American Superconductor®

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"Renewable Energy – Connecting Wind Farms to the Grid"

IEEE PES – Milwaukee Chapter Meeting

April, 2008

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Discussion Topics

- Wind Farm Basics
- Grid Integration Issues
- Interconnection Standards
- Wind Farm Modeling
- Wind Farm Integration Analysis
- Integration of Wind into the Grid using Dynamic Reactive Compensation (D-VAR®)

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Global Wind Generation: Capacity (YE 2006)

GWEC
GLOBAL WIND ENERGY COUNCIL

• Germany	20,622 MW	27.8%
• Spain	11,615 MW	15.6%
• USA	11,603 MW	15.6%
• India	6,207 MW	8.4%
• Denmark	3,136 MW	4.2%
• China	2,604 MW	3.5%
• Italy	2,123 MW	2.9%
• UK	1,963 MW	2.6%
• Rest of world	14,288 MW	19.2%
Global Total	74,223 MW	

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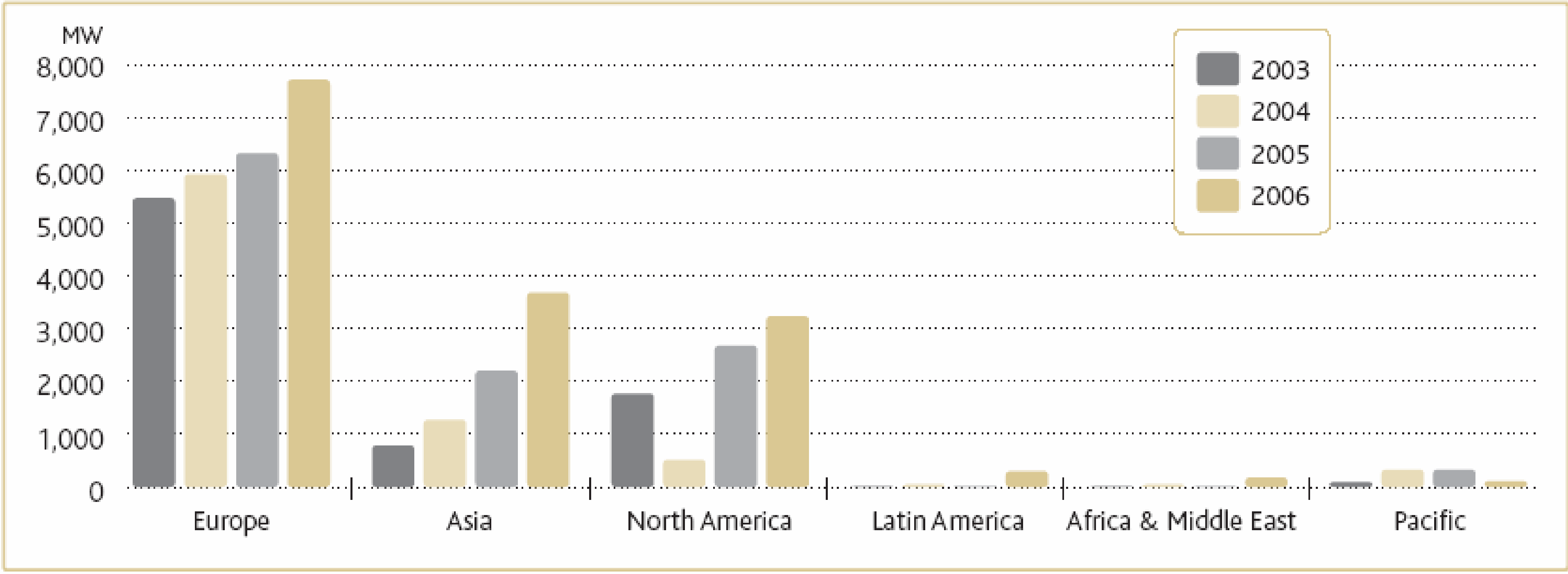
Global Wind Generation: New Capacity (YE 2006)

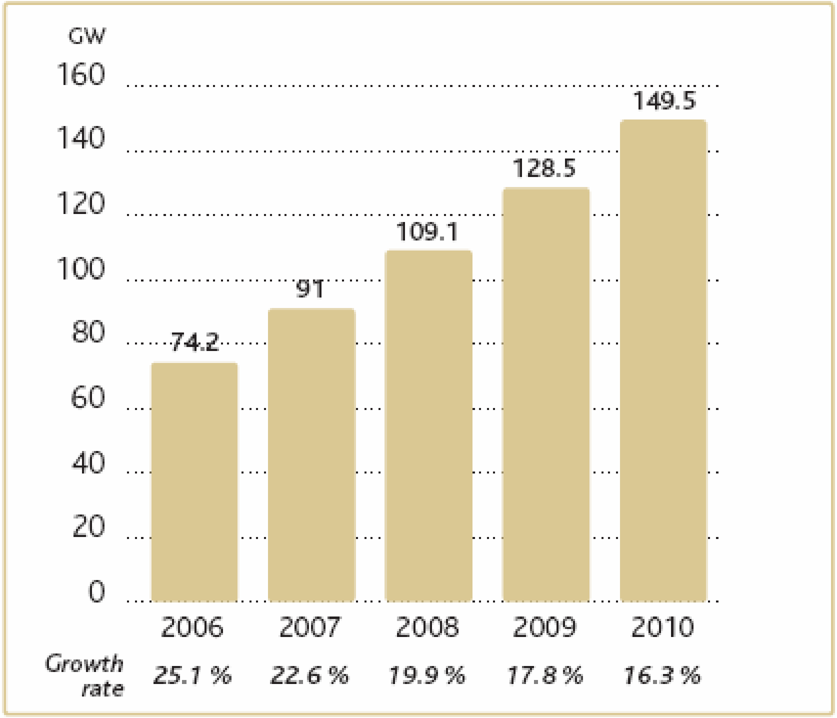
• USA	2,454 MW	16.1%
• Germany	2,233 MW	14.7%
• India	1,840 MW	12.1%
• Spain	1,587 MW	10.4%
• China	1,347 MW	8.9%
• France	810 MW	5.3%
• Canada	776 MW	5.1%
• Portugal	694 MW	4.6%
• Rest of world	3,456 MW	22.7%
Global Total	15,197 MW	

Capacity by Region (YE 2006)

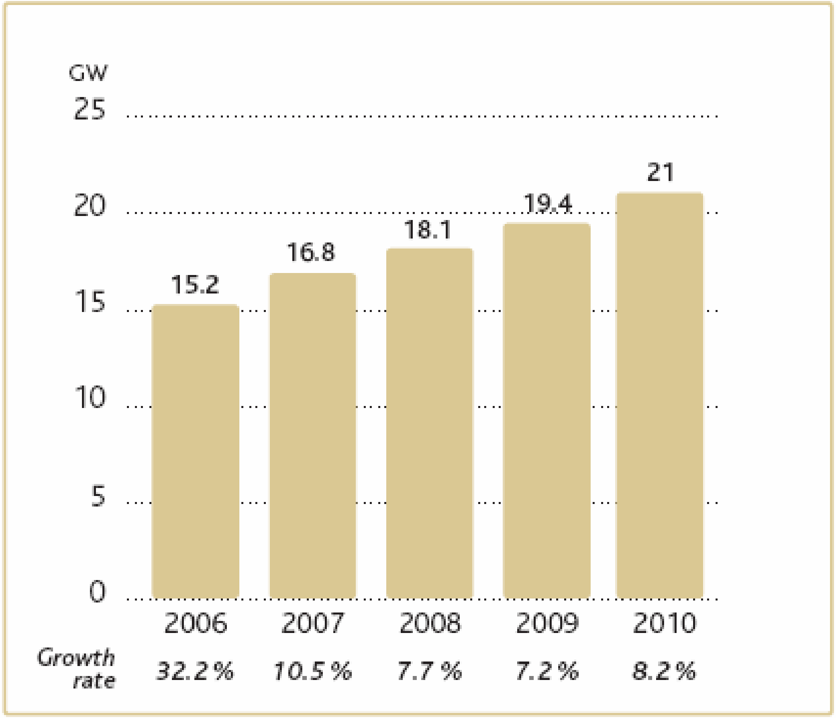


Global Forecast 2006-2010

Cumulative Capacity



Annual Growth

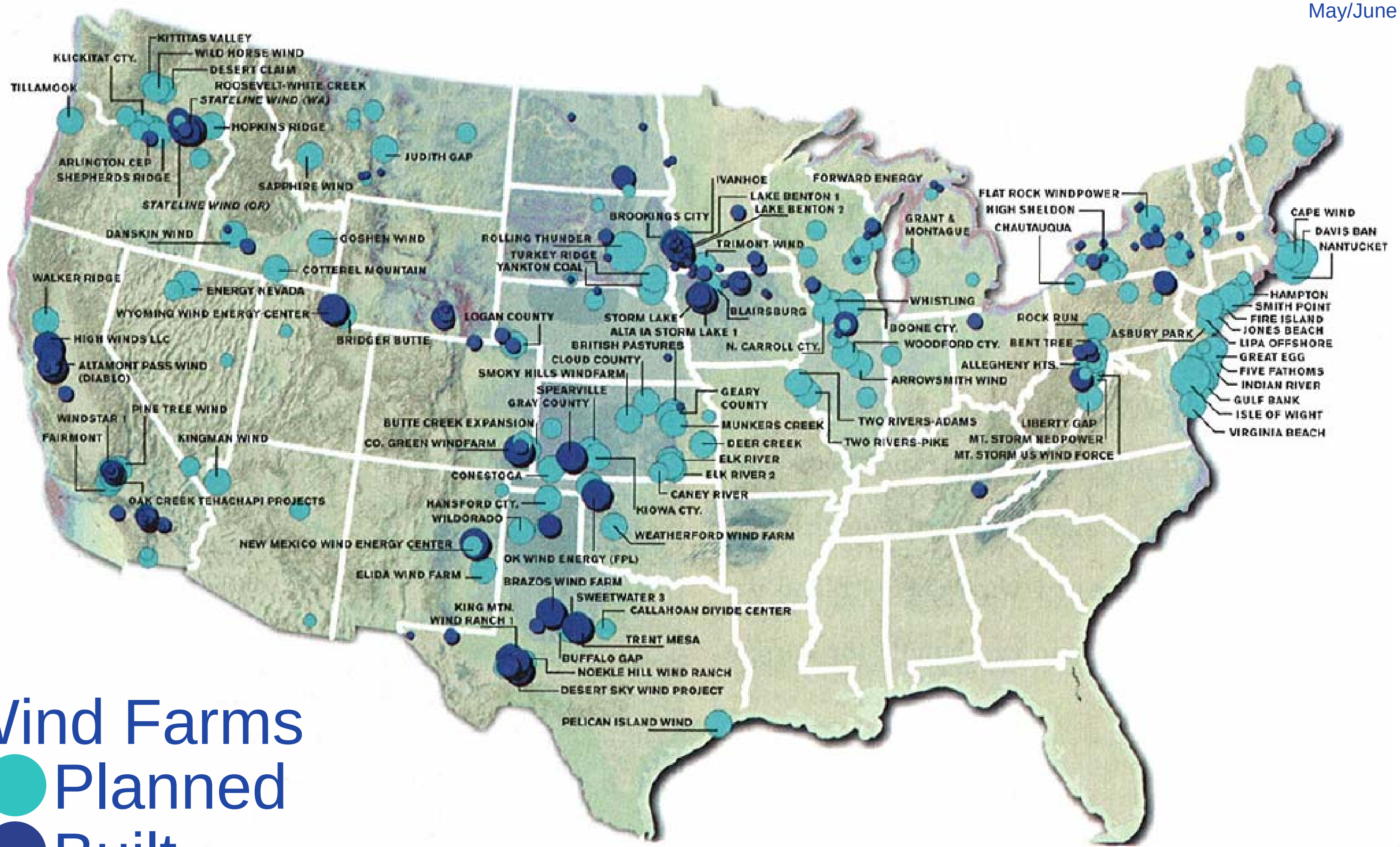


Global Wind Turbine Sales Leaders

	2004	2005
• Vestas	32%	27%
• GE	12%	17%
• Enercon	16%	13%
• Gamesa	10%	10%
• Suzlon	3%	6%

