Wind Power

An Overview of Utility-Scale Wind Power Production & Distribution

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Overview

- Introductory Topics
  - General Power Facts
  - Power Grid Overview
- Wind Power Topics
  - Wind Power Facts
  - How Wind Energy Works
  - Building a Wind Farm
  - Wind Farm Site

Power Facts

- Electrical power measured in Watts
- Consumption is measured in KWh
- 1 KWh = 3412 BTU = 1 hour’s use of:
  - microwave oven
  - ten 100w light bulbs
  - medium stovetop burner
  - three computers
- 1 MWh = 1000 KWh
  - 1 average home for 1 month

Power Facts

- Typical utility-scale wind turbine generates 1.6 MW
  - Equivalent to ~2000 hp of diesel generation
  - 4 tractor/trailers, 1 small tug boat, or 1000 homes
- Ten turbines = 16 MW
  - 10,000 homes,
  - At nominal speed: 1 train (10,000 tons) or 1 large cargo ship (100,000 tons)

Power Grid Overview

- Components:
  - Generation
  - Transmission
  - Sub-transmission & Collection
  - Distribution
  - Load
- Technical Issues
  - Stability
  - Power Flow
  - Daily wind/load variations
  - Spinning Reserve
  - Power Quality
  - Fault Protection
  - Distribution of components

Grid Components

- Generation
  - Typically generated at ≤ 15 KV
  - Types:
    - Hydro (water/gravity turbines) Hoover Dam = 2000 MW
    - Coal (steam turbines) 2 KWh/kg, 6MW/ton
    - Nuclear (steam turbines) 1000 MW
    - Diesel (direct drive generator) 1000hp = 750KW
    - Solar (photovoltaic) 75MW plant $300M ($4M/MW)
    - Wind (wind turbines) 1.6 MW ea, $1.5M ea = $1M/MW

Grid Components

- Transmission
  - Transport of large amounts of power from one location to another
  - Typically transmitted at high voltage
    - 345 KV, 230 KV, 120 KV
    - Transmitted power $P = I * V$ $\uparrow V \rightarrow \downarrow I$
    - Dissipated power $P = I^2 * R$ $\downarrow I \rightarrow$ smaller conductors and/or less power loss
    - AC is most common, but there is some DC transmission
  - Conductors can not be assumed ideal, real wire properties become part of system model
    - Resistance
    - Impedance (capacitance & inductance)

Grid Components

- Sub-transmission & Collection
  - Intermediate voltage
    - 120 KV, 40 KV, 20 KV
  - Collects generators together
  - Substation levels for distribution
- Distribution
  - From substation to neighborhood or industrial consumer
  - 13.3 KV, 8.3 KV, 4.8 KV
- Load
  - Where business & residential power is consumed
  - 480 V, 240 V, 208 V, 120 V

Grid Technical Issues

- Stability & Power Flow
  - Generation must keep up with demand
  - Load, generation & distribution balancing throughout grid
  - Steady & Transient state
- Energy resource variations
  - wind production vs other types
    - Nuclear, coal, hydro, solar, diesel
  - Spinning Reserve

Grid Technical Issues

- Power Quality
  - Voltage stability
    - +/- 5% (per unit .95 to 1.05 times nominal)
    - θ > 0 → V ↓ (inductive, lagging), θ < 0 → V ↑ (capacitive, leading)
  - Frequency & harmonics
  - Flicker
  - Power Factor
    - Phase shift θ between voltage & current $\theta = \theta_v - \theta_i$
    - Power Factor = Cos θ leading or lagging
      - θ > 0 → V ↓ (inductive, current lags voltage),
      - θ < 0 → V ↑ (capacitive, current leads voltage)
    - Complex power $P_{inst} = P + jQ$ = real + reactive power
    - Ideal Q = 0 for Cos θ = 1, θ = 0.
    - Reasonable +/- 10% PF lead/lag
    - Example & Demo

Wind Power Topics

- Wind Power Facts
- How Wind Energy Works
- Building a Wind Farm
- Wind Farm Site

Wind Power Facts

- Small Scale Wind Power
  - Typically generated by consumers
  - Uses generators of 1KW or less
  - Does not serve as sole power source
  - Requires energy storage and/or grid separation system
  - Can take advantage of Net Metering

