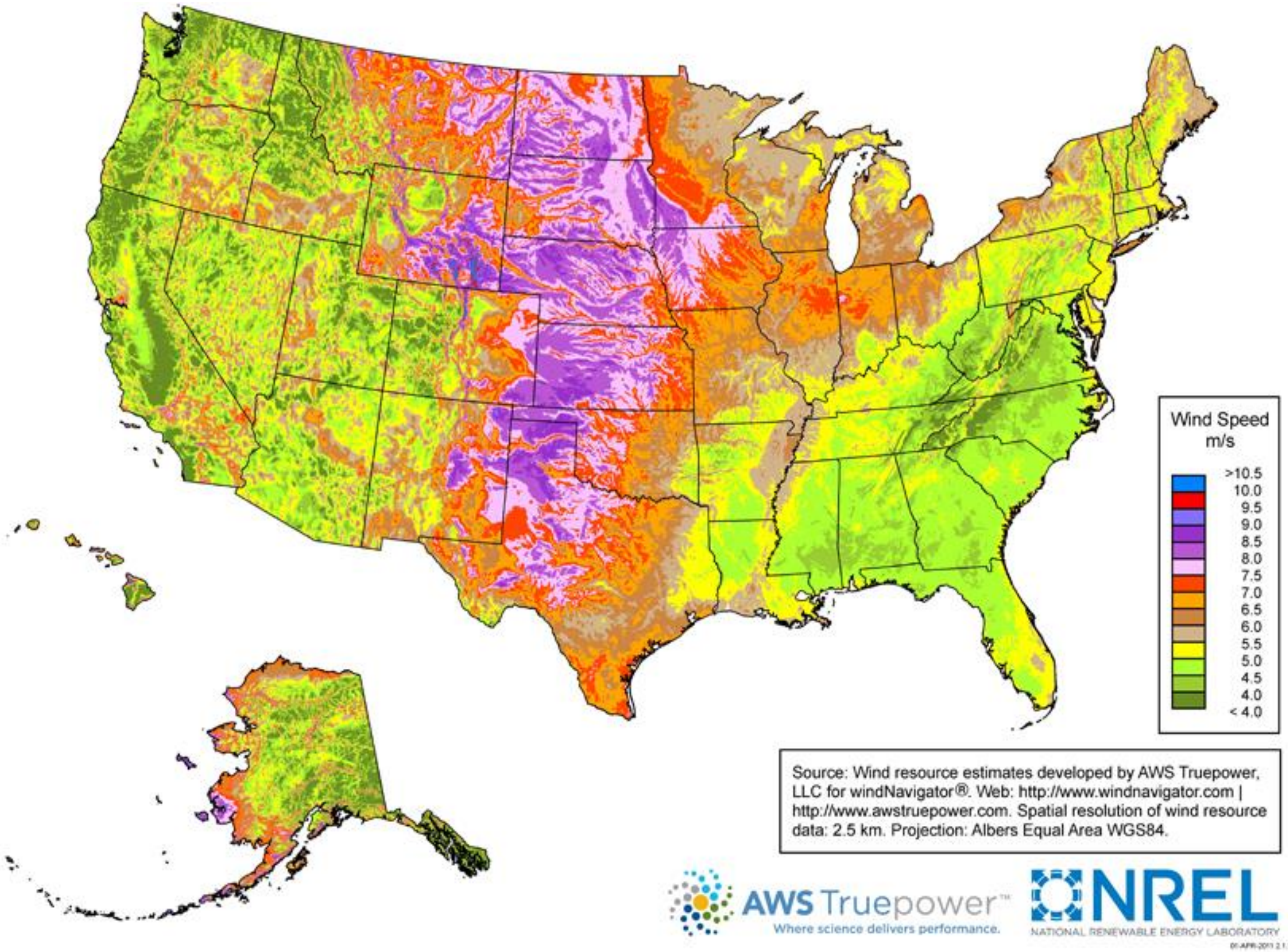
ECEN 667
Power System Stability

Lecture 26: Modeling Wind and Solar

Prof. Tom Overbye
Dept. of Electrical and Computer Engineering
Texas A&M University
overbye@tamu.edu

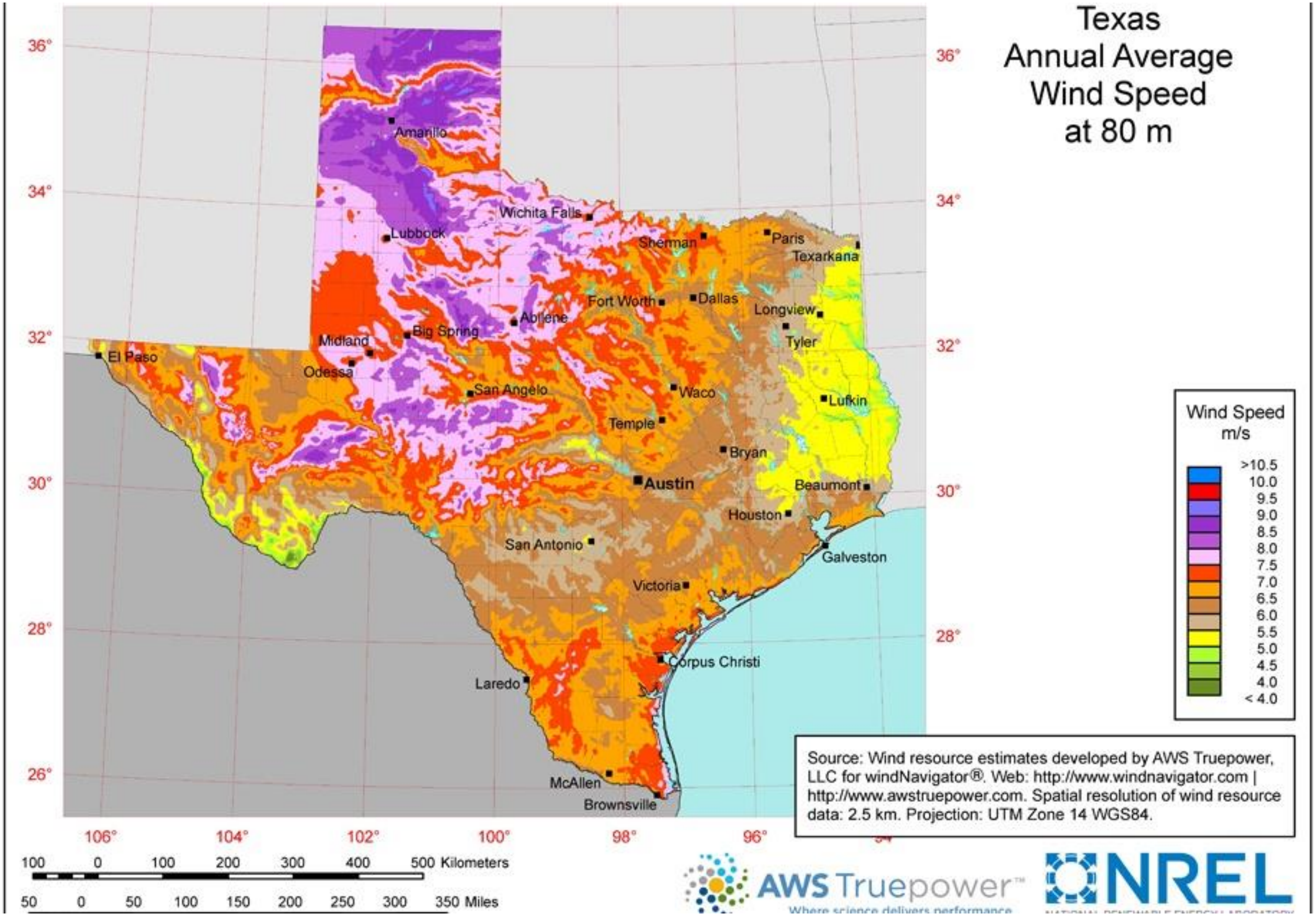
TEXAS A&M UNIVERSITY

US Wind Resources



Source: http://www.windpoweringamerica.gov/wind_maps.asp

Wind Map Texas– 80m Height



https://windexchange.energy.gov/files/u/visualization/image/tx_80m.jpg

US Wind Farm Locations

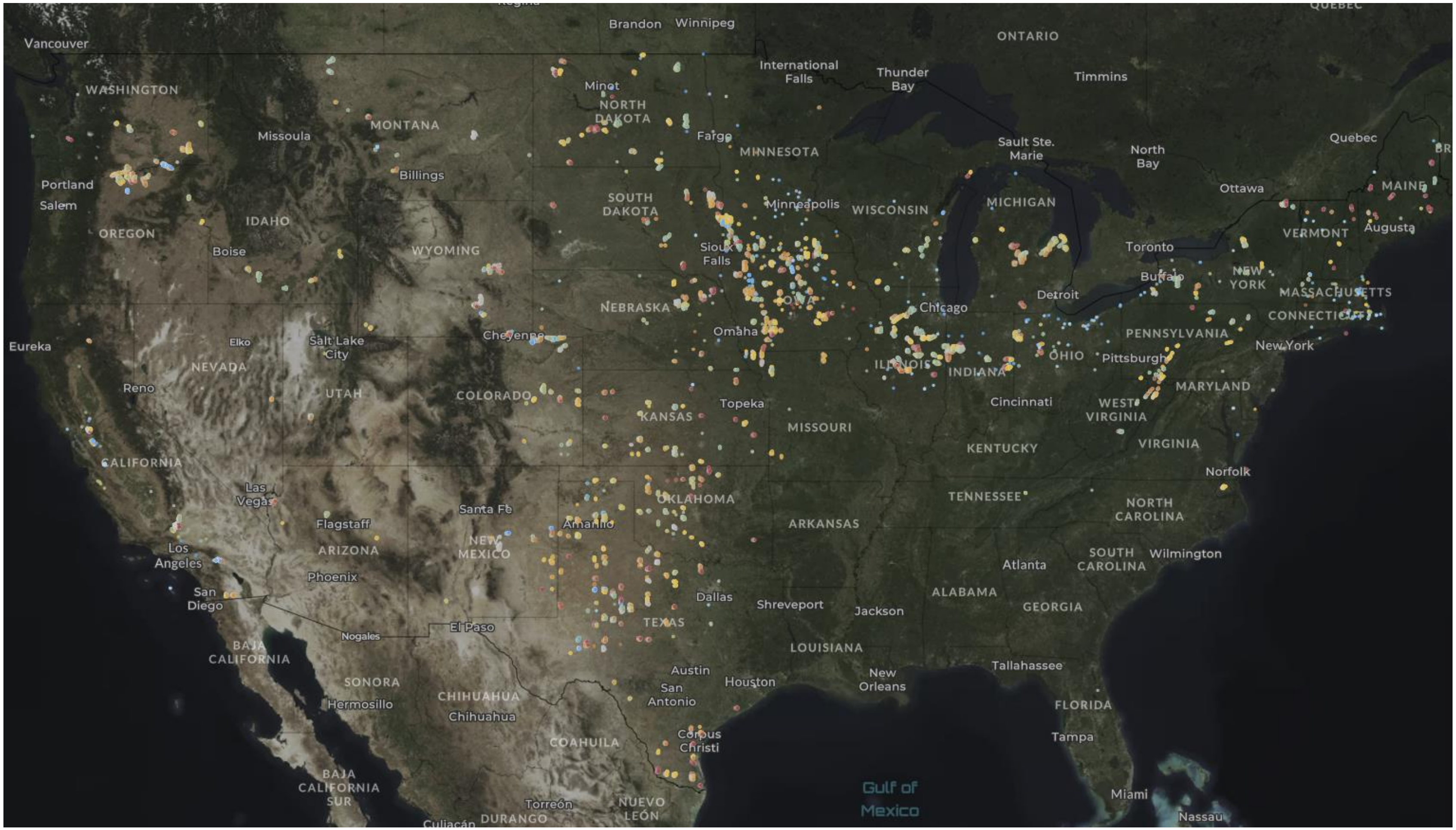
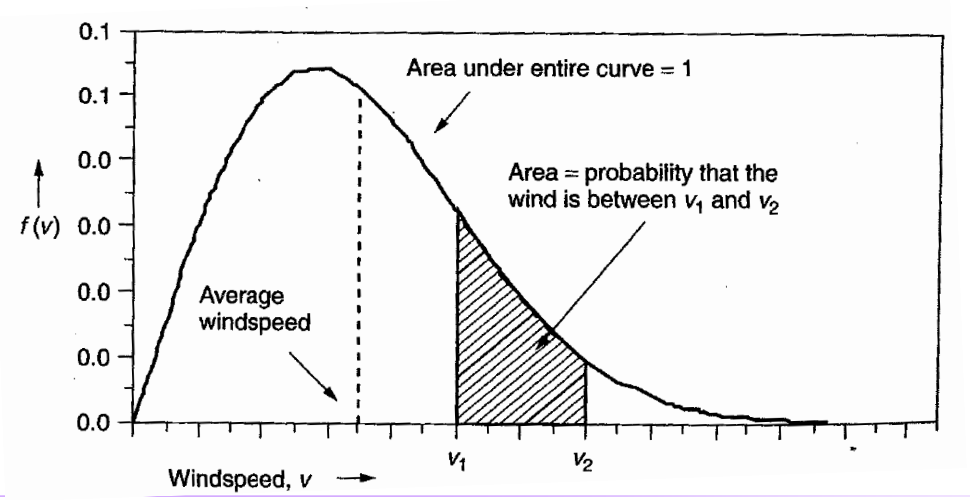