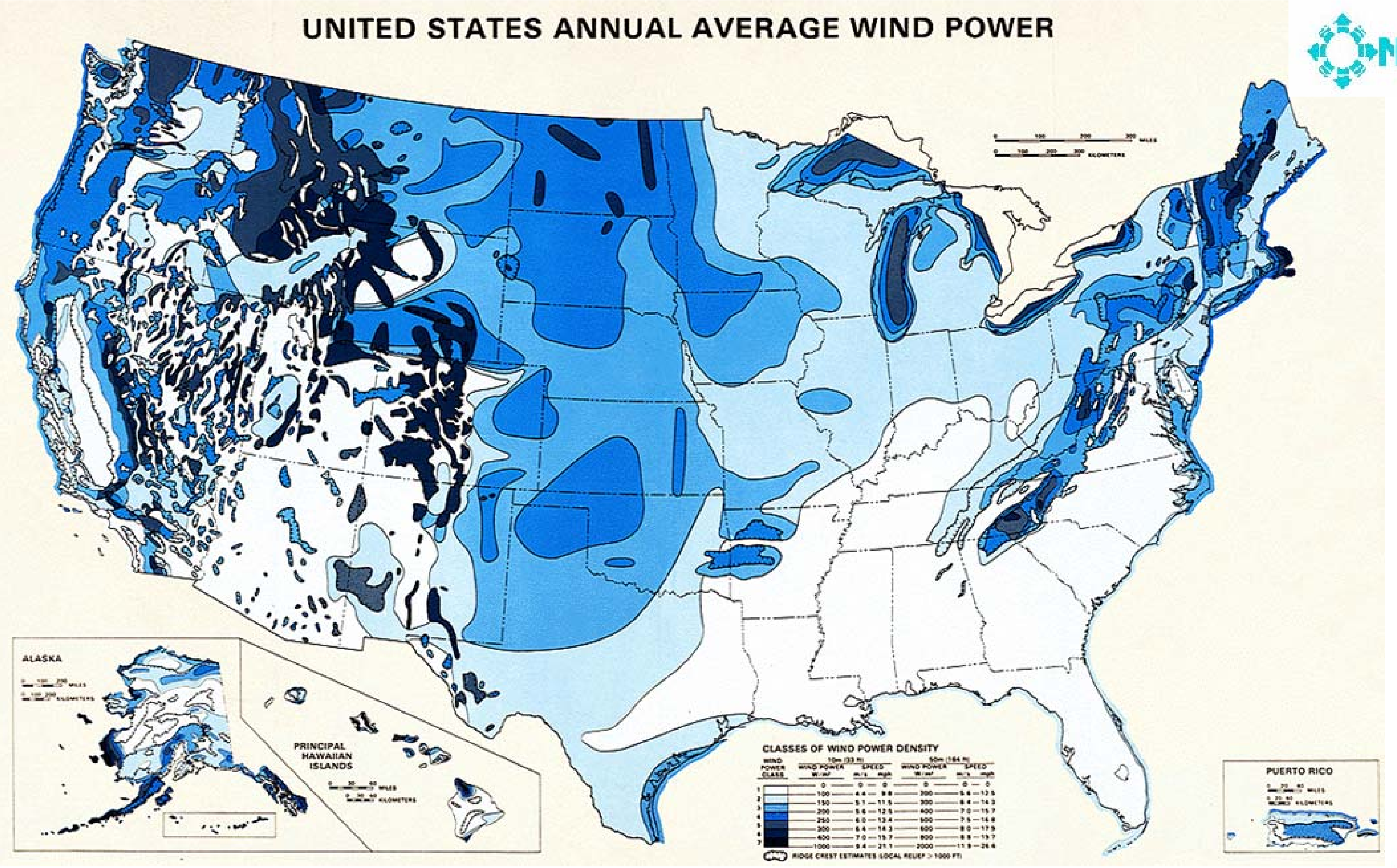
Wind Farms Across the USA

From energybiz™ Magazine
Catching the Wind
May/June 2005



Wind Farms
- Planned
- Built

USA Annual Average Wind Power



Wisconsin State Journal – 04/04/08

Put wind turbines offshore?

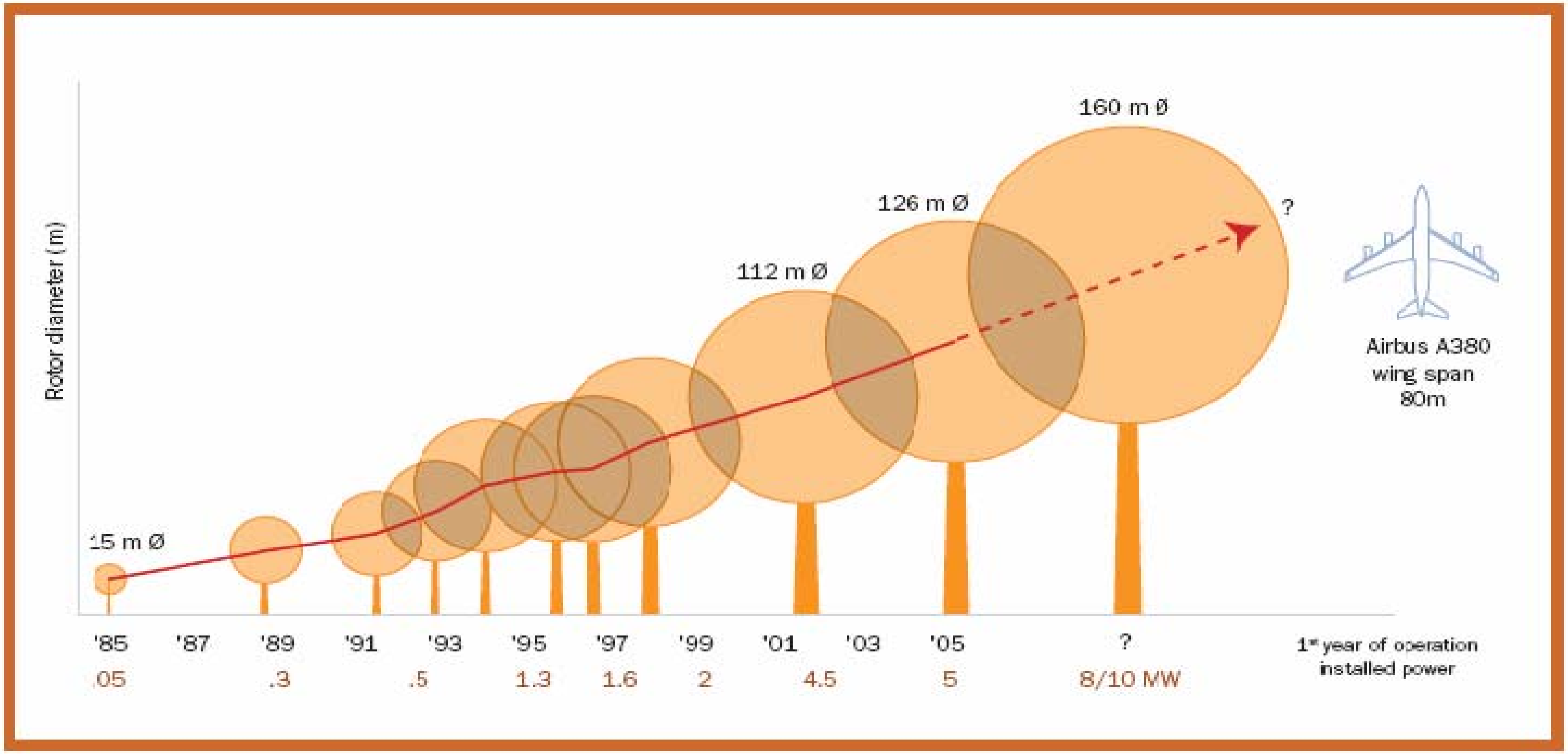
By TODD RICHMOND
Associated Press

State regulators want to study what it would take to put giant wind turbines in Lake Michigan and Lake Superior, a move that might someday lead to new power for Wisconsin but cost millions of dollars and transform serene lake views.

Wind Generator Sizes

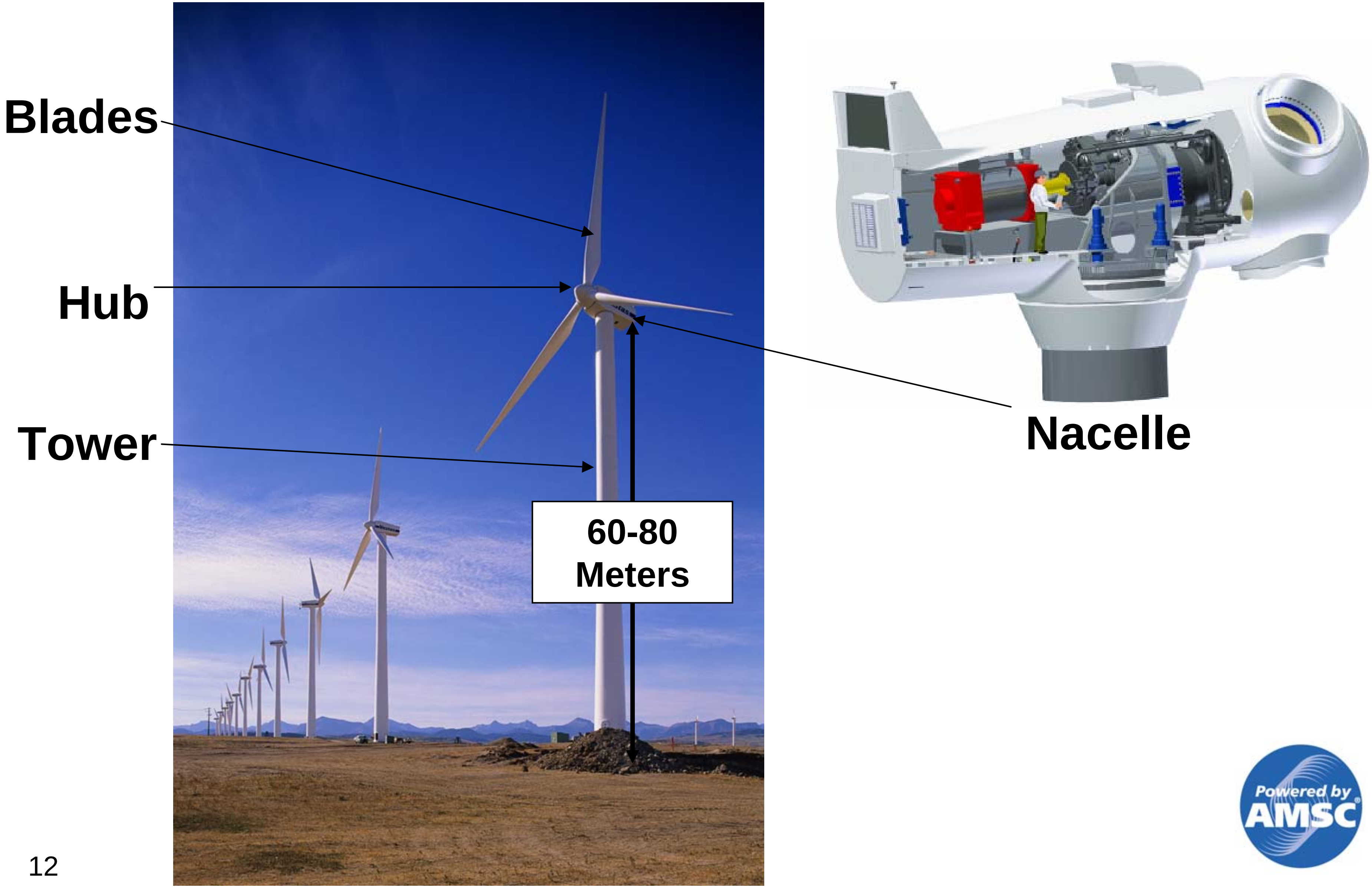
Figure 3.5

The size of wind turbines at market introduction. Mid 2005 the largest wind turbine had a diameter of 126 metres and an installed power of 5 MW.



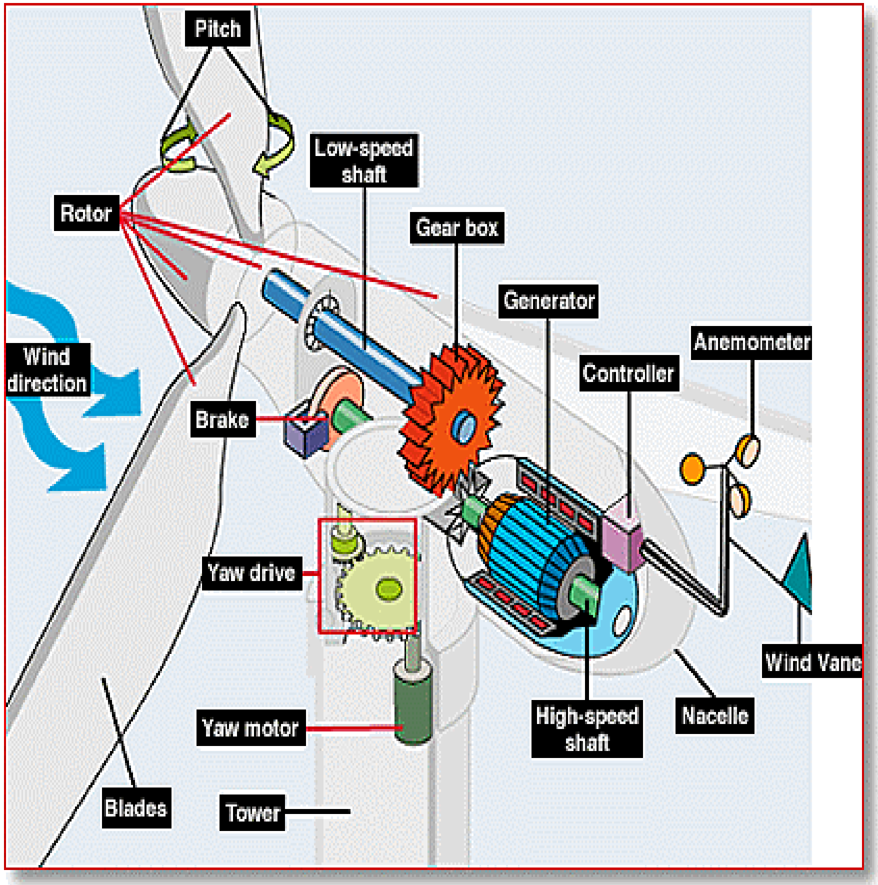
Source: Jos Beurskens, ECN

Typical Wind Turbine



Wind Turbine Overview

- Wind turbines use wind to make electricity.
- The wind turns the blades, which spin a shaft, which connects to an induction generator and makes electricity.
- Active wind turbine controls (blade pitch, turbine yaw) maximize the generation output while providing power factor (or voltage) control.



