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Full-Converter Wind Turbine Technology

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Siemens Wind Turbines - Americas

Comparison of Full Converter (Type 4) Design to Other WTG designs

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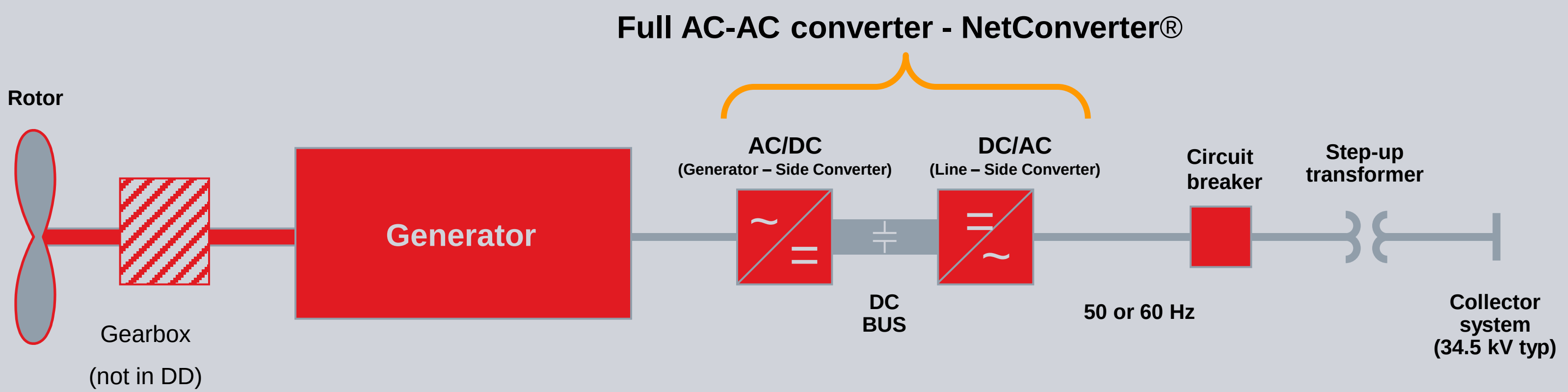


Siemens has used Type 4 (variable-speed, full-converter) design exclusively for new products since 2005 and is the only major manufacturer with a large fleet of Type 4 machines in the USA.

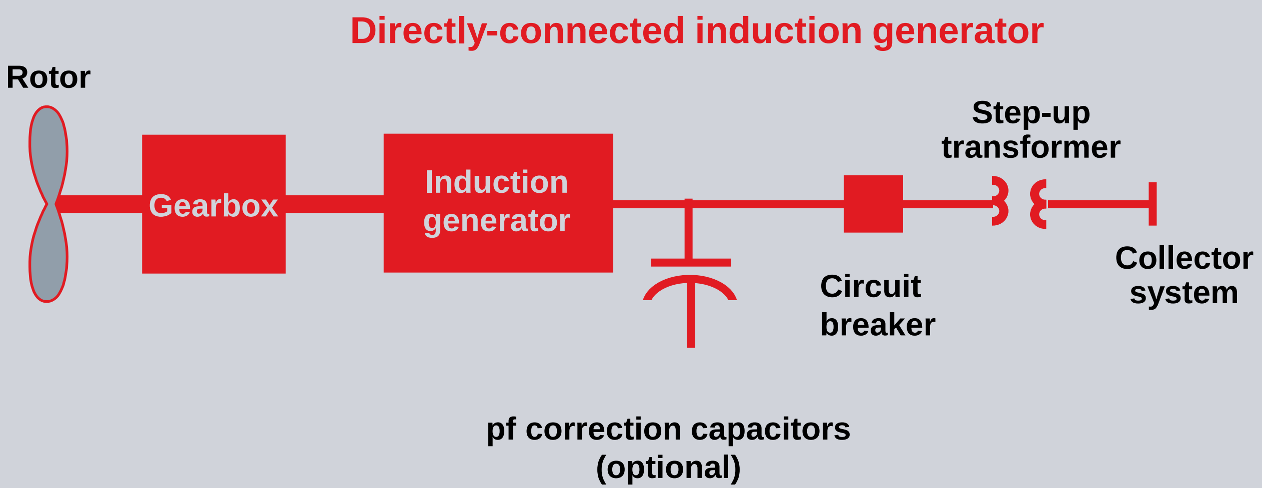
Siemens is the largest manufacturer of Type 4 WTGs in the Americas

Why did Siemens move to the full converter design?

Compare to other available designs→

Type 1 and type 2 induction generator wind turbines

Basic operation of type 1 and 2 – typical configuration



Fixed speed system

- **Capacitors supply magnetizing current and system reactive support**
- **Gearbox to increase shaft speed by, typically, ~100 times**
- **Slip rings for Type 2 (wound rotor), not for type 1 (squirrel cage)**
- **No inherent voltage regulation capability; must be supplemented by reactive sources (usually capacitors)**
- **Torque controlled by adjusting pitch (and/or rotor resistance in type 2)**
- **Susceptible to system conditions, especially low voltage**

Type 1 and 2 IG wind turbines
Advantages/disadvantages

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Main Advantages

- Simple and low cost
- Rugged, low maintenance (esp. type 1)

Main Disadvantages

- Poor voltage control ability
- Large starting inrush; required capacitors and/or staggered starts
- Difficult to control output per schedule
- No speed control in type 1, very limited in type 2
- High mechanical stress on turbine components, especially gearbox, during system faults
- Slip ring/brush maintenance in nacelle for type 2
- Poor zero-voltage ride through capability

Not applied in North America for new transmission applications.

Type 3 – Doubly-fed induction generator (DFIG)

Basic operation of DFIG – typical configuration

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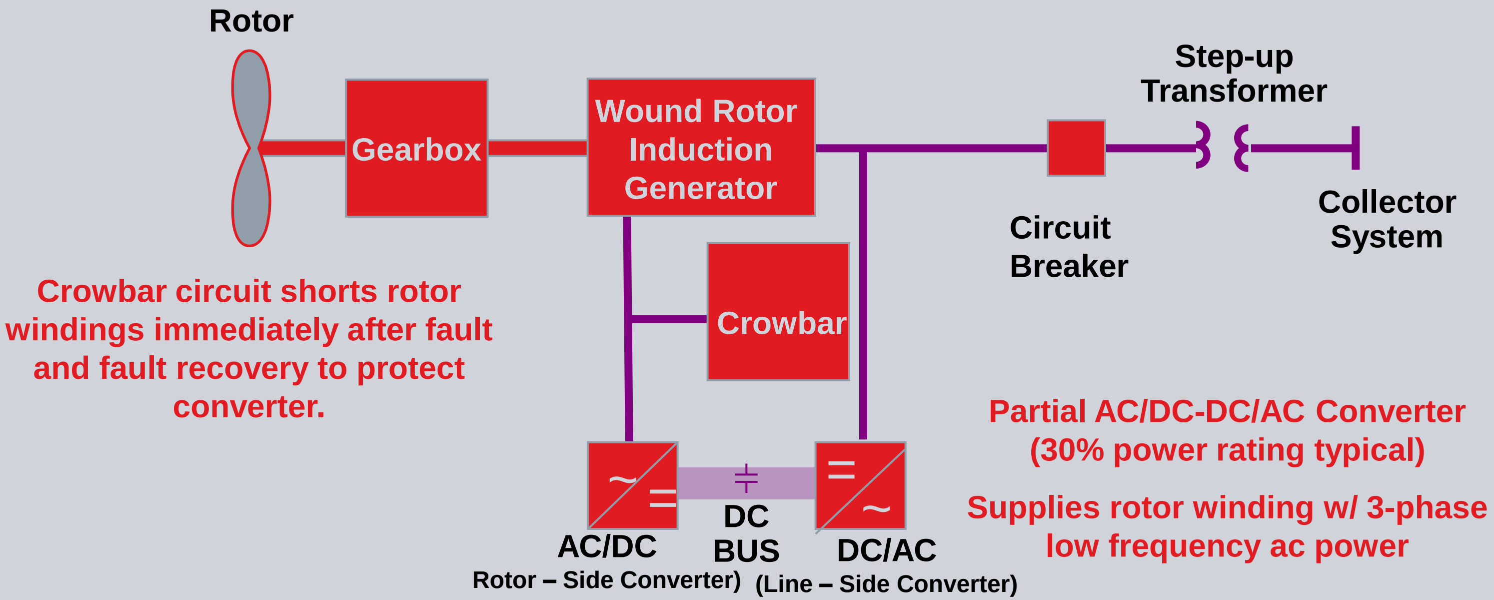
Doubly-Fed Induction Generator (DFIG)



DFIG system

- Rotor- and line-side converters (back-to-back, connected by dc bus) sized for, typically, ~30% of rated output
- Gearbox to increase shaft speed by, typically, ~100 times
- Rotor-side converter supplies (low) slip frequency magnetizing 3-phase AC voltage to wound rotor windings via slip rings
- Crowbar circuit often used to short rotor windings after fault and fault recovery to protect rotor-side converter

Type 3 – Doubly-fed induction generator (DFIG)
Advantages/disadvantages

Main Advantages

- Good conversion efficiency
- Decoupled control of active/reactive power
- Capable of ancillary service (voltage/frequency regulation) support

Main Disadvantages

- Regular maintenance of slip ring and brush assembly in nacelle
- Limited fault ride-through and voltage regulation capability
- Rotor and gearbox stresses during system faults, esp. unbalanced faults
- Crowbar circuit limits system support during contingencies
- Negative sequence heating/vibrations in some power systems
- Large short circuit contribution
- Interactions between grid and generator; susceptible to subsynchronous interaction (SSI), system shorts, etc.
- Damage can result from improper synchronization

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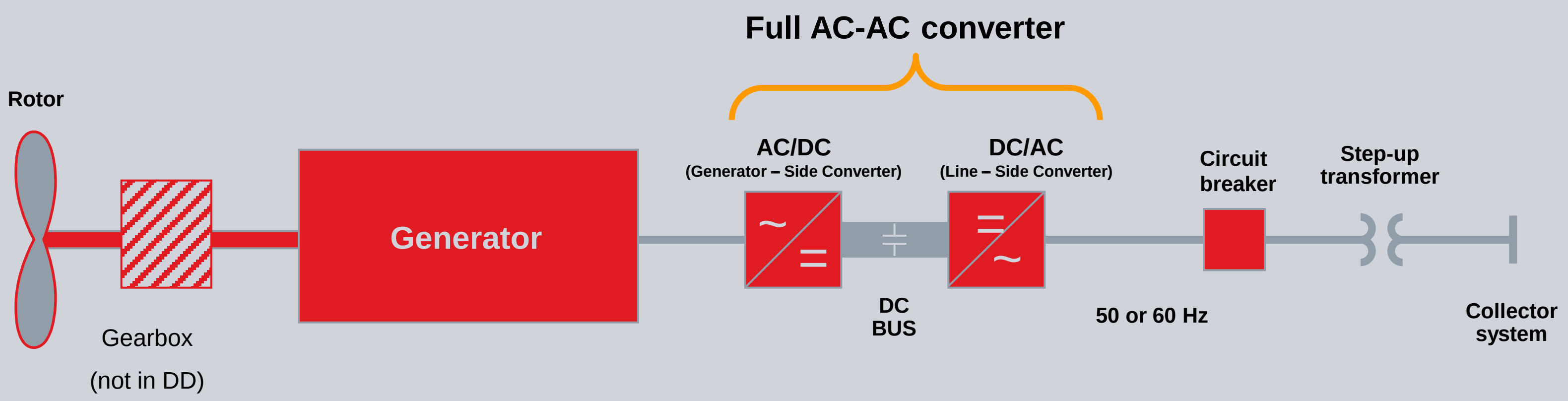
How does the Full-Converter (type 4) system work?



- Rotor drives gearbox in geared systems – increases generator shaft speed
- Gearbox eliminated in DD (direct drive); rotor directly drives low-speed, multi-pole generator
- Generator converts mechanical power to AC electric power. Generator can be asynchronous, permanent magnet or synchronous for geared system, pm or synchronous for DD.
- Generator-side converter converts AC electric power to DC
- Line-side converter converts DC to system-frequency AC (50 Hz or 60 Hz, as appropriate) and provides voltage regulation capability
- Converter decouples machine from grid.

What are the advantages of the Full Converter system?

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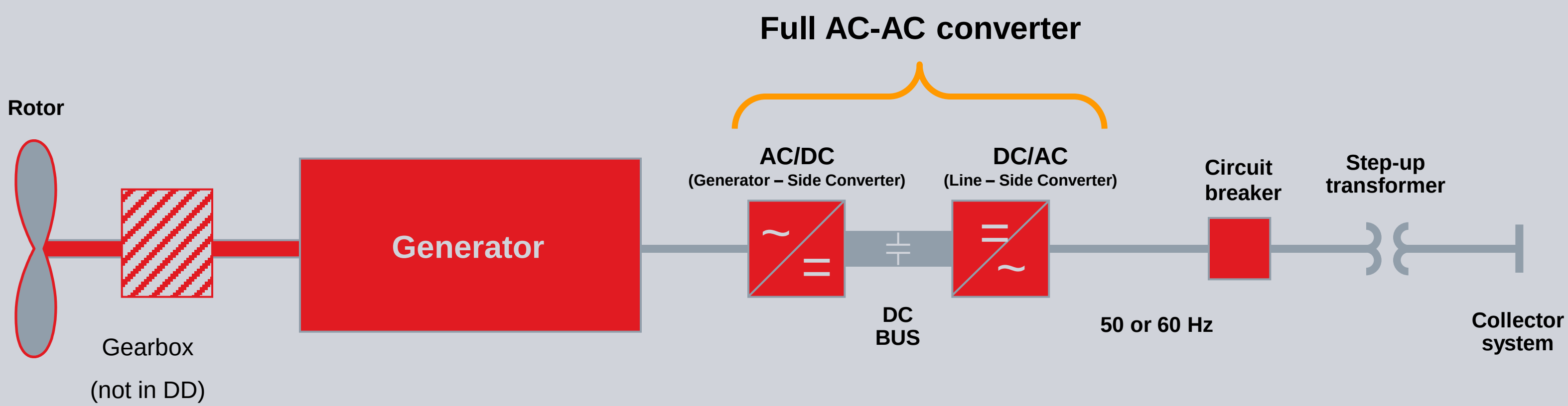

Variable Speed:

During abnormal conditions, can increase or decrease shaft speed/kinetic energy to satisfy system needs

- Increase shaft speed during low-voltage ride-through – extra kinetic energy stored in shaft when Pgen→0.
- Shaft can absorb energy from gusts without changing output

Full Converter:

Maximum flexibility and fast response; decouples machine:

- Rapid response – short time delays compared to directly connected magnetic machines, with winding time constants
- Full control of short circuit current from >100% of nominal output current to zero (standby); useful for voltage regulation during low-voltage ride-through and response to faults
- Precise control of output and rate of change of output as required (subject to availability of wind power)
- Turbine can be used for frequency response (for regulation down) or, with standby reserve, for spinning reserve/regulation up
- Decouples machine from power system – no SSTI, negative sequence heating concerns, minimal short circuit torques.