Wind Power Facts

- Medium Scale Wind Power
  - Single utility-scale turbine can power a college campus
  - Provides 30% of peak load power, 100+% during min load
  - 1.65 MW max, 1.0 MW typical output at 600 VAC, 3-phase, 60 Hz
  - Functions in 8 to 29 mph winds
  - Adjusts to campus avg power factor of ~.9 lagging (+25°)

Wind Power Facts

- Large/Utility Scale Wind Power
  - Typically generated in Wind farms
  - High Net Energy Gain (18 vs. 5 for solar)
  - Low Capacity factor (30% vs. 95% Nuke)
  - High space-to-energy ratio (20x coal)
  - High green factor, low natural cost

Wind Power Facts

World's largest producers by gross production and percentageof wind vs. other forms (as of 2008)

- Total Production:
  - Germany 22 GW
  - USA 17 GW
  - Spain 15 GW
  - India 8 GW
  - China 6 GW
  - World Total 74 GW
- Penetration Ratio:
  - Denmark 18%
  - Spain 9%
  - Portugal 9%
  - Germany 6%
  - Ireland 6%
  - World Wide 1%

Wind Power Facts

- Typical 1.6 MW turbine
  - Generates reactive power (requires reactive compensation)
  - Can power ~ 1000 homes or a small college
  - Produces energy for ~ 4¢ per KWh
  - Displaces 1800-3000 tons of CO_2 annually
  - Kills less than 5 birds per year