U.S. Department of Energy
Energy Efficiency and Renewable Energy

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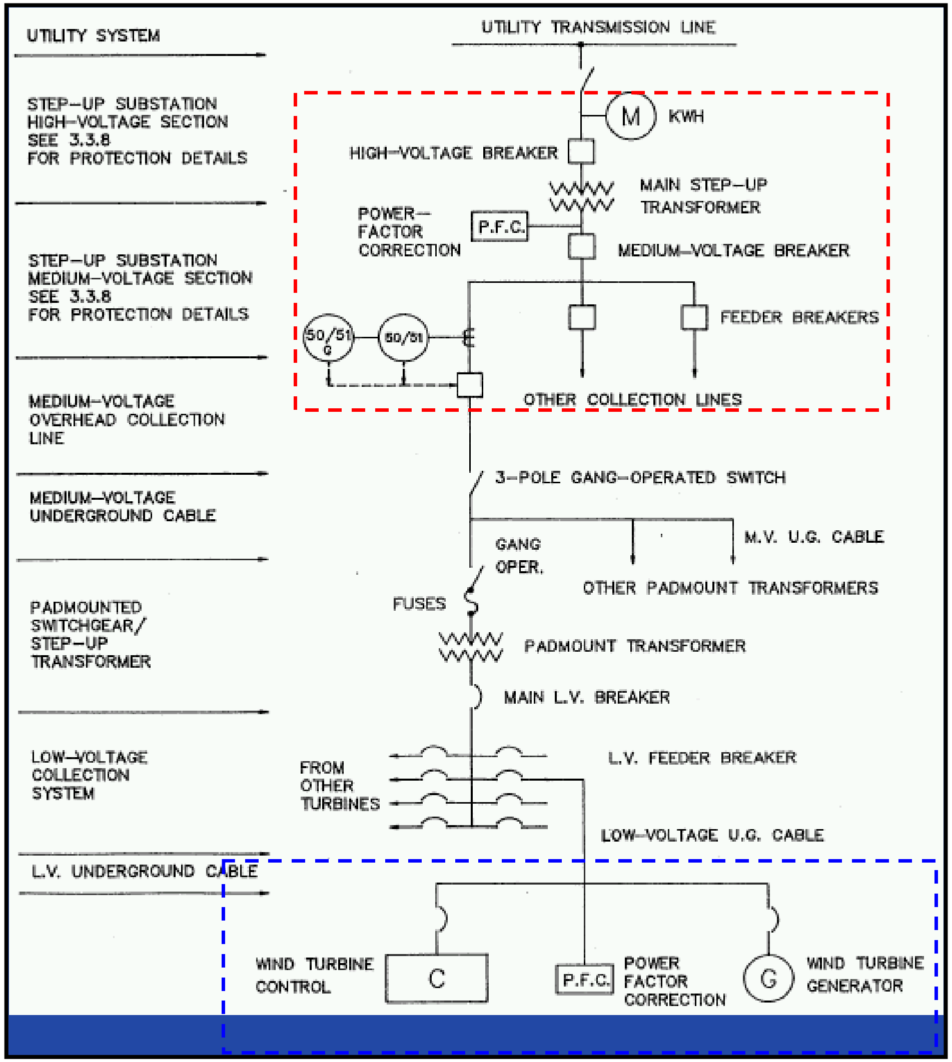
Wind Plant Overview



- The wind plant connects to the utility grid at the interconnection substation (typically 69-230 kV) which includes:
  - Breakers
  - Step-Up Transformer
  - Voltage/PF Control Equipment
- A network of underground feeders (typically 34.5 kV) connect the wind turbines to the substation.
- Wind turbines integrate:
  - Generation Control
  - Voltage/PF Control
- Wind plants utilize automated (voltage/PF) control schemes

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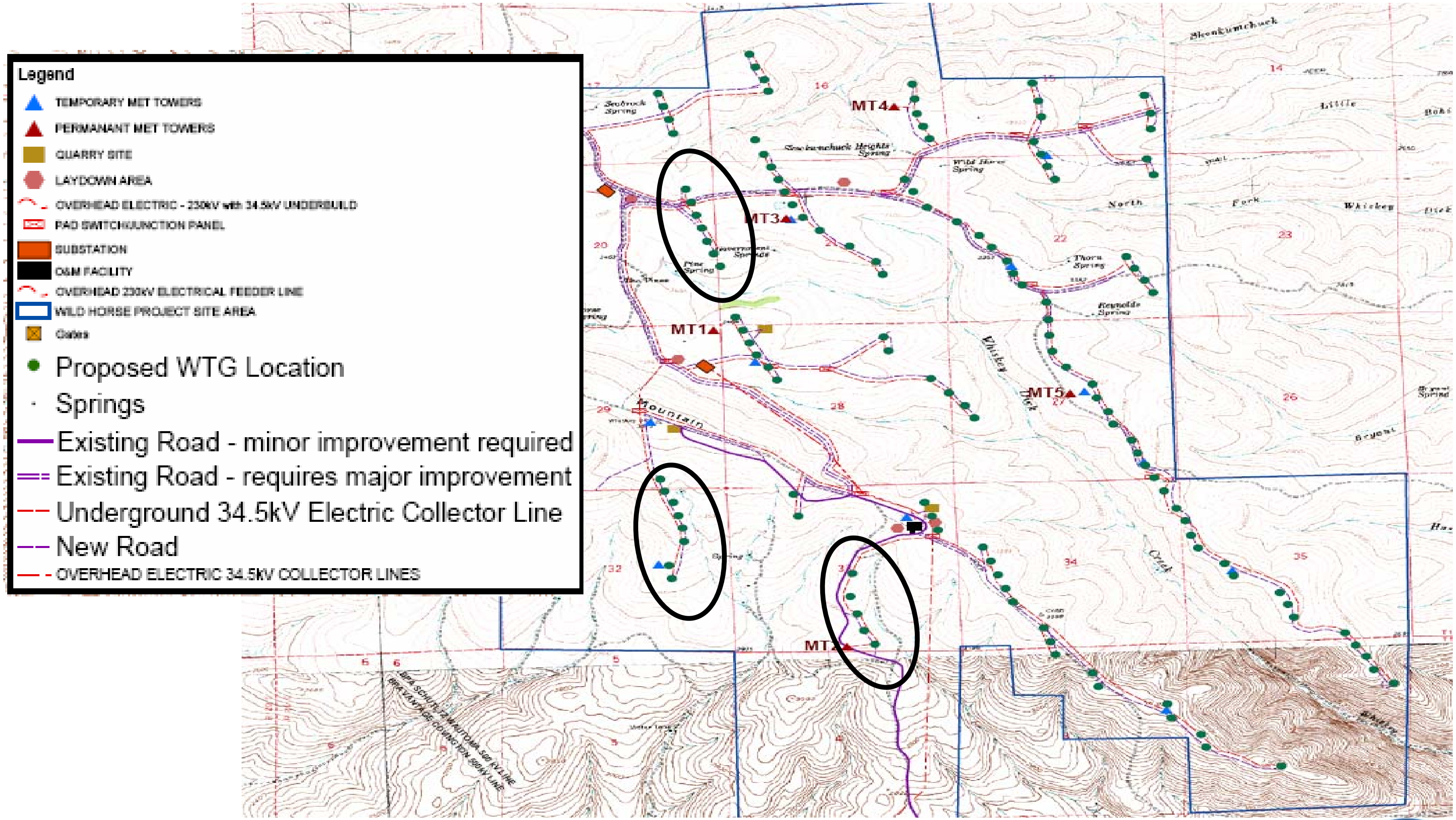
Actual Wind Farm Generator Location and Feeder Layout



1. Installed along ridge lines or hilltops
2. Arranged to catch prevailing winds
3. Clustered arrangement

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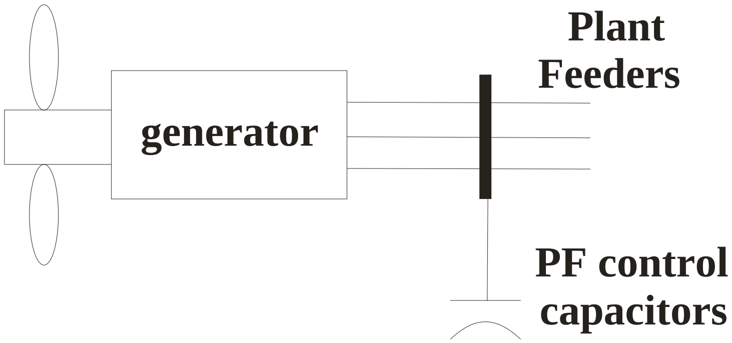
Types of Turbines

1. Direct Connected Asynchronous



Characteristics

- Induction generator connected direct to line
- Fixed Speed @ 1-2% above synchronous
- No power converter
- No voltage control capability
- Susceptible to voltage and frequency disturbances
- Absorbs VARs while generating real power
- PF correction is through LV capacitors in Nacelle
- Typical of the older style generators
- Examples: Mitsubishi, NEG Micon, Bonus

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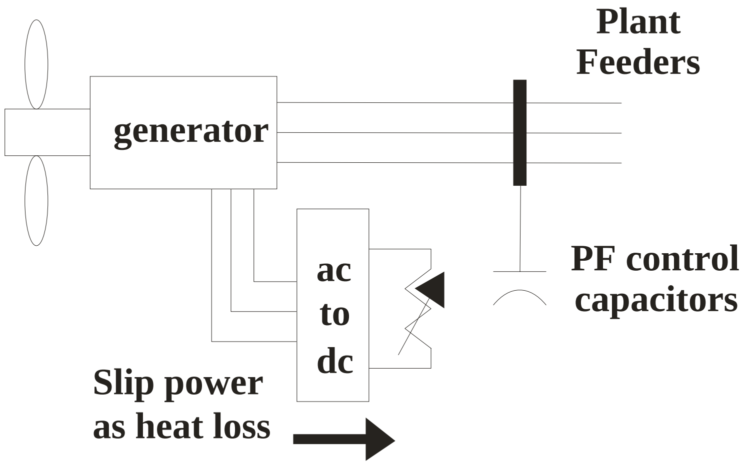
Types of Turbines

2. Direct Connected Variable Resistance Rotor

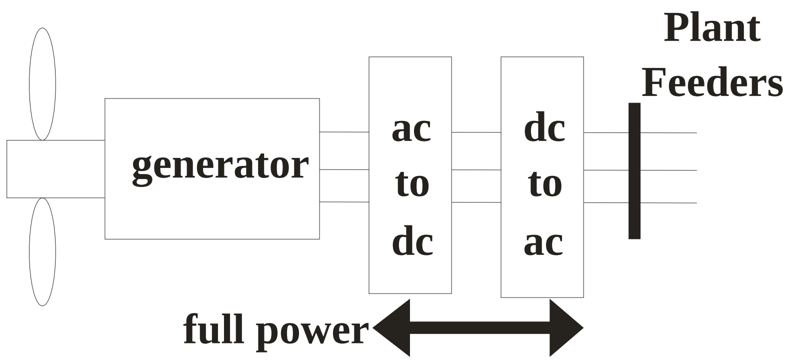


Characteristics

- Induction generator connected across the line with variable resistance control of rotor winding
- Variable slip with speed = 0-10% above synchronous
- Simple power converter
- No voltage control capability just PF control
- Improved voltage and frequency disturbances
- Absorbs VARs while generating real power
- PF correction is through LV capacitors in Nacelle
- Examples: Gamesa, Vestas V80 and V47

Types of Turbines

3. AC-DC-AC Converter Connected

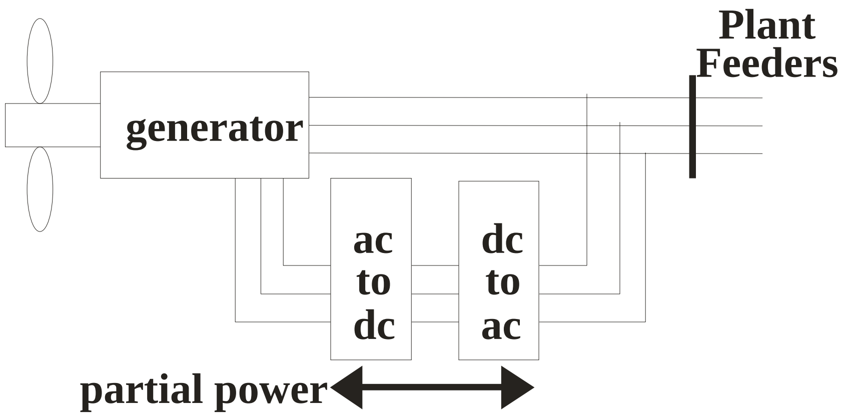


Characteristics

- Induction generator connected to the line
- Variable speed = up to 100% of synchronous
- Full rated back-to back four quadrant power converters
- Reactive control through inverters is independent of real power
- Requires full sized inverters as all power passes through both inverters
- Mechanical drive train isolated from electrical grid
- Good voltage and frequency disturbance ride through capability
- Full voltage regulating capability without use of shunt caps
- PF control also available
- Examples: Kenetech, Enercon, GE 2.0 MW