Type 4 Variable-speed, full-converter wind turbine-generator
Advantages/disadvantages

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Main Advantages

- Maximum flexibility – fully controllable converter interface
- Decoupled control of active power and voltage regulation
- Controllable short circuit contribution
- Theoretically infinite duration low-voltage ride-through capability
- No exposure to system faults for generator, gearbox (in geared systems)
- No power system-machine interactions; SSR immunity possible
- Reactive capability curve – similar to synchronous machines
- Minimal moving parts in direct drive configuration
- No slip rings; easy maintenance
- Self-synchronizing; no supplemental equipment or capacitors required; no requirement for staggered startup

Possible Disadvantages

- Limited (but controllable) fault current contribution – may require sophisticated collector protection

Comparison of WTG Designs to Comply with Interconnection Requirements

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	Variable Speed Full Converter (FC)	Doubly –Fed Induction Generator (DFIG)	Traditional Induction Generator (IG)	Comments
LVRT/ZVRT	YYY	YY	X	FC capable of extended ZVRT. DFIG typically goes into "crowbar" during rapid voltage changes. IG must be supplemented for LVRT capability.
Fast Dynamic Voltage Regulation	YYY	YY	X	FC capable of STATCOM-like behavior. DFIG has machine time constants, limited reactive capability. IG has no voltage support capability.
Fast Active Power Regulation	YYY	YY	Y	FC has fast, precise converter response.
Frequency Response	YYY	YY	Y	FC has fast, precise converter response.
Ability to operate in series capacitor-compensated system	YYY	Y	X	DFIG and IG machines are susceptible to SSTI and/or SSCI; FC not susceptible to SSTI and can be tuned to avoid SSCI
Negative Sequence Withstand	YYY	Y	Y	Negative sequence causes heating and vibration in machines; std IEC limit is 2%
Generic Model Availability	YYY	Y	YY	FC generic model fidelity generally very good; few of the concerns that have shown up in other generic models

X = Capability generally not available w/o supplemental equipment

Y = Generally OK, but shortfalls in some apps YY = Generally acceptable YYY = Excellent

Comparison of Type 4 with Synchronous (conventional) generation

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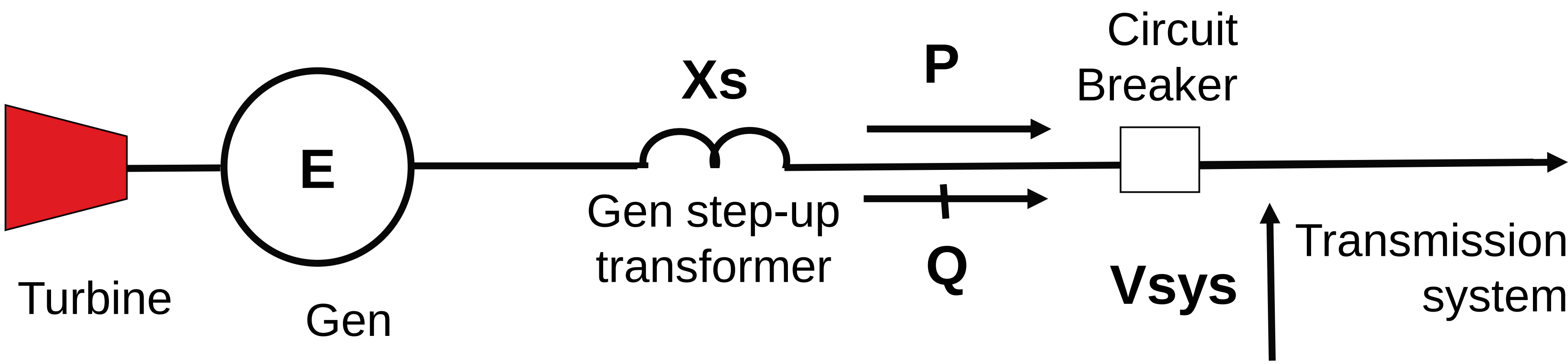
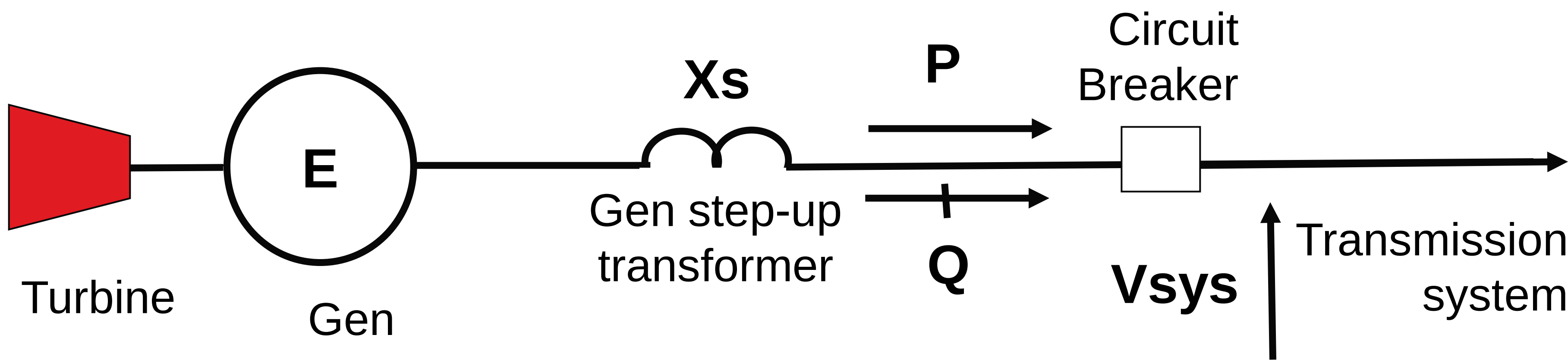


- **Turbine drives generator, which converts mechanical energy to electric power at synchronous speed (3600 or 1800 rpm, typically, in Americas)**
- **Generator step-up transformer steps output from generator (typically at voltage of 13.8 kV to 27 kV) to transmission voltage (usually 69kV, 115kV, 138kV, 161kV, 230kV, 345kV, 500kV or 765kV in North America)**
- **Inertial Response –** When system frequency drops suddenly, shaft kinetic energy is converted to electric power, which slows the frequency decline naturally – not a control action, but physics.
- **Voltage Regulation –** Adjusts system voltage by injecting reactive power to raise voltage or absorbing reactive power to decrease voltage; can operate in voltage regulation, power factor control (constant ratio of Q to P) or reactive power control (fixed Q).

Advantages and Disadvantages of Conventional generation



Advantages:

- Long history and familiarity with operation.
- Excellent controllability, both for active power control and reactive (voltage) control.
- Inertial Response is a function of shaft inertia, not controls

Disadvantages:

- Speed of response, especially active power control
- Lose synchronism during power system faults
- Limited range of voltage regulation- susceptible to voltage collapse
- Large short circuit contributions

Reactive capability characteristic of synchronous generator

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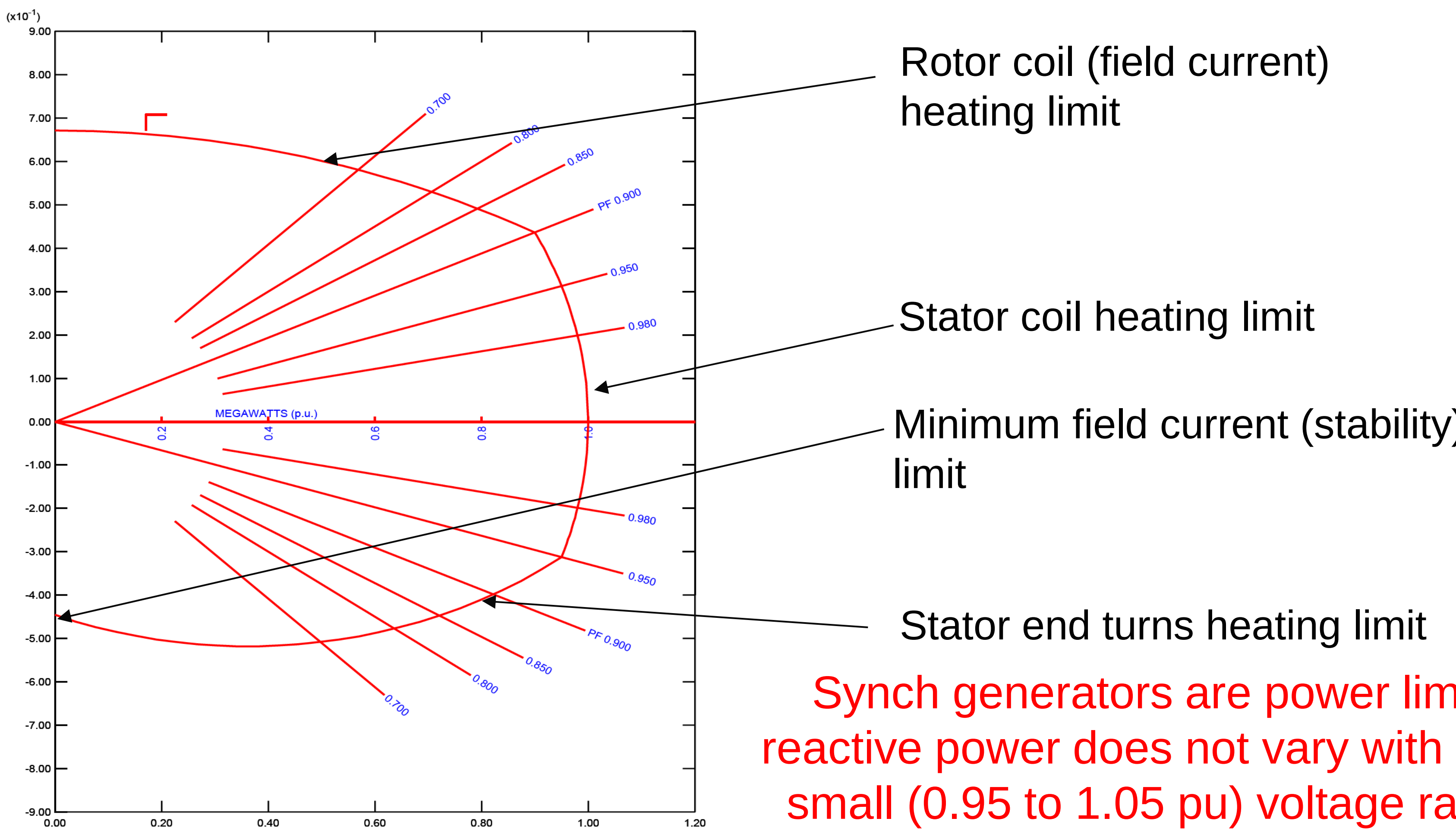

Synch generators are power limited; reactive power does not vary with Vt in small (0.95 to 1.05 pu) voltage range.

Modeling Full Converter Machines – Reactive Capability

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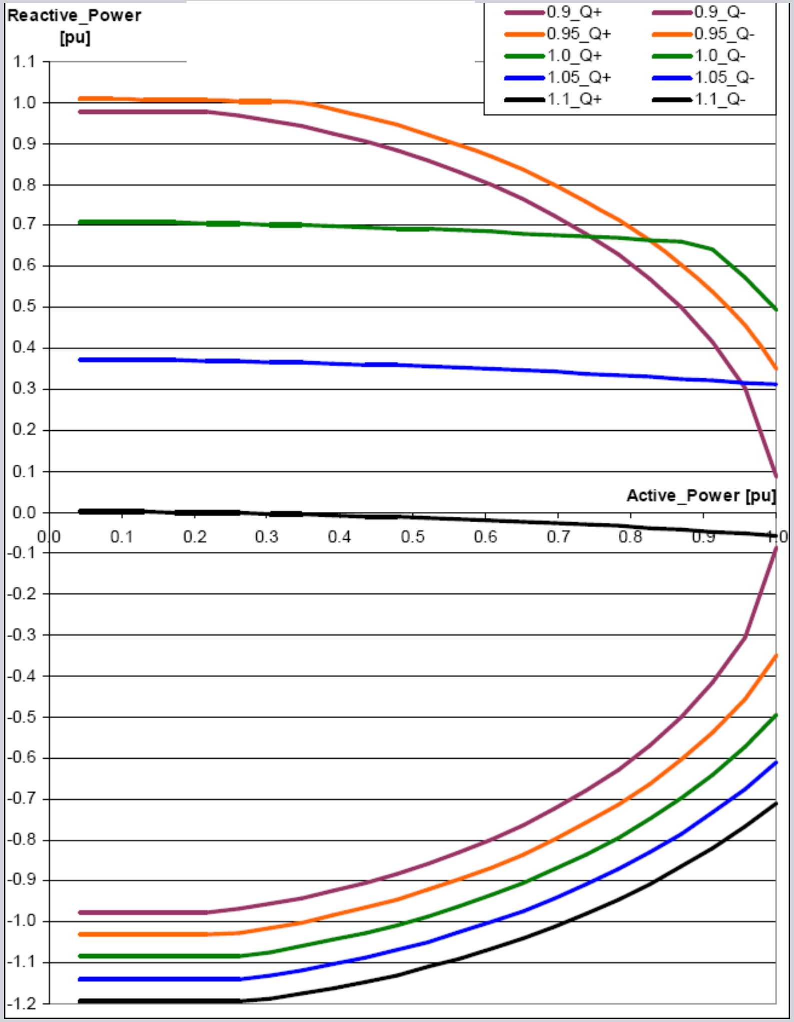

Converters have distinct voltage and current limits and a relatively wide voltage range (90% to 110% of nominal, so reactive capability varies with terminal voltage, unlike synchronous generator, which has a power-invariant reactive capability characteristic.