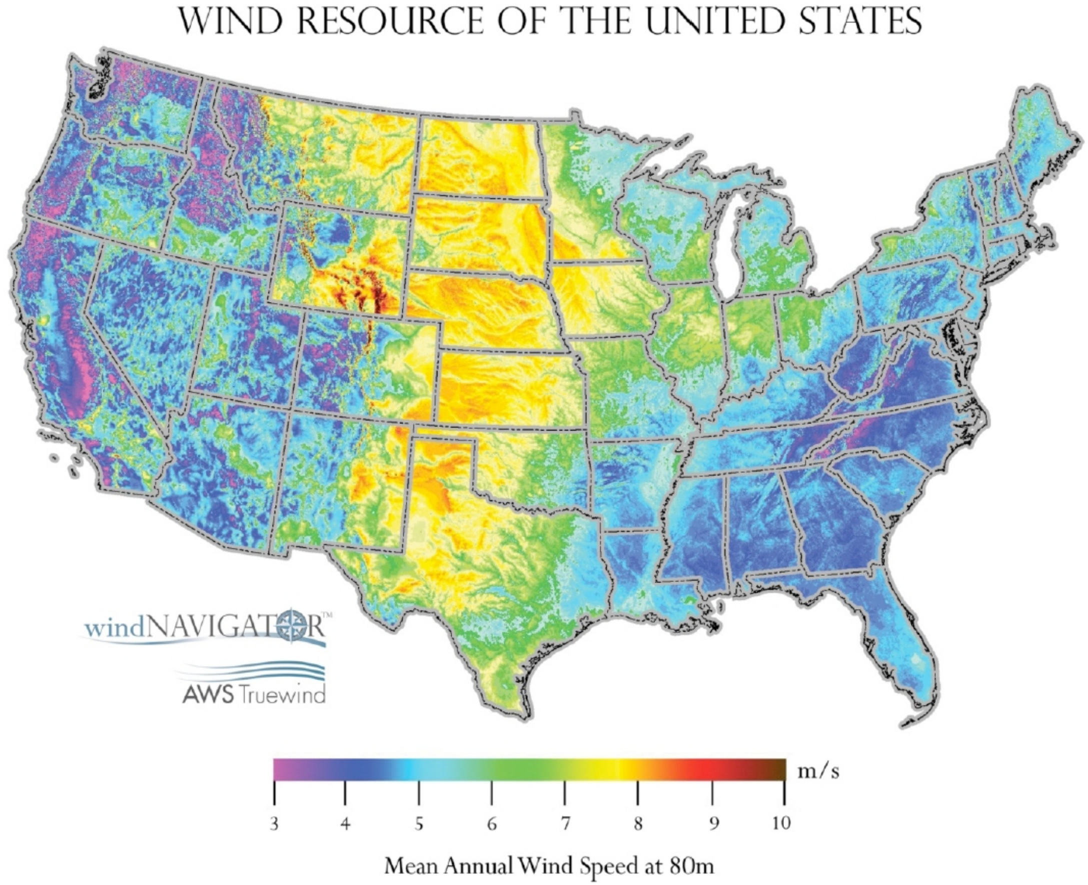
Wind Power Facts

- Typical 1.6 MW turbine
  - 400 ft tall (25 story building) weighs >200 tons
    - Tower: 250 ft, 115 tons
    - Nacelle: 50 tons
    - Blades: 140 ft, 10 tons
    - Rotor: 300 ft dia, 43 tons (hub & blades)
  - Costs $1.5 million, 20-yr life span
    - @ 30% capacity factor & retail of 10¢/KWh
      - generates $420K/yr
      - 4 year capital payback
      - 6 month energy payback

How Wind Energy Works

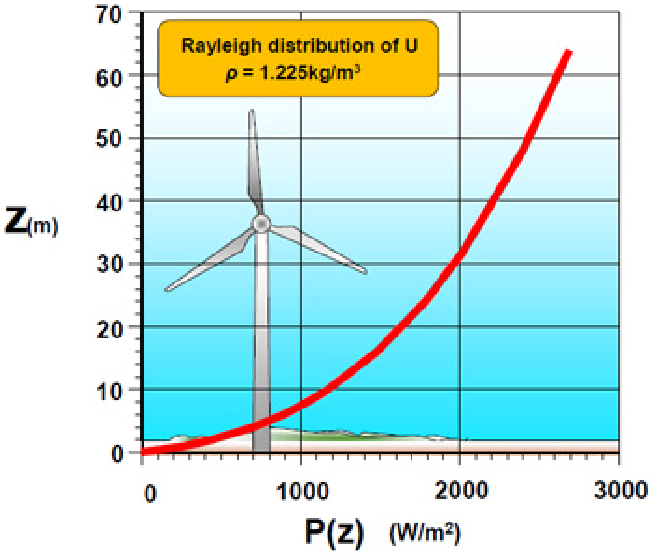
- Wind is air flowing from high to low pressure
- Created by trade winds, jetstream, local meterological phenomena
- Affected by topography, cloud cover, surface texture, uneven heating
- Energy is extracted in Boundary layer between upper atmosphere and Earth surface

How Wind Energy Works



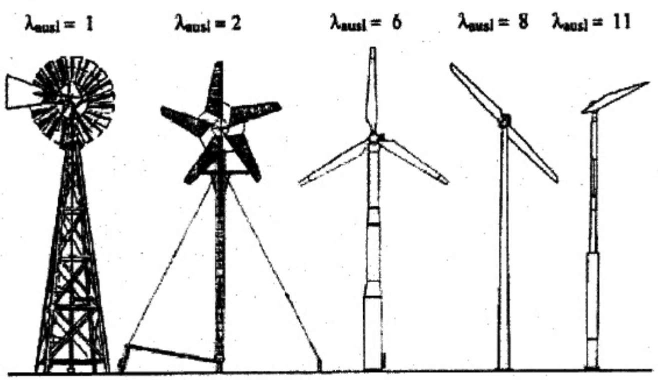
How Wind Energy Works

- Wind speed increases with altitude (shear)
  - Taller turbines for more energy resource & distance from surface disturbances
- Power in the wind
  - Power density = ½ ρ A U^3
    - Function of swept area and wind speed cubed
- Betz's Theory
  - Maximum energy extraction is 59.3%
  - Determined by maximizing power extracted while minimizing wind obstruction
  - Lift vs. Drag
    - Old windmills use drag/friction devices, new turbines use wings
    - Lift requires wind penetration of blade plane