Types of Turbines

4. Doubly Fed Induction Generator (DFIG)



<u>Characteristics</u>

- Induction Generator connected across the line with variable frequency and voltage control of rotor windings
- Variable speed = +/-30% of synchronous
- Partially rated power converters with reactive control through converters
- Requires smaller (~30% rated) converters but adds slip rings to generator
- Good voltage and frequency disturbance ride through capability
- Full voltage regulating capability without use of shunt caps
- Examples: Vestas V90, GE 1.5 MW

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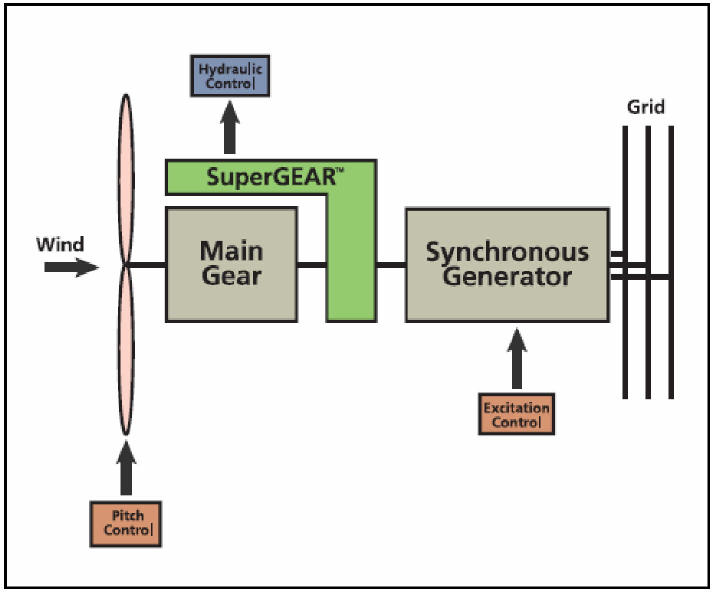
5. Synchronous Generator



Characteristics

- Three-phase synchronous generator
- No power electronics
- Speed = Synchronous
- Uses SuperGEAR™ technology - Hydrodynamic controlled component added to the standard gearbox that supplies constant speed to the synchronous generator
- Good voltage and frequency disturbance ride through capability
- Reactive control by changing the field voltage
- Full voltage regulating capability without use of shunt caps
- Examples: Windtec™ WT1650sg

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Grid Integration Issues for Wind - IMPACTS

- Impacts of wind farms on the utility transmission system and distribution systems
- Impacts of utilities on wind farms
- Impacts on planning and modeling

Impacts on the Transmission Grid

- High VAR consumption (induction machines)
- Voltage fluctuations
- Inability to regulate voltage
- Tripping off due to either sudden low or high voltage
- Changes in wind speed can cause sudden power output changes
- Frequency issues

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Impacts on the Distribution Grid

- Voltage sags due to inrush current at startup
- Voltage flicker due to tower shadowing effects or power output changes
- Harmonics

Impacts of Utility on Wind Farms

- Unique or unusual interconnection requirements
- Tripping of turbines due to variations in steady state voltage on transmission grid (+/-10%)
  - Requires LTC on power transformer(s)
  - Adds cost to collector grid design
- Gearbox damage due to sudden voltage changes on transmission grid – large cap or reactor banks
- Tripping of wind farm due to sudden voltage sag on transmission grid
- Phase voltage imbalance
- Harmonics

Impacts on Planning and Modeling

- Wind turbine/collector system/utility model data is difficult to get
- System configuration changes
  - Developed in pieces or stages with different turbines in each stage
  - May have separate 34.5 kV buses
  - Unavailability of collector grid design information

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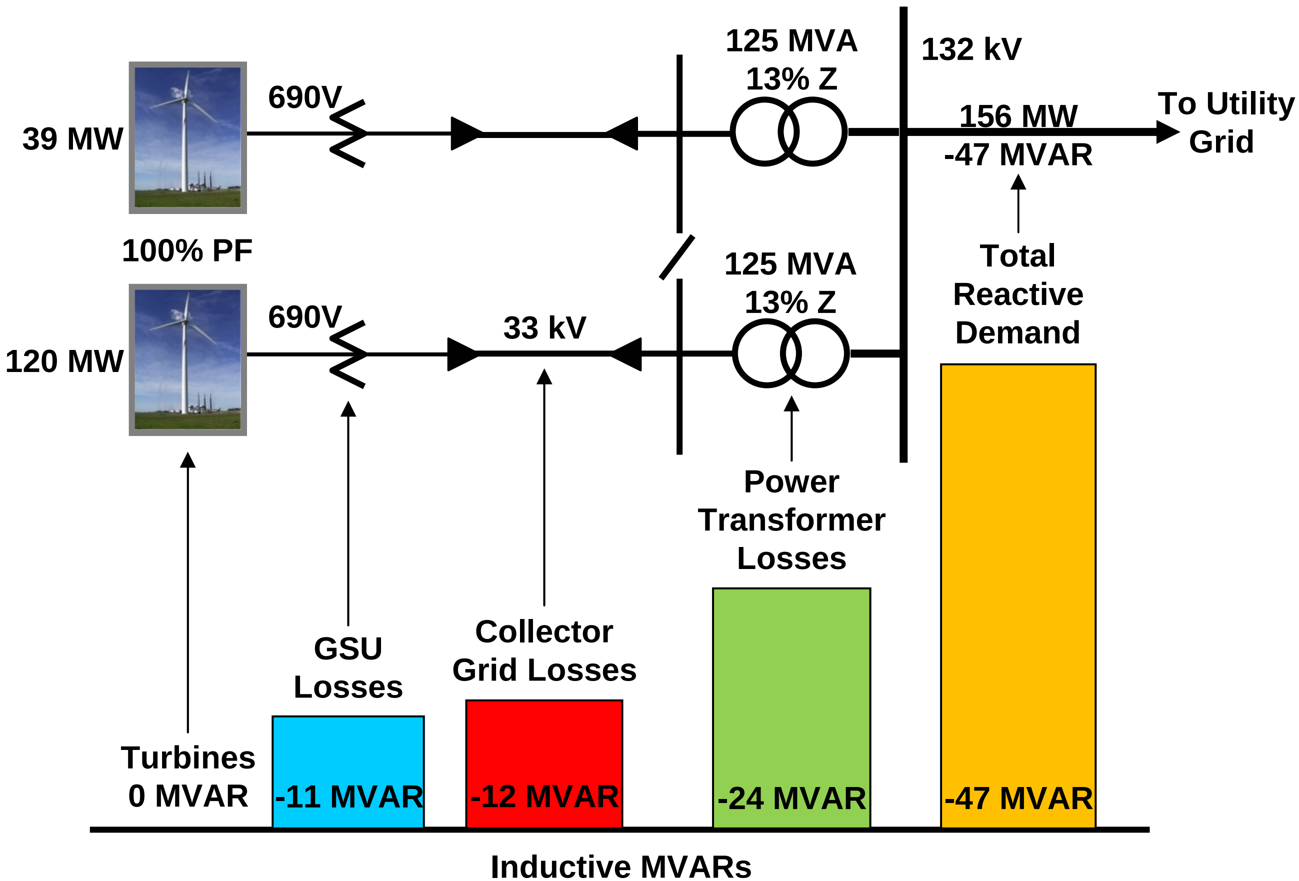
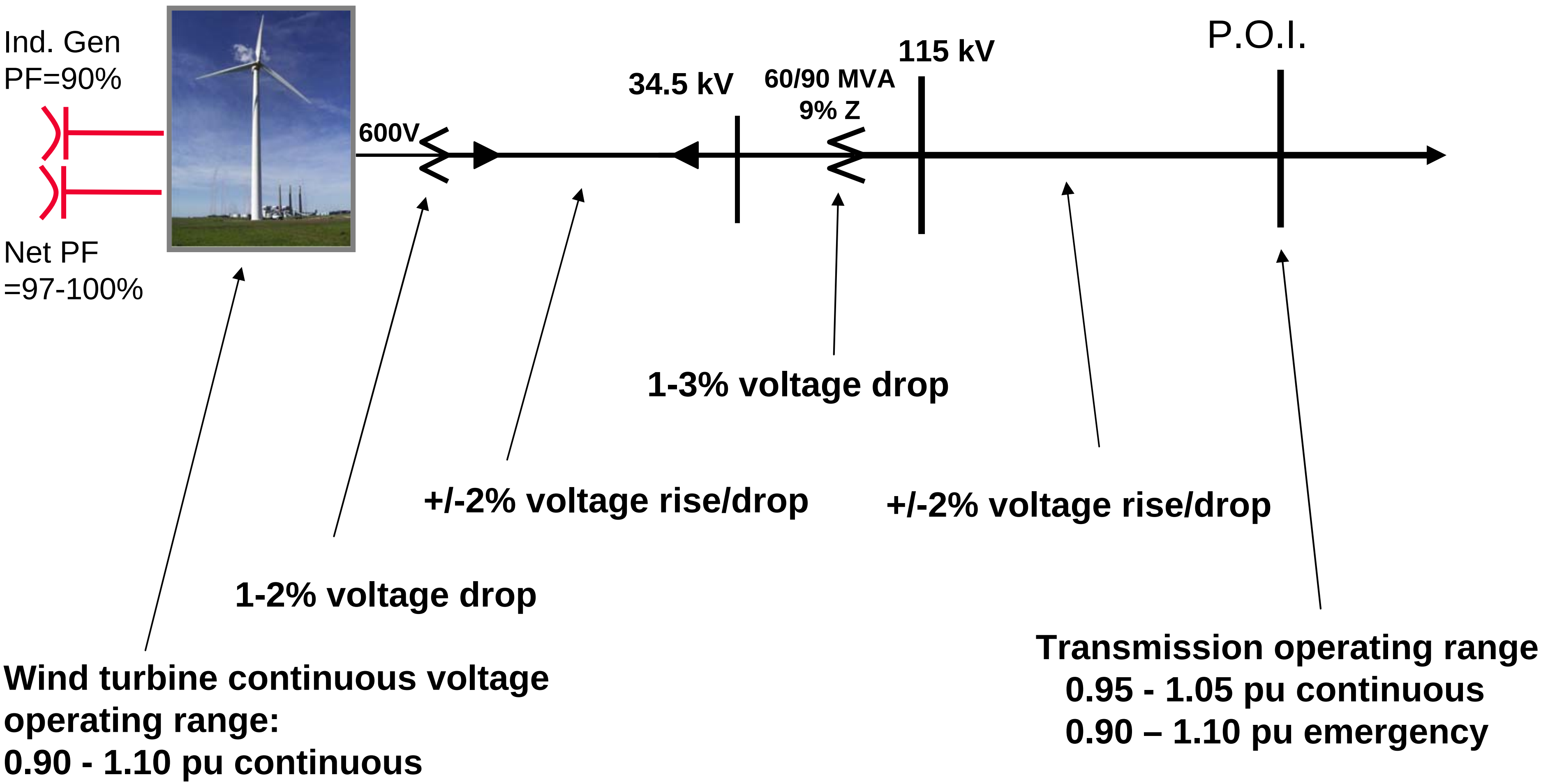
Lake Bonney Wind Farm - Sources of Reactive Demand