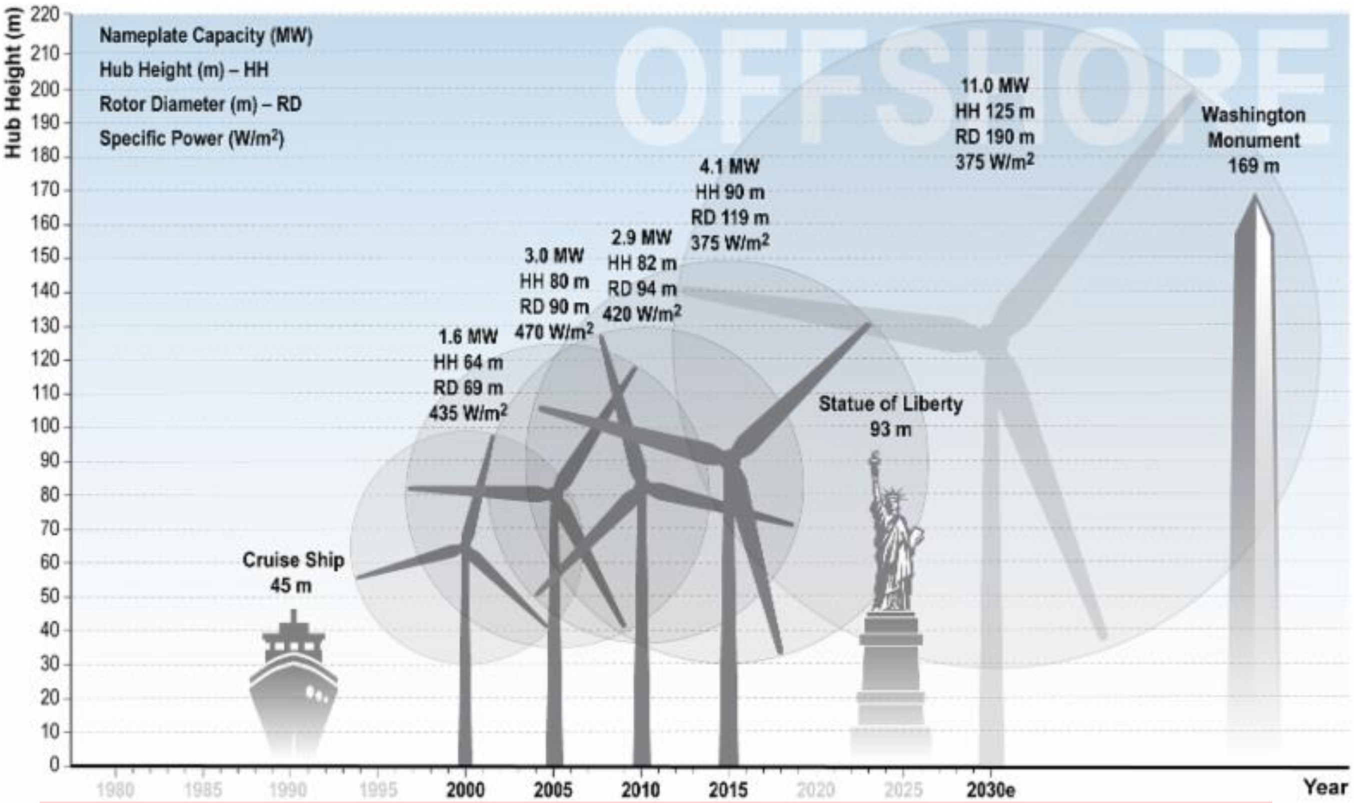
Image source: USGS at https://eerscmap.usgs.gov/uswtdb/

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



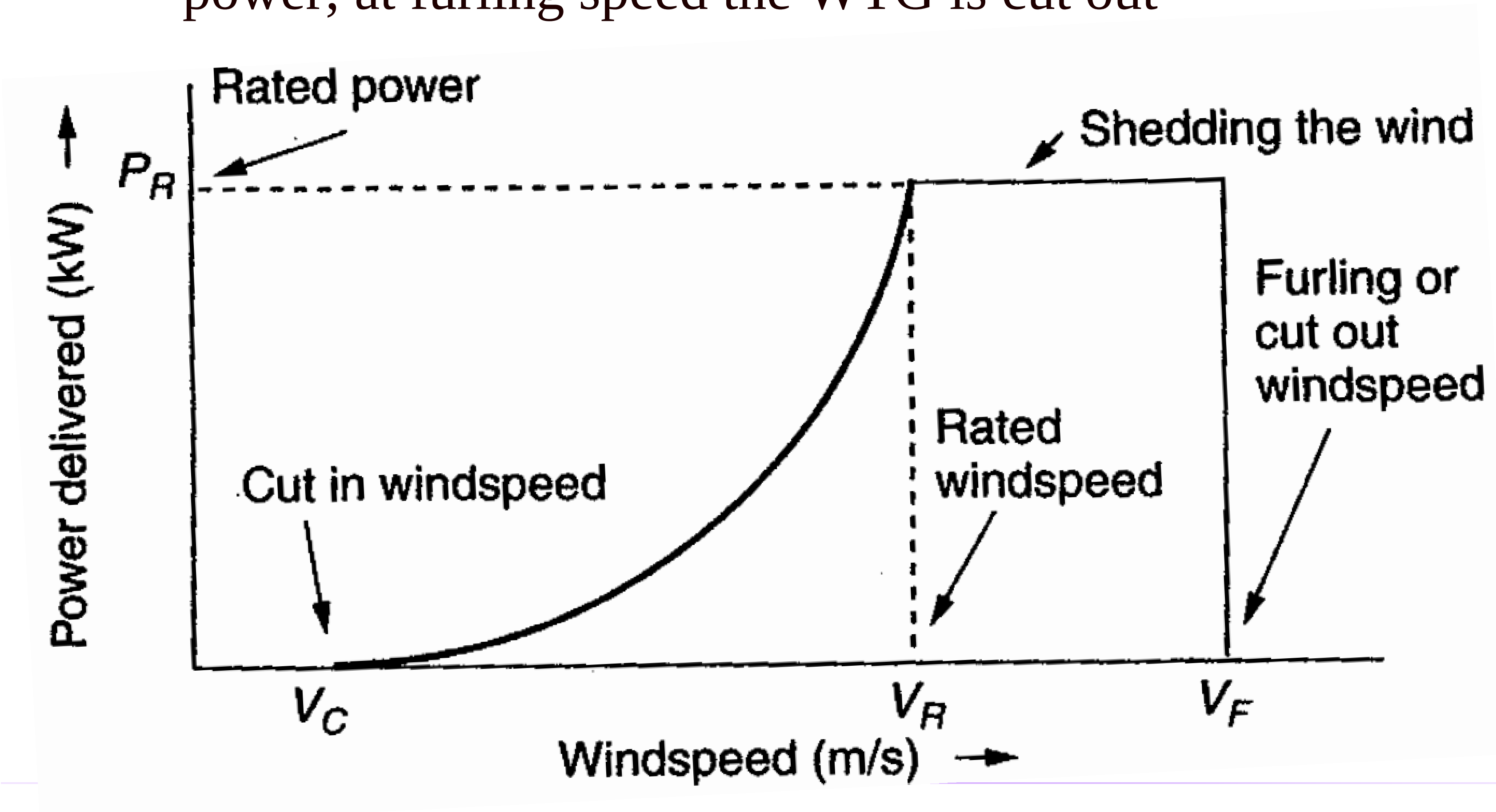
The current largest wind turbine by capacity had been the Vestas V164 which has a capacity of 9.5 MW, a height of 220 m, and diameter of 164 m.

As of 2021 the largest wind turbines have capacities of about 14 MW; diameters are now > 200 meters!

Source: cdn.arstechnica.net/wp-content/uploads/2016/11/6e9cb9fc-0c18-46db-9176-883cbb08eace.png

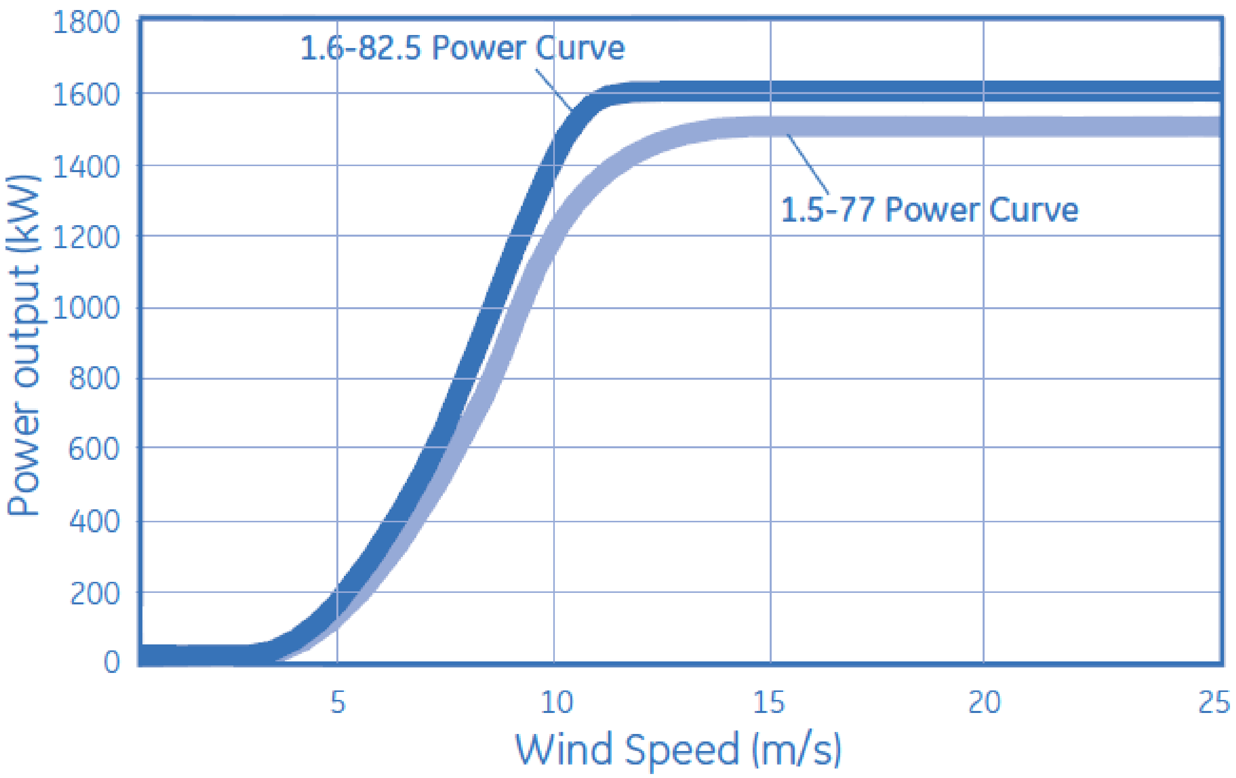
Extracted Power

- 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)

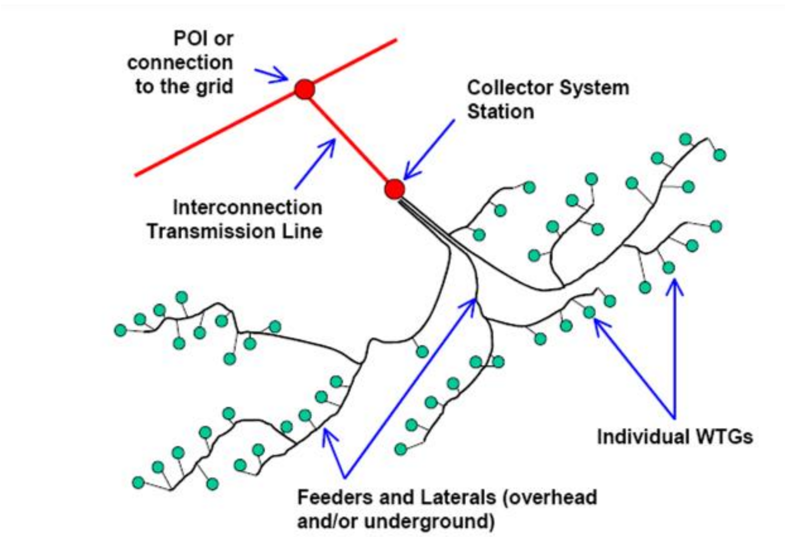


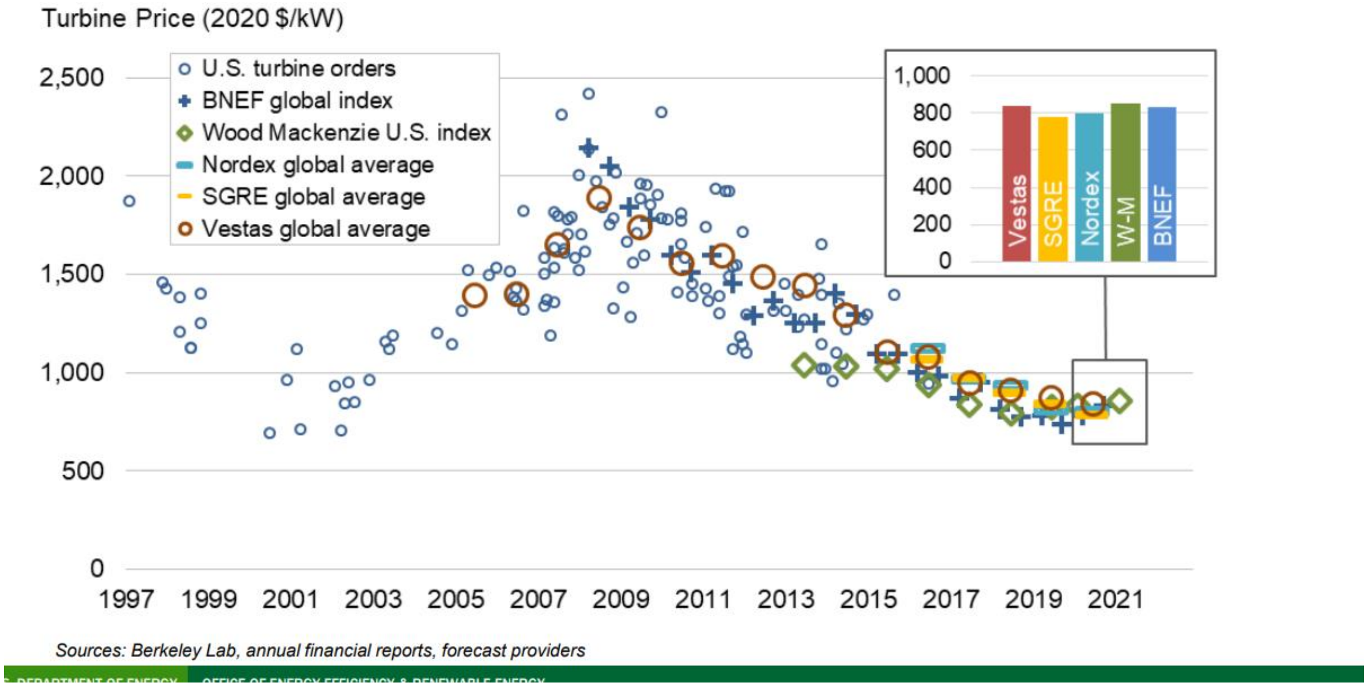
Photo Source: www.energyindustryphotos.com/photos_of_wind_farm_turbines.htm