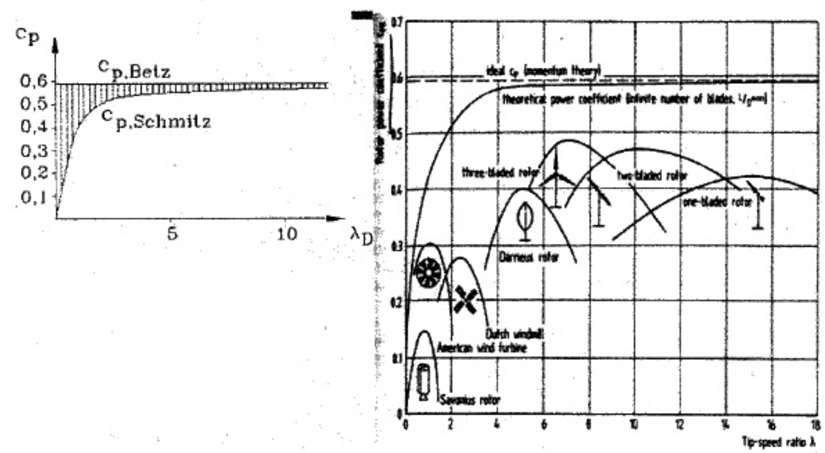


How Wind Energy Works

Blades



Betz versus Schmitz



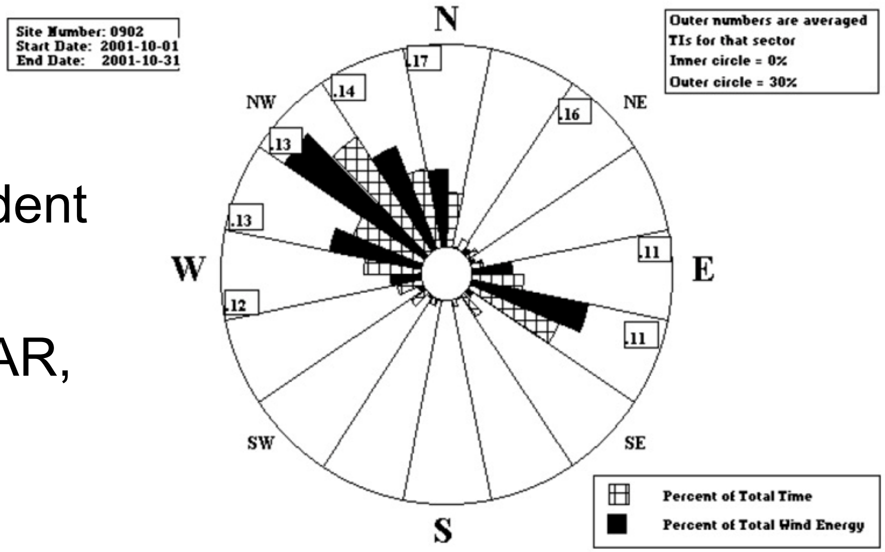
- Optimal configuration is 3-blades on horizontal axis
- Maximizes power coefficient while minimizing tip speed
- Reduces noise and increases aesthetic tolerance

Building a Wind Farm

- Critical issues:
  - Site assessment
  - Land use and availability
  - Permits
  - Transmission
  - Buyer
  - Financing

Building a Wind Farm

- Site Assessment
  - Wind Resource
    - Site-specific, terrain dependent
    - Evaluated over 1-5 years
    - Meteorological towers, LIDAR, data from NOAA and other sources
    - Wind Rose
    - Absolute power requirement (avg w.s. > 16 mph)



