

ECEN 667

Power System Stability

Lecture 27: Wind and Solar Resources

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UNIVERSITY

Announcements



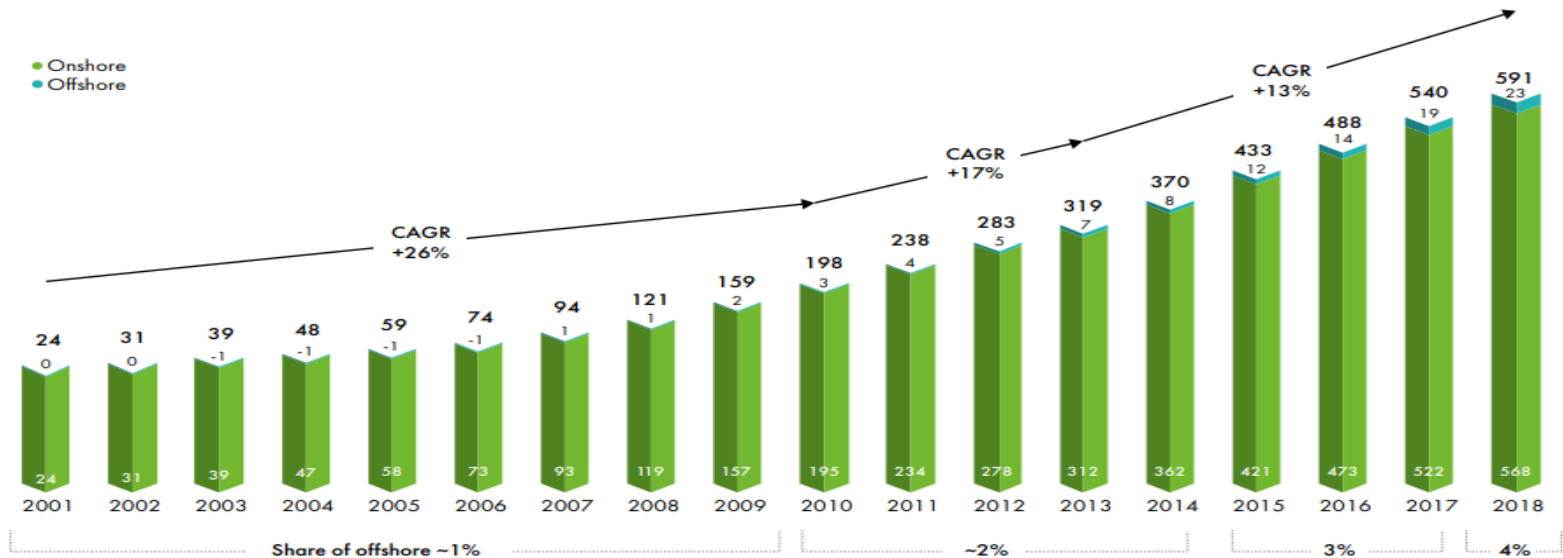
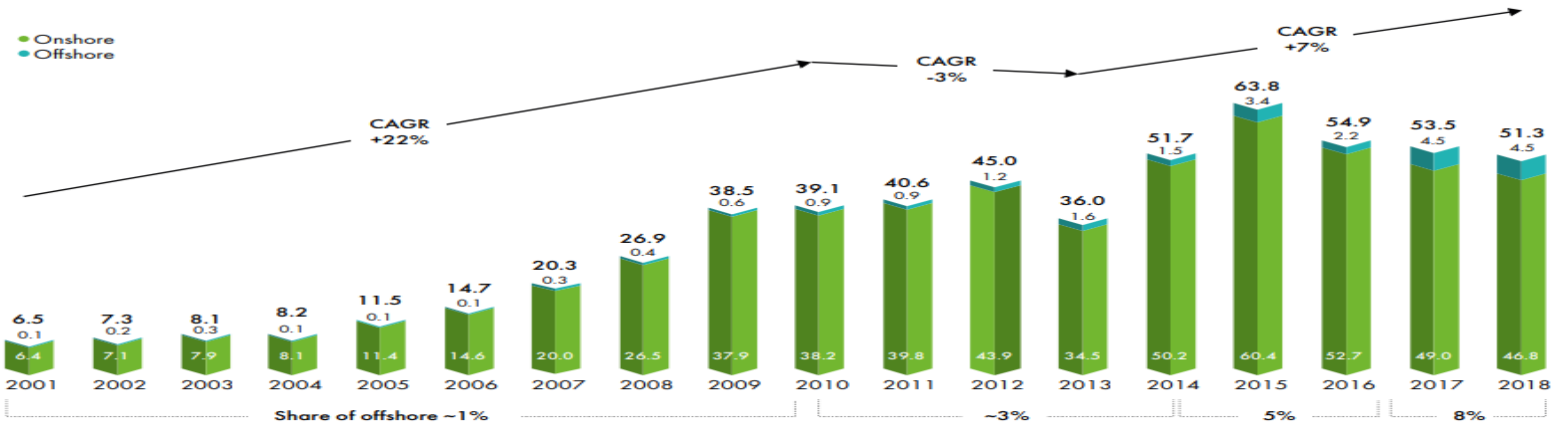
- Read Chapter 9
- Homework 6 is due on Wednesday December 4
- Final is at scheduled time here (December 9 from 1pm to 3pm)

Renewable Resource Modeling



- With the advent of more renewable generation in power systems worldwide it is important to have correct models
- Hydro systems have already been covered
- Solar thermal and geothermal are modeled similar to existing steam generation, so they are not covered here
- Coverage will focus on transient stability level models for wind and solar PV for integrated system studies
 - More detailed EMTP-level models may be needed for individual plant issues, like subsynchronous resonance
 - Models are evolving, with a desire by many to have as generic as possible models

Growth in Wind Worldwide

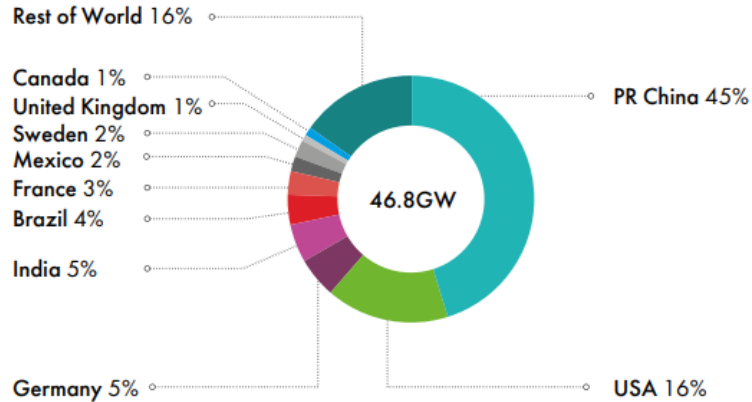


Source: Global Wind 2018 Report, Global Wind Energy Council

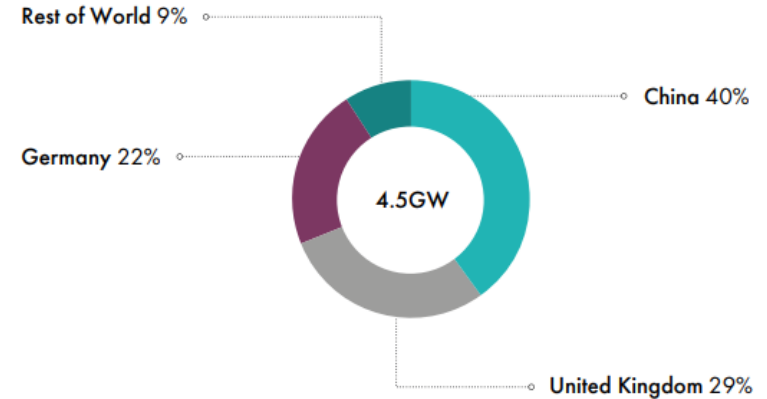
Growth in Wind Worldwide



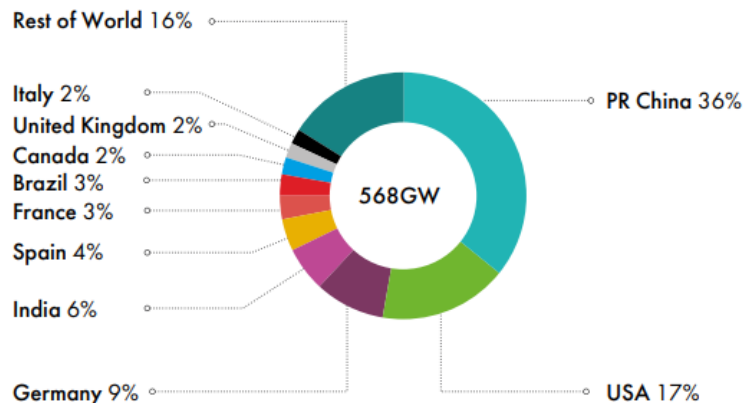
New installations onshore



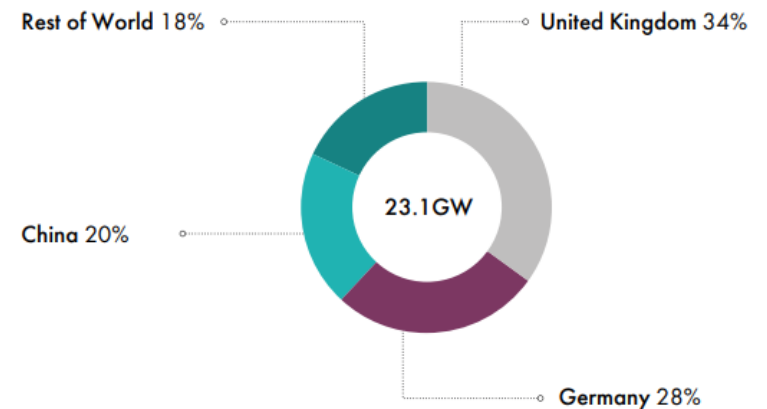
New installations offshore



Total installations onshore



Total installations offshore

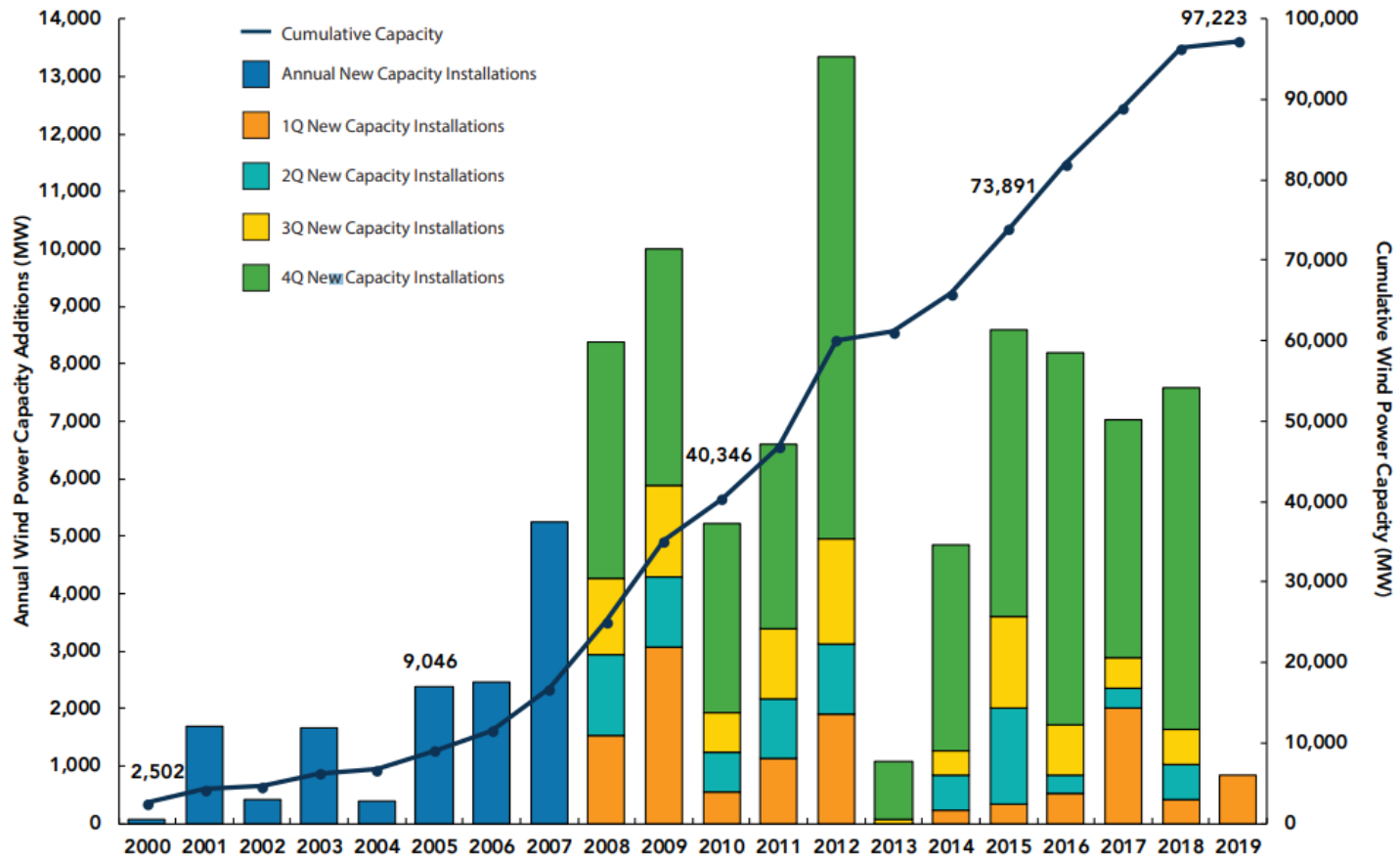


Source: Global Wind 2018 Report, Global Wind Energy Council

US Annual and Cumulative Wind Power Capacity Growth

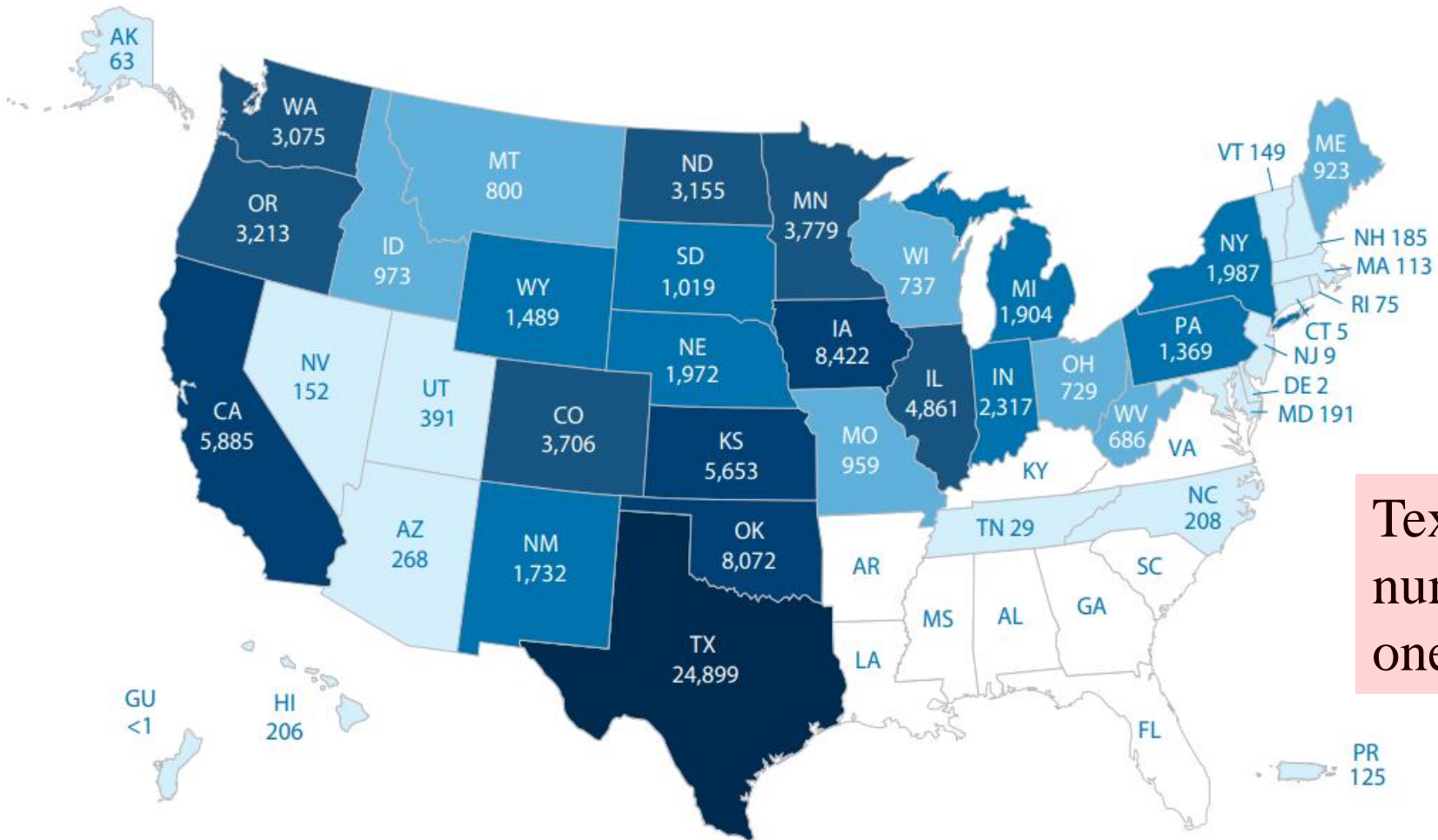


U.S. Annual and Cumulative Wind Power Capacity Growth



Note: Utility-scale wind capacity includes installations of wind turbines larger than 100-kW for the purpose of the AWEA U.S. Wind Industry Quarterly Market Reports. Annual capacity additions and cumulative capacity may not always add up due to decommissioned and repowered wind capacity. Wind capacity data for each year is continuously updated as information changes. AWEA did not track quarterly activity prior to 2008.