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%



Source: https://www.energy.gov/eere/wind/wind-market-reports-2021-edition

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

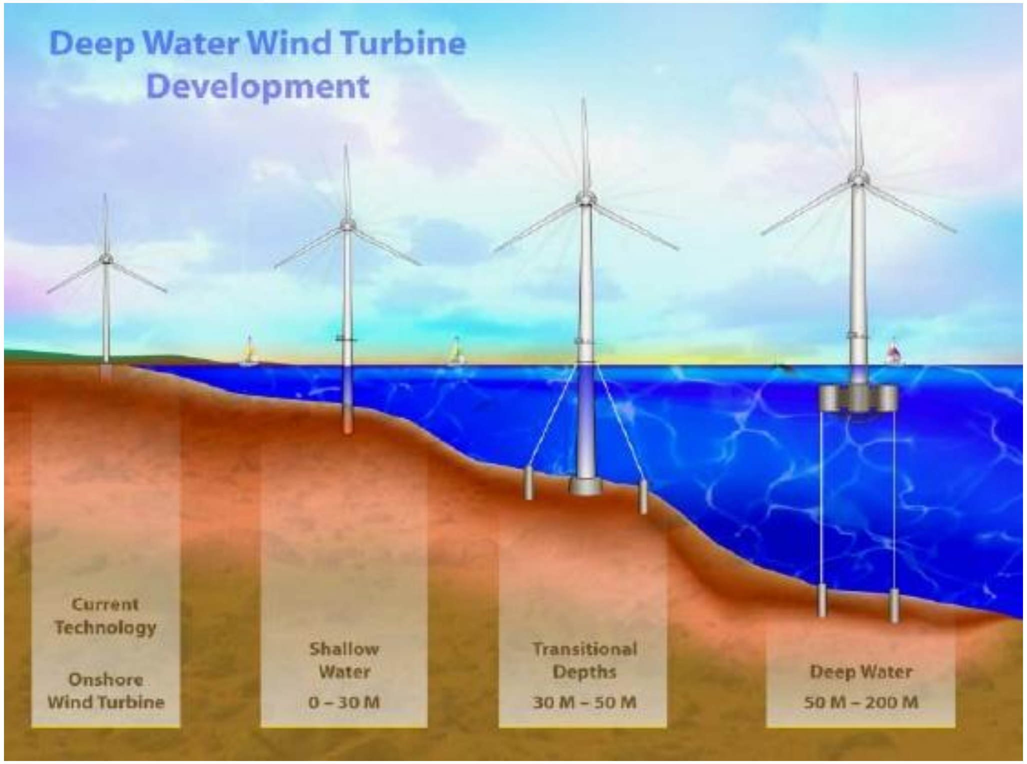
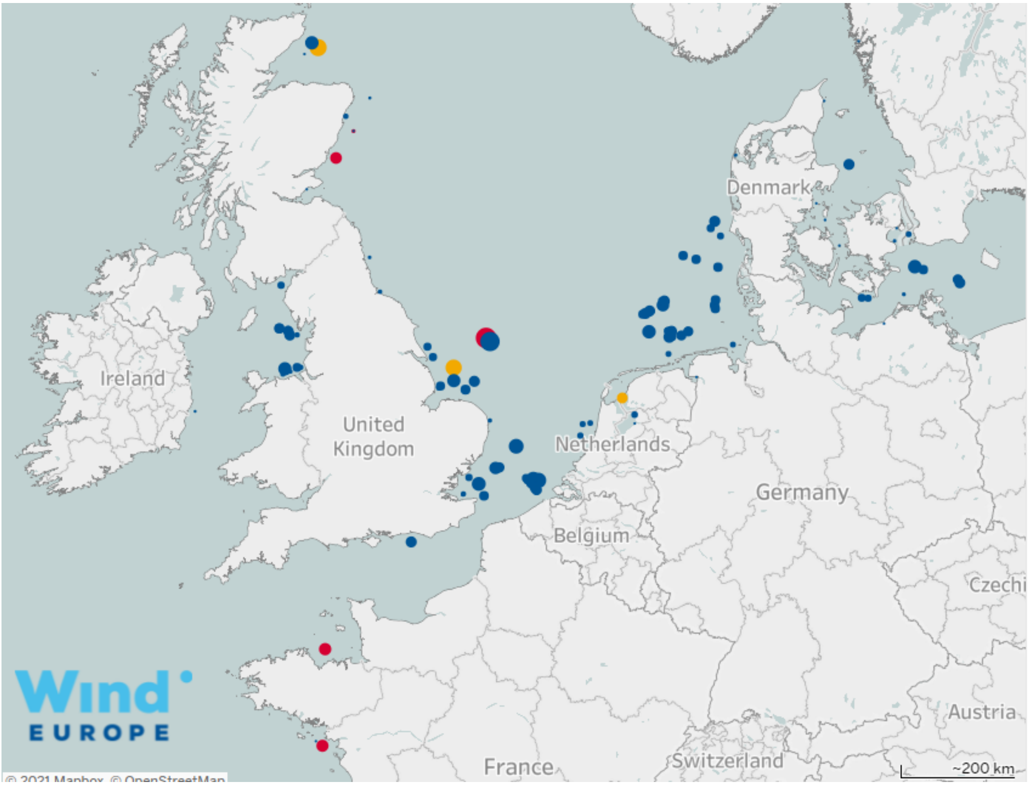


Image Source: National Renewable Energy Laboratory

Offshore Wind Installations



Partially online
Under construction

Technology
(All)

Country details

	MW connected	Turbines connected
UK	11,021	2,355
GERMANY	7,689	1,501
NETHERLANDS	2,749	568
DENMARK	2,308	631
BELGIUM	2,261	399
SWEDEN	192	80
FINLAND	71	19
IRELAND	25	7
PORTUGAL	25	3
SPAIN	5	1
NORWAY	2	1
FRANCE	2	1

Status update 01/07/2021

The first US offshore wind, Block Island (Rhode Island) with 30 MW, became operational in December 2016; there is also 12 MW now in Virginia. However, the project pipeline is quite large (35 GW), with 800 MW approved. Total worldwide in 2020 is 35.5 GW, with UK and China with the most.

https://windeurope.org/about-wind/interactive-offshore-maps/

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 to 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

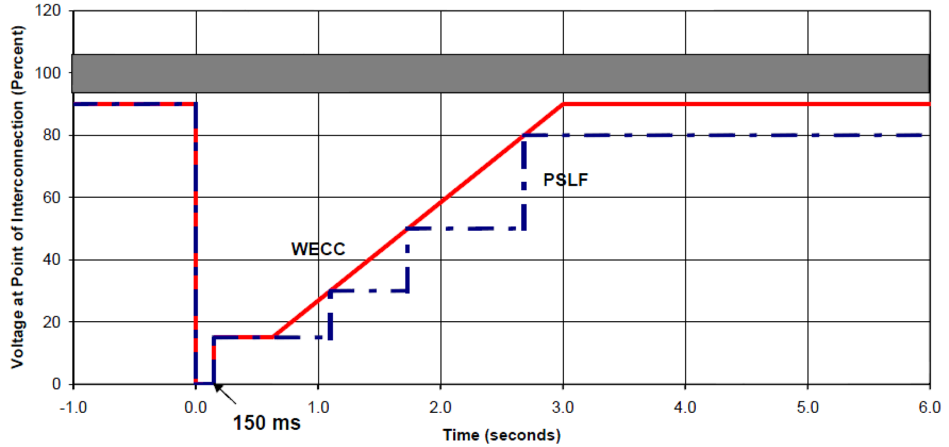


Image from California ISO presentation

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

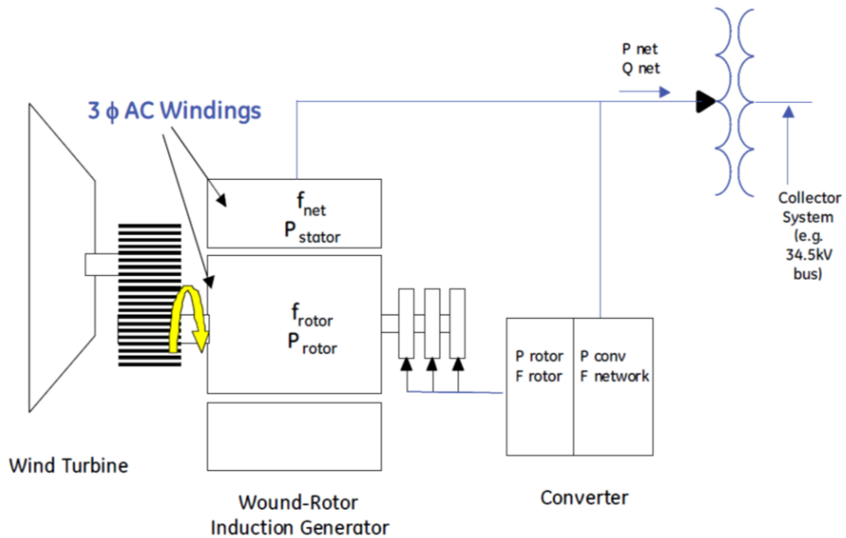


Figure 2-1. GE Doubly Fed Asynchronous WTG Major Components.

Image Source: Figure 2.1 from Modeling of GE Wind Turbine-Generators for Grid Studies, version 4.6, March 2013, GE Energy

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

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

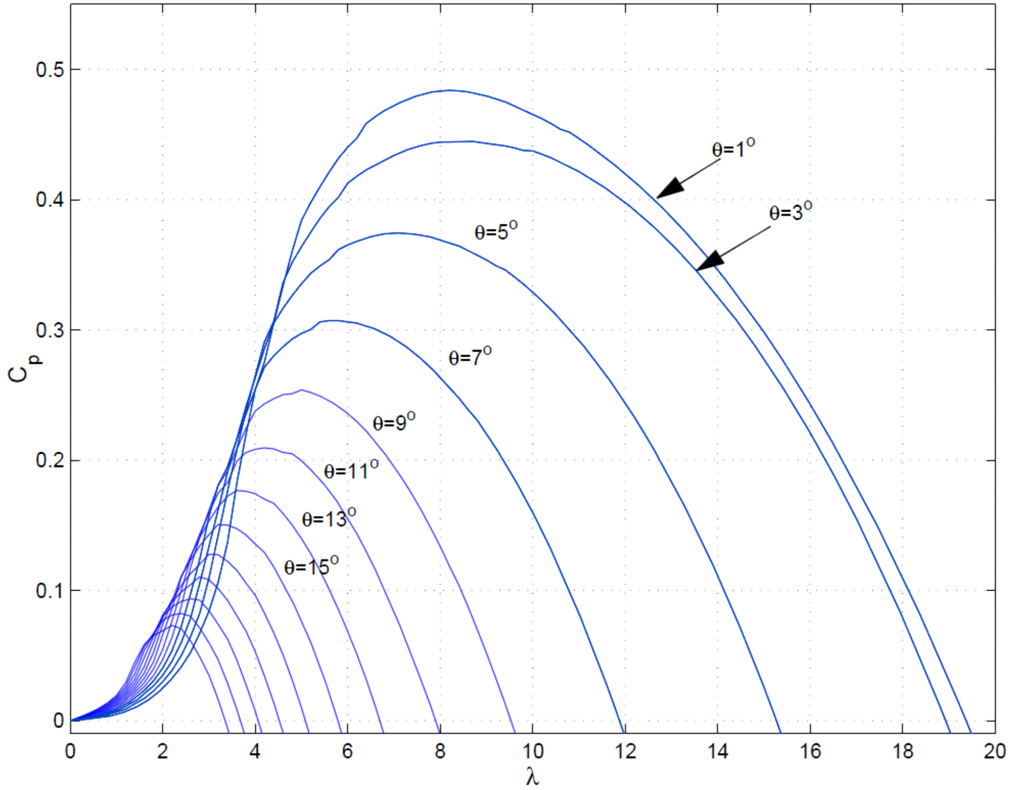
where ρ is the density of air, A is the area swept by the blades, v_w is the wind velocity, λ is the tip to wind speed ratio.