Building a Wind Farm

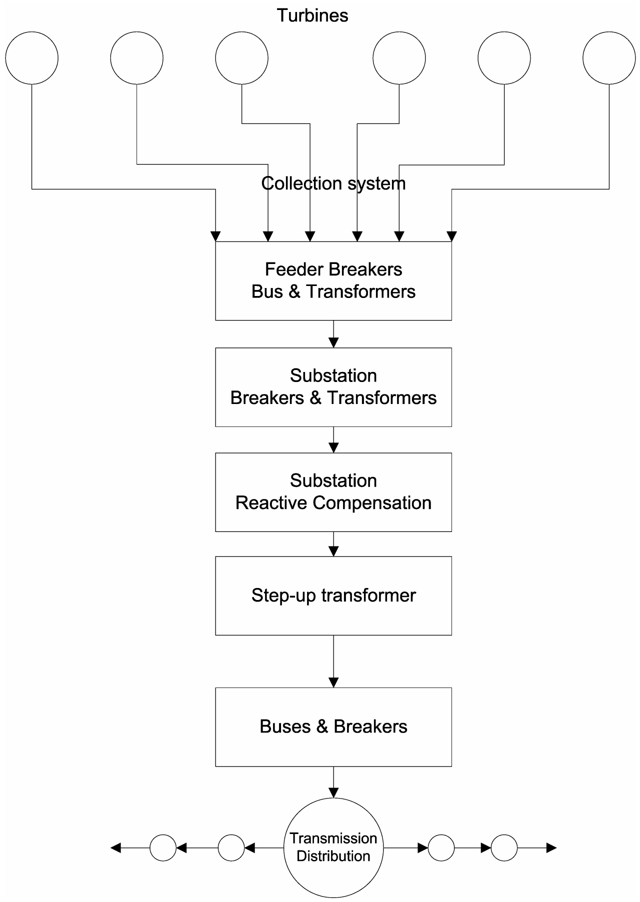
- Land use & availability
  - Land owner issues
    - Compensation (typically $3-5k/yr per turbine)
    - Single owner sites easier to coordinate
    - Multi-owner sites generate competition for compensation
  - Agricultural compatibility
  - Proximity to population & habitat
  - Accessibility

Building a Wind Farm

- Permits
  - Local, state, federal jurisdictions
  - Code ambiguity: Structure or machine?
  - Public acceptance (NIMBY & PIMBY)
  - Environmental/wildlife impact
- Transmission
  - Proximity to transmission/distribution network
  - Quality/compatibility/capacity of network
  - Existing infrastructure
- Buyer
- Financing

Wind Farm Site

- Turbine
  - Structure
  - Mechanical components
  - Electrical components
  - Types
- Collection system
  - Interconnection
  - Cabling
  - Grounding & Bonding
- Substation
  - Collector circuits
  - Breakers & Buses
  - Reactive compensation
  - Transformers
- Interconnect
  - Breakers & Buses

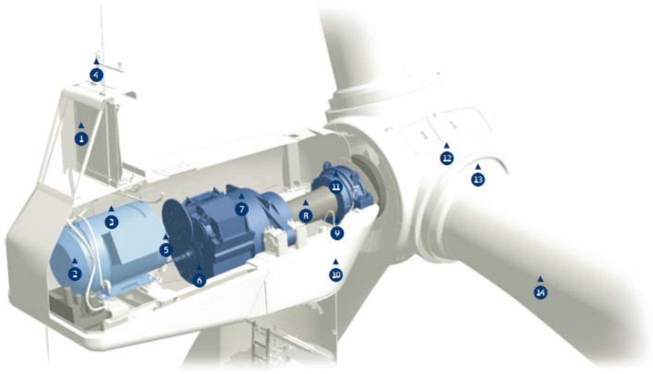


Wind Farm Site

- Turbine
  - Structural Components
    - Blades/Hub/Rotor
    - Nacelle
    - Tower
      - Rolled plate steel, thicker for taller tower
      - 13 ft max width
    - Foundation
      - Spreadfoot: 6’ deep x 40’ dia, 300-400 yd^3 concrete
      - Tubular cylinder: 30’deep x 4’ thick x 16’ OD

Wind Farm Site

- Turbine
  - Mechanical Components
    - Rotor Blades
      - Fiber shell over mechanical armature
      - Wing shape for lift, skew
      - Root & root bearing
    - Rotor Hub & Spinner
      - Pitch control, hydraulic or electric
    - Drive Train
    - Gearbox typically 50-100 : 1
      - Converts low-speed high torque to high speed low torque
    - Direct drive designs use gearless large rotor/stator with many poles
    - Pumps (cooling & lube oil)
    - Yaw & Pitch motors (typically electric drive)