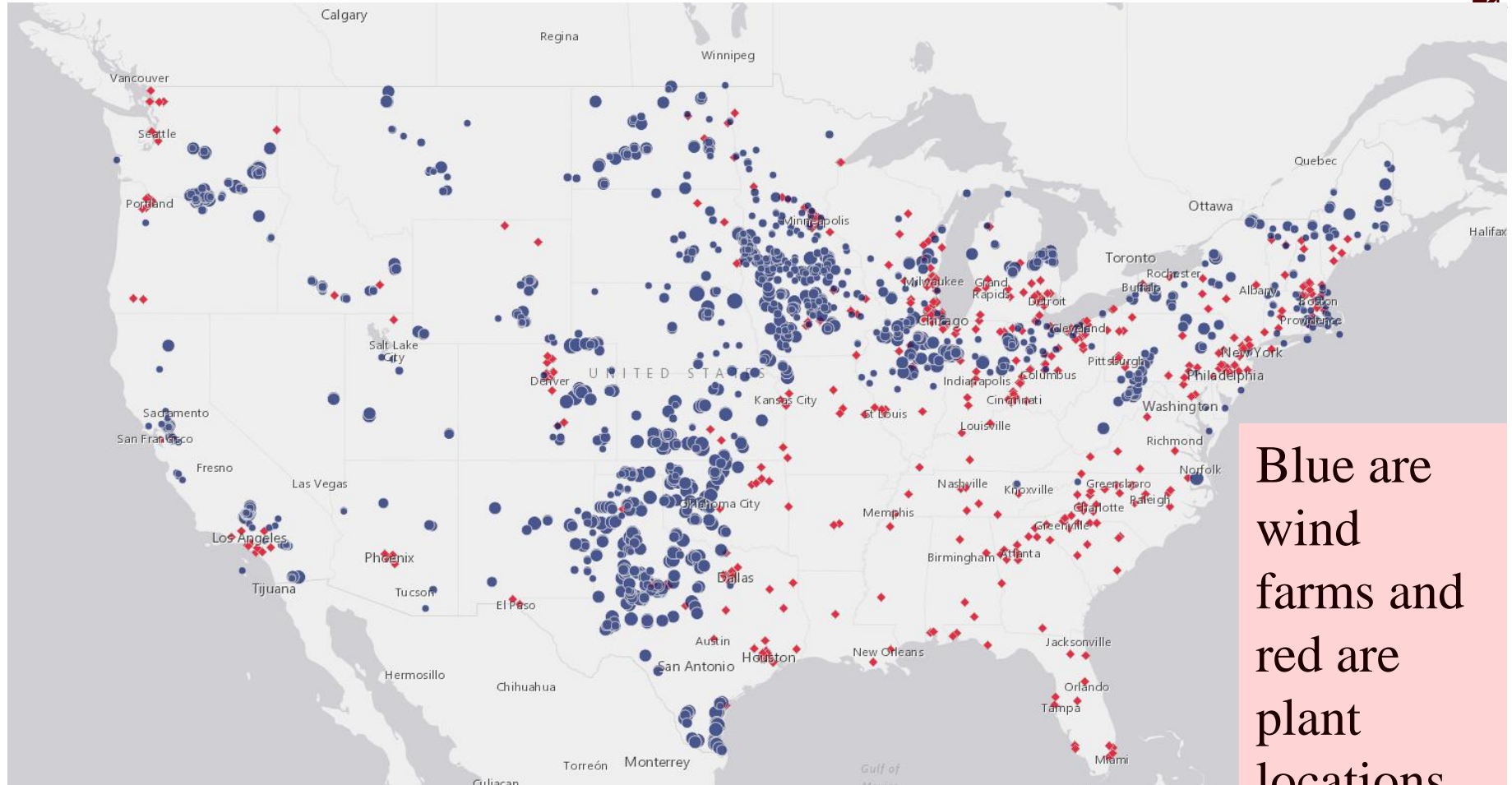
2018 Installed Capacity by State



Texas is number one!

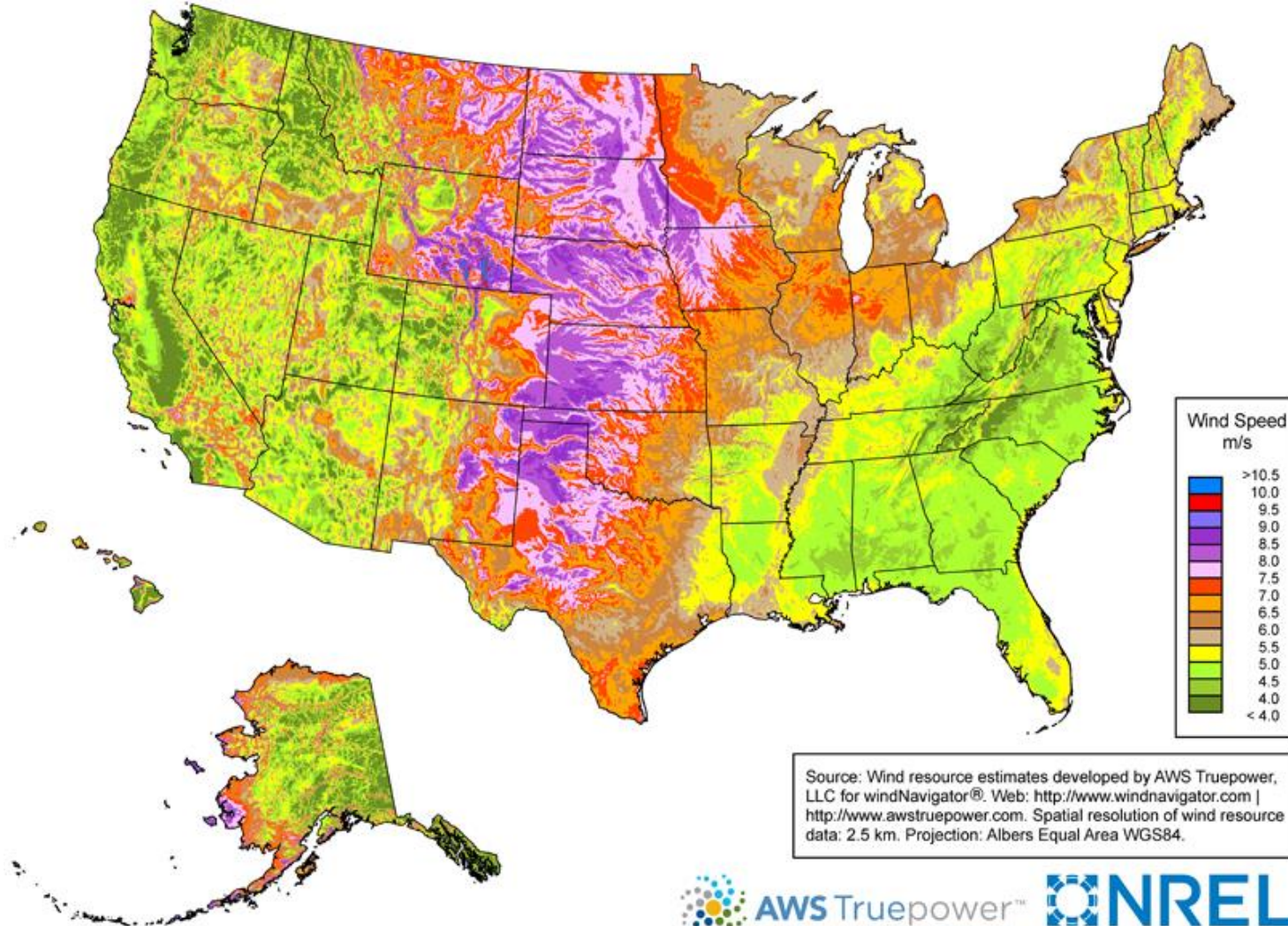


Wind Farm and Wind-Related Plant Locations

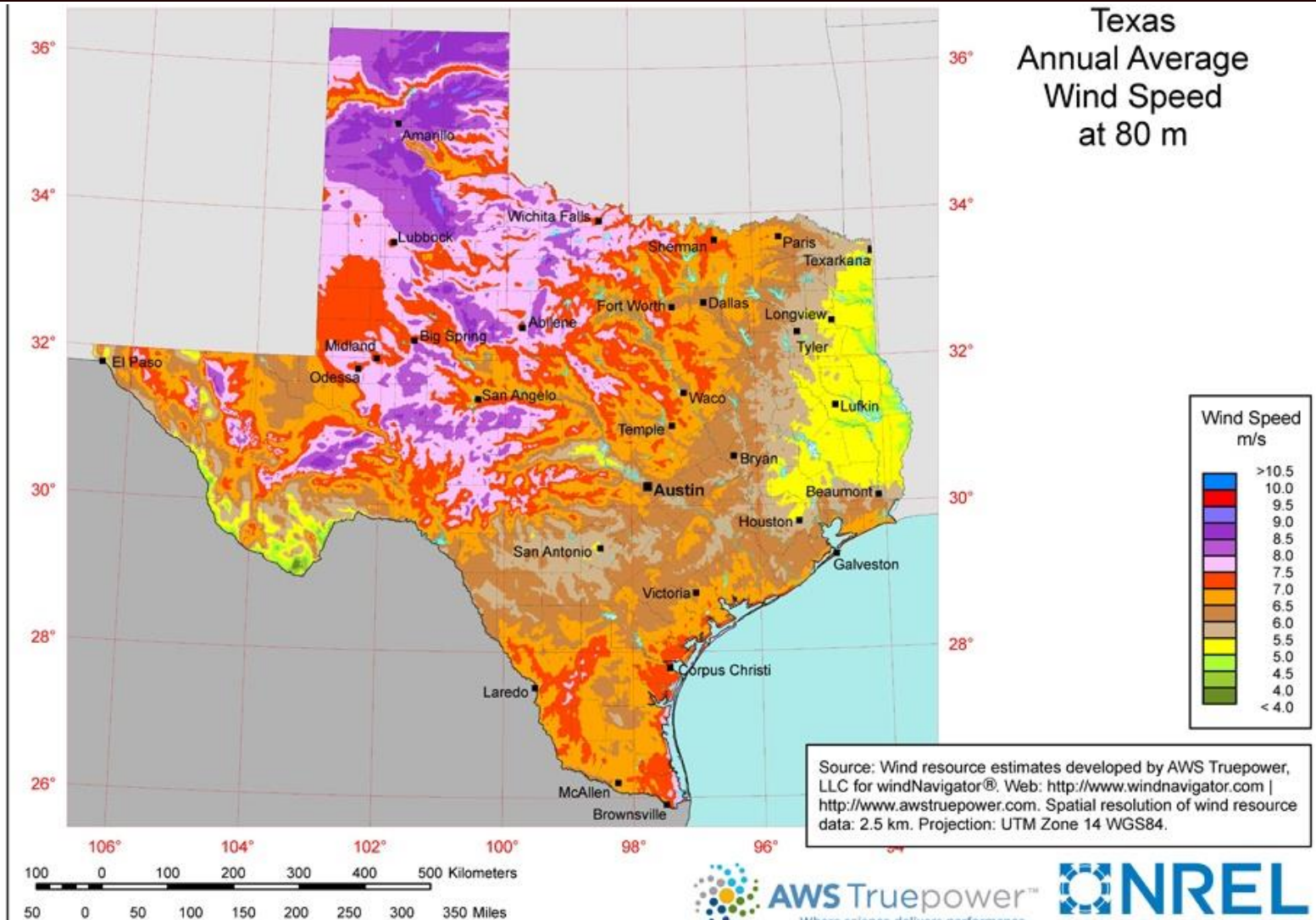


Blue are
wind
farms and
red are
plant
locations

US Wind Resources



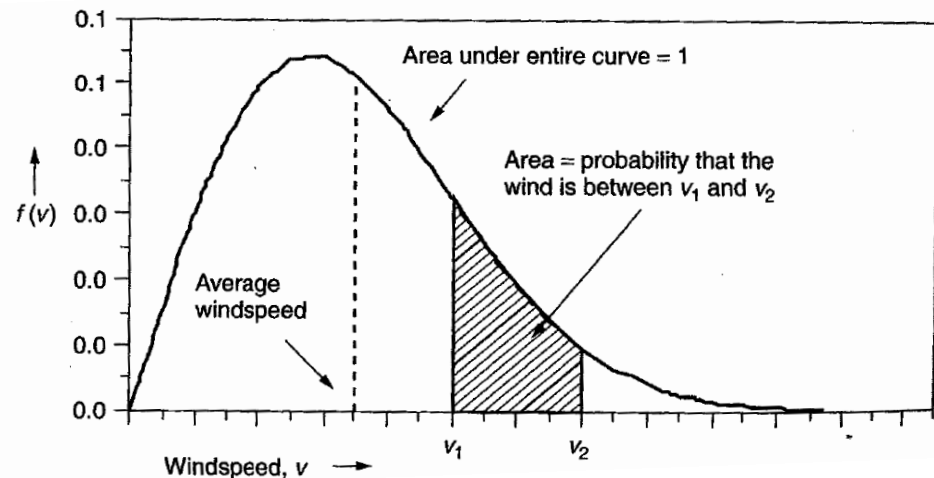
Wind Map Texas– 80m Height



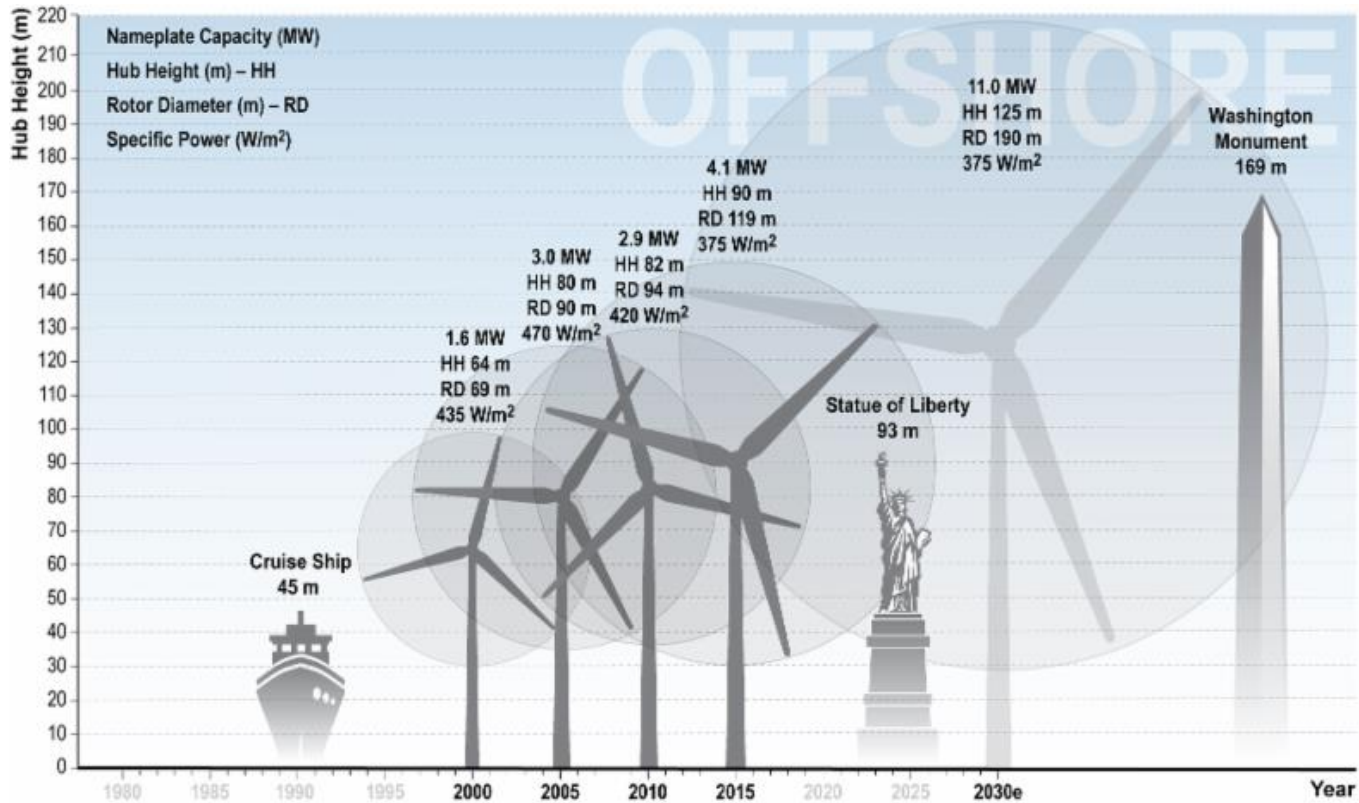
Power in the Wind



- The power in the wind is proportional to the cube of the wind speed
 - Velocity increases with height, with more increase over rougher terrain (doubling at 100m compared to 10m for a small town, but only increasing by 60% over crops or 30% over calm water)
- Maximum rotor efficiency is 59.3%, from Betz' law
- Expected available energy depends on the wind speed probability density function (pdf)



Wind Turbine Height and Size

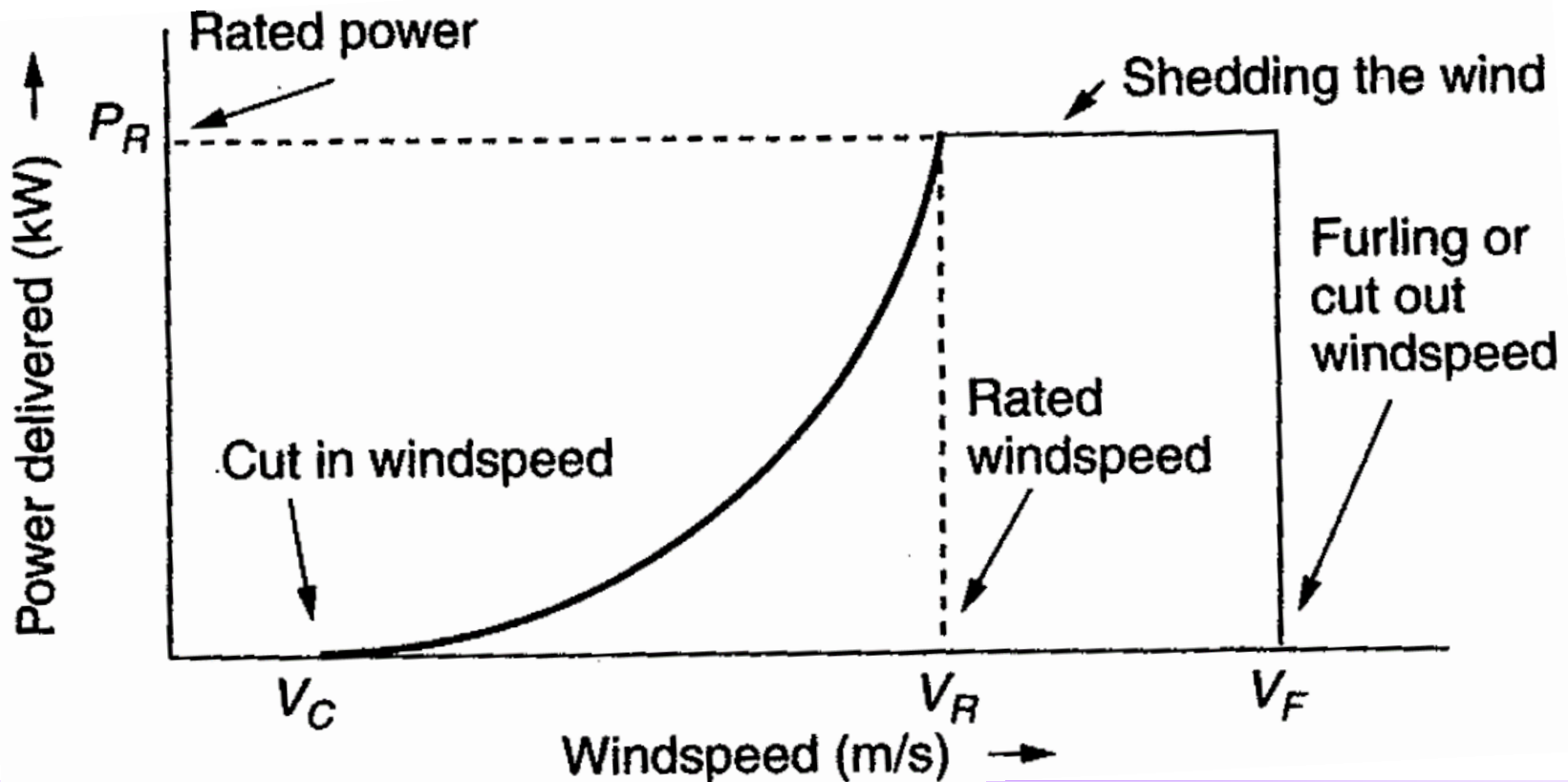


The current largest wind turbine by capacity is the Vestas V164 which has a capacity of 9.5 MW, a height of 220 m, and diameter of 164 m.

