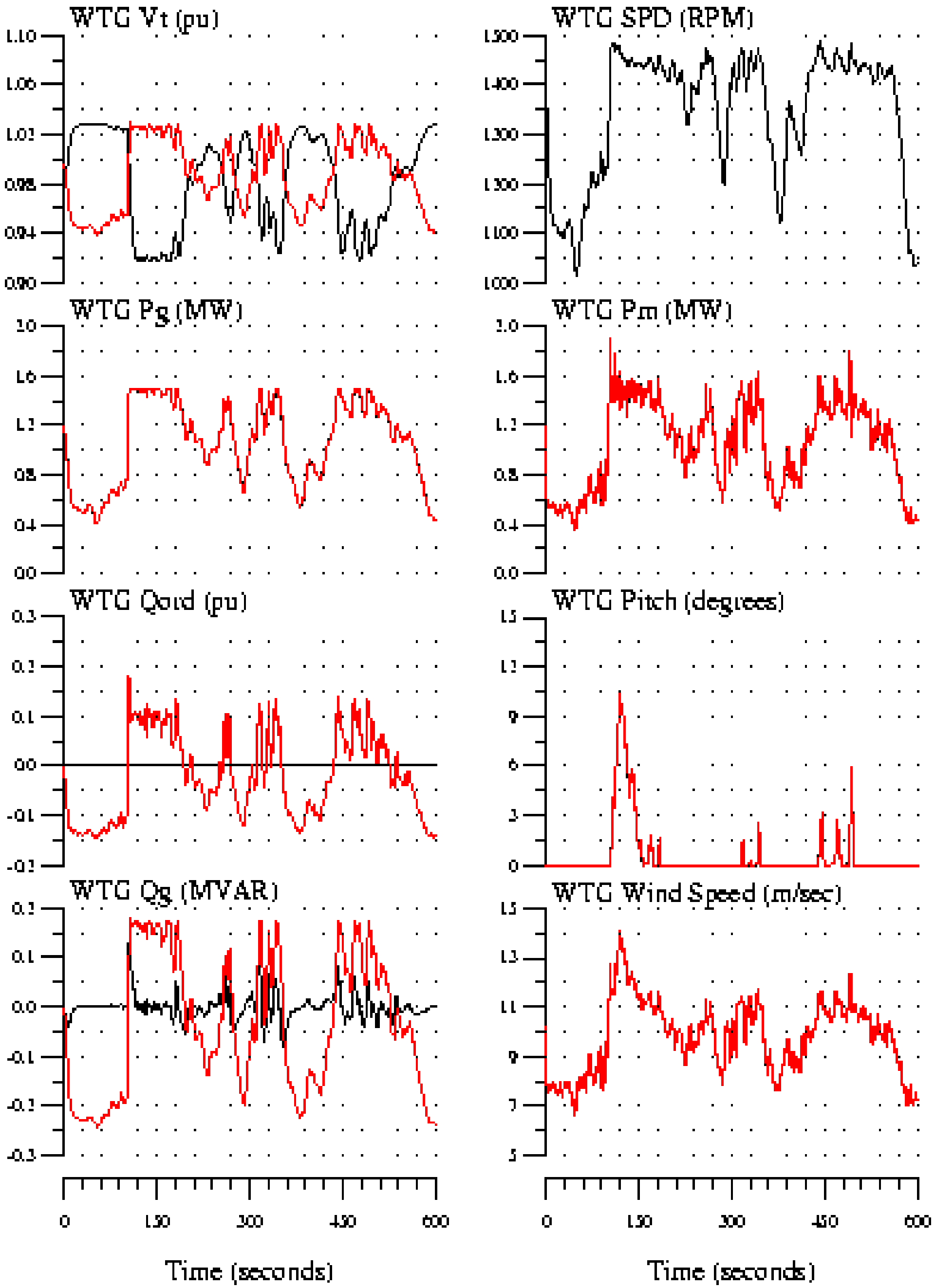
Voltage Regulation

- **System Response**
- **Voltage, P & Q Flows at POI**
- **Input Wind Speed**





Voltage Regulation

- **Individual WTG Response**
- **Selected Variables**

Wind Turbine Fault Tolerance

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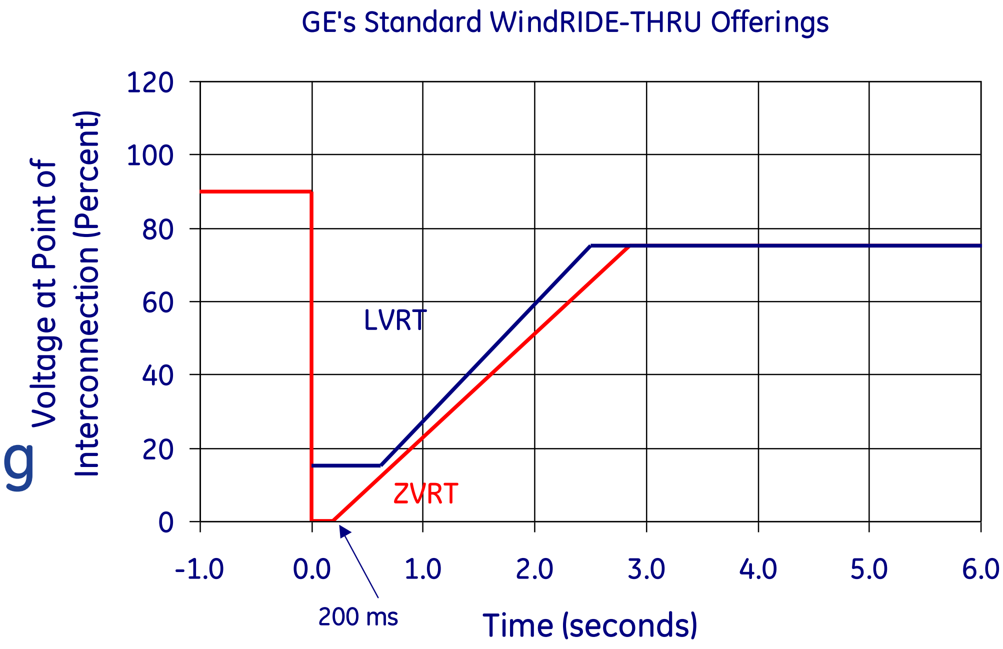
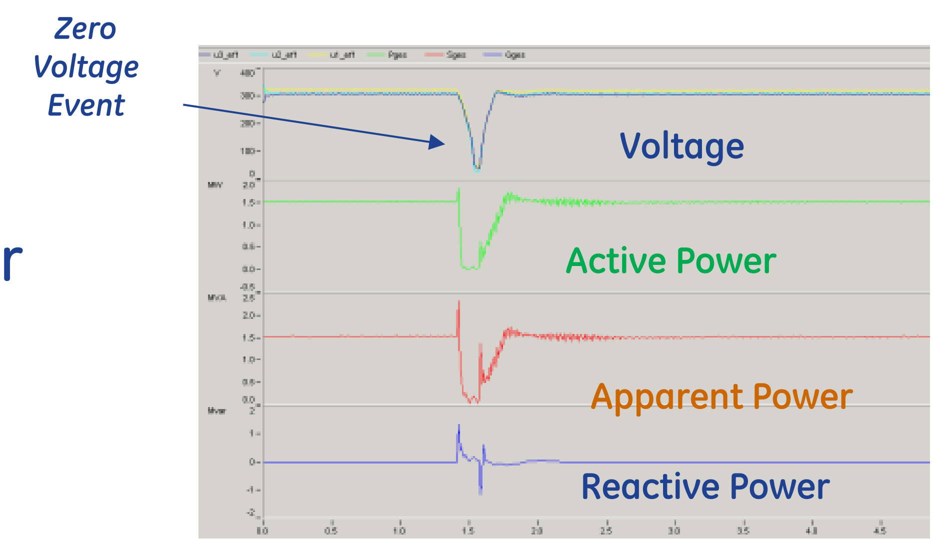
Ride-Thru Capabilities