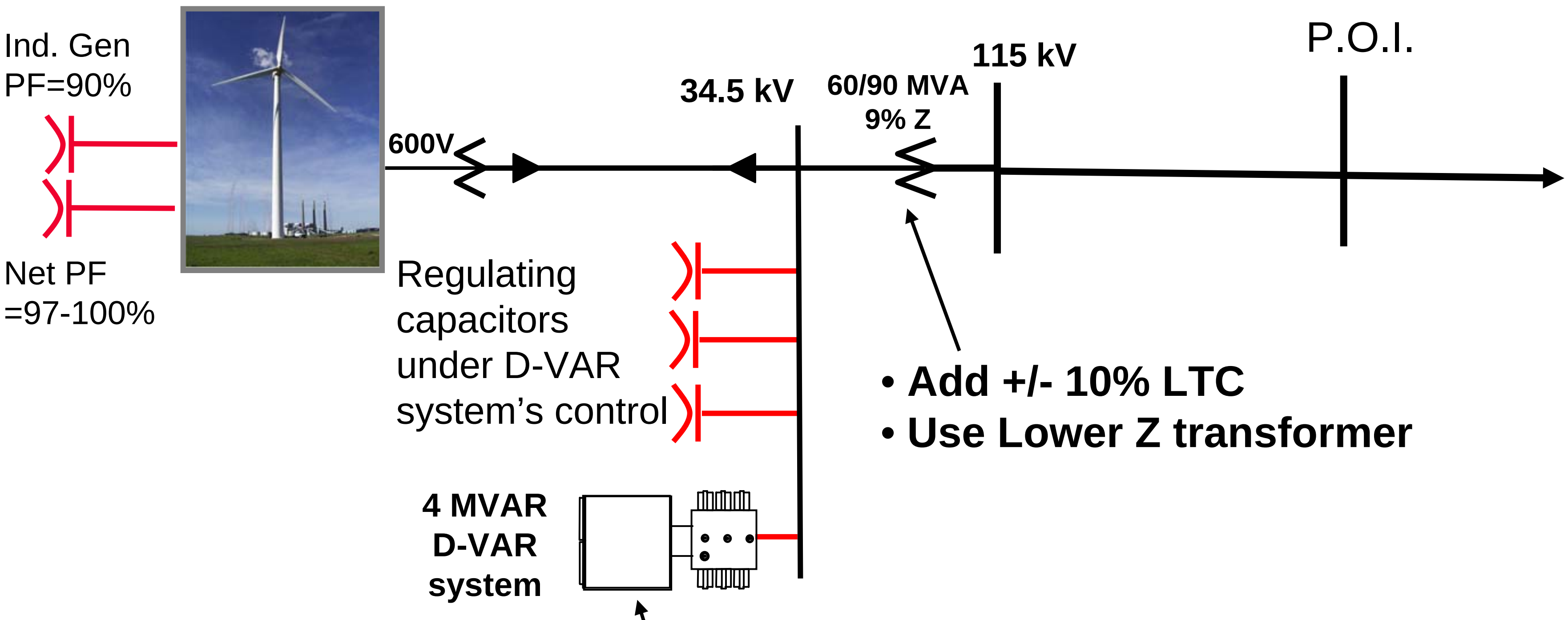


Sources of Voltage Variation at Wind Farm



Sum of voltage variability at turbines = 30% or more

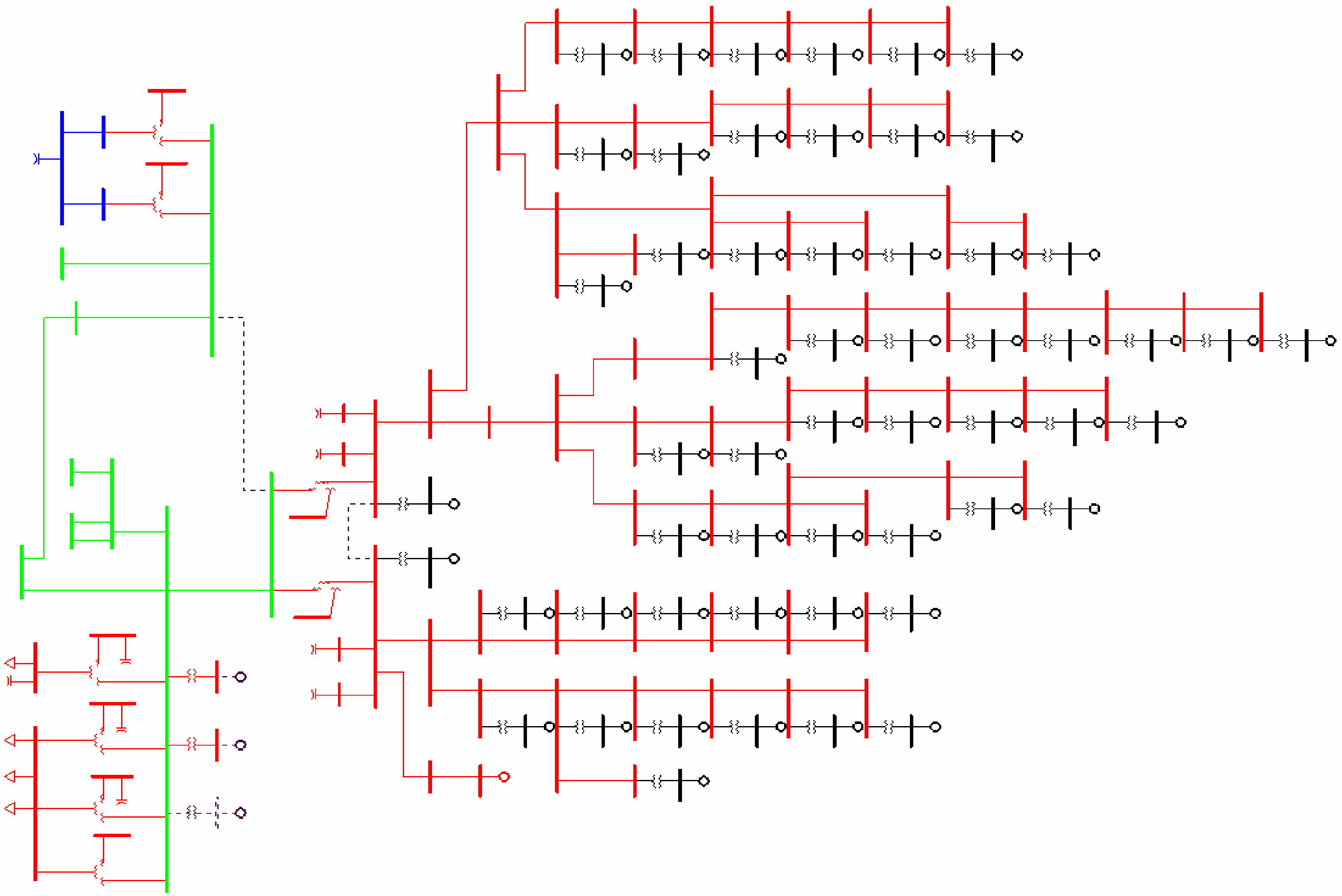
Managing Voltage Regulation and Variability at the Wind Farm



- **Add collector based Dynamic reactive solution**
- **Use D-VAR® system to regulate transmission system voltage**

Sum of voltage variability at turbines < 10% at turbines

Lake Bonney Wind Farm One-Line Diagram



Interconnection Requirements for Wind Farms

Typical Utility Interconnection Requirements

Utility	Power Factor Requirements	Ride Thru Requirements	Voltage Regulation
1. ERCOT	+/-95% @ HV	None	HV Bus
2. Alberta	+90/-95%@ Dist V	Eon Netz	HV Bus
3. Exelon	+95/100% @HV	None	HV Bus
4. Pacificorp	100% PF@HV POI	None	Dist Bus
5. Xcel	100% @HV POI R	Worst faults	HV Bus R
6. Sask Power	+90%/-95%	Post Fault Recov.	Dist Bus
7. SDGE	+90%/-95%	WECC 20%/20~	HV Bus
8. HELCO	100%/-88%@ HV	Worst faults	HV Bus
9. IESO	+90%/-95%	Worst Fault	HV Bus
10. S. Australia	+/-93% @ HV POI	HVRT/LVRT	HV Bus

POI: Point of Interconnection
WECC: Western Electricity Coordinating Council
LVRT: Low Voltage Ride Through
HVRT: High Voltage Ride Through

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USA - Joint NERC/ FERC Interconnection Standards for Wind Energy (Dec 2005)

- Power factor of +/- 95% at the point of interconnection
- Voltage regulation capability
- Low Voltage Ride Through (LVRT) down to zero remaining voltage for:
  - 3 phase faults at high side of power transformer cleared in 4-9 cycles
  - Single line-ground faults with delayed clearing
  - Need to be supported by case specific studies

Canadian Wind Interconnection Requirements

IESO (Ontario)

AESO (Alberta)

Saskatchewan

Total installed wind generation in Canada as of June 06 was1049 MW. Alberta 284 MW, Ontario 220 MW and Quebec 212 MW installed.

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Additional Utility Requirements

- Wind farm dynamic compensation system to meet post fault voltage recovery targets
- Provide dynamic PF control and susceptance control
- Provide high voltage ride through at voltages up to 130-140%
- Regulate voltage at remote points
- Remain on line during emergency conditions (Voltage range 0.90-1.10 pu)

Options to Address these Standards

- Add capability within the wind generator turbine itself
- Add equipment at the collector bus level
- Add a combination of improved turbine capability plus some equipment at the collector bus
- Add equipment at the HV point of common coupling.

A Solution at the Collector Bus Has Many Advantages

- Less expensive for larger wind installations
- Provides full voltage regulation capability even when wind plant is not generating
- Allows for a more flexible collector grid design
- Allows a wider voltage control range for the utility
- Solution is modular and expandable

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D-VAR® System - Dynamic VAR Device

- Fully Integrated STATCOM with proprietary overload capability of 2.67 times its continuous rating
- Provides dynamic reactive capability – both leading and lagging
- D-VAR system can seamlessly switch other capacitors and reactors as part of a larger dynamic solution
- 33 wind farms use D-VAR systems for
  - PF correction
  - Voltage regulation
  - LVRT
  - HVRT

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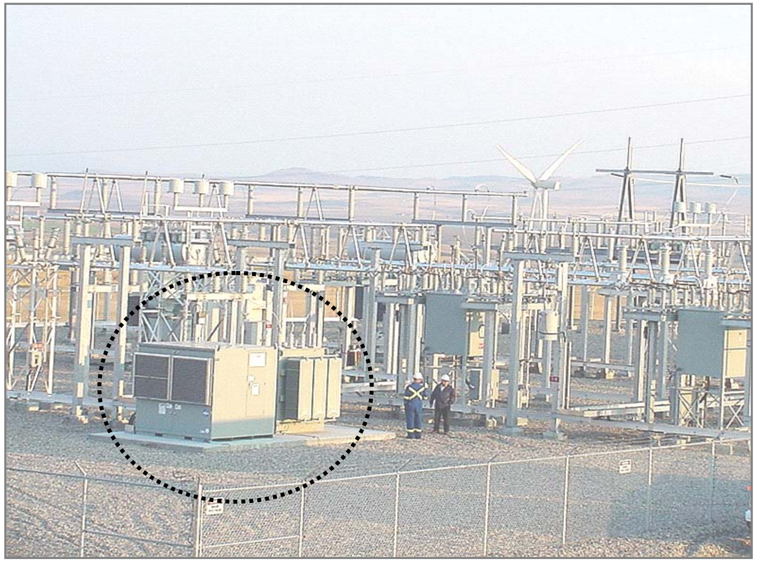
D-VAR® System Basics….

Proprietary power electronics technology



Each phase is individually controlled

D-VAR systems mitigate wide variety of voltage and power quality related transmission problems

Why Integrating Wind Generation with Transmission is so Difficult

Asynchronous Generation Must Follow the Same Rules as Synchronous Generation to Connect

<u>Wind Generating Plants</u>

(Induction Generators)

- Minimal transmission added to support remote wind generation
- Asynchronous machines
- Wind generation is non-dispatchable, generally has limited reactive power control, and marginal voltage ride-through

<u>Coal, Gas and Hydro Plants</u>

(Synchronous Generators)

- Transmission added to move generation to load center
- Machines are synchronous, providing dispatchable real and reactive power
- Machines provide excellent voltage and frequency control.

Transmission System

(Operating Criteria)

Simulation Tools and Uses

It is important to use the right tool for the right job

- **Siemens/PTI PSS/E, GE PSLF-** Load Flow, Stability, PF, LVRT, HVRT
- **PSCAD -** EMT, Switching transients, Harmonics
- **DigSilent Powerfactory** – EMT, LF, Stability, Short Circuit, System Protection

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Wind Turbine Software Model Availability

- **PSS/E** – 4 turbine models publicly available
  - Two for GE WTGs and two for Vestas WTGs
  - Models have been developed for many other manufacturers and are available for release with approval by manufacturer
- **PSLF** – 4 turbine models publicly available
  - GE 1.5 and 3.6 MW
  - Vestas V80 and V47
- Turbine Manufacturers reluctant to share data with competitors
  - GE PSLF is part of GE who makes GE Wind turbines
  - PTI is part of Siemens who makes Siemens (Bonus) turbines
- PTI is in the process of developing a generic wind turbine model for each of the four different types of WTG we saw earlier.
- For specific wind farm studies, use the manufacturers model and data, and for the NERC data base, use the PTI generic wind turbine model with the manufacturer given data.