Extracted Power



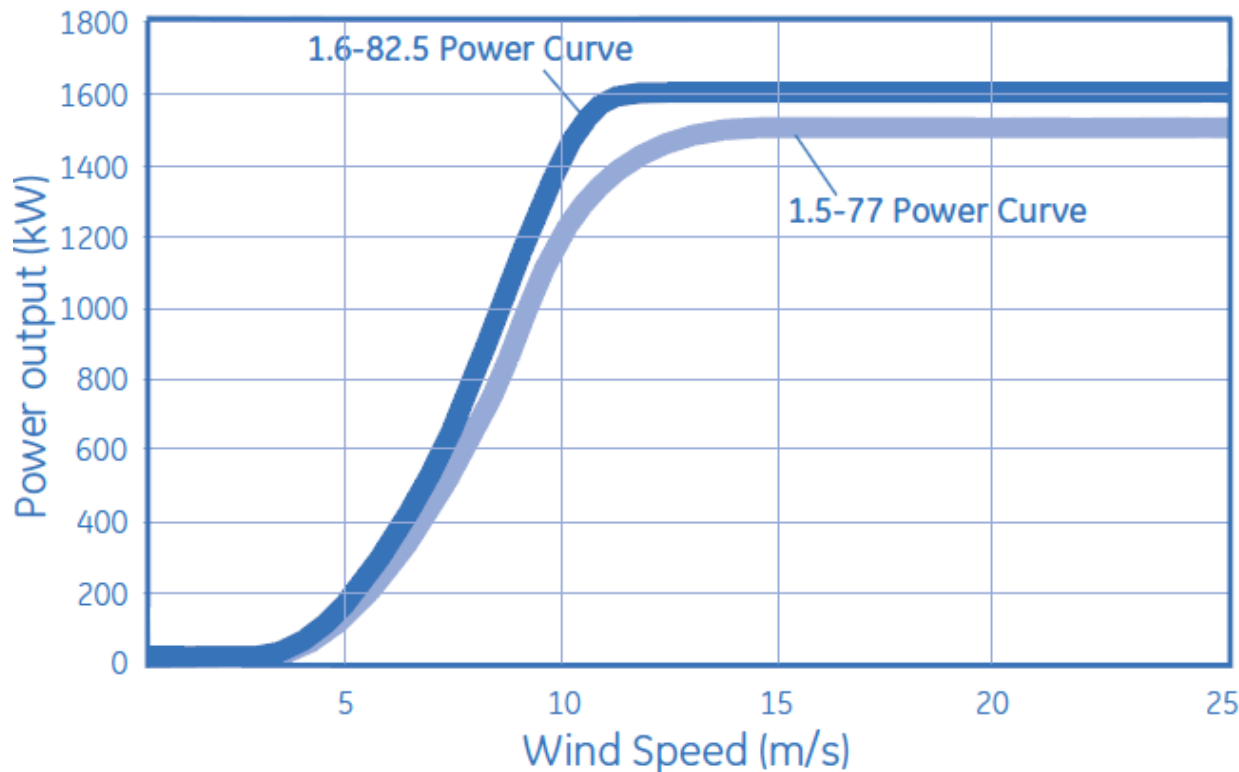
- WTGs are designed for rated power and windspeed
 - For speeds above this blades are pitched to operate at rated power; at furling speed the WTG is cut out



Example: GE 1.5 and 1.6 MW Turbines



- Power speed curves for the GE 1.5 and 1.6 MW WTGs
 - Hub height is 80/100 m; cut-out at 25 m/s wind

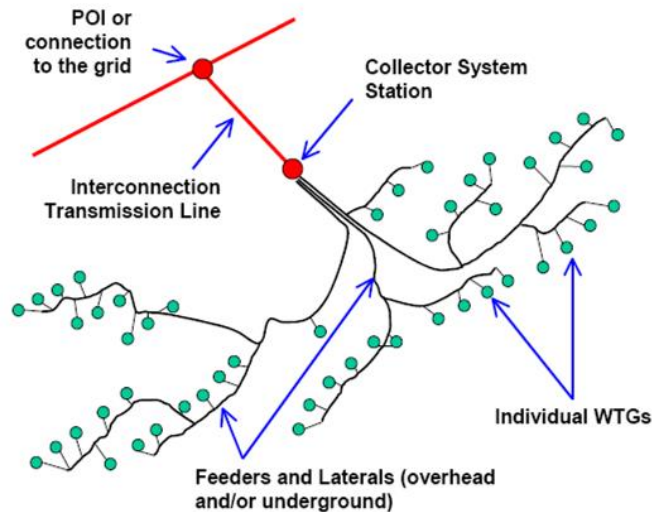


Source: http://site.ge-energy.com/prod_serv/products/wind_turbines/en/15mw/index.htm

Wind Farms (or Parks)



- Usually wind farm is modeled in aggregate for grid studies; wind farm can consist of many small (1 to 3 MW) wind turbine-generators (WTGs) operating at low voltage (e.g. 0.6kV) stepped up to distribution level (e.g., 34.5 kV)



Economies of Scale

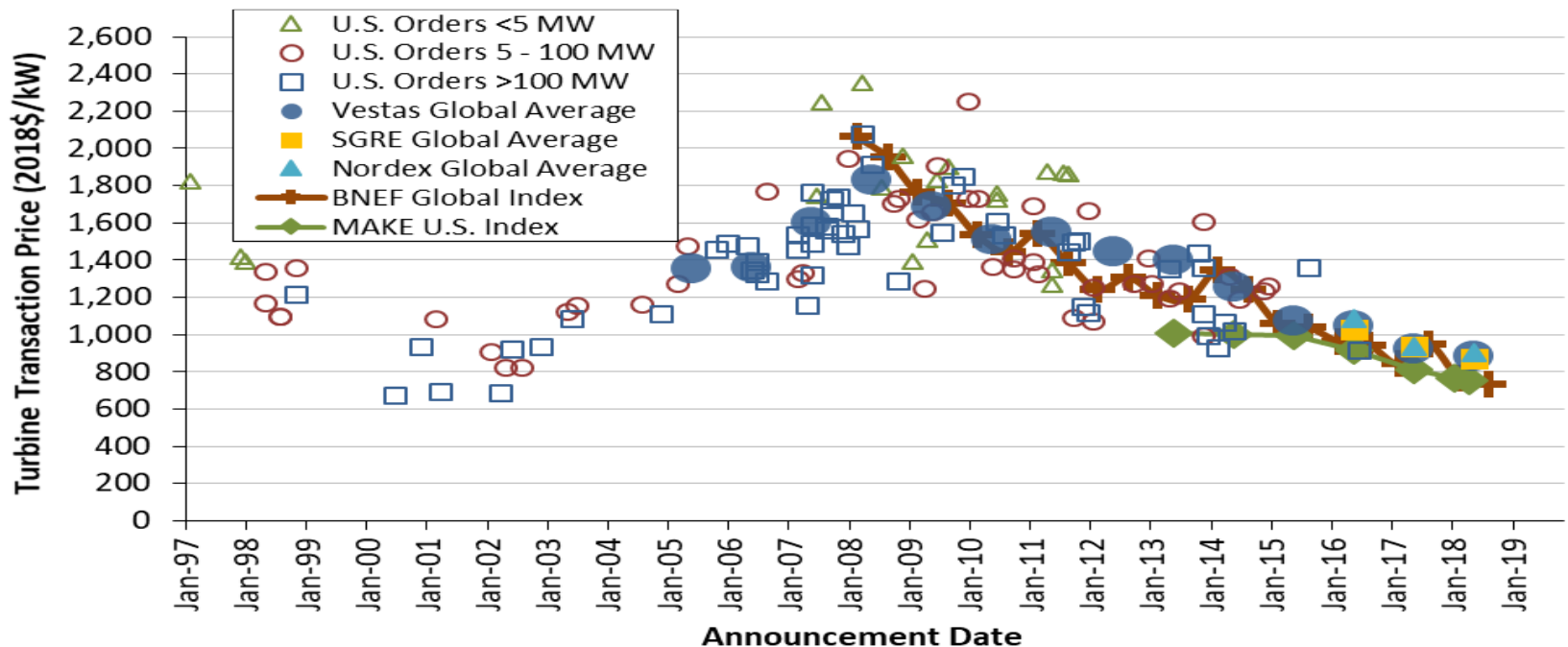


- Presently large wind farms produce electricity more economically than small operations
- Factors that contribute to lower costs are
 - Wind power is proportional to the area covered by the blade (square of diameter) while tower costs vary with a value less than the square of the diameter
 - Larger blades are higher, permitting access to faster winds, but size limited by transportation for most land wind farms
 - Fixed costs associated with construction (permitting, management) are spread over more MWs of capacity
 - Efficiencies in managing larger wind farms typically result in lower O&M costs (on-site staff reduces travel costs)

Wind Energy Economics



- Most of the cost is in the initial purchase and construction (capital costs); current estimate is about \$800/kW; how much wind is generated depends on the capacity factor, best is about 40%



Trends in US Turbine Size

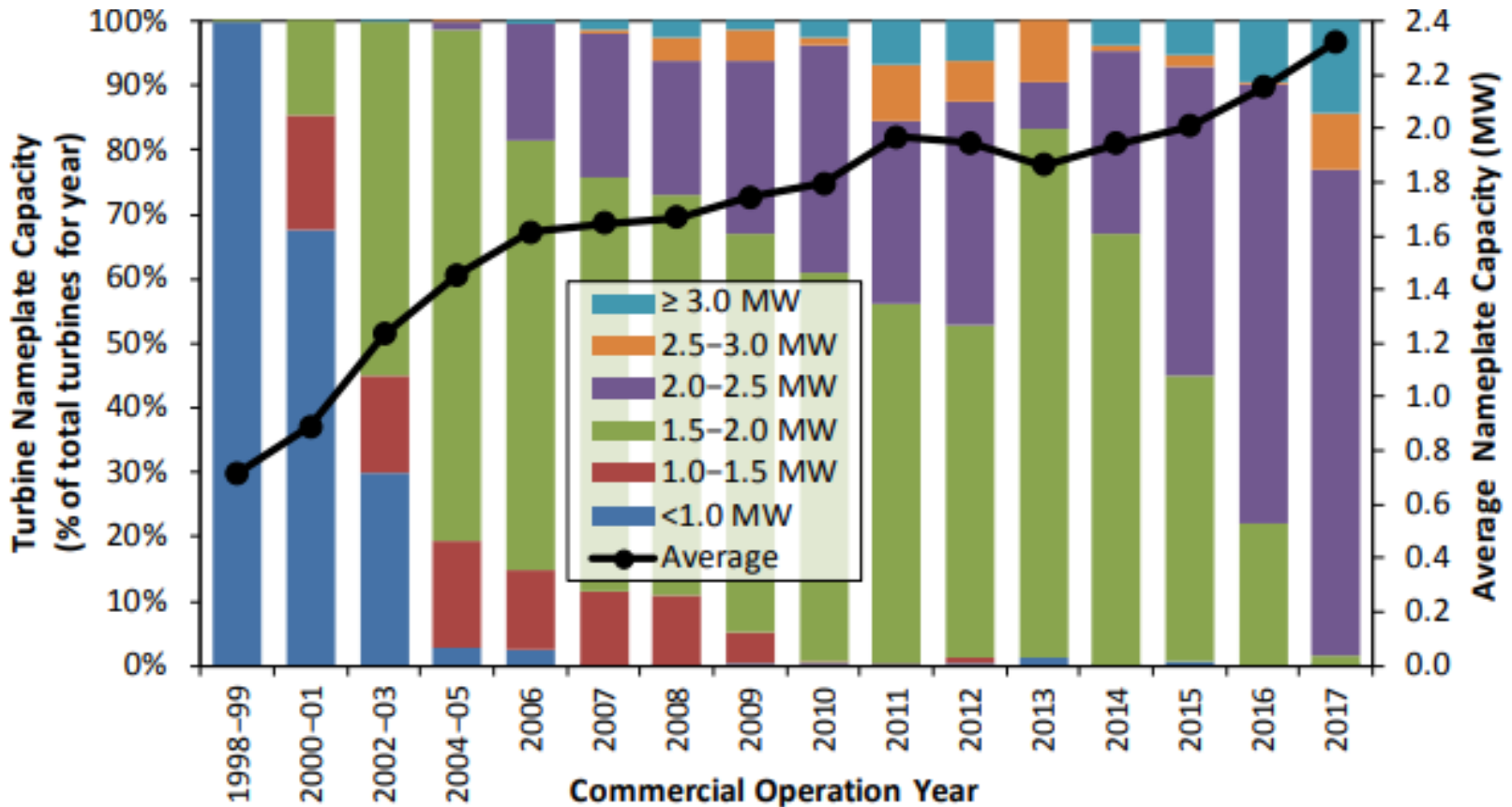


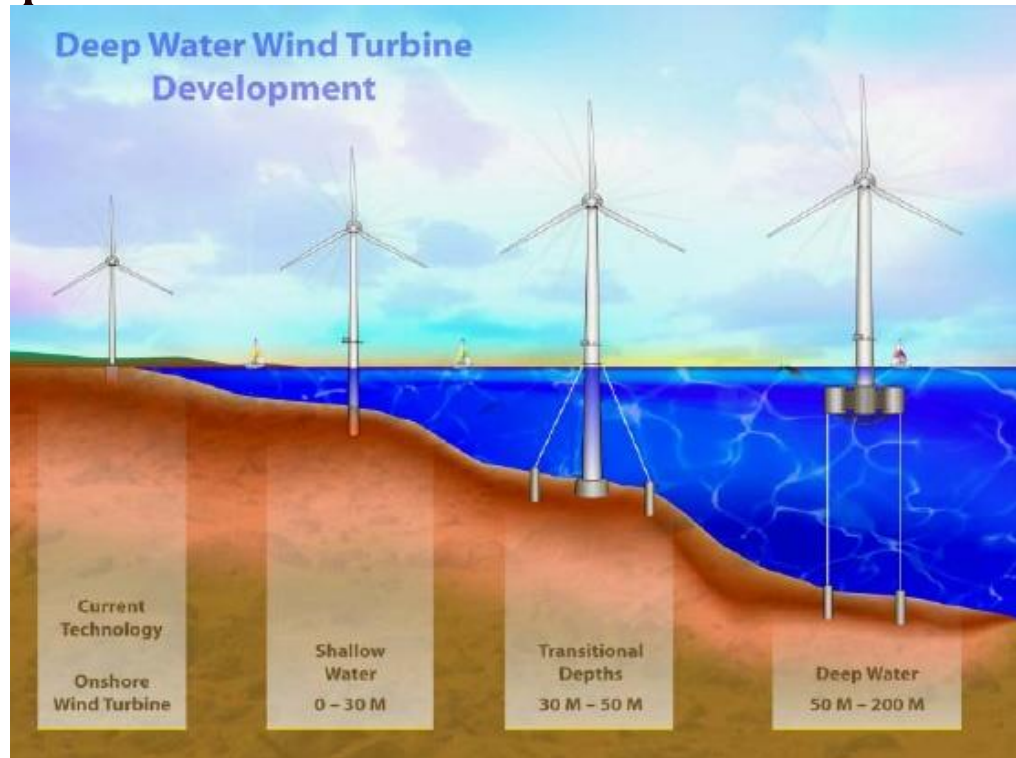
Figure 21. Trends in turbine nameplate capacity

Source: US DOE 2017 Wind Technologies Market Report

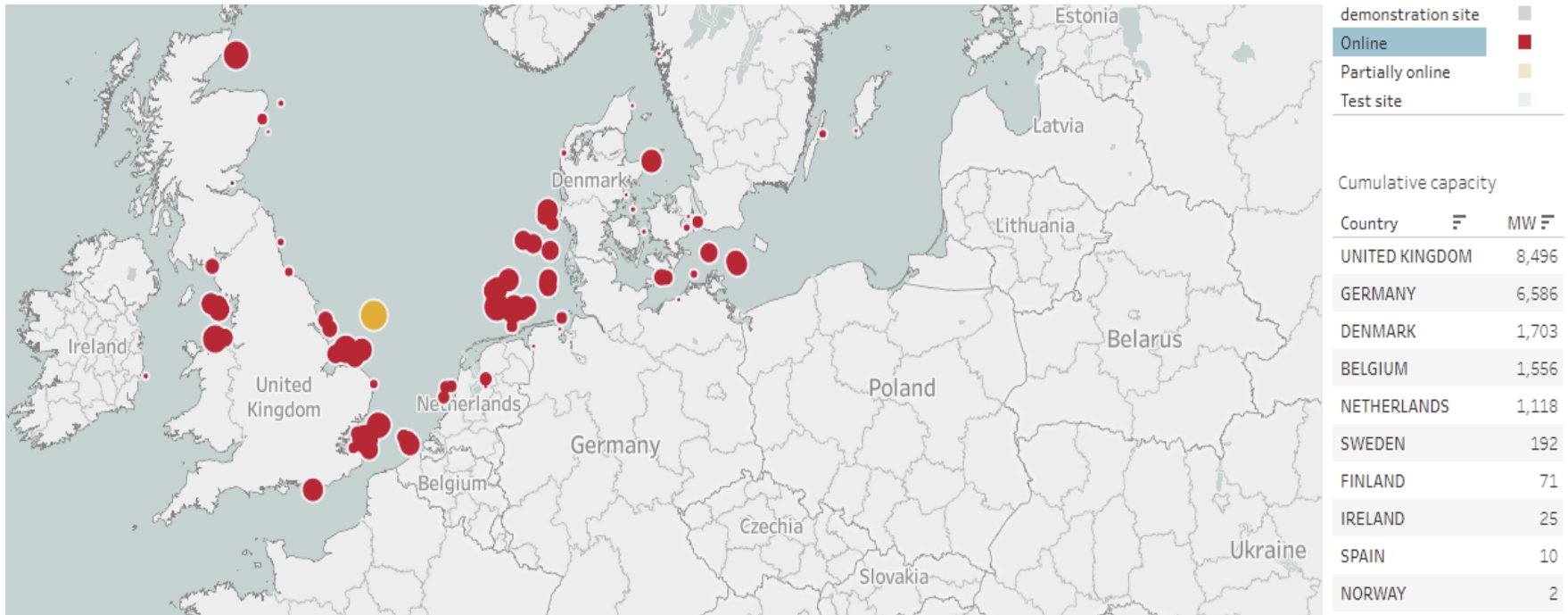
Offshore Wind



- Offshore wind turbines currently need to be in relatively shallow water, so maximum distance from shore depends on the seabed
- Capacity factors tend to increase as turbines move further off-shore



Offshore Wind Installations



The first US offshore wind, Block Island (Rhode Island) with 30 MW, became operational in December 2016, though a large amount is planned. China now has 4.6 GW offshore.