Reactive capability characteristic of full-converter wind turbine

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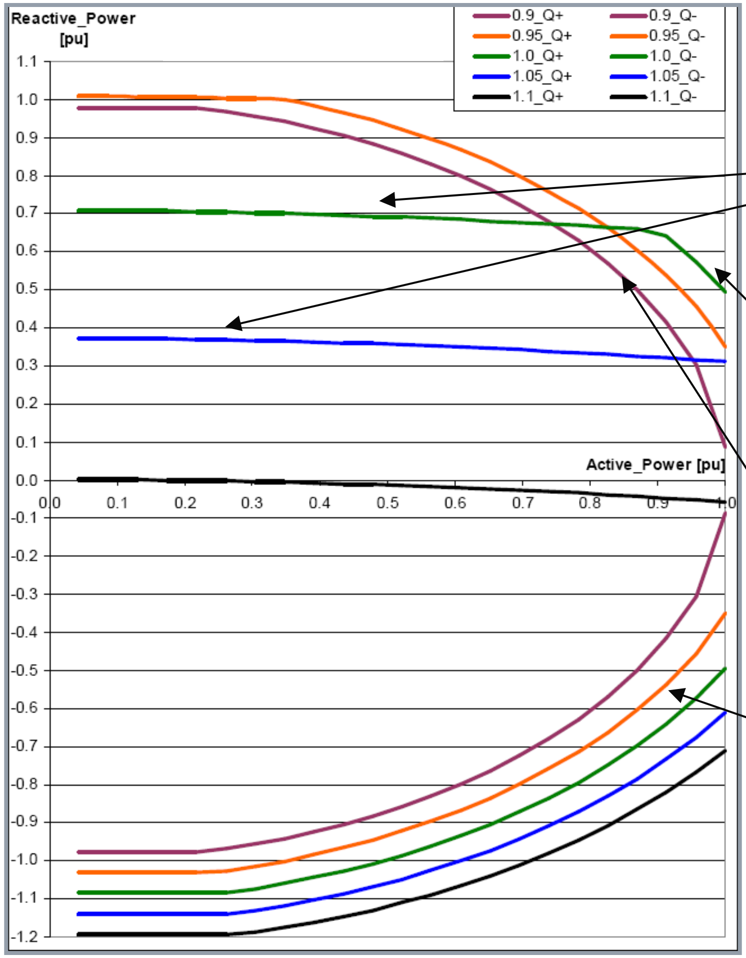


Voltage-limited; linear with shallow slope

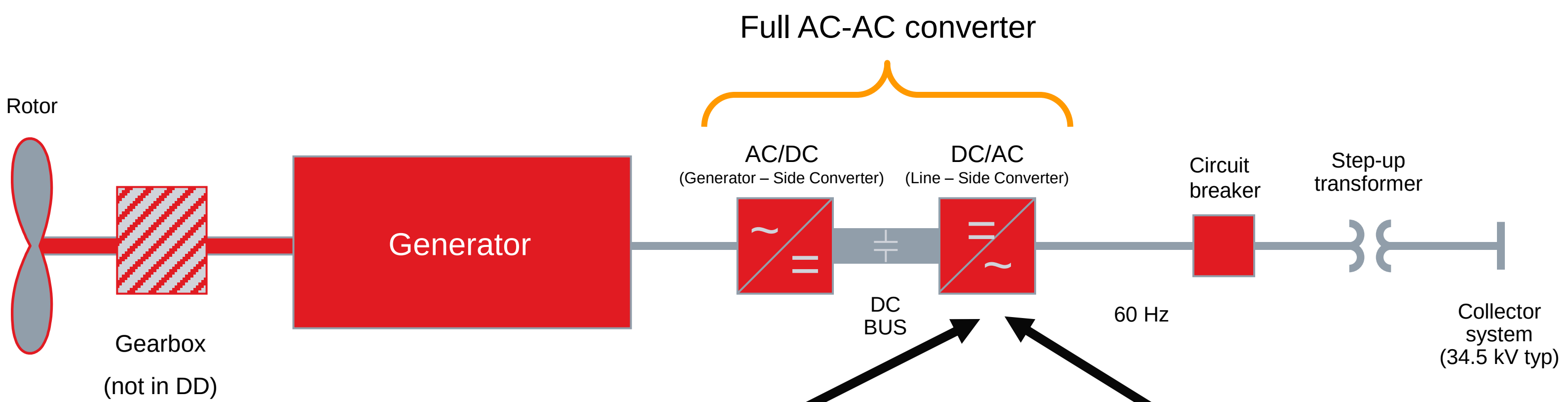
Voltage and current-limited; linear with steep slope

Current-limited; arcs

Reactive capability characteristic of full-converter wind turbine

Why?

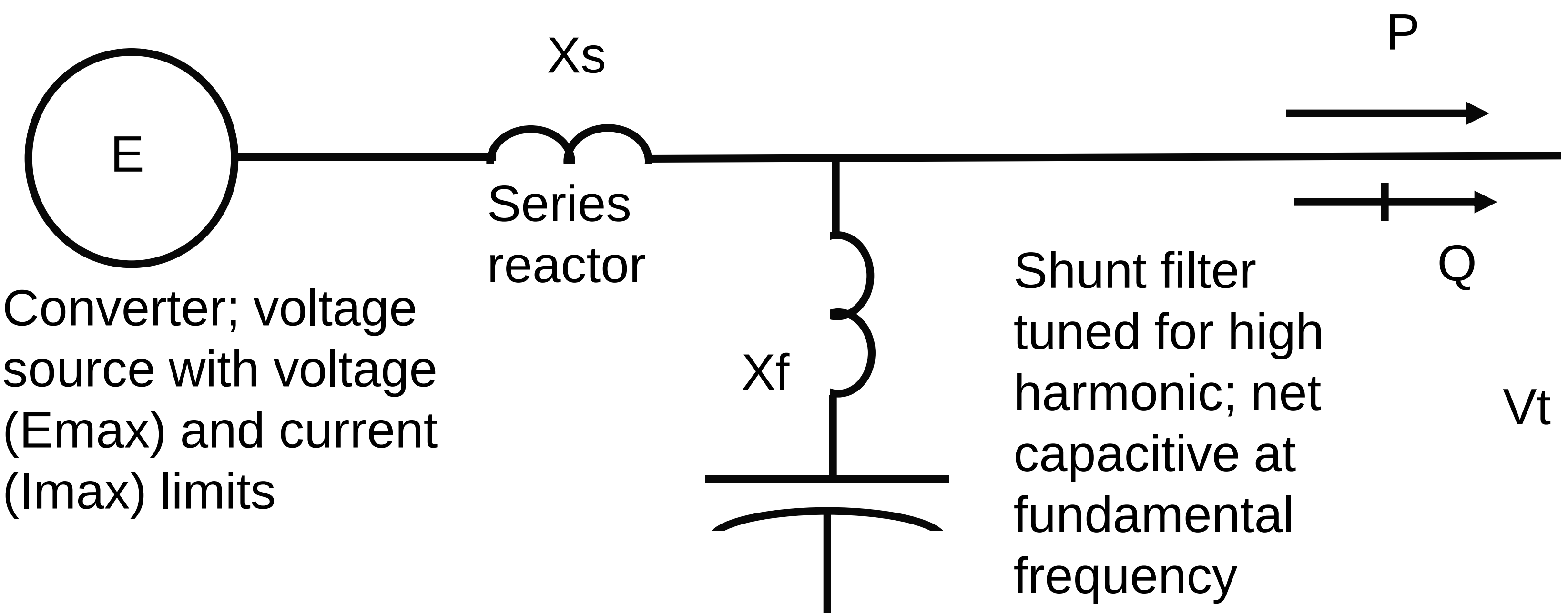
Schematic of full-converter wind turbine:



Reactive capability determined by line-side converter

Reactive capability characteristic of full-converter wind turbine

Equivalent circuit of representative line-side converter used in WTs:



Converter; voltage source with voltage (Emax) and current (Imax) limits

Shunt filter tuned for high harmonic; net capacitive at fundamental frequency

Reactive capability characteristic of full-converter wind turbine

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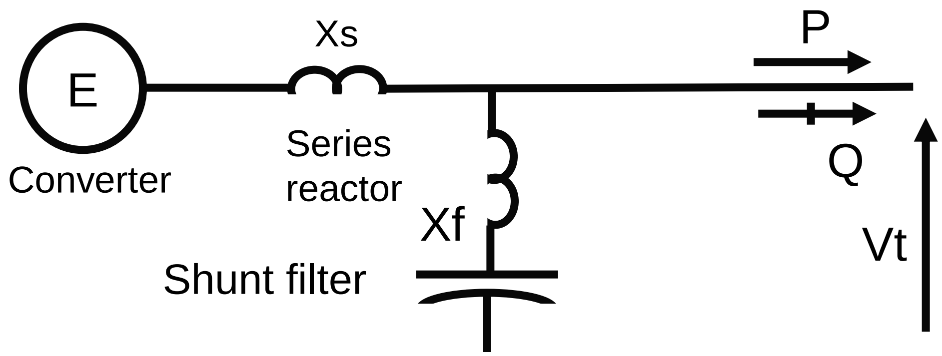


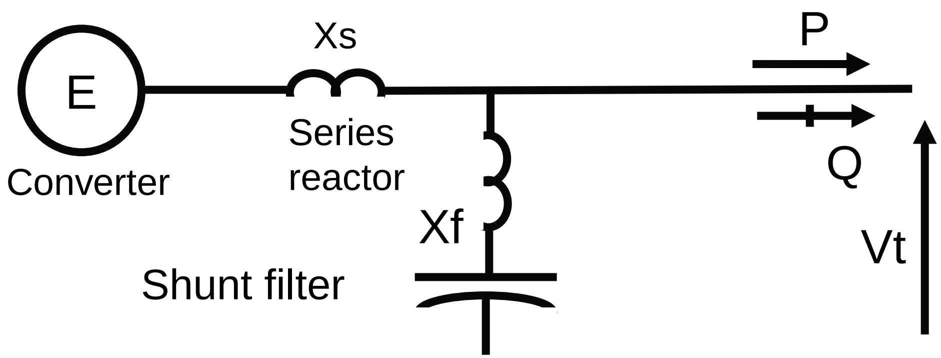
For any terminal voltage, Vt, and converter voltage, E∠δ (using Vt as reference), after some algebra:

$P = Vt * E / Xs * \sin \delta$

$Q = (Vt / Xs) * (E * \cos \delta - Vt) + Vt^2/Xf$

Note: δ is sometimes called the "power angle".

Reactive capability characteristic of full-converter wind turbine



$P = Vt * E/Xs * \sin \delta$

At internal voltage limit, E = Emax (lagging pf only), and

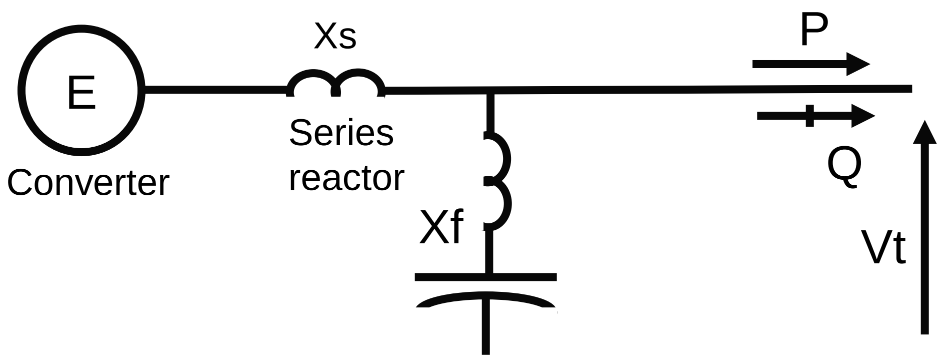
$$Qe = (Vt / Xs) * (E * \cos \delta – Vt) + Vt^2/Xf$$

At current limit, $Qi = \sqrt{(Vt * Imax)^2 – P^2} + Vt^2/Xf$ (lagging pf; producing VArs)

$$Qi = -\sqrt{(Vt * Imax)^2 – P^2} + Vt^2/Xf$$ (leading pf; absorbing VArs)

Lagging (Producing): Q = Min (Qe, Qi). Leading (Absorbing): Q = Qi

Reactive capability characteristic of full-converter wind turbine



Example:

Vt = 1.0 pu

Xs = 0.15 pu

Xf = 15 pu (capacitive, so Zf = -j15 pu)

Imax = 1.2 pu; Emax = 1.1 pu

Calculate reactive capability from P = 0 to P=1.0

Reactive capability characteristic of full-converter wind turbine

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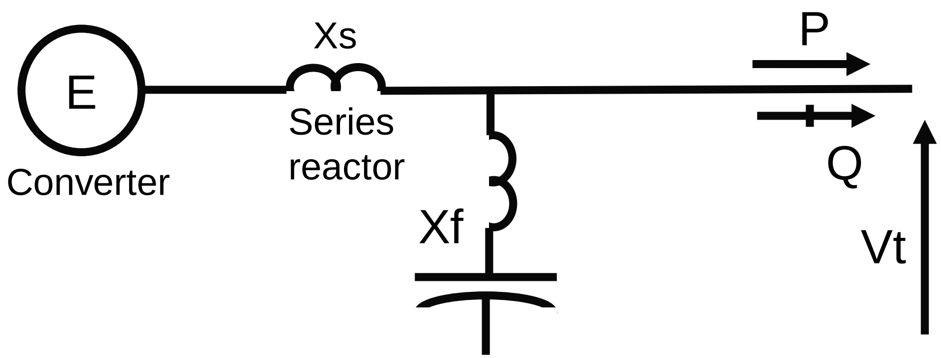

P = 1; lagging case

Assume E = Emax = 1.1

$P = Vt * E/Xs * \sin\delta$ so $\delta = \sin^{-1}(Xs*P)/(Vt*E) = 7.8°$

$Qe = (Vt/Xs)*(E*\cos\delta - Vt) + Vt^2/Xf = (1/0.15)*(1.1 \cos 7.8° - 1) + 1/15$