Wind Farm Site

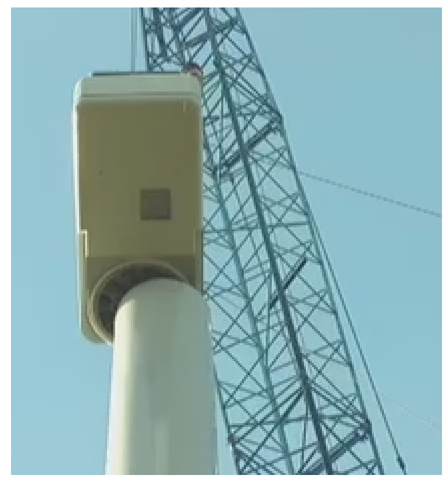
- Turbine
  - Electrical Components
    - Generator – four types (next slide)
    - Transformer
      - Steps up from < 1 KV to collection voltage (10-35 KV)
      - Mounted in nacelle or at base of tower
    - Down cables
      - DLO cables
      - Twist issues
    - Controls
      - In base, nacelle & rotor
      - Sensors for machine & environment
      - Constantly optimizing production for existing winds and power quality

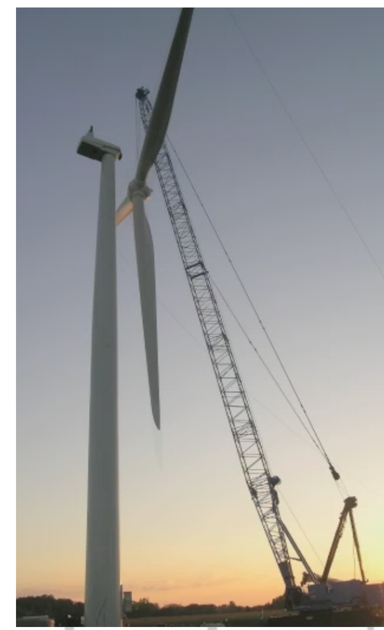
Wind Farm Site

- Turbine
  - Four main generator types
    - 1/A. Fixed Speed (synchronous)
      - Speed maintained by controlling blade pitch
      - Limited control of slip and power quality 1-3%
      - Consumes reactive power, requires/includes cap bank
    - 2/B. Limited Variable Speed (synchronous)
      - Greater control of slip and power quality ~10%
      - Consumes reactive power, requires/includes cap bank
    - 3/C. Variable Speed with Partial Scale PE Converters (asynchronous)
      - DFIG / DFAG
      - Most common type sold currently
      - More control of slip 50%
      - Can control VAR to self-compensate for power factor
      - ~30% of machine power uses power electronics converters
    - 4/D. Variable Speed with Full Scale PE Converters
      - Next generation upcoming
      - 100% slip control
      - Full VAR control for complete power factor compensation
      - 100% of machine power uses power electronics converters
      - Can utilize any motor type, including direct drive