Offshore: Advantages and Disadvantages



- All advantages/disadvantages are somewhat site specific
- Advantages
 - Can usually be sited much closer to the load (often by coast)
 - Offshore wind speeds are higher and steadier
 - Easier to transport large wind turbines by ship
 - Minimal sound impacts and visual impacts (if far enough offshore), no land usage issues
- Disadvantages
 - High construction costs, particularly since they are in windy (and hence wavy) locations
 - Higher maintenance costs
 - Some environmental issues (e.g., seabed disturbance)

Types of Wind Turbines for Power Flow and Transient Stability



- Several different approaches to aggregate modeling of wind farms in power flow and transient stability
 - Wind turbine manufacturers provide detailed, public models of their WTGs; these models are incorporated into software packages; example is GE 1.5, 1.6 and 3.6 MW WTGs (see Modeling of GE Wind Turbine-Generators for Grid Studies, version 4.6, March 2013, GE Energy)
 - Proprietary models are included as user defined models; covered under NDAs to maintain confidentiality
 - Generic models are developed to cover the range of WTGs, with parameters set based on the individual turbine types
 - Concern by some manufacturers that the generic models do not capture their WTGs' behavior, such as during low voltage ride through (LVRT)

Types of Wind Turbines for Power Flow and Transient Stability



- Electrically there are four main generic types of wind turbines
 - Type 1: Induction machine; treated as PQ bus with negative P load; dynamically modeled as an induction motor
 - Type 2: Induction machine with varying rotor resistance; treated as PQ bus in power flow; induction motor model with dynamic slip adjustment
 - Type 3: Doubly Fed Asynchronous Generator (DFAG) (or DFIG); treated as PV bus in power flow
 - Type 4: Full Asynchronous Generator; treated as PV bus in power flow
- New wind farms (or parks) are all of Type 3 or 4

Generic Modeling Approach



- The generic modeling approach is to divide the wind farm models by functionality
 - Generator model: either an induction machine for Type 1 and 2's or a voltage source converter for Type 3 and 4
 - Reactive power control (exciter): none for Type 1, rotor resistance control for Type 2, commanded reactive current for Type 3 and 4
 - Drive train models: Type 1 and 2 in which the inertia appears in the transient stability
 - Aerodynamics and Pitch Models: Model impact of changing blade angles (pitch) on power output

Wind Turbine Issues



- Models are designed to represent the system level impacts of the aggregate wind turbines during disturbances such as low voltages (nearby faults) and frequency deviations
- Low voltage ride through (LVRT) is a key issue, in which the wind turbines need to stay connected to the grid during nearby faults
- Active and reactive power control is also an issue

Low Voltage Ride Through (LVRT)



- The concern is if during low voltages, such as during faults, the WTGs trip, it could quickly setup a cascading situation particularly in areas with lots of Type 3 WTGs
 - Tripping had been a strategy to protect the DFAG from high rotor currents and over voltages in the dc capacitor.
 - When there were just a few WTGs, tripping was acceptable
- Standards now re performance

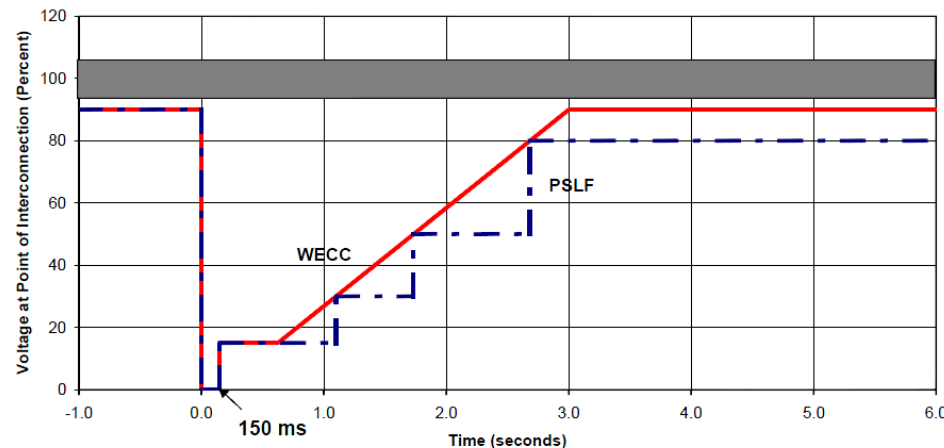


Image from California ISO presentation

Type 3: Doubly Fed Asynchronous Generators (DFAG)



- Doubly fed asynchronous generators (DFAG) are usually a conventional wound rotor induction generator with an ac-dc-ac power converter in the rotor circuit
 - Power that would have been lost in external rotor resistance is now used
- Electrical dynamics are dominated by the voltage-source inverter, which has dynamics much faster than the transient stability time frame

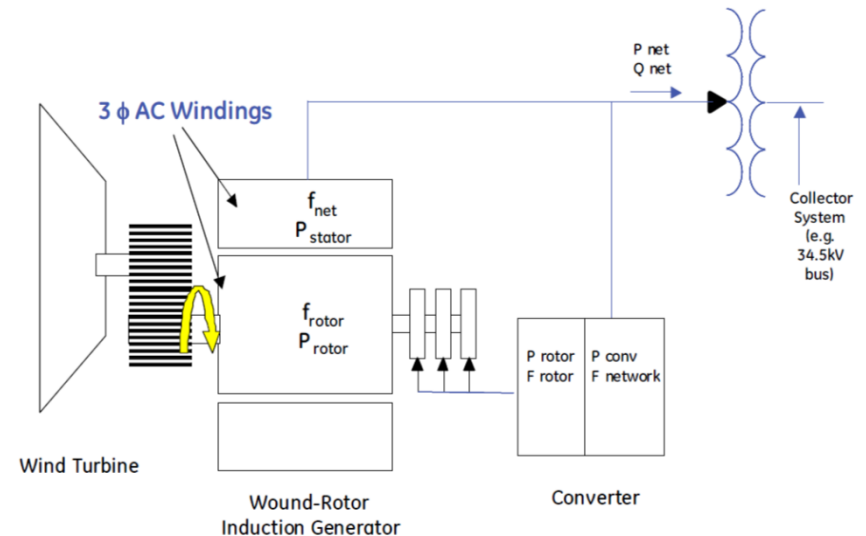


Figure 2-1. GE Doubly Fed Asynchronous WTG Major Components.

Type 3 Converters



- A voltage source converter (VSC) takes a dc voltage, usually held constant by a capacitor, and produces a controlled ac output
- A phase locked loop (PLL) is used to synchronize the phase of the wind turbine with that of the ac connection voltage
 - Operates much faster than the transient stability time step, so is often assumed to be in constant synchronism
- Under normal conditions the WTG has a controllable real power current and reactive power current
- WTG voltages are not particularly high, say 600V

Type 3 Converters



- Type 3 machines can operate at a potentially widely varying slip
 - Example, rated speed might be 120% (72 Hz for a 60 Hz system) with a slip of -0.2, but with a control range of +/- 30%
- Control systems are used to limit the real power during faults (low voltage)
 - Current ramp rate limits are used to prevent system stress during current recovery
- Reactive current limits are used during high voltage conditions

Aerodynamics



- Type 3 and 4 models have more detailed models that directly incorporate the blade angle, so a brief coverage of the associated aerodynamics is useful
- The power in the wind is given by

$$P = \frac{\rho}{2} A v_w^3 C_p(\lambda, \theta)$$

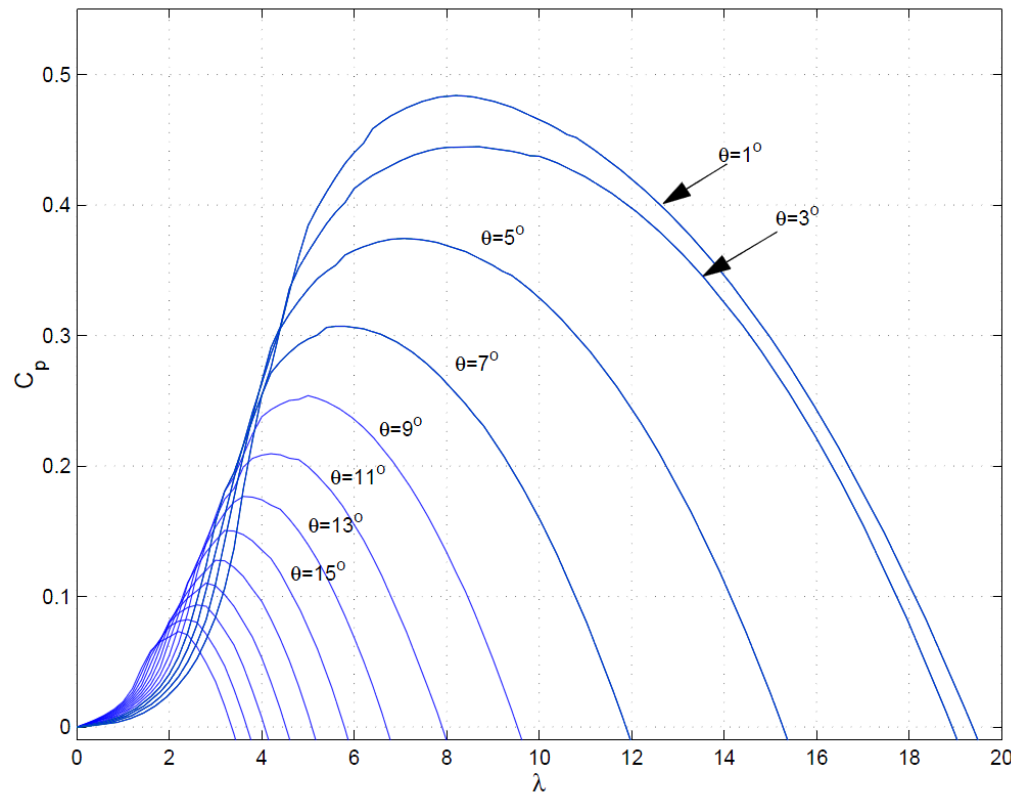
where ρ is the density of air, A is the area swept by the blades, v_w is the wind velocity, λ is the tip to wind speed ratio.

For a given turbine with a fixed blade length, $\lambda = K_b (\omega / v_w)$

Aerodynamics



- The $C_p(\theta, \lambda)$ function can be quite complex, with the GE 1.5 curves given below



If such a detailed curve is used, the initialization is from the power flow P . There are potentially three independent variables, v_w , θ and ω . One approach is to fix ω at rated (e.g., 1.2) and θ at θ_{\min}

Type 4 Converters

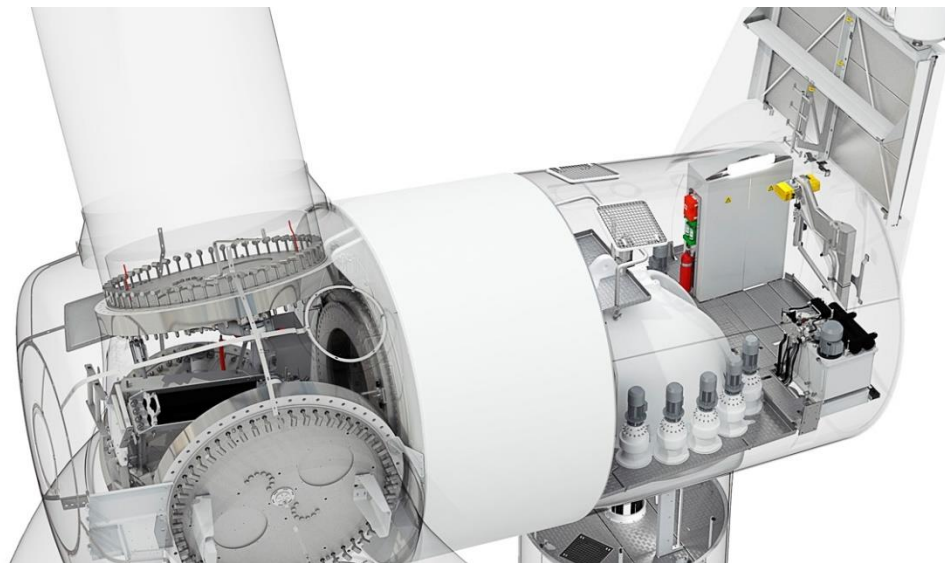


- Type 4 WTGs pass the entire output of the WTG through the ac-dc-ac converter
- Hence the system characteristics are essentially independent of the type of generator
 - Because of this decoupling, the generator speed can be as variable as needed
 - This allows for different generator technologies, such as permanent magnet synchronous generators (PMSGs)
 - Traditionally gearboxes have been used to change the slow wind turbine speed (e.g., 15 rpm) to a more standard generator speed (e.g., 1800 rpm); with Type 4 direct drive technologies can also be used

Example: Siemens SWT-2.3-113



- The Siemens-2.3-113 is a 2.3 MW WTG that has a rotor diameter of 113m. It is a gearless design based on a compact permanent magnet generator
 - No excitation power, slip rings or excitation control system

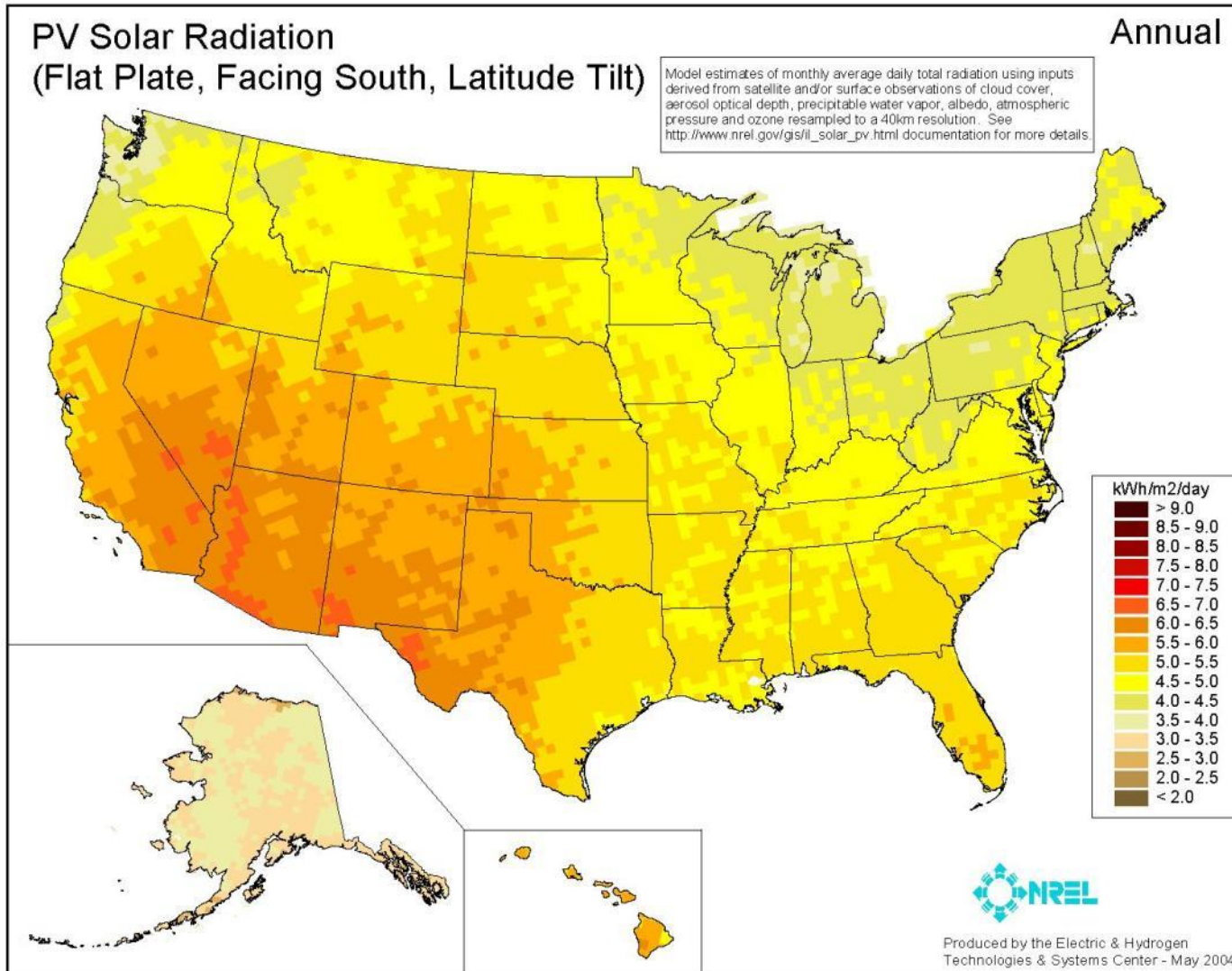


Solar Photovoltaic (PV)