Qe = 0.6 + 0.07 = 0.67 pu, based on Emax

Reactive capability characteristic of full-converter wind turbine

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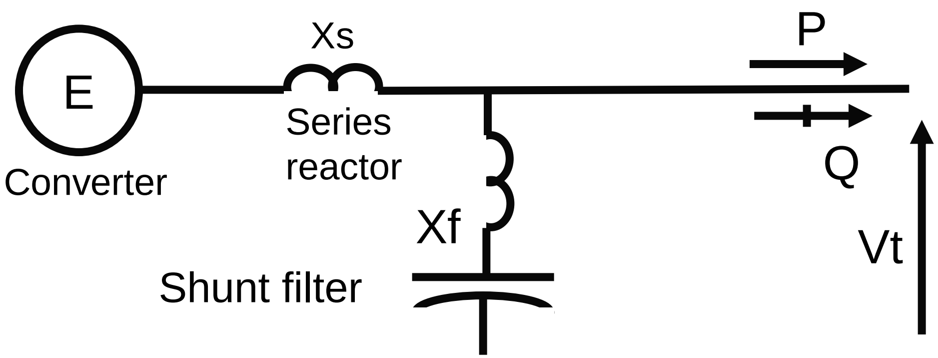
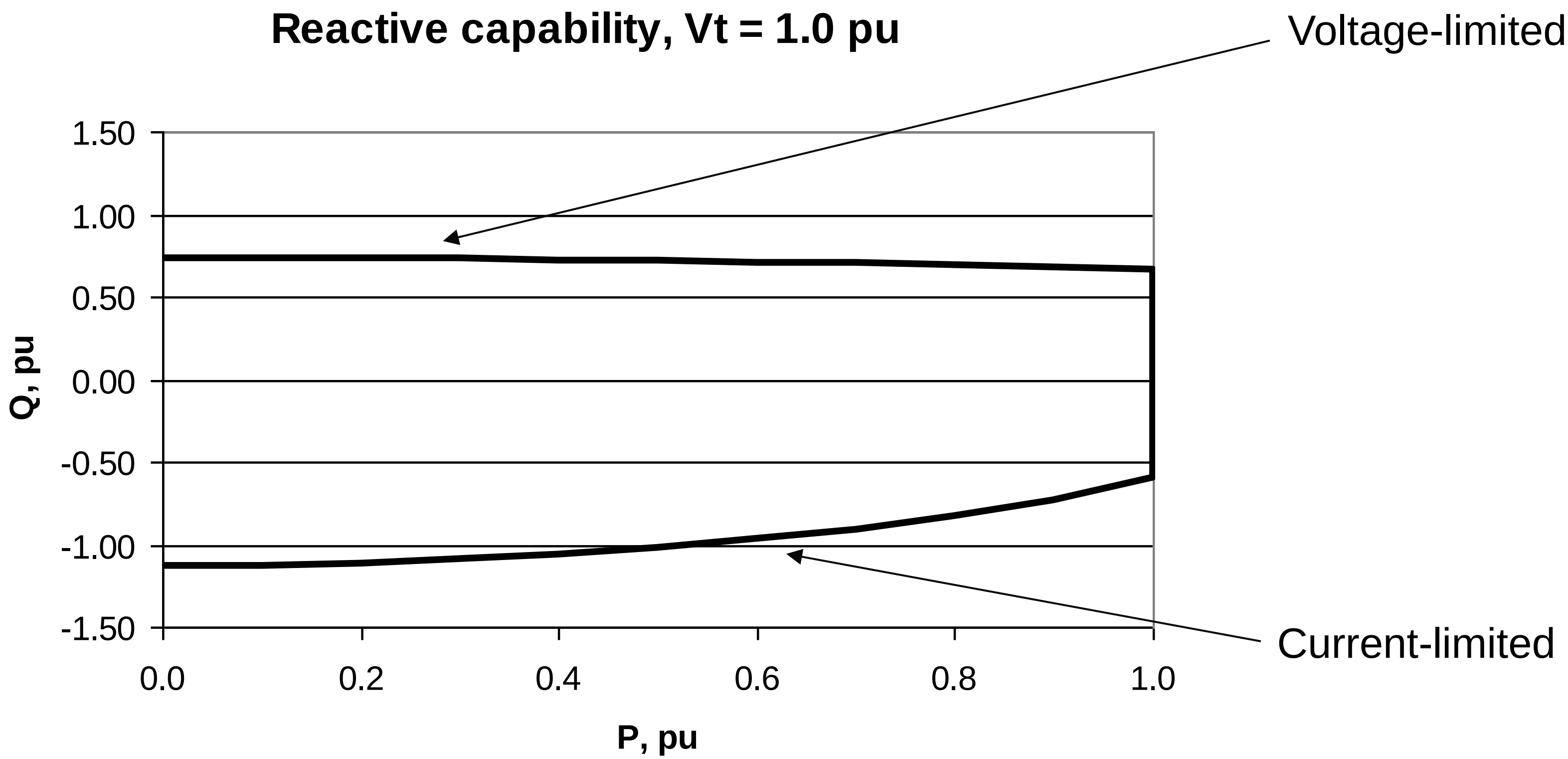


Other cases can be done the same way.

Tips:

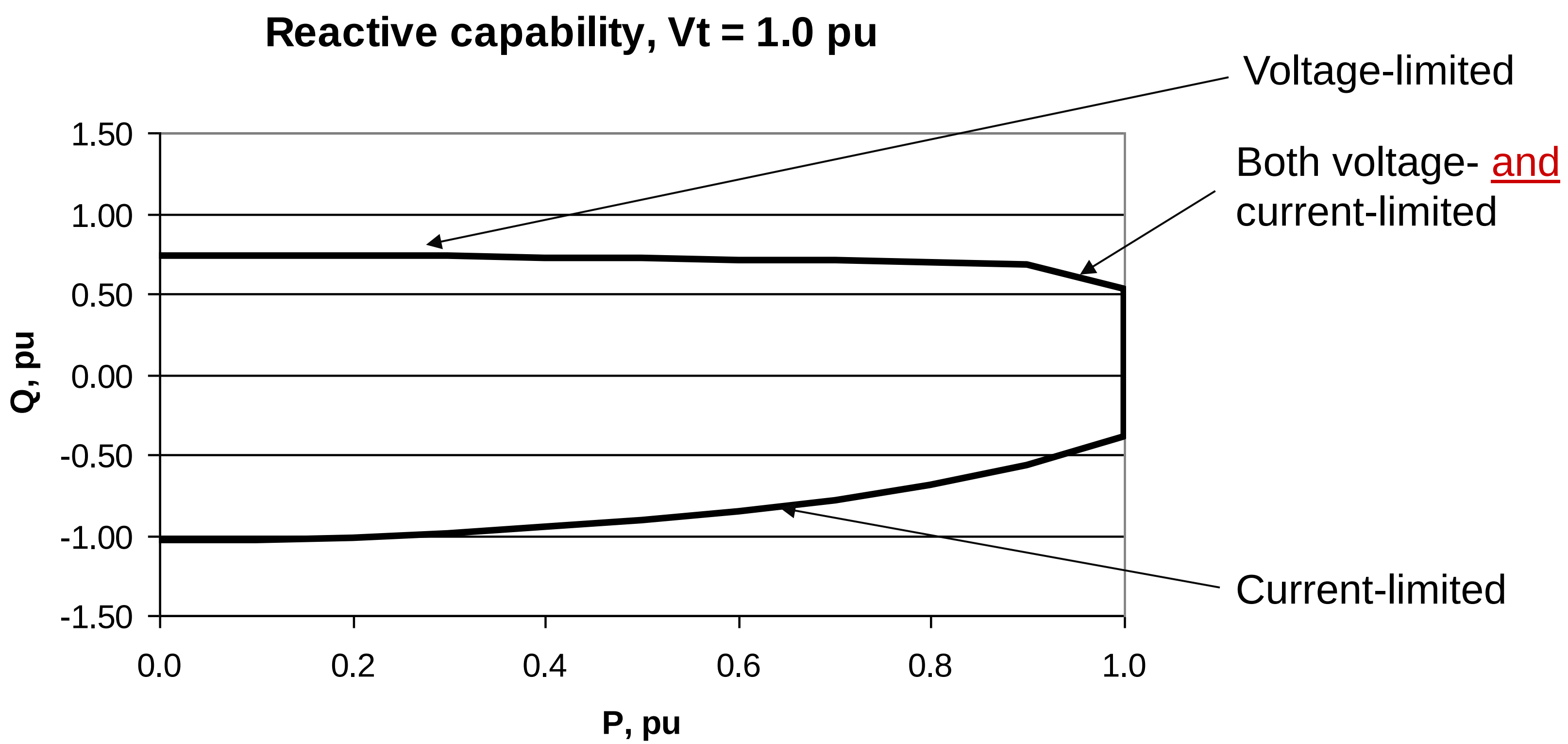
- Leading pf (turbines absorbing VArs) cases generally current limited, but some vendors may have a leading pf current restriction or Emin
- Lagging pf (turbines producing VArs) cases can be voltage- or current-limited; sometimes both.
- Not generally necessary to check power angle (δ<90°) with typical parameters used in full converters.

Curves for different terminal voltages (example)

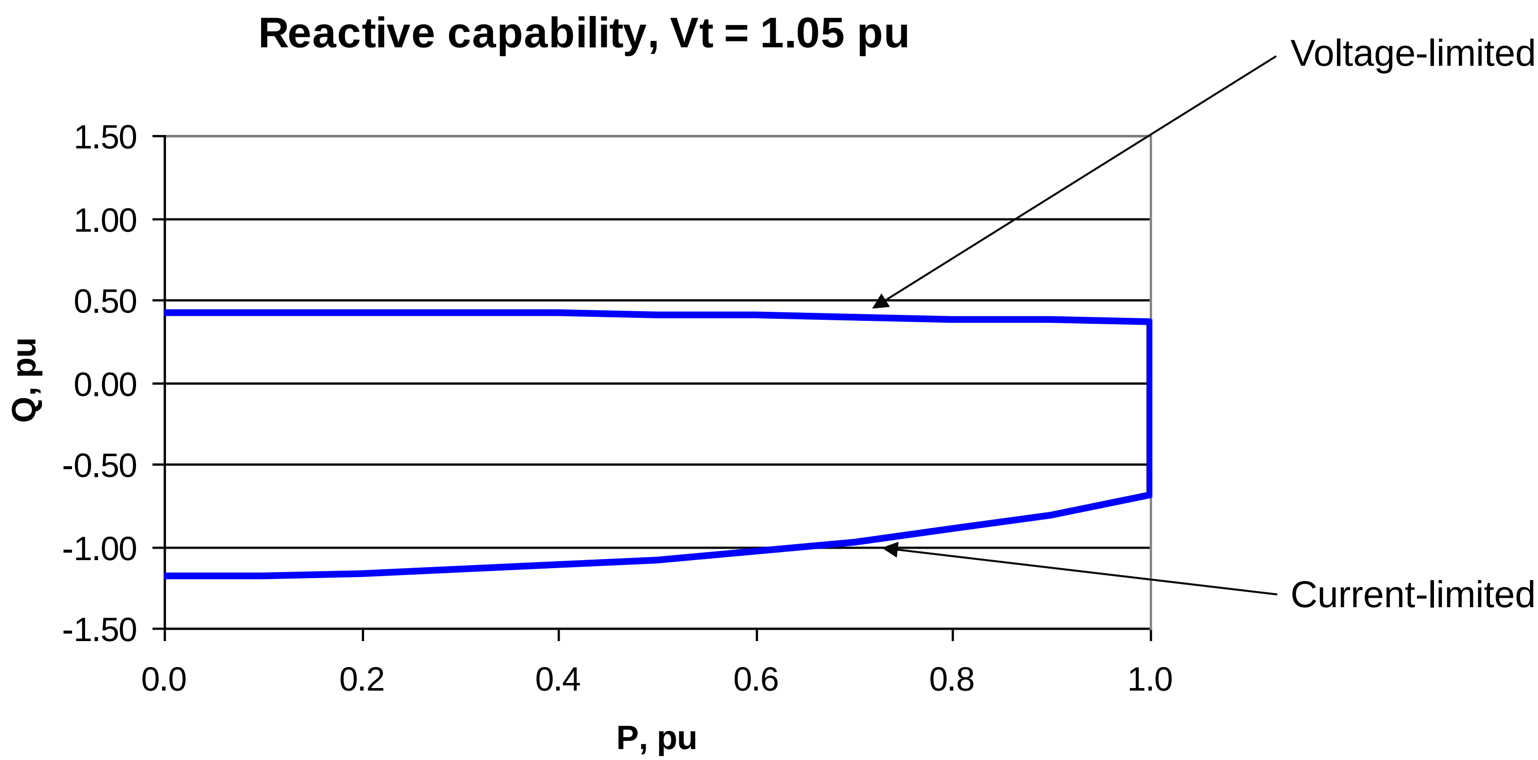


Curves for different terminal voltages (example)

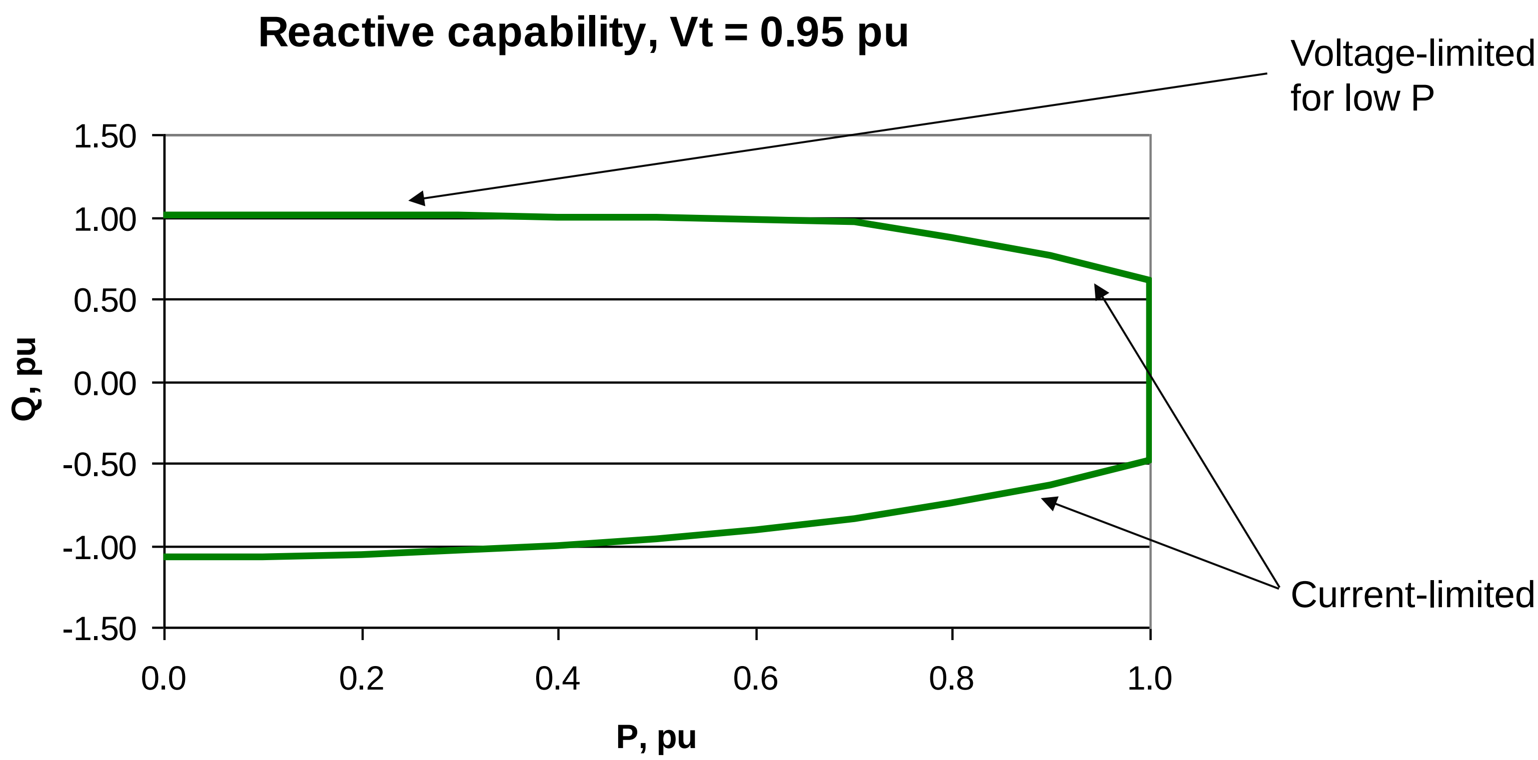
It is possible to have voltage and current limits simultaneously.
Consider what would happen if we reduced the current limit to 110%:



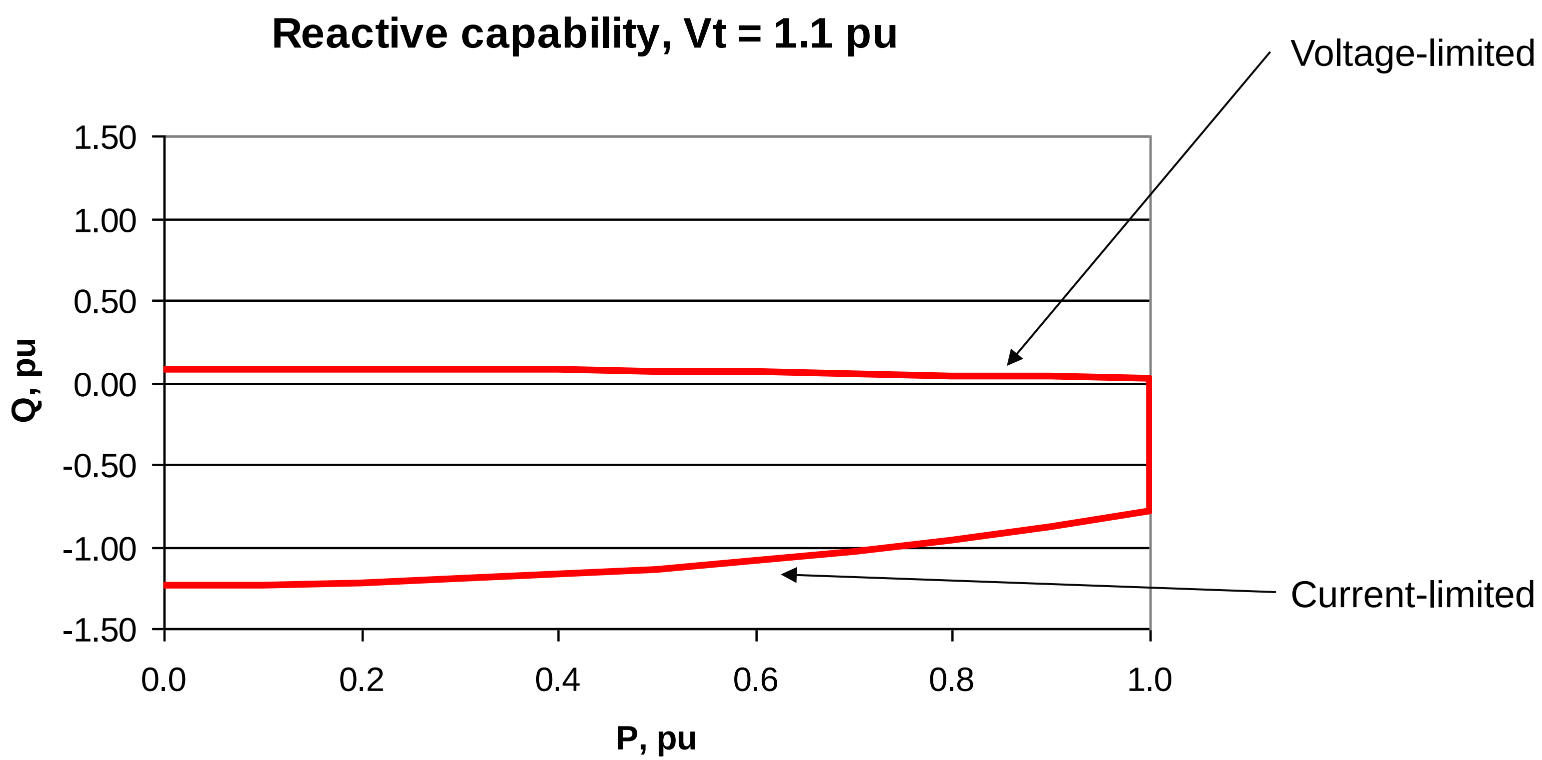
Curves for different terminal voltages (example)



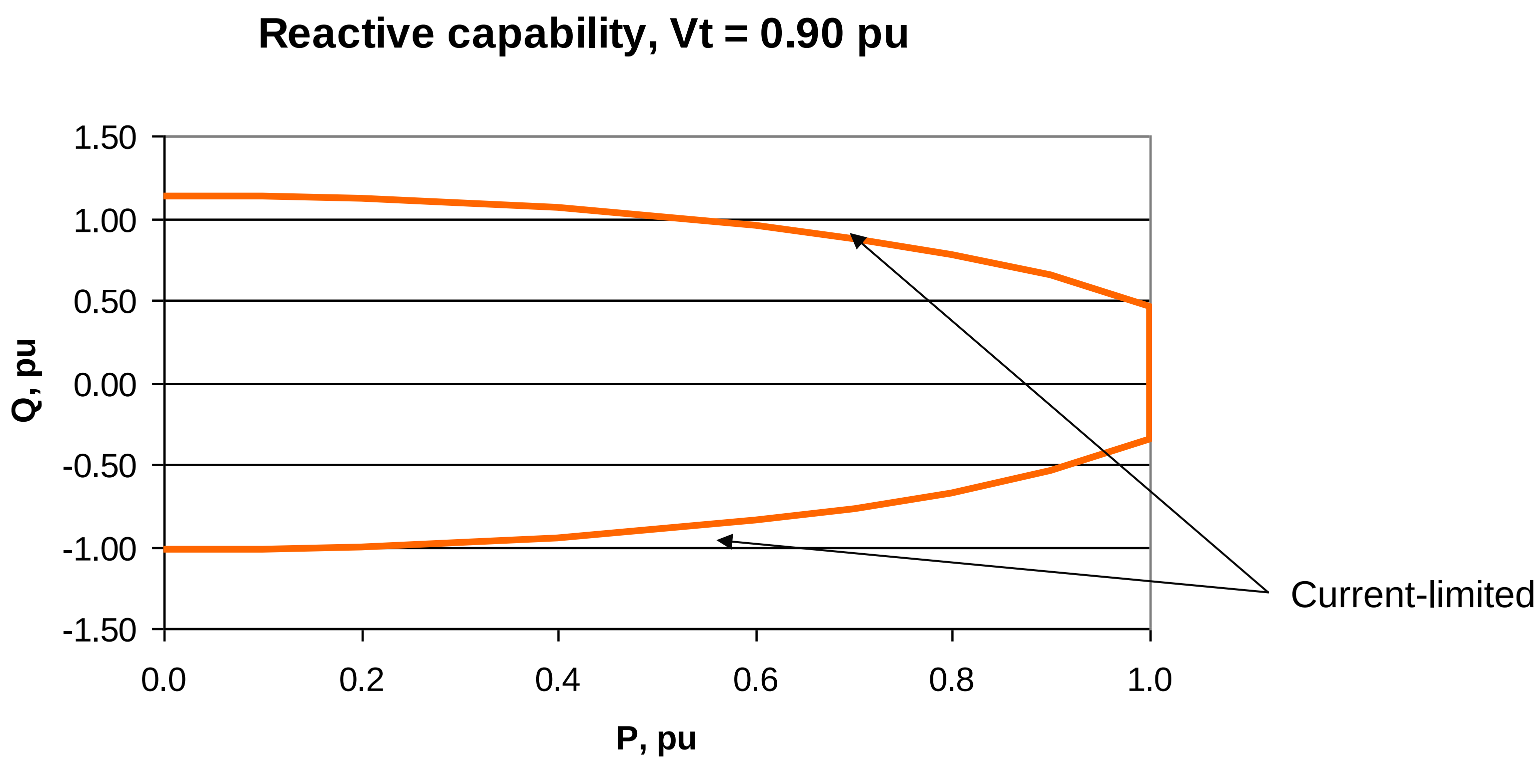
Curves for different terminal voltages (example)



Curves for different terminal voltages (example)



Curves for different terminal voltages (example)



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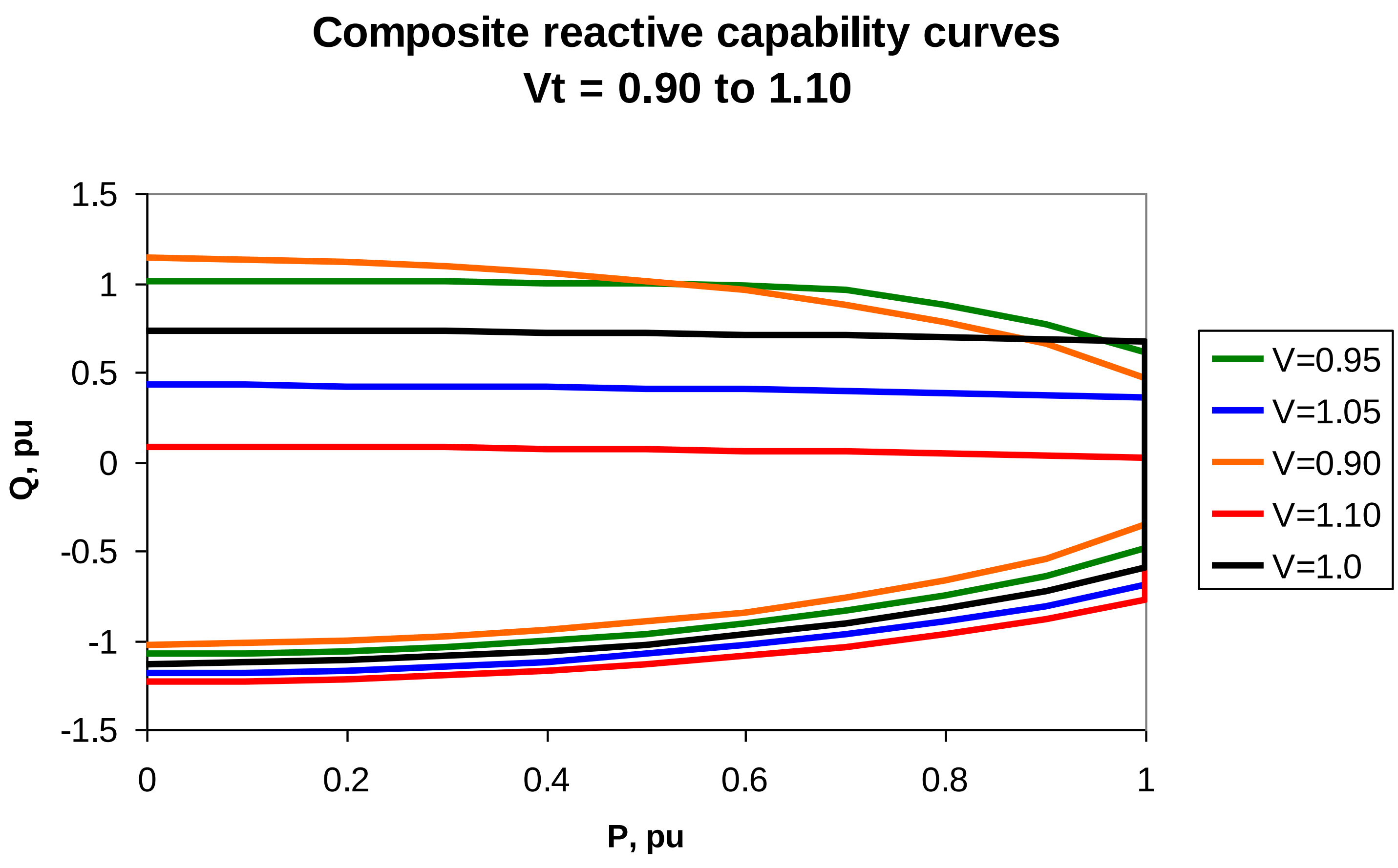
Curves for different terminal voltages (example)

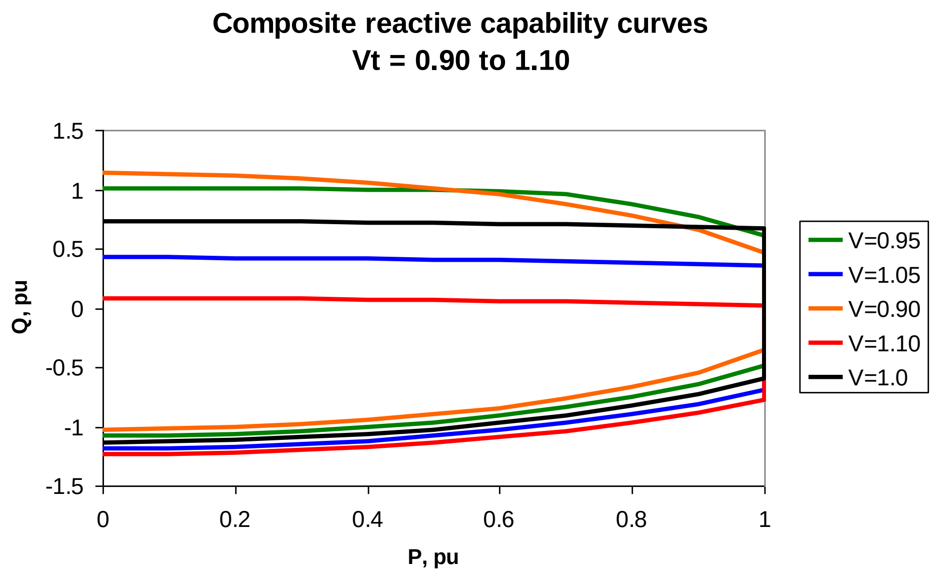


Curves for different terminal voltages (example)

Observations:

Most of the lagging and leading capability is available in typical operating range of Vt = 0.95 to 1.05 pu.