- Remains on-line and feeds reactive power through system disturbances
- Meets present and emerging grid requirement with Low/Zero Voltage Ride Through (LVRT/ZVRT) capability
- Meets transmission reliability standards similar to thermal generators





FAULT RIDE-THROUGH

NERC PRC-024: Generator Frequency and Voltage Protective Relay Settings

Requirement 1: Frequency Ride-Through

- Each Generator Owner (GO) shall:
  - Set in service frequency protective relaying so that it does not operate to trip the generating unit during frequency excursions within the band described in Attachment 1
  - Conditions and exceptions:
    - Must operate between 59.5 and 60.5 Hz continuous
    - May trip if rate of change >2.5 Hz/sec (Aurora exclusion)

Requirement 2: Voltage Ride-Through

- Each Generator Owner (GO) shall:
  - Set in service voltage protective relaying so that it does not operate to trip the generating unit during voltage excursions within the specified band
  - Conditions and Exceptions:
    - Consider 3-phase Zone 1 faults with normal clearing
    - Site-specific clearing time may be used
    - Generator tripping for SPS, RAS or to clear the fault allowed

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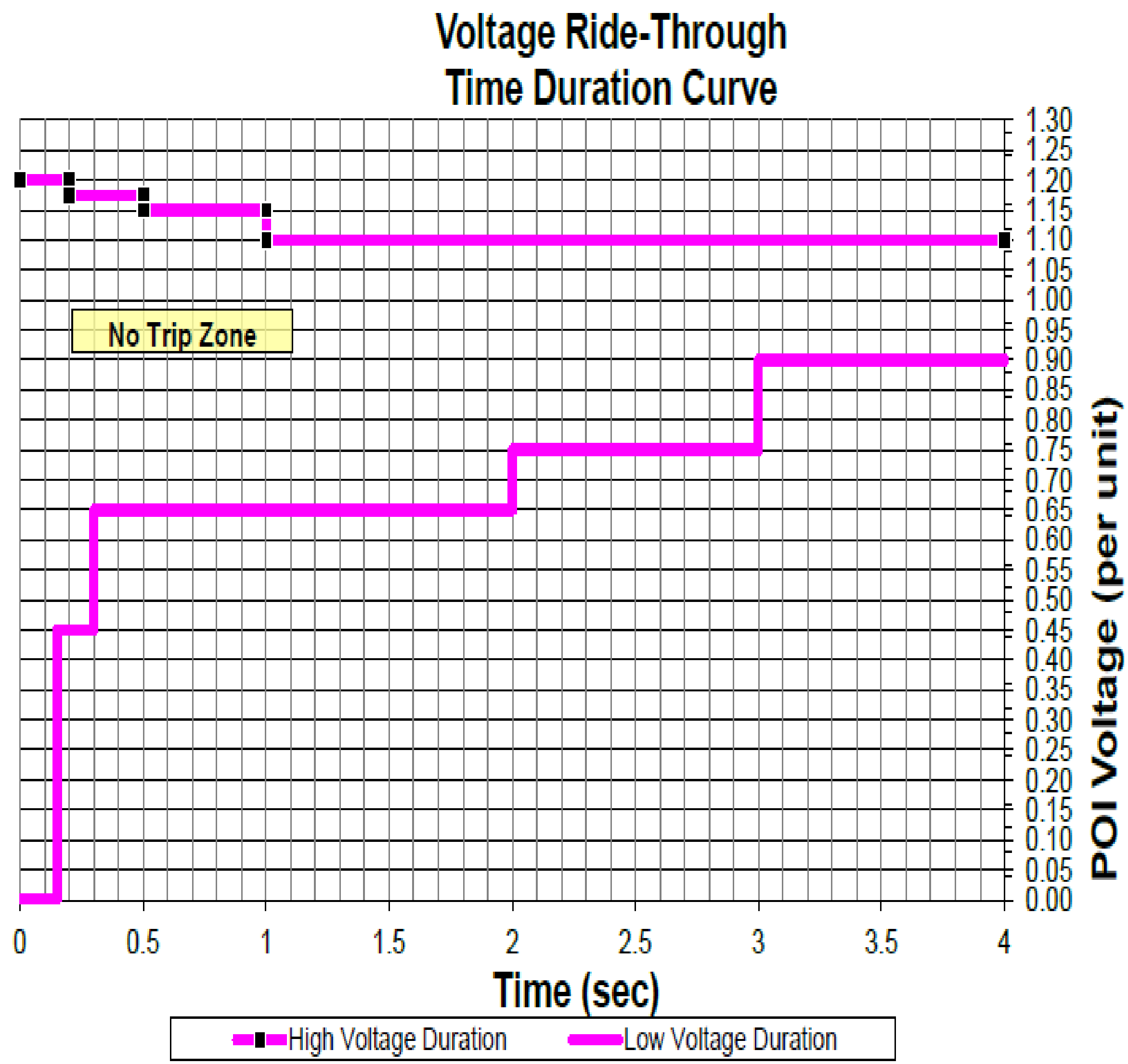
NERC PRC-024: Voltage Ride-Through

HVRT DURATION		LVRT DURATION	
Time (Sec)	Voltage (p.u.)	Time (Sec)	Voltage (p.u.)
Instantaneous	1.20	Instantaneous	0.00
0.20	1.175	0.15	0.45
0.5	1.15	0.30	0.65
1.0	1.10	2.0	0.75
		3.0	0.9



Generators / Plant must not trip for credible faults inside the zone unless:

- SPS / RAS requires it
- Generator critical clearing time requires it (synchronous generators)