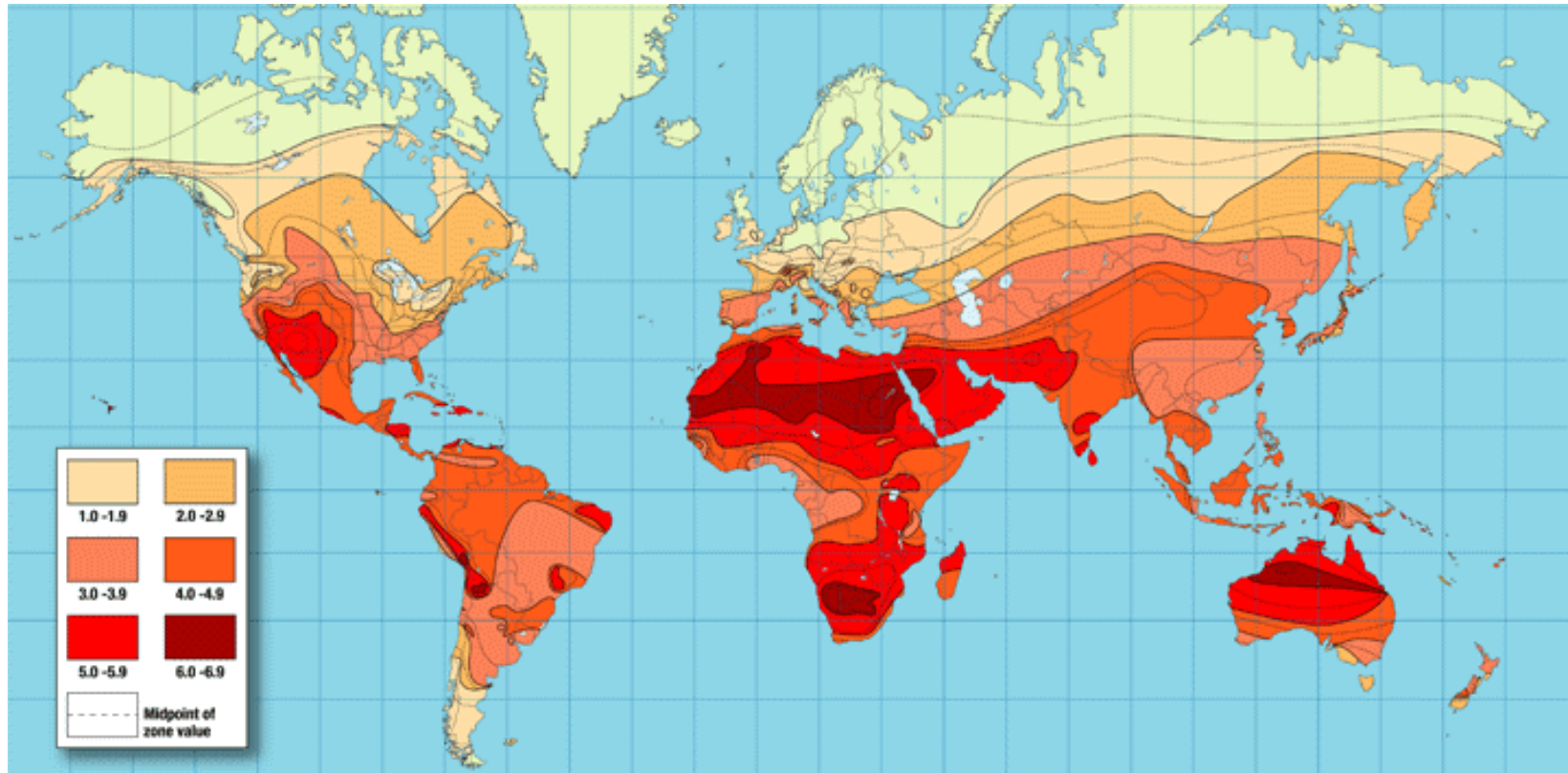
- **Photovoltaic definition-** a material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current
- Solar cells are diodes, creating dc power, which in grid applications is converted to ac by an inverter
- For terrestrial applications, the capacity factor is limited by night, relative movement of the sun, the atmosphere, clouds, shading, etc
 - A ballpark figure for Illinois is 18%
 - "One sun" is defined as 1 kW/m^2 , which is the maximum insolation that reaches the surface of the earth (sun right overhead)

US Annual Insolation

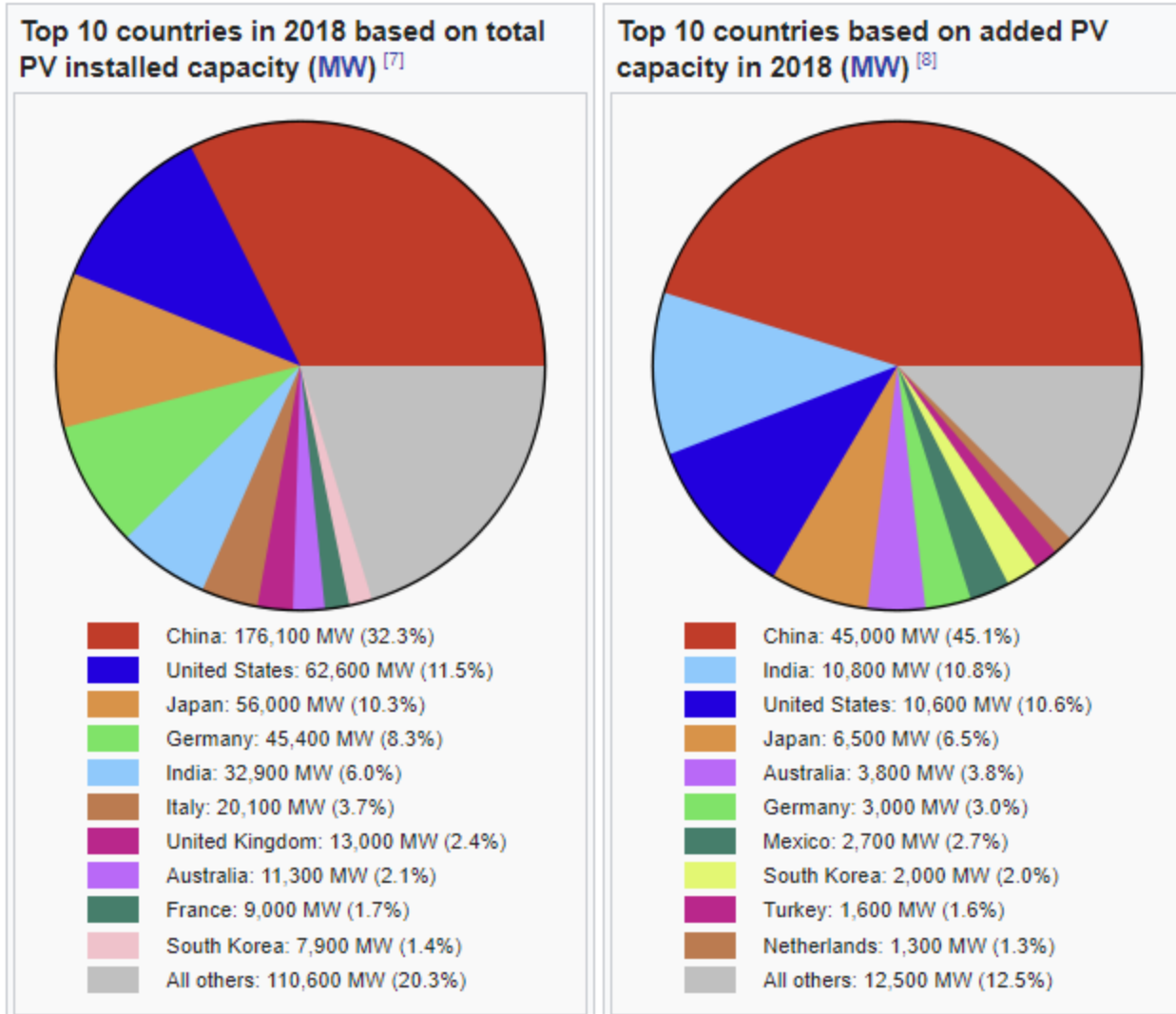


The capacity factor is roughly this number divided by 24 hours per day

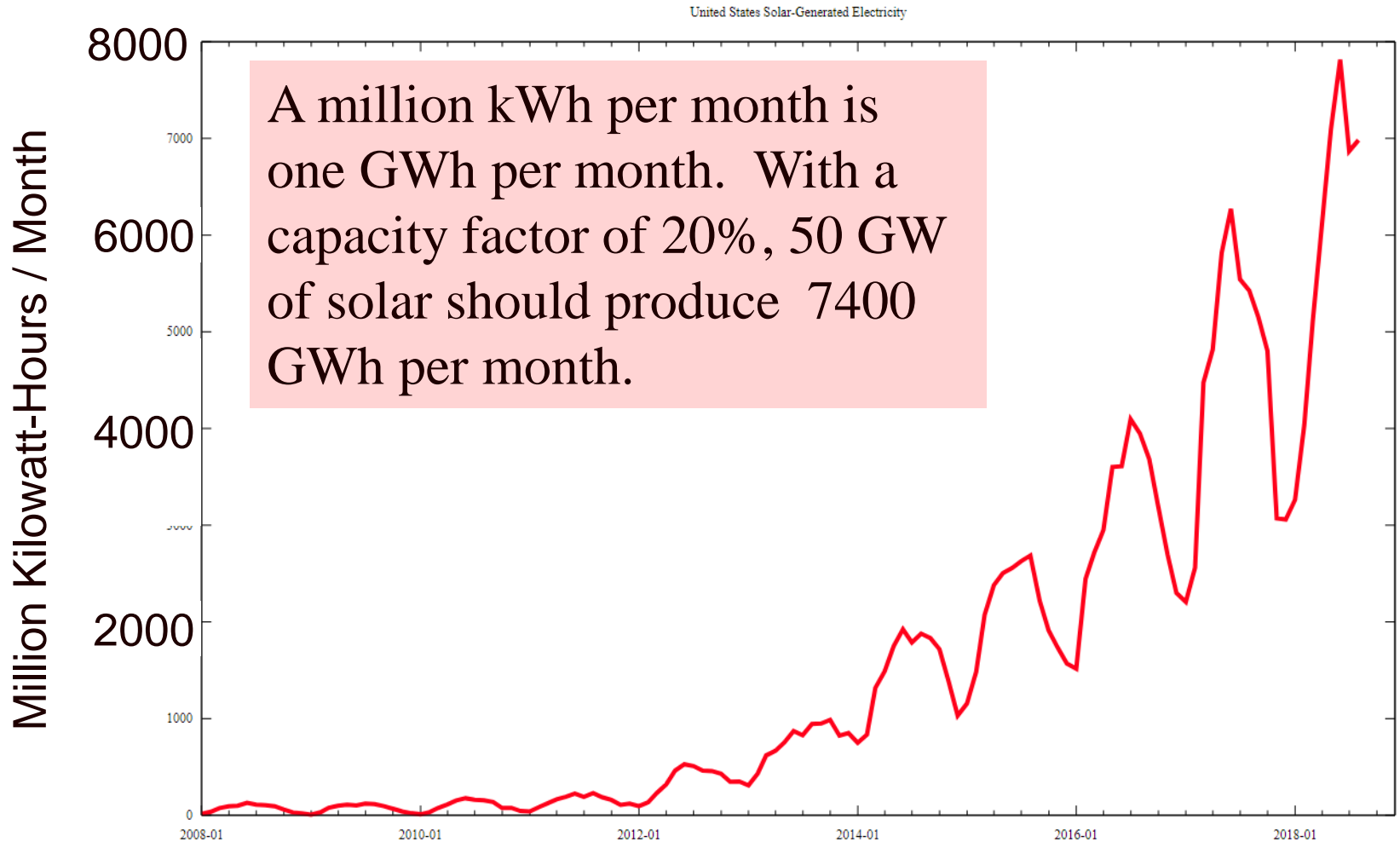
Worldwide Annual Insolation



Solar Capacity by Country



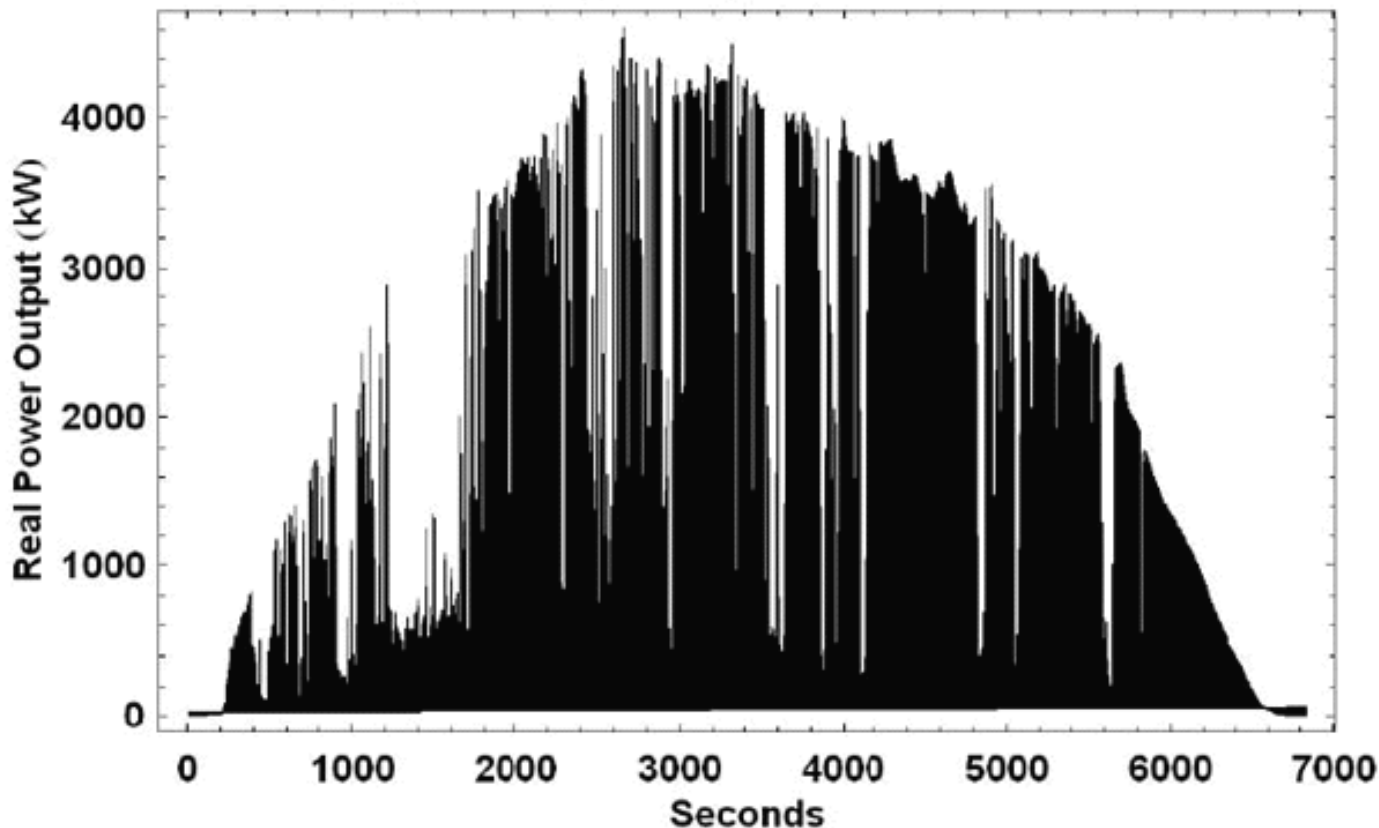
US Solar Generated Electricity



Solar PV can be Quite Intermittent Because of Clouds



Springerville AZ, One Day at 10 Second Resolution



Intermittency can be reduced some when PV is distributed over a larger region; key issue is correlation across an area

Image: <http://www.megawatts.com/gridstorage/gridstorage.htm>

Modeling Solar PV



- Since a large portion of the solar PV is distributed in small installations in the distribution system (e.g., residential rooftop), solar PV modeling is divided into two categories
 - Central station, which is considered a single generation plant
 - As part of the load model

Distributed PV System Modeling



- PV in the distribution system is usually operated at unity power factor
 - There is research investigating the benefits of changing this
 - IEEE Std 1547 now allows both non-unity power factor and voltage regulation
 - A simple model is just as negative constant power load
- An issue is tripping on abnormal frequency or voltage conditions
 - IEEE Std 1547 says, "The DR unit shall cease to energize the Area EPS for faults on the Area EPS circuit to which it is connected." (note EPS is electric power system)

Distributed PV System Modeling



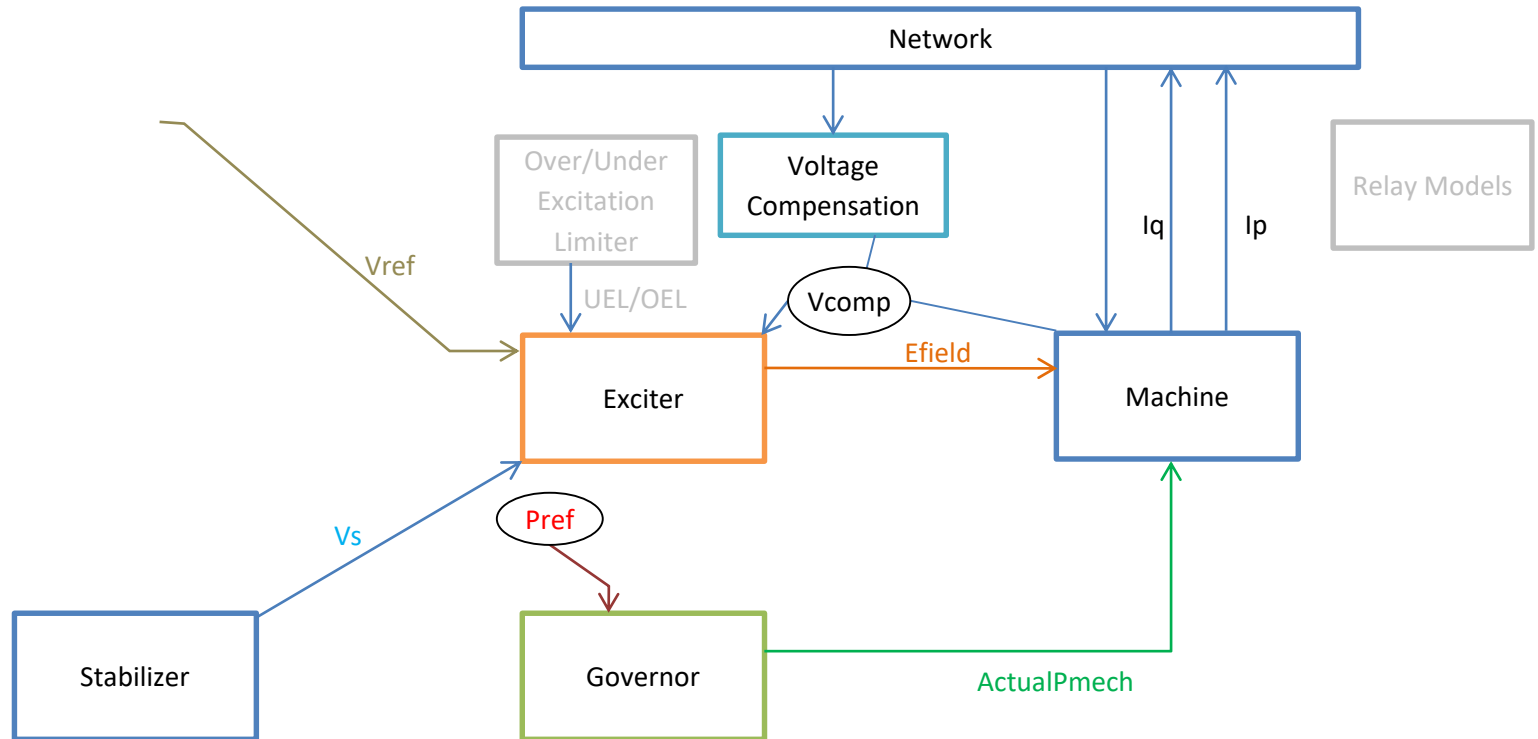
- An issue is tripping on abnormal frequency or voltage conditions (from IEEE 1547-2003, 2014 amendment)
 - This is a key safety requirement!
 - Units need to disconnect if the voltage is < 0.45 pu in 0.16 seconds, in 1 second between 0.45 and 0.6 pu, in 2 seconds if between 0.6 and 0.88 pu; also in 1 second if between 1.1 and 1.2, and in 0.16 seconds if higher
 - Units need to disconnect in 0.16 seconds if the frequency is > 62 or less than 57 Hz; in 2 seconds if > 60.5 or < 59.5
 - Reconnection is after minutes
 - Values are defaults; different values can be used through mutual agreement between EPS and DR operator