Lagging capability drops off sharply outside of this range; important to adjust transformer taps to be compatible with system operation.



What Are Common Reactive Control Requirements in the Americas (including Latin America)?

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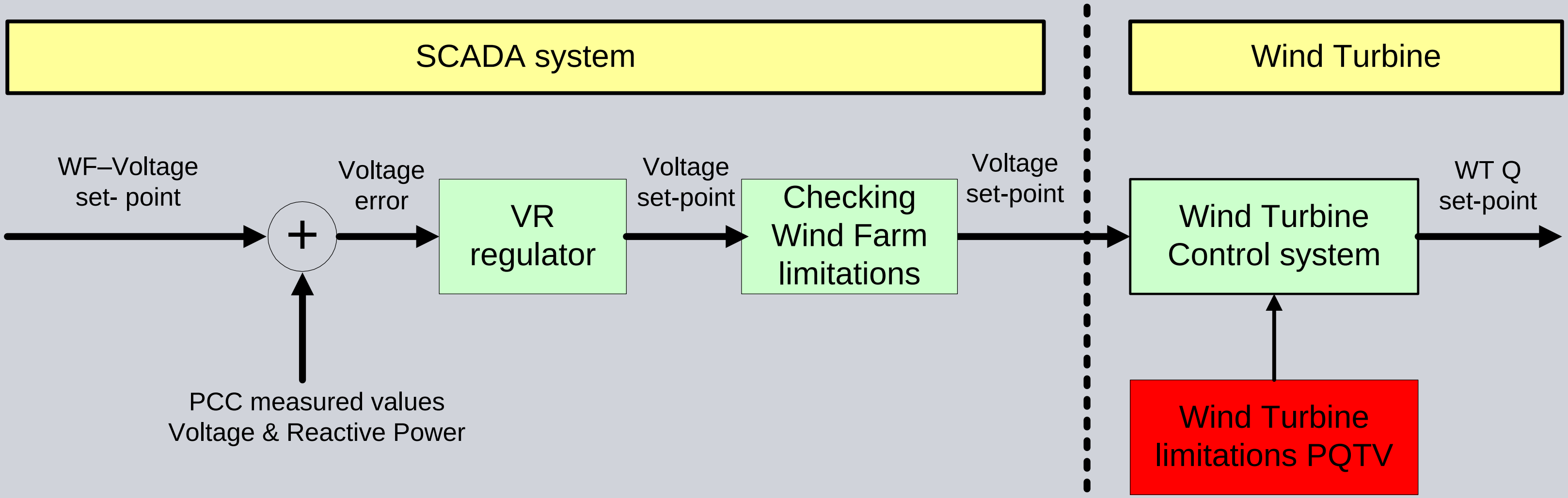
Existing:

- Voltage Regulation
- Reactive Power Control (constant Q)
- Power Factor Control (constant ratio of Q to P)
- Reactive Control without Active Power Production
  - Voltage Regulation (adjustment of reactive power to satisfy voltage regulation schedule)
  - Reactive Power Control

All are capabilities currently provided on a routine basis by synchronous generators, except reactive power control without active power production (“synchronous condenser operation”), which typically requires extra equipment.

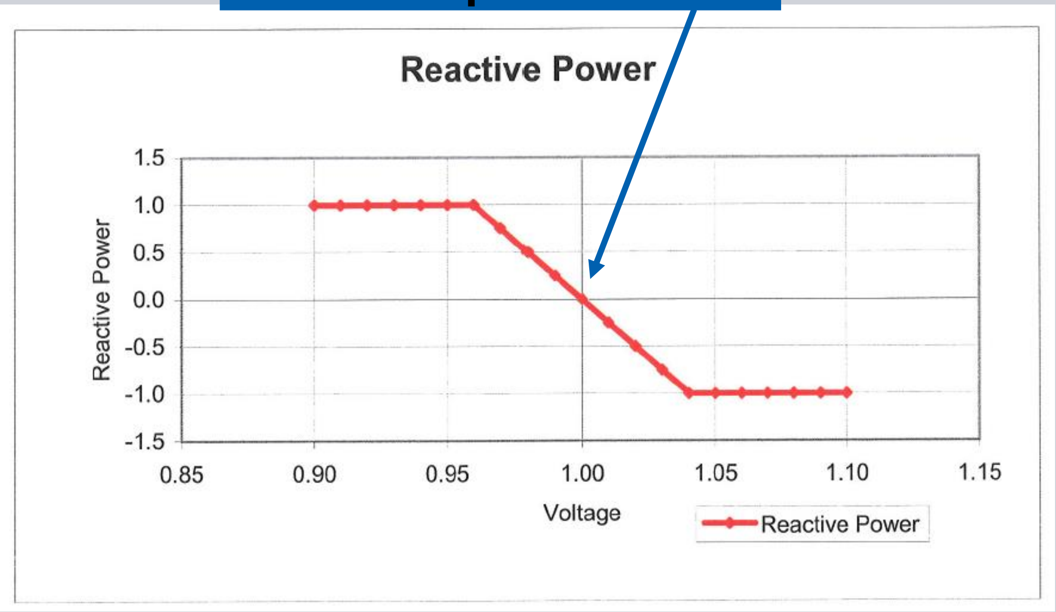
Wind Plant Reactive Power and Voltage Control



- Distribution of voltage set-points
- Wind turbine limitations secured by the embedded WT control system – PQTV (Active Power, Reactive Power, Temperature, Voltage)
- Can operate in voltage regulation, reactive power control (constant Q), or power factor control (constant ratio of P to Q)

Wind Plant Voltage Control – Reactive Droop

Droop of 4 %



Typical Droop of 1% to 5%

Option for Voltage Deadband

How does a full-converter wind park compare with a synchronous generator for steady-state voltage control?

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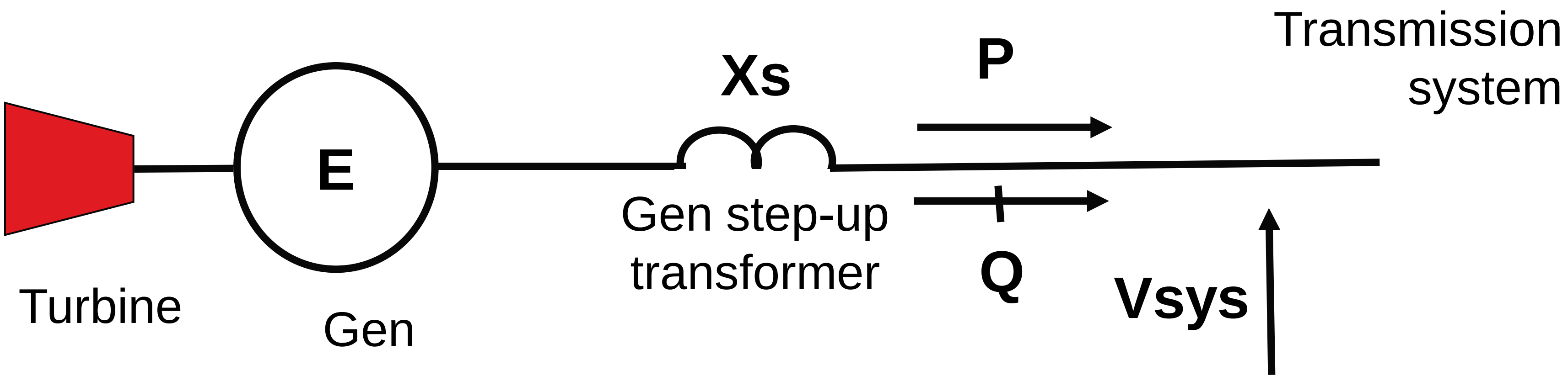
Compare reactive capability of 100 MW (rated pf of 0.9 lag to 0.95 lead) synch generator with Xt = 13% with 100 MW wind park with equivalent reactance (inc. turbine transformer, park transformer and collector system) of 22% and RC curve developed in example. Assume both are connected to a 230kV transmission system and the collector system is 34.5kV; ignore resistance and collector charging.

1) Determine how much lagging reactive power can be delivered to transmission system, varying Vsys from 0.85 to 1.0 pu, with P=1.0 pu
2) Determine how much reactive power can be absorbed from the transmission system, varying Vsys from 1.0 to 1.15 pu, with P=1.0 pu



How does a full-converter park compare with a synchronous generator for voltage control?

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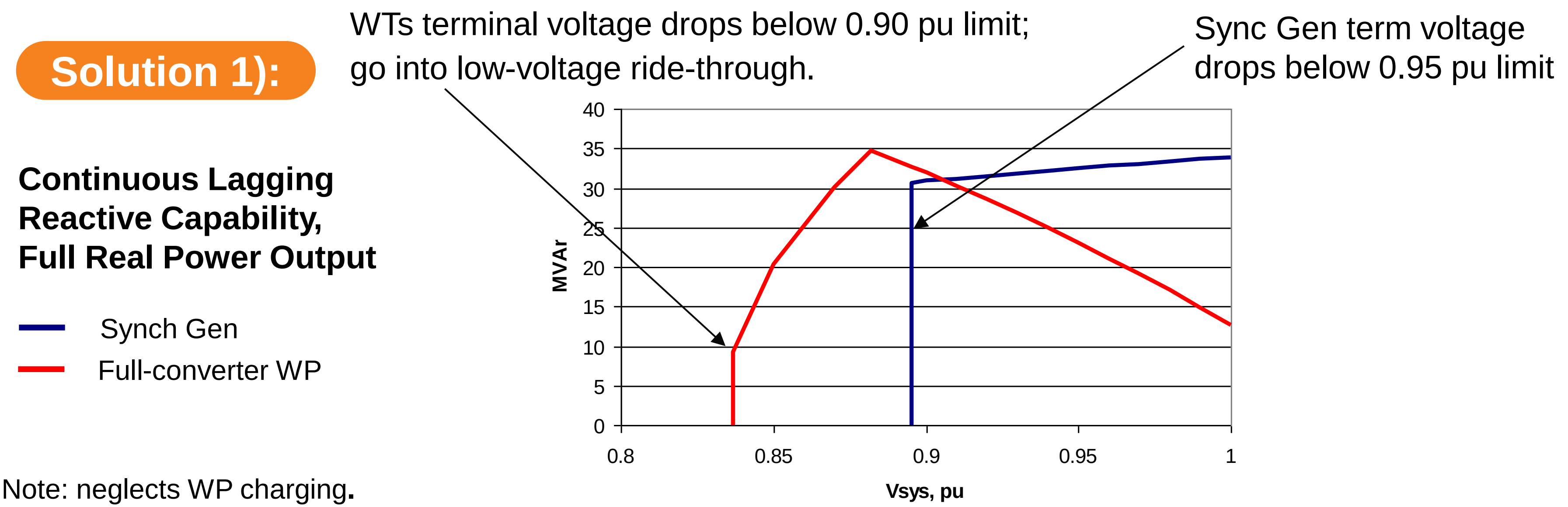
Solution 1):

Continuous Lagging Reactive Capability, Full Real Power Output



Note: neglects WP charging.

Similar max capabilities, but

- **The synchronous generator has a narrower operating voltage range and significantly greater capability near nominal voltage**
- **The WP has a wider control voltage range and is superior for very low transmission voltages (significantly below 0.90 pu, where the synchronous generator cannot provide continuous voltage support)**

How does a full-converter park compare with a synchronous generator for voltage control?

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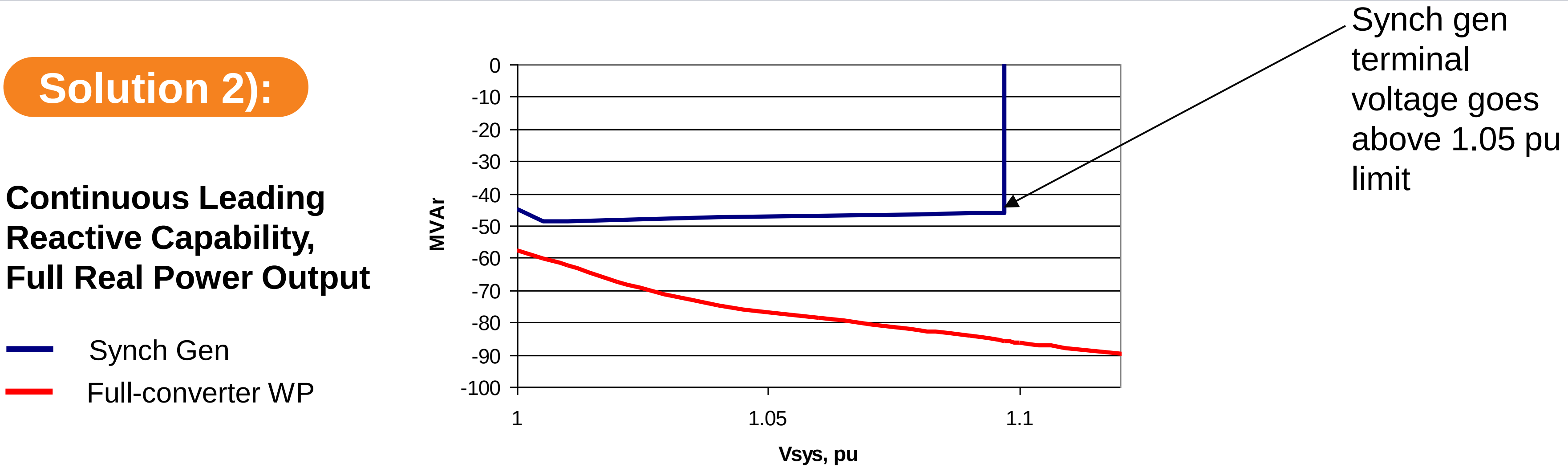
Solution 2):

Continuous Leading Reactive Capability, Full Real Power Output



Note: neglects WP charging.