Wind Farm Site

- Installation





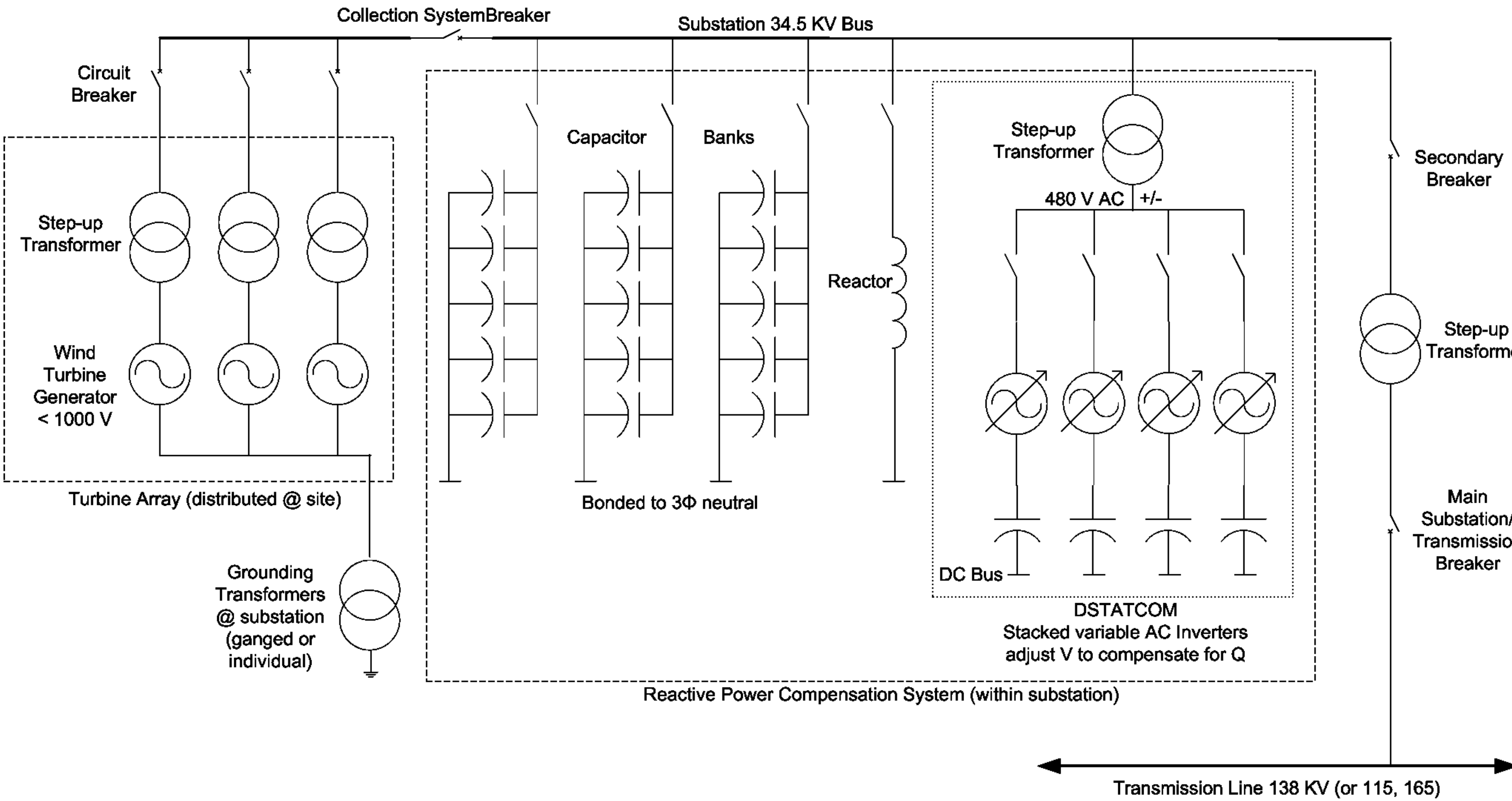
Wind Farm Site

- Collection System
  - Interconnect between turbines and substation
  - Collector/feeder circuits ~35 KV
  - Cabling issues
    - Underground vs overhead
      - Underground preferred for aesthetics
      - More expensive, better protection, larger cable size
    - Soil Rho
    - Gounding/bonding

Wind Farm Site

- Substation
  - Interface between wind farm and grid and/or transmission lines
  - Collector circuit breakers & buses
  - Transformers (grounding and intermediate step-up/down between 34.5 KV and 115, 138, 165 KV)
  - Reactive Compensation
    - Capacitor banks: ~ 5‖caps per Φ, ~10 to 50 uF total, 50-600 KVAR
    - Reactor: 1 inductor per Φ, ~315 mH, 120 Ω, 35 KV @ 10MVAR
    - STATCOM/DSTATCOM
      - Uses inverter to synthesize variable under/over voltage to compensate for PF
      - $V_{inv} > V_{util} \rightarrow$ looks like capacitor, compensates for inductive PF
      - $V_{inv} < V_{util} \rightarrow$ looks like inductor, compensates for capacitive PF
      - Multiple sources stacked to add more compensation (switchable)
      - Power electronics technology is expanding capabilities (thyristors)
  - Transmission output
    - Grid/transmission interconnect

Wind Farm Site



Substation Flow

Wind Farm Site

Collector
Breakers &
Transformers

Collection Bus
Breaker &
Substation
Bus

Reactor

Reactor &
Cap Banks

DSTATCOM

Substation

Wind Farm Site

Substantion-transmission interconnect

Main Breaker

Transmission Line

Transmission Connection

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References

- Banner image: www.horizonwind.com
- Images, tables, figures: *Fundamentals of Wind Power Plant Design,* University of Wisconsin
- Transportation images: Lake Superior Warehousing Co. Inc. www.lswci.com
- Installation images: http://stolafturbine.blogspot.com/, Pat Kelly
- Turbine/Farm photos: Andrew Tubesing

Questions…