Modular Approach to Wind and Solar Unit Modeling



- Industry has always used a modular approach for generator models
 - Machine
 - Exciter
 - Governor
 - Stabilizer
 - Under Excitation Limiter
 - Over Excitation Limiter
 - Relay Model
 - GP1, LHFRT, LHVRT
 - Compensator Model
 - Often is part of the machine model, but can also be a separate model
 - The old BPA IPF program models included this in the Exciter model

“Traditional” Synchronous Machine Modules

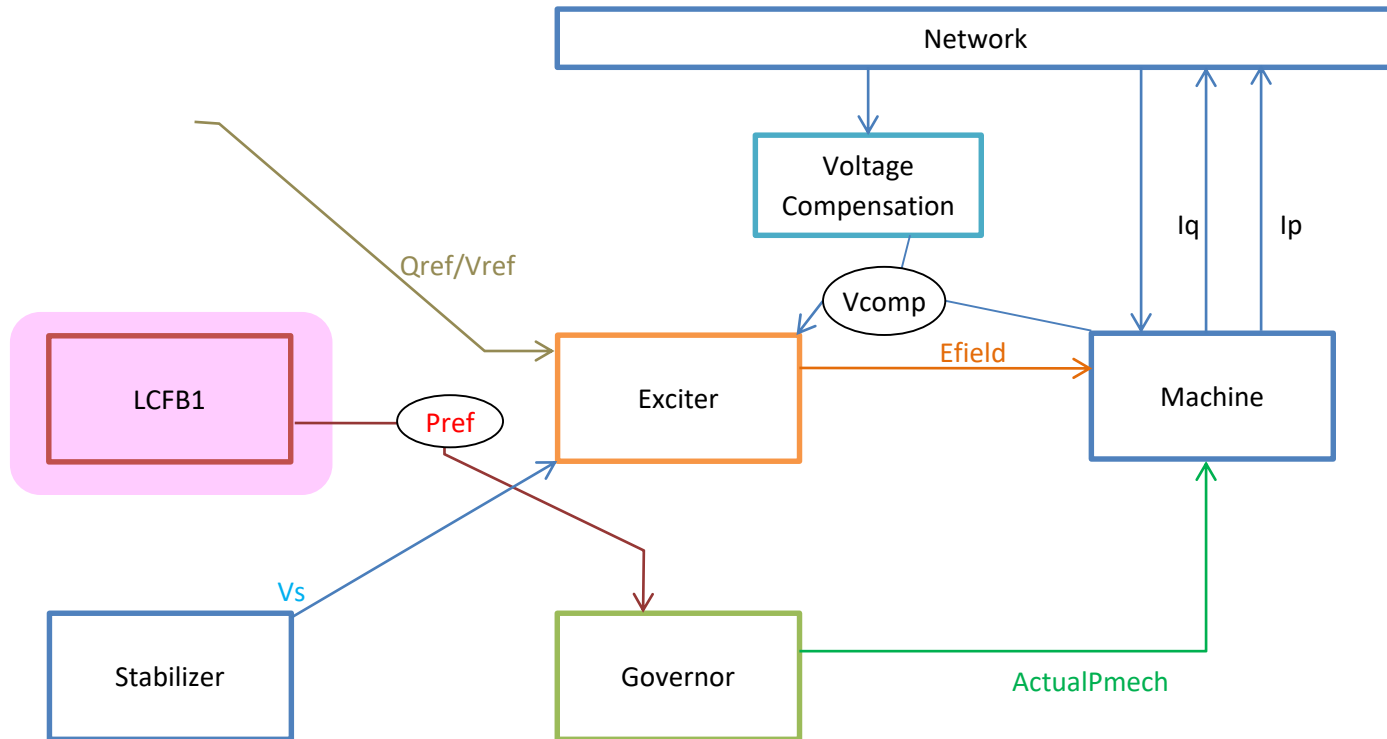


Modular Approach to Generator Modeling



- First generation wind turbine models stuck with this structure
 - Added additional signals to pass between modules
 - Don't get hung up on nomenclature “Exciter” just means the electrical control
- Unrelated to wind turbine modeling, another module was added for better modeling of large steam plants
 - LCFB1 – extra controller feeding the governor allowing control of *Pref*

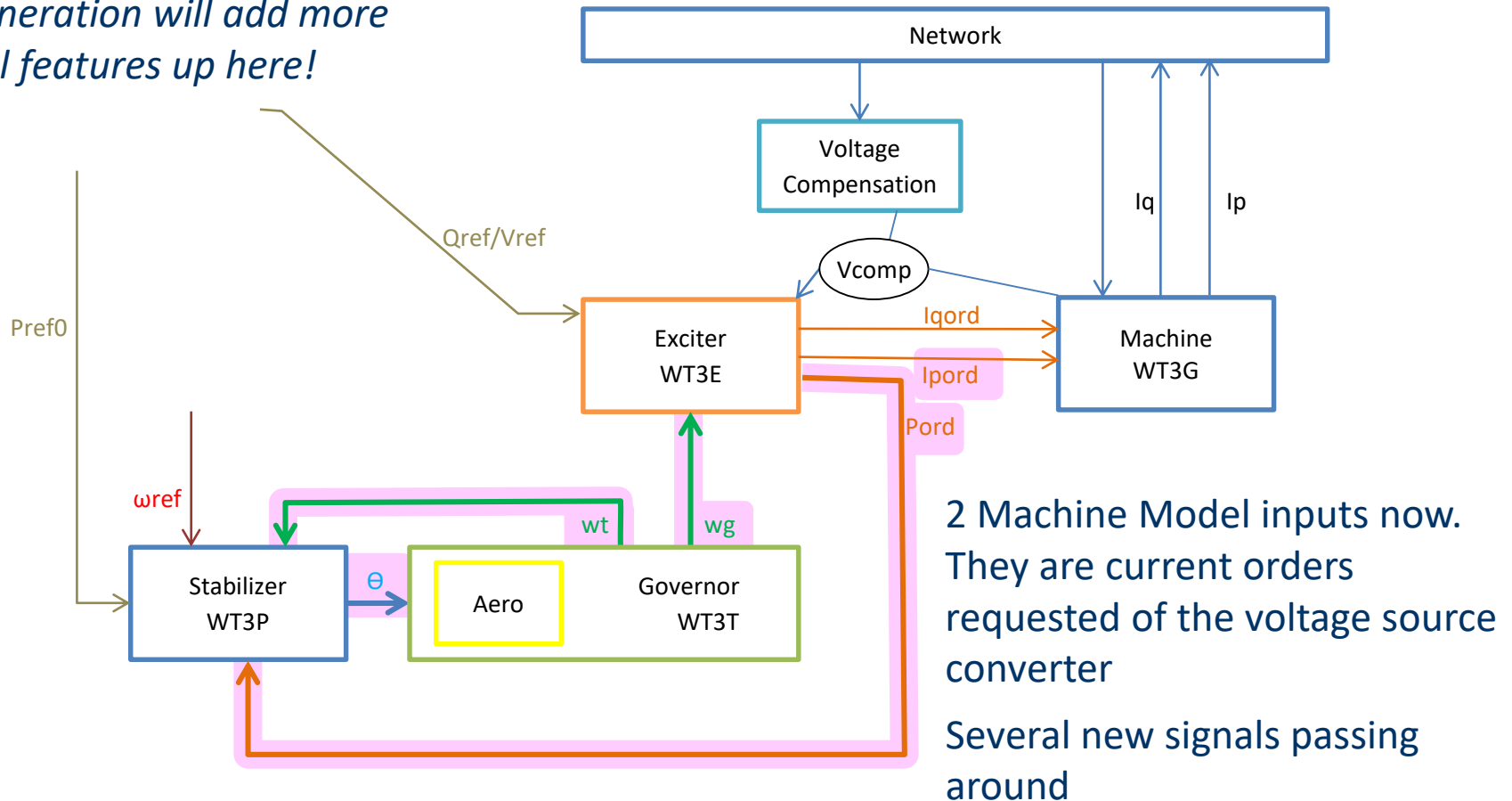
LCFB1 model: Controller for Pref



First Generation Type 3 Wind Turbine (WT3G, WT3E, WT3T, WT3P)



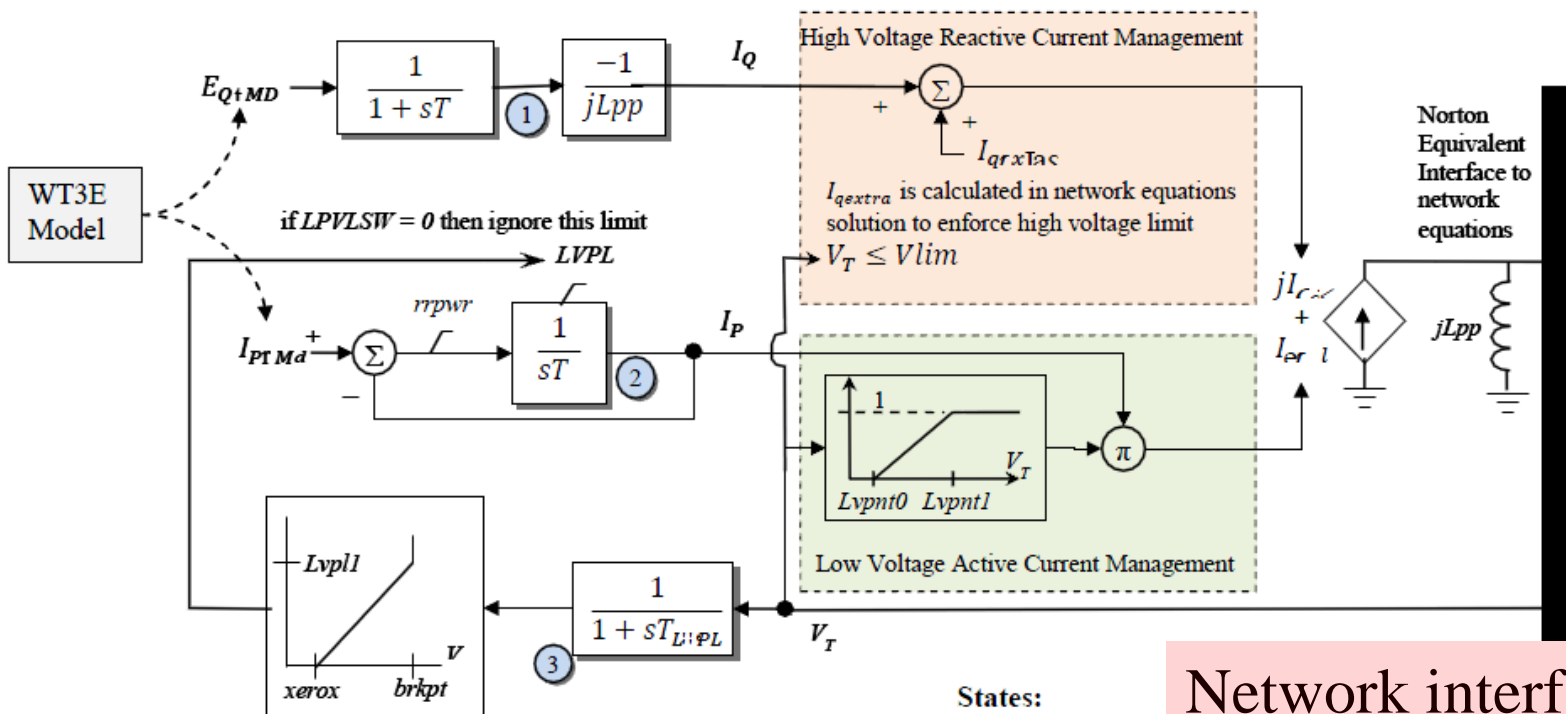
2nd Generation will add more control features up here!



Type 3 WT3G Converter Model



Generator/converter Model for Type-3 (Double-Fed) Wind Turbines WT3G



- States:
 1 - E_q
 2 - I_p
 3 - V_{meas}

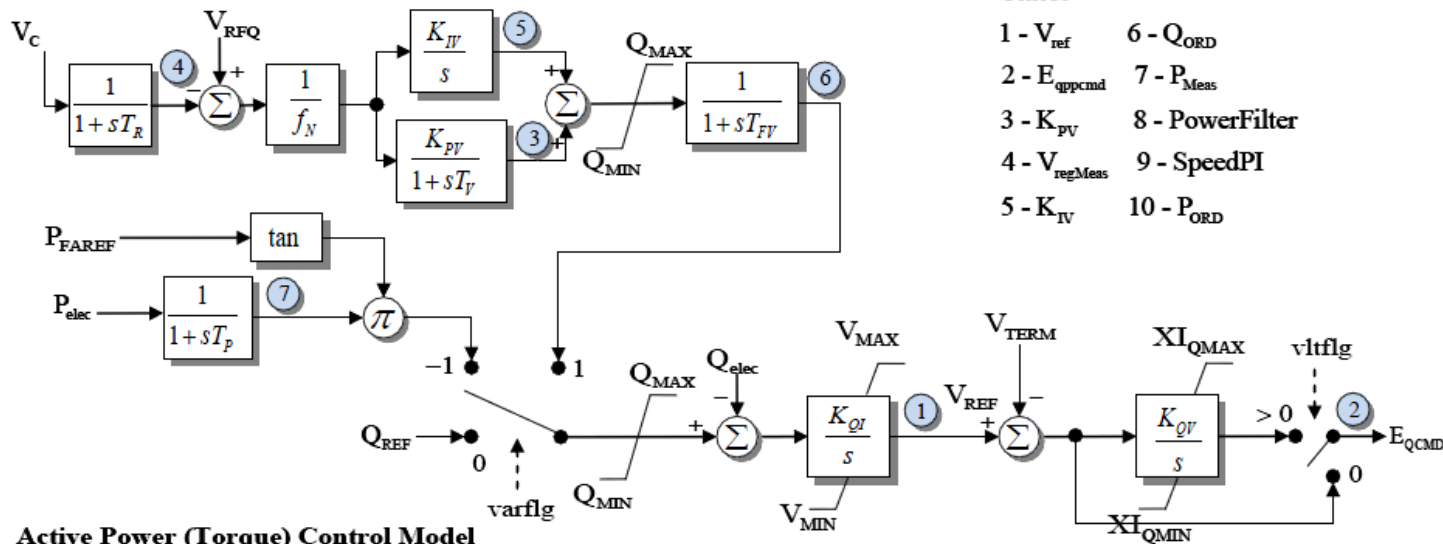
Network interface is a Norton current in parallel with a reactance jX''

Type 3 Reactive Power Control

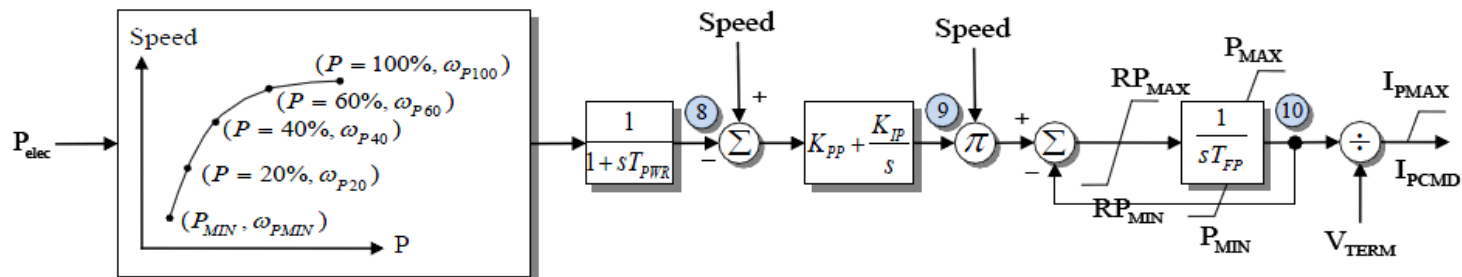


Exciter WT3E and WT3E1 Electrical Control for Type 3 Wind Generator

Reactive Power Control Model



Active Power (Torque) Control Model



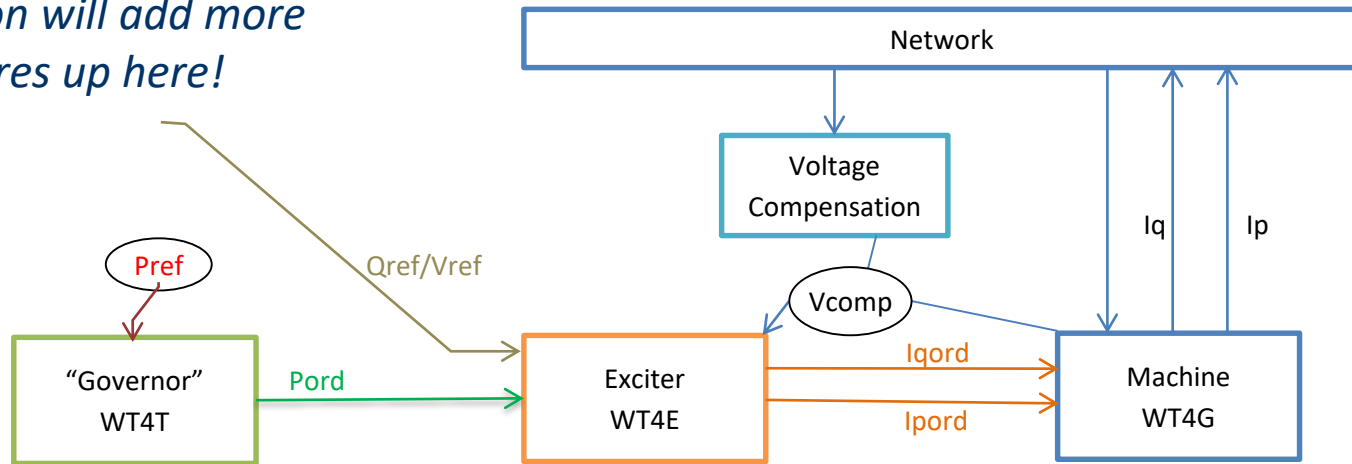
WT3E supported by PSLF with $RP_{MAX} = P_{wrat}$ and $RP_{MIN} = -P_{wrat}$, $T_{FV} = T_C$

WT3E1 supported by PSSE uses vltflg to determine the limits on E_{QCMD} . When vltflg > 0 Simulator always uses XI_{QMAX} and XI_{QMIN} .

First Generation Type 4 Wind Turbine (WT4G, WT4E, WT4T)



2nd Generation will add more control features up here!