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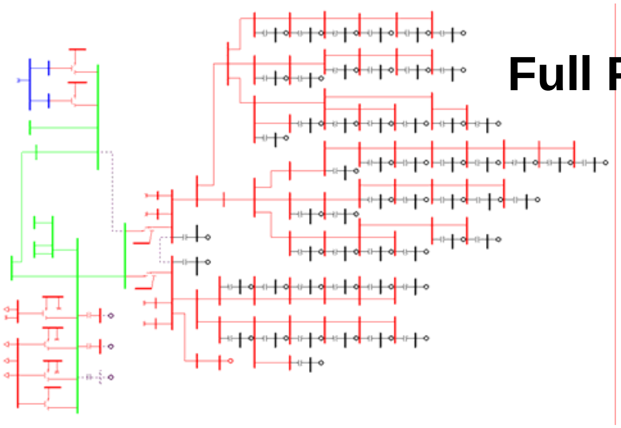
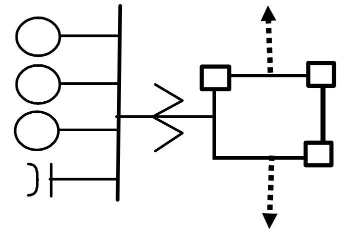
Possible Solutions for Wind Plant Modeling

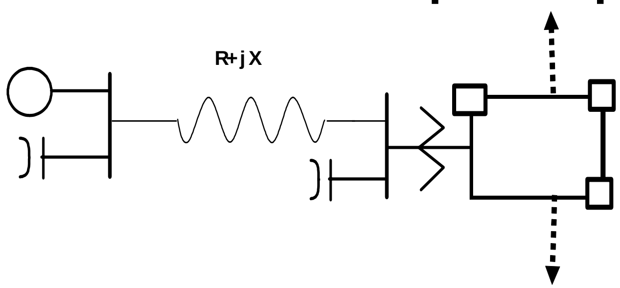
Full Plant



One Turbine Per Feeder

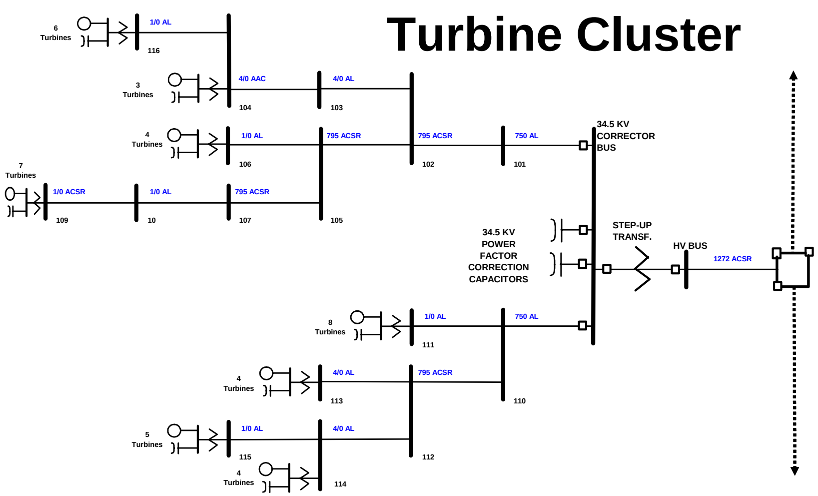


Single Turbine Behind Complex Impedance



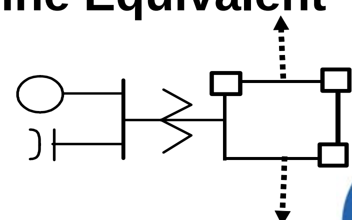
Analyzing the Wind Farm or Areas Around It

Turbine Cluster

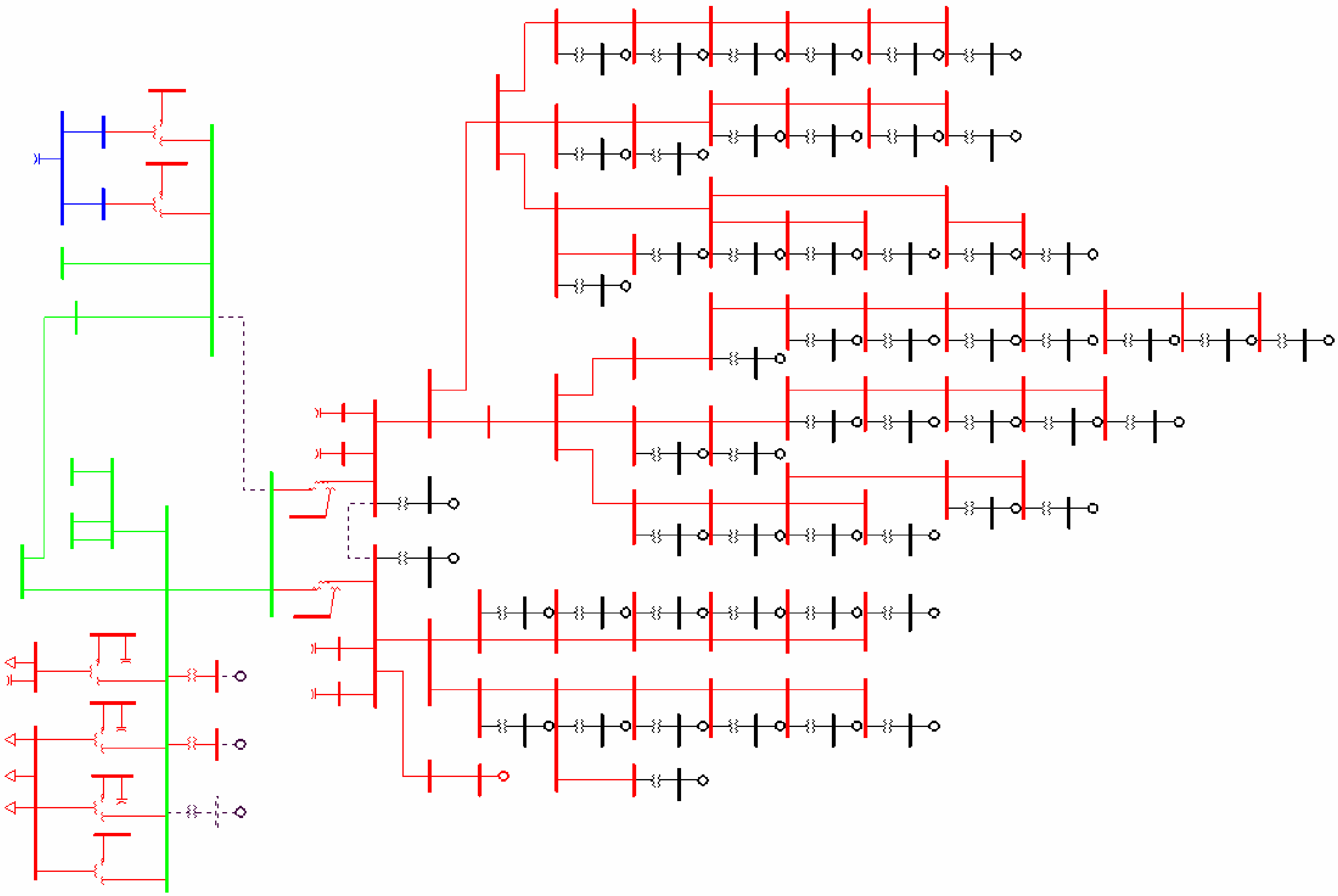


Sending Modeling Data to NERC

Single Turbine Equivalent



Lake Bonney Wind Farm One-Line Diagram



Generator Parameter Differences

Value Description	Default Values	LS Values	Weier Values	ABB Values
H, Inertia constant, pu in seconds	0.8000	0.7638	0.9634	0.0896
RS, Stator winding resistance, pu	0.0055	0.0051	0.0058	0.0067
RR, Rotor winding resistance, pu	0.0067	0.0058	0.0070	0.0092
XM, Magnetizing reactance, pu	3.2485	4.1504	3.4109	3.3611
XSL, Stator leakage reactance, pu	0.0819	0.0970	0.0860	0.0830

These differences can be important depending upon the type of study you are performing. More important for LVRT and stability studies.

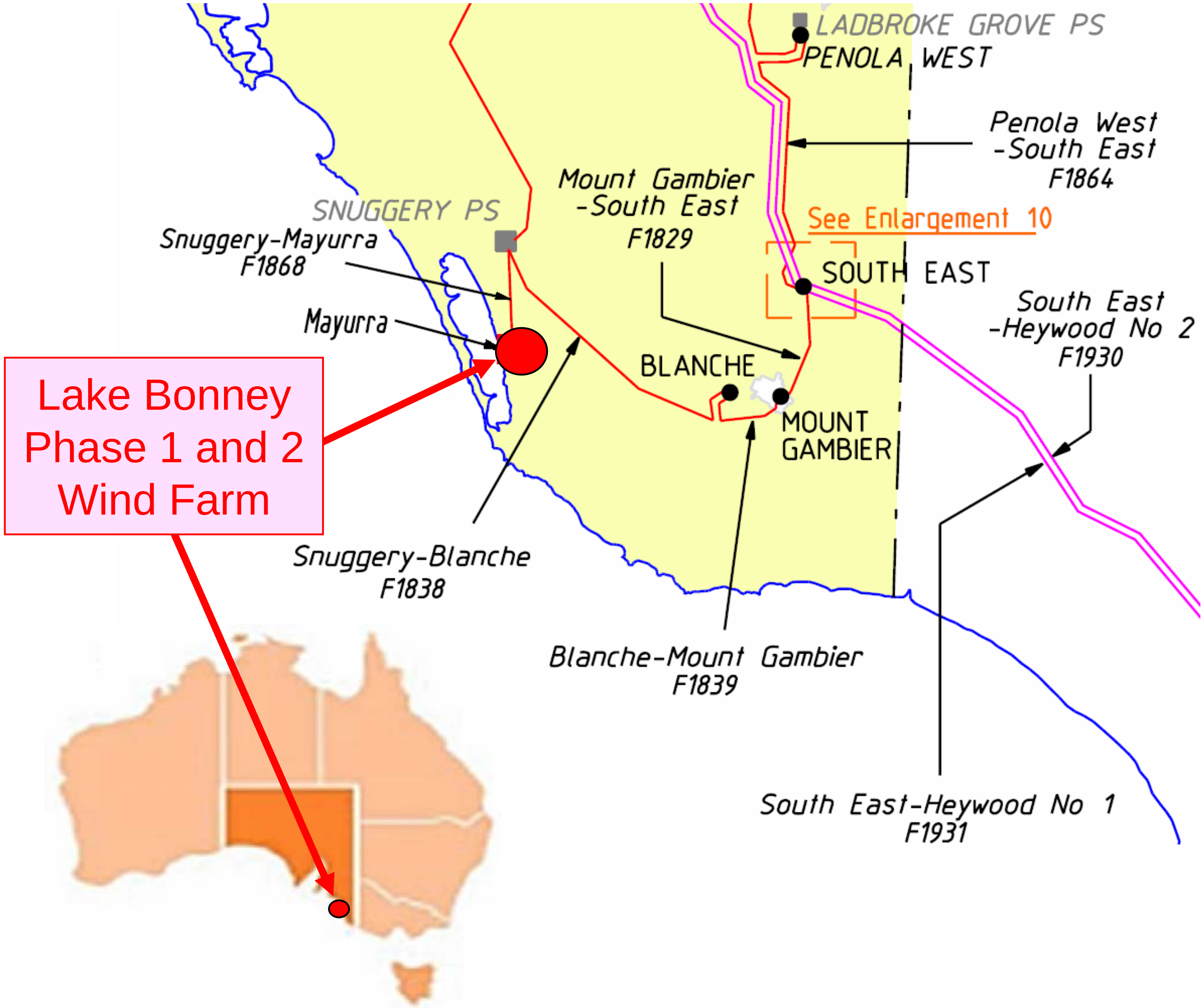
Integration of Wind into the Grid using Dynamic Reactive Compensation

An example of where the AMSC D-VAR® system has been successfully used to address power factor, voltage regulation and various forms of low & high voltage ride through problems

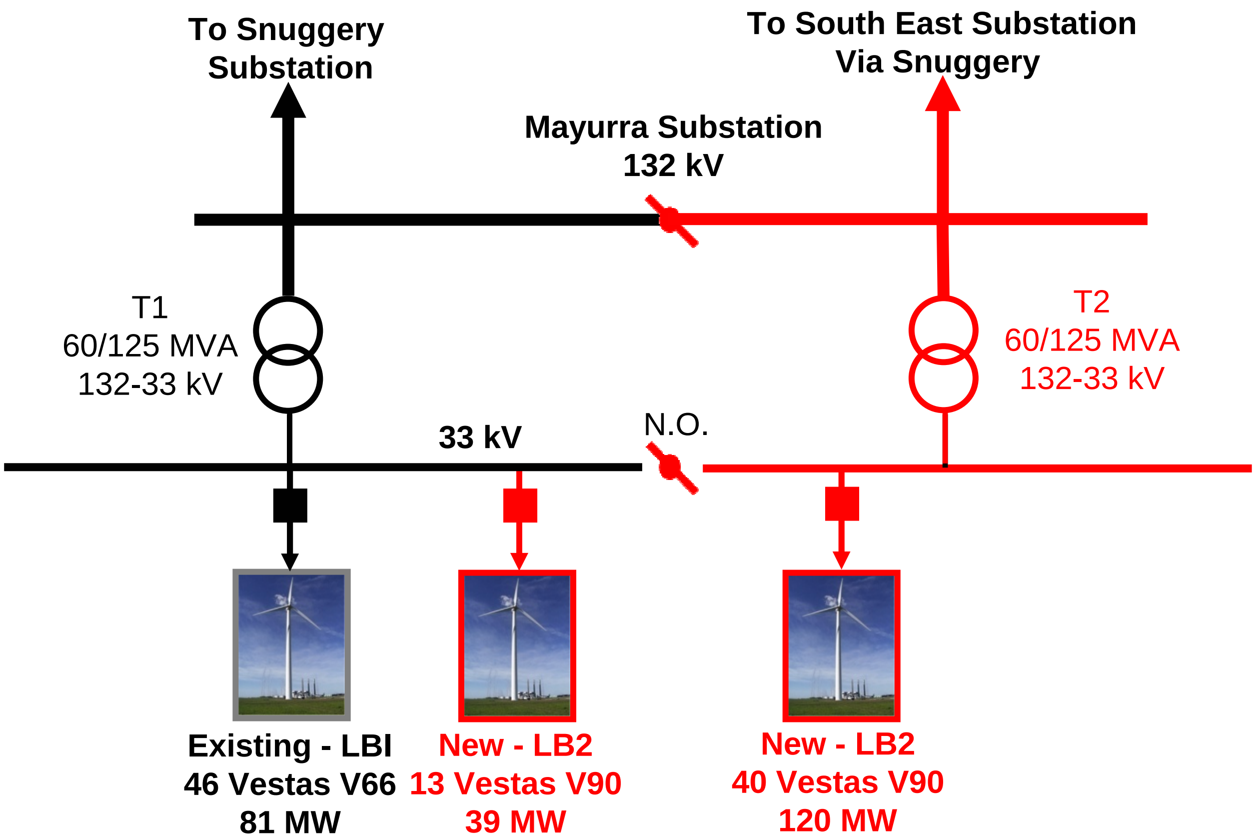
Lake Bonney Wind Farm Phase 2
Australia

Voltage Regulation and
High Voltage Ride Through

South Australia Transmission Grid and Lake Bonney Wind Farm



Lake Bonney 1 and 2
Wind Farms (240 MW total)