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

Modeling of GE Wind Turbine-Generators for Grid Studies, version 4.6, March 2013, GE Energy

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}

Source: Modeling of GE Wind Turbine-Generators for Grid Studies, version 4.6, March 2013, GE Energy

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

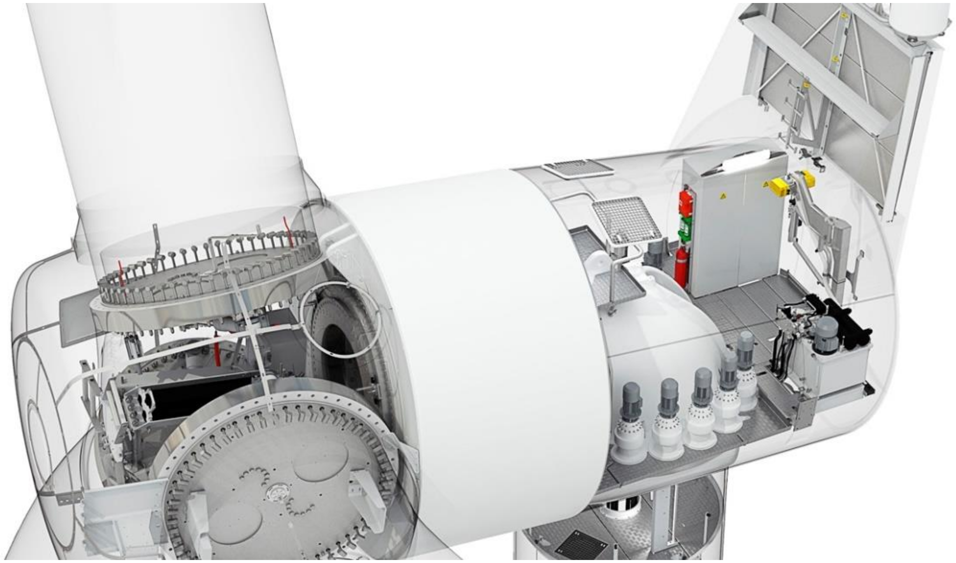
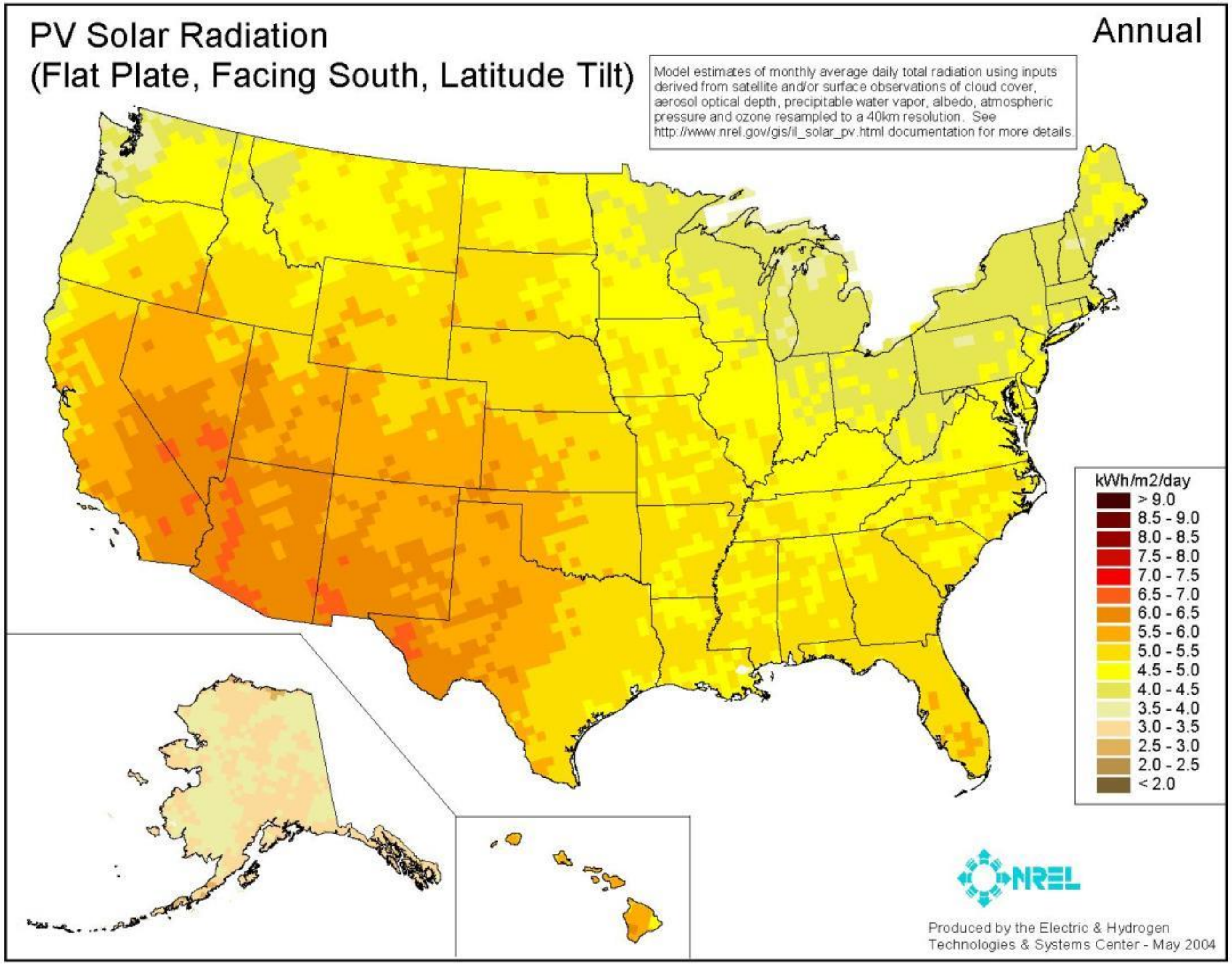


Image: www.siemens.com/press/pool/de/pressebilder/2011/renewable_energy/300dpi/soere201103-02_300dpi.jpg

Solar Photovoltaic (PV)

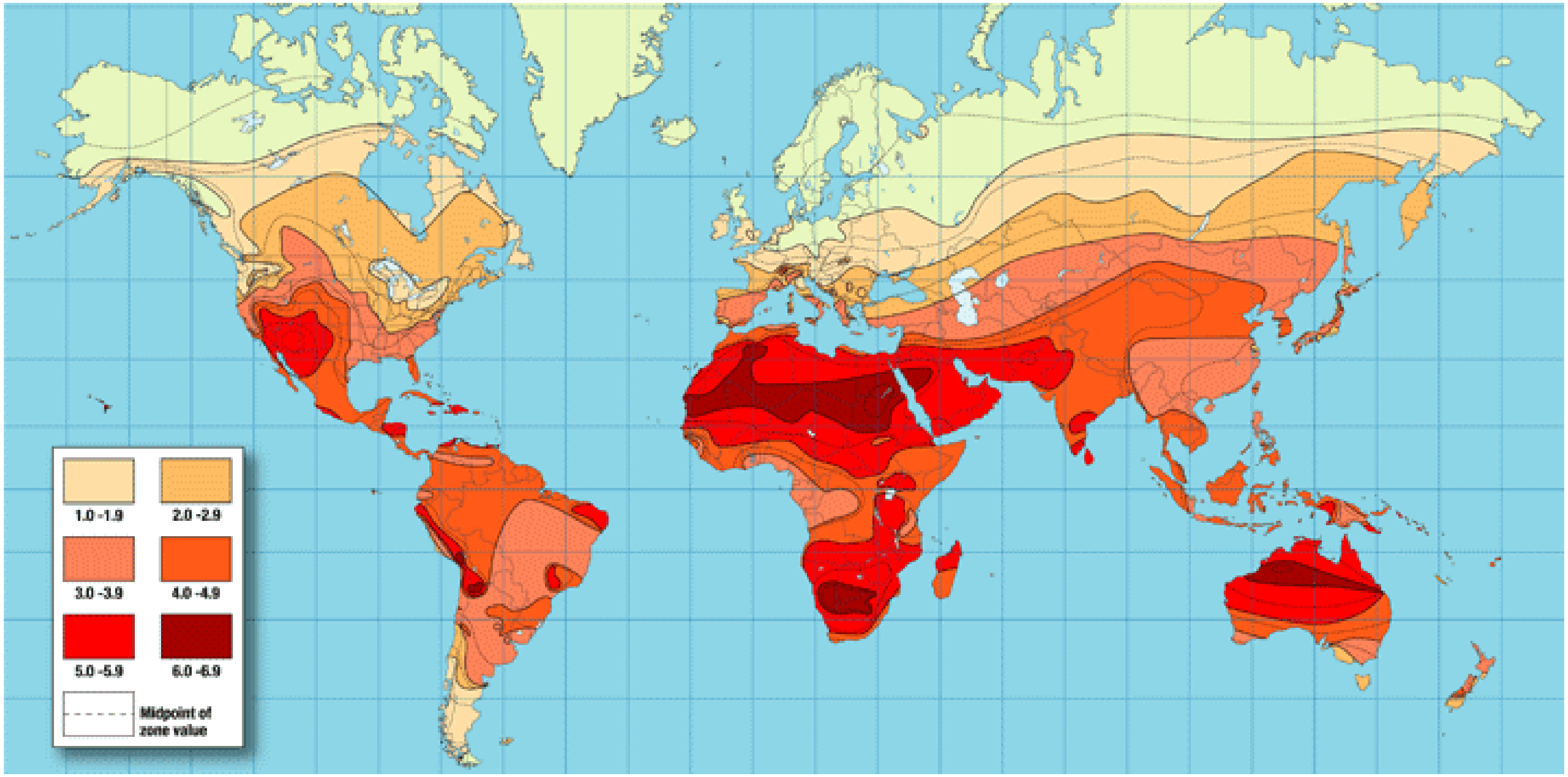
- **Photovoltaic definition-** a material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current
- Solar cells are diodes, creating dc power, which in grid applications is converted to ac by an inverter
- For terrestrial applications, the 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 a 1 kw/m^2,which is the maximum insolation the reaches the surface of the earth (sun right overhead)

US Annual Insolation

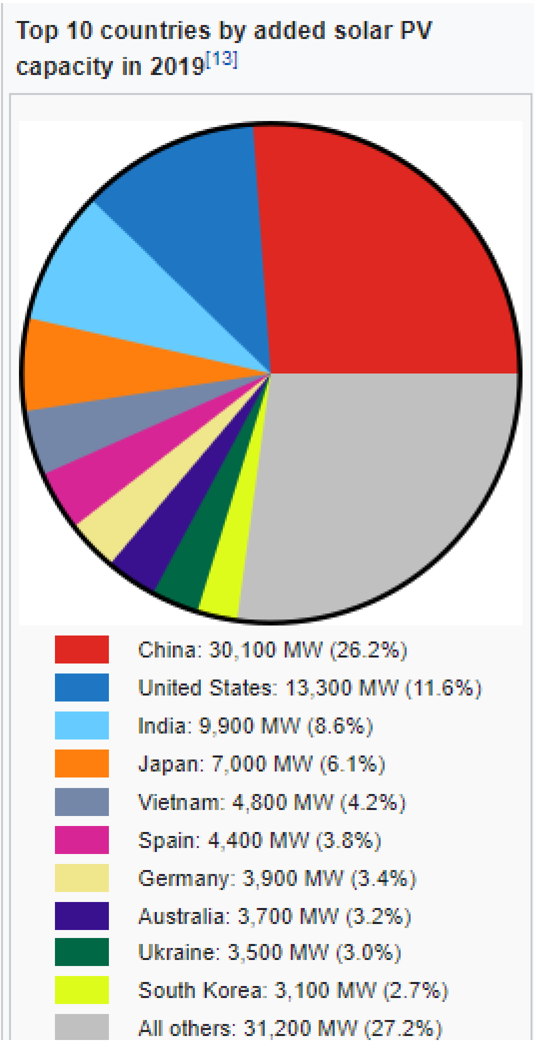


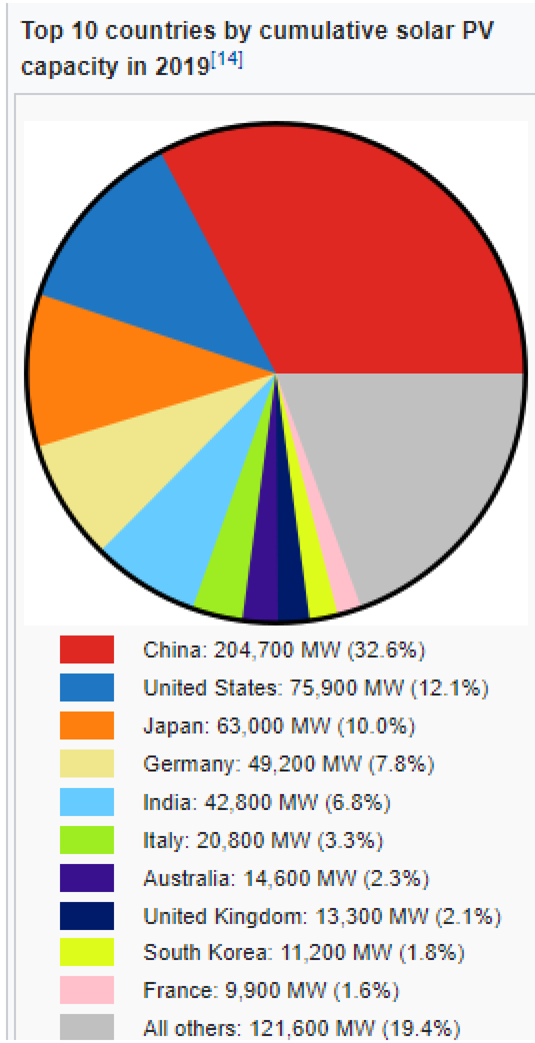
The capacity factor is roughly this number divided by 24 hours per day