Legacy "Governor" WT4T

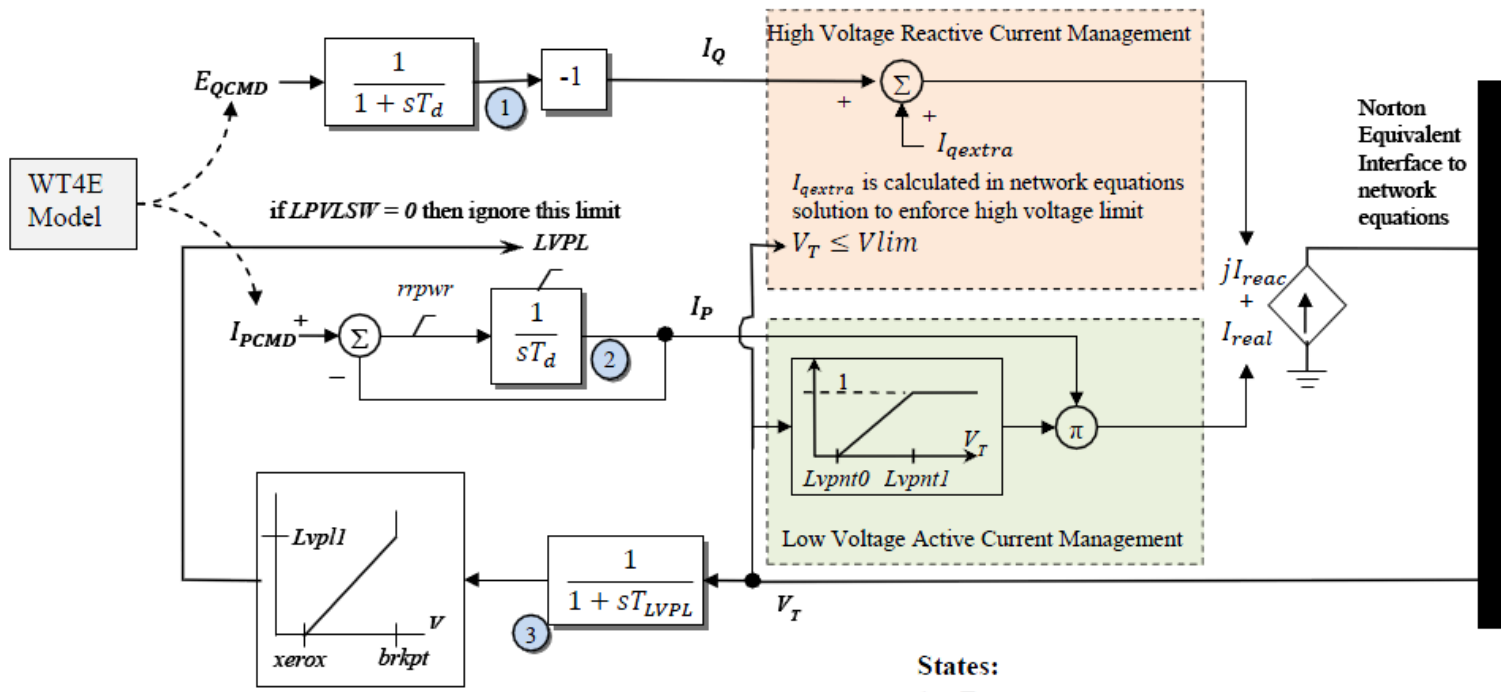
This really acts like the new PRef controller

We will leave it in the toolbox as a "Governor" anyway

Type WTG4 Model



Model WT4G
Type 4 Wind Turbine with Full Converter Model



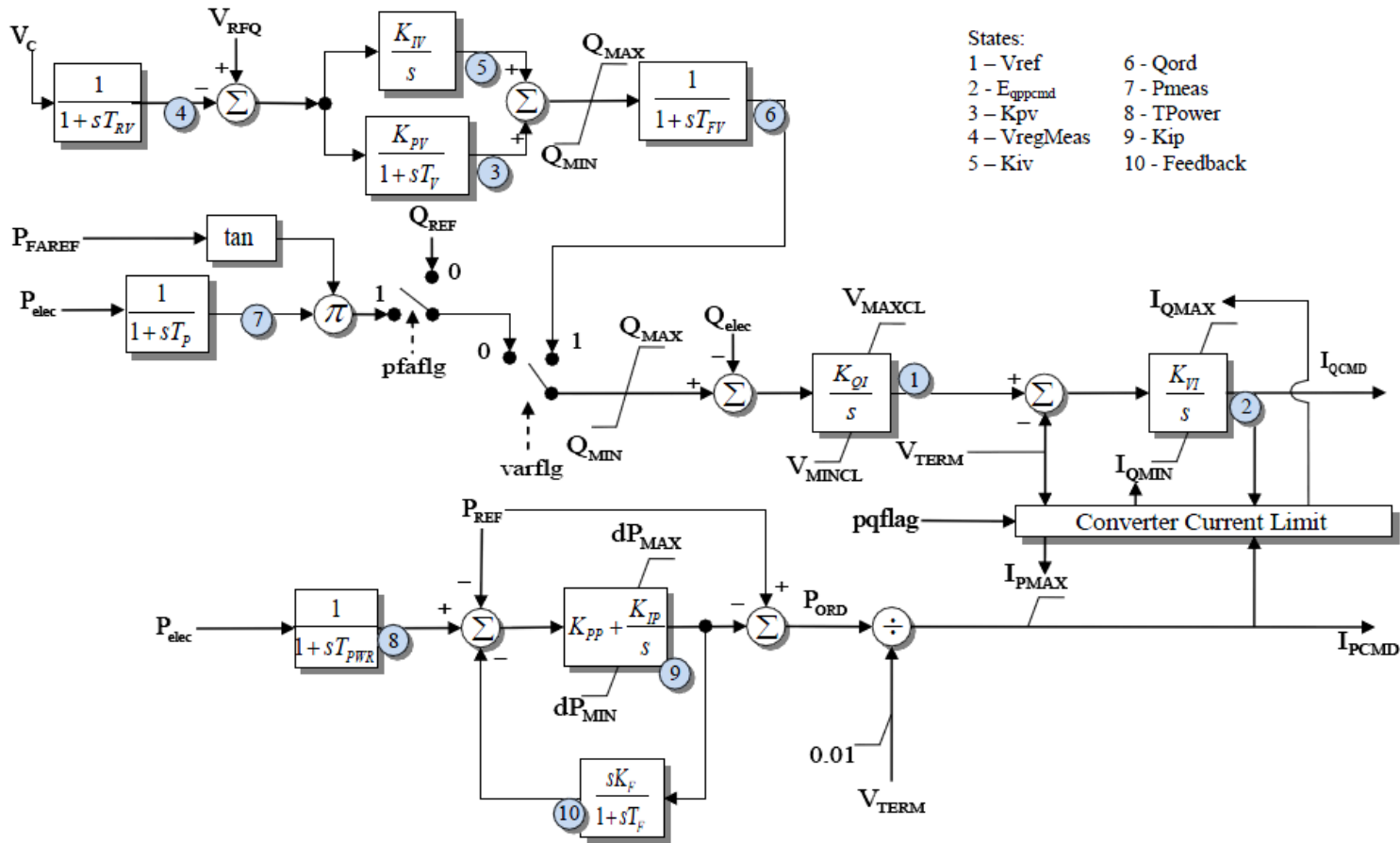
- States:**
- 1 - E_q
 - 2 - I_p
 - 3 - V_{meas}

Very similar to the WTG3, except there is no X"

Type 4 Reactive Power Control



Exciter WT4E1
Electrical Control for Type 4 Wind Generator



Also similar to the Type 3's, as are the other models

Limitations of First Generation Wind Models



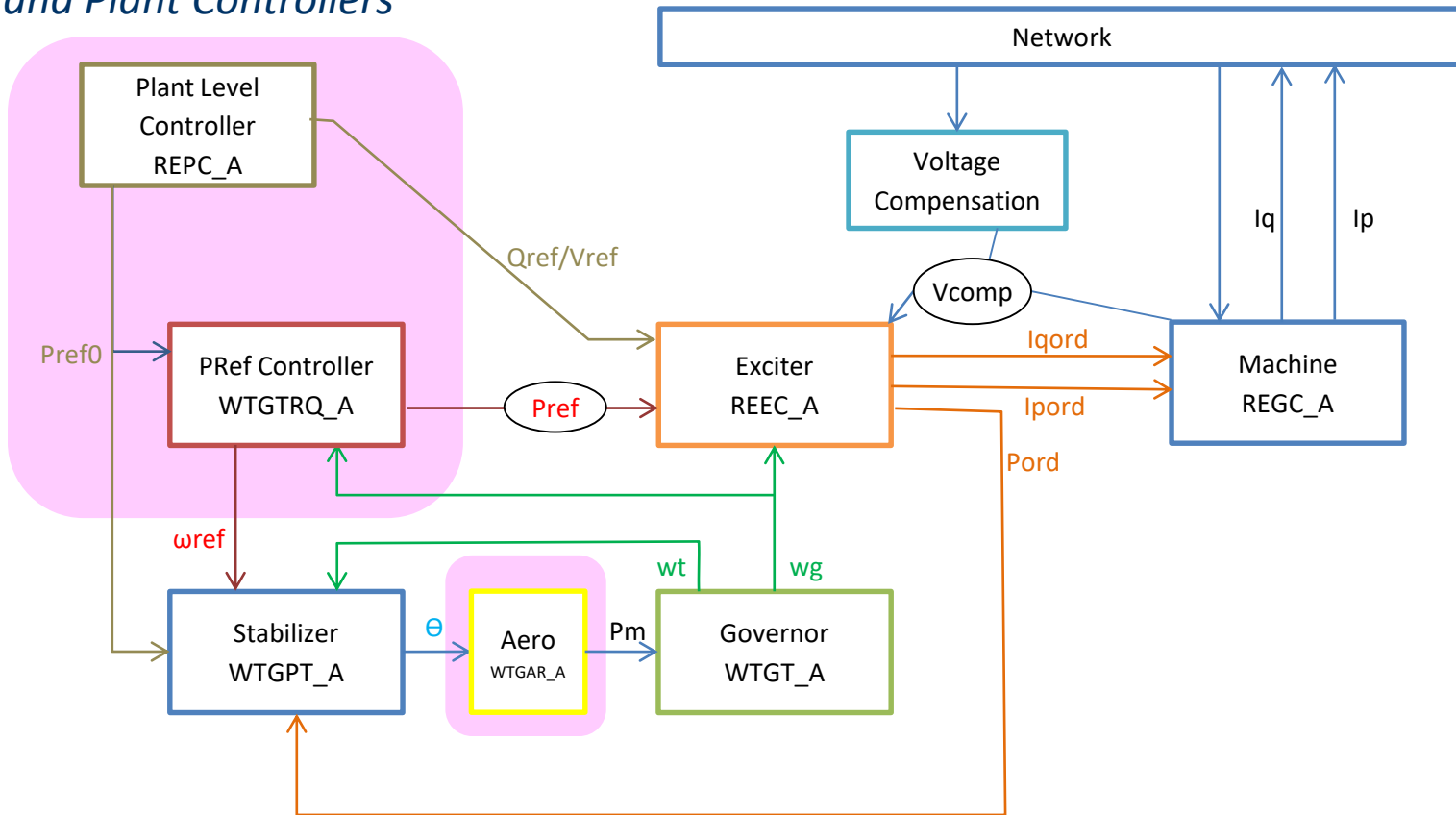
- First Generation model had few mechanisms to provide control features of
 - Real Power or Torque Control
 - Reactive Power
 - Voltage Control
 - For First Generation models, the wind turbine basically tried to bring values back to the initial condition
 - Pref bring power back to initial Power
 - Qref or Vref or PowerFactorRec

2nd Generation Type 3 Wind Turbine

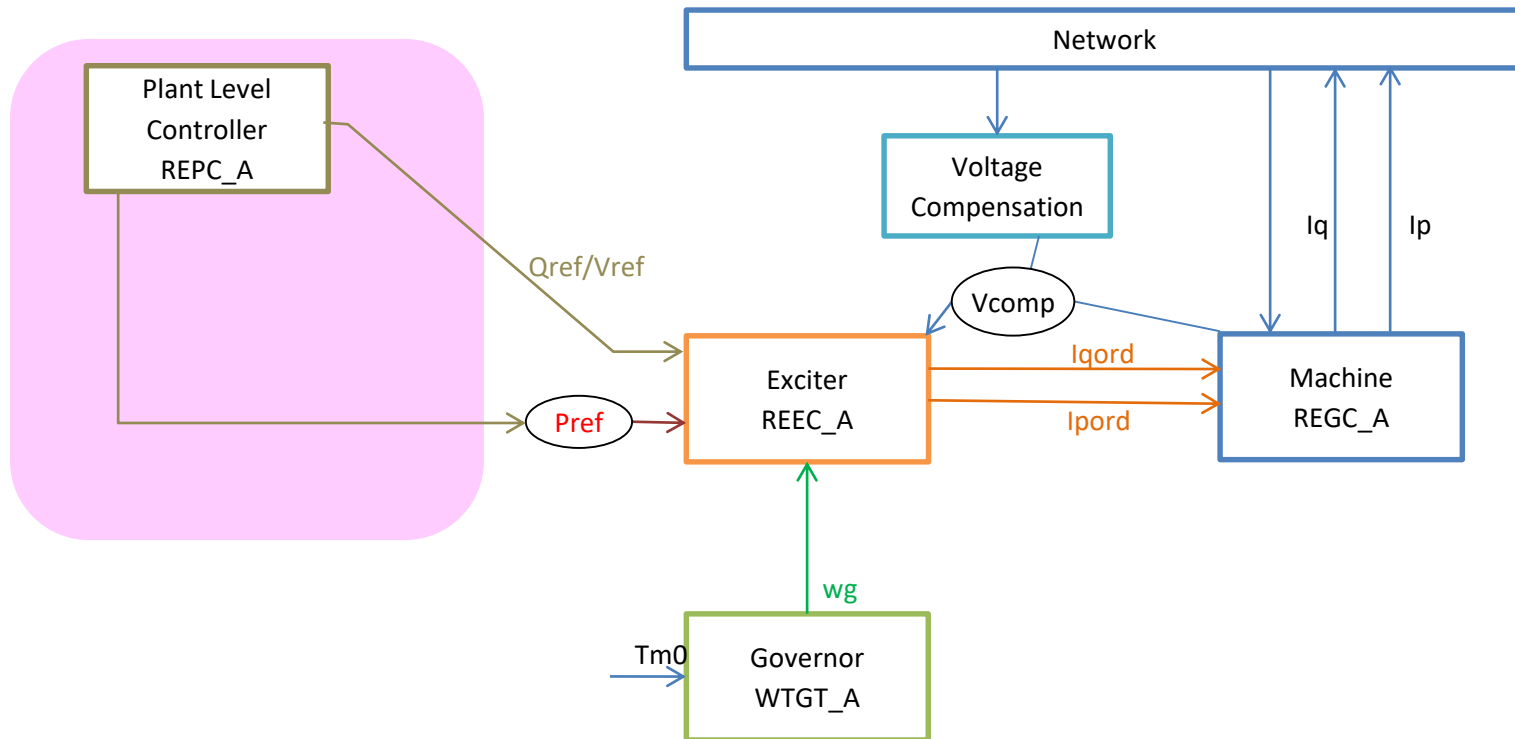
(REGC_A, REEC_A, WTGT_A, WTGAR_A, WTGPT_A, WTGTRQ_A, REPC_A)



2nd Generation adds the Aero, PRef and Plant Controllers

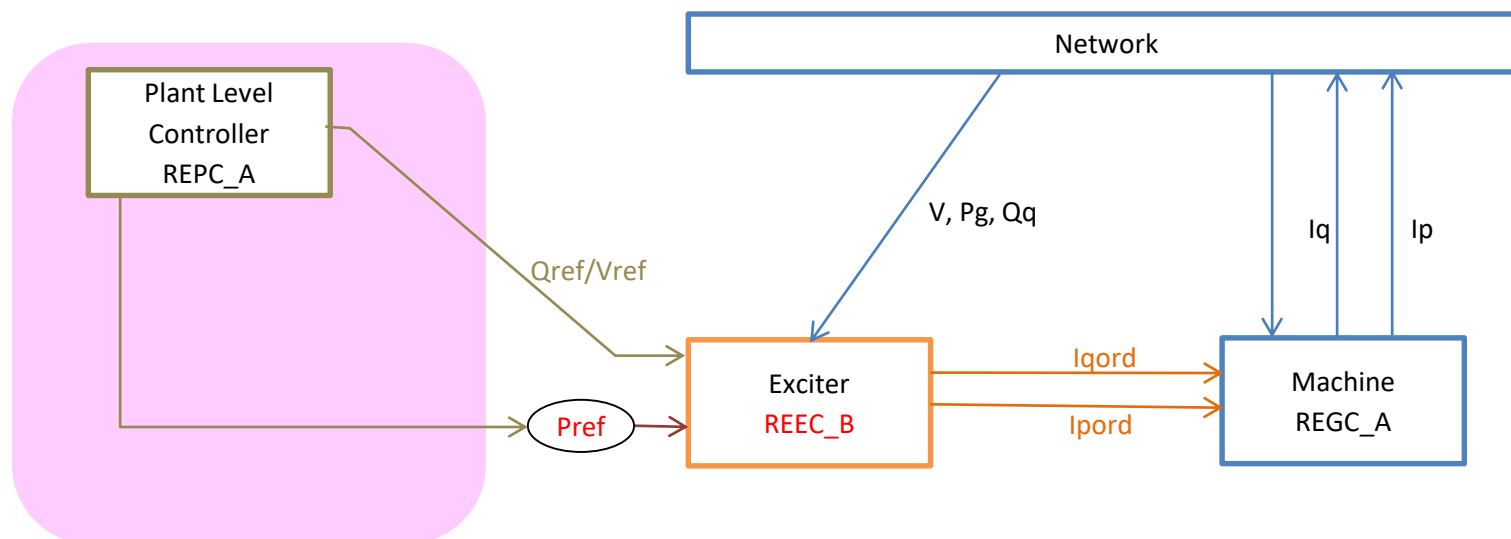


2nd Generation Type 4 Wind Turbine (REGC_A, REEC_A, WTGT_A, REPC_A)