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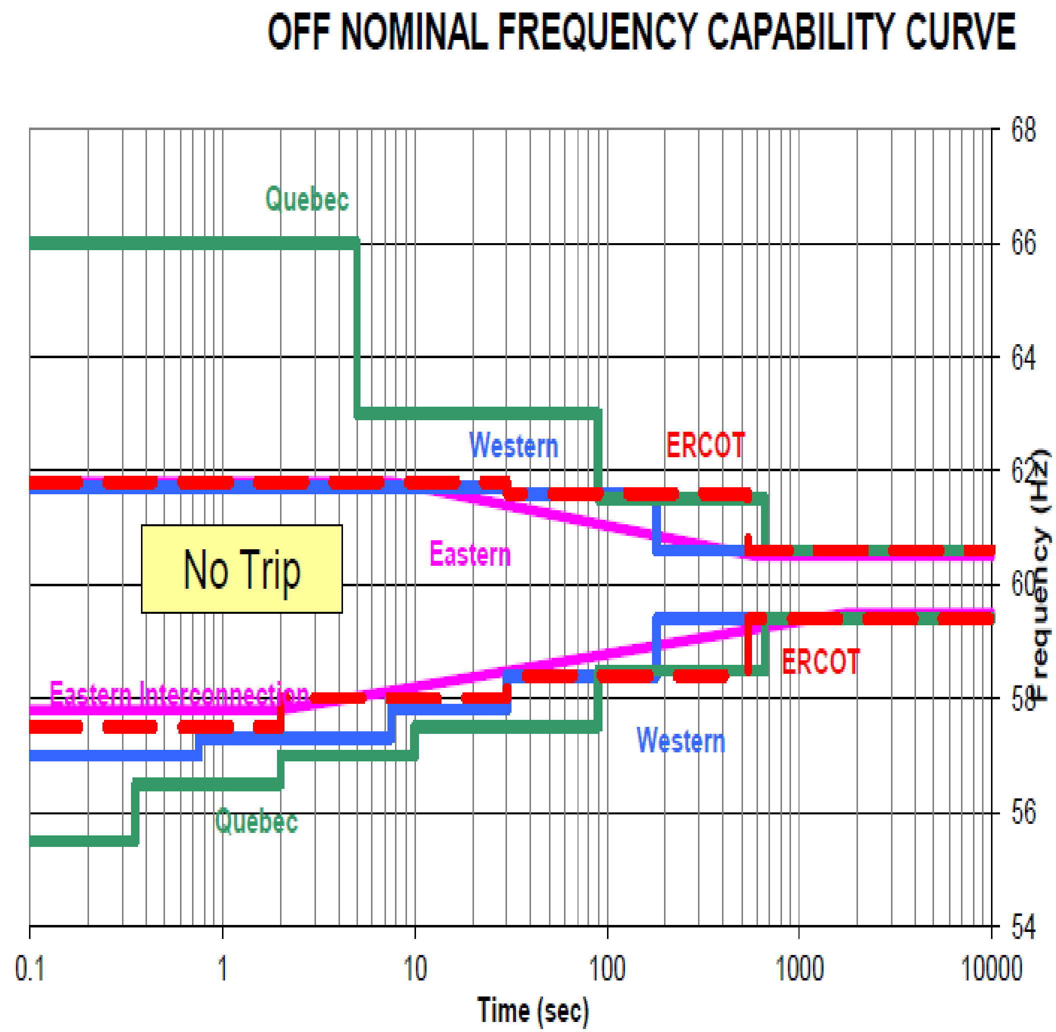
NERC PRC-024: Frequency Ride-Through

QUEBEC			
High Frequency		Low Frequency	
Time (Sec)	Frequency (Hz)	Time (Sec)	Frequency (Hz)
0 - 5	66	0 – 0.35	55.5
5 -90	63	0.35 - 2	56.5
90 - 660	61.5	2 - 10	57
> 660	60.6	10 - 90	57.5
		90 - 660	58.5
		> 660	59.4

WECC			
High Frequency		Low Frequency	
Time (Sec)	Frequency (Hz)	Time (Sec)	Frequency (Hz)
0 – 30	61.7	0 – 0.75	57
30 – 180	61.6	7.5 - 30	57.3
>180	60.6	7.5 - 30	57.8
		30 - 180	58.4
		>180	59.4

ERCOT			
High Frequency		Low Frequency	
Time (Sec)	Frequency (Hz)	Time (Sec)	Frequency (Hz)
0 - 30	61.8	0 – 2	57.5
30 - 540	61.6	2 - 30	58
>540	60.6	30-540	58.4
		>540	59.4

EASTERN INTERCONNECTION			
High Frequency		Low Frequency	
Time (Sec)	Freq. (Hz)	Time (Sec)	Freq. (Hz)
0 – $10^{(90.935-1.45713*f)}$	61.8	0 – $10^{(1.7373*f-100.116)}$	57.8
$10^{(90.935-1.45713*f)}$ - Continuous	60.5	$10^{(1.7373*f-100.116)}$ - Continuous	59.5
Continuous	60.5	Continuous	59.5



Transient Stability

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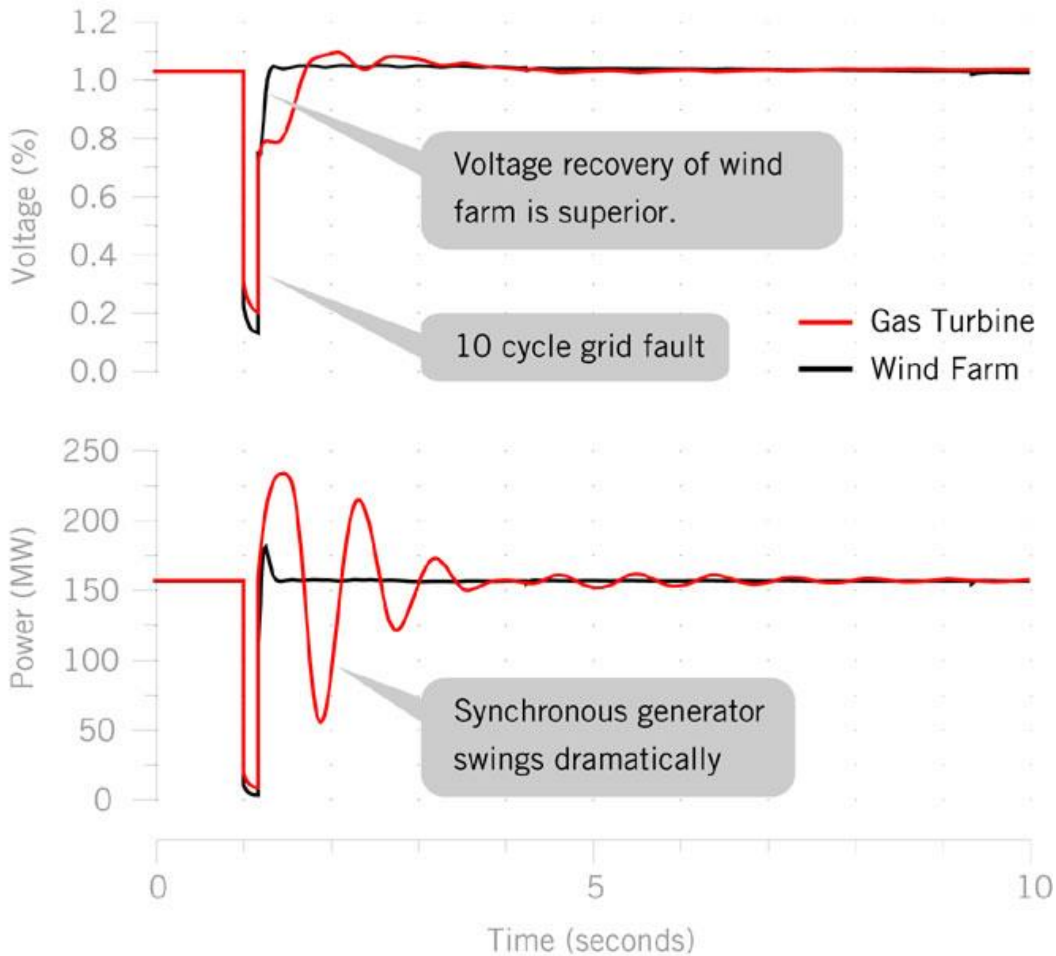
Transient Stability