Worldwide Annual Insolation



Solar Capacity by Country



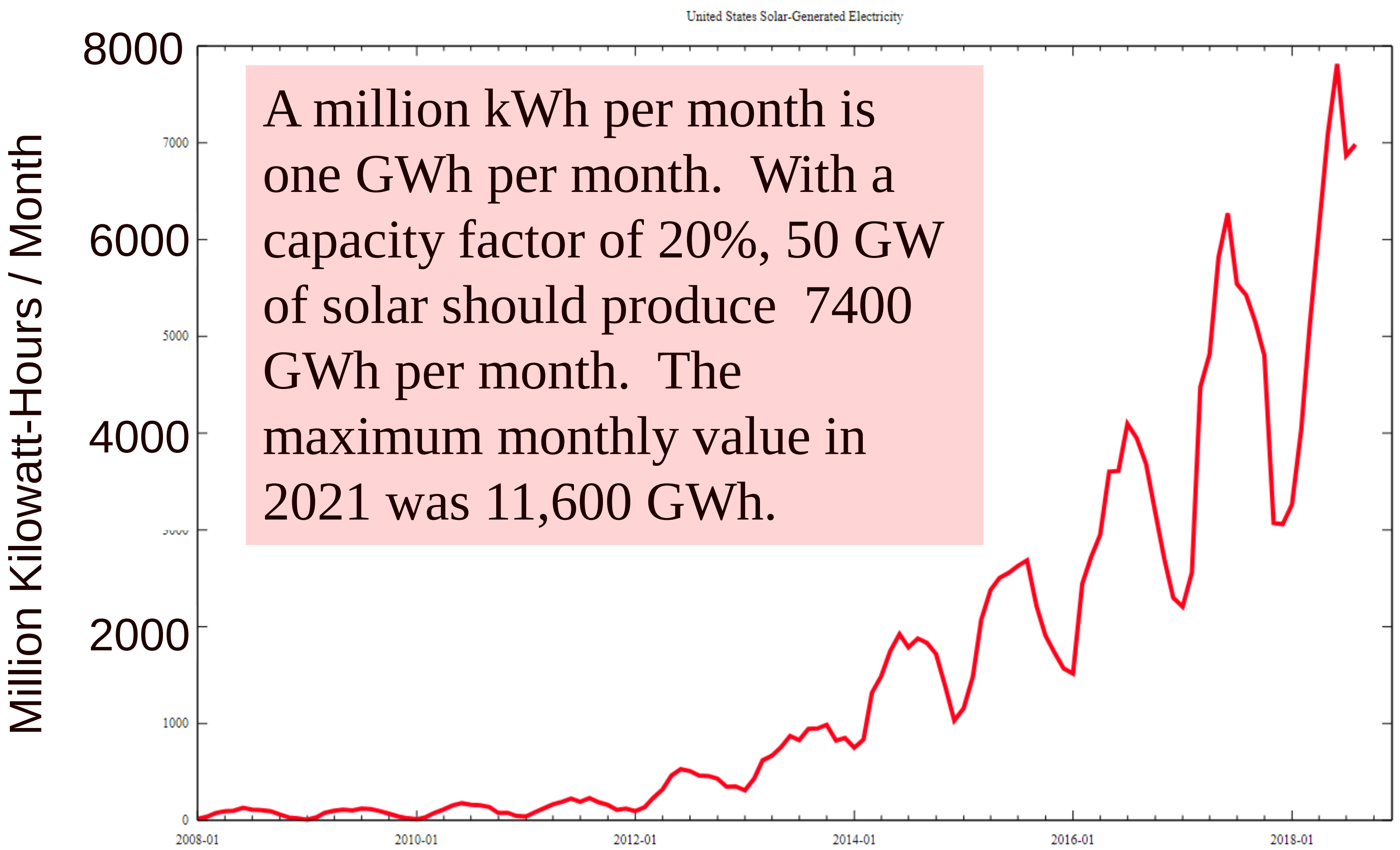


Total values in 2020 are 254 GW for China, 75 GW for the US, 67 GW for Japan and 53.8 GW for Germany

Source: en.wikipedia.org/wiki/Solar_power_by_country

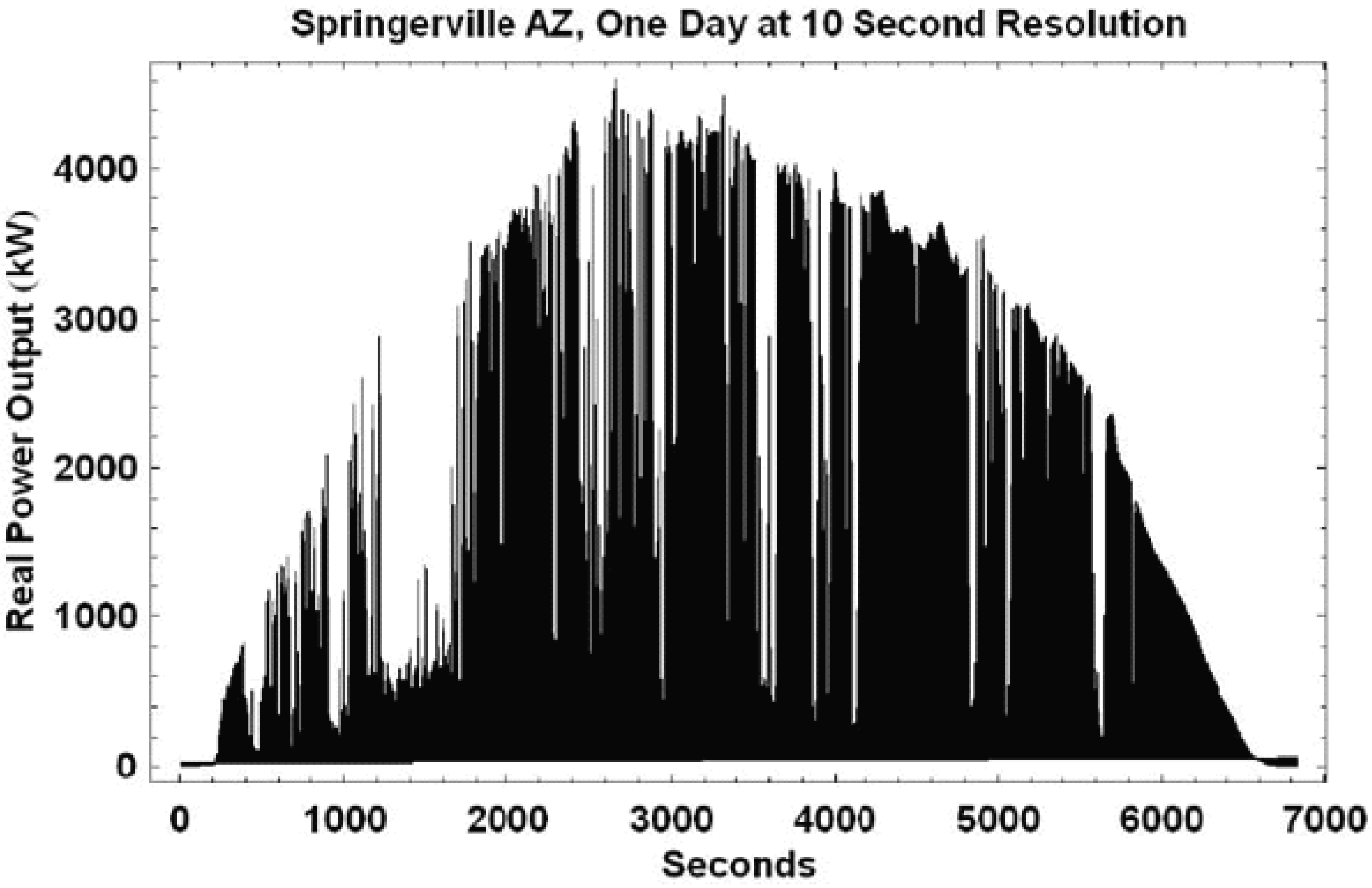
US Solar Generated Electricity

A million kWh per month is one GWh per month. With a capacity factor of 20%, 50 GW of solar should produce 7400 GWh per month. The maximum monthly value in 2021 was 11,600 GWh.



https://upload.wikimedia.org/wikipedia/commons/4/4e/US_Monthly_Solar_Power_Generation.svg

Solar PV can be Quite Intermittent Because of Clouds



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

Image: http://www.megawattsf.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)

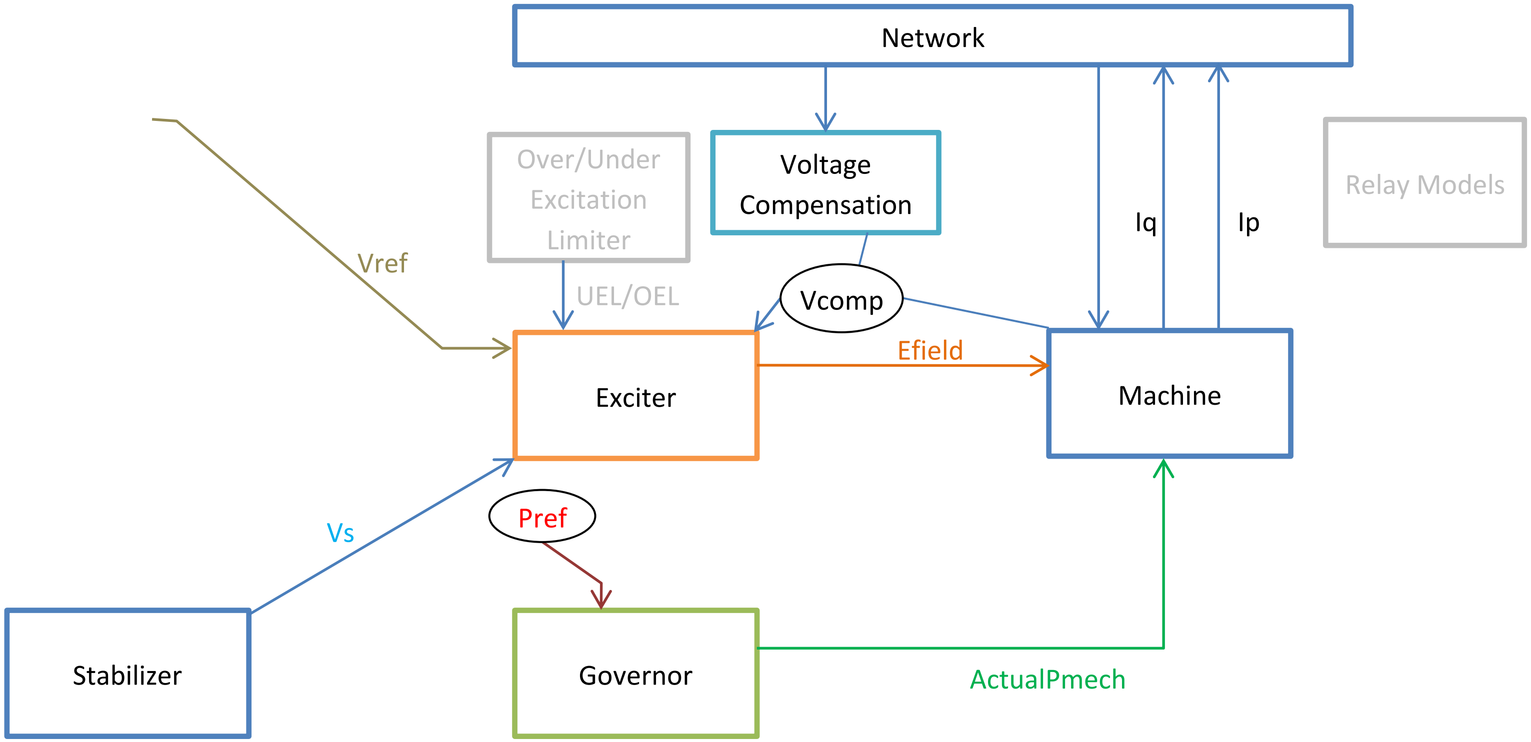
Distributed PV System Modeling

- An issue is tripping on abnormal frequency or voltage conditions (from IEEE 1547-2003, 2014 amendment); latest is IEEE 1547a-2020
  - 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