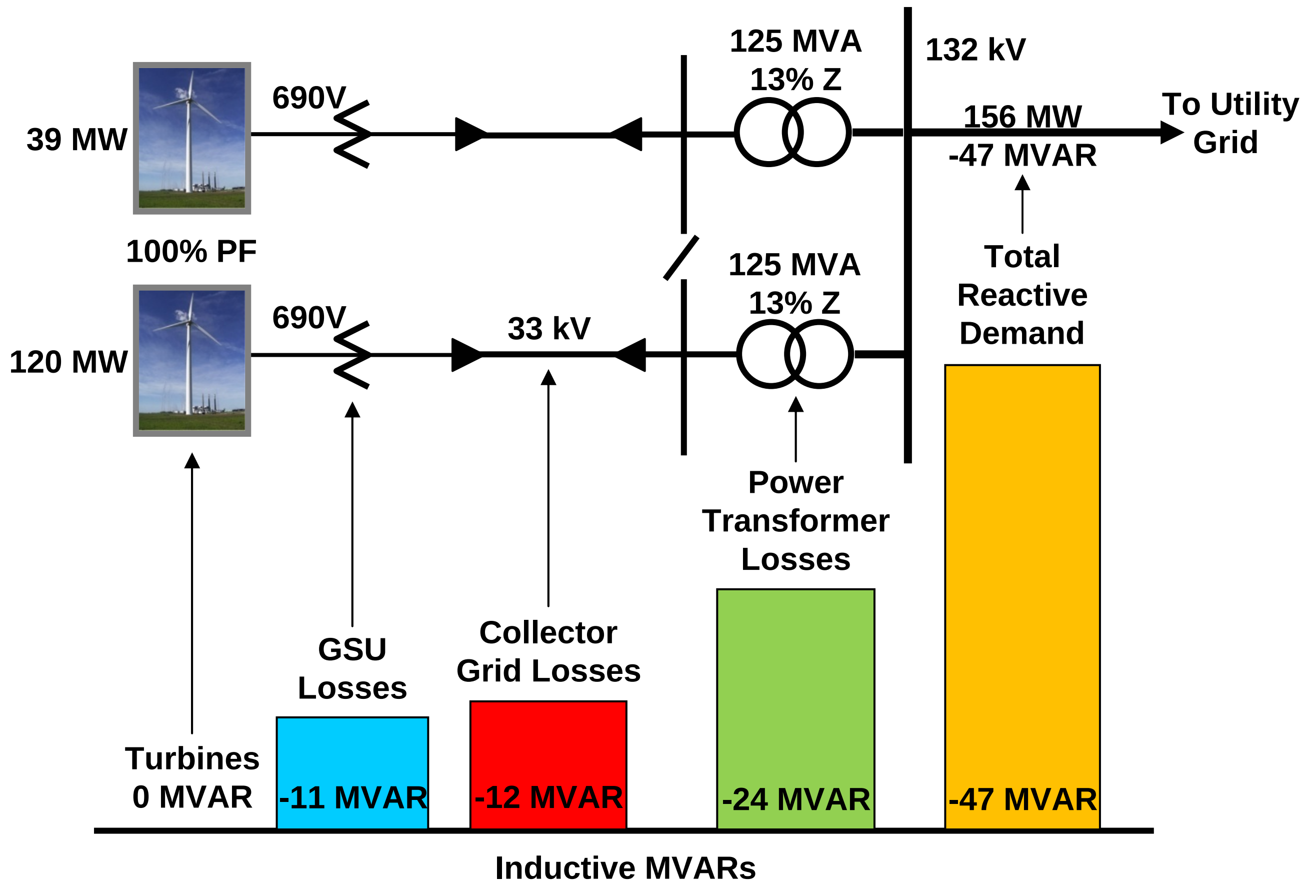
Lake Bonney 1 had no reactive compensation equipment installed.

ESCOSA - Wind Interconnection Requirements

- Capable of +/-93% PF at high side of power transformer at full generation.
- Half of PF correction capability shall be dynamic.
- Reactive output proportional to generation level.
- Regulate transmission system voltage.
- Avoid tripping wind farm for nearby transmission grid faults and high voltage (LVRT, HVRT).
- Restore transmission system post fault voltage to a minimum of 90%.

Requirements can be met primarily by installing dynamic and static reactive resources.

LB2 159 MW Wind Farm - Sources of Reactive Losses at Full Generation



Bottom Line - Add 47 MVAR to the capacitive reactive compensation target value.

Lake Bonney 2 Reactive Compensation Requirements at Full Generation

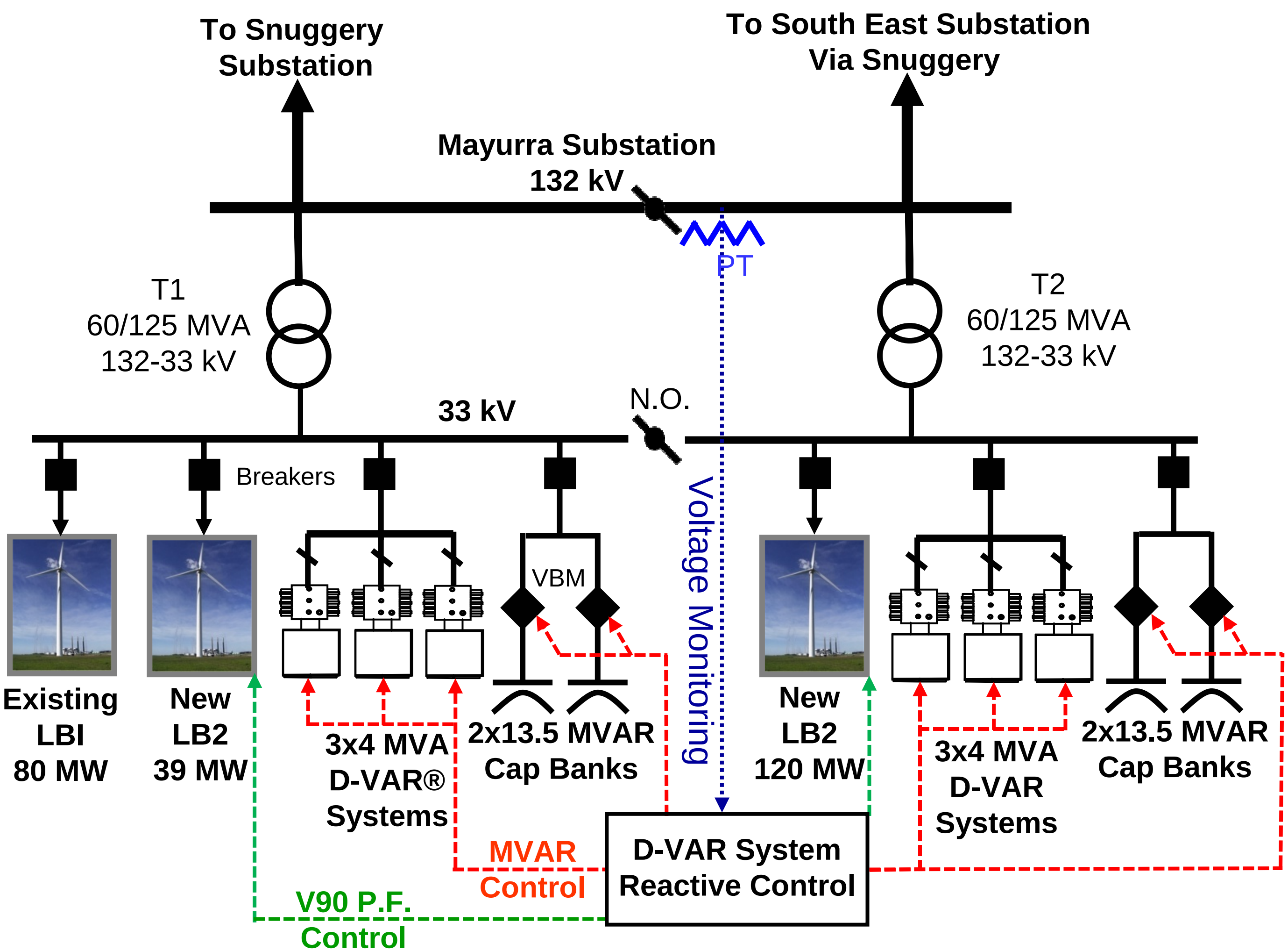
Target Requirements	Capacitive	Inductive
• +/-93% PF at 132 kV	63	63
• Include reactive losses		
- GSU transformer	12	-12
- 33 kV collector grid	11	-11
- 132-33 kV transformers	24	-24
Total Reactive Required	110	16
50% Dynamic	**55**	**8**
50% Non-dynamic	55	8

47 MVAR (GSU transformer, 33 kV collector grid and 132-33 kV transformers losses)

Lake Bonney 2 Reactive Compensation Resources at Full Generation

Resources	Capacitive	Inductive
• Dynamic VARs (reqmt. is	+55 Cap	-8 Ind)
- Generator VARs	0	0
- D-VAR® System (24 x 2.67 O.L.)	64	-64
• Dynamic + Static VARs		
- Generator(+98/-96%PF)	32	-46
- D-VAR System (24 MVAR)	24	-24
- Capacitors (4 x 13.5)	54	0
Total Dynamic + Static	110	-70

Lake Bonney 1 and 2 Wind Farms and AMSC's D-VAR® Solution



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D-VAR® System Basics

What are **D-VAR®** Units?

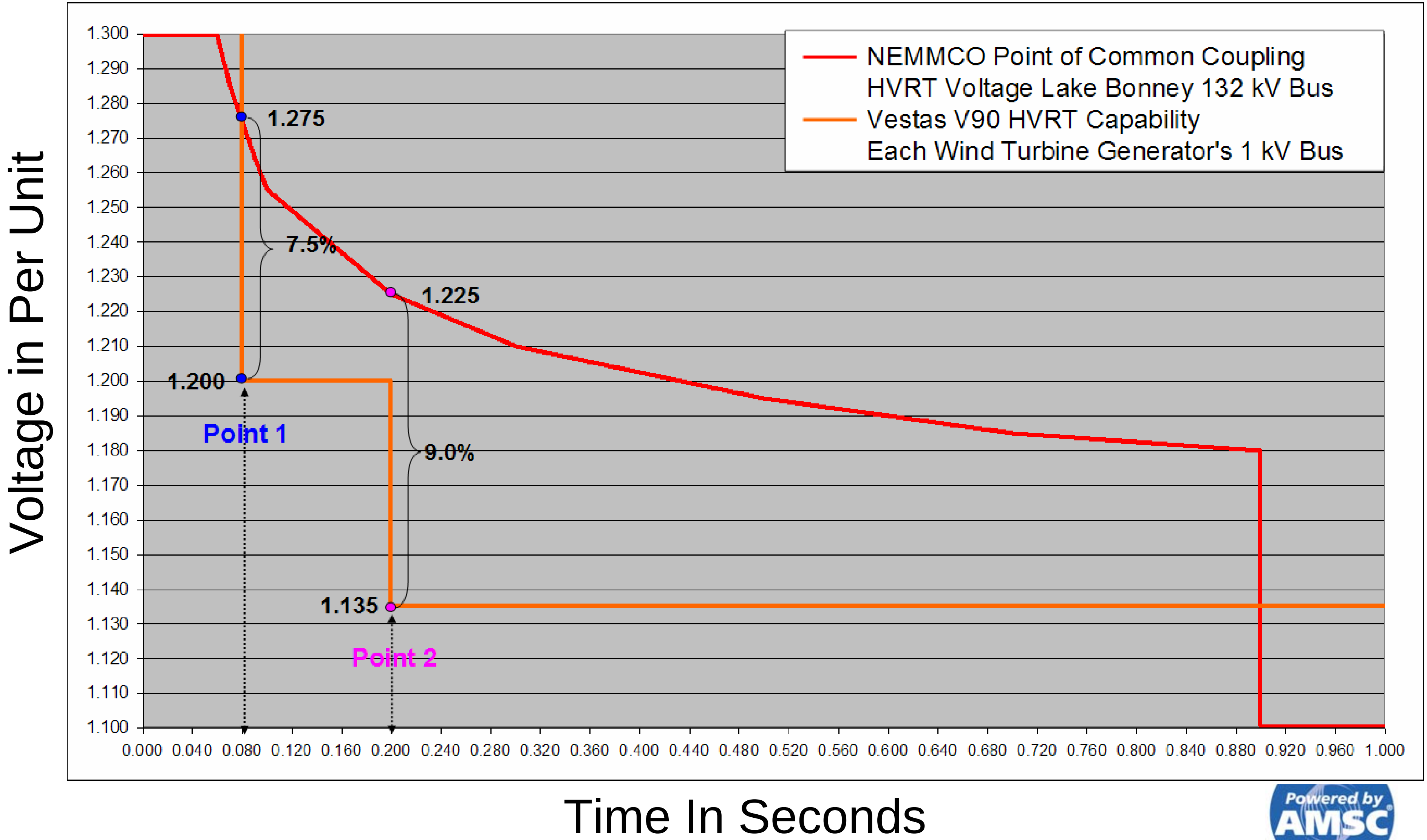
- **<u>D</u>**ynamic **<u>VAR</u>**s… Fully Integrated STATCOMs with proprietary 2.67 times the continuous rating (Overload).
- Instantaneously injects precise amounts of reactive power into a network.
- Can be *seamlessly* integrated with static shunt devices as part of a larger solution.
- Can control the PF of a wind farm's wind turbine generators.