DFAG wind farms are more stable than conventional synchronous generators.



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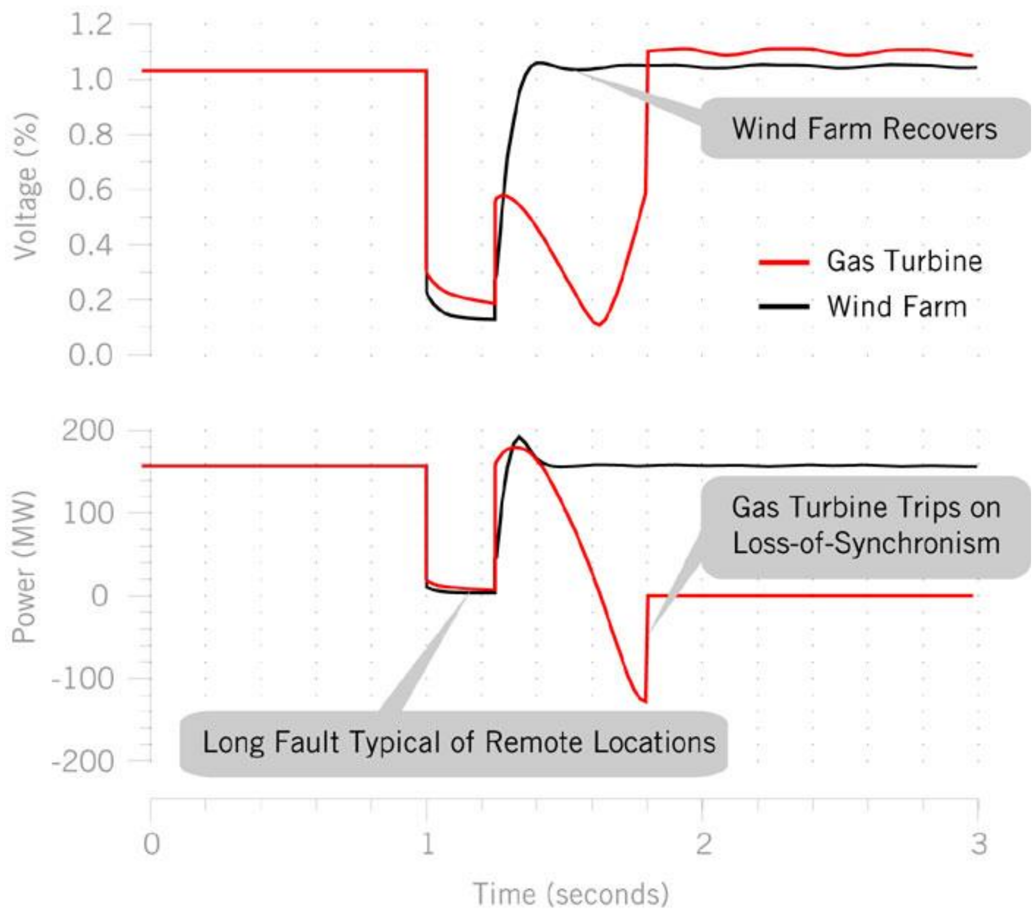
Transient Stability

In fact, wind farms will survive some disturbances that trip conventional synchronous generators.



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Plant reactive coordination problems and solutions