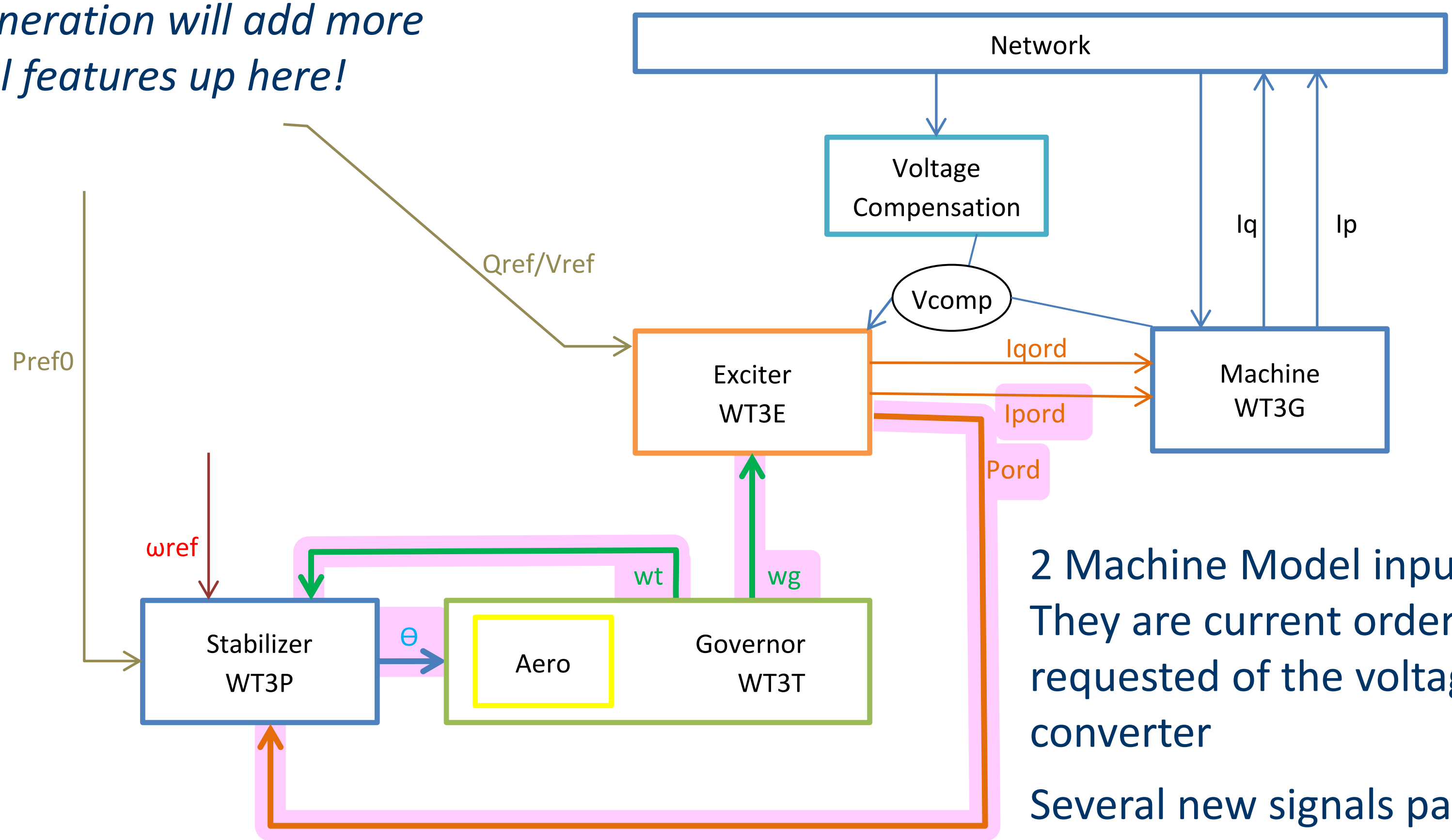


Modular Approach to Generator Modeling

- 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*

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

2nd Generation will add more control features up here!

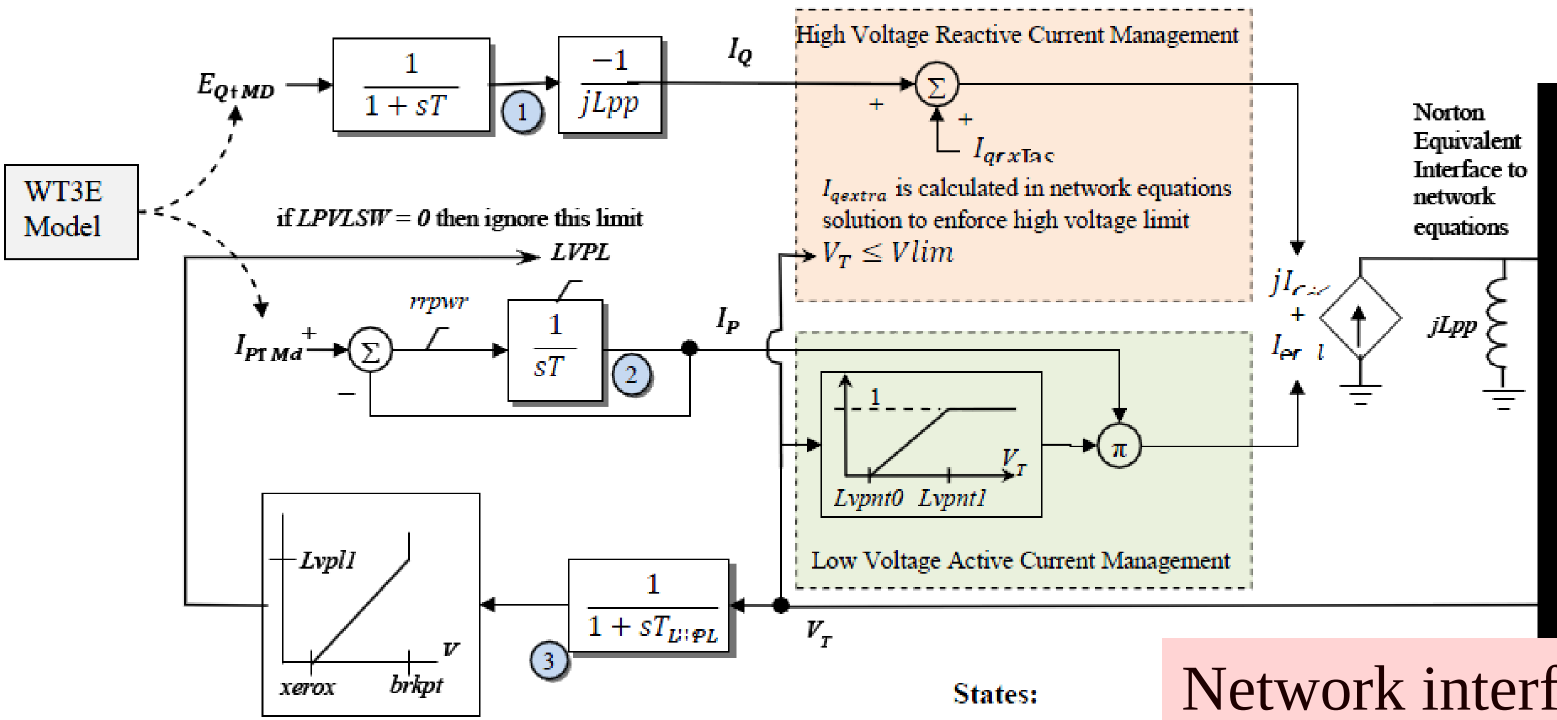


2 Machine Model inputs now. They are current orders requested of the voltage source converter

Several new signals passing around

Type 3 WT3G Converter Model

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

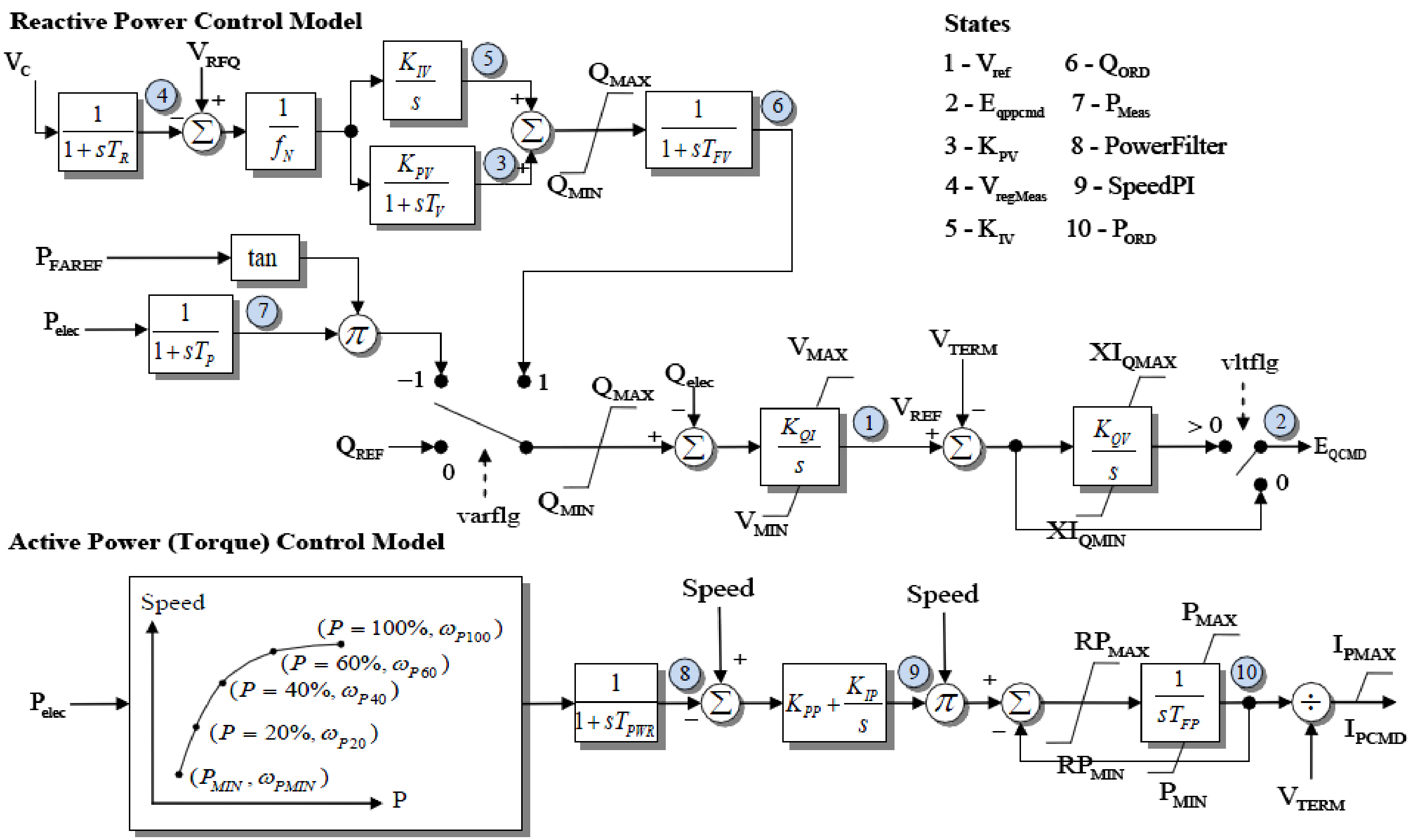


States:
1 – E_q
2 – I_p
3 – Vmeas

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

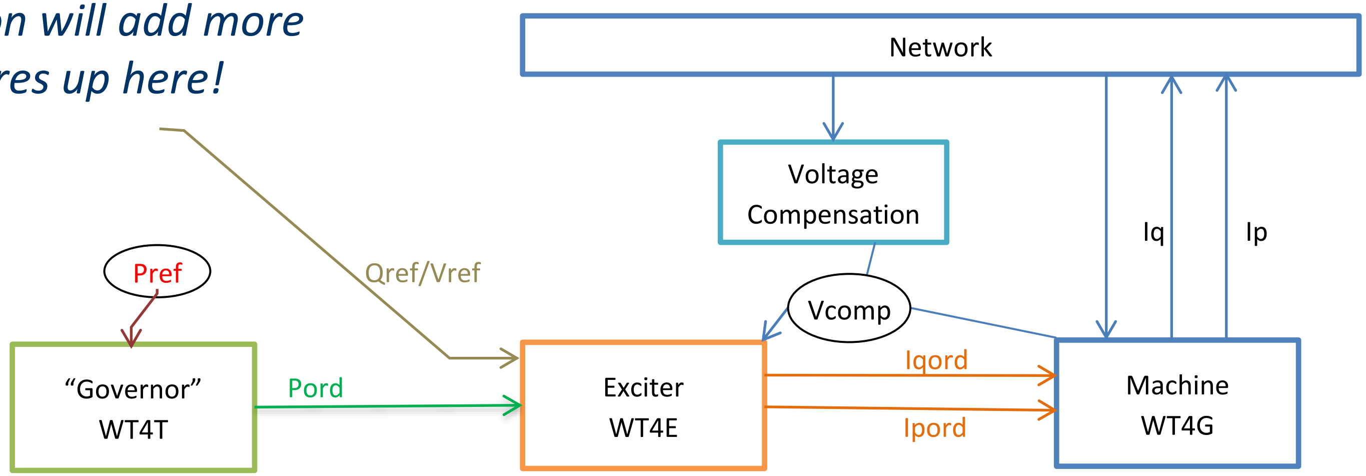


WT3E supported by PSLF with $RP_{MAX} = P_{wrat}$ and $RP_{MIN} = -P_{wrat}$, $T_{FV} = T_C$

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!