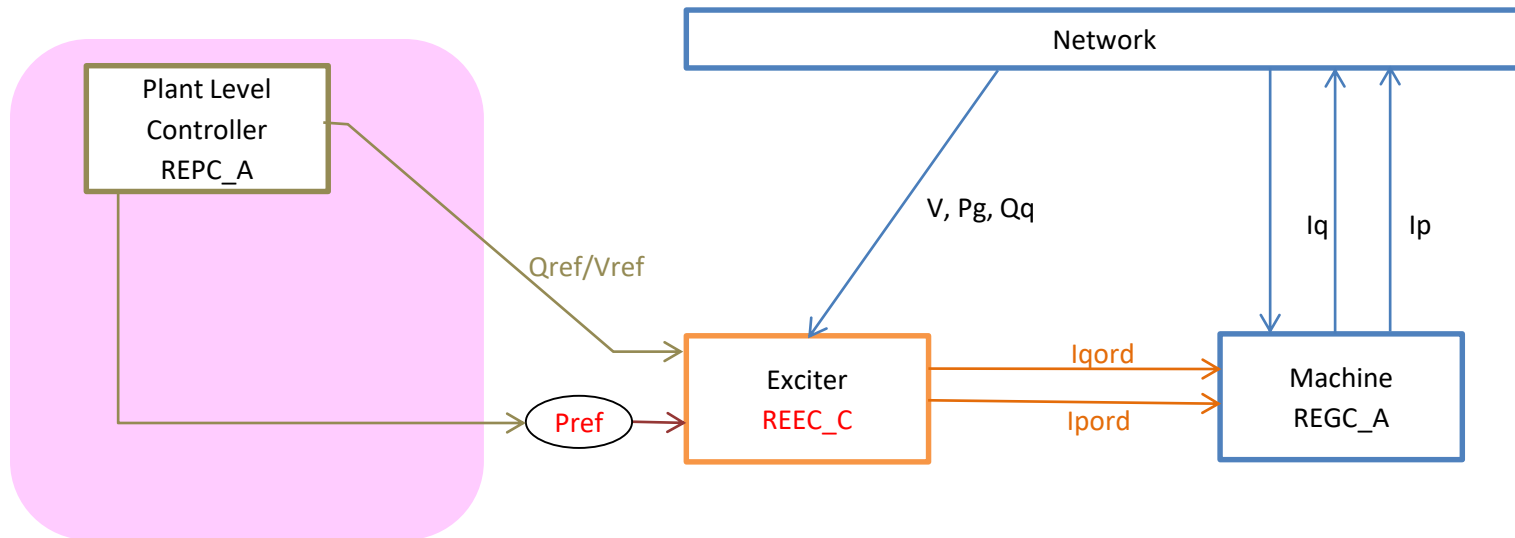
Note: If REEC_A parameter Pflag = 0, then WTGT_A really doesn't do anything so it can be omitted completely

2nd Generation Solar Plant



Used REEC_B Initially,
But actually don't anymore!
Go back to REEC_A

2nd Generation Energy Storage

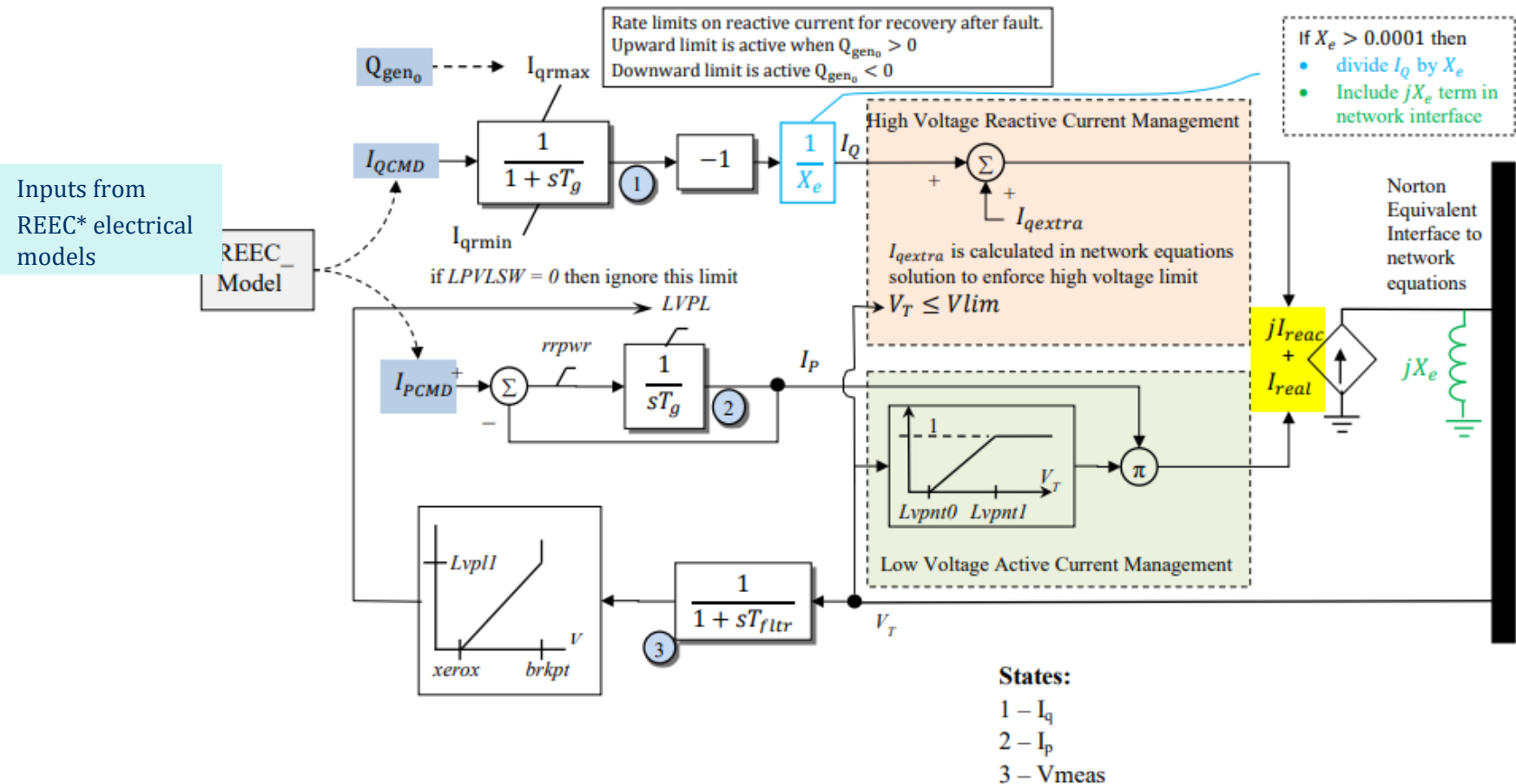


Use REEC_C

REGC_A (or REGCA1)



- “Machine Model”: Really a network interface



REGC_A Description

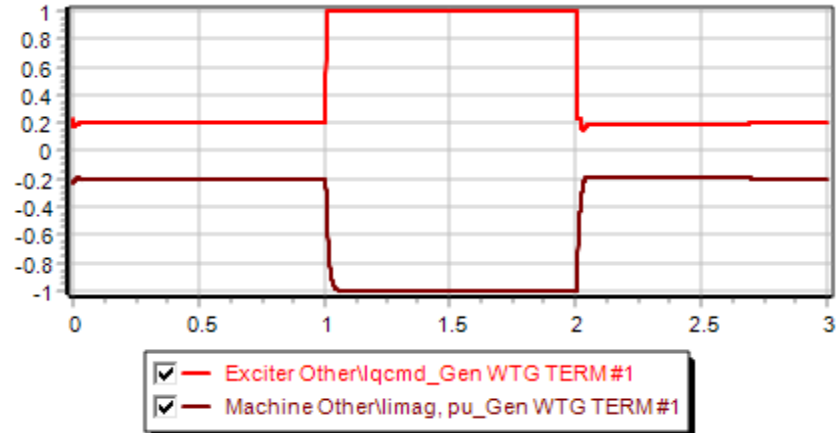
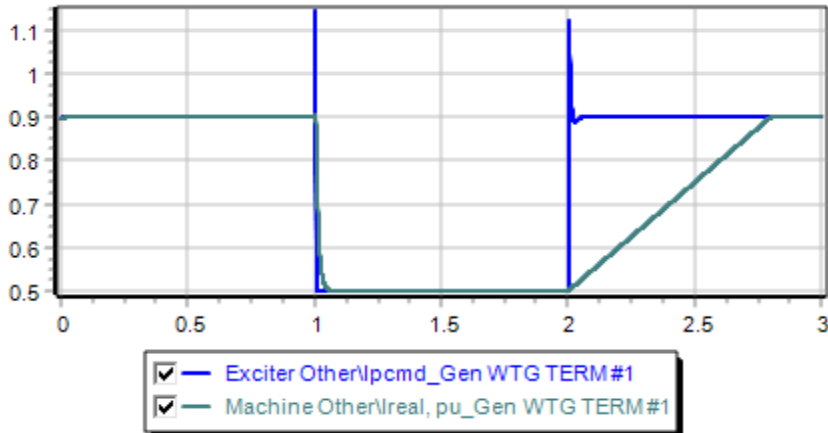
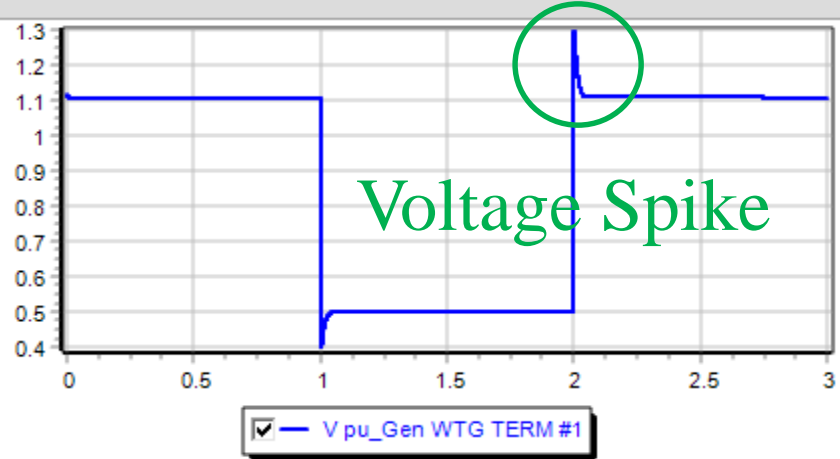
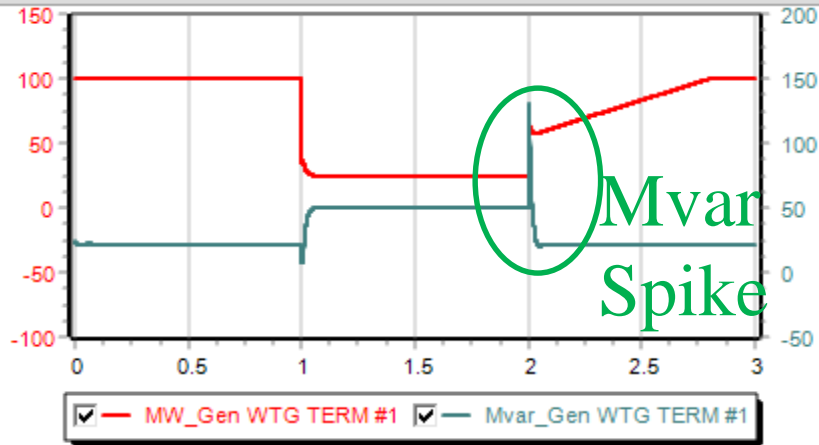


- This model is doing very little actually
 - Time delay T_g is the entirety of the converter model
 - Crudely, the model says
“Electrical Controller asks for a real and reactive current → 0.020 seconds later the converter creates this”
 - We are NOT modeling any of the power electronics at all
 - We are not modeling any phase-locked-loop (PLL)
 - Our assumption is all of that stuff is really fast
- “High Voltage Reactive Current Management” and “Low Voltage Active Current Management”
 - These are a dubious names because we aren’t modeling things in enough detail to really have “control” here
 - This control happens in the less than 1 cycle time-frame!

What is Happening? Voltage and Mvar Spike



New Wind Turbine Test



Renewable Energy Models (Wind, Solar, Storage Models)



1st
Generation
Models

| Class of Model Type | Wind Type 1 | Wind Type 1 | Wind Type 2 | Wind Type 2 | Wind Type 3 | Wind Type 3 | Wind Type 4 | Wind Type 4 | Solar PV |
|---------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|----------|
| Machine | WT1G | WT1G1 | WT2G | WT2G1 | WT3G | WT3G1 | WT4G | WT4G1 | PV1G |
| Electrical Model | | | WT2E | WT2E1 | WT3E | WT3E1 | WT4E | WT4E1 | PV1E |
| Mechanical | WT1T | WT12T 1 | WT2T | WT12T1 | WT3T | WT3T1 | WT4T | | |
| Pitch Controller | WT1P | WT12A 1 | WT2P | WT12A 1 | WT3P | WT3P1 | | | |

2nd Generation Models

| Class of Model Type | Wind Type 1 | Wind Type 2 | Wind Type 3 | Wind Type 4 | Solar PV | Distributed PV Model | Energy Storage |
|---------------------|----------------|----------------|---------------------|------------------------|------------------------|----------------------|------------------------|
| Machine | WT1G WT1G1 | WT2G WT2G1 | REGC_A | REGC_A | REGC_A | PVD1 DER_A | REGC_A |
| Electrical Model | | WT2E WT2E1 | REEC_A | REEC_A | REEC_B | | REEC_C |
| Mechanical | WT1T WT12T1 | WT2T WT12T1 | WTGT_A | WTGT_A | | | |
| Pitch Controller | WT1P_ B | WT2P WT12A1 | WTGPT_A | | | | |
| Aerodynamic | | | WTGA_A | | | | |
| Pref Controller | | | WTGTRQ_ A | | | | |
| Plant Controller | | | REPC_A or REPC_B | REPC_A or REPC_B | REPC_A or REPC_B | | REPC_A or REPC_B |

3 new
classes of
models

Additional
Uses

REPC_B = Plant controller for up to 50 machines and SVCs

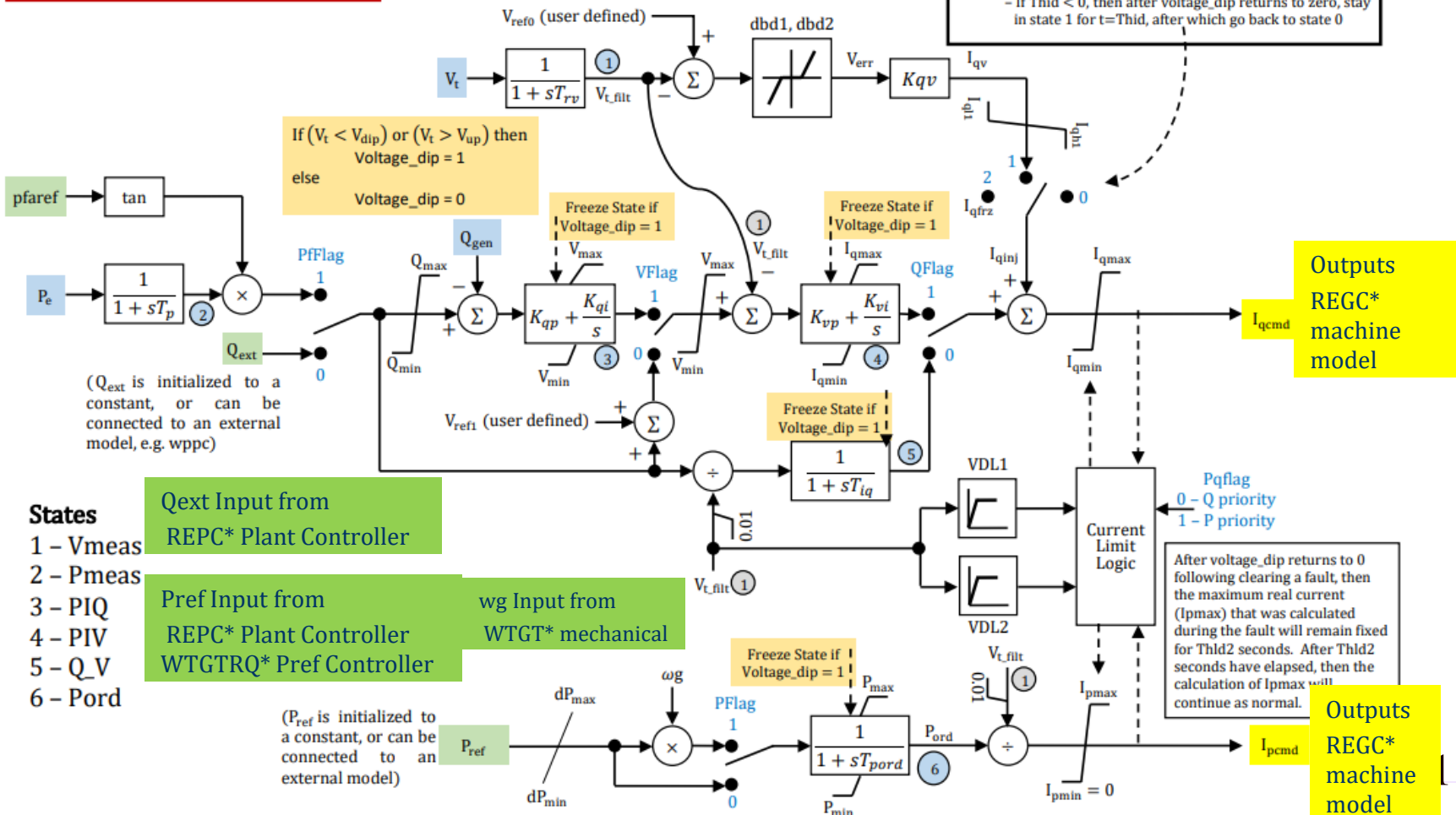
REEC_A (same as REECA1)



Warning!!
 Extreme care should be taken in coordinating the parameters dbd1, dbd2 and V_{dip} , V_{up} so as not to have an unintentional response from the reactive power injection control loop.

Electrical Model

State Transition - switch position
 State 0 - If Voltage_dip = 0; normal operation ($I_{qinj} = 0$)
 State 1 - If Voltage_dip = 1; I_{qinj} goes to position 1
 State 2 - If $Thid > 0$, then after voltage_dip goes back to zero, set value to I_{qfrz} for $t = Thid$, after which go back to state 0
 - If $Thid < 0$, then after voltage_dip returns to zero, stay in state 1 for $t = Thid$, after which go back to state 0



Outputs
 REGC*
 machine
 model

Outputs
 REGC*
 machine
 model

- States**
- 1 - Vmeas
 - 2 - Pmeas
 - 3 - PIQ
 - 4 - PIV
 - 5 - Q_V
 - 6 - Pord

Qext Input from
 REPC* Plant Controller

Pref Input from
 WTGTRQ* Pref Controller

wg Input from
 WTGT* mechanical

(P_ref is initialized to a constant, or can be connected to an external model)

After voltage_dip returns to 0 following clearing a fault, then the maximum real current (I_{pmax}) that was calculated during the fault will remain fixed for $Thid2$ seconds. After $Thid2$ seconds have elapsed, then the calculation of I_{pmax} will continue as normal.

Comparing First and Second Generation Models



- Many parts actually change very little
 - “Machine”: Voltage Source Converter model of the generator is nearly identical
 - WT3G/WT4G is pretty much same as REGC_A
 - “Governor”: Mechanical Model of wind turbine is identical
 - Combination of WTGT_A and WTGAR_A is *identical* to WT3T
 - “Stabilizer”: Pitch Control model has only a small addition
 - WT3P is pretty much same as WTGPT_A
- What’s Different – Control System Models
 - The WT3E and WT4E models essentially embedded voltage control and power control inside the model
 - This is now split into separate models
 - REEC_A: models only control with setpoints are as inputs to this model. Control features a little more flexible than the WT3E and WT4E models
 - WTGTRQ_A: control system resulting in the output of PRef
 - REPC_A : control system resulting in output of both a P and V/Q signal



Questions?



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