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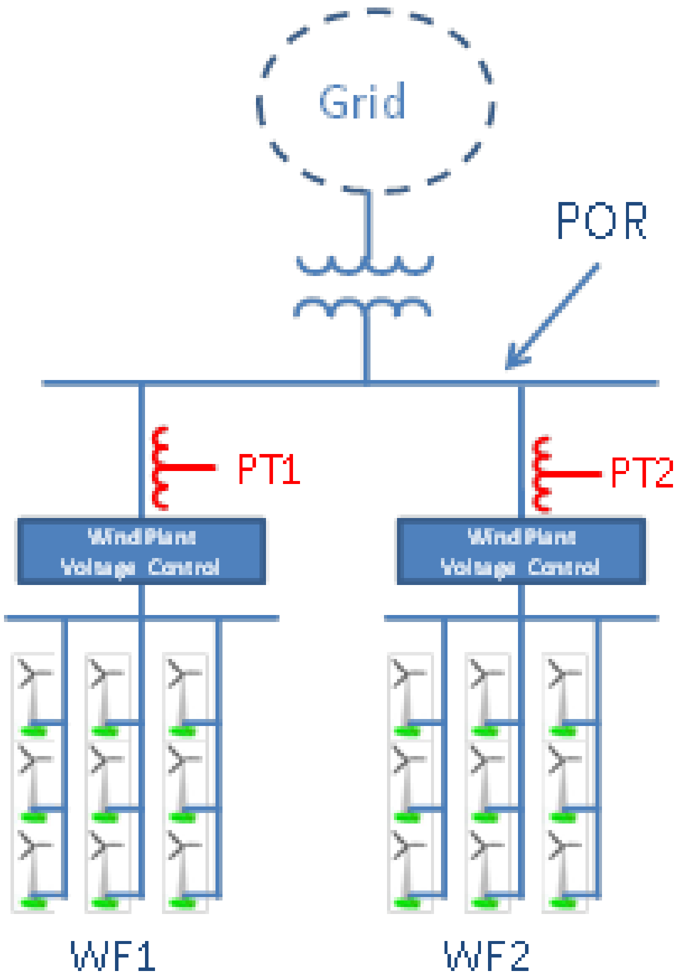
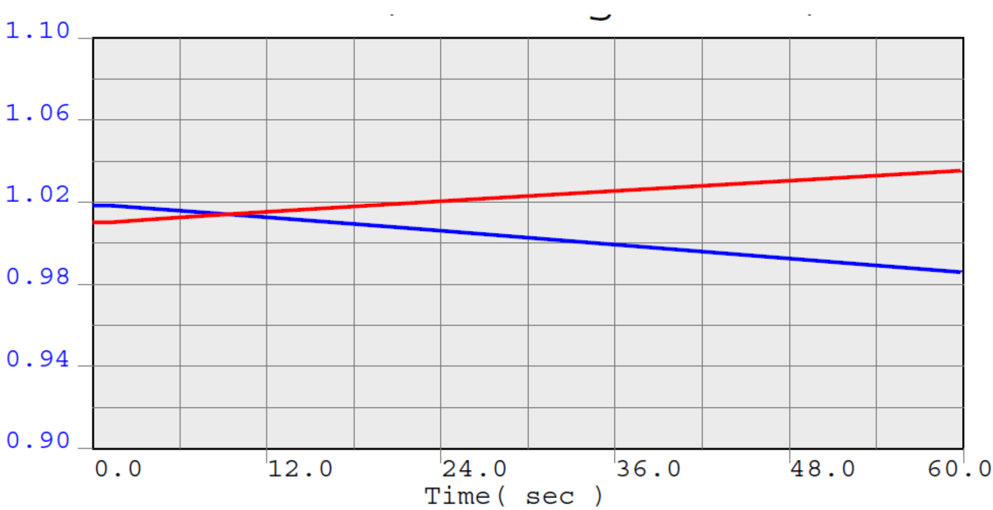
WTG terminal Voltage with Uncoordinated PI regulators with PT error





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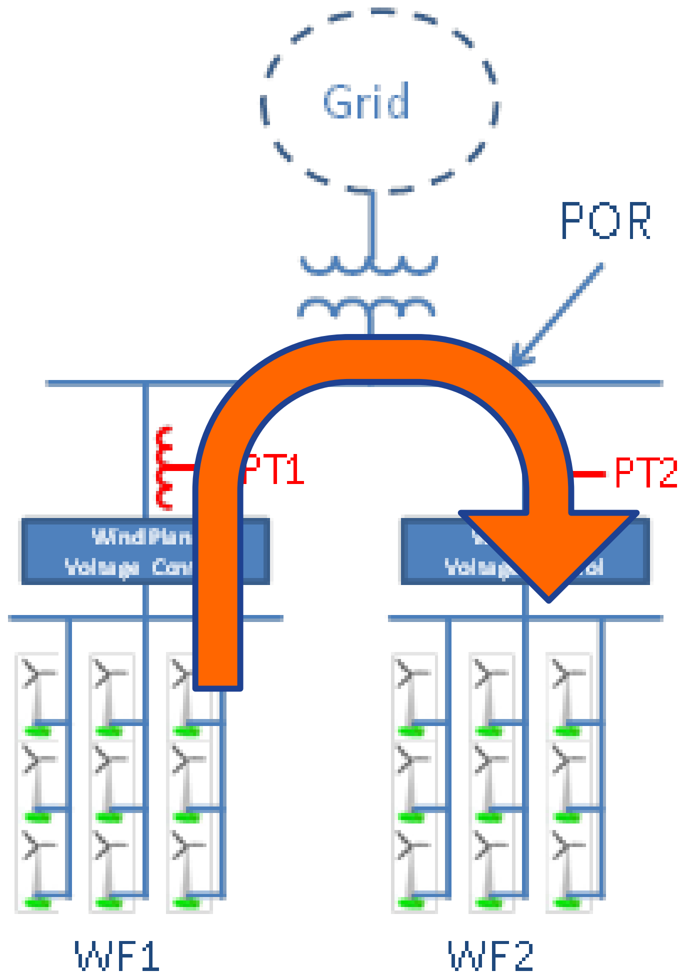
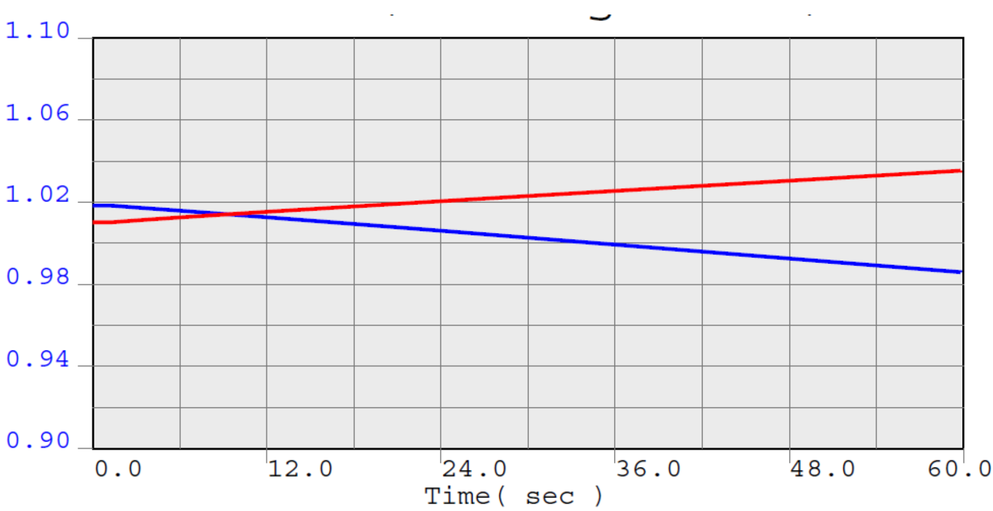
WTG terminal Voltage with Uncoordinated PI regulators with PT error