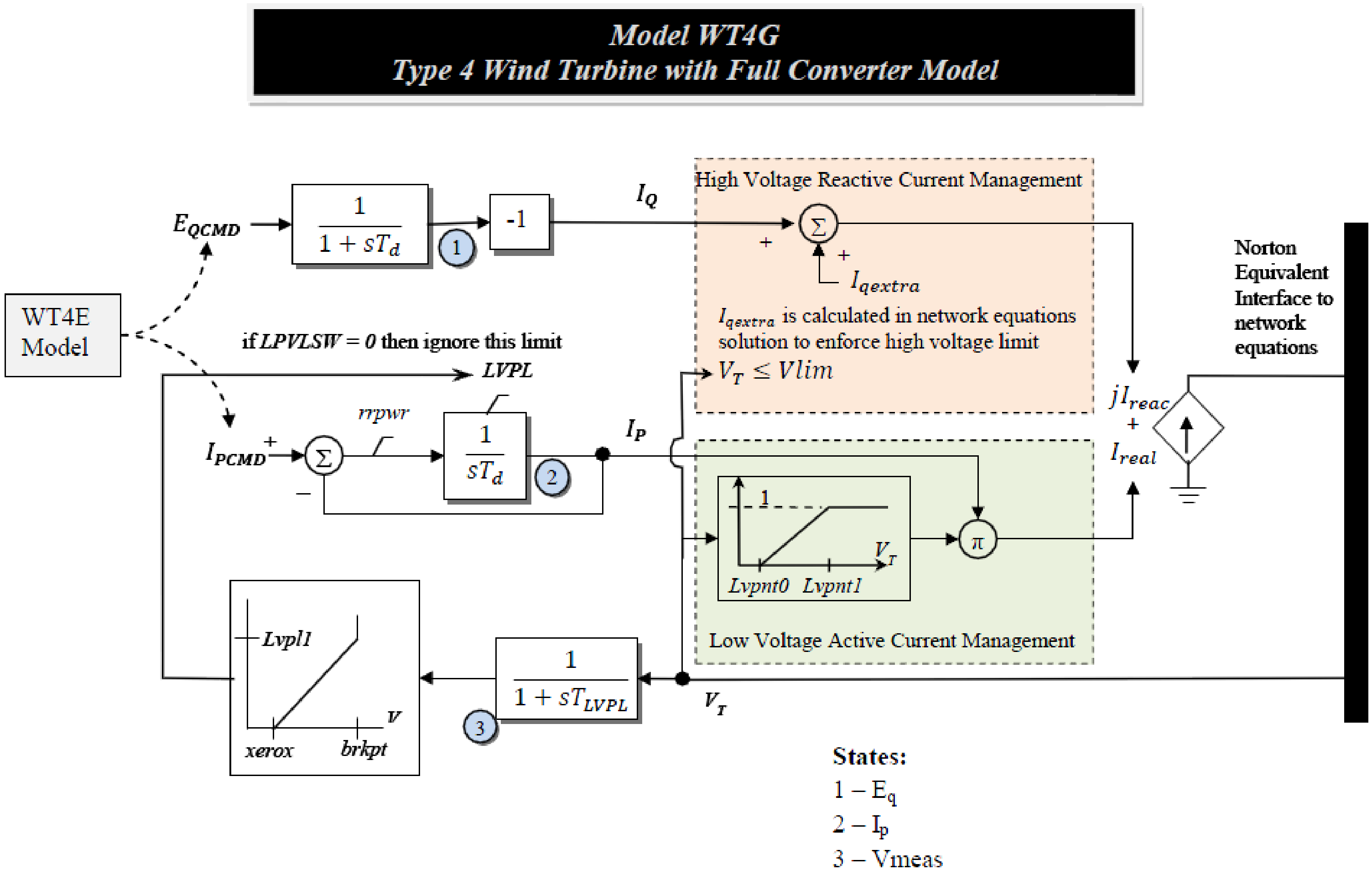


Legacy "Governor" WT4T

This really acts like the new PRef controller

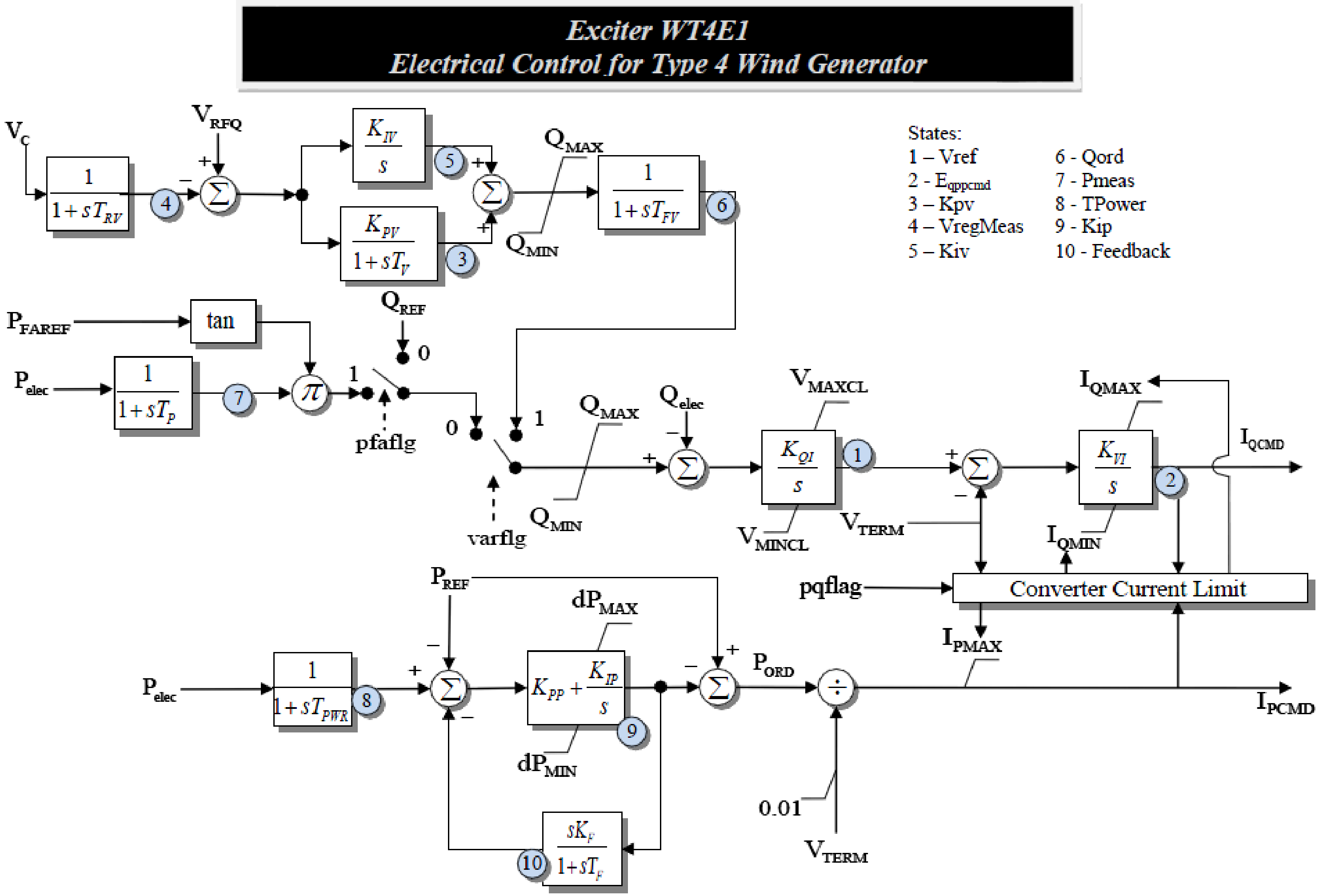
We will leave it in the toolbox as a "Governor" anyway

Type WTG4 Model



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

Type 4 Reactive Power Control



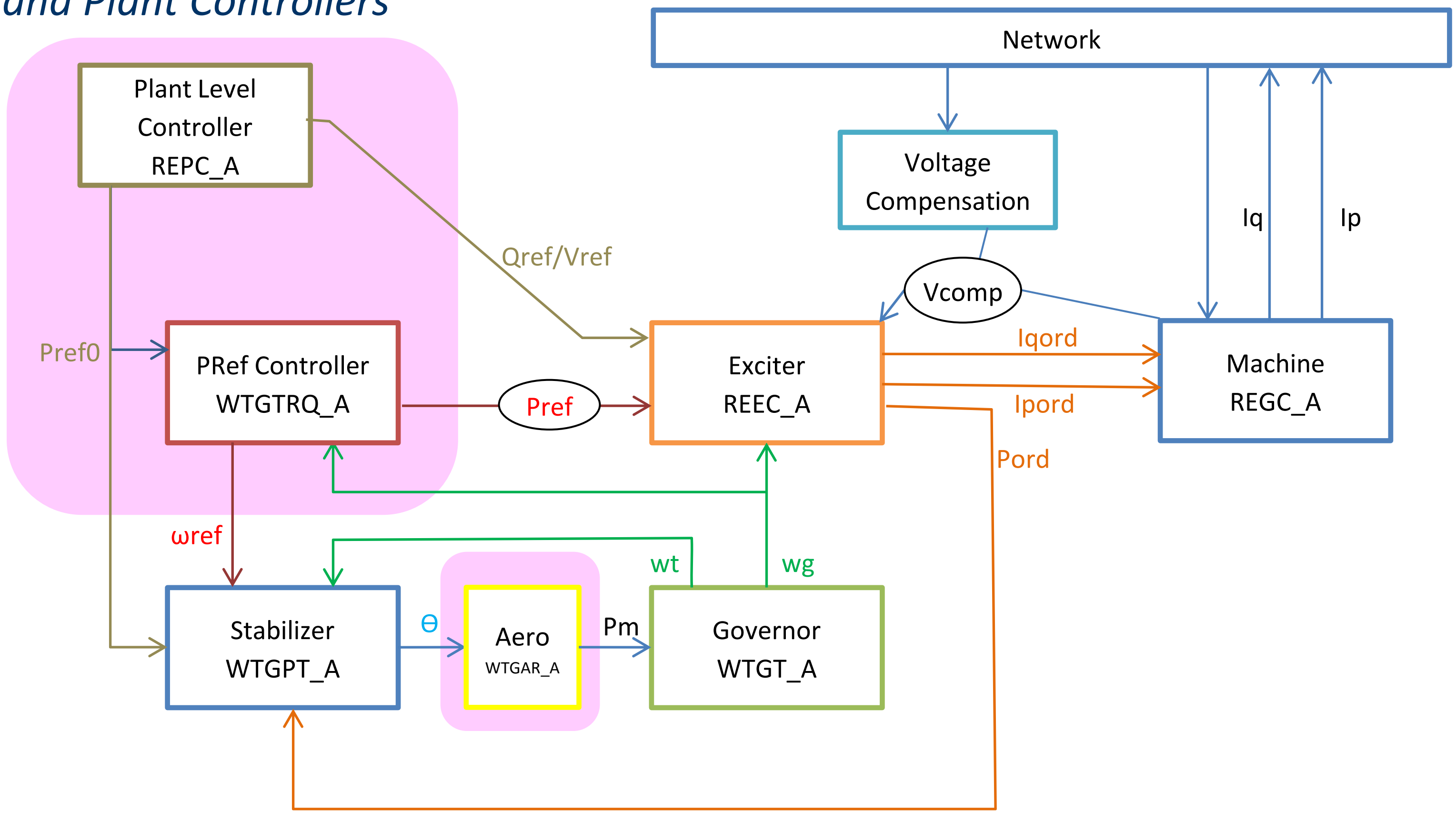
Also similar to the Type 3's, as are the other models

Limitations of First Generation Wind Models

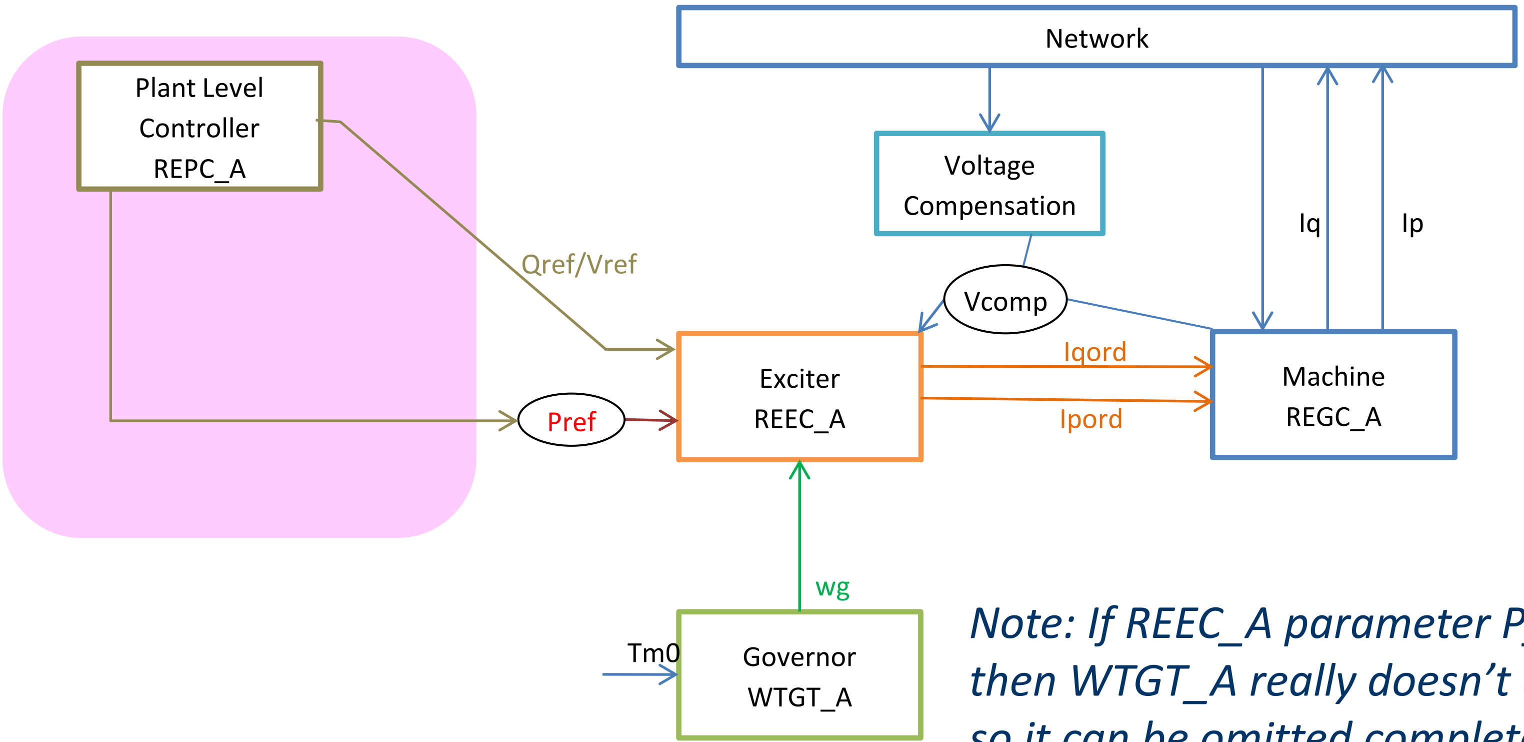
- First Generation model had few mechanisms to provide control features of
  - Real Power or Torque Control
  - Reactive Power
  - Voltage Control
  - For First Generation models, the wind turbine basically tried to bring values back to the initial condition
    - Pref bring power back to initial Power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