No Trailers

Innovative Approaches to Addressing Wind Interconnection Requirements

- Use D-VAR® system's overload capability to address transient reactive requirements – during both low and high voltage events
- Use slower speed power factor correction capacitors to address post fault voltage issues
- Use turbine variable power factor (PF) output capability to meet PF requirements

High Voltage Ride Through PCC and WTG Capability



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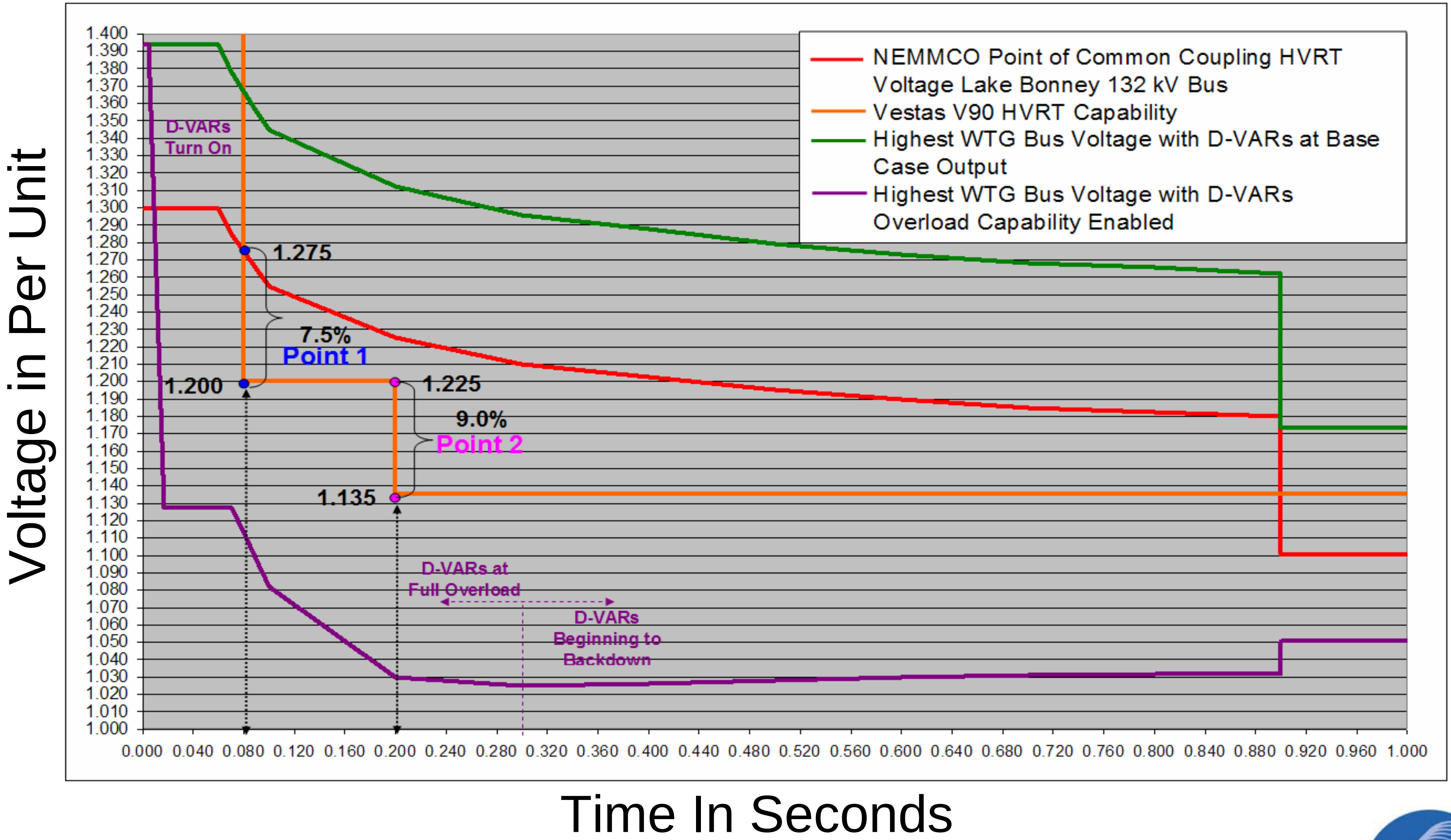
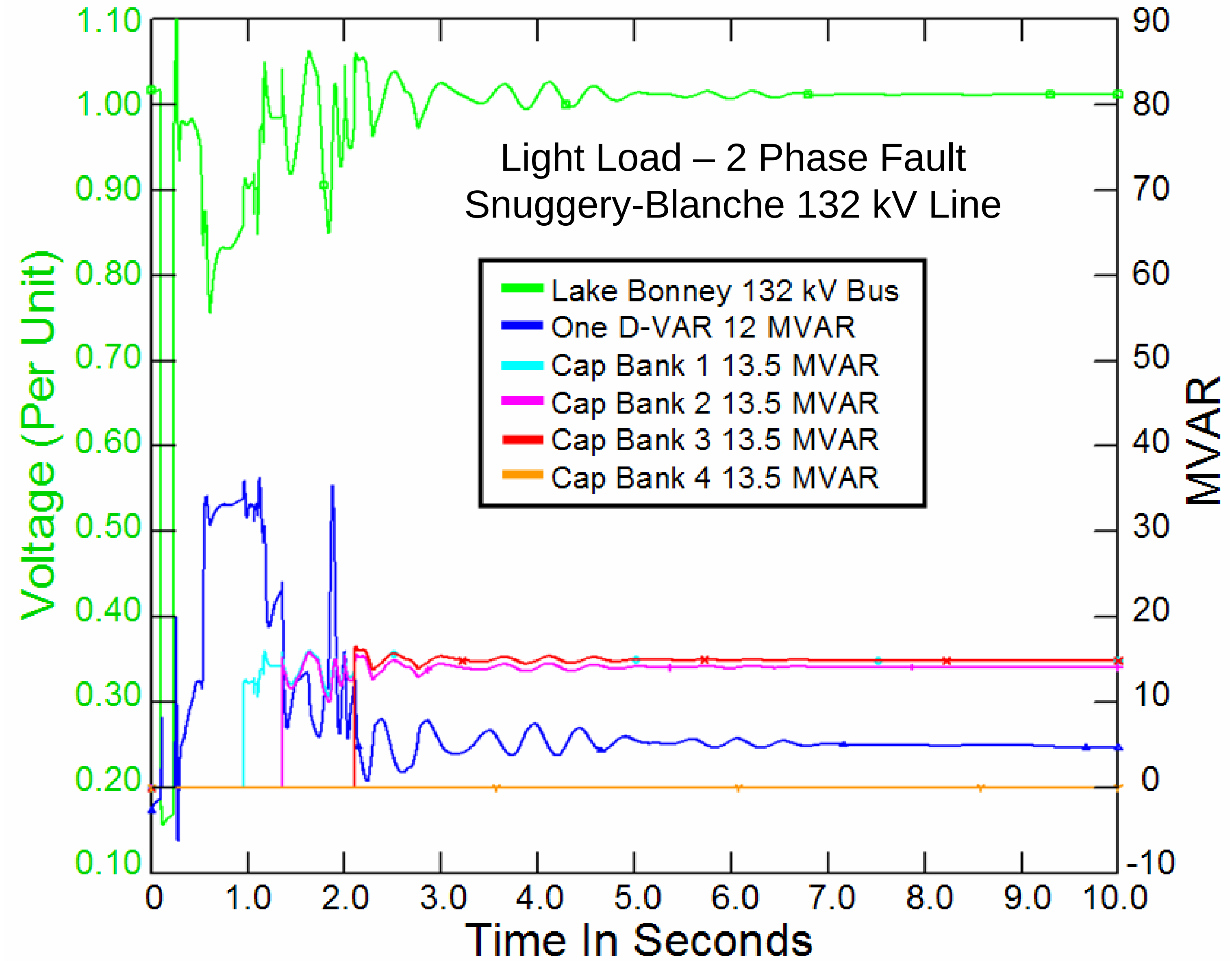
Method of How HVRT Analysis Was Conducted

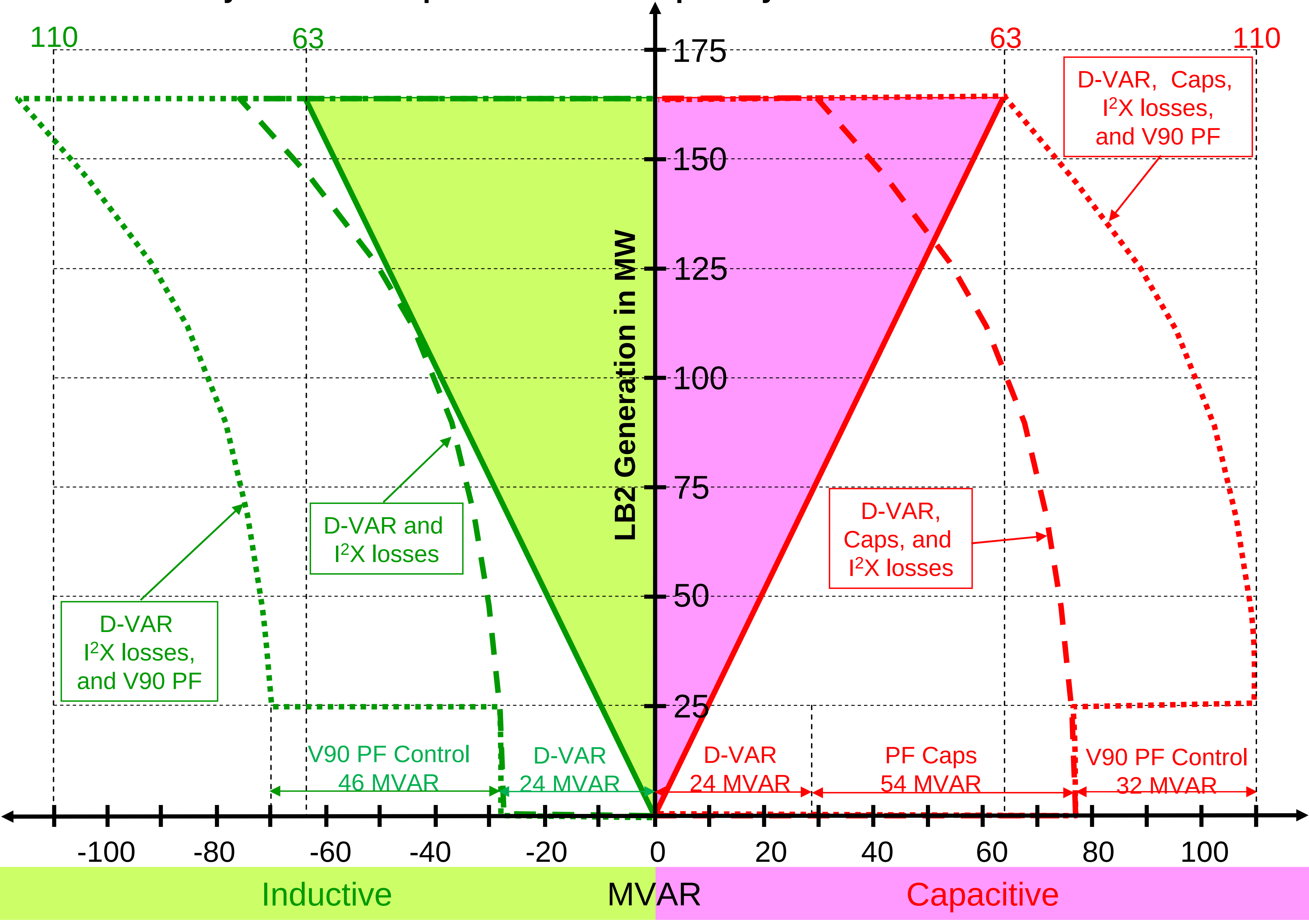
Analysis of the Impact of the D-VAR® Systems on the Highest WTG Voltage



Post Fault Voltage Recovery Simulation Showing Innovative Solution Results



Lake Bonney Reactive Requirements and Capability as a Function of Generation Level



Lake Bonney 2
Reactive Compensation Summary

- LVRT met with improved turbine capability.
- D-VAR® system met all other dynamic and static interconnection requirements.
- Innovative D-VAR system approach minimizes interconnection investment requirements.
  - D-VAR unit's overload capability used to meet post fault voltage and HVRT requirements.
  - D-VAR system's switches caps and controls variable turbine PF capability to achieve PF and voltage regulation targets.

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Recent AMSC D-VAR® System Installations in Asia

Questions?

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