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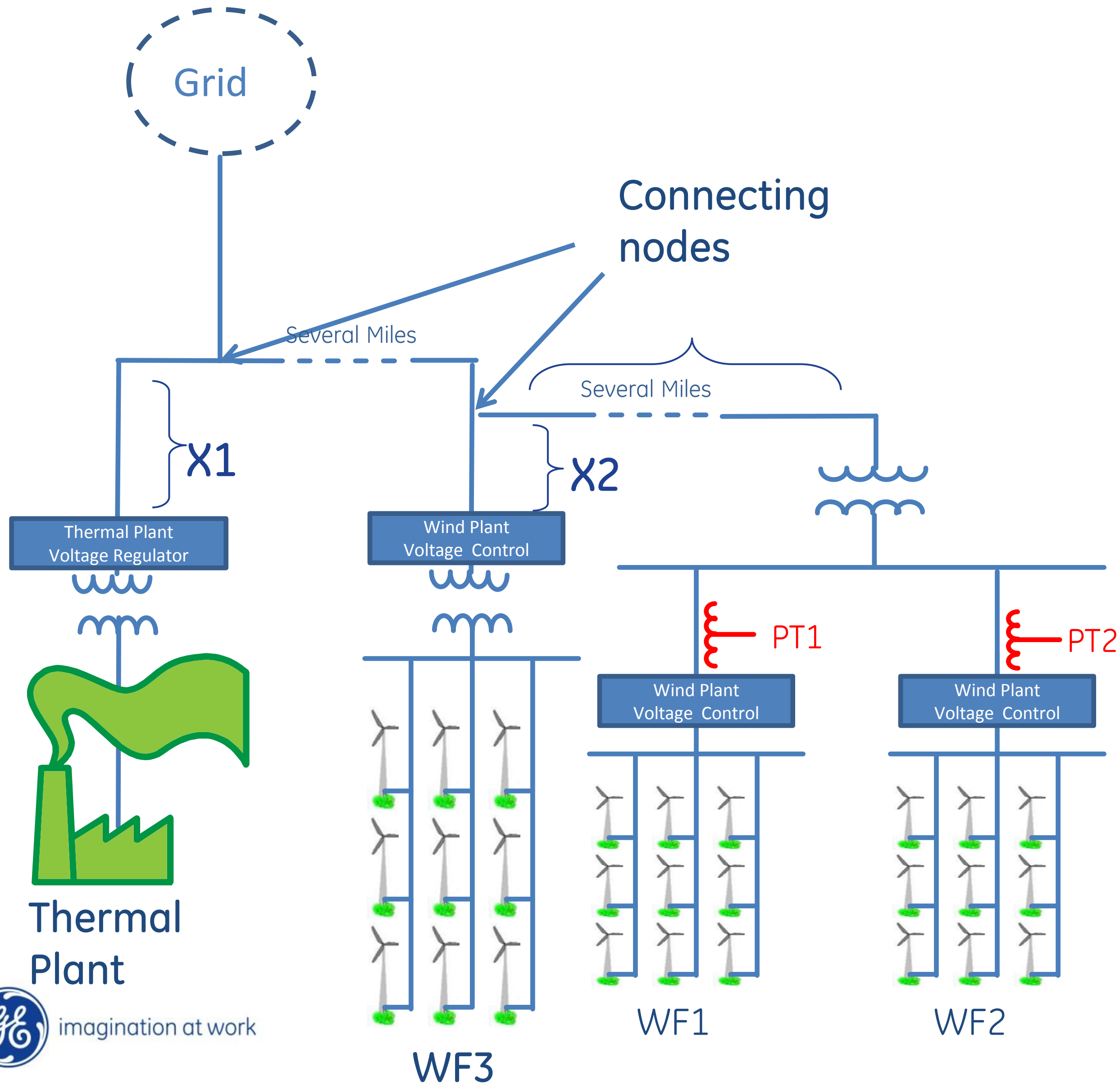
Multi-Plant Topology is Complex



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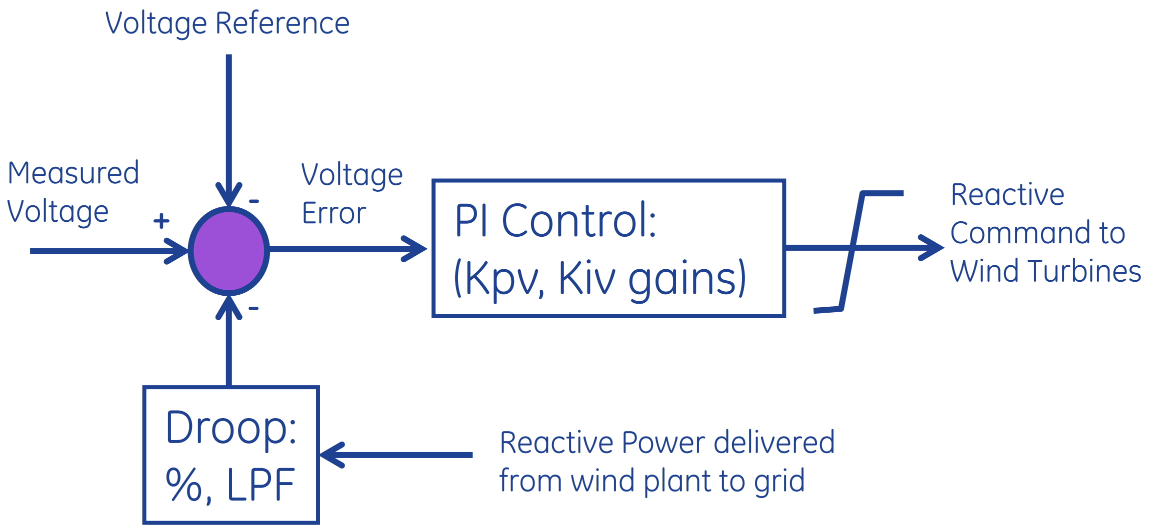
Volt/Var Control (simplified block diagram)



Study results demonstrating voltage droop

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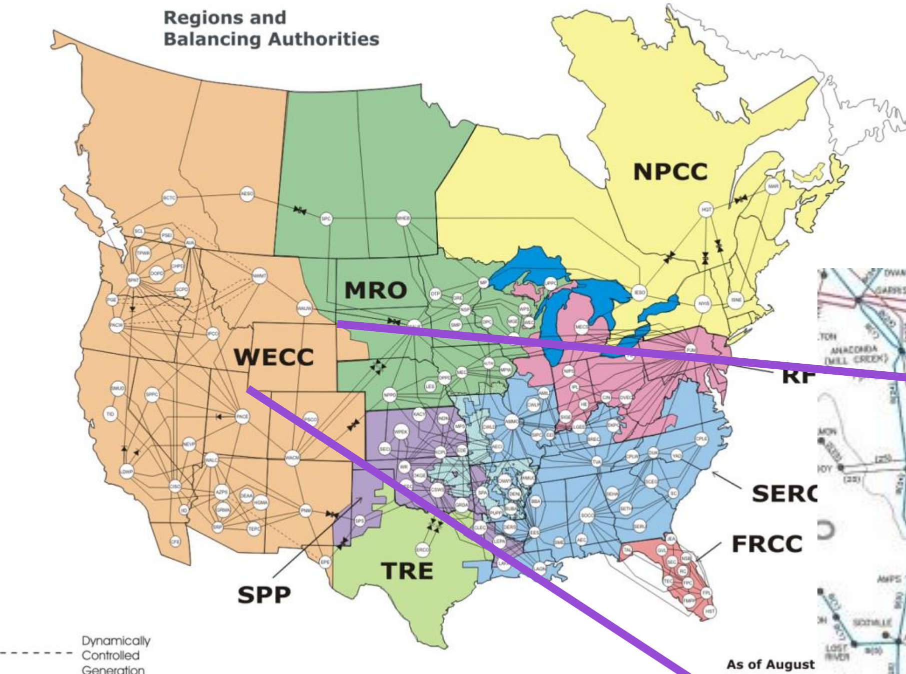
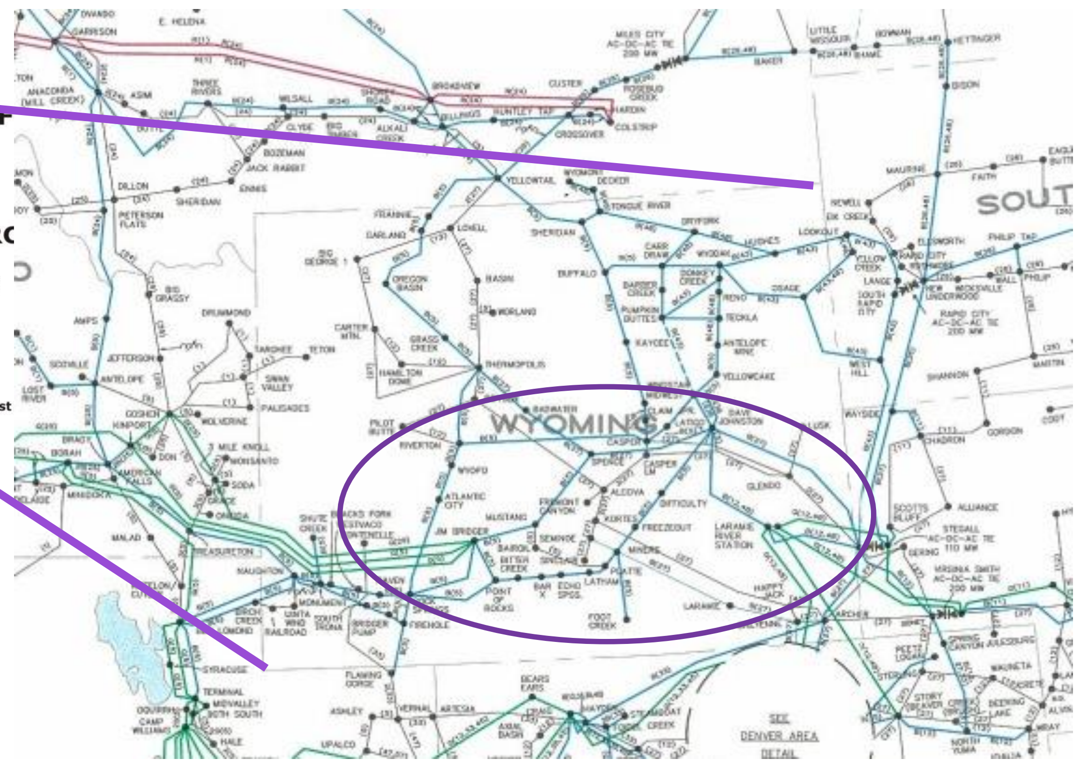
Where are we?

Six Wind Plants in a region with relatively little load and a couple large thermal plants that normally anchor system voltage. Local penetration is high. Voltage management is significant challenge.





20% change in power from Wind causes ~4% dV at 230kV

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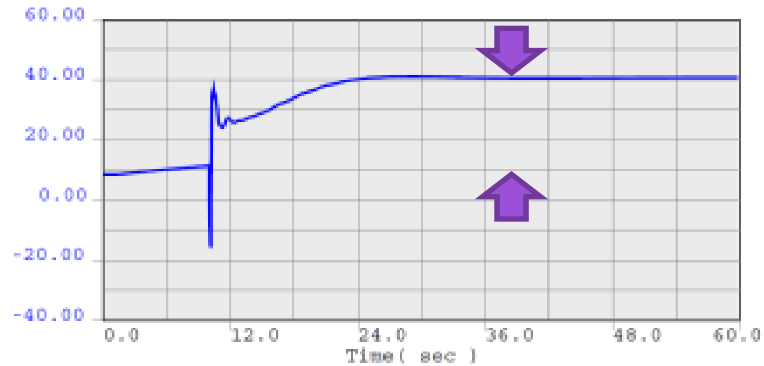
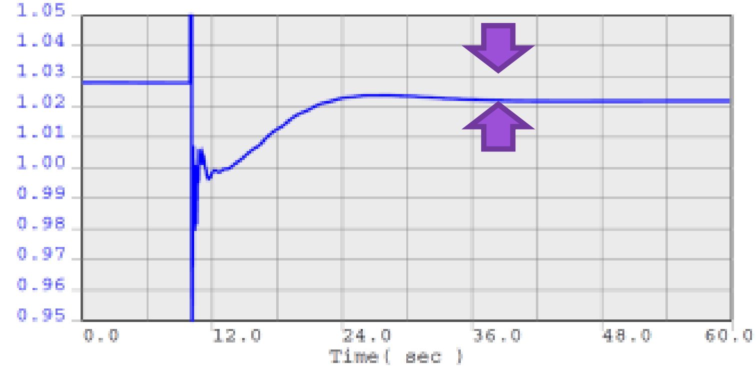
Response of One Plant to a major line outage

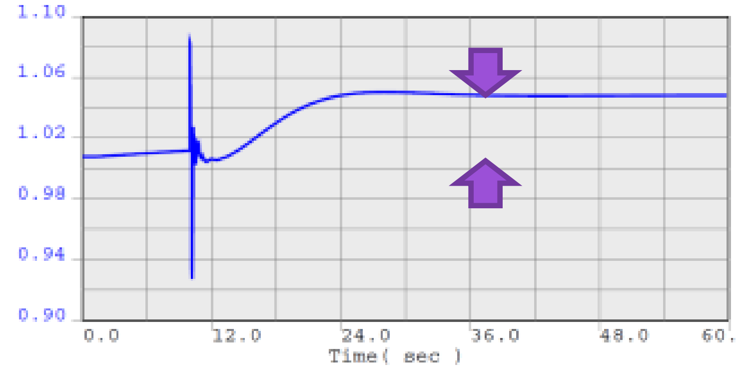
Reactive Power Output



Point-of-regulation Voltage



Terminal Voltage Behavior



Wind Plant Droops Field and Tuned Gains

Wind Plant	Droop % (on plant MVAr base)	Proportional Gain	Integral Gain
Plant 1	5	6.0	1.5
Plants 2	1.3	1.5	0.5
Plants 3	1.3	3.5	0.83
Plant 4	2.0	0.18	0.09
Plant 5	1.3	1.5	0.5
Plant 6	1.5	0.4	0.2

Field test results

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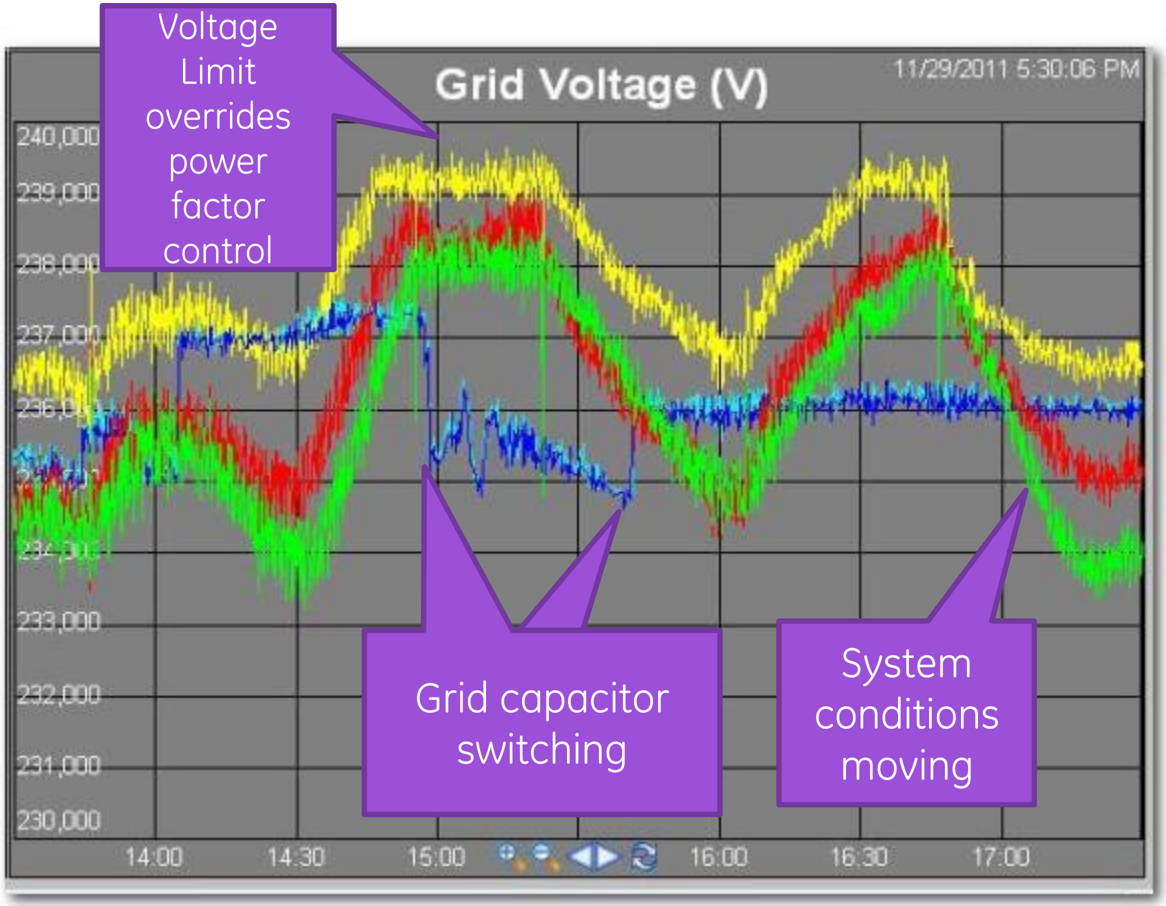
Voltage Behavior – 5 Uncoordinated Wind Plants



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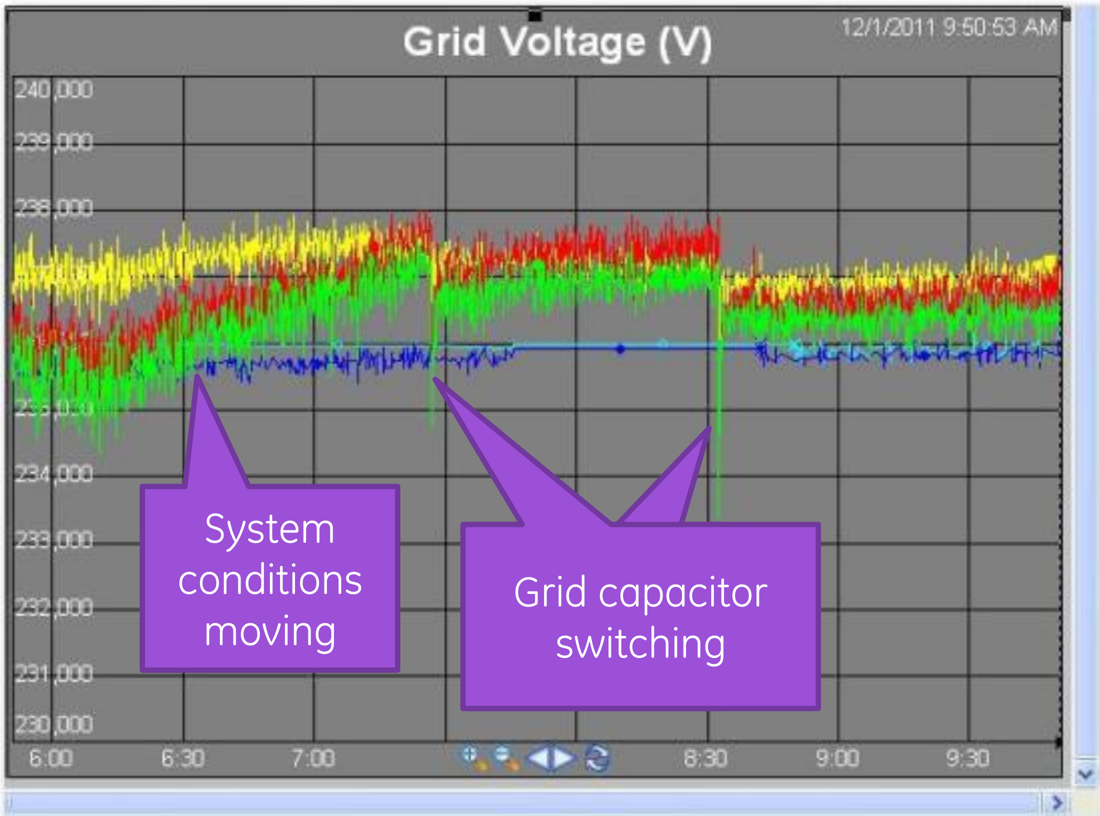
Voltage Behavior – 5 Coordinated Wind Plants



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Thank You

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