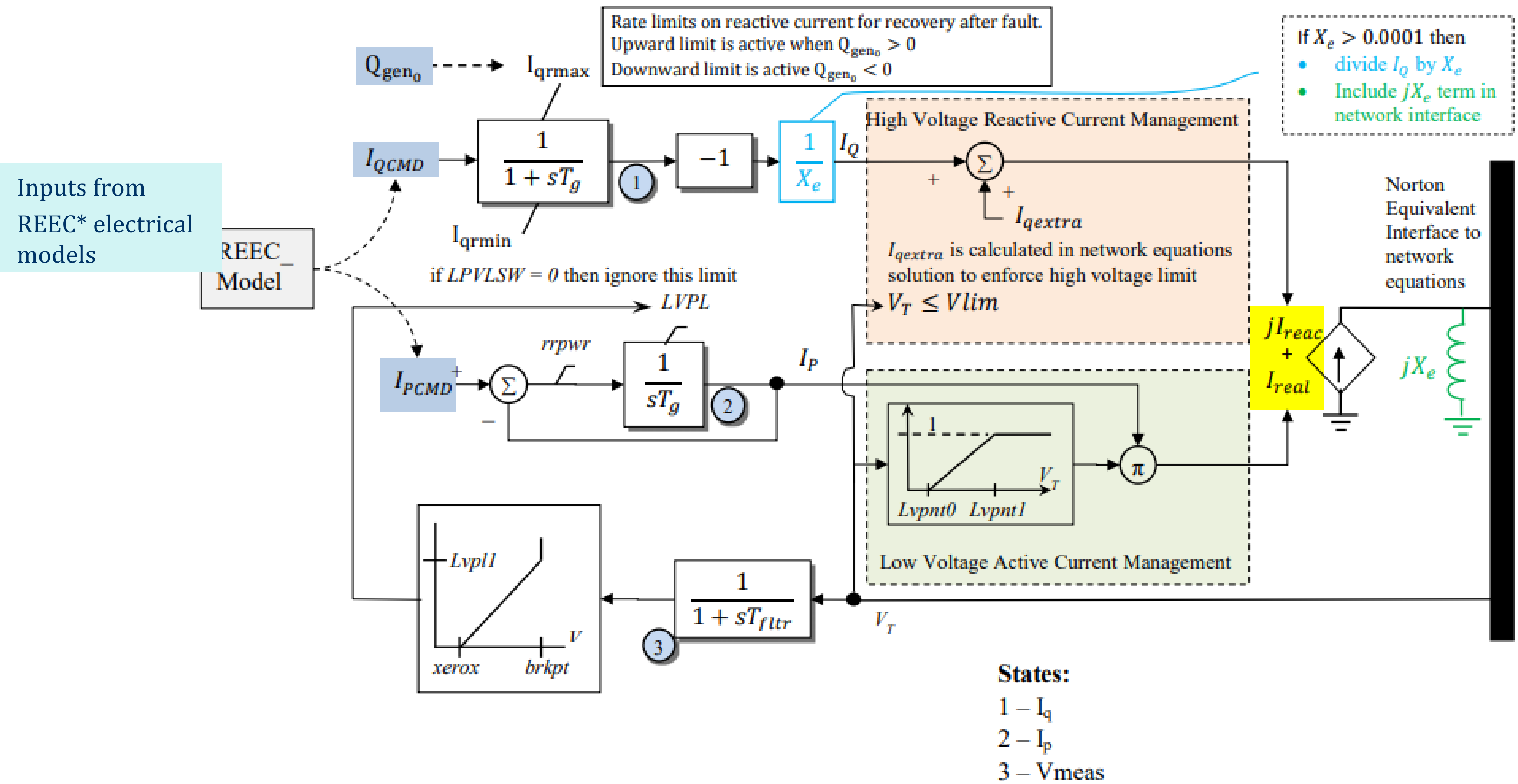
2^{nd} Generation Type 4 Wind Turbine (REGC_A, REEC_A, WTGT_A, REPC_A)



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

REGC_A (or REGCA1)

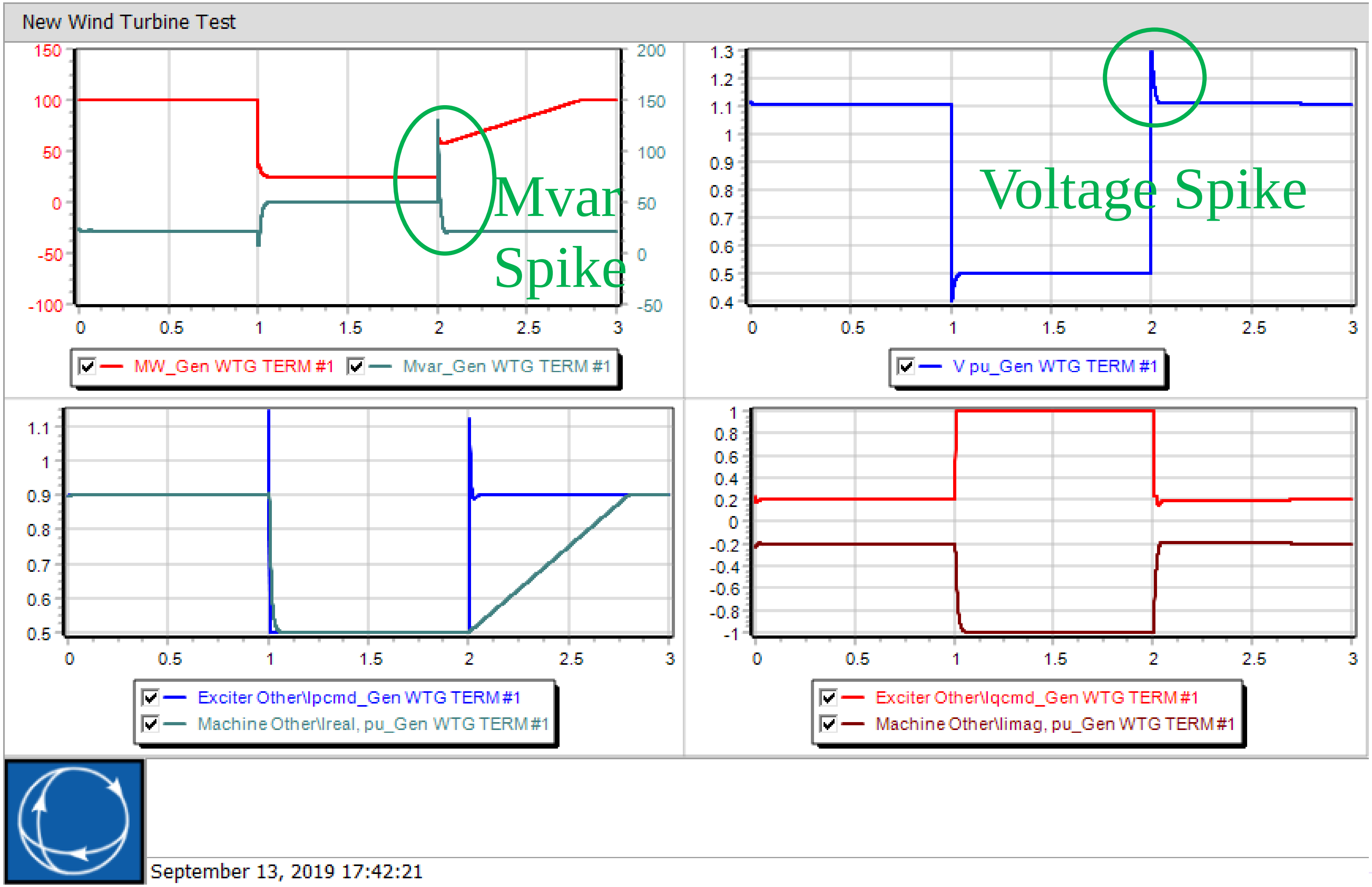
- "Machine Model": Really a network interface



REGC_A Description

- This model is doing very little actually
  - Time delay Tg 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



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

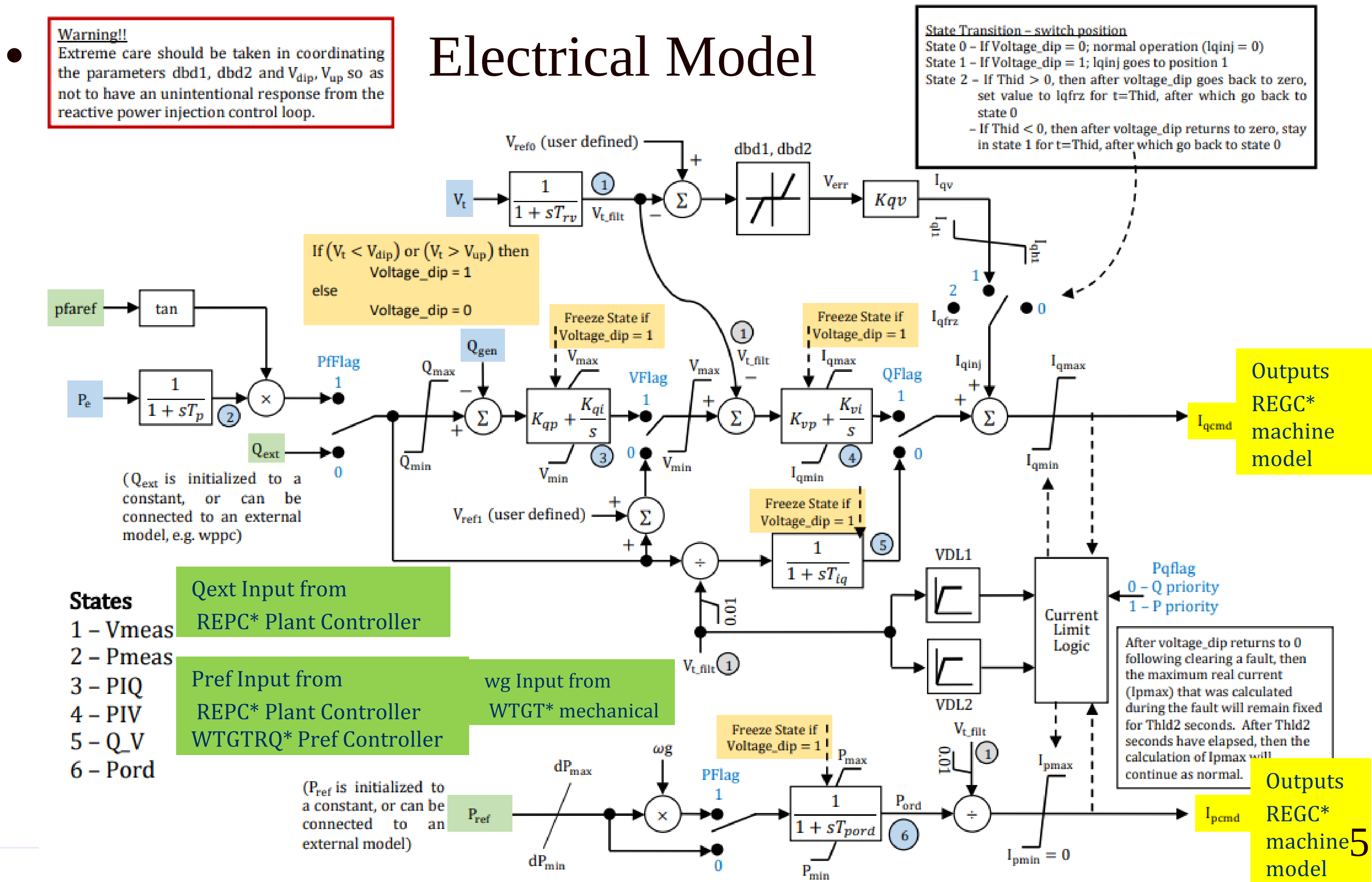
Class of Model Type	Wind Type 1	Wind Type 2	Wind Type 3	Wind Type 4	Solar PV	Distributed PV Model	Energy Storage
Machine	WT1G WT1G1	WT2G WT2G1	REGC_A	REGC_A	REGC_A	PVD1 DER_A	REGC_A
Electrical Model		WT2E WT2E1	REEC_A	REEC_A	REEC_B		REEC_C
Mechanical	WT1T WT12T1	WT2T WT12T1	WTGT_A	WTGT_A			
Pitch Controller	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

Additional Uses

3 new classes of models

REPC_B = Plant controller for up to 50 machines and SVCs

REEC_A (same as REECA1)



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