Similar capabilities near rated voltage, but

- **The synchronous generator has a narrower operating voltage range and less capability above 100% system voltage.**
- **The WP has a wider control voltage range and is superior for very high transmission voltages (above 1.0 pu, and particularly above 1.1 pu, where the synchronous generator is incapable of providing voltage support).**

Voltage control:
Fast response to change in reference

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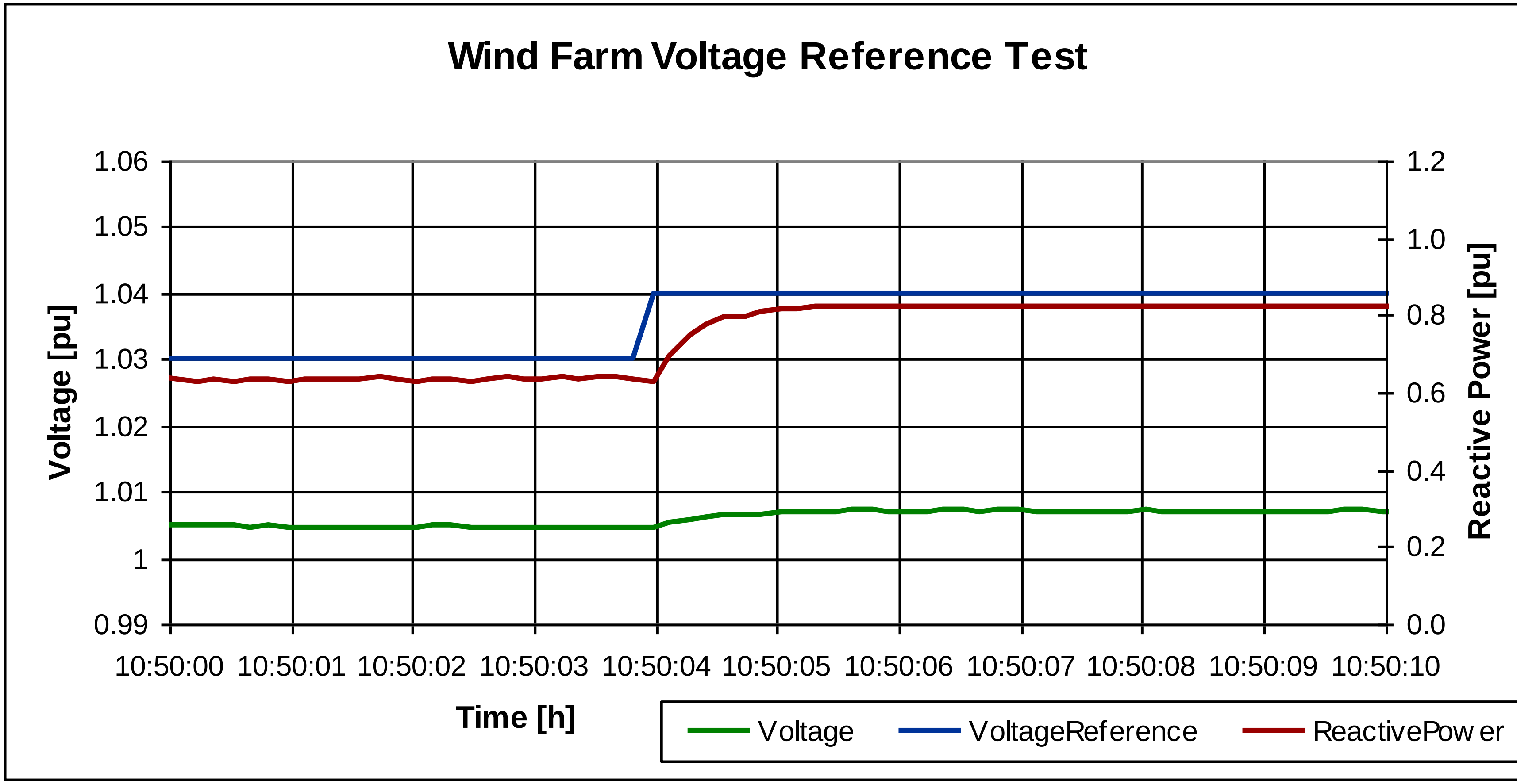

Wind plant response very comparable to synchronous generator response.

WTG response very similar to excitation system response.

New option: Voltage Regulation without Active Power Production (“STATCOM Mode”)

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- Voltage Regulation (reactive droop), or
- Reactive Power Control (constant MVAr)

Converters operate in “STATCOM mode” to regulate voltage or reactive power under control of Park Pilot; comparable to synchronous generator operating as a “synchronous condenser” (generator disconnected from turbine).

Appropriate for:

- Sites that receive compensation for reactive control or where voltage regulation is required at all times.
- Sites where reactive control is required for very low output levels

Summary – How Full-Converter WTGs provide Reactive Power Control

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Capability	*Now*	*Possible*
Voltage Regulation with reactive droop		
Medium Voltage		
Transmission Voltage		
Reactive Power Control		
Power Factor Control		
Voltage Reg without Active Power Production		

What Are Common Active Power Control Requirements in the Americas (including Latin America)?

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Existing:

- Power Output (Curtailment) Control
- Ramp Rate Control
  - Curtailments
  - Start-up
- Regulation Up for Underfrequency
  - Adjustable Droop
- Regulation Down for Overfrequency
  - Adjustable Droop
- Low Voltage Ride Through
- High Wind Ride-Through
- Rate Variation Control

Ramp rate control - smooth, controlled transition from one output level to another

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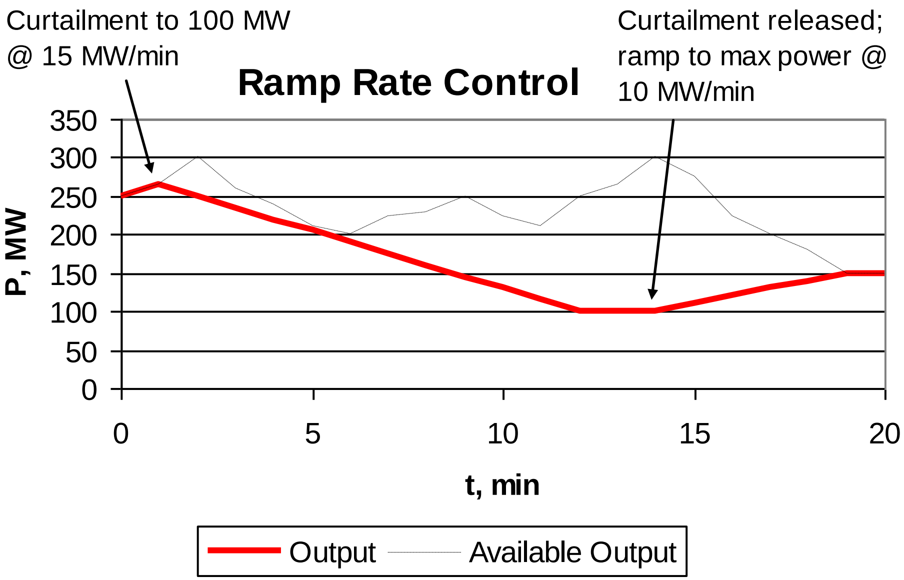
Some system operators require ramp rate control to smoothly transition from one output level to another during curtailments.

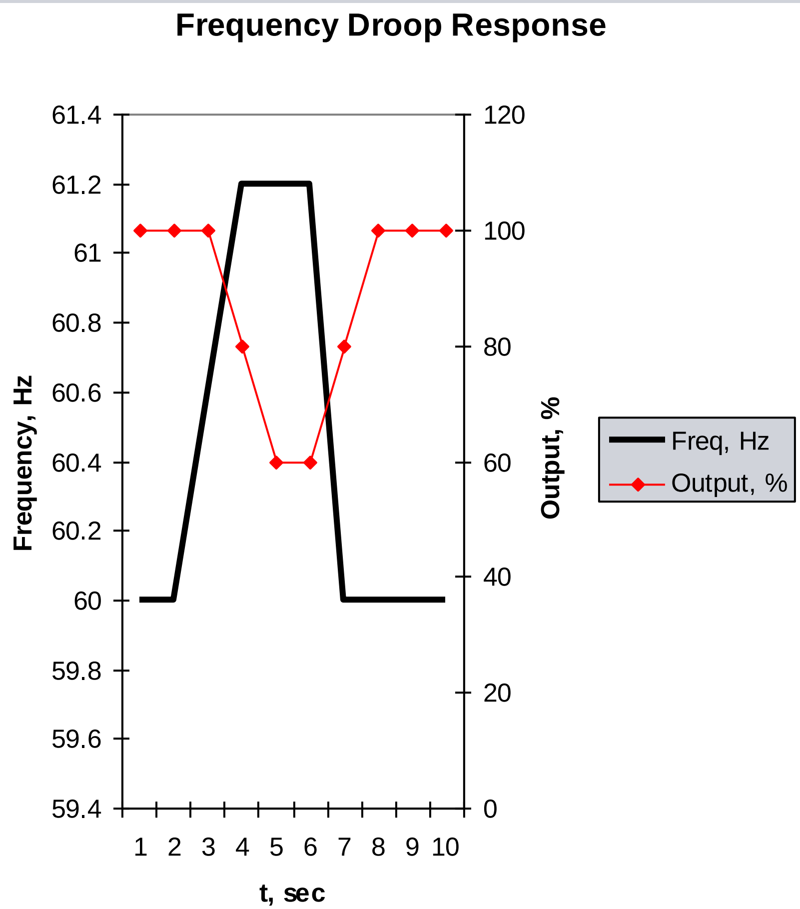
- Ramp-rate control is available in wind plants at rates of 10%/sec and slower.
- Can select any ramp rate (%/min MW/min, MW/sec, etc.), in range, assuming availability of adequate wind power



Frequency Droop Control - Primary Frequency Response

Some system operators require the use of frequency droop response from wind parks

- Normally constant (5%) frequency droop (5% change in freq → 100% change in output), but variable droop sometimes required (e.g., larger droop for small frequency excursions, smaller droop for larger excursions).
- Both reg up (underfreq), assuming curtailed state, and reg down (overfrequency) required.
- Sometimes conflicts w/ curtailments, Special Protection System operations.



Frequency response – Simulations calibrated with test in Electric Reliability Council of Texas (ERCOT), USA

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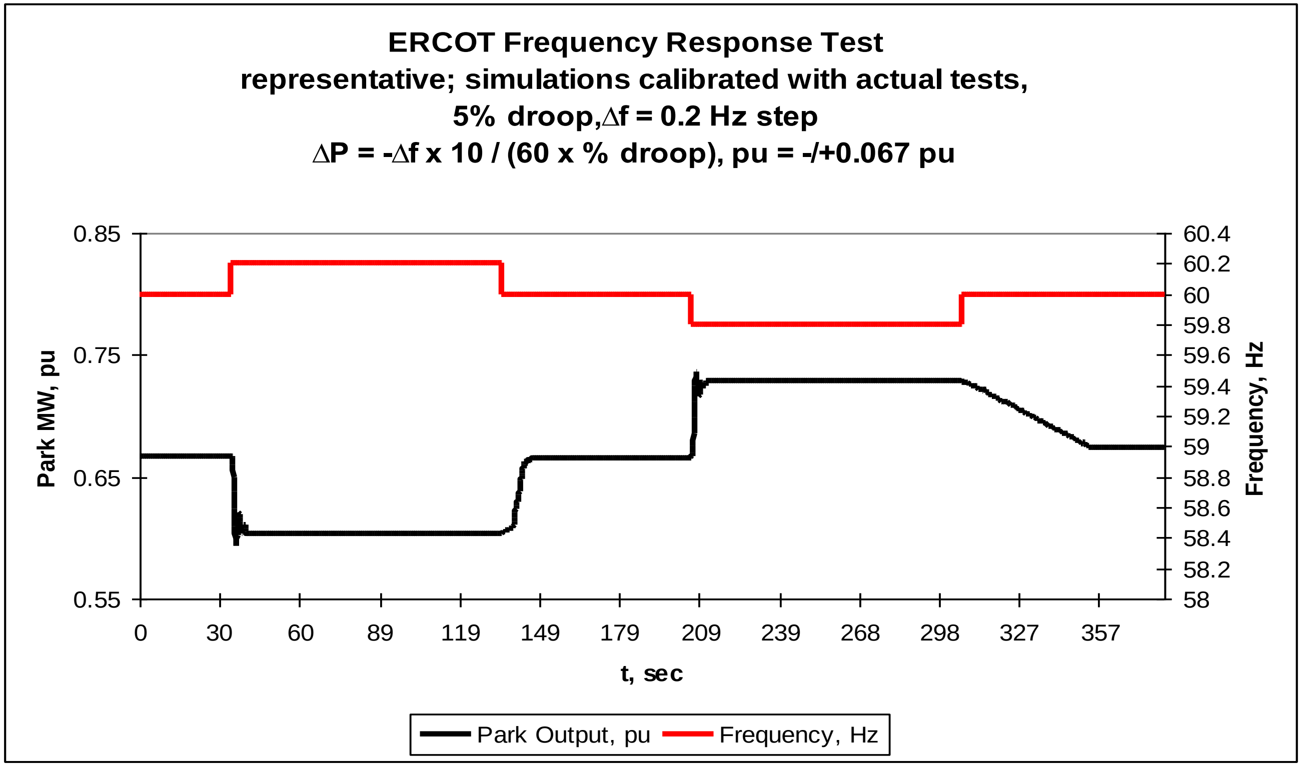
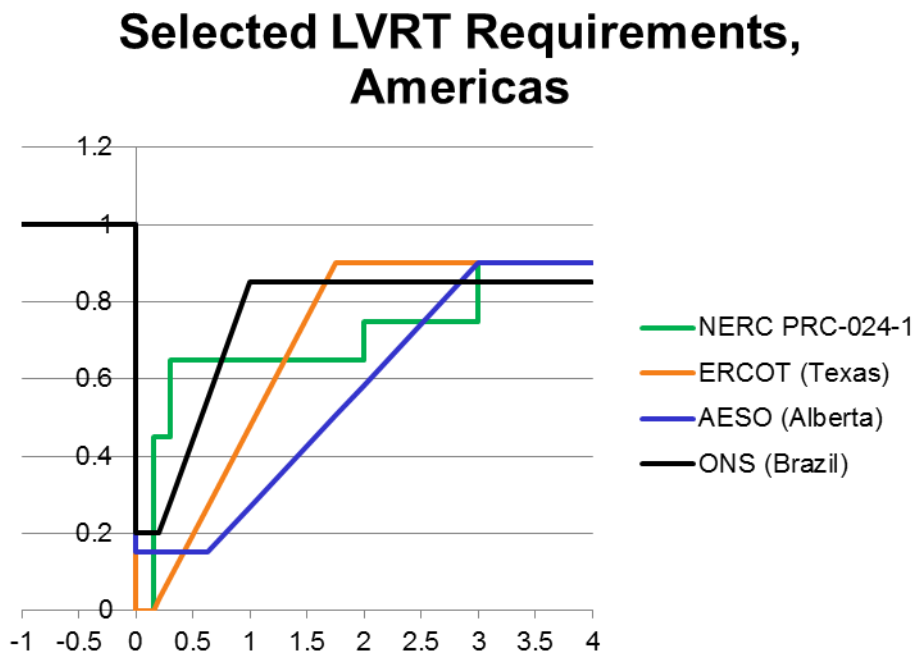


Much faster than fossil response, which may require over a minute to fully respond.

Low-voltage ride-through (LVRT)

- Requirements vary, but typically impose need for turbine to withstand extended (several second) low-voltage event (see below for most severe known requirements in North and South America)
- Wind turbine generators must conform to major LVRT requirements in Americas (e.g., ERCOT, proposed NERC PRC-024-1, most Canadian provinces, Brazilian ONS, Mexican CFE, etc).
- NERC PRC-024-1, recently passed, will apply to all large generation plants (wind, fossil, PV, etc).



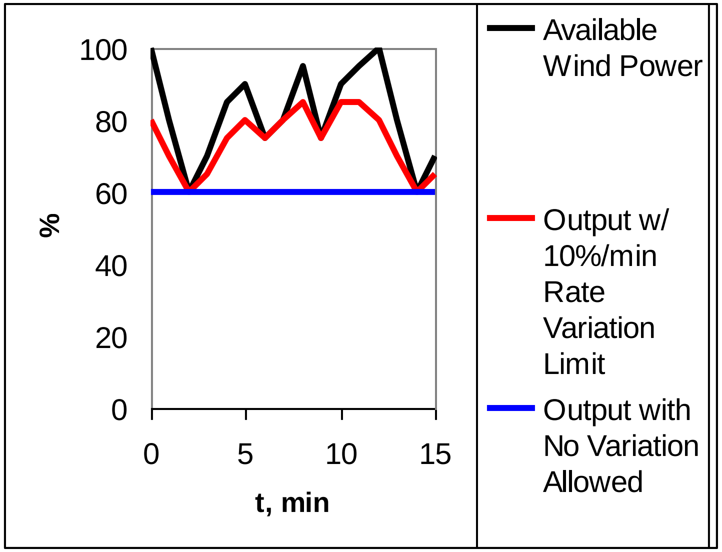
Rate Variation Control

Control of output power change, e.g., “no more than 10% change per minute”

Since electric power varies as cube of wind speed, rate variation control requires operation at reduced output power levels during conditions when wind speed varies or use of energy storage.

Controls typically assume persistence and use recent history to set output.

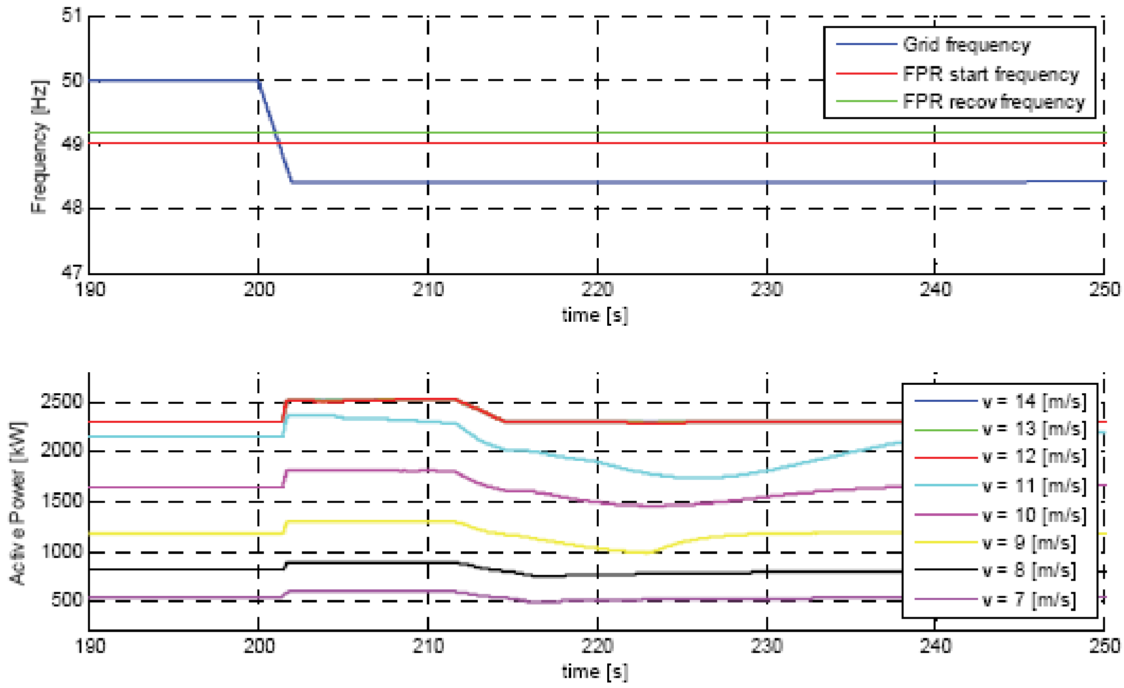
Seldom used.



Transient underfrequency response ("inertial response")

Rapid response required after sudden frequency drop – necessary to forestall load shedding, especially on island systems

Industry is developing new controls to address this need



Delta control – operate with a constant delta below maximum output

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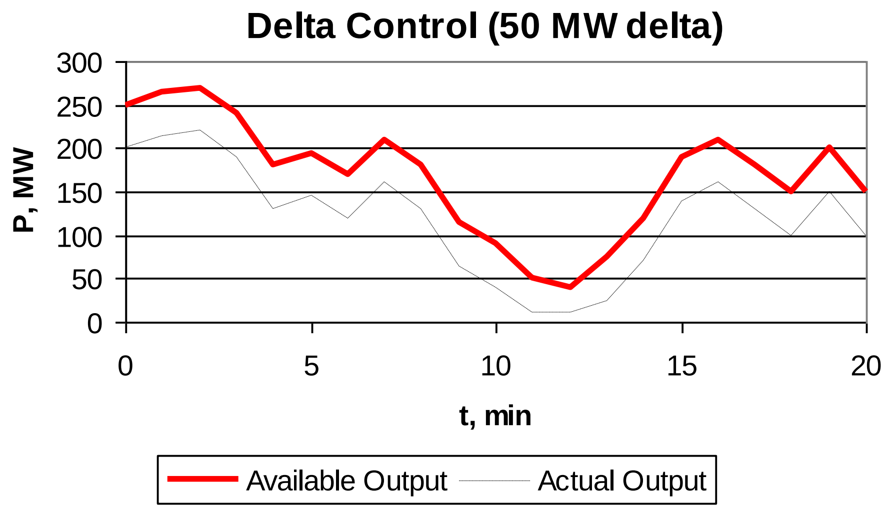
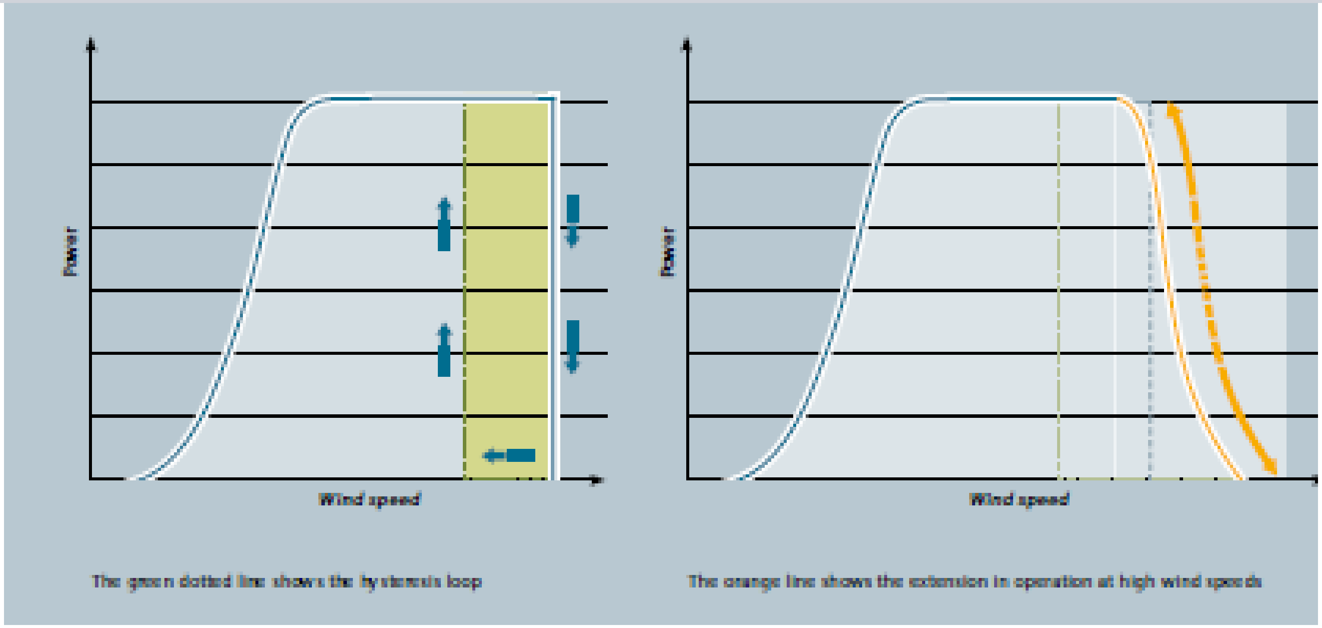
Some Transmission Operators are considering the use of wind for regulation up and spinning reserve duty at some times of the day to release fossil capacity.

- Requires “spilling wind,” but may be the least expensive way to provide capability
- Can select any delta (MW) assuming availability of adequate wind power
- Similar in concept to spinning reserve function for fossil units



High Wind Ride Through (HWRT)



High wind speeds (above 25 m/s) caused widespread tripping in the past;

HWRT allows operation at higher wind speeds without turbine tripping

- Reduces likelihood of turbine trip
- Increased energy production while waiting for wind speed to drop to normal range
- Improved frequency regulation for system operators.

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Modeling for power system analysis

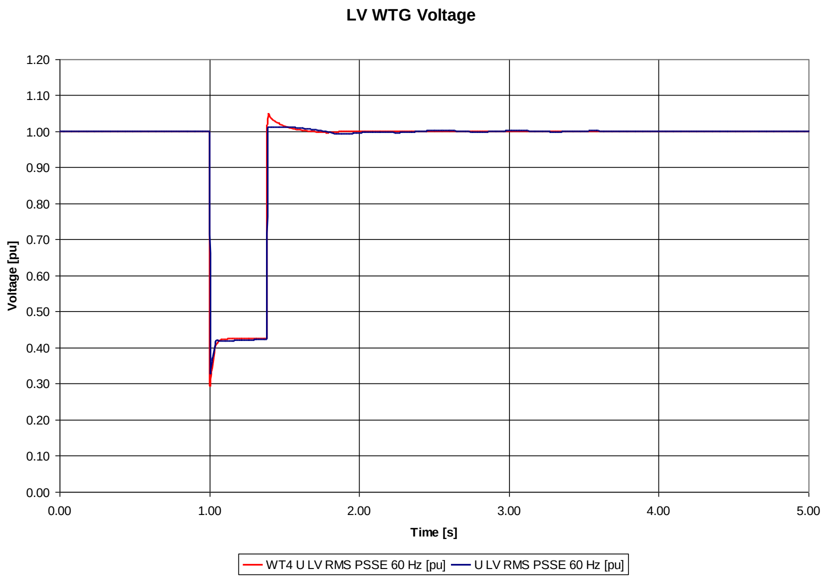
Dynamics models available in major simulation platforms

- Generic (library) – simple models for interconnection studies, contingency assessments, etc. (PSS/E, PSLF, ETAP, etc.)
- User-defined – more detailed models for optimization, in-house studies, etc. (usually selected packages that are widely used, like PSS/E, DigSilent)

Transient models

Detailed equipment specific time domain – for protection coordination, insulation coordination, subsynchronous resonance assessments, special protection schemes, etc. – now available in selected packages (e.g., PSCAD, NETOMAC).

PSS/E LVRT Benchmark Simulation



Summary – How FC WTGs provide Power Control (existing and anticipated)

Capability	*Now*	*Soon*
Power Output (Curtailment) Control		
Ramp-Rate Control (ref change and startup)		
Frequency Droop Regulation Up		
Frequency Droop Regulation Down		
Frequency-Dependent Droop		
Spinning reserve (“delta control”) capability		
Transient underfrequency (“inertial”) response		
High wind ride-through		
AGC Response (from Park RTU)		
Rate Variation Control		

Comparison of FC WTG with Synchronous Generation to Comply with Interconnection Requirements

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	Variable Speed Full Converter (FC)	Turbine-driven synchronous generator (SG)	Comments
Fault Ride-Through (Zero- and Low-Voltage)	YYY	Y	SGs may have fault clearing times as short as 6 cycles (0.1 sec) before instability. FCs can withstand for extended periods – theoretically forever.
Fast Dynamic Voltage Regulation	YY	YYY	SG is still the "gold standard". FCs are very comparable, but generally have more impedance to system. FCs can have issues in very weak (low sc strength) systems.
Fast Active Power Regulation and Frequency Response	YYY	YY	FC has fast, precise converter response. Can change output power at 10%/sec or more. SGs are limited by turbine ramp rates – generally an order of magnitude slower – 10% per minute or slower.
Short Circuit Current	YYY	X	FC sc contributions are roughly 1-2 pu after 3 cycles. SGs can have sc over 6 pu, with large dc offsets.
Ability to operate in series capacitor-compensated system	YYY	X	Sub-Synchronous Resonance (SSR) is a major problem for synchronous machines; FCs generally immune to SSR concerns.
Abnormal Frequency Operation	YYY	Y	SGs generally have +/-2% continuous range; some have far less. FCs have much wider continuous range.
Generic Model Availability	YY	YYY	Wind Turbine models are new, still have some bugs. SG models are well-established by long usage.

X = Capability generally not available w/o supplemental equipment

Y = Generally OK, but shortfalls in some apps YY = Generally acceptable YYY = Excellent

Possible Future Developments for Full Converters

•**Weak grid controls** for sustained stable operation in systems with SCR < 3

(SCR = 3-phase short circuit MVA at regulation point / aggregate turbine MW)

• **Power oscillation damping** for inter-area power oscillations.

• **Sub-synchronous resonance damping** for series compensated systems

• **Isochronous operation** – standalone operation

These are capabilities that can presently be provided by synchronous generators.

Each generator has its advantages and disadvantages, but Full Converter WTGs generally have many advantages and few major disadvantages.

If we could only control the wind…

Thank you for your time